Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

A SURVEY OF POWDER FORGING LITERATURE, 1960-1974

H.M. Skelly

SEPTEMBER 1976

MINERALS RESEARCH PROGRAM
PHYSICAL METALLURGY RESEARCH LABORATORIES
CANMET REPORT 76-38

Available by mail from:

Printing and Publishing
Supply and Services Canada,
Ottawa, Canada K1A 0S9

CANMET
Energy, Mines and Resources Canada,
555 Booth St.,
Ottawa, Canada K1A 0G1

or through your bookseller.

Catalogue No. M38–13/76-38 Price: Canada: $3.75
ISBN 0-660-00975-7 Other countries: $4.50

Price subject to change without notice.

En vente par la poste:

Imprimerie et Édition
Approvisionnements et Services Canada,
Ottawa, Canada K1A 0S9

CANMET
Énergie, Mines et Ressources Canada,
555, rue Booth
Ottawa, Canada K1A 0G1

ou chez votre libraire.

N° de catalogue M38–13/76-38 Prix: Canada: $3.75
ISBN 0-660-00975-7 Autres pays: $4.50

Prix sujet à changement sans avis préalable.

ERRATA SHEET FOR CANMET REPORT 76-38

A SURVEY OF POWDER FORGING LITERATURE, 1960-1974

H.M. Skelly*

* Research Scientist, Metal Processing Section, Physical Metallurgy Research Laboratories, CANMET, Department of Energy, Mines and Resources, Ottawa, Canada.

FOREWORD

Although forming or forging of metal powders, for example platinum and tungsten, was first carried out many years ago, it is only in recent years that interest and activity have become widespread in this field. The reason for this development is chiefly one of economics. In many cases it is cheaper to produce a part of desired properties in this way than by the conventional methods of casting, forging, or machining. In some instances it is also a question of necessity, as this is the only way in which a given component can be made. The energy crisis also provides another very potent stimulus for using this method of fabricating parts, because it is energy-saving. It is possible to make finished parts from metal powders simply by compacting the powder, heating the compact to sintering and forging temperature and then forging to finished dimensions with one stroke of the press. The process is also very clean and therefore environmentally attractive. Forging of metal powders looks very promising also for the future as it is possible that more metals will be recovered from the ore in the form of powders thus eliminating the need for an additional operation to produce them. Iron and nickel are produced as powder from the ore in the Hoeganaes and Sherritt Gordon processes, respectively. The iron used in Quebec Metal Powders' process is obtained as a by-product from the purification of ilmenite ore.

The present status of preform forging is that the process is actually being used to manufacture some parts, and that considerable research and development work is being undertaken. It is difficult for a new process to become generally accepted because there is a tendency to resist anything new or different when the old techniques are satisfactory and the purchase of new equipment is involved. However, there is no doubt that preform forging is here to stay and that the future will see greatly expanded use of it. An important spur to this greater use will be energy conservation.

The purpose of this survey has been to collect information on powder forging from as many literature references as possible, for the convenience of workers in this field.

D. F. Coates,
Director-General,
CANMET

AVANT-PROPOS

Bien qu'on effectuait le forgeage ou le façonnage de poudres métalliques, telles que le platine et le tungstène, par les années passées, ce n'est que récemment qu'on s'est intéressé à cette activité et qu'on l'a développée. La raison principale en est l'économie. Dans la majorité des cas, il est plus économique de produire une section, ayant les propriétés recherchées, par le forgeage, plutôt que par les méthodes classiques de moulage, forgeage ou usinage. Dans d'autres cas, cette méthode s'avére indispensable pour obtenir la pièce désirée. La crise énergétique procure une autre raison valable pour l'emploi de ce procédé de fabrication, car il est avare d'énergie. La façon de fabriquer des pièces finies à partir des poudres métalliques consiste simplement à comprimer la poudre, chauffer le comprimé jusqu'à la température de frittage et de forgeage et ensuite à le forger à l'aide d'un coup de presse pour obtenir les dimensions voulues. Ce procédé est très propre et ne pollue pas l'environnement. L'avenir du forgeage des poudres semble très prometteur, étant donné la possibilité de récupérer, du minerai, beaucoup plus de métaux sous forme de poudres, éliminant ainsi une opération supplémentaire. On produit donc du fer et du nickel sous forme de poudre à l'aide des procédés Hoeganaes et Sherritt Gordon, respectivement. Le fer qu'utilise la compagnie Québec Metal Powders est le sous-produit obtenu de la purification du minerai d'ilménite.

Le forgeage de comprimé est présentement employé pour fabriquer certaines pièces et on est à faire de plus amples recherches pour élaborer cette technique. Il est toujours difficile de faire accepter une nouvelle méthode, surtout lorsque les vieilles techniques satisfont les besoins et que le nouveau procédé requiert l'achat d'équipement supplémentaire. Par contre, le forgeage de comprimé s'est imposé malgré tout et il sera sûrement plus utilisé a l'avenir. De plus, la conservation de l'énergie stimulera grandement son utilisation.

Le but de cette étude était de compiler le plus de références possible sur le forgeage de comprimé afin de faciliter la tâche des travailleurs dans ce domaine.

D. F. Coates,
Directeur général,
CANMET

TABLE OF CONTENTS

INTRODUCTION

The Department of Energy, Mines and Resources has identified Fabrication and Metallurgical Processing as one project under the general Minerals Research Program. Powder forging is an important branch of metals fabrication which can utilize Canadian-produced minerals. The development of powder forging in Canada would be an important step in increasing the economic base of the Canadian secondary metals industry. Powder forging can save energy and materials and it is environmentally clean.

Establishment of powder forging in Canada would have important implications for Canadian industry as it can produce high-strength powder-metallurgical products economically, utilizing raw materials produced in Canada.

The conversion of metal powder or granules to useful objects was carried out at least 5,000 years ago. This method was used in ancient times because the primitive furnaces could not attain temperatures sufficiently high for fusion to occur. Eventually, heating methods improved and melting and casting became possible.

Modern powder metallurgy is said to have had its beginnings in the work of Wollaston in Britain, in 1829, when he produced platinum ingots from powder. Another important development was the work of Coolidge in the U.S.A. in the early part of this century when he successfully converted tungsten powder to ductile filaments. Later it was realized that, in some instances, the powder metallurgy process could produce finished articles more cheaply than the established methods of casting, forging, and machining. This led to the growth of the sintered engineering-components industry, starting in the late 1930's. Today, the powder metallurgy process is used to make a great variety of products from ferrous and non-ferrous metals and alloys, refractory metals, superalloys, and composites. It is interesting to note that, in recent times, there has been an increasing tendency to develop methods of ore treatment that result in the metal being

*Research Scientist, Metal Processing Section, Physical Metallurgy Research Laboratories, CANMET, Department of Energy, Mines and Resources, Ottawa, Canada.

produced in the form of powder. This is done very successfully by Sherritt Gordon Mines in Canada for nickel and other non-ferrous metals. It is probable that the future will see more primary metals being recovered as powders. This method of extraction can be economical and it results in less pollution than do conventional methods involving smelting and casting. For example, in the production of iron and steel, the growing shortage of metallurgical grade coke and increasing concern over atmospheric pollution are causing producers to consider other processes. One of those being considered is a process in which methane is reacted with steam in the presence of a suitable catalyst and the hydrogen produced is used to reduce iron ore. The heat for such a process could come from the High-Temperature Nuclear Reactor (HTR)[i]. As Roll[ii] has pointed out: "Powder metallurgy saves materials as well as energy by not generating scrap. It saves materials and energy by recycling scrap from other sources. It uses energy efficiently and has the potential for conserving even more. It does not foul the atmosphere, or dump pollutants into the streams". As a consequence of future developments, the practice and technology of converting metal powders into useful products will become increasingly important in the primary and secondary metals industries.

Production,research,and development work on metal powders grows impressively each year in both the West and the communist-bloc countries. Interest and investment in powder metallurgy are also on the increase in the so-called "third world" countries. The countries where most production, development, and research are being undertaken today are Japan, France, Sweden, United Kingdom, United States, U.S.S.R., and West Germany. However, many other countries are active in these fields, for example Australia, Brazil, East Germany, Eire, Finland, India, Israel, Italy, Poland, Rumania, South Korea, Spain, Switzerland, and the United Arab Republic. One can name several reasons for this interest and activity on the part of such a variety of countries, but the most important reasons are economy of material, less consumption of energy, reduction in skilled labour requirements, and less pollution. In the United States and Japan, considerable research and development work is being conducted in industrial and government laboratories. In the Soviet Union there are important research centres in which all activities are in the field of powder metallurgy. The British Steel Corporation is actively engaged in powder metallurgy. West Germany is also very prominent in powder metallurgy production and technology. The French were reported to be establishing a technical research centre for powder metallurgy in 1975[iii].

(i) Chemistry in Britain, Vol.11, No.6, 206-207, June 1975.

(ii) Roll, Kempton H. "Impact of the energy and materials resource problems on powder metallurgy", Soc.Automotive Engineers. Preprint No.750101, for meeting of Feb.24-28,1975, 8 p.

(iii) "Metal Powder Report", Vol. 30, No. 6, 170, June 1975.

Canada's involvement in powder metallurgy is modest but significant. This country is an important producer of metal powders, especially iron and nickel. There are also several plants in Canada that make parts from metal powders, mainly for the automotive industry. However, in order to keep abreast, and preferably ahead, of modern technological developments and to help establish more secondary industry, it is important that Canada expand its research and development work on methods and techniques of converting metal powders into useful products. The applications are diverse, involving light and heavy engineering, transportation, and ordinary, every-day products for use in home and office.

Many of the advantages of powder metallurgy can be seen clearly in powder forging. Powder, or preform, forging is the consolidation and densification of metal powders, using forging as one of the steps in the process. Preform forging combines the advantages of conventional powder metallurgy, such as dimensional accuracy and minimal material waste, with the high strength of forgings. Whereas conventional forging requires several blows and dies, preform forging can usually produce a fully formed component with one blow only. These and other advantages of powder forging are brought out in this literature survey.

A typical powder forging procedure would be as follows:

1. Prepare green compact, or preform, by compaction in a metal die or by isostatic compaction.

2. Sinter the preform in a controlled atmosphere.

3. Forge the preform in a closed die.

Although experimental work on preform forging was carried out about 30 years ago, it is only comparatively recently that the process has attracted much attention. During the last ten years considerable interest has been generated in the process and many papers and reports have been published. Also, there is little doubt that much interesting but unrevealed work is being carried out behind closed doors. Interest has been focussed mainly on the production of forgings made from ferrous powders, but non-ferrous, refractory and superalloy powders have also received attention.

Because of the obvious importance of powder forging, experimental work was undertaken in the Physical Metallurgy Research Laboratories. A natural ancillary activity to this work was keeping informed and up-to-date on new developments, through the literature. It was felt that it would be useful to have the references abstracted and collected for the benefit of those interested in this rapidly growing technological field.

The survey encompasses articles on a variety of powder forging techniques and procedures, utilizing ferrous and non-ferrous powders. Also included are some references dealing with the hot-compaction of powder into billets for subsequent forging, extruding or rolling. Such a practice has been used for beryllium, refractory metals and superalloys. Several abstract journals were systematically searched. As most of the pertinent work has been published comparatively recently, it was decided that the survey of abstract journals need go back no farther than 1960. Many of the articles contained relevant references which were also obtained and read; two references to work published before 1960 were obtained in this way. This survey ends with 1974.

The following abstract journals were searched:

J. Iron and Steel Inst. Abstracts (UK), Vol. 194, 1960 to Vol. 211, 1973 (last edition).

ASM Review of Metal Literature, Vol. 17, 1960 to Vol. 24, 1967 (last edition).

Metallurgical Abstracts, (UK), Vol. 27, 1959-60 to Vol. 32, 1964-65 (last edition).

Metals Abstracts (New. USA/UK), Vol. 1, 1968 to Vol. 8, 1975.

In addition to the above, the following journals were regularly consulted:

Metal Powder Report (abstract journal UK)
Powder Technology (UK)

Powder Metallurgy (UK)

International J. of Powder Metallurgy and Powder Technology (USA)

Powder Metallurgy International (West Germany)

Precision Metal (USA)

Metal Progress (USA)

Soviet Powder Metallurgy and Metal Ceramics (Translated from Russian)

Iron Age (USA)

J. of Metals (USA)

Metals Engineering Quarterly (USA)

P/M Technology, APMI (USA)

Metallurgia and Metal Forming (UK)

Materials Engineering (USA)

Product Engineering (USA)

Whenever possible, the original articles were read and abstracted, but where an abstract only was consulted, the source of the abstract is acknowledged.

Generally, articles or papers in a language other than English or French were not included unless a translation was available. The bulk of non-English references are in German, Japanese, or Russian, and most of these have been presented in English at various conferences. Most of the work reported has been done in the United States, Japan, West Germany, United Kingdom and Sweden. Although patents relating to various aspects of powder forging have been issued, they are not included in the survey.

An attempt has been made to extract the essence of the articles and, in doing so, to provide useful and practical information rather than a mere catalogue of references. The abstracts are listed chronologically and grouped under year(s) of publication. In some instances, papers presented at conferences were not published until the year following the conference and, in such cases, the paper is listed under year of publication.

In order to augment the usefulness and convenience of the survey, author and subject indices are provided. Where no author's name is given for an article, the name of the publication in which the article appears is listed in the author index.

1945-1959 (1-2)

1. Henry, Otto H. and Cordiano, J.J. "Hot pressing of iron powders", Metals Technology T.P. 1919, 10 p, Oct. 1945.

Henry and Cordiano investigated the hot pressing of electrolytic iron powder. It is of interest to note the broad similarity between their technique and preform forging of powder as practised today. The powder was compacted and then hot pressed in a heated die. Hot pressing was done at 138 MPa (20 ksi) at temperatures up to 780°C and for periods up to 450 sec. The properties obtained were far superior to those of conventionally pressed and sintered specimens.

2. Mott, Lambert H. "Progress report on hot forging prealloyed metal powders", Precision Metal Molding, Vol. 10, No. 10, 38-39, 89-94, Oct. 1952.

This comparatively early article reports that recent development of prealloyed powders has enabled metallurgists to design methods of fabrication directed towards manufacture of high-density, high-strength, heat-treatable objects from metal powders. Mott's article deals with the elimination of porosity from compacts by pressure and plastic deformation, i.e., hot coining. Hydrostatic pressure alone will not bring about the desired densification - metal movement similar to that in shear is essential. The porous nature of the compact or preform invalidates calculations concerning the direction or amount of plastic flow during forging. Ferrous and non-ferrous powder alloys that are hot coined exhibit physical properties and response to heat treatment as good as, or superior to, the same alloys made as conventional forgings. Cobalt-based high-temperature prealloyed powders contain the carbides as fine, uniformly distributed particles, resulting in properties superior to those of cast material in which the carbides occur as coarse inclusions. Mott predicts that, within a few years, the powder forging process will begin to compete commercially in the production of small parts.

1960-1969 (3-34)

3. Anon. "Forgeable tungsten ingots of large size produced by new powder metallurgy process", Industrial Heating, Vol. 27, No. 7, 1446, 1448, 1450, July 1960.

Cylinders of tungsten, about 20 cm diameter by 20 cm high, were compacted from powder, sintered, and then forged at high temperatures.

4. Anon. "Advanced forming techniques spur beryllium usage", Iron Age, Vol. 188, 111-113, Dec. 14, 1961.

This article describes some of the advances in beryllium fabrication technology reported at a Beryllium Metallurgy Conference held at New York University.

One of the major reasons for the restriction in the use of beryllium has been the difficulty in forming it. However, the fabrication problems are being solved. Most beryllium components are now being produced by hot pressing beryllium powder, followed by machining to the desired shape. Details of the hot-forming process are given. Forging of beryllium has recently been successful. Two methods are used - pressing of encapsulated powder and forging of hot-formed metal. The former is used for simple shapes which have no special property requirements and the latter is used for more complex shapes.

5. Cieslicki, M.E. "Forging beryllium powder", J. Metals, Vol. 14, No. 2, 149-153, Feb. 1962.

A technique developed at Wyman-Gordon for the press forging of beryllium powder is described. The powder is enclosed in a container of nickel, stainless steel or plain carbon steel. The process has resulted in a lowering of the price of beryllium parts by as much as 50%. Parts have been made whose as-forged thickness ranges from 0.3 cm to 30 cm. Depending upon thickness and other configuration considerations, parts can be forged up to about 250-cm diameter. Structural members, cones, containers, sheet and other mill forms have been produced. Work to date indicates that an engineering material with reasonable fatigue, notch, tensile, bend and bulge test properties can be made by the forging process.

6. Young, A.W. "Tough alloys become formable", Iron Age, Vol. 195, No. 6, 65-66, Feb. 11, 1965.

Young describes a process, which he calls "powder forging", whereby a metal powder, contained in a "can", is heated and then pressed to shape with conventional forging equipment. The powder is compacted and formed to shape during pressing, and the can subsequently removed by chemical or mechanical means. Development work on this process was done by Wyman-Gordon Co., Worcester, Mass. The process is not more economical than conventional methods, its main advantage being that it can be successfully used for "difficult" materials such as refractory metals and certain nickel-base alloys. Young also reports that Wyman Gordon has done work on producing forging preforms by isostatic compaction. This technique is said to reduce costs over conventional forging methods.

7. Parikh, N.M., Farrell, K.F. and Spachner, S.A. "Final report on improved production of powder metallurgy items", Technical Rep. No. AFML-TR-65-103. Prepared under contract AF33(657)-9140 by IIT Research Inst., Chicago, Ill. Mar. 1965.

(See also: Farrell, K. "Technical note on forging Inconel 713C powder compacts", Int. J. Powder Met., Vol. 2, No. 1, 3-5, Jan. 1966, and Parikh, N.M. "Properties of superalloys made by hot working of prealloyed powders", 1968, Plansee Conference Proc. - reproduced in "Forging of powder metallurgy preforms", New Perspectives in Powder Metallurgy, Vol. 6, 273-298. Ed. by Hausner, Henry. H., Roll, Kempton H. and Johnson, Peter K. Published by MPIF, New York, 1973.)

Parikh and his co-workers report that superalloys Udimet 700 and Inco 713C can be forged in sintered powder billet form, giving properties as good as, or better than, those of the cast and wrought materials.

8. Cross, Allen. "Forgings from sintered aluminum", Precision Metal Molding, Vol. 23, No. 8, 23-25, 46-47, Aug. 1965.

A commercial process for the fabrication of sintered products from aluminum powders is now available. The sintered compacts can be worked by forging and other commonly used metal working processes. Lack of preferred orientation permits sintered aluminum to flow uniformly when worked. This allows the material to be cold forged into complex shapes with simple starting blanks. Sintered preforms for hot or cold forging can be made at lower cost than the cast wrought blanks normally used.

Blanks suitable for hot forging are prepared by compacting and sintering a mixture of aluminum powder and alloying elements. For a forged part with a complex shape, a preform approximately the shape of the finished part is made. Products made from the aluminum preforms have good mechanical properties, uniform composition, few inclusions, fine grain size and non-directional properties.

9. McIntire, H.O. "Trends in powder metallurgy", Battelle Technical Review, Vol. 17, No. 1, 16-21, Jan. 1966.

In this review the author discusses various aspects and developments in powder metallurgy. Forging of metal powder preforms is one of the fabrication or consolidation techniques described.

10. Smith, T.J. and Weber, E.P. "Forging of 410 stainless steel made by powder metallurgy", Proc. New and Exotic P/M Materials Clinic Conference, Spring 1967, Cleveland, Ohio. Sponsored by In-Plant Powder Metallurgy Assoc. (Copyright by MPIF, New York.)

It was demonstrated that 410L stainless steel powder could be consolidated and forged to give properties as good as those of conventionally wrought material, except for elongation which, however, was still adequate. The powder, made by water-atomizing a prealloyed melt, was isostatically compacted at 345 MPa (50 ksi) and sintered in hydrogen at 1120-1230°C for 1 or 4 hr. Forging reductions of up to 70% were achieved. The structure of the forged and heat-treated powder product was essentially that of tempered martensite, with no evidence of porosity.

11. Hirschhorn, J.S. "Powder metallurgy research - contemporary trends", J. of Metals, Vol. 19, No. 9, 25-30, Sept. 1967.

Hirschhorn reports that Inconel 713C powder compacts which were successfully forged gave tensile strengths almost double those of vacuum-melted and cast materials. The powder compacts are said to have greater forgeability than cast ingots because of higher purity and greater uniformity of composition.

12. Kobrin, C.L. "Forging powder preforms combine strength, economy", Iron Age Metalworking International, Vol. 6, No. 11, 38-39, Nov. 1967.

Powder producers, aware of the significance of powder forging, are beginning to produce powders specifically for forging. Cadillac engine connecting rods, made by powder forging, are said to have successfully completed trial runs. The Haller Division of Federal Mogul Corp. announced the availability of powder forgings with properties equivalent to those of wrought steels.

13. Orrell, N.G. "Beryllium powder forging", Perspectives in Powder Metallurgy, Vol. 1: New Methods for the Consolidation of Powders, Plenum Press, New York, 203-220, 1967.

The first successful forgings made from beryllium powder were produced by Wyman-Gordon in 1959. Since then, Wyman-Gordon has forged several thousand beryllium components in different configurations. The size of the forgings has ranged from less than 2 kg to 545 kg. Mechanical properties obtained are about 550 MPa (80 ksi) UTS and 12% elongation.

The powder is first degassed and sealed in steel cans, the design of which varies according to the part's shape. After heating to forging temperature, the cans are press-forged in one pass to final shape. The can is removed either by pickling, machining or mechanical means. The part is then machined to final dimensions, either for a rough contour or a finished design.

Although experience in powder forging of beryllium has still not reached the stage of sophistication of wrought bar materials, the powder forging technique offers considerable savings in material as compared with machining from a press-sintered block.

The mechanical properties of forged beryllium powder are generally intermediate between those of parts produced by press sintering and those shaped by solid forging.

Some limited experimental work indicates that certain advances offer great potential for improvements in forged beryllium products. It is expected that future efforts in re-forging cycles and bare forging techniques will permit the manufacture of sophisticated shapes commensurate with the present capability in typical die-forging of other materials.

14. Roll, K.H. "Projecting powder-metal progress", Machine Design, Vol. 40, No. 2, 30, 32, Jan. 18, 1968.

This is a brief review of future prospects for powder metallurgy. Preform forging is already being used for beryllium and tungsten and the process appears to be economically feasible for iron powder. Connecting rods, hot forged from iron alloy preforms, have successfully passed engine-life tests. Progress is predicted in the forging of preforms made from superalloys and titanium.

15. Hirschhorn, Joel S. "Advances in powder metallurgy". Presented at Interamerican Conference on Materials Technology, May 20-24, 1968, San Antonio, Texas. Published by Amer. Soc. Mech. Engrs., 222-230, 1968.

Hirschhorn points out that preform forging will be of great benefit to the powder metallurgy and forging industries. The latter will benefit from smaller energy requirements, reduced scrap losses, superior properties because of the elimination of inhomogeneities and impurities, and the possibility of fabricating novel alloys and composite materials. The powder metallurgy industry will benefit from increased powder consumption which will result from increase in powder products, improved properties over conventional forgings, and increase in size and complexity of powder metallurgy parts.

16. Greenspan, J. "Some effects of powder particle size on the physical behaviour of press-forged beryllium", Europäisches symposium über pulvermetallurgie, Stuttgart, Vol. 1, 1-19, May 1968.

The effect of powder particle size distribution on the properties of open-die forgings made from hot-pressed beryllium compacts was investigated. It was found that strength depended on powder particle size and thermal history.

17. Reilly, W.E. "Fabrication process determined by Ti64AV powder characteristics". Presented at Fall Meeting Met. Soc. AIME., Detroit, Michigan. Paper No. A68-49, Oct. 13-17, 1968.

To determine a suitable process for the manufacture of turbine engine hardware, prealloyed and blended powders of Ti64AV alloy were fabricated in various ways. The process found to offer the greatest potential was isostatic pressing of attrited powders, followed by vacuum sintering and closed-die forging.

(See also: "New Perpectives in Powder Metallurgy", Vol. 6 Forging of Powder Metallurgy Preforms, 299-317. Ed. by H.H. Hausner, K.H. Roll, and P.K. Johnson. Published by MPIF, 1973.)

18. Joyce, J.F. Preliminary information from TRW Inc., Cleveland, Ohio on U.S. Air Force Contract AF33(615)-5411, Abstracted in DMIC Review of Recent Developments, Powder Metallurgy, Battelle Memorial Inst., Columbus, Ohio, Nov. 1, 1968. (See also Ref. No. 23.)

TRW Inc. carried out work on closed-die forging of preforms made from alloys B-1900, MAR-M200, TD nickel-10% ThO_2 and TD nickel-chromium, all of which are difficult to forge from cast billets. Superalloys B-1900 and MAR-M200 were slip cast using -200 mesh particles, sintered, and successfully forged, but the stress-rupture properties were considerably below those of the cast material; this was attributed to high oxygen content and porosity. Forgeability of pressed and sintered compacts of TD nickel-chromium was very poor in comparison with that of hot-upset fully dense material. It was concluded that, since TD nickel-chromium must be densified prior to forging, the alloy was not suitable for powder forging. Sintered compacts of TD nickel-10% ThO_2 forged almost as well as their fully densified counterparts that had been hot upset. The strength and ductility at 1095°C of the wrought, sintered TD nickel-10% ThO_2 powder were below that of wrought, fully dense material. It was thought that proper working procedures might improve the strength and ductility of TD nickel-10% ThO_2 sufficiently to make it competitive with extruded bar stock.

19. Anon. "Ferrous powder for forging preforms", Precision Metal, Vol. 27, No. 2, 54-55, Feb. 1969.

A prealloyed, atomized steel powder containing 2% Ni and 0.5% Mo was developed by A. O. Smith Corp. specifically for preformed and hot-forged parts. The new powder is said to be particularly suitable for parts such as ring gears, pinions, connecting rods and other heavy-duty applications.

20. Khol, Ronald. "Forged powder metal", Machine Design, Vol. 41, No. 8, 142-146, Apr. 3, 1969.

This review gives the following as the two main reasons for the interest in powder forging: (a) method of producing lower-cost forgings and (b) possible way to form new, untractable, heat-resistant alloys. Khol mentions several U.S. companies that are investigating the powder forging process: Federal Mogul Corp., IBM, Ford Motor Co., General Motors, Dynamet Inc., Fansteel Inc., TRW Inc., Pratt and Whitney, and Wyman-Gordon. The following parts are said to have been made, mainly for development purposes, but in some cases for production: gears, shafts, valves, bearing rolls, sprockets, levers and connecting rods. Materials being used include low- and high-alloy steels, titanium alloys and nickel-base superalloys. The difficulty of obtaining satisfactory inter-particle bonding of superalloy powders is being overcome by processing in an evacuated steel can. Preforms have been made by slip casting, isostatic pressing and conventional unidirectional pressing. Khol reports the importance of knowing how to shape the preform for optimum properties, but such information is a well-guarded secret. The part should be designed as a close-tolerance forging rather than a sintered product.

21. Brandstedt, Sven B. "New powder-making process may expand P/M's capabilities", Precision Metal, Vol. 27, 52-55, Apr. 1969.

Powder made by the "Coldstream Process" is said to be very suitable for preform forging. In this process a high-velocity, high-pressure airstream shoots material through a venturi nozzle at a target in an evacuated blast chamber. At the nozzle exit there is a rapid drop in pressure and temperature. The chilled material shatters when it hits the target. The particles produced are very small and uniform with nearly oxide-free surfaces. This product is said to have an advantage over the coarser atomized powder which usually has a high degree of surface oxidation.

22. Anon. "The expanding role of powder metallurgy", Metal Progress, Vol. 95, No. 4, 60-69, Apr. 1969.

The "hot re-forming" of powder was one of the topics discussed during a meeting of eighteen specialists representing various facets of powder metallurgy. Important advantages of the hot re-forming process are said to be elimination of expensive preliminary forging operations, improvements realized by densifying the compact and close size control. Hot re-forming makes it possible to switch from conventional low-density steel parts with UTS of 550 MPa (80 ksi) to re-formed parts with 1380-2065 MPa (200-300 ksi) UTS. Cleaner powders, containing less oxide and less insolubles, are required. Development work is being done with everything from plain carbon to spring steels and Type 4600 and 8600 materials. The views expressed regarding prealloyed versus "blended" powders were not conclusive, both being said to be successful.

23. Kortovich, C.S. "Close tolerance forgings from powder metallurgy preforms". Final report AFML-TR-69-181, TRW Inc., Cleveland, Ohio. Contract AF33(615)-5411, June 1969. Abstracted in DMIC Review of Recent Developments, Powder Metallurgy, Joyce, J.F., Battelle Memorial Inst., Columbus, O., 24 Oct. 1969. (See also Ref. No. 18.)

Describes a program conducted to establish a process for precision forging of powder preforms. Powders of B-1900, MAR-M200, TD Ni-10 vol % ThO_2 and TD Ni-Cr were evaluated for compaction, forgeability and strength. Slip-cast preforms gave the best forgeability for both superalloys. Low stress-rupture properties obtained for the superalloys were attributed to high oxygen content and to porosity. For alloy TD Ni-10 vol % ThO_2, forgeability was as good as that of fully dense material but the elevated temperature tensile properties were lower than those of extruded bar stock. Forgeability of TD Ni-Cr was poor compared with that of fully dense material.

24. Anon. "P/M hot forging in the U.K.", Powder Metallurgy Information Bull. (260) July/Aug. 1969.

G.K.N. (Guest, Keen and Nettlefolds) have been carrying out development work on powder forging since 1965 at their research centre in Birmingham, England. Automobile engine tests on connecting rods made from powder forgings have proven to be satisfactory.

25. Anon. "Aluminum powder metallurgy: recent progress in the USA", Metal Forming, Vol. 36, No. 8, 222-224, Aug. 1969.

Cold forging and coining are said to be simplified with aluminum powder, and enhanced properties and closer tolerances obtained.

26. Walker, P. "New forging techniques point to P/M boom", Metalworking News, Vol. 6, Sept. 1969.

Recent advances in the manufacture of parts made by preform forging of powders may lead to rapid growth of the P/M industry. Possible applications are in farm machinery, garden tractors, appliances and automobiles. A.O. Smith-Inland is planning to double its powder capacity in view of the predicted boom.

27. Anon. "An emerging process: P/M forging preforms", Precision Metal, Vol. 27, No. 9, 55-56, Sept. 1969.

Engineering Sinterings and Plastics report on the results of three years of investigating the hot forging of preforms in closed dies. Ferrous parts, pressed to a density of 6.0 g/cm^3, were successfully hot forged to a minimum density of 7.5 g/cm^3. It was not sufficient to simply make the preform thicker than the finished part, but it had to be shaped to provide the extra metal needed for lateral flow at the high forging temperature used. Internal oxidation of the preform prior to forging was avoided by induction-heating to forging temperature.

28. Raymont, W. "Production of P/M titanium fittings", Presented at Metal Powder Industries Federation's Fall Conference, Philadelphia, Pa., Oct. 1969.

Elemental mixtures and prealloyed powders of titanium alloys were compacted and sintered and compared with the forged preform powder product.

29. Hense, V.C. "Forging powder metal preforms for the automotive industry". Presented at Metal Powder Industries Federation's Fall Conference, Philadelphia, Pa., Oct. 1969.

Differential side pinions, pump gears and ring gears for the automotive industry have been successfully forged from powder preforms. Cost of powder is not a cost deterrent when the saving in raw material is greater than 50%.

30. Anon. "P/M shoots for the big time", Steel, Vol. 165, No. 20, 41-45, Nov. 17, 1969.

A review article which states that powder producers, parts manufacturers, forging companies and automakers are investigating the various ways of converting ferrous powders to forgings. Federal-Mogul produced pinion gears by striking a hot preform once. No machining was required on the part and tensile strengths were about 2065 MPa (300 ksi) with 3% elongation. The article points out that a forged preform lacks the characteristic flow lines of a conventional forging and has uniform stress resistance in all directions. Other applications being considered are those conventional forgings in which the ratio of finished part to raw material weight is about 1:2. These include differential side gear, transmission input ring gear, transmission output ring gear, rear axle ring gear and connecting rods. Also under study are furnaces for hot forging aluminum preforms, featuring a hot holding chamber from which parts will go directly to the forging press. Nickel superalloy powders are being consolidated by hot isostatic pressing, upsetting and extruding.

31. Walker, P. "Buick may kick off P/M forging", Metalworking News, Vol. 1, Nov. 17, 1969.

The Buick Division of GMC may replace one of its parts with a P/M forging on new cars by 1971, although only for experimental purposes. The part is said to be a beveled gear. The use of P/M forgings could mean a 47% decrease in metal cost. It is also possible that by 1972, additional P/M forgings will be used in the drive trains.

32. Sabroff, A.M. "New developments in hot forging", J. Korean Inst. Metals, Vol. 7, No. 3, 210-218, Dec. 1969.

The sintering and forging of preforms are discussed.

33. Carlson, E.E. "New high-strength ferrous P/M materials", Progress in Powder Metallurgy, Vol. 125, 63-69, 1969.

In order to expand the range of mechanical properties and make use of new materials such as prealloyed steel powder, considerable effort in the powder metallurgy industry is being directed to developing other consolidation techniques such as hot forging of powder preforms. Hot forming of sintered metal preforms offers the following advantages over present techniques:

a) achievement of fully dense structures, if required

b) capability of manufacturing larger parts than possible previously

c) manufacture of certain large powder parts at a lower investment in capital equipment

d) finer grain structure than normally available in cast or wrought products

e) ability to begin with a chemically purer material.

34. Stefanides, E.J. "Extrusion from P/M blank improves forged parts", Design News, Vol. 24, No. 24, 40-41, 1969.

Forging blanks are prepared by compacting and sintering prealloyed powders of super-alloys and tool steels. When two or more metals or alloys are to be combined in the same part, separate preforms are made for each metal. The resulting preforms are hot forged to the desired contours. In this way, single- or multi-metal parts of difficult-to-fabricate alloys are made with minimal waste.

1970 (35-61)

35. Finlayson, P.C. and Morrell, A.P. "Review of iron powder markets and production processes", Proc. 9th Commonwealth Min. and Met. Congress, 1969. Mineral Processing and Extractive Met., 823-836, 1970.

Mention is made of the work done by General Motors on the forging of connecting rods from preformed powder. It is suggested that high-energy rate forming (HERF) may eventually supplant present methods of making preforms.

36. Knopp, Walter V. "Properties of hot-forged P/M steels", Fall Powder Metallurgy Conf. Proc., Oct. 14-16, 1969, Philadelphia, Pa. Sponsored by MPIF and APMI. Published by MPIF, New York, 11-24, 1970.

The results of experimental hot forging of preforms made from blended and prealloyed ferrous and non-ferrous alloys are reported. The ferrous materials included prealloys and blends made to the compositions: 0.4% C-balance Fe; 1.35% Mn-0.65% C-balance Fe; 1.85-2.0% Ni-0.2% Mn-0.5% Mo-0.4% C. These were compacted at about 550 MPa (80 ksi) and sintered at 1095°C for 15 min. The forgings, made from prealloyed powder, gave tensile properties superior to those of forgings made from blended powder, but both sets of forgings had properties comparable to wrought material.

37. Haller, John. "Hot forging of metal powder preforms", Industrial Heating, Vol. 37, No. 1, 34,36,38, Jan. 1970.

Haller states that the main reasons for the great interest in powder forging are its simplicity and the fact that a large variety of materials can be custom-blended. The preform must be shaped so that, in forging, the material is evenly distributed in the die cavity, thus achieving uniform density throughout the part. Conventional die steels have been found to be inadequate for good die life. Lubrication is important, and certain types of graphite lubricants have been found to be useful. As the preforms are porous, they have to be protected against oxidation, but this porosity is also advantageous in that it permits pressures lower than can be used in conventional forging.

38. Patton, W.G. "Systems that keep automakers on top", Iron Age, Vol. 205, No. 4, 55-64, Jan. 22, 1970.

The rapid growth in the use of powder metallurgy parts by automobile manufacturers is helping to reduce machining expense. Transmission and differential gears are among the hot-forged metal parts expected to go into limited automotive production in 1970. Ring gears and connecting rods are in the advanced development stage. Truck manufacturers and builders of other heavy equipment are expected to start pilot-plant operations on gears and other parts that are now forged conventionally. At its Research Centre, the Haller Division of Federal-Mogul Corp. is setting up a pilot line for the production of hot-forged powder metal parts.

39. Allen, M.M., Athey, R.L. and Moore, J.B. "Application of powder metallurgy to superalloy forgings", Metals Eng. Quarterly (ASM) Vol. 10, No. 1, 20-30, Feb. 1970. (See also Ref. Nos. 44 and 209.)

The authors found that gross segregation in superalloys, such as Astroloy, IN 100 and MAR M-200, could be avoided by casting small, fine-grain ingots. However, segregation problems increased with increasing size of cast billet, and the authors decided that it was unlikely that the same structure could be reproduced in large ingots. The powder metallurgy route was therefore investigated because the degree of segregation should then be no more than occurs in a particle of powder. Astroloy powder was made, collected and hot compacted in an argon atmosphere. The consolidated powder was enclosed in a stainless steel jacket and forgings weighing up to 23 kg were produced by upsetting. After forging, there was no evidence of powder particle origin in the microstructure. The mechanical properties of the powder product were at least the equal of those of conventional forgings. It was forecast that even better material would be obtained by carrying out all operations, from powder production to densification, in vacuum.

40. Jobling, A.V. "Some thoughts on the future of die forging", Metal Forming, Vol. 37, No. 3, 65-73, Mar. 1970. (Presented at 20th Technical Convention of National Association of Drop Forgers, Droitwich Spa, England, Nov. 1969.)

This is a review of die forging and competitive processes such as casting, machining, welding and powder metallurgy. Brief mention is made of preform forging of powders. Two important advantages of the powder process are that only one common stock is necessary for each type of material and the ease with which a precise weight can be dispensed without any complicated equipment or additional operations. One minor drawback of the use of powder is said to be that it cannot be stored in bulk or roughly handled because of the risk of segregation and contamination. One leading manufacturer goes so far as to vacuum-pack in plastic bags to avoid these risks.

One of the criticisms levelled at the use of powder to make high-strength components is that the final product will contain oxide inclusions. However, the author points out the same is true of most commercial cast billets. Also, although powder may contain more oxide in total, it is fine and well distributed, whereas in the billet it is inclined to occur in relatively large inclusions, haphazardly distributed.

In the discussion following presentation of the paper, P.K. Jones (GKN Forgings Ltd.) gave two examples in which forgings made from powder were compared with conventionally made forgings. One was a gear which required a billet three times the weight of powder required for the same component. The other component contained splines on the internal bore which were formed during powder forging, but had to be machined when forged conventionally.

41. Simpson, C. "Progress in powder metallurgy", Engineering, Vol. 209, No. 5418, 240, Mar. 1970.

This article describes work on forging of powder preforms being carried out at Birmingham University, England. The sintered preform is transferred directly from the sintering furnace to the forging press, thus eliminating a forging preheat. It is claimed that the process can already compete economically with conventional processes and, if powder costs are lowered in the future, the economics will favour powder forging even more.

42. Schwartz, N.B. "Sights set on PM preforms", Iron Age, Vol. 205, No. 16, 63-64, Apr. 16, 1970.

According to this article, Universal-Cyclops Specialty Steel Division, Pittsburgh, was the first U.S. steel producer to recognize the potentials of powder forging. This company intends to atomize various alloys and to consolidate them by hot pressing into preforms and mill shapes. Cyclops has the facility for forging, rolling, welding and hot-pressing in an inert atmosphere.

43. Scrase, Terry. "Preforms hold key to major forging, savings", Metalworking Production (U.K.), Vol. 114, No. 18, 41-42, 6 May 1970.

It is revealed that the British Drop Forging Research Association is conducting tests into various methods of producing preforms, including transverse roll forming, casting, horizontal upsetting and sintering powder. The latter is said to have interesting possibilities, although its future depends largely on powder price.

44. Athey, R.L. "New concepts in disk materials through the use of powder metallurgy". Paper presented at Air Force Mat'ls. Symposium, Miami, Florida, 7 p, May 18, 1970. (See also Ref. Nos. 39 and 209.)

Work done at Pratt & Whitney showed that small forgings made from Astroloy powder possessed mechanical properties superior to those of conventional forgings and with a uniformity of microstructure not seen in the latter. Both Astroloy and IN 100 powder billets have been produced in large enough sizes to prove that there is no metallurgical reason why billets large enough for any aircraft engine disc cannot be produced from nickel-base superalloy powders. The powders are described as "all inert" (produced in an inert atmosphere) and are said to permit the forging of superalloys which would be difficult, if not impossible, to produce from cast ingots.

45. Hirschhorn, Joel S., Samat, Manohar and Maxwell, George M. "Induction sintering has potential for powder metal parts", Metal Progress, Vol. 97, No. 5, 135-136,138, May 1970.

It is shown that induction sintering has potential for use in preform forging. Because the forging operation enhances interparticle bonding, the degree of sintering can be reduced, particularly for plain carbon steels.

46. Schwartz, N.B. "Forging P-M preforms: say when", Iron Age, Vol. 205, No. 26, 55-57, June 25, 1970.

The market for forging preforms is divided between the high-volume, low unit-price automotive industry, and the low-volume, high unit-price aerospace industry. Estimates from several industry sources place the potential titanium and super-alloy market at between 7 1/2 and 22 million dollars by 1973. One metal producer projects a market of one million pounds per year for superalloys. Powder requirements for the auto industry, mainly iron, should reach 300,000 tons per year. Pilot production of 300,000 gears from preforms has been completed. Turbine discs in military aero engines are thought to be the first application of powder forgings.

47. O'Connor, J. "Capital spending ante is high in P/M preform systems game", Metalworking News, Vol. 11, (524), 1 July 20, 1970.

Industry representatives attending an International Powder Metallurgy Conference in the U.S.A. estimated that, by 1980, potential sales of P/M forgings will amount to about 300,000 tons per year. The development of integrated systems for production of various powder forging components will cost at least one million dollars. Preliminary estimates of a pilot-plant system being developed indicate that a 10% savings may be achieved over conventional production methods.

48. Pietrocini, T.W. "Newest data on hot forged P/M alloys", Precision Metal, Vol. 28, No. 7, 79, July 1970.

This is an introductory article to a "comprehensive series" on P/M forging of ferrous alloys. Ferrous preforms were sintered at 1120°C for 20 min. Low-ash lubricant was mixed with the powder to minimize inclusions. Special graphite-based forging lubricants were required to ensure correct metal flow. Forging was done at 980°C and 415 MPa (60 ksi). Preform design was extremely critical and considered proprietary.

49. Wick, Charles H. "Forging powder metal preforms: a new production technique", Machinery, Vol. 76, No. 12, 50-52, Aug. 1970.

A description is given of the Cincinnati Inc. pilot-plant method for producing automotive side pinion gears by preform forging in a closed die. Forging is done in a single operation, and machining loss is less than 3%, compared to 70% when parts are machined from bar stock. A high-purity Ni-Mo alloy steel powder of high compressibility is used. Weight control of the preform is maintained within ±0.5%(±1 g). The preforms are made by conventional compacting and sintering. Preforms are induction heated to 845°C for forging, with no protective atmosphere.

50. Hirschhorn, Joel S. and Bargainnier, Roger, B. "The forging of powder metallurgy preforms", J. of Metals, Vol. 22, No. 9, 21-29, Sept. 1970. (See also: Metal Forming, Vol. 37, No. 11, 320-327, Nov. 1970.)

In this review article it is stated that preform forging offers great potential for commercial exploitation. Because of their purity, atomized and electrolytic powders are said to be preferred over other powders. There is some indication that larger fractions of coarser particles might be beneficial in ferrous preforms, and this could lead to low powder cost because such fractions are usually removed or minimized. Prealloyed powders are preferred because high compressibility is no longer a major consideration, densification being accomplished during forging; also, lower sintering temperatures can be used because, with prealloyed powders, it is not necessary to achieve homogenization by diffusion. Isostatic compaction has advantages over rigid die compaction; for example, lubricants are not required in the powder, complex shapes and large sizes can be produced, and tooling can usually be made quickly and at low cost. Slip casting is another powder consolidation method being studied for production of complex shapes from powders of poor compressibility and green strength.

It may be possible to combine sintering and forging preheat in one operation. Sintering of ferrous materials is normally done at 1120-1150°C and indications are that forging can be done 150-350°C lower. Induction heating is an interesting possibility for sinter-preheat of preforms.

The shape of the preform is very important. It appears that preforms with 15 to 30% porosity would be acceptable. Preform weight might have to be controlled within ±1% to achieve desired dimensional control, densification and elimination of flash. If a powder contains large amounts of -325 mesh particles it is possible that there would be large amounts of closed porosity and this would be undesirable as it might promote material contamination and lower forgeability. The effects of rate of pressure application on forgeability, die filling, tool life and densification require investigation.

51. Anon. "P/M forgings poised for production", Materials Engineering (Metals News) Vol. 72, No. 2, 24, Sept. 1970.

Powder forgings are believed to be in production in Britain and Japan, and about to be accepted for automotive parts in U.S.A., where 50,000 automobile side pinion gears have been produced on a pilot-plant basis for the Delco Moraine Division of General Motors. Research workers at Ford have found that the magnetic properties of forged iron powder preforms are comparable to those of low-carbon steels used for high-permeability structural parts.

52. Pietrocini, T.W. and Gustafson, D.A. "Fatigue and toughness of hot formed Cr-Ni-Mo and Ni-Mo prealloyed steel powders", Int. J. Powder Metallurgy, Vol. 6, No. 4, 19-25, Oct. 1970. (See also: Proc. 1970 Int. Powder Met. Conf. sponsored by MPIF and APMI, ed. H.H. Hausner, published Plenum Press. Vol. 4, 431-439, 1971.)

The hardness of hot, densified compacts of four prealloyed steel powders is correlated with tensile, impact and fatigue properties. Test specimens (89 x 13 x 13 mm) were compacted to 80% density, sintered at 1120°C for 20 min and hot pressed at 980°C to 98% theoretical density. The choice of 98% density was dictated by economics as it costs more to produce denser parts. The mechanical properties varied as a function of hardness. The materials were comparable in properties and microstructure to similar ferrous alloys but did not exhibit the flow lines of a typical forging.

53. Brown, G.T. and Jones, P.K. "Experimental and practical aspects of the powder forging process", ibid, 29-42. (See also: Modern Developments in Powder Metallurgy, Proc. 1970 Int. Powder Met. Conf., sponsored by MPIF and APMI, Vol. 4 - Processes, ed. Henry H. Hausner. Plenum Press, 369-383, 1971.)

Practical aspects of powder forging production and properties of forgings are considered. Main variables in the process are (a) preform density, (b) forging temperature, (c) forging pressure and, (d) lubrication. Porosity has to be eliminated and non-metallic inclusions controlled for attainment of optimum properties. For steels, forging temperature limits are about 900-1200°C and forging pressures about 138-690 MPa (20-100 ksi). The density, weight and shape of the preform are very important in obtaining sound forgings. Too much porosity in the preform can result in a type of hot cracking and, in this connection, the hot bend test has been effective in assessing hot-shortness characteristics. Die design can be complex because of the need to use a fully enclosed die cavity and the fact that the preform has a greater volume than the finished part. The properties of the forgings are equivalent to those of wrought steel and, in addition, are isotropic. A large number of components of both simple and complicated shapes have been made in the course of development work. These include automotive gears, drive-shaft flanges, toothed-belt pulley, connecting rods, side-gear blanks and a universal joint inner race. Weight tolerances are such that a balancing operation on connecting rods may be eliminated. Connecting rods and gear box parts made from powder have been subjected to engine tests without failure.

54. Sellors, R.G.R. "Preliminary examination of some factors affecting the isostatic pressing of ferrous powders", Powder Metallurgy, Vol. 13, No. 26, 85-99, Autumn, 1970.

Sellors concludes that isostatic compaction is suitable for the production of forging preforms. It is possible that isostatic equipment will never fully match the economics production rates and fine tolerances achieved when pressing simple shapes on a conventional uniaxial press. However, isostatic pressing is a means of producing components that would be impossible or expensive to produce by any other method. It is feasible to isostatically press complex and large preforms. Vibration of the isostatic-mould assembly is advantageous in moving powder to irregular cavities and in promoting uniformity of fill. In addition, vibration reduces the compaction ratio of the powders so that closer dimensional tolerances can be maintained.

55. Dower, R.J. and Miles, G.I. "High-velocity extrusion forging of billets compacted from iron and steel powders", ibid, 100-113.

In high-velocity extrusion forging a heated billet or preform is extruded at a high strain rate into a closed die. Some of the billets were presintered but most were forged as-compacted. The preforms were coated with an anti-scaling compound (Berkatekt No. 1) and heated to forging temperature without a protective atmosphere. Extrusion forging was carried out in a Dynapak 620D high-velocity forging machine. It is concluded that extrusion forging can be carried out on preforms of iron and steel powders without prior sintering and without using a protective atmosphere during forging preheat. The density of the green preforms was found to be relatively unimportant. However, with sintered preforms, the higher the starting density the greater is the ductility of the extrusion forgings.

56. Jones, P.K. "The technical and economic advantages of powder-forged products", ibid, 114-129.

First-hand experience in the development of techniques for producing ferrous powder forgings is described by Jones. The relationship between forging pressure and density of the forging was determined for a gear forging. Much of the final shape is developed during the early stages of forging when the loads required are relatively low, and by the end of the forging stroke, when load requirement is at its maximum, most shape detail has been achieved. The last stages of forging are simply hot compaction involving very little metal flow. A density of 7.5 g/cm^3 was obtained at a forging pressure of 117 MPa (17 ksi) and a density of 7.8 g/cm^3 at a pressure of 386 MPa (56 ksi). Forging temperature may be in the range 900-1200°C. Design of preform, forging tool, and die are important. In the automotive field there is a great need for prealloyed powders containing manganese and chromium as principal alloying elements, although it is claimed that these elements can give problems not encountered with nickel and molybdenum, during atomization and subsequent processing, because of the reduction characteristics of the oxides. Jones lists the following advantages of the powder forging process: simplified forging route, improved detail and surface finish, material saving, reduced machining costs, and accurate weight control. The following examples of powder forging applications are illustrated and discussed: automotive gear, automotive drive-shaft flange, toothed-belt pulley, connecting rod and side-gear blank. According to Jones, the preform forging technique offers many possibilities for producing bimetallic parts, and components having different properties in different locations, the latter being achieved by varying the powder composition.

57. Zapf, G. "The mechanical properties of hot-recompacted iron-nickel sintered alloys", ibid, 130-155.

Zapf found that alloys with relatively high strength and very high toughness could be produced by hot recompaction of unsintered blanks prepared by compacting mixtures of iron and nickel powders. Hot recompaction was followed by sintering.

58. Cull, G.W. "Mechanical and metallurgical properties of powder forgings", ibid, 156-164.

Process variables and properties of ferrous powder forgings are described by Cull. Preforms can be protected from oxidation and decarburization during heating by coating them with graphite or using an atmosphere of endothermic gas. The preform should be within ±1/4% of the forging weight to avoid defects arising from an incorrect amount of forging material. Ideally, the powder-forging process should consist simply of hot consolidation to maximum density with little or no lateral movement of metal. Attainment of satisfactory heat-treated properties is no problem if the material is homogeneous. Powder-forged connecting rods and automotive gears have been subjected to very severe engine-testing programs with no failures.

59. Cundill, R.T., Marsh, E. and Ridal, K.A. "Mechanical properties of sinter/forged low-alloy steels", ibid, 165-194.

Cundill et al describe experimental work on powder-forged iron and low-alloy steels in which the mechanical properties and microstructures of forgings made from atomized and blended alloys were investigated. The sintered compacts were forged in a die with dimensions close to those of the sintered compact so that the specimens were, in effect, hot coined. By using a good-quality atomized powder of the SAE 4600 type, tensile and fatigue properties equivalent to those of wrought steels were obtained. Atomized alloys with comparatively high oxygen content gave low properties because certain oxides on the surface of the powder particles were not reduced and so prevented full bonding during sintering. The blended alloys were not homogeneous and this resulted in lack of hardenability and generally poor heat-treatment response.

60. Hirschhorn, Joel S. "Forgings from powder preforms", Tech. Paper No. EM70-509. Soc. Mfg. Engrs., Dearborn, Mich., U.S.A. Pamphlet, 12 pp, 1970.

Hirschhorn presents data showing that the density and tensile properties of powder forgings are comparable to conventional forgings. To obtain acceptable mechanical properties it is essential to practically eliminate porosity and to maintain residual impurities at a low level; this means using a high-quality powder. The weight of the preforms may have to be controlled within 1/2 to 1% of the weight of the finished forging in order to obtain maximum benefits from the process. The better forgeability of the porous preform and low scrap loss make the process attractive for the more costly non-ferrous alloys and the highly alloyed ferrous materials possessing poor forgeability, but the most important area is likely to be plain carbon and low-alloy steel components. The following are cited as possible advantages over conventional forgings: one-step forging, reduction in forging temperature, practical elimination of scrap, reduction or elimination of secondary operations such as machining and sizing, increased automation, and isotropic properties.

61. Witt, R.H. "Close tolerance airframe titanium forgings from sintered preforms", Abstract Bulletin: TMS and ASM Fall Meeting, 1970, Cleveland, Ohio. (See also Ref. No. 210.)

The progress of work is described on a U.S. Navy-sponsored program on the feasibility of fabricating close-tolerance, simulated titanium airframe forgings made from powder preforms. Among the points considered are (i) prealloyed vs elemental powder mixtures, and (ii) relative costs of powder and processing for preforms vs conventional forging of titanium. The work is still in progress.

1971 (62-154)

62. Roll, Kempton H. "Powder metallurgy - facing a new responsibility", Modern Developments in Powder Metallurgy, Proc. 1970 Int. Powder Met. Conf., sponsored by MPIF and APMI, Ed. by H.H. Hausner, Vol. 4, Processes. Plenum Press, 1-19, 1971.

In an introduction to the Proceedings of the 1970 International Powder Metallurgy Conference, Roll stated that powder forging could be the most important development in powder metallurgy in the last five years. Starting with powder, two forging techniques are used. One uses "forging preforms" and ends with what is essentially the same as a traditional forging but at substantial cost savings. The other technique produces a true "P/M forging", and has been called "hot densification", "hot coining", "hot pressing", and at least one proprietary name "HRC". According to a leading market research organization, P/M forgings represent an existing potential of about 180,000 tons/year. By the year 1980, U.S. auto makers could be consuming about 250,000 tons of powder per year, and much of this would probably be P/M forgings. A leading sparkplug maker has started to produce sparkplug shells made from iron powder by what might be considered a P/M forging variation. Other potential applications for P/M forgings in autos are a side pinion gear and a mating gear.

63. Huseby, Robert A. and Scheil, Merrill A. "Forgings from P/M preforms", ibid, 395-413.

Work on preform forging of prealloyed ferrous powders is described. Compositions studied included low-carbon steel with graphite additions, resulphurized 0.40% carbon steel and Types 8600, 9400 and 4600 with up to 0.50%C. With a preform density of 6.0 g/cm^3 and press-forging at 1105°C, it was necessary to use a pressure of 965 MPa (140 ksi) to achieve full density. The final 2% above 98% theoretical density is very important if maximum properties are required. When carbon is added to melts containing manganese and chromium, their oxides can be reduced during sintering. Oxides of silicon, aluminum and titanium are not reduced because of the low temperatures involved. Resulphurized, atomized powder will forge more readily than resulphurized bar stock, because the sulphur exists as discrete particles rather than stringers. There is evidence that coarser atomized steel powders (down to 30 mesh) are suitable for forging and extrusion of preforms. The Ceramic Research Laboratory of A.O. Smith Corp. has developed a refractory coating with the trade name "Ceram-Guard" which will protect steel surfaces from oxidizing and decarburizing over the temperature range 815-1260°C; the coatings spall off on cooling or quenching, leaving a bright steel surface. Prealloyed, atomized steels mentioned as being suitable for preform forging are:

EMP Type 4660 (0.37% C, 0.17% Mn, 0.02% Si, 0.08% Cr, 1.73% Ni and 0.44% Mo) and Types 8600 and 9400 (8600: 0.4% C, 0.29% Mn, 0.13% Si, 0.58% Cr, 0.63% Ni and 0.4% Mo).

64. Antes, Harry W. "Cold forging iron and steel powder preforms", ibid, 415-424. (See also: Ref. Nos. 85 and 92.)

A study was made of the room-temperature deformation characteristics of sponge and atomized iron powder preforms. Various amounts of graphite were added to atomized iron to provide sintered steel preforms containing 0.06 to 0.41% C. The preforms were sintered in dissociated ammonia for 30 min at 1120°C. Preforms were lubricated before deformation by spraying with a suspension of teflon. At higher preform densities the sponge iron preforms exhibited a somewhat greater tendency to crack.

65. Lusa, George. "Differential gear by P/M hot forging", ibid, 425-430. (See also: The Mines Magazine, Vol. 61, No. 2, 24-26, Feb. 1971.)

The differential side pinion gear was considered to be an attractive application for powder forging because it offered potentially high-volume, high-strength requirements, elimination of excessive material loss, uniform shape and size, and reasonable tool costs. A completely automated pilot line was developed which did everything from induction heating the preform to transferring the forged gear away from the die. Die temperatures up to 315°C and preform temperatures up to 1095°C were evaluated. The P/M forging process would benefit greatly from the following work: development of P/M raw materials specifically for forging, refinement of methods for briquetting unlubricated powder, and continued investigation of induction heating and forging of green compacts, which would eliminate sintering and be a significant breakthrough in the P/M forging process.

66. Ishimaru, Yasuhiko, Saito, Yuichi and Nishino, Yoshio. "On the properties of forged P/M alloys", ibid, 441-449. (See also: Powder Metallurgy International, Vol. 3, No. 3, 126-130, Aug. 1971, and DMIC Review of Recent Developments: Metalworking, Popoff, A.A., Boulger, F.W. and Byrer, T.G., Battelle Memorial Inst., Columbus, Ohio, Aug. 11, 1971.)

Commercial iron powders were investigated to determine a suitable powder for P/M forging. The powders were pressed at 358 MPa (52 ksi), sintered at 1120°C for 30 min, forged in a closed die at 900°C and annealed at 1120°C. It was concluded that almost all kinds of commercial iron and ferrous alloy powders can be used in the P/M forging process. Ferrous alloy forgings made this way have higher strength and ductility than conventional ones and can be heat treated like wrought steels.

Compacts containing mixed alloying additions such as nickel, molybdenum, manganese and chromium had to be sintered at higher temperatures than compacts of iron-carbon mixtures to enable diffusion of the alloying elements to occur. In a mixture containing 2% Ni, 0.5% Mo and 0.5% C, the nickel and molybdenum diffused completely into the ferrous matrix and a fine, homogeneous, martensitic structure was obtained. A preform-forged atomized tool-steel powder had hardness and impact values close to those of conventional material but its transverse rupture strength was about 30% higher.

67. Mocarski, S., Winquist, L.A. and DeAngelis, L.E. "Properties of magnetically soft parts made by hot forging of P/M preforms", ibid, 451-462. (See also: Ref. No. 76.)

It is pointed out that volume production of high-purity atomized iron powders has lowered their cost to the level of forging bar stock and made the P/M forging process economically feasible. The process is said to have the advantage of material savings due to absence of flash, machining savings, good surface finish leading to improved fatigue life, and absence of defects connected with steelmaking, such as seams, pipes, and segregation originating from the ingot. Mocarski and his co-workers investigated eight iron powders for development of magnetically soft parts hot forged from P/M preforms. The powders were compacted at 400-480 MPa (58-70 ksi) to a density of 6.7 g/cm^3 and the compacts were sintered at 1120°C for 15 min in exothermic gas. The sintered preforms were reheated to 980°C in "nyrogen" gas (90% N_2, 10% H_2, dew point -40°C). Forging was done at pressures from 410-1170 MPa (60-170 ksi) in a closed die heated to about 260°C. Forging temperature was estimated at 925-955°C. Forging at 1170 MPa (170 ksi) and 925°C resulted in fully dense parts, whereas 410-468 MPa (60-68 ksi) and 760°C resulted in residual porosity of the order of 1%. It is concluded that P/M forging can produce parts with superior saturation magnetization and, that with further work, it will produce parts with excellent magnetic properties.

68. Kuhn, H.A., Hagerty, M.M., Gaigher, H.L. and Lawley, A. "Deformation characteristics of iron-powder compacts", ibid, 463-473.

Kuhn et al report initial results of a study of the deformation of sintered preforms and its relation to porosity and contaminant level with the aim of establishing tolerable levels and optimum combinations of impurities. With further development, plasticity equations will enable prediction of forming pressures and side pressures in forging operations, thus aiding in the design of dies for preform forging. Preliminary tests showed that a model 1-in. cube with holes drilled perpendicular to each face accurately simulates the macroscopic deformation behaviour of a powder compact. Electron microscope studies were made of sintered specimens before and after compression. Characteristic features of the as-sintered condition included low dislocation density, sub-boundaries, and isolated relatively straight dislocations. After axial compression to 17% reduction in height, the electron-transparent areas exhibited a well-defined cell structure.

69. Vernia, Peter. "Short cycle sintering by induction heating", ibid, 475-486.

Vernia points out that recent developments make sintering by induction heating look more attractive. In preform forging the strength of sintered compacts is not critical and so it may be possible to sacrifice some sintered strength for higher productivity. Other developments encouraging the use of induction sintering are ready availability of prealloyed powders, eliminating the necessity for diffusion alloying during sintering, and development of die-wall lubrication, making it unnecessary to remove lubricant during sintering. Vernia conducted the induction heating in a quartz tube in an atmosphere of 5% or 10% hydrogen in nitrogen.

70. Brandstedt, Sven B. "Effects of atomization media and consolidation techniques upon physical properties of a P/M cobalt-base alloy", ibid, 487-500.

Segregation and other limitations of a cast structure in cobalt-base and nickel-base alloys can be avoided when prealloyed powders are used. As a result, normally non-forgeable compositions can be hot-formed when in the form of compacted, prealloyed powder. Canning and hot-extrusion of low-oxygen powder produced 100% dense material with satisfactory tensile strength and high ductility. Brandstedt believes that cold-pressing and sintering, as well as hot-forging and extrusion, of powders in the stellite family will expand use of such alloy powders into areas other than castings, such as forgings, bar-stock, and rod, as well as other applications which require freedom from alloy segregation.

71. Abkowitz, S., Siergiej, J.M. and Regan, R.D. "Titanium P/M preforms, parts and composites", ibid, 501-511.

It is shown that forging of titanium and titanium alloy powder preforms to full density results in properties equivalent to those of wrought products. The material made from powder machined more readily than the wrought product. Preform forging of titanium and its alloys is said to have a potentially strong economic advantage, particularly for high surface area to weight ratio forgings with poor material utilization. Preforms can eliminate wasted material and preliminary forging operations, and reduce die costs. Reduction in processing time appears to be the major economic advantage for titanium forging preforms. Alloys produced by diffusion of "elemental" powder additions are said to have an advantage over prealloyed powder. With the elemental powder blend, a density of 84% of theoretical can be achieved with a compacting pressure of 410 MPa (60 ksi) whereas a pressure of 965 MPa (140 ksi) is required to obtain the same density in a prealloyed powder. The high green density of the blended powder facilitates sintering, and the catalytic effect of diffusion of the alloying elements also assists sintering.

72. Triffleman, Bernard, Wagner, F.C. and Irani, Keki K. "Experimental manufacture of Inconel alloy 718 compressor rotor blades from metal powder preforms", ibid, Vol. 5, Materials and Properties, 37-46.

Using standard powder compacting equipment and standard forging practice, Triffleman et al produced, on an experimental basis, aircraft-quality parts from forged Inconel 718 alloy powder preforms. Fully dense compressor blades, meeting specification requirements, were successfully produced.

73. Knopp, Walter V. "Furnace heating vs induction heating of P/M preforms", Fall Powder Metallurgy Conf. Proc., Oct. 20-21, 1970, Cleveland, Ohio. Sponsored by MPIF and APMI. Published by MPIF, 104-118, 1971.

The powders investigated by Knopp were: (a) prealloyed 0.2% Mn- 2.0% Ni- 0.50% Mo- balance Fe mixed with carbon, and (b) a mixture of 1.85% Ni + 0.50% Mo + C. Carbon analyses of the forgings showed that no free graphite was present. The preforms were preheated to 540°C to remove lubricant. Furnace sintering was carried out at 1095°C for 15 min in hydrogen and then the specimens were forged on removal from the furnace. The induction-heated preforms were placed in a quartz tube, heated to 1095°C for 30 to 45 sec and then immediately forged. Density of the forged bars was at least 98% of theoretical.

It was concluded that carbon diffuses very rapidly, even with the short time of induction heating. However, with elemental mixtures, time is required for diffusion of metallic elements. For the prealloyed powders, either furnace- or induction-sintered, the hardness, tensile and yield strengths are comparable to wrought properties, but elongation and impact strength are lower.

74. Halter, Richard F. "Pilot-plant production system for hot forging P/M preforms", ibid, 119-133. (See also: Proc. 1970 Int. Powder Met. Conf., sponsored by MPIF and APMI. Ed. H.H. Hausner, Vol. 4, Processes. Plenum Press, 385-394, 1971.)

Halter describes a pilot production system for forging iron powder preforms into differential side-pinion gears. Forging was done at temperatures such that rate of recrystallization was not rapid enough to eliminate strain hardening entirely in the time the material was at elevated temperature. Experimental production runs showed that a protective atmosphere was not necessary. Preforms were heated by induction. Lubrication for the tools was a fine dispersion of graphite in water. The preforms were dipped in a graphite dispersion. Preform weight and shape were important--accuracy of weight control within ± 0.5% was necessary. Over 50,000 preforms were forged to densities of over 99% of theoretical at production rates of 6, 10 and 15 parts per min. Gears from the pilot-line operation have accumulated over 500,000 miles of severe road testing.

75. Alves, A.L. "Powder forging technique and physical properties", ibid, 135-165.

Alves describes his company's (Eng. Sinterings & Plastics Inc., Connecticut) experience in the powder forging field, starting in 1967. First tests used a simple forging die shape and Swedish sponge iron. More complicated dies and alloy powders were used next. Work was also done on the forging of magnetic materials. Alves forecasts that P/M forging will grow significantly, but not too rapidly.

76. Mocarski, S., DeAngelis, L.E. and Winquist, L.A. "Influence of controlled atmospheres on magnetic properties of forged powder metal preforms", ibid, 167-189. (See also: Ref. No. 67.)

The properties of magnetically soft parts made by forging iron powder preforms are described. Earlier work showed that gases in powder forgings, particularly nitrogen, had considerable influence on some magnetic properties. The preforms were sintered and heated for forging in various atmospheres. Forging was carried out at 1170 MPa (170 ksi) and 925-955°C. The die was heated to about 260°C. Sintering was conducted at 1120°C for 20 min. Furnace atmospheres were found to significantly affect residual gas contents of the forgings. The magnetic properties were also affected by the atmospheres used.

77. Bargainnier, R.B. and Hirschhorn, J.S. "Forging studies of a Ni-Mo P/M steel", ibid, 191-235.

Bargainnier and Hirschhorn investigated closed-die forging of small (40 g) preforms prepared from prealloyed type 4600 steel powder (2.0% Ni-0.55% Mo-0.04% Mn, blended with 0.45% C). Preform weight and forging pressure were held constant, and the minimum reduction in thickness was 32%. The forging preheat atmosphere was cracked ammonia. Residual porosity in the forgings was confined to a shallow surface layer and was associated with locations where there was relative lack of restraint during deformation. Surface layers were also characterized by varying degrees of decarburization and cracking. Forging preheat temperature had the greatest influence on forging properties--final density increased, and incidence of surface cracking decreased, with increasing temperature. Also, as temperature increased, oxygen content decreased and depth of decarburization increased. When preheat temperature was high enough (1150°C) to allow carbon alloying, green preforms gave the same results as sintered preforms, indicating that sintering might be combined with forging preheat. Coarse powder (-28 +200 mesh) gave as good results as fine powder (-200 mesh). It was concluded that processes involving the use of dry reducing atmospheres with the proper carbon potential, high forging pressures and provisions for retarding chilling during deformation could be expected to give best results.

78. Cook, John P. "Degradation of P/M forging preforms during interim exposures in air", ibid, 237-259. (See also: Ref. 123 and 153, and Cook, John P. "Oxidation and decarburization of metal powder preforms", Soc. of Mfg. Engrs., Paper No. MF72-803, 12 p, 1972.)

A study was made of the effect of exposing hot sintered preforms to air after they had been heated to various temperatures in a protective atmosphere. Preforms made from atomized Type 1040 material (0.4% C) were compacted to provide sintered preforms with densities from 5.3 to 7.2 g/cm^3. The sintered preforms were exposed to air for periods of 0 to 32 sec and at forging temperatures ranging from 565°C to 1120°C. At 565°C and 650°C, oxidation occurred with no decarburization, and maximum depth of oxide penetration after 32 sec was 5.0 mm (0.2 in.). Oxidation occurred very rapidly at 1120°C. Coating preforms with commercial graphite-based hot-forging lubricants was found to eliminate almost all oxidation and a great deal of decarburization at 1120°C for even the lowest density preforms (5.3 g/cm^3).

79. Kuhn, H.A. and Downey, C.L. "Deformation characteristics and plasticity theory of sintered powder materials", Int. J. Powder Metallurgy, Vol. 7, No. 1, 15-25, 1971.

An understanding of the deformation behaviour of powder preforms is an important factor for successful utilization of the preform forging process. The porosity of sintered powder materials results in a behaviour that is considerably different from that of conventional cast and wrought materials. The authors determined the basic deformation characteristic of sintered sponge iron powder from simple compression tests. Although the results are directly applicable only to cold forging of iron powder, the plasticity theory and experimental procedures described can be applied to any material and temperature. (See also: "Deformation characteristics and plasticity theory of sintered metal powders", Kuhn, H.A. and Downey, C.L. Soc. Manufacturing Eng. Paper No. MF72-804. 14 p, 1972.)

80. Marx, J.B., Davies, R. and Guest, T.L. "Some considerations of the hot forging of powder preforms", Proc. 11th Int. MTDR Conf., Birmingham, England, Sept. 1970, Vol. B, Ed. S.A. Tobias and F. Koenigsberger, Pergamon Press, 1st ed. 729-744, 1971.

The forging of powder preforms made from sponge iron powder (Hoeganaes MH100) was investigated using simple upsetting tests. The effect of preform design on the forging of three components was also studied. Satisfactory results were obtained by sintering and forging at 1100°C, but it is pointed out that sintering at 1100°C, followed by forging at 900-950°C might be more desirable. The effect of initial preform density on final density was very small when forging to a high reduction. Forged densities of up to 99.5% of theoretical were readily obtained by forging in closed dies. The tensile properties of the forged powder compared favourably with that of solid pure iron, but the elongation values were low. Both slow-speed and high-speed compaction techniques were used to form the preforms. All forging was done on a Petro-Forge MkII HERF machine. "Copaslip" was brushed on the forging dies for lubrication.

81. Wrigley, A. "Buick eyes P/M forging". Metalworking News, Vol. 12, No. 551, 11, Jan. 18, 1971.

The date that the Buick Division of GMC is aiming to start high production work on a powder-forged gear is 1972. Some machining will still be required on the forging.

82. Pietrocini, T.W. "Hot densification of P/M alloy 8360". Precision Metal, Vol. 29, No. 1, 58-60, Jan. 1971.

Pietrocini reports on the hot densification of a modified AISI 8630 alloy steel powder made by atomization. According to Pietrocini, hot working utilizing lateral flow can be classed as a forging operation, but hot working with virtually no lateral flow should be considered as only a densifying operation. The parts had 98% theoretical density and there was substantially zero lateral flow. Components made in this way had almost the same properties as those of wrought material of comparable composition and heat treatment. The compositions of the P/M and AISI alloys were as follows:

Element	P/M 8630 (%)	AISI 8630 (%)
C	0.25 - 0.35	0.28 - 0.33
Mn	0.10 - 0.60	0.70 - 0.90
Si	0.05 - 0.25	0.20 - 0.35
Mo	0.35 - 0.60	0.15 - 0.25
Ni	0.40 - 0.70	0.40 - 0.70
Cr	0.40 - 0.60	0.40 - 0.60
S,P	each 0.04 max	
Fe	balance	

Manganese is lower in the P/M alloy because of its effect on the work-hardening rate which would result in increased equipment requirements for briquetting. Manganese can also cause sintering problems since it has a high affinity for oxygen and requires a dewpoint of -46°C for reduction. Molybdenum is higher in the P/M alloy because it has the second highest multiplication factor for increased hardenability. Through these two compositional changes it is possible to obtain hardenability characteristics in the P/M alloy close to those of the wrought material while maintaining excellent processing characteristics. Chromium can cause processing problems due to its affinity for oxygen.

83. "Battelle proposes $360,000 P/M forging research program". Powder Met. Info. Bull.(MPIF)No. 273, Jan./Feb. 1971. (See also: P/M Technology, monthly newsletter published by APMI, No. 278, 6, Sept./Oct. 1971; Metal Bull. 5642, 33, Oct. 9, 1971; Metals and Materials, Vol. 5, No. 11, 345, Nov. 1971.)

It is reported that Battelle Memorial Institute is proposing to initiate a $360,000 research and development program in the field of preform forging. The joint financial support of at least 15 companies will be required and each company will be asked to invest $8,000 per year for a 3-year period. Among areas to be covered in the program are forgeability in various die shapes, preform design principles, tooling and process design for preforming and forging, heat treatment response, mechanical properties, and machinability. Emphasis will also be placed on quality assurance procedures for forged powder metal components.

84. Anon. "Powdered steel: a tough customer", Metallurgia, Vol. 83, No. 496/7, 63-4, Feb.-Mar. 1971.

In this brief news article it is reported that superalloys, normally sold by specialty steelmakers, are being shipped by a few powder makers (in the U.S.A.) in the form of 1,000-lb forging billets. Federal-Mogul is reported to be building a new plant in Princeton, Kentucky, that will sell superalloy powders at about $7 per lb (about $2 above the cost of "conventional" metal), whereas the prevailing cost of those powders is $15-$20 per lb. Superalloy powders can be furnished to forgers as billets or as preforms moulded to the approximate shape and size of the final part, eliminating preliminary forging steps and much of the usual metal waste. Up to at least 50% of the costly superalloys becomes scrap in conventional forging.

85. Moyer, Kenneth H. "Cold forging of 316L powder preforms". Paper presented at 1971 Western Metal and Tool Conference and Exposition, under auspices of ASM and SME, 8-11 March, 1971, Los Angeles, California. Paper W71-5.3.

The work reported is a continuation of a program to determine the cold forging characteristics of powders. Cold forging of iron and carbon steel had been reported earlier. (See Reference No. 64). The 300 series of stainless steels contain 18% Cr and, as this element is readily oxidized at temperatures over 540°C, it may be advantageous to forge cold in order to reduce oxidation. It is not made clear in the paper whether the alloy powder was a mixture or a prealloy, although the latter appears more likely. Sintered preforms were deformed in plane strain or in uniaxial compression. Densification characteristics as a function of true strain and of the load required for deformation were studied. Preforms sintered in hydrogen could sustain a true strain of 1.0 without visual evidence of failure, whereas those preforms sintered in dissociated ammonia could not sustain true strains of 1.0 without fracturing. The type of lubricant blended with the powder (lithium stearate or Nopco wax) had no effect on forging behaviour. The rate of densification decreased as preform density increased. The densest preforms (6.8 g/cm3) achieved the highest forged density (7.78 g/cm3 in uniaxial compression). The preforms measured 32 mm x 13 mm x 13 m and loads of up to 54,500 kg (120,000 lb) were applied. (See also: Forging Seminar, Hoeganaes Corp., 8 pp, 1971, and references Nos. 64 and 92).

86. Mocarski, S. and Eloff, P.C. "Equipment considerations for forging powder preforms", Int. J. Powder Met., Vol. 7, No.2, 15-25, Apr. 1971.

Mocarski and Eloff describe the processing equipment required for powder forging and suggested improvements for optimum production. Press manufacturers should consider increased press speed, improved weight control of specimens, and die-wall lubrication. Development of isostatic press equipment must be directed towards improved life of vessels and tool materials, automation and mass production, and improved dimensional accuracy of preforms. Sintering furnaces are required to provide higher sintering temperatures, more refined atmosphere control to maintain carbon content of preforms, and high production-rate feeding systems to automatically take preforms to the forging dies. Induction heating for sintering sounds attractive, but work requires to be done on burn-off procedures, selection of optimum frequencies and time cycles,and atmospheres to allow reduction of oxides. Hydraulic presses may find only limited application in preform forging as they are generally too slow. Principal areas for development in forging machines are provision of automatic lubrication and ejection devices, flexibility to accept a wide variety of tooling, and automatic handling devices with oxidation protection for the hot preform.

87. Anon. "Where powder metallurgy is growing. Application outlook for forging P/M preforms", Metal Progress, Vol. 99, No. 4, 54-60, Apr. 1971.

The outlook for powder forgings is reviewed. Various automotive parts, such as connecting rods, crankshafts and gears, are near production in the U.S.A. and U.K. One British company (GKN) has produced and tested 16 different automotive parts, and 10 more are in advanced development. General Motors Corp. (GMC) and Cincinnati Inc. in the U.S.A. have co-operated in the development and production of a differential gear; in addition to improved performance GMC reports savings in material and machining. Cincinnati has developed a completely automated pilot-line system, including induction heating of the preform, transfer of heated preform to the die, lubrication of die, forging, and transfer of forging away from the die. Geometry of the preform is important, but information on this is not readily available. Material redistribution should be kept to a minimum during forging so that non-uniform die wear can be avoided. Observers feel that powder development lags behind processing technology. It is generally considered that powders should be developed for the job rather than merely duplicating wrought material. Low-cost Cr-Mo alternatives for Ni-bearing grades are needed, but oxide inclusions at present rule out their usage. There is a need for development work on die materials and lubricants.

88. Anon. "Outlook for aluminum P/M parts", ibid, 60-64, 66.

The feasibility of processing aluminum by powder forging has been demonstrated by more than one partmaker. Some parts, including a knob for a movie projector, are already being preform-forged in aluminum.

89. Bufferd, Allan S. and Gummeson, P.U. "Application outlook for superalloy P/M parts", ibid, 68, 70-71.

The primary interest in superalloy powders centres on the preparation of dense material as preforms for subsequent forging into components such as discs, hubs, and spacers for turbine engines.

90. Weisert, Edward D. and Schwarzkopf, Peter. "Isostatic pressing: a three-dimensional process", ibid, 71-74.

The three-dimensional shapes characteristic of isopressing may be used to good advantage for forging, as stock can be located in places which would not be feasible with prior forging operations.

91. Anon. "Metals outlook", Materials Eng., Vol. 73, No. 4, 17, Apr. 1971.

This short article reports that the future of powder forging looks bright. The Buick Motor Division of GMC is stated to be ready to introduce a 1.5-kg powder-forged automatic transmission input ring gear. Powder forging of bi-metallic components is predicted. For example, a component subject to high surface loading could have a wear-resistant material on the outside surface and a cheaper material on the inside.

92. Antes, Harry W. "Cold and hot forging P/M preforms", Soc. Mfg. Engrs., Tech. Paper EMR71-01. Presented at SME Conf., Philadelphia, Apr. 26-29, 1971.

The design and fabrication of preforms, behaviour of preforms during forging, and lubrication are described and discussed in general terms. Deformation-densification studies are described for cold and hot forging of iron, iron-carbon, and alloy steels. This paper is based on the results of work reported by various investigators and already abstracted in this survey. (See also: reference Nos. 64 and 85.)

93. Pietrocini, Thomas W. "Hot forming P/M relationships between manufacturing, design, and component cost", Soc. Mfg. Engrs., Tech. Paper EM71-260. Presented at SME Conf., Philadelphia, Apr. 26-29, 1971.

This article is concerned mainly with hot densification which is defined as a process in which there is virtually no lateral flow of metal during densification. The process variables in hot forming (or hot densification) of ferrous powders are listed. Hot pressing is compared with hot forging with respect to preform, die and press requirements. The mechanical properties and dimensional characteristics of hot-formed preforms are compared with those of hot-forged preforms and hot-rolled bar. Cost breakdown is shown for the powder metallurgy product and products made by more conventional methods, such as forging, casting and machining. A wide variety of hot-formed parts are currently in various stages of development, and a few small parts have been approved for production.

94. Lawley, A. and Kuhn, H.A. "Sintered metal preforms and the future". Paper presented at conference sponsored by Soc. Mfg. Engrs., Philadelphia, 12 p, Apr. 26-29, 1971.

The preform forging process is analysed in terms of the following parameters: powder characteristics (purity, inclusions, size, shape distribution), preform (porosity, uniformity, structure, shape) and forging operation (tooling, die design, lubrication). A semi-quantitative picture of flow and fracture in the forging operation is obtained by application of ductile-fracture criteria and by analysis of the mechanics of deformation of semi-dense materials.

95. Eloff, P.C. and Kaufman, S.M. "Hardenability considerations in the sintering of low-alloy iron powder preforms", Powder Met. Int., Vol. 3, No. 2, 71-75, May 1971. (See also: Fall Powder Met. Conf. Proc. sponsored by MPIF, APMI and ASM, Detroit, Mich., 5-17, Oct. 19-21, 1971.)

Eloff and Kaufman compare prealloyed powders with blended compositions from the standpoint of sintering behaviour and retention of hardenability. They conclude that prealloyed powders which contain unoxidized alloying elements in solution in iron are the most promising for production of low-alloy steel forgings. However, even with elements in solution, care must be taken when using highly oxidation-prone elements to avoid selective oxidation. It was shown that the diffusion rates of all substitutional elements were too slow to obtain a homogeneous alloy during sintering of a blended composition. The use of hot-work and annealing to homogenize such an alloy did not substantially improve the situation.

96. Westerman, Richard E.and Sump, Kenneth R. "Properties of prealloyed steel powder metallurgy products", Battelle Mem. Inst. Pacific Northwest Labs., ADA 727660. AMSWE-RE-71-22, May 1971.

This report describes an investigation of the forging of prealloyed steel powders representing six major alloy types. Preform-forged specimens processed to about 98% theoretical density had tensile strength and hardness values close to those of equivalent products processed by conventional means. Initial compaction pressure was found to be of minor importance when the final step was a forging operation.

97. Goetzel, C.G. "Tensile properties of titanium alloy forgings made from spark-sintered preforms", ASM Metals Eng. Quart., Vol. 11, No. 2, 53-61, May 1971.

Goetzel describes the properties obtained by forging spark-sintered Ti-6%Al-4%V preforms. Main interest of the article is in spark-sintering, a process in which an initial electric discharge is followed by resistive heating of the compact under increased pressure until densification is completed. Both alternating and direct current are applied. Two forging procedures were employed -- upset forging into pancakes and stepdown forging into rectangular bars.

98. Brown, G.T. "The powder-forging process: a review of the basic concept and development prospects", Powder Met., Vol. 14, No. 27, 124-143, Spring, 1971.

This is a review of the powder-forging process and its prospects. Of the three preforming techniques available, namely, conventional linear die pressing, isostatic compaction, and slip casting, die pressing is said to be the method most likely to be used in the early stages of process exploitation. The three principal variables in powder forging are said to be preform density, forging temperature, and forging load. A low-density preform needs only a light forming load at the start of the stroke, whereas one of very high density requires more force throughout. A study of the relative merits of high and low forging temperature would be useful. As a first approximation, a practical working-temperature range would appear to lie between 900 and 1200°C, and within this range the forming pressure would appear to lie within the limits 150-770 MPa (22-112ksi). Design of the preform and of the tooling at the hot-compaction stage are both very important. Greatest interest in this powder-forging process has been in the field of stressed engineering components, such as connecting rods, gear wheels, and transmission parts. Prealloyed powders are more effective than powder mixes. The water-atomizing process for making powders appears to be the most favoured at present but there is a problem with oxidation. Following atomization, it is common practice to anneal in a hydrogen atmosphere to soften the particles and reduce the surface film back to the elemental metallic state. Manganese and chromium are relatively difficult to reduce, whereas nickel and molybdenum are much easier. Work on the role of oxide films and the manner in which they may be subsequently reduced would be rewarding.

99. Fischmeister, H.F., Arén, B. and Easterling, K.E. "Deformation and densification of porous preforms in hot forging", ibid, 144-163.

This article describes an investigation of the effect of preform porosity on the deformation and densification during hot forging of preforms between unlubricated flat punches at 1160°C. Densification was most rapid in the initial stage of deformation when lateral flow was almost absent. In closed-die forging, this will delay the onset of die-wall friction, which forms the main obstacle to the attainment of high densities in conventional powder compaction. Original preform density had a strong and persistent effect on the deformation characteristics. Density distribution in the forgings was charted by means of hardness measurements. Zones of incomplete densification were revealed where local pressure was reduced by lack of constraint, or where strain was impeded by friction effects.

100. Krishnamoorthy, G.M. "Influence of iron powder type on the properties of sintered iron at various density levels, ibid, 164-178.

The properties and hot-forging behaviour of six different iron powders, representative of various methods of production, were investigated. The main difference noted between the powders was in impact strength, which was highest for atomized and carbonyl powders and lowest for electrolytic powder.

101. Anon. "Metals here and there", Precision Metal, Vol. 29, No. 6, 32, June 1971.

Preform forgings appear to be one solution to some of the problems created by the latest high-thrust jet engines. There is less segregation in the complex alloys required when metal powder is used. Material utilization is also better. Forgings have been made from powders with the compositions of Inco 100, Inco 792 and René 95.

102. Perkins, B.E. "Sinter forging", Metals Australia, Vol. 3, No. 4, 105-108, June 1971.

This is a review of the "sinter-forging" process and its future prospects, with particular reference to Australia. "Sinter forging" is defined as"the technique of obtaining near-100% density by the severe working of a powder preform by either cold, warm or hot densification". It is pointed out that development of sinter forging could lead to consumption of large tonnages of iron powder, and it is estimated that by 1975 it could consume 130,000 tons in the U.S.A. alone. Perkins discusses the advantages and disadvantages of sinter forging vis-a-vis conventional forging, and lists the main factors to be considered when developing production parameters. He notes that sinter-forged connecting rods are being used in cars in the U.K. and U.S.A. and that sinter-forged differential pinion gears are used in cars in the U.S.A. and Japan. Perkins considers that the most difficult problem to be overcome is the attainment of consistently high impact and ductility properties, and he concludes that the future looks good for sinter forging. One prominent company in the U.S.A. is said to be quoting 2065 MPa (300 ksi) UTS and 3% elongation for sinter forgings and spending some $2 million in-plant for the process.

103. Durdaller, Neil. "Status of new advances in P/M technology: iron P/M forging", Progress in Powder Met., Vol. 27, Part 1: "P/M in Ordnance", 135-141, June 1971. Proc. of first tutorial seminar on P/M in ordnance, sponsored by MPIF and presented at Frankford Arsenal, Philadelphia, Pa., June 2-3, 1971.

Powder forging is discussed in general terms and examples of component forgings are given. Much of the value of this article is lost as figures and data are not reproduced.

104. Buchovecky, K. "Status of new advances in P/M technology: aluminum P/M forging", ibid, 143-148.

This deals with powder forging of aluminum, but no figures or data are given.

105. Anon. "High performance materials exhibition", Machinery and Production Eng. (London), Vol. 119, No. 3060, 25-28, 7 July 1971.

Titanium forgings made by the powder metallurgy route were on display at an exhibition of high performance materials held at the U.S. Trade Centre, London, England, in 1971.

106. Staff report. "Powder metallurgy trends", Automotive Industries, Vol. 145, No. 14, 39-44, July 15, 1971.

This is a general survey of recent trends in the powder-metallurgy industry, including powder forging. To the automotive engineer, P/M forging offers a more efficient, economical production system for producing high-strength components having adequate impact and fatigue properties. With respect to cost savings, P/M forging is highly attractive because approximately 50% of the total cost of a conventional forging is in the material. Using P/M forging, scrap losses should be reduced to less than 5%. Also, die life is extended because the material does not have to be struck as many times as in conventional forging. Automobile components being seriously considered for P/M forging in the U.S.A. and Europe include ring gears, pinion gears, clutch races, pole pieces, connecting rods, valve guides, drive-shaft flange, toothed belt pulley, crank-shaft gear, gear clusters, and engine valves. Although several large forging companies are looking at powder metallurgy as a way of extending their own product lines, industry sources in the U.S.A. see P/M parts fabricators becoming the major supplier of P/M forgings.

107. Wigotsky, Victor W. "Powder metallurgy past the hoopla", Design News, Vol. 26, No. 14, 15-18, July 19, 1971.

In this review article it is pointed out that, although there has been no significant commercial production of forged P/M parts, it has been demonstrated that it is now possible to produce fully dense parts from ferrous, non-ferrous and superalloy powders. Parts under consideration for production are differential ring and pinion gears, exhaust valves, power-input gears, connecting rods, pole pieces, sprockets and valve lifters. Availability of new high-compressibility alloy powders has helped in the development of preform forging.

108. Kaufman, S.M. and Mocarski, S. "The effect of small amounts of residual porosity on the mechanical properties of P/M forgings", Int. J. Powder Met., Vol. 7, No. 3, 19-30, July 1971.
(See also: Fall Powder Metallurgy Conf. Proc., Detroit, Mich., sponsored by MPIF, APMI and ASM, 125-136, Oct. 19-21, 1971.)

Low-alloy-steel powder forgings with densities varying from 95 to 100% of theoretical were tensile tested and their microstructures examined. Tensile properties fell off sharply in the density range examined. Mechanical properties appeared to be a function of final pore shape but not of initial powder particle size. The appearance of fracture surfaces changed significantly below about 0.5% residual porosity.

109. "Critical point", Metal Progress, Vol. 100, No. 1, 55, July 1971.

A news item reveals that Honda, Japanese producer of cars and motorcycles, is producing two hot-forged powder metallurgy gears.

110. Anon. "Sintering stainless steel", Stainless Steel, No. 19, 13-15, Summer 1971.

Brief mention is made of the prospects for "sinter forging" stainless steel, which is showing signs of gaining commercial acceptance. The process is said to be most competitive for components weighing less than 1 kg that are required in quantities of more than 250,000.

111. Ridal, K.A. and Cundill, R.T. "Sinter forging of alloy steel forgings", Metallurgia and Metal Forming, Vol. 38, No. 8, 204-209, Aug. 1971.
(Based on paper presented at Annual Technical Convention of National Association of Drop Forgers and Stampers, Droitwich, Eng., Nov. 1970.)

This article discusses the procedures and potentialities for P/M forging, or "sinter forging" as the authors call it. There are three basic methods of producing fully dense components from sintered preforms: (1) hot repressing, i.e., densification, with little movement of metal, (2) closed-die forging, which is similar to conventional forging but without the preliminary preforming stages; the metal flows to take up the final shape and some flash is produced, and (3) confined die forging, which is also a true forging process, but a totally-enclosed die is used and so no flash is produced; this method combines the advantages of both powder metallurgy and forging processes. Oxides on powder particles can adversely affect toughness and ductility of the forgings but this effect can be minimized by movement of the metal during the forging operation. Advantages of the preform forging process include cost saving through increased material utilization, simpler forging operations, reduced labour costs, and high production rates. Disadvantages include high capital outlay. The cost of powder is about twice that of equivalent steel in billet form, but over the past 10 to 15 years the cost of powder has remained at about the same level while billet prices have doubled. In some cases the higher cost of powder can be entirely recovered by the high yield of the process compared with that of existing forged or cast alternatives.

112. Anon. "Metals outlook", Materials Eng., Vol. 74, No. 3, 17, Sept. 1971.

This news item reports that major U.S. automobile manufacturers were questioned about the use of P/M forgings in 1972 cars. All replied that the technology was now available and that they were anxious to make parts by this process but the necessary high-volume production equipment was not available. All were hopeful that 1973 would see the use of P/M forgings. Rising labour and material costs virtually dictated the use of P/M forgings.

113. Miska, Kurt H. "What's new in powder metallurgy", ibid, 22-28.

This is a review article in which it is noted that latest thinking is that prealloyed, atomized iron powders will be used in preform forging. It has been shown that all AISI low-alloy heat-treatable steels can be made into powders and processed into parts. The problem with atomizing many AISI steels is that they contain alloying elements that oxidize in post-atomizing operations. Chromium and manganese fall into this category, but powders containing these elements have been hot forged to full density under carefully controlled conditions without significant oxidation. With powder metallurgy techniques, it is possible to use alloys or alloying elements that are not common in conventional forging. Addition of prealloyed carbon can eliminate sintering if sufficient bonding can be obtained during hot forging. Prealloyed carbon and manganese drastically reduce compressibility. Nickel and molybdenum have a moderate effect on compressibility, but are expensive. Chromium is not expensive and does not have much effect on compressibility. Carbon offers oxidation protection to the alloying elements. Oxidation precautions must be taken for carbon, chromium and manganese. Hoeganaes obtained good forged properties by preform forging a series of prealloyed steel powders made to AISI compositions. Cold forging of preforms is a process that should be considered for iron, low-alloy steels, and some stainless steels. Federal Mogul, using their proprietary HRC process, now offer forged alloy-steel powder-metallurgy parts with strength properties and fatigue-life advantages over wrought steel forgings. If Federal Mogul P/M forgings prove themselves, the way will probably quickly open up for such automotive applications as exhaust valves, connecting rods, transmission gears, and clutch and bearing races. Alcoa are said to be active in hand forging two aluminum powder alloys, viz. MA-58 (5.9%Zn-2.2%Mg-0.1%Zr-balance Al) and MA-39 (8.8%Zn-3.4%Mg-0.7%Cu-0.7%Co-balance Al). General Electric have recently forged parts from preforms of prealloyed titanium powder (6%Al-4%V-balance Ti). Nuclear Materials and Equipment Corporation have developed two prealloyed titanium powder alloys for preform forging. U.S. Bronze Powders predict extensive use of aluminum bronze powder for hot forging. Cubraloy (Cu-Al) powders for hot forging are under development. Cubraloy 5 (95% Cu-5% Al) is not practical when prealloyed because the compaction pressures required are too high due to the hardness of individual powder particles.

114. Joyce, J.F. "Review of powder metallurgy methods on extrusions and forgings", Light Metal Age, Vol. 29, Nos. 7 and 8, 10, Sept. 1971

In this brief review, Joyce mentions an Alcoa study of hand forging of aluminum-base P/M alloys. High-quality hand forgings were produced directly from hot-pressed compacts of two alloys: MA58 (5.9%Zn-2.2%Mg-0.5%O_2-balance Al) and MA39 (8.8%Zn-3.4%Mg-0.7%Cu-0.7%Co-0.3%O_2-balance Al). Best properties were obtained with the following processing conditions: (a) cold press to at least 70% theoretical density, (b) preheat 1 hr at 540°C in dry argon, (c) hot press at 620 MPa (90 ksi), (d) forge at 315°C for MA58 and at 370°C for MA39, and (e) forge by any standard hand-forging press technique with as much reduction as possible.

115. Davies, R. and Dixon, R.H.T. "The forging of powder preforms using petro-forge machines", Powder Met., Vol. 14, No. 28, 207-234, Autumn 1971.

This article reports on work done on preform forging of iron powders with a petro-forge machine. Tests were carried out with closed forging dies using iron powder blended with graphite, prealloyed powders and blended alloy powders. A wide range of forged components was made. One of the main advantages of using petro-forge high-speed machines is the rapid rate of forging possible, so that oxidation and chilling of the preform on removal from the forging furnace are kept to a minimum. Added attractions of using the petro-forge machines are the possibilities of reduced size of equipment and lower capital costs. The preform should have as simple a shape as possible consistent with the production of a sound forging because the cost of compaction dies increases markedly with the degree of complexity of the compact and it is more economical to produce as much detail as possible at the forging stage where die costs are considerably less.

116. Anon. "Powder metallurgy: a sleeping giant", Iron Age, Vol. 208, No. 15, 63-67, Oct. 17, 1971. (Report on four-day conference on "Powder metallurgy for high performance applications" held early Sept. 1971 and co-sponsored by U.S. Army Materials and Mechanics Research Center and Syracuse University.)

This article reports that the viability of hot forming metal powder preforms is being demonstrated in automotive applications and that other applications are pending. Differential side pinion gears made by hot forming AISI 4620 steel powder meet all the specification requirements. Buick Motor Division of General Motors Corp. has announced the introduction of a 1.5-kg powder-forged input gear in AISI 4620 alloy for automatic transmissions on 1972 models. Pratt and Whitney Aircraft have formed nickel-base superalloy powders into forging billets.

Billet and bar stock of A286, Inco 901, Astroloy, Waspaloy, B1900, IN100, and titanium 8-1-1 and 6-4 have been produced by "controlled processing" so that they behave in a superplastic manner over a moderately wide temperature range if strain rates are properly controlled. The controlled, isothermal-forging practice which utilizes superplastic behaviour of the alloy being forged has been registered under the trade name "Gatorizing" and covered by U.S. patent.

117. Jarrett, M.P. and Jones, P.K. "Automotive forgings. Powder leads to higher precision", Metallurgia and Metal Forming, Vol. 38, No. 10, 280-286, Oct. 1971. (See also: Jarrett, M.P. and Jones, P.K. "Powder forging", Automobile Engineer, Vol. 61, No. 11, 50-53, Nov. 1971.)

In conventional forging, 50% of costs are for material. As over 50% of the forging weight may be removed by machining for intricate components such as gears, there is an obvious incentive for producing precision forgings with minimal material wastage. Three factors influence the deformation characteristics of the powder preform: (a) forging characteristics of the hot powder, (b) ability to make the preform so that material redistribution during forging is minimized, and (c) absence of flash. Much of the final shape is developed during the early stages of forging when the loads required are relatively low. The cost of powders, especially alloy powders, is very important. The cost of prealloyed powders containing nickel, such as the AISI 4600 series, is high at 13-17¢ per lb. There is a great need for powders containing manganese and chromium as alloying elements in place of nickel, although it is claimed that such powders can give atomization difficulties due to the reduction characteristics of the oxides. The techniques used in preform manufacture lend themselves to the production of bi-metallic components, or components with different densities in different sections. Initial work suggests that a very homogeneous product can be obtained by forging preforms made from carefully prepared superalloy powders.

118. Smith, Y.E. and Pathak, R. "New hardenability data for application in low alloy ferrous powder forging", Fall Powder Met. Conf. Proc., Detroit, Mich. Sponsored by MPIF, APMI and ASM, 19-33, Oct. 19-21, 1971.

An investigation was made of the hardenability effects of individual alloying elements in low-alloy steels intended for application in the powder-forging process. Thirty-three compositions were prepared by normal casting and forging techniques to provide bar stock for the Jominy hardenability test. The steels contained 0.2% and 0.4% C and various combinations of 0 to 0.8% Mn, 0 to 0.8% Ni, 0 to 0.75% Cu and 0 to 0.75% Mo. An attempt was made to design steels with hardenability levels up to and including the hardenability of the SAE 4600 composition, with and without manganese. At the low levels of manganese believed necessary to develop good impact resistance after powder forging, some molybdenum was required to maintain significant hardenability at either 0.2 or 0.4% C. Copper, up to 0.4%, was found to be a good supplementary alloying element to accompany the molybdenum. Nickel added significantly to the hardenability at the 0.4% C level, but only slightly at the 0.2% C level. A 0.4%Mn-0.4%Ni-0.4%Cu-0.5%Mo steel and a 0.4%Ni-0.4%Cu-0.8%Mo steel were recommended as alternatives for the SAE 4600 composition at the 0.4% C level. A 0.4%Mn-0.4%Cu-0.75%Mo steel was recommended as an alternative for the SAE 4600 composition at the 0.2% C level.

119. Smith, Kenneth V. "The heat treatment of hot densified powder metal alloys", ibid, 35-51.

Smith investigated the heat treatment of hot densified ferrous alloys 4620 and 4650. The samples were hot-pressed to a density of 7.70 to 7.80 g/cm^3. Heat treatments investigated included gas carbo-nitriding, salt bath carburizing and salt bath cyaniding. It was found that the alloys could be heat treated by these processes providing the component did not contain designed low density regions.
(See also: Metals Eng. Quart., Vol. 12, No. 2, 13-20, May 1972.)

120. Moyer, Kenneth H. "The effect of preform density on the impact properties of atomized iron P/M forgings, ibid, 53-63.

The preforms had densities ranging from 5.7 to 7.2 g/cm^3. The forged densities varied from 7.2 to 7.8 g/cm^3. It was found that for all preform densities impact strength increased with increasing forged density. However, for the highest preform density, forged to intermediate and full density, the impact properties varied over a wide range for a specific forged density. The amount of flow or strain imparted to a preform is important for achieving high impact strength. Highest impact strength was obtained with an intermediate preform density (6.2 g/cm^3).
(See also: Metals Eng. Quart., Vol. 12, No. 3, 34-38, Aug. 1972.)

121. Woulds, Michael J., Pitcairn, David R. and Weber, Earl K. "Hot forging of sintered stainless steel", ibid, 65-82.

Woulds et al determined the process parameters necessary to produce forged stainless steel shapes from powder and to develop properties comparable or superior to conventionally forged bar stock. The material used was minus 100-mesh commercially available powders of stainless steel Types 304, 316, 410 and 430, representing typical austenitic, martensitic and ferritic grades. The powders were compacted to give preforms of various densities and these were sintered in dissociated ammonia, hydrogen or vacuum. Sintering in vacuum gave the best densification in all cases. The preforms were heated at various temperatures from 815 to 1230°C in different atmospheres and forged at 140-1655 MPa (20-240 ksi). Densities increased with temperature and force and were independent of preform density.

Mechanical and corrosion properties comparable to those of wrought bar stock were obtained in fully dense forgings. Forgings made with severe metal deformation had properties similar to those of forgings made with minimal metal movement, indicating that severe metal flow was not essential for optimum properties. Preheating of ferritic and martensitic compacts prior to forging should be carried out in a hydrogen-free atmosphere to avoid cracking.

122. Halter, Richard F. and Rajan, Sunder S. "Die wall lubrication for P/M parts and preforms", ibid, 83-85.

The use of die wall lubrication for high-volume production of parts and preforms was investigated. A variety of powders, including commercial iron, prealloyed steels, stainless steel and aluminum were successfully tested. Use of die wall lubrication removed the necessity of mixing lubricant into the powder with the attendant problem of subsequently removing the lubricant. The consequences are lower production costs and improved forging quality.

123. Cook, John P. "Effect of air exposure on oxidation and decarburization of low alloy steel P/M preforms", ibid, 97-108.

Cook investigated the effect of temperature on air oxidation of preforms of four low-alloy steels containing 0.4% C and various amounts of nickel, molybdenum and manganese. Similar work had been carried out by Cook on iron containing 0.4% C (see ref. No. 78). The preforms were prepared from water-atomized alloy powders that were compacted and sintered. Preform densities ranged from 5.3 to 7.2 g/cm^3. The preforms were heated to temperatures ranging from 565°C to 1120°C and exposed to air for periods up to 32 sec and then oil quenched. At 565°C and 650°C, oxidation occurred with no decarburization. The amount of decarburization then increased as the temperature increased to 1120°C. Graphite-based lubricant coatings were found to decrease the amount of decarburization at 1120°C, and it was concluded that they would probably eliminate oxidation and decarburization at temperatures in the range of 760°C to 980°C. (See also: Ref. Nos. 78 and 153.)

124. Guichelaar, Philip J. and Pehlke, Robert D. "Gas-metal reactions during induction sintering", ibid, 109-123.

Induction heating has been proposed for use in the sintering of preforms because it has possible advantages such as higher productivity, improved process control, cleanliness, and lower costs. Guichelar and Pehlke investigated induction sintering by studying the rates of particle-surface deoxidation and carbon absorption into the matrix. The compacts were made from water-atomized iron powder blended with graphite. Carbon monoxide evolution occurred at a high rate initially, decaying to a low rate in a relatively short time. The time required for carbon to diffuse into the iron particles is comparable to that of the deoxidation reaction. It was concluded that induction heating was at least attractive for sintering small preforms.

125. Huseby, R.A. and Landgraf, C.J. "Commercial powders for forging of P/M preforms, ibid, 137-150.

Huseby and Landgraf describe the properties of six commercial steel powders available from their company (A.O. Smith Inland Inc.) for preform forging. The powders are prepared by prealloying and refining in a basic electric-arc furnace, followed by water atomizing.

126. Kuhn, H.A. and Downey, C.L. "P/M preform design for hot forging", ibid, 151-162.

The mechanism of the preform forging process was studied. Special attention was given to deformation, densification, and fracture of the material and their relationship to design of the preform and to the forging process. A preform design criterion was presented based on the requirement of full densification. A simple cylindrical shape in aluminum alloy 601AB was considered. By determining the densification and fracture behaviour of the preform material, a graphical representation was used to establish preferred preform geometry. (See also: H.A. Kuhn and C.L. Downey. "Powder preform design" Soc. Mfg. Engrs. Report No. MF72-506, 13 p, 1972.)

127. Buchovecky, K.E. and Rearick, M.R. "Aluminum P/M forging", ibid, 163-174.

Buchovecky and Rearick describe the technology used to produce forgings from aluminum preforms. The preforms were made of blended compositions 601AB (0.25%Cu, 0.6%Si, 1.0%Mg, balance Al) and 201AB (4.4%Cu, 0.8%Si, 0.5%Mg, balance Al), each with 1.5% lubricant. Compacts were sintered in nitrogen with a furnace dew-point of -40 to -50°C and a temperature control of ±3°C. Hot forging was carried out in closed dies. Upsetting the preform 50% in a confined die developed higher tensile properties, elongation and fatigue limit than simple re-pressing. A forging pressure of 345 MPa (50 ksi) ensured full densification and high properties. Tensile strengths up to 455 MPa (66 ksi) and a fatigue limit of 120 MPa (17.5 ksi) for aluminum P/M forgings permit the use of powder metallurgy material in critical applications. Although the properties of the P/M forgings are similar to those of conventional forgings, costs are significantly lower and closely approach those for P/M parts. (See also: K.E. Buchovecky. "Aluminum P/M forging", Soc. Mfg. Engrs. Paper No. MF72-502, 20 p, 1972.)

128. Matthews, Paul E. "Cubraloy, a new development in aluminum-bronze powder metallurgy", ibid, 205-216.

Forging of experimental aluminum bronze blended powder alloys is discussed briefly by Matthews. Blending was preferred as the atomized alloys were very difficult to compact and sinter. The alloys were Cubraloy 5 (94.5%Cu, 5.0%Al, 0.1%Fe) and Cubraloy 11 (85.0%Cu, 11.0%Al, 4.0%Fe). The forged material had a density of 98% theoretical. The strength of the powder product is comparable to that of conventional wrought and cast material.

129. Lawley, A. "Fundamentals of deformation-processing of metal powders. Overview", ibid, 245-249.

Lawley briefly discusses preform forging in an "overview" of Drexel University's powder-metallurgy program. The over-all objective of the preform forging research is to understand the basic phenomena involved so that full utilization of the process is possible.
(Compare Ref. No. 141.)

130. Kuhn, Howard A. "Flow and fracture criteria for powder forging", ibid, 299-312.

Kuhn describes fundamental studies of the deformation and fracture behaviour of preforms made from iron and aluminum alloy powders. A relation between Poisson's ratio and density was found to be accurate for a wide range of materials. A plasticity theory gives accurate predictions of forging stresses under simple, combined-stress states. It is concluded that fracture at the free surfaces of a preform as it is forged depends on the geometry and friction conditions of the process; fracture of this type is found to be relatively independent of the preform density.

131. Niessen, Jörg. "Production experience in forging P/M parts", ibid, 314-322.

Niessen describes the so-called Krebsöge hot-forging process in which a green ferrous preform is recompacted hot and then sintered. The hot recompacting is done at 850°C with the die at 300°C. Recompacting pressure is 345 MPa (50 ksi) for carbon-free powder mixes and 445 MPa (65 ksi) for prealloyed powder, semi-alloyed powder and graphite-containing mixtures. Sintering is done at 1120°C. According to Niessen, tool life is the important economical factor in preform forging, and the comparatively low forging temperature and pressures of the Krebsöge process lead to increased tool life. Using this technique, forged densities 97 to 99% of theoretical are obtained, and Niessen believes these densities to be more realistic and reproducible in mass production than densities greater than 99% of theoretical.

The Krebsöge process is said to have proven to be competitive with conventional forging of wrought steel. More than 100,000 parts manufactured by this process have been sold to industry.

132. Gale, Keith. "Sintering squeezes out the shapes for profit", The Engineer, 30-32, 21 Oct. 1971.

This short review mentions that automobile gears offer perhaps the greatest potential benefit from powder forging. Other promising applications are automobile driveshaft flanges, toothed belt pulleys as used in overhead camshaft engines, and connecting rods.

133. Anon. "Sintered iron powder cold forging technique perfected", Technocrat (Japan), Vol. 4, No. 11, 8, Nov. 1971.

This short news item reports that cold forging of sintered iron powder had been successfully carried out by the Nakagawa Research Laboratory, University of Tokyo. Billet density before forging was 6.57 g/cm^3 and after forging it was 7.85 g/cm^3.

134. Obrzut, John J. "PM forging logjam starts to break up", Iron Age, Vol. 208, No. 20, 64-65, 11 Nov. 1971.

This is a review of the outlook for P/M forging. Automakers have worked hard to prove the technical and economical feasibility of the process. Hoeganaes are confident that P/M forging will fulfil expectations; their new steel atomizing plant is capable of producing 55,000 tons per year of powders particularly suitable for making high-density forged parts. Forging powders must be clean internally and externally. Most powders for forging preforms are based on additions of molybdenum and nickel with some manganese. However, Hoeganaes is investigating iron alloys containing manganese and chromium with the hope that these lower-cost additions will eventually prove profitable. R.R. Holmes, vice-president of marketing for Hoeganaes, forecasts consumption of 100,000 tons annually of powder for forging.
(See also: Southam's Metalworking, Vol. 35, No. 3, 24-25, Mar. 1972.)

135. Byrne, J.G. and Ferriss, D.P. "The mechanical behaviour of forged iron powder preforms", Powder Met. Int., Vol. 13, No. 4, 202-205, Nov. 1971.

This is a belated presentation of work done in 1957 on the relationship between the specific surface area of three types of iron powder and the mechanical properties of forged preforms. It was concluded that ultimate tensile strength and hardness increased with increasing specific surface area. Also, finer grain sizes were produced by higher values of specific surface area.

136. Malim, Thomas H. "Now, titanium parts from powder", Iron Age, Vol. 208, No. 21, 60, 18 Nov. 1971.

Malim notes that forging preforms provide the largest potential for a tonnage market for titanium and titanium alloy powders. Turbine blades hot forged from powder preforms are being evaluated by jet engine and air frame manufacturers.

137. Anon. "Materials progress", Metal Progress, Vol. 100, No. 6, 7, Dec. 1971.

A short news note mentions a new technique developed in Germany in which preforms are hot forged in the green condition. This is followed by sintering in order to alloy the mixed powders used in the process. Lower than usual temperatures and pressures are required in forging. Forged parts have densities ranging from 97 to 99% of theoretical. It is considered unnecessary and uneconomical to aim for 100% density. Green preforms are induction heated in an inert atmosphere. Forging is done in a toggle press, and tooling is electrically heated to a maximum of 300°C. Sintering is done at 1120°C. Mixtures such as Fe-Ni-Cu and Fe-S are used, emphasis being placed on tailoring the material for the application. Thus, sulphur is added to improve machinability. Examples of two parts being production-forged are (1) exhaust gas and fuel-air mixture distributor for auto engines (made from low-alloy steel powder containing sulphur), and (2) ratchet that engages gearbox shaft (made from Fe-Ni-Cu alloy).

138. Huseby, Robert A. "New prealloyed steel powders for forging preforms", ibid, 84-86.

Huseby discusses prealloyed steel powders available for forging of preforms and gives details of compacting, sintering and forging procedures. According to Huseby, the final 1 to 2% of theoretical density above 98% is very important if maximum properties are desired. Prealloys containing manganese and chromium are effective and, although oxides of these elements will not be reduced in hydrogen during normal sintering, they can be reduced if carbon is present. Oxides of silicon,aluminum and titanium are not reduced because of the low temperatures involved.

139. Anon. "Prealloy Mn-Mo steel powder introduced for P/M forging", Materials Eng., Vol. 14, No. 7, 52, Dec. 1971.

A.O. Smith-Inland developed the atomized, prealloyed steel powder, 40F2, for forged parts requiring intermediate hardenability. Its nominal composition is 0.55%Mo-0.50%Mn-0.02%Si-0.01%P-0.01%C-balance iron.

140. Aronin, L.R. and Greenspan, J. "Potentials of powder metallurgy products in military applications", Progress in Powder Metallurgy, Vol. 27, part 2: "P/M in Government Products", 23-43, Dec. 1971. (Proc. of second tutorial seminar on P/M in ordnance, sponsored by MPIF and presented in Detroit, Mich., Dec. 8-9, 1971.)

Aronin and Greenspan report on the utilization of powder metallurgy products in military hardware. Present technology permits preform forging of parts weighing 60g to 2.3 kg, though a 3.6-kg transmission gear is scheduled for limited production soon. Press requirements are about 275 MPa (40 ksi) for preform moulding and 415-895 MPa (60-130 ksi) for forging. Preform forgings of up to 114-kg size are envisaged for the future. Data are presented to show how costs are lowered when forgings are made from powder as compared to the conventional method. The principal economies of the powder metallurgy approach are in savings in material and machining. Details are given of the design and properties of a machine-gun trigger accelerator produced by preform forging of 4640 steel; properties are equivalent to those of conventional forgings. Aronin and Greenspan also make brief mention of the use of the spark sintering process in preform forging. In this process, loose powder in the die is heated rapidly by a combination of alternating and direct currents and simultaneously pressed to final shape and density. Preform forging of military components in titanium alloys and nickel- or cobalt-base superalloys is also touched upon. Isothermally forged panels in Ti-6%Al-4%V alloy exhibit promising properties when made from elemental mixtures but not when made from prealloyed powder. However, spark sintering and forging of prealloyed powders produce good properties. The homogeneity and fine grain of superalloy powder compacts permits isothermal forging of large, contoured turbine components otherwise not feasible when the alloy is in segregated condition and/or of large grain size; thus, alloys such as IN-100, previously unforgeable, can now be forged.

141. Lawley, Alan. "Powder metallurgy production of structural shapes", ibid, 45-61.

The objectives and accomplishments of the powder metallurgy program at Drexel University (Philadelphia, U.S.A.) are described. Part of the program is a study of preform forging, the objective being "to provide a means for complete utilization of the process through a thorough understanding of the basic phenomena involved". A simple upset (compression) test was used to simulate a large class of forged shapes. Friction conditions at the die/compact interface were studied. Iron- and aluminum-base alloy powders were forged. The preform was a sintered compact with a density of over 80% theoretical.

The following relationship between lateral flow (in terms of Poisson's ratio) and density has been found:

$$\nu = 0.5\left(\frac{\rho}{\rho_t}\right)^{1.92}$$

where ν = Poisson's ratio

$\frac{\rho}{\rho_t}$ = fraction of theoretical density.

It was also noted that greater density was achieved for a given amount of compression in preforms with smaller height-to-diameter ratios and greater friction at the die/preform interface. (Compare Ref. No. 129.)

142. Durdaller, Cornelius. "Status of new advances in P/M technology-iron P/M forging", ibid, 103-115.

Durdaller gives a general account of the preform forging process. He attributes the recent rapid development of preform forging to increased acceptance of powder metallurgy parts, improved equipment for parts manufacture, improved quality of iron powder, and availability of prealloyed powders. Preform forging greatly expands the number and kinds of parts that can be made from powder. Particle bonding is important in the powder-forged part even if forged to maximum density. It appears that a certain amount of material flow is necessary during the forging operation to ensure that bonding among powder particles is sufficient to achieve maximum mechanical properties. The author describes the distinguishing features of the three kinds of preform forging -- hot repressing, confined die without flash and closed die with limited flash. Preforms and finished forgings are illustrated.

143. Coyne, James E. and McKeogh, John D. "What's new in forging". Machine Design, Vol. 43, No. 31, 39-44, Dec. 23, 1971.

Some advantages of powder forging are mentioned briefly in this review article. The main benefit is said to be that complex alloys can be developed and utilized in a fraction of the time required with melt-and-cast technology.

144. Bockstiegel, G. and Olsen, H. "Processing parameters in the hot forming of powder preforms". Third European Powder Metallurgy Symposium 1971. Conference supplement, part 1. Powder Metallurgy (U.K.) 127-149, 1971.

These investigators studied the influence of ferrous preform density, pressing temperature and speed, die temperature and lubrication on the density, porosity and cracking of the resulting forgings. The results showed that full densification could be obtained at the centre of forging worked at 260-520 MPa (38-76 ksi) and 1100°C, but full density in the peripheral parts could be achieved only when the repressing tool was preheated and lubricated. Pressing temperatures of about 800°C may be preferable in special cases.

145. Zapf, G. and Niessen, J. "Investigations of the effect of temperature of press tool and compact and of the sintering state of the compact on additional hot compacting or hot forming with various sintered ferrous materials", ibid, 151-171.

Processes for hot forming of sintered materials have attracted considerable interest in the last decade, and large-scale production has already been planned and has even reached the running-in stage of quantity production. However, there is still a lack of knowledge of many of the parameters that influence the process, both technically and economically. According to the authors, the best chance of being able to compete with existing conventional processes lies with hot forming of sintered preforms and with the so-called Krebsöge process, in which a partially sintered preform is hot formed and then fully sintered. When high physical properties are not required, the sintering stage may be omitted from the latter process. The paper reports on an investigation of the Krebsöge process. The following parameters were studied for compacts made from unalloyed and prealloyed powder, and powder mixes: die temperature, hot-forming temperature, degree of sintering, and clearance between tool and workpiece.

Optimum die temperature was found to be 300°C. A pre-compacting density of 80% theoretical density gave the highest density after hot compacting. To obtain the same density, prealloyed powders had to be subjected to much higher pressures than those required for mixed-alloy powders of the same compaction. Optimum recompacted density was obtained in mixed Fe-Cu alloys at a workpiece temperature of 850°C. The gap between preform and die wall was found to affect the density after hot forming, optimum recompaction being obtained with a clearance of 0.6-1.2 mm without initiating cracks. Prealloyed powders gave higher mechanical properties than did mixed powders.

The authors give examples of components made by hot forming -- ratchet, safety nut and distributor part.

146. Dautzenberg, N. and Hewing, J. "Steel powder for hot compacting and physical properties of materials manufactured from it", ibid, 173-192.

According to the authors, iron powder produced by direct reduction of iron ore or mill scale is not suitable for powder forging because of its high inclusion content. An average inclusion content of 0.6% of difficult-to-reduce oxides (e.g., SiO_2, Al_2O_3, MnO and Cr_2O_3) has been found in sponge iron, and this amount is unacceptable for forgings subject to dynamic stresses. As the powder-preform forging process is aimed at the production of highly stressed machine components such as gears, which may require heat treatment, a prealloyed powder is a necessity.

Dautzenberg and Hewing chose for study a water-atomized prealloyed steel powder with the composition 0.44%C-1.73%Mn-0.28%Cr-0.32%Mo-balance iron. The powder was prepared without any special precautions and contained 0.38% oxygen (equivalent to >0.6% oxides) from difficult-to-reduce oxides. The most common inclusion was SiO_2 associated with manganese silicate, originating from the fire clay of the launder and the slag. Other inclusions identified contained Cr_2O_3, MnO, Al_2O_3 and CaO. The total oxygen content was lowered to 0.02% by improvements in the atomizing equipment and by removal of the slagging and deoxidation products suspended in the melt. The tensile, impact and fatigue properties of forgings made from the low-oxygen powder were as good as, and sometimes better than, the properties of wrought material of similar composition.

147. Lindskog, P. and Skoglund, G. "Alloying practice in the production of sintered steels", ibid, 375-396.

The advent of powder forging makes it necessary to re-examine both the selection of alloying elements and the method of alloying. Since powder forging makes it possible to eliminate porosity completely, the mechanical properties, particularly toughness, become related to other defects, such as inclusions. Hardenability is important for many powder forging applications and this means that composition and homogeneity must be carefully considered. On the other hand, cold compressibility of the powder is less important in powder forging than in conventional powder metallurgy since most of the densification in the former is done at elevated temperatures.

Alloying additions are usually added to the powder before consolidation, employing one of the following methods:

(1) mixtures of elemental powders
(2) mixtures of pure iron powder with master-alloy powder
(3) partially prealloyed powders
(4) completely prealloyed powders.

Alloying elements that oxidize readily can be utilized to a greater extent in prealloyed powders than in mixed elemental powders. However, the high cost of prealloyed powder favours the use of mixed or partially prealloyed powders where complete homogenization is not essential.

Examples of elements which diffuse comparatively rapidly in iron and are acceptable in mixed form are carbon, copper, nickel and molybdenum. Chromium and manganese create problems, both in mixtures and in prealloys, because of the difficult-to-reduce oxide skin that forms on the surface of the powder particles.

Homogenization of alloying additions and the oxidation-reduction reactions during sintering in different atmospheres are discussed.

148. Lindsay-Carl, L.W. "The possibility of using powder forgings in highly stressed automobile components". Third European Powder Metallurgy Symposium 1971. Conference supplement, part II. Powder Metallurgy (U.K.), 517-529.

The author considers the possibility of powder forgings becoming acceptable for mass production by 1973. Before this goal can be reached certain conditions must be met, including availability of the right type of powder at the right price and recognition by engineers of the differences between powder-forged material and its wrought-forged counterpart.

Because of the advanced state of fabrication in the automotive industry, it is insufficient to produce forgings that merely require less machining. What is required is a forging that eliminates complete machining operations. Powder forgings are especially advantageous for reciprocating components such as connecting rods because weight-adjustment bosses can be omitted. The surface finish of powder forgings is good enough to eliminate the machining often required on conventional forgings to render them dynamically balanced.

Fatigue and impact strengths of powder forgings are lowered when the oxygen content of the powder is greater than 0.05%. Low oxygen content can be obtained in Ni-Mo prealloyed powders but it is difficult to achieve this in the less-expensive alloys containing Mn, Cr and Si since the oxides of these elements are not reduced during sintering, even in the presence of carbon.

There are several ways of sintering the preforms and heating them to forging temperature, but the best method would appear to be conventional sintering with transfer to the forging die directly from the hot zone of the furnace. However, the sintering furnace would have to be specially designed for such a procedure.

Production of powder forgings will have to be fully automated and there must be a high level of co-operation between producer and user. The author concludes that, in view of the unsatisfactory economic situation, it is unlikely that there will be large-scale use of powder forgings by 1974.

149. Fischmeister, H.F., Easterling, K.E., Larsson, L-E., Olsson, L., Nickolausson, P.Å. and Heurling, K. "Comparison of the mechanical properties of sintered and sinter-forged Ni-Cu steels with cast and wrought alloys using yield-strength and toughness criteria", ibid, 530-560.

The authors compared the mechanical properties of typical sintered steels (2%Ni-1%Cu-0.35% C and 0.62%C-balance Fe) with the properties of conventional alloys. The density of the powder product varied from 80 to 99% of theoretical, the higher levels being obtained by sinter-forging. Sintered steels are usually tested for ultimate tensile strength and elongation, but data on proof stress, toughness, fatigue strength and hardness are more relevant. The parameters chosen for comparison were proof stress and tensile fracture energy. The powder alloys were mixtures of atomized iron powder with additions of nickel, copper and carbon powders.

Test data for ultimate tensile strength and elongation put the sintered and sinter-forged metal in a poor light, whereas the more relevant test parameters of proof stress and tensile fracture energy are more favourable for the powder product. Yield strength of the powder material can be described as a function of porosity and of the yield strength of the pore-free metal. Fracture strength can be described as a function of the density of crack-nucleation centres.

150. Peebles, Roger E. "Titanium powder metallurgy for forgings; final report, Mar. 30, 1968 - June 30, 1971". Air Force Materials Laboratory NTIS, AD 736477, 283 pp, 1971.

A powder production process (hydride-dehydride) capable of meeting the program objective of less than $10/lb was realized. NUMEC, the powder vendor, estimates a cost of $5.50/lb for Ti-6Al-4V powders with an oxygen content of less than 1500 ppm (AMS 4928C specification is 2,000 ppm max), and meeting all other composition requirements of AMS 4928C.

Isostatic compaction in a cast polyurethane mould at a pressure of 345 MPa (50 ksi) and sintering at 1400°C for 2 to 6 hr in vacuum gave densities of 85-92% of theoretical. This was achieved using prealloyed powder as starting material.

An aircraft structural part, a cargo tie-down ring, was produced at 100% theoretical density from pressed and sintered Ti-6%Al-4%V powder preform via forging in two blows. A jet engine component, an inlet guide vane, of 100% theoretical density, was produced in the same way.

The cargo tie-down ring was not tested due to surface contamination by nitrogen. Testing of the inlet guide vane was hindered by surface-associated high oxygen. These parts, when tested for component fatigue life (10^7 cycles) demonstrated fatigue endurance limits of 355 MPa (51.5 ksi) which compares with a value of 356 MPa (51.7 ksi) for the same part produced by conventional means (forging centreless-ground barstock). (See also Ref. No. 151.)

151. Blakeslee, H.W. "Powder metallurgy in aerospace research". A survey prepared under contract for NASA by Franklin Institute Research Laboratories, Philadelphia, Pa., U.S.A., 1971.

A hot-working step after sintering, such as forging, is required for the development of full strength in titanium powder alloys. Cargo hold-down rings made for the U.S. Air Force are illustrated. They were forged to final shape from Ti-6%Al-4%V alloy powder produced from hydride. (See also Ref. No. 150.)

152. Antes, Harry W. "Powder-forging fundamentals", P/M Forging Seminar, Hoeganaes Corp., 17 pp., 1971.

In contrast to the constancy of volume for working conventional material, is the non-constancy of volume or definite decrease in volume that occurs in working powder metal preforms. Stress and strain are fundamental properties and their relationship to one another are critically reviewed. Application of these quantities to the flow of fully dense and porous materials are given and related to experimental results. The application of strain to predicting densification is covered by the results of experiments. The object of the paper, it is stated, is to demonstrate the importance of fundamentals so that P/M forging technology may be developed and applied.

Data obtained indicate that densities calculated from deformation strains agree well with actual measured densities. This indicates that, at least for simple shapes, preform density and dimensions may be calculated so that, in closed-die forging, essentially full density can be achieved when the preform flows to the die wall.

153. Cook, John P. "High temperature oxidation of 1040 and 4640 powder preforms", Forging Seminar, Hoeganaes Corp., 8 pp., 1971.

Preforms of Type 1040 and 4640 steels made from powder were compacted to densities from 5.3 to 7.2 g/cm^3. The sintered preforms were then exposed to the atmosphere for temperatures of 565°C to 1120°C for the 1040 alloy and 760°C to 1120°C for the 4640 alloy. Exposure times ranged up to 32 sec. Metallographic evaluations were made to determine the effects of variables of preform density, exposure time and exposure temperature on the degree of oxide penetration and decarburization.

At 565°C and 650°C, oxidation occurred with no decarburization, while the maximum depth of oxide penetration after 32 sec was 0.5 mm. The only difference between the samples exposed at 760, 815 and 980°C was more decarburization in the latter. Oxidation of 1040 preforms occurred very rapidly at 1120°C with all the particle surfaces oxidized within 2 sec with the 5.3 g/cm^3 preforms. Material compacted at 690 MPa (100 ksi), 7.2 g/cm^3 preforms, had oxide 1.88 mm deep within 2 sec. Only a thick surface layer of oxide formed on the 4640 preforms exposed at 1120°C. Coating preforms with commercial graphite-based hot forging lubricants was found to eliminate almost all oxidation and a great deal of decarburization at 1120°C for even the lowest density preforms (5.3 g/cm^3). (See also Ref. Nos. 78 and 123.)

154. Durdaller, Cornelius. "Powders for forging", Forging Seminar, Hoeganaes Corp., 21 pp., 1971.

There is a need for developing powders specifically for powder forging. The economics of the powder manufacturing process restricts the range of useful powders that can be produced. The great majority of iron powders used for conventional P/M parts are made by the solid-state reduction of iron oxides, although the usage of atomized iron is growing rapidly. Owing to the limitations on press size and sintering furnaces, the method of mixing other powders with the base powder is the one normally used to increase the strength of conventional P/M parts. Typical mixes include C, Cu, Ni and Mo powders. Only in the case of the graphite addition is a homogeneous alloy formed. The others are inhomogeneous and the structures are unique to powder metallurgy. There is little doubt that prealloyed homogeneous powders will find widespread use in P/M forging. The only question is the extent that conventional P/M structures made by powder mixing will be acceptable. If sponge (solid-state reduced) iron powders are to be used in P/M forging, they will be used in the premixed or semi-alloyed form. Atomized powder, on the other hand, can be readily used to make prealloyed powders and they are being widely evaluated for use in P/M forging.

Just 2.3 to 4.5 kg of powder forged parts per car would take more powder than most powder producers could produce just a few years ago. To replace conventional forged parts by P/M forgings requires that the latter be homogeneous and the only practical way to make a homogeneous powder is by atomization.

The superalloy example is especially instructive because it illustrates the advantages of P/M forging. Nickel-base superalloys contain Al or Ti which are very strong oxide-formers and, for them to remain effective in the atomized alloy, no more than 0.0050% of oxygen can be added during processing from melt to part. But superalloy powders have been made and successfully fabricated into parts within the specification limits. Superalloys cost several dollars per pound more as powder, but give these advantages that justify the added cost: increased yield from the forging operation, increased forgeability, more predictable property response during heat treatment, broader range of alloys can be used for forging, and new alloys can be developed specifically from the powder approach.

Most AISI compositions can be made by water atomization, the cheapest atomization method. Standard AISI alloys containing Cr and Mn, the two major alloying elements which oxidize more readily than iron, have been made and hot forged to full density under controlled conditions without any significant oxidation. The use of Cr and Mn is essential to the production of cheaper low-alloy heat-treatable steel powders. The use of prealloyed atomized powders containing these elements will make it easier to protect them from oxidation than if mixtures of the elemental powders were used.

P/M methods are ideal for developing dispersion-strengthened alloys or for creating alloys from materials which are incompatible like the cermets.

All the reasons for using the fine P/M particle sizes are not valid for P/M forging. A coarse powder, for example, would give void structure in a preform that would be easier to eliminate than in a fine powder. Coarse powder may very well minimize the contamination and oxidation problems.

A successful P/M forging process must control the oxidation of the powder preform from compaction through the final forging step. In general, any oxidation that occurs must be less than that which would affect the dynamic properties or the hardenability if the properties of conventional forgings are desired. This level of oxidation has yet to be determined and remains one of the major pieces of design information required to put the technology of P/M on a firm commercial basis.
(See also: Cornelius Durdaller, "Powders for P/M forging", Soc. Mfg. Engrs., Report No. MF72-501, 24 p, 1972.)

1972 (155-224)

155. Anon. "Technology forecast for 1972", Metal Progress, Vol. 101, No. 1, 76,78, Jan. 1972.

Development of equipment, procedures, and applications for P/M forging will accelerate in 1972. Under investigation are automotive parts such as differential side and pinion gears, pinion gears requiring no further machining on the teeth, connecting rods and differential ring gear blanks. A new inert-gas atomization facility will be producing 2000-lb heats of high-purity superalloy powders. Preforms will be densified to close-to-final configuration by hot isostatic pressing. Turbine components will be made from these preforms.

The first production P/M forging (a 4600 series part due for production in 1972) will be produced on modified conventional equipment. With improved densification techniques and equipment, hot-forged P/M parts could compete with most cast and wrought products.

156. Nayar, H.S. "Powder metallurgy review 4. Strip products via particle metallurgy", Powder Metallurgy International, Vol. 4, No. 1, 30, 32-36, Feb. 1972.

This is a review article which includes comments on forging of powder preforms. The preform forging industry is in the process of emerging as a viable production method. The particle size of the powder used for this application can be up to about 40 mesh. The consumption of powder used may reach a level of 400,000 to 800,000 tons per year by 1980.

157. Buchovecky, Kalman E. and Rearick, Milton R. "Aluminum P/M forgings", Metal Progress, Vol. 101, No. 2, 74-78, Feb. 1972. (See also: Buchovecky, K.E. and Rearick, M.R. "Aluminum P/M forging", Precision Metal, Vol. 30, No. 4, 37-40, Apr. 1972).

Buchovecky and Rearick describe the powder forging of two aluminum-base alloys (0.25% Cu-0.6% Si-1.0% Mg-Al and 4.4% Cu -0.8% Si-0.5% Mg-Al).

The properties obtained compare favourably with those of conventional wrought products. It is the authors' view that there is a need for aluminum powder forgings in the "strength-cost gap" between castings and conventional forgings. Possible applications are connecting rods, pistons, gears and other parts now produced as conventional aluminum forgings. Aluminum powder forgings can replace steel or aluminum castings in applications where properties need to be upgraded without moving to more costly conventional forgings. Many applications now utilizing infiltrated steel P/M parts with tensile strengths up to 480 MPa (70 ksi) can be satisfied at lower cost with aluminum P/M forgings.

158. Dorofeev, Yu.G., Zherditskii, N.T., Mishchenoko, V.N., and Tsyrkin, A.T. "Sintered diesel locomotive components produced by dynamic hot pressing", Soviet Powder Metall. and Metal Ceram., Vol. 11, No. 2, 159-161, Feb. 1972.

"Dynamic hot pressing" (DHP) is another way of expressing preform forging. The work described was undertaken for the purpose of developing a process for the manufacture of a 'rocker follower', a diesel locomotive part which is characterized by high pressures and impact loads and an absence of lubrication in the friction zone. The component was made from a plain carbon steel. It required no machining and shows promise of successful field testing.

159. Cull, G.W. "Some practical aspects of the sinter-forging process", Metallurgia and Metal Forming, Vol. 39, No. 4, 123-127, Apr. 1972.

This is a practical account of powder forging, termed "sinter-forging" by the author. One of the major advantages of sinter-forging over conventional forging is material saving. Powder mixes give poor mechanical properties as a result of heterogeneity and, to overcome this, long diffusion treatments would be required to homogenize the material. Because of this, fully prealloyed powders are required. Porosity is the dominant influence on the strength of conventionally made P/M parts, but in the case of sinter-forgings the greatest influence is inclusion content as porosity is very small or non-existent. The design or shape of the preform is very important, but tolerances are generally more generous than in P/M parts. Isostatic compaction has great potential but its main disadvantages are poor dimensional control and low production rate. It is not economical to tool up a forming and forging line for a run of less than about 5,000 or even 10,000, parts. A sales volume of 20,000 to 50,000 parts per annum is a desirable minimum. The future of sinter-forging depends on the powder producers and on the customers. (See also: Steel Times, Vol. 200, No. 4, 343-348, Apr. 1972.)

160. Durdaller, Cornelius. "An overview of developments in iron-base powders and processes for forging", Metal Progress, Vol. 101, No. 4, 44-45, 48-49, Apr. 1972.

The past two years have seen considerable advancement in the technology of powder forging. Independent fabricators like GKN (U.K.) and Gould Inc., Federal-Mogul Corp. and Burgess-Norton Mfg. Co. (all U.S.A.) are able to forge commercial parts economically. Also, the three major automotive companies in the U.S.A. are actively involved in developing applications. Powder development and forging process development are related because the mechanical properties of a powder-forged part are determined by the physical properties and chemical composition of the powder and the manner in which the powder is consolidated. A large market for forgings made from premixed powders is expected to develop. However, atomized, homogeneous, low-alloy steel powders are required for the most demanding applications. Precautions must be taken to avoid formation of oxides of metals such as Cr, Mn, V, Ti and Al, as they are difficult or impossible to reduce during sintering. Powders being actively considered for most production of powder forgings do not contain these alloying elements. Decarburization is also a serious concern. The two most commonly available powders are based on additions of Ni and Mo. Other elements of interest that can be readily protected from oxidation are Cu and Co. When Mn and Cr are present in dilute solution in the iron (<1%) they can be protected from oxidation. Inclusion content must be kept low as they can reduce ductility and impact strength. Graphite-base coatings on the preform help to prevent decarburization. The deformation given to the preform must accomplish some material flow in addition to removing porosity in order to obtain dynamic properties equivalent to those of wrought steels.

161. Gustafson, D.A. "HD:P/M" and "high density via P/M techniques", ibid, 49, 52.

This is a brief article listing some of the major applications of the process. The automotive industry has been a leader in the field. The parts most favoured for conversion to the powder route are pinion and side gears for differential applications and a transmission side gear. Farm equipment manufacturers have approved parts for garden tractors, chain saws, and similar equipment.

The author does not approve use of the term "P/M forging" and suggests using HD/PM, meaning high density via P/M techniques.

162. Diman, William C. "Surveying trends in furnace technology", ibid, 58, 61-62.

Most of the furnaces presently available for P/M forging systems are inadequate. Development in the following areas is required: (a) higher sintering temperatures, 1200-1315°C, (b) more refined automatic atmosphere controls to closely maintain carbon content of preforms and, (c) provision for high-production-rate feeding systems to automatically transfer preforms to the forging die.

163. Anon. "Al-alloy P/M forgings make more advances", Materials Eng., Vol. 75, No. 5, 12, May 1972.

Hand forgings and extrusions were fabricated from the following powder alloys: (a) 6.5% Zn-2.3% Mg-1.6% Cu-balance Al, (b) 8.0% Zn-2.5% Mg-1.0% Cu-balance Al and, (c) 8.0% Zn-2.5% Mg-1.6% Co-1.0% Cu-balance Al. Compacts up to 77 kg in weight were made.

Based on visual and ultrasonic quality ratings, optimum forgeability was obtained with powders containing 75 to 90% of -325 mesh. Hot pressing was done at 620 MPa (90 ksi) and the billets were scalped to remove 3 to 6 mm or more from the surface.

164. McGee, Sherwood W. and Waller, Gustav M. "Five case histories reflect state of P/M technology", Metal Progress, Vol. 101, No. 5, 76-77, 79, May 1972.

Details are given of two components made by forging SAE 4640 alloy powder - a "special nut" and an "end plate for tank track link".

(See also: G.M. Waller, J.H. Mikoda and S.W. McGee, "Structural part applications of sintered ferrous alloys", Progress in Powder Metallurgy, Vol. 28, 1972 National Powder Metallurgy Conf. Proc., ed. by Allan S. Bufferd, MPIF, New York, 115-128, 1972.)

165. Price, V.T. "A look at the present and future of powder metallurgy", ibid, 83.

This brief article points out that it is only after years of development work that 1972 will see significant progress in hot forging of powder preforms. The writer cautions against over-enthusiasm for the process.

166. Clare, L. Paul. "Where high-temperature P/M metals are being used", ibid, 84, 86-87.

This brief article describes some of the applications for sintered and forged heat-resistant metal and alloy powders. A 1360-kg forging billet has been made from molybdenum powder. A forging made from tungsten powder is the key part of the exhaust system forming the venturi in solid fuel missiles. There is growing interest in producing superalloys via powder metallurgy to avoid the heterogeneity associated with castings. Alloys such as IN-100, Astroloy, and Inconel 718 have been produced in powder form for forging. It is also possible that superalloy powders may be isothermally forged in dies made from molybdenum alloy powder.

167. Wentzell, Joseph M. "Trends in processing alloy powders and shapes", ibid, 87-88.

When conventional melting and casting techniques are used for highly complex alloys, segregation often occurs, rendering the material unworkable. Several new techniques, including direct forging, have been used to consolidate spherical alloy powder particles to nearly 100% theoretical density. A less than fully dense powder compact can be made to flow readily, with full compaction coming at the end of the stroke. It appears that the price of superalloy powder will be equivalent to that of cast billets in 3 to 5 years. A 50% price advantage for forged powder components is possible if artificial price structures are not maintained.

168. Abkowitz, Stanley. "Potentials of as-sintered and forged titanium parts", ibid, 88, 90.

Forging of titanium and titanium alloy powder preforms to full density results in properties which are essentially equivalent to those of wrought products. The pressed and sintered preform approach for titanium and titanium alloys has a potentially strong economic advantage, particularly for high surface area to weight ratio forgings with poor material utilization. Such forgings can require as many as seven dies for blocking and multiple intermediate forging steps, followed by the final forge operation. The finished forging can weigh as little as 10 to 20% of the starting billet stock.

169. Waller, G.M., Mikoda, J.H. and McGee, S.W. "Structural part applications of sintered ferrous alloys", ibid, 115-128.

This paper presents five case histories of applications for structural powder metallurgy parts. Two of the examples are produced by preform forging: (a) a special nut for retaining piston pins in place within pistons of large diesel engines and, (b) an end plate for a tank track link.

170. Challis, Harry. "Forming with metal powder", Engineering, Vol. 212, No. 5, 486-488, May 1972.

This is a brief description of powder metallurgy techniques with data relating to properties and applications components. Sinter forging and its possibilities are discussed.

171. Roll, Kempton H. Metal Progress, Vol. 101, No. 6, 12, June 1972.

All of the major automakers have active development programs and should be using some variety of post-densification on powder metallurgy parts in cars by no later than 1975. Initial applications will include a ring gear, a differential side pinion gear, and an output ring gear for automatic transmissions. Also under consideration are an alternator pole piece, a stator clutch, overrunning clutch races, other gears and connecting rods.

172. Anon. "What's ahead in forging P/M parts?" Precision Metal, Vol. 30, No. 60, 70-72, June 1972.

The Director, Manufacturing and Development Office, Ford Motor Co., is interviewed regarding position of powder forging in automotive industry. Work on forging of powder preforms is being done at Ford, but they prefer to call it hot coining or hot forming as the preform is deformed with little or no plastic flow. The hot-forming process is in competition with almost every automotive steel forging made by conventional means. The isotropic property of the P/M part is considered to be an important advantage. There is expected to be limited production of various kinds of gears by the powder method within the next few years (from 1972). It is estimated that by 1980 there will be at least 23 kg of forged or hot-densified steel powder parts per car. Within about 10 years the total consumption of iron and steel powders in the U.S.A. could reach one million tons per year. Premixed powders are preferred to prealloyed powders because the composition of the former can be readily modified, and a powder mix can be "tailored" for a specific job.

173. Wakefield, Brian D. "Forging PM preforms leads to part economy", Iron Age, Vol. 210, No. 4, 53-54, 27 July 1972.

Work carried out by A.O. Smith-Inland, Inc., indicates that conventional forging practices can be adapted to use metal powder preforms. Most powder forging is being done by the "trapped die" method in which a preform of accurate weight is hot forged to form a flashless forging, with consequent conservation of material. To permit the preforms to be heated in air without harmful oxidation a new type of "Ceram-Guard" coating was developed by the company. This coating is applied to the green preform. After sintering, the "Ceram-Guard" is removed, but it leaves a protective layer on the preform.

174. Cambal, L. and Lund, J.A. "Supersolidus sintering of loose steel powders", Int. J. Powder Met., Vol. 8, No. 3, 131-140, July 1972.

Loose atomized iron powder prealloyed by gas-carburizing to a level of 0.95% carbon was sintered at temperatures above and below the equilibrium solidus temperature. Densities ranging from 86 to 91% of solid were attained in only seconds of sintering time. It is suggested that this process could be used for producing simple-shaped preforms for drop forging.

175. Obrzut, J.J. "Forged P/M parts seem ready to move ahead", Iron Age Metalworking International, Vol. 11, No. 7, 33-34, July 1972.

There has been considerable speculation as to when powder forging would begin to make real progress. Now that this appears to be happening, press builders have redesigned their equipment to provide the kind of compaction required for forging.

Hoeganaes Corp. is confident that P/M forging has a big future. The U.S. company has completed an atomizing plant capable of producing 50,000 tons per year of powders specifically suitable for making high-density forged parts. The company has significantly increased its research and development facilities and is fully committed to the development of suitable powders for forging and to a study of the powder forging parameters.

176. Anon. "Hot formed steel P/M part nears mass production", Materials Engineering, Vol. 176, No. 2, 21, Aug. 1972.

This is a short news item stating that a ring gear produced by hot P/M forming was expected to be in full production at one of the major automobile manufacturers later in 1972. The part was previously machined from a ductile iron casting and conversion to hot P/M forming reduced scrap loss by 27%.

177. Arén, B.G.A., Olsson, L. and Fischmeister, H.F. "The influence of presintering and forging temperature in powder forging", Powder Metallurgy International, Vol. 4, No. 3, 117-123, Aug. 1972.

The influence of presintering and forging temperature was studied for open-die forging of iron preforms between flat platens. It was concluded that there was no beneficial effect from sintering prior to forging. Prolonged presintering increases the risk of internal oxidation by producing smoother, rounded pore channels, allowing faster effusion of the protective atmosphere during transfer from forging preheat furnace to die. The authors conclude that when diffusion alloying is attempted the heat treatment should be given after forging unless excessive grain growth is a danger. Contrary to the findings of other investigators, no special effects were found in the vicinity of the gamma-alpha transformation despite careful study of this region.

178. Tremblay, R. and Angers, R. "Hot-pressing of iron powder: The role of transformations", Paper presented at CIM Conf. of Metallurgists, Halifax, N.S., Aug. 27-30, 1972.

The compaction of iron powder was studied during hot pressing at 8.3 MPa (1.2 ksi) between 100 and 1000°C. The results indicate that iron powder could be more easily hot-pressed and possibly more easily forged below the Curie point than at higher temperatures. It is shown that iron powder hot-pressed at temperatures below the Curie point have better general properties than powder hot-pressed at higher temperatures.

179. Gale, Keith. "Powder forging makes the best of both worlds", The Engineer (U.K.), Vol. 235, No. 6078, 54-55, 7 Sept. 1972.

This is a short review of developments in powder forging. One of the most important developments is that GKN Forgings (U.K.) is in pilot-stage production. Accuracy and surface finish are superior for powder forgings compared with conventional forgings, and there is a complete absence of scale in the former, whereas scale cannot be avoided in conventional forging. Material utilization in powder forging can be more than 90%, whereas it is usually 40 to 50% for conventional forging. Powder purity is essential for preforms.

Powder-forged connecting rods have been engine tested on a manufacturer's standard 500-hr endurance test, which included 2-hr periods at full load at maximum engine speed; the performance was entirely satisfactory. Gears are particularly suitable for production by the powder forging route, for of all components they offer the greatest potential savings. Another automobile component which lends itself to powder forging is a clutch hub. Conventionally, this is made from a forged disc which is machined all over. As a powder forging the hub comes off the forging press almost in finished condition; the windows are in and the faces are accurate enough to need no machining. Only a broaching operation is necessary.

180. Patton, Walter A. "PM parts production finally hits the big time", Iron Age, Vol. 210, No. 10, 86, 7 Sept. 1972.

This is a short note on developments in the commercial production of powder forgings with particular reference to the Federal-Mogul Company. The note claims that the long-anticipated, big-volume production of hot-formed powder parts by the automobile industry has begun. Federal-Mogul recently started its fully automated line for production of hot-formed components. This company is said to be the only commercial-quantity producer of such parts. Automatic transmission clutch components are being produced at production rates in the 3- to 5-sec cycle range. Service life of some of the P/M gears has exceeded the life of conventionally forged gears. Recent reductions in the price of 4620 alloy powder has eliminated the price disadvantage that once existed between the powder and 4620 wrought alloy steel bars.

181. Anon. "Gearmakers watch new developments", Iron Age, Vol. 210, No. 11, 61-64, 14 Sept. 1972.

The probability is very strong that, within the next 12 to 18 months, the major car producers will begin to capitalize on their ability to make gears and pinions for automobiles without generating any scrap. This will be done by hot forging P/M preforms which require almost no secondary machining. Advantages of hot forged P/M gears include material savings up to 50% compared to conventional wrought gears.

182. Davies, R. and Marx, J.B. "Production of components by forging of powder preforms", 13th International Machine Tool Design and Research Conf., University of Birmingham, Birmingham, England, 18-22 Sept. 1972.
(From: Boulger, F.W. and Byrer, T.G. Review of Metals Technology, Metals and Ceramics Information Center, Metalworking, "A Review of Selected Developments", Battelle-Columbus Laboratories, Columbus, Ohio, May 11, 1973.)

The design of preforms for producing sound steel parts was investigated. Iron powder with added graphite was used. It was shown that powder preforms could not be forged in dies with flash gutters. A completely closed-die design was considered preferable. Procedures were developed for making preforms for gears, brackets and cups. It was also demonstrated that parts can be made with different compositions at different locations in the final component.

They concluded that holes in powder preforms should be smaller than those desired in the final forging. Small radii on the preforms are often essential if small radii are desired on the final component. Preforms should be designed to produce uniformly high densities in the finished component. Flow of material from one level to another in the forging should be avoided, but flow around corners in the same horizontal plane may be beneficial.

183. Nakagawa, T.,Amano, T., Obara, K., Nishino, Y., and Maeda, Y., "On the cold forging of sintered iron powder preforms", ibid, 7p.
(From: Boulger, F.W. and Byrer, T.G. Review of Metals Technology, Metals and Ceramics Information Center, Metalworking, "A Review of Selected Developments", Battelle-Columbus Laboratories, Columbus, Ohio, May 11, 1973.)

Nakagawa and his co-workers believe that cold forging applications will be restricted to high ductility powders and that high costs of materials and sintering are the main factors delaying production operations. The experiments were conducted on a high-purity iron pressed and sintered (30 min at 1150°C) to an average density of 6.75 g/cm^3. They conclude that cold forging can give better properties than conventional P/M processes, and permits the production of a wider variety of shapes. Compared with hot forging of P/M preforms, cold forming saves some operations but the tooling loads are much higher and the limits for single-stage reductions and part complexity are severe.

184. Anon. "Forging gives bigger muscles to powder metal products", Product Engineering, Vol. 43, No. 9, 40-41, Sept. 1972.

Powder metallurgy parts were at one time considered merely as low-cost replacements for small components operating in low-stress conditions. However, with the coming of new powders, better equipment and forging techniques, powder parts are beginning to compete with high-strength conventional forgings. In tests conducted on connecting rods, hot forged P/M aluminum parts had about twice the endurance limit of a die-cast part. Automotive engineers are now testing ferrous powder forgings for critical high-stress applications such as connecting rods. Hoeganaes Corp. is developing atomized powders with low inherent porosity, especially for forging applications. Where final properties are not so critical, sponge iron grades are usually adaptable to P/M forging applications. More exotic metals also lend themselves to advanced P/M techniques. Titanium, beryllium, superalloys and refractory metals have been formed into parts from powders.

185. Anon. "Powder metallurgy offers many routes to lower cost", Metal Progress, Vol. 102, No. 3, 57-58, Sept. 1972.

This is a brief note on recent and possible future developments in powder metallurgy. Iron powders are expected to find use in preforms for hot forming into high-density components competing with conventional forgings. Some day, P/M superalloys may be forged in dies made from molybdenum powder.

186. Marx, J.B. and Davies, R. "The consolidation of powder preforms by hot forging", Proc. First International Conf. on the Compaction and Consolidation of Particulate Matter, ed. by A.S. Goldberg, Brighton, England, 203-210, 3-5 Oct.1972.

Some theoretical aspects of powder forging are dealt with, and an equation predicting forging load in upsetting is presented for low values of friction, and assuming slipping over the entire die/billet interface. Some experiments in simple upsetting enable a semi-empirical equation predicting the manner of densification during forging to be presented.

By evaluating the optimum preform design for a variety of components the following design principles are recommended for sponge iron powder.

(a) In order to make the best use of current industrial experience in compacting operations a preform pressure of about 415 MPa (60 ksi) is suggested. This will result in densities of about 80% and will ensure that the preform will withstand a fair degree of deformation without cracking.

(b) For the MH100 iron powder used in these experiments it is suggested that 1100°C is the optimum temperature for sintering and forging.

(c) The preform should be designed in such a way as to eliminate, wherever possible, the flow of metal from one depth of the forging to another. In other words, flow around corners in the vertical plane is to be avoided, but flow around corners in the horizontal plane may be considered beneficial if grain flow is required into, say, a gear tooth.

(d) The preform should be designed such that all sections of the forging densify to the same final density simultaneously.

(e) Forgings with holes can readily be forged from preforms with corresponding holes.

(f) Small radii on the preform can be forged and are often essential if small radii are to be achieved on the forging.

(g) Adequate location of the preform in the lower die must be provided to ensure a sound forging.

(h) Where large changes in cross-section are being forged it is desirable to forge the preform in both parts of the section simultaneously.

(i) Excessive lubrication will cause the metal to flow easily around corners where such a movement may not be desirable.

187. Marshall, A.F. and Taylor, H.G. "Densification of metal powders and preforms for large parts", ibid, 213-218.

The continued growth of the powder metallurgy industry in the next decade will be increasingly dependent upon the production of larger and more highly stressed components. Machines for densifying powder and preforms are already a limiting factor in the industry. Inertial energy machines of both single impact(H.E.R.) and multiple impact (vibratory compaction) types are discussed, and their distinctive characteristics examined in relation to the production requirements of the industry, in particular to the production of large area/volume ratio parts.

Machines of both types have been designed and built by the B.S.A. Group Research Centre specifically for the study of powder densification. It is shown that inertial energy machines can produce compacts to the industry's normal tolerances without the use of mechanical stops. As a means of densifying powders or preforms into large and relatively thin components, hydraulic or mechanical pressure is less efficient than inertial energy. The inertial energy machine should find a place in the competitive world of powder densification as a complement to, rather than in competition with, conventional presses.

188. DuMond, T.C. "Parts 'born-to-shape' for economy", Iron Age, Vol. 210, No. 14, 79-81, 5 Oct. 1972.

This is a brief review of some of the methods used to make parts close to final shape. It is predicted that 35 kilos of hot-formed P/M parts will be used per passenger automobile in the near future. Although there have been reports of a number of automotive applications for powder forgings, it is thought that the Federal-Mogul Corp. facility is the first to reach full production. Use of existing equipment rather than equipment designed specifically for the purpose is said to have restrained development of powder forging. As a result of the price equality between some powders and some wrought shapes, forged P/M parts can compete on an equal basis with most wrought products.

189. Kaufman, S.M. "The role of pore size in the ultimate densification achievable during P/M forging", Int. J. of Powder Metallurgy, Vol. 8, No. 4, 183-190, Oct. 1972.

With the increasing possibility of using powder forgings as structural components, weaknesses caused by residual porosity have become more important. After a mathematical treatment of the problem, the author concludes that, theoretically, it is impossible to eliminate all residual porosity by mechanical deformation. Also, shearing loads are shown to be more efficient than compression in improving final densification. It was also concluded that the theoretical degree of densification attainable under any specific condition of loading is relatively insensitive to temperature. For steel, the smallest pores that can be closed using existing types of equipment are of the order of 5 microns. It is suggested that, if small pores behave as foreign particles which are harder than the matrix in which they exist, dispersion strengthening technology should be adaptable to powder forging and powder deformation processes in general.

190. Tremblay, R. and Angers, R. "Hot-pressing of iron powder. The role of transformations", ibid, 235-242.

This work was undertaken to investigate the compaction of iron powder at various temperatures, particularly during the alpha-gamma transformation. It was thought that such a study could prove to be of interest for possible application to the consolidation of powder by hot pressing, forging or rolling. Compaction of the iron powder was studied during hot pressing at 8.3 MPa (1.2 ksi) between 100 and 1000°C. It was found that the compaction rate was greater during the alpha-gamma transformation than at temperatures just above or below the transformation. It was also observed that compaction rate was larger below the Curie point than above it. However, it is felt that if forging is carried out on a preform that has already been sintered at a temperature above the Curie point rather than on a compact that has only been cold pressed, grain growth would have occurred and forging would probably be more difficult below the Curie point than above it.

191. Anon. "Metals News: Titanium P/M forgings for aircraft appear practical". Materials Engineering, Vol. 76, No. 5, 22, Oct. 1972.

This is a brief news item. Material and cost savings are very real possibilities if close-tolerance, low-draft angle aircraft forgings can be produced from titanium alloy powder metallurgy preforms. Metallurgists at Grumman Aerospace Corp. have fabricated simulated F-14 forgings from Ti-6% Al-4% V preforms prepared from elemental titanium and Al-V master alloy powders.

192. Mocarski, S. "Hardenability and microstructure of hot-formed P/M steels", 1972 Materials Eng. Congress Abstracts, Cleveland, Ohio, Abstract No. 247, 14-19 Oct. 1972.

Prealloying of metal powders is most easily achieved with Mo, Ni and Cu to increase hardenability of hot-formed P/M steels. Recent experience has shown that up to 0.5% Mn can be present in the alloy, contributing significantly to hardenability. An attempt was made to establish hardenability factors for experimental alloys from powders containing Mo, with or without additions of Cu or Ni. The powders were compacted, sintered in hydrogen, and hot formed to ensure full densification. Jominy bars were machined, normalized and end quenched. Excellent hardenability of alloys with Mn in solution and much lower hardenability with oxidized Mn are demonstrated. Suggested alloys for carburizing (mostly gears), quenching and tempering, and induction hardening are described.

193. Bertolo, R.B. and Ault, R.T. "The influence of density and microstructure on the mechanical properties and hardenability of P/M forgings made from gas atomized alloy steel powder", ibid, Abstract No. 248.

The tensile, impact fatigue and hardenability characteristics of gas-atomized low-alloy steel powder were determined. A rectangular stainless steel can was filled with loose powder, heated to 900-1120°C under argon, soaked and upset in the thickness direction into a slab. Properties determined on powder material were compared to properties of identically heat-treated samples of conventionally cast wrought bar stock.

194. Cook, John P. "Mechanical properties of hot formed 1040 P/M steel", ibid, Abstract No. 249.

Metal powder preforms of atomized iron plus graphite for 0.4% combined carbon were hot-upset-formed to full density. Material tested in a normalized condition failed in a ductile manner in a tensile test, but displayed brittle failure in an impact test -- lower than conventional wrought 1040 steel. Microstructural studies revealed that the fracture followed a continuous carbide network that formed in the ferrite grain boundaries in the normalized material and a semi-continuous network in the quenched and tempered material. Faster quenching rates produced a smaller grain size and a less continuous carbide network with a subsequent improvement in impact properties.

195. Kaufman, S.M. "Dependence of mechanical properties of hot-formed P/M steels on porosity concentration and morphology", ibid, Abstract No. 250.

Measurements of tensile, impact, and elastic properties of hot-formed 1040 steel with controlled amounts of residual porosity (0-3% by vol) were made. Results indicated that tensile properties were not a function of porosity concentration. The elastic moduli of these materials were found to be linearly related to density as expected. Impact properties were generally poor and could not be improved by subsequent heat treatments. Analysis of these data, along with the results of previous work on other materials, indicates that the presence of small amounts of residual porosity alone is not sufficient to cause appreciable losses in strength. The state of oxidation of pore surfaces prior to hot-forming is suggested as a primary factor in determining eventual mechanical properties. Oxides present at a pore surface can prevent formation of sound grain boundaries, retard rates of pore spheroidization during sintering or heat treatments and can also retard the rate of pore closure during deformation. The implications of this hypothesis on alloy design for P/M hot forming in terms of restrictions on Cr and Mn useage are discussed.

196. Moyer, Kenneth H. "The importance of flow in the hot forming of atomized iron preforms", ibid, Abstract No. 335.

Work to date has shown that proper preform density is critical for achieving high impact properties. For instance, hot formed (6.2 g/cm^3 density) atomized iron preforms (7.86 g/cm^3 formed density) which were deformed in plane strain achieved impact strengths greater than 180 ft lb. Higher density preforms that were hot formed in plane strain to the same density had lower impact strengths -- the higher the preform density the lower the impact strength. It is believed that the additional flow received by the 6.2 g/cm^3 preforms to achieve the same density as the higher density preforms was responsible for the higher impact strengths. To further understand the importance of flow, fracture surfaces of the impact specimens deformed in plane strain were examined with a scanning electron microscope. It was found that (a) as the amount of porosity increased, the amount of extended shear fracture increased, (b) as the number and size of inclusions increased, extended shearing occurred around the inclusions and, (c) the stress-raising capacity of the inclusions led to cleavage. Since the work to date involved only plane strain deformation, the formed preforms did not achieve full density. Additional preforms (6.2 g/cm^3, 7.0 g/cm^3 and 7.2 g/cm^3 density) were closed-die formed to full density by being upset in plane strain to fill the die. All material achieved high impact strengths regardless of the preform density. Charpy impact energy transition curves were similar to those for wrought products of similar composition.

197. Hansen, James E. and Woulds, Michael J. "Comparison of flowed and repressed properties of hot forged P/M stainless steel", ibid, Abstract No. 336.

When a cylindrical powder metal preform is forged in a closed die, the properties obtained, apart from being a function of the forged density, show significant differences whether the compact was merely densified or whether metal movement occurred. Various degrees of lateral spread in forging yield improved mechanical properties over a merely repressed cylinder. Also, lower forging forces are required to obtain these properties. The surface condition is also improved in the flowed case to the betterment of corrosion resistance. The paper describes the production of flowed and repressed stainless steel forgings by upsetting various diameter preforms into a constant diameter die. A range of forging forces and temperature was also incorporated and the correlation between microstructure and properties obtained was compared for the various conditions of densification.

198. Koczak, M.J., Kuhn, H.A. and Lawley, A. "Structure property relationships in aluminum and steel forgings", ibid, Abstract No. 337.

The structure/property relationships of aluminum and steel forgings have been examined in terms of flow, densification and a correlation with mechanical properties. Following forging of aluminum (601 AB) and steel (4600) preforms, the densification behaviour was examined with respect to a correlation of internal porosity with lubrication and flow. In addition, a structural examination by scanning electron microscopy and optical metallography of hot upset and repressed aluminum forgings reveals a transition in fracture mode. An interparticle fracture mode appears to be associated with low impact properties. With increased flow, a transgranular, ductile fracture results with an attendant improvement of properties. These results suggest that optimum properties for aluminum forgings are developed through increased flow.

199. Eloff, Peter C. and Guichelaar, Philip J. "Hot-formed powder preforms: the relationships among deformation, induction sintering, and mechanical properties", ibid, Abstract No. 338.

Isostatically pressed cylindrical preforms of varying height:diameter ratios were made of prealloyed, atomized steel powder with a graphite addition to give 0.20% nominal final carbon content. The preforms were induction sintered in a nitrogen-10% hydrogen atmosphere at either 1150°C or 1290°C. Upsetting and densification were done in a trapped die of 76-mm diameter immediately after the preforms had cooled to 980°C and stabilized. The lateral flow during forming ranged from 4 to 82%, based on the change in cross-sectional area. Tensile and impact bar blanks were cut from the formed discs, "mock carburized", and oil quenched. The blanks had hardnesses in the range of Rc 37-42, simulating the core properties of carburized components. Tensile and impact properties were correlated with amounts of lateral flow, sintering temperatures, and oxygen contents. Fracture surfaces were studied with a scanning electron microscope. Lateral flow during forming was found to enhance tensile strength, ductility and impact resistance, but the effect was diminished at the higher sintering temperature.

200. Zapf, G., Niessen, J. and Dalal, K. "Dimensional changes of sintered Fe-Ni, Fe-Cu, Fe-Ni-Cu alloys", Powder Metallurgy, Vol. 15, No. 30, 228-246, Autumn 1972.

Dimensional behaviour is a very important parameter in manufacturing powder parts and, since it is treated as confidential by P/M manufacturers, it was felt that a paper on the subject would be helpful. Besides the established P/M techniques, hot pressing (or hot forging) was also investigated. The latter consisted of hot pressing green compacts and then sintering them. There was no evident effect of powder particle size on dimensional change for Fe-Ni alloys processed by hot forging. There was hardly any effect from sintering temperature or dimensional change in hot forging. Sintering in a laboratory furnace gave the highest degree of shrinkage, followed by a walking-beam furnace, while shrinkage during sintering in a pusher-type furnace was practically zero.

201. Anon. "Cincinnati introduces 800-ton hot forming press", P/M Technology, Vol. 1, No. 8, 116, Oct.-Nov. 1972.

A brief news item reveals that Cincinnati Inc. has introduced an 800-ton mechanical press for P/M hot forming with a 150-kW-capacity induction heater. The press is designed primarily for the forming of simple shapes with most metal flow along the pressing axis. It can produce 15 parts per minute single-action or 30 strokes per minute double-action, running continuously.

202. Stefanides, E.J. "Hot formed P/M preformed parts", Design News, Vol. 27, No. 23, 60-61, 4 Dec. 1972.

Federal Mogul's"Sinta-Forge"process is being used to hot-form two automatic transmission components. The preforms are compacted from a special alloy powder mixture that approximates SAE 4620.

203. Anon. "Gleason developing P/M hot forming system", Technology/Industry News, P/M Technology (APMI), Vol. 1, No. 9, 131, Dec. 1972.

This news item states that Gleason Works, Rochester, N.Y., would introduce a demonstration, integrated P/M hot-forming system in 1973. The company reported that it was evaluating an automated three-unit system that would include a dry bag isostatic compacting press, an induction sintering and heating unit and a forging press. After powder is fed into the system, there will be no physical handling of the parts until the production cycle is completed.

204. William, D.N. "General Motors converts scrap turnings into metal powders", Iron Age Metalworking International, Vol. 11, No. 12, 35-36, Dec. 1972.

A pilot plant has been built by General Motors Corp. for converting steel scrap into powder. Two important considerations for successful reclamation are sufficient machine chips to support the operation and a reasonably narrow composition range. General Motors generates nearly 45,400,000 kg of machine chips annually from which it hopes to reclaim 227,000 kg per month of powder. A modified mill is used to produce the powder (called "Macro-Mesh").

GM considers that the heat-treat response of Macro-Mesh will direct them to some warm forging applications in the near future.

205. Lawley, A. "Emerging technologies in powder metallurgy", Powder Metallurgy for High-Performance Applications, ed. by John J. Burke and Volker Weiss, Proc. 18th Sagamore Army Materials Research Conf., Syracuse University Press, 3-23, 1972.

The potential of the powder-metallurgy process in high-performance applications has brought about significant advances in the technology of powder production, compaction, sintering, and deformation processing. Full density can be achieved by hot or cold working a porous powder preform. One of the most frequently used working operations is forging. Potential areas of application for powder forging in the aerospace industry are turbine blades, trunnion rings, starter rotor blades, turbine discs, and inlet guide vanes. Possible applications in the automotive industry are manual transmission gears, drive-shaft flanges, connecting rods, side gear and pinion, alternator poles, and ring gears. For iron-base powders, tensile strengths of about 2065 MPa (300 kg) with about 12% elongation are now commonplace after forging to full density. Impact and fatigue properties are found to be comparable to those of conventional wrought material. The terms repressing, sizing, coining, and restriking are used in the context of preform forging. However, in these operations, the major effect is one of densification and only a limited amount of flow occurs. Linking these terms with conventional forging is misleading since forging involves significant amounts of material flow. Other suggested descriptions of the process are hot recompacting and sinter-forging. The latter term has validity if the preform is cooled after sintering and subsequently reheated for the forging step.

Application of ductile fracture criteria developed for conventional materials and the use of a quantitative analysis of the mechanics of deformation of semi-dense materials provide a semi-quantitative picture of flow and fracture in preform forging. In turn, this establishes guidelines for design of the total process sequence. The ultimate goal of preform forging studies should be the establishment of a fail-safe criterion. With increasing emphasis on high or full density, and with properties comparable to those of the wrought state, it becomes advantageous and important to conduct detailed structural studies on powder metallurgy materials.

206. Kuhn, H.A. "Fundamental principles of powder preform forging", ibid, 153-169.

The mechanical aspects of powder forging were studied by means of experimental techniques and analytical methods normally used in the study of conventional cast and wrought materials. The behaviour of preforms under compression was determined for iron and aluminum alloy powders. The densification, flow, and fracture behaviour of hot-worked preforms closely resembled that of cold-forged materials. It was found that decreasing the height-to-diameter ratio of the preform and increasing friction at the contact surfaces gave increased densification for a given amount of compression. However, the same factors decrease the amount of allowable compression to fracture. Preform design can be approached graphically by considering allowable deformation to fracture and then accomplishing the remaining densification by repressing. The following relation was found for the materials tested:

$$\nu = 0.5\ (\rho/\rho t)^{1.92}$$

where ν = Poisson's ratio

and $\rho/\rho t$ = fraction of theoretical density.

This relation quantitatively expresses the decreasing rate of densification (increasing Poisson's ratio) of a porous material under compression as density increases, reaching the value of one-half at full density.

207. Antes, H.W. "Processing and properties of powder forgings", ibid, 171-210.

This is a comprehensive review of the powder forging process which quotes freely from laboratory work done by the author and others in the field.

Variables and fundamentals of the different powder forging processes are described. Three distinct processes have evolved: (1) hot repressing, (2) confined-die flashless and, (3) closed-die limited flash. Atomized powders are preferred over other types of powder for most powder forging applications when full density and maximum properties are desired; these powders are relatively clean and can be prepared in various compositions. One disadvantage of prealloying carbon is that higher loads are required to prepare the preform.

Shearing and hydrostatic stresses during the forging operation affect residual porosity and void formation associated with inclusions. Precoating of preforms with graphitic materials has been used to extend the tolerable exposure time of the hot preform to air.

Mechanical properties of cold-forged preforms are good at full density and compare favourably with conventional wrought materials. The properties are sensitive to residual porosity, especially dynamic properties such as notched impact strength. Hardenability of powder forgings will fall within the H-bands provided that alloying elements are not oxidized and that grain size is not too fine.
(See also: H.W. Antes, "Forming metal powders", Soc. of Manufacturing Eng., Report No. MF72-504. Pamphlet 18 pp, 1972.)

208. Lyle, J.P. and Cebulak, W.S. "Fabrication of high-strength aluminum products from powder", ibid, 231-254.

This paper describes work done on the production of extrusion and forging billets from prealloyed atomized aluminum powder. Better combinations of strength, resistance to stress-corrosion cracking, and resistance to exfoliation can be obtained in extrusions and forgings made from the alloy powder than in corresponding products made from ingot. Products having high internal quality can be fabricated from atomized Al-Zn-Mg-Cu alloy powders by a process consisting of cold compacting, preheating, hot pressing, and hot working. (See also Ref. No. 276.)

209. Athey, R.L. and Moore, J.B. "Development of IN-100 powder-metallurgy discs for advanced jet engine application", ibid, 281-301.

Powder metallurgy is becoming increasingly important for the production of highly-alloyed nickel-base superalloys used for turbine and compressor discs in jet engines. These alloys are very prone to segregation, especially when cast as large ingots. Work carried out at Pratt and Whitney Aircraft has demonstrated that production and compaction of prealloyed atomized powder in an inert atmosphere makes it possible to produce large billets, free from segregation, of IN-100 superalloy. The billets are worked by a controlled, isothermal forging technique, which utilizes the superplastic behaviour of the alloy and has been given the name "Gatorizing".
(See also Ref. Nos. 39 and 44.)

210. Witt, R.H. and Paul, O. "Potential titanium airframe applications", ibid, 333-349.

Isostatically pressed and vacuum-sintered titanium alloy preforms from various sources were forged using conventional, high-energy rate and isothermal forging processes. Elemental powders were primarily employed to obtain the composition Ti-6% Al-4% V in preforms. It was shown that sound, high-strength, ductile forgings could be produced from this alloy.
(See also Ref. No. 61.)

211. Halter, R.F. "Production system and high-performance automotive applications", ibid, 365-374.

This article describes developmental work done on the production of a differential pinion gear by powder forging. The application was attractive because it offered (1) high potential volume, (2) high strength requirements, (3) elimination of excessive material loss, (4) uniform shape and size and, (5) tooling cost that was not excessive. The process was shown to be repeatable and controllable. Many thousands of parts have been forged with excellent dimensional reproducibility and superior mechanical properties.

212. Antes, H.W. "Deformation of porous materials", Progress in Powder Metallurgy, Vol. 28, 1972 National Powder Metallurgy Conf., Proc., ed. by Allan S. Bufferd, MPIF, New York, 6-40, 1972.

The author gives a mathematical treatment of the deformation of porous materials such as metal powder compacts or preforms. Yielding, flow and fracture are the major factors considered. The shortcomings of yield theories used for conventional full-density materials are presented with the modifications necessary for a yield theory applicable to porous materials. Experimental data are presented to support the latter.

The "V" notch impact test is the most sensitive test for assessing the integrity of material formed from powder. In the development of powder forging material and processing techniques it is important to measure impact properties.

213. Lenel, F.V. "Metal powder consolidation processes", ibid, 42-52.

In a survey of processes used to consolidate metal powders, Lenel included hot forging and hot repressing. The process is called hot forging when the preform has a much simpler shape than the final product and the more complex shape is attained through hot deformation during forging. It is called hot repressing when the compact has a shape very similar to the final product and the hot recompacting step mainly increases the density of the compact. Development work during the last five years in Europe, Japan and the U.S.A. has shown that both of these processes are economically viable, particularly for certain automotive components, such as gears and connecting rods. Most of the development work has been done on iron, iron alloys, and plain carbon and low-alloy steels, but the process will no doubt be extended to include non-ferrous metals and alloys.

214. Lawley, Alan. "The properties of consolidated powders", ibid, 67-92.

This is a review of the properties of consolidated powders. The main objective is to relate fundamental concepts with mechanical properties. A distinction is made between semi-dense materials produced by compacting and sintering, and high-density materials, produced by compacting and/or working a preform. Forging is the most advanced of the developing techniques based on preform processing. Property data are given for iron, iron-base alloys,aluminum-base alloys, superalloys and titanium-base alloys. Property combinations now attainable at high density, establish powder metallurgy as a technologically attractive means of producing materials currently fabricated by traditional cast and wrought processes.

215. Lyle, J.P., Cebulak, Walter S. and Buchovecky, K.E. "Properties of high density aluminum P/M products", ibid, 93-114.

Factors affecting the mechanical properties of aluminum powder-metallurgy products are presented and discussed. Mechanical properties can be improved by decreasing porosity. The method used to diminish porosity affects strength and toughness. Increasing the density of sintered compacts by cold coining raises the strength but may lower the ductility. Density, strength, toughness and elongation are improved by hot coining. Further improvements result from hot working. Al-Mg-Si and Al-Cu alloys are suitable for compacting and sintering as well as subsequent coining and working operations. Highest properties are obtained with Al-Zn-Mg-Cu alloys, but substantial amounts of hot deformation are required to develop these properties.

The "blended" powder compositions considered are 201AC (4.4% Cu-0.8% Si-0.5% Mg-balance Al) and 601AC (0.25% Cu-0.6% Si -1.0% Mg-balance Al). A prealloyed atomized powder (6.5% Zn-2.3% Mg-1.5% Cu-balance Al) was also studied.

216. Cheney, R.F. "Consolidation of tungsten and molybdenum powders", ibid, 143-164.

The production of wrought tungsten and molybdenum products from powder is described. The powders are usually consolidated by isostatic compaction into billets which can be worked in one of several ways. Large and small parts can be formed from the molybdenum and tungsten alloy billets.

217. Thellmann, Edward. "Recent developments in titanium P/M", ibid, 166-178.

Practical examples of components made from titanium powder alloys are given, including forgings made from sintered billets.

218. Brown, G.T. "The powder forging of low cost materials", ibid, 244-258.

Although the cost of metal powders is relatively high, two factors make powder forging attractive economically. These are high utilization of material and the necessity for little or no machining. Brown reports on work done using less expensive materials to replace the iron powders normally used. The three materials investigated were (1) a 'direct-ore' product obtained by mixing a high-purity iron ore with graphite and so producing iron 'in situ' during sintering, thus eliminating the separate production of powder, (2) spent cast-iron shot produced during descaling by abrasive grit blasting, and (3) cast-iron machine turnings (so-called "Fibriron" process).

The direct-ore process represents a fundamental step capable of operation in technical terms but with an expensive heating cycle which puts the economics in question. Spent shot is economically attractive but contains some technically difficult stages. Cast-iron swarf as "Fibriron" is technically and economically attractive for a range of products now made as machined castings.

219. Beddow, J.K. "On the use of grey cast iron powder for making low cost P/M forgings", Comment on paper by G.T. Brown, ibid, 259-260.

One of the main disadvantages of using cast-iron turnings as a raw material for powder forging is that the resultant briquettes are brittle due to the presence of graphite-filled flaws throughout the matrix. Beddow suggests that the objective of using a low-cost cast-iron raw material may be better achieved by using commercially available cast-iron powder.

220. Lally, F.T., Toth, I.J. and DiBenedetto, J. "Forging of steel powder products", ibid, 276-302.

The objective of the work described in this paper was to develop a process for the forging of prealloyed steel powders capable of producing complex-shaped high performance components having a quality level equivalent to conventional forgings but at a significantly lower cost. After compacting and sintering tests on prealloyed powders of the 4300 and 4600 series, the former were eliminated from the program. Difficulties experienced in compacting and sintering the 4300 materials were attributed to Cr_2O_3 formed during atomizing; this oxide is difficult to reduce by normal practice. A forging study on prealloyed 4640 powder showed that P/M forging can be competitive with wrought materials from a property standpoint. The applicability of the powder forging process was demonstrated on a high-performance weapon component which, it was estimated, could be produced at a cost about 50% lower than by conventional forging.

221. Moyer, Kenneth H. "The effect of flow on impact properties of hot-formed atomized iron powder preforms", ibid 304-312.

Preforms of densities 6.2 g/cm^3, 7.0 g/cm^3 and 7.2 g/cm^3 were made from atomized iron powder. The sintered preforms were hot formed to give densities ranging from 7.4 to 7.83 g/cm^3. It was found that at formed densities greater than 7.7 g/cm^3 the lower density preforms (6.2 g/cm^3) provided the highest impact strength and it is suggested that the reason for this was the greater amount of deformation or flow that occurred. Impact strength increased with increasing density of hot-formed material. A duplex grain size was observed in most of the specimens cut from the outer portion of the hot-formed preforms. Grain growth had taken place in the portion of the specimen located closest to the die surface of the formed material.

222. Roll, Kempton H. "State of the P/M industry - 1972", ibid, 313-322.

With respect to P/M forging, it was stated that the process was entering a critical phase. The next two years should see commercial production and account for substantial tonnages of powder forged products by 1976. At least three,and perhaps five, General Motors Divisions have installed, or are in the process of installing, pilot production lines. Production quantity auto parts should be available during 1973.

223. Lenel, F.V. "P/M preforms", Soc. of Manufacturing Eng., Paper No. MF72-505, 11 p, 1972.

This is a critical review of preform forging with the emphasis more on the practical rather than the theoretical aspects of technique. Most of it is drawn from articles which are abstracted in this survey.

Hot forging of preforms has become economical in the 1970's because the price of iron and steel powders has been dropping and the price of semi-fabricated steel has been on the increase.

224. Hoefs, R.H. and Scharnick, E.C. "Prealloyed powders for P/M hot densification", Soc. Manufacturing Eng., Dearborn, Michigan, Technical Paper No. MF72-801, 9 pp., 1972. (See Metals Abstr. Vol. 6, 1843, 54-0461, Nov. 1973.)

The development of prealloyed water-atomized powders is one of the factors that has made the preform forging process economically feasible. The method of production of these powders is described. The types of prealloyed powders currently being used (8600 and 9400 steels) and their mechanical properties after hot densification are given.

1973 (225-270)

225. Abkowitz, S. "Titanium P/M preforms, parts and composites", Titanium Science and Technology. Proc. 2nd Int. Conf. held at Cambridge, Mass., 2-5 May, 1972; Ed. by R.I. Jaffee, and H.M. Burte. Plenum Press, Vol. 1, 381-398, 1973.

It is only recently that technical advances have made available titanium powders suitable for consolidation into P/M products. Titanium powders of satisfactory purity are now being produced by several processes.

There is an advantage in using elemental powder mixtures rather than prealloyed powders in that lower compacting pressures are required to achieve equivalent green density. This high density facilitates sintering of the mixture, which is probably aided by the catalytic effect of diffusion of the alloying elements.

The forging of P/M titanium and titanium alloy preforms to full density results in properties which are essentially equivalent to wrought products. P/M titanium machines better than wrought titanium. Some forging preforms are particularly suited to isostatic compaction because of their unusual material distribution. Examples are given of preform forgings.

Preform forging of titanium and its alloys has a potentially strong economic advantage, particularly for high surface-area-to-weight-ratio forgings with poor material utilization. When forged conventionally, such forgings can require as many as seven dies for blocking and multiple intermediate forging steps, followed by the final forge operation; the finished forging can weigh as little as 10 to 20% of the starting billet stock. Preforms can eliminate the cost of wasted material and, more important, the preliminary forging operations and die costs. The reduction in processing time appears to be the major economic advantage for titanium forging preforms.

226. Anon. "Aluminium P/M forgings", Metallurgia and Metal Forming, Vol. 40, No. 1, p. 7, Jan. 1973.

This brief article claims that aluminum powder forgings are on the verge of commercial production. Development work is being done by Alcoa. The tensile, yield and fatigue properties of 601AB and 201AB aluminum powder forgings are comparable to those of wrought 6061 and 2014 aluminum forgings and much higher than those of die castings and sintered parts. Yet the costs of aluminum powder forgings can be significantly lower than for conventional forgings. Some advantages of aluminum powder forgings are: (1) preforms are preheated in air to only 425°C (800°F), (2) preforms can be cold forged to nearly 100% density and, (3) low forging pressures (e.g., 50 ksi, 344 MPa) are satisfactory.

227. Anon. "Trends in Powder Metallurgy", Metal Progress, Vol. 103, No. 1, 90-92, Jan. 1973.

In this news feature it is reported that, hot forming of powder preforms having graduated to the production floor in automobile plants, the powder metallurgy industry is talking about applications ranging from differential pinion, side, and ring gears to connecting rods, alternator pole pieces and clutch parts. The potential is indicated by the production of a hot-formed ring gear, which will account for one million parts annually after the 1973 model year.

Special hot-forming grades of powders are being developed, including sulphurized types with improved machinability. High sintering temperatures, 1175-1260°C (2150-2300°F), will mean that powders with common alloying additions can be used. Most hot-formed parts will be made from prealloyed powders with nickel and molybdenum additions. A real benefit would be the development of a low-cost prealloyed grade with the hardenability of AISI 4620, but without a high nickel content. Properties of parts made from aluminum powder are being improved by hot forming of preforms.

228. McGee, Sherwood W. "Sinterforging: the advance beyond P/M", Modern Machine Shop, Vol. 45, No. 8, 46-50, Jan. 1973. (See Metals Abstracts, Vol. 6, 845, Abs. 54 0253, May 1973.)

Sinterforging includes a preform step in which metal powder is pressed into shape in a special press, intermediate heating to 1010-1180°C and then final forging. Sintering may be used after forging to improve density. The finished parts are tough, dense and very clean, with a fine homogeneous grain structure. Sinterforged parts, such as a 4640-steel diesel-engine fuel-injector retaining lug and a 4620-alloy steel wing bearing are illustrated.

229. Anon. "Conventional forging practice uses metal powder preforms", Iron Age Metalworking Int., Vol. 12, No. 2, 25-26, Feb. 1973.

Conventional forging practices can be adapted to use powder metal preforms. Normal forging procedures involve a loss of 30% metal volume compared with a loss of 3-5% when using P/M forging. The automotive industry is leading the way in forging of metal powders. Emphasis has been placed on parts such as gears, which can be precision-forged to final size, reducing flash loss and machining costs.

Most forging shops cannot afford the higher equipment costs involved in converting to P/M for short runs. A.O. Smith-Inland have attempted to overcome this disadvantage with encouraging results. Much of the data developed resulted from production of a crankshaft and connecting rod. A special feature of the process is that preheating of the preforms for forging is done in an open-fired furnace of the type normally used in forge shops. Because of the tendency for powder preforms to suffer severe oxidation and decarburization, a new type of protective coating was developed for applying to the green compacts prior to sintering. This is called "Ceram-Guard". After sintering, the Ceram-Guard is removed but leaves in its place a coating which protects the preform during heating for forging. The development of this coating has enabled forge shops to try P/M forging in their existing non-atmosphere controlled furnaces.

230. Pietrocini, T.W. "Hot densification of P/M alloy 4630", Precision Metal, Vol. 31, No. 2, 23-25, 42, Feb. 1973.

The 4630 alloy powder is free from elements which create sintering problems, which means it can be sintered in commercial furnaces using economical endothermic atmospheres. This powder is used for producing steel parts at the production rate of 8 to 12 strokes/min. Two new applications are a flat sprocket used in a chain saw, and an output gear for a small transmission.

231. Anon. "Prospects for P/M forging", Metallurgia and Metal Forming, Vol. 40, No. 2, 31-32, Feb. 1973.

In this "comment", it is stated that powder forging is entering a critical phase. The next two years should see commencement of commercial production and, by 1976, there should be substantial tonnages of powder forgings. However, there is a danger than many individual undertakings could lead to excessive production capacity. It is estimated that, by 1980, the consumption of iron powder for forging will be 130,000 tons in Western Europe, 120,000 tons in North America and 50,000 tons in Japan.

232. Anon. "Presses for forging sintered preforms", ibid, 50-51.

This short article describes some of the presses developed by Cincinnati Inc. for powder forging. Powder forging is uniquely suited to the production of intricately shaped parts that are difficult or impractical to obtain by other methods. Finished parts such as pinion gears can be produced at a rate of 15 per min, and production of up to 1800 per hr in simpler configurations is attainable. Cincinnati has developed an automatic system for forging sintered preforms with presses in the 400- to 800-ton range. A 100-kW induction heating unit is provided as a standard part of the 400-ton forging system and a 150-kW induction unit is provided as part of the 800-ton system.

233. Patton, W.G., Mullins, P.J. and Shah, Raymond. "New developments in gear making", Iron Age Metalworking Int. Vol. 12, No. 3, 26-29, Mar. 1973.

Recent improvements in gearmaking include hot forging of powder metal preforms to produce high-density gears for automobiles.

234. Jarrett, M.P. and Jones, P.K. "The powder-forging process and its potentialities", Engineers' Digest, Vol. 34, No. 3, 41-43, Mar. 1973.

This article discusses the basic features of powder-forging and describes a few examples of applications where advantages are being exploited, with particular reference to components used in the automotive industry.

The major characteristic of the powder-forging process is that the mechanism of deformation differs significantly from that in conventional hot forging, resulting in lower tool stresses and hence longer die life. It is this characteristic that gives the process its great potential for the production of components of intricate shape. Furthermore, it is possible to forge components in powder with a single blow in one set of closed dies, whereas a similar conventionally forged component would normally require a succession of blows in a series of dies, generally with manual transfer between the dies.

The authors' company (GKN Forgings Ltd.) has been actively engaged in exploring the potentialities of powder-forging and furthering its development. The results are so encouraging that the company is currently producing a series of different automotive components on a pilot-scale basis. In most cases steel powders are used, ranging from plain carbon steels to low-alloy carburizing steels, manganese-molybdenum steels, nickel-molybdenum steels, and austenitic stainless steels. Included in a variety of automotive components that have been produced successfully by the process are clutch hubs, driveshaft flanges, connecting rods, and gears and ancillary transmission items. In some cases material utilization is over 90%.

Three examples of powder forging are illustrated and discussed - a splined driveshaft flange, a connecting rod, and an automatic gear blank. In the latter case, the detailed form of the gear teeth is such that only a subsequent shaving operation is necessary. An important consideration in connection with the gear blank, is that by a single blow in the axial direction, on a plain round shape, the metal has been moved to an appreciable extent in a radial direction to form the teeth extremely accurately.

235. Anon. Metals News: "Mass-produced P/M forging for automatic transmission", Materials Eng., Vol. 77, No. 3,26, Mar. 1973.

The inner race for an automatic transmission one-way clutch is the only high-volume commercial forging made from a powder preform. The part is made from 4600 type steel, weighs 0.34 kilo and has a density of at least 99.6% theoretical. The ultimate tensile strength is 230 ksi (1580 MPa) after case hardening by carburization. Federal Mogul, the manufacturer, previously produced the part by machining and broaching. At present, 4600 Type premixed powders are preferred, but prealloyed powders are being investigated.

Federal Mogul is also working on a number of developmental parts forged from powder preforms, including bearing rings, outer races, clutch races, straight tooth gears, bevel tooth gears and bi-metal valves (high-silicon steel bonded to a cobalt-base alloy, such as Stellite 31). Most of these parts are 4600 Type steels and they have been made from premixed or prealloyed powders.

236. Eshelman, Ralph. "P/M parts forge ahead", Automotive Industries, 36-37, 15 Mar. 1973.

This article describes the operation and products of Federal Mogul's "Sinta-Forge" system. The term signifies a system of sintered P/M compacts hot forged to virtually finished parts.

Powder metal hot-forming looks like a process of the future. It affords such flexibility and materials strength that engineers feel it could someday turn out Wankel rotors, and even combustion chambers for smaller rotary power units such as chain saws or outboards.

Federal Mogul has a press line in operation at its Greensville, Indiana plant making clutch bearings for automatic transmissions. The company president estimates this product could be a $50 million market per year. According to the firm's development engineers, many other high-density, high-strength parts can be formed by this process to semi-finished shapes. Besides clutch bearings the list includes annular parts like cams; spur, bevel and helical gears; pump rotors and bronze-coated shaft bushings; high-temperature engine valves and a host of other hot extruded, hot coined, upset, formed or die-forged mechanical and structural automotive parts. Some of the more intriguing possibilities are use of bi-metallic compacts, superalloys and composite piece parts. A technique of "strata-forging" forms special bearings with an expensive alloy in the centre surrounded by less expensive automotive steel outside. Present production equipment may be suitable for many conventional, high-strength automotive parts.

237. Wakefield, Brian D. and Mullins, Peter J. "Bicycle technology may not show, but it's there", Iron Age, Vol. 211, No. 11, 52-55, 15 Mar. 1973.

Some of the technology involved in the production of bicycles is described for two of the world's best known bicycle builders, Schwinn Bicycle Co., Chicago, and Raleigh Industries, Ltd., Nottingham, England. Raleigh regards powder forging as perhaps the most promising of the new technologies. It opens the possibility of using highly stressed parts made from powder. The sharp increase in the cost of steel to Raleigh, about 19% from 1971 to 1973, has made powder competitive.

238. Dower, R.J. and Oakley, D.R. "The utilization of mild steel machining swarf in hot forging", Dept. of Trade and Industry, Nat. Eng. Lab., East Kilbride, Scotland, Report No. 542,16 p, Apr. 1973.

This report describes experimental work on the reclamation of machining swarf by the hot-forging of compacted swarf billets. Because of the rising cost of raw materials, industry is seeking new ways of improving material utilization. At present about half of the raw material purchased by manufacturing industry ends up as scrap, which is sold at a low price compared with the cost of the raw material. The authors conclude that hot-forging of components from compacted swarf is possible. General structural integration of swarf into the product is good, but the surface is necessarily poor.

239. Anon. "The future of forging - a Delphi Probe", Precision Metal, Vol. 31, No. 5, 46-47, May 1973.

The Forging Industry Association, Cleveland, Ohio, carried out three simultaneous "probes" (technological forecasts by experts) on the topics of forging of ferrous P/M preforms, forging of non-ferrous P/M preforms and cold forging. Some of the forecasts given an almost certain chance of occurring (0.9 probability) by a certain date are as follows:

a) <u>Forging of ferrous P/M preforms</u>

i) Parts weighing more than 9 kilos will be made from ferrous powders, 1987.

ii) Forged P/M parts in general will be made at substantially lower cost (say 20%) than conventionally hot-forged parts, 1977.

iii) Sintering will be eliminated from hot-forged P/M part production, 1980.

iv) Forged parts over 45 kilos will be possible, 1985.

v) Hot-forged P/M parts will be in mass production, 1980.

vi) Hot forged P/M parts will be used significantly:

1) for hardware, 1980

2) for machine-tool applications, 1985

3) for guns (sport and military), 1980

4) for power tools, 1980.

vii) Automobiles on the average will utilize at least 23 kilos of powder parts per car, 1985.

viii) Hot-forged P/M parts for non-automotive applications will reach $25 million in annual sales, 1985.

b) <u>Forging of non-ferrous P/M preforms</u>

i) In the aircraft engine market, 20 to 50% of all parts in the hot end of the compressor and turbine will be forged high-temperature P/M parts, 1980.

ii) The initial use of forged aluminum P/M parts will occur in commercial and military or aerospace applications, 1978.

iii) Forged titanium P/M parts will make significant inroads into:

1) commercial aircraft, 1983

2) military aircraft, 1982

3) ordnance, 1984

4) aerospace applications, 1981.

iv) Use of forged copper P/M parts in the electrical and electronic industries will become a reality, 1980.

v) Close tolerance forgings will be produced by hot forging directly (without a separate sintering step) from powder in one operation, 1980.

vi) Initial use of forged titanium P/M parts in chemical and food processing industries will occur, 1980.

c) <u>Cold forging</u>

i) Advances in powder metal processes will enable tonnage shipments of cold-formed parts to surpass tonnage shipments of hot-formed parts (excluding cold heading and fasteners), 1988.

ii) The major non-captive companies in cold forming will also be involved in one or more of the following: warm forming, hot forming, forming of powder metal preforms, furnishing a full range of parts made by more than one method, 1981.

240. Hoefs, Ralph H. "The present status of P/M forging - Part 1", ibid, 55-57.

Substantial savings are realized in powder forging in comparison with conventional forging because in the former there is no material waste and only one forging die is required.

If quantities are large, the powder preforms can be made in dies using practices standard for P/M parts. If the quantities are small, it may be preferable to use isostatic pressing since tooling costs are low by this method.

Temperatures of 760-980°C (1400-1800°F) are presently being used to preheat powder preforms for forging. This is considerably lower than the temperatures of 1150-1290°C (2100-2350°F) used in conventional forging. Also, the latter may require 3 or 4 die impressions with as many as 10 to 15 blows of the hammer, whereas in powder forging one blow suffices.

Non-alloy iron powders are readily available which can be converted to steel forgings of any desired carbon content. Prealloyed powders are also available to make forgings that require heat treatment to develop optimum mechanical properties. Mechanical properties of powder forgings are as good as, and in some cases better than, the properties obtained with conventional forgings.

The atmosphere pollution (heat and dirt) which characterizes forge shops will be minimized by powder forging because it will be economically advantageous to use furnaces operating at lower temperatures with lower heat losses, and without scale formation. Noise pollution will also be minimized due to the use of single rather than multiple hammer blows.

Currently, the automotive industry is actively investigating the P/M hot-forging process, and the results look very promising both technically and economically. If successful, it is probable that the process will quickly spread into the independent forge shops.

241. "Gould hot densifies P/M parts". Staff report. Metal Progress, Vol. 103, No. 5, 42-44, May 1973.

The main difference between hot forming and hot densifying is that in the latter operation the sintered preform is quite close to final shape. Hot densification is essentially a re-striking operation in which the surface area of the part is reduced by about 25%. There is little or no lateral flow of metal. Gould favours hot densification over hot forming because tool life is longer.

Since 1967, Gould Inc. has considered more than 300 potential applications for hot-densified parts. Production has started on one part, an auto valve lifter body. Another part, a sector gear for truck turbine engines, has been approved for production. Development work continues on seven other parts.

The valve-lifter body is made of 4620 Type powder, an iron-based 2% Ni-0.6% Mo alloy. An iron-based powder containing 15% Mo and 15% Co is specified for the sector gear, which operates at 425-650°C (800-1200°F).

242. Kuhn, H.A. and Downey, C.L. "Mechanics of forging sintered powder materials", Proc. of the North American Metalworking Research Conf., Vol. I, Metal Forming, 205-220, May 1973. (See Metals Abstracts, Vol. 6, 1696, Abs. 54 0420, Oct. 1973.)

Mechanical behaviour of sintered powder material is presented for consideration in the design of sintered powder preforms for forging. Design involves establishment of the process parameters such that full density and a sound metallurgical structure are achieved in a manner consistent with the avoidance of fracture. The forming of a cylindrical preform of aluminum alloy 601AB and 4620 steel powders into a disc is considered, as an example, to demonstrate the design procedure. A rational approach to the design of preforms for forging of complex parts is suggested by this technique.

243. Hoefs, Ralph H. "The present status of P/M forging - Part 2", Precision Metal, Vol. 31, No. 6, 65-67, June 1973.

A.O. Smith-Inland made some experimental powder forgings to demonstrate to forge shops how it could be done, using standard forging equipment. The parts chosen were a connecting rod and a crankshaft. For demonstration purposes, and as only a few were required, the preforms were machined from sintered slugs.

A new type of protective coating, called "Ceram-Guard", was developed so as to allow the preform to be heated in existing open-fired furnaces without harmful effects. Ceram-Guard is applied to the green preforms and a thin oxidation-resistant layer, integral with the surface of the preform, is formed by diffusion during sintering. After sintering, the remaining Ceram-Guard residue is readily removed, leaving the protective layer in place. During forging, the Ceram-Guard coating flows readily as the preform is deformed.

The experimental forged crankshafts were made from high-compressibility, water-atomized, non-alloy iron powder with sufficient added graphite powder to give a combined carbon content of 0.54% in the forgings. The experimental connecting rods were made from high-compressibility, water-atomized prealloyed powder of 4600 Type (1.90% Ni-0.5% Mo-balance iron), and sufficient graphite was added to give 0.25% C (combined) in the forgings.

Performance tests demonstrated that the two parts had satisfactory properties.

244. Halter, R.F. and Belden, B.B. "P/M parts with strength of forgings", Machine Design, 116-121, July 12, 1973.

This is a practical review of powder forging, with reference to mechanical properties and manufacturing potential.

245. Durdaller, Cornelius. "P/M forging: will it replace bar stock forging?", Precision Metal, Vol. 31, No. 7, 43-45, July 1973.

Various aspects of the P/M forging process are discussed by Durdaller. Forging can be done cold (less than 260°C, 500°F), warm (540-675°C, 1000-1250°F), or hot (815-1150°C, 1500-2100°F) and involves four basic steps: preform, sinter, forge and finish. Production costs are reduced by practically eliminating waste due to flash. Parts are usually formed with one forging blow, and the good surface finish obtained eliminates most secondary cleaning and tumbling operations.

Powder forgings intended to replace forgings made conventionally cannot be produced from mixed powders because, apart from carbon, the alloying elements would not diffuse sufficiently into the iron matrix during sintering to give a homogeneous microstructure. Since carbon can alloy completely at temperatures over 980°C (1800°F) it can be either premixed or prealloyed.

Theoretically, powder of every alloy steel can be produced by atomization. Most AISI compositions can be made by water atomization which is the least expensive atomization method. The use of chromium and manganese is essential to the production of low-alloy heat-treatable steel powders. Prealloyed atomized powders containing these elements are easier to protect from oxidation than mixtures containing these powders. It is probable that sufficient protection can be given to ferrous alloys containing manganese and chromium to protect them from oxidation during the various powder forging steps.

The powder approach makes it possible to use other alloys which are not common to conventional forging practice. Elements that make conventional hot working difficult can be used for the contribution to hardenability in P/M forging because hot-working temperatures can be reduced. P/M methods are ideal for developing dispersion-strengthened alloys or for creating alloys from materials normally incompatible, like cermets.

Three powder forging processes are receiving active consideration: hot re-pressing, confined die forging and closed-die forging. Hot re-pressing uses a powder preform that resembles the final part; little material flow occurs and it is difficult to reduce the void content below 2%. In confined die forging the preform shape can differ considerably from that of the final part; flash is minimal and parts with 100% theoretical density can be produced. Closed-die forging is essentially a conventional forging process but without the preliminary steps required to shape a piece for final forging; slight flash occurs on the forging, but weight control of the part is not as critical as with the confined die technique.

In a time when the metalworking industry is plagued by high labour costs, P/M forging offers a way to lower labour costs both in number of workers and the skills required of them, while still producing a superior product.

246. Pavlov, V.A., Zhivou, L.I., Scherbina, V.V., Lyashenko, A.P., Petrykina, R.Ya., and Litvin, V.M. "Hot die forming of compacted titanium powder", Sov. Powder Metall. Met. Ceram., Vol. 12, No. 8, 615-618, Aug. 1973.

A process has been developed for the manufacture of parts from titanium powder in which production costs are lower than in processes involving the use of cast metal. The new process is based on the powder metallurgy technique combined with a high-productivity plastic working process - hot die forming. It consists essentially of the operations of cold pressing of preforms, then hot die forming and final heat treatment.

Adoption of parts die-formed from titanium and titanium alloy powders instead of parts made in cast metal may be expected to lead to appreciable savings, making it possible to use a cheaper raw material, decreasing the number of intermediate operations, prolonging useful die life, increasing operating efficiency and reducing waste of material.

247. DuMond, T.C. "Powder metal progress tempered by shortages", Iron Age, Vol. 212, No. 5, 30-31, 2 Aug. 1973.

This is a short article on recent developments in the P/M field.

U.S. Steel Corporation has developed a P/M forging process called loose/pack preform and forge technique (LP process). As-atomized powder is blended with an inexpensive organic binder. The mixture is poured into a sheetmetal mould, vibrated to increase powder packing, then baked at about 200°C. When removed from the mould the preform is heated in a protective atmosphere, to a temperature suitable for sintering and forging. The organic binder serves to give green strength to the preform. When the preform is heated for forging or sintering, the binder reduces the particle surface oxides without leaving a residue. The binder also serves as a source of carbon and helps to protect the preform from decarburization and oxidation during heating. Two major advantages cited are ability to use less expensive unannealed powders and elimination of the preform press.

Gleason Works, Rochester, N.Y., is planning a fully integrated powder-forming system. Gleason's system will concentrate on a range of symmetrical parts such as bevel gears, transmission slip clutch races, spur gears and other similar high-production, high-strength parts. Initially, it will encompass parts weighing up to 1 kilo and up to 114-mm diameter.

As a result of a recent 'Delphi Probe' the forging industry is stepping into the field of P/M forgings. The study indicated that the market for P/M forgings will quintuple by 1980 or 1985. Contributing to this conclusion is the belief that by that time the parts in the hot end of gas turbines will be made of isostatically compacted superalloy powders. Most of these parts now are forgings.

248. Porter, John W. "Hot forming of powdered-metal parts", Machinery and Production Eng., 414-416, 19 Sept. 1973.

This article gives a short account of efforts by Cincinnati Inc. to produce presses for hot-preform forging. During the last five years it has been realized that conventional powder metallurgy offers many advantages in connection with the production of input material for hot forming. By using powdered-metal compacts, forming can be completed at one blow, automation is simplified, trimming of flash is eliminated, and finish dimensions can be obtained directly from the dies.

The first true hot-forming system was built by Cincinnati in 1971. After sintered preforms were loaded into a magazine, all succeeding operations were controlled and performed by the unit itself until finished parts were discharged from the rear of the press.

Early investigations indicated that induction heating was particularly suitable for inclusion in a fully automated hot-forming system, provided that the preform shapes were relatively uniform. Coil designs were generally available for vertical magazine feeding, and neutral atmosphere protection was readily adaptable where it was required for minimizing oxidation.

249. Eshelman, R. "P/M parts forge ahead", Automotive Industries, Vol. 148, No. 9, 36-37, 1973.

This is a brief survey of P/M parts in the automotive industry, and a look at future prospects.

250. Vaccari, John A. "P/M forgings: a rapidly emerging technology", Materials Eng., Vol. 78, No. 3, 20-27, Sept. 1973.

This is a state-of-the-art report on the materials and processes used and the types of parts produced by preform forging. Preform forging of powder is, at present, an extension of P/M technology but, for the long term, it promises to enhance the competitive position of forgings as well as the versatility of P/M parts. The author gives many examples of parts that are in production or at the development stage.

The automotive industry is leading the way in applications. The manufacturers include General Motors, Chrysler and Ford. The parts include a torque converter component, transmission components, input gear, steering-axle pinion flanges, and differential ring gears. At A.C. Spark Plug, spark plug shells and the centre electrode are now being produced in millions from powder preforms; both parts are formed cold in what is essentially an extrusion operation.

Other companies said to be interested in powder forgings are Fafnir, Timken, New Britain Machine, The Moore Co., GKN Forgings (U.K.), and Toyota and Honda (Japan). Potential applications include bearing rings and races, sockets and wrenches, transmission components, connecting rods, and machine gun accelerators.

Custom P/M parts producers have also made P/M forgings and are carrying out development work. These include Federal Mogul (inner race for automatic transmission clutch, bearing rings and races, clutch races, straight and bevel gears and bimetal valves). Gould is making production auto valve-lifter bodies and a sector gear for truck turbines. Wakefield Bearing has made several production parts and others are at the development stage. Production items include a differential gear for garden tractors, a chainsaw sprocket, a magnet pole piece, a ring gear for impact wrenches and toolmakers' clamps. In development are steel power-tool ball clutches, power hammer parts and a bronze valve component. Engineering Sinterings and Plastics have powder-forged steel cable crimping jaws, a gun hammer part and wrenches.

GKN Forgings (U.K.) has one part in production and is tooled for ten others in the 0.5-2.0 kg size range. Most of these are automotive gear-train parts. In Japan, Toyota Motors is planning to go into production on connecting rods. However, Honda Motors is looking into ways of improving die life before going ahead with production of P/M forged motorcycle transmission spur gears.

Although all production and most developmental P/M forgings are currently made of iron and steel, development efforts are also being carried out on aluminum and, to a lesser extent, on titanium. Alcoa has done much research work on both hot and cold P/M forging of aluminum. Connecting rods and eccentric straps for small motors and refrigeration compressors are major potential applications.

Dynamet Technology has shown that excellent properties can be obtained from titanium preform forgings. The Air Force Materials Laboratory has also investigated titanium forgings for turbine vanes and cargo tie-down rings.

The author goes on to describe the P/M forging process. He describes the automated Cincinnati method for forming P/M forgings, and states that an automated, fully integrated system for making P/M forgings will be introduced next year by Gleason Works.

Mention is made of U.S. Steel's "loose/pack" preform and forge technique in which an atomized powder is mixed with an inexpensive organic binder. The mixture is poured into a sheet-metal mould, vibrated to increase density and baked at 200°C. The resulting preform which has adequate strength for handling, is then sintered and forged.

The various steels and their compositions, favoured for powder forging, are described. Hoeganaes and A.O. Smith are the major producers of these powders. The International Nickel Co. has also developed several steel powders. Alcoa is the main producer of aluminum alloy powders.

The article includes a short interview with A.L. Alves, President of Engineered Sinterings and Plastics, Inc., who concludes by saying that his company is very optimistic of the future of P/M forgings and is investigating the technology on a broad front.

251. Anon. "The closed impression die forging industry", Precision Metal, Vol. 31, No. 9, 38-40, Sept. 1973.

This is part of a survey made by Precision Metal on the "health of the precision metal industries". Among the new developments in the closed-die forging industry are listed hot and cold densification, and hot forging of powder metal preforms.

Hot densification of P/M preforms should not, in all probability, be classed as a forging technique but rather as hot coining. There is little, if any, lateral movement of metal. There appear to be two drawbacks to the process. One is the difficulty of eliminating and preventing internal oxidation before complete densification occurs and the other is entrapped gas pockets when the normal interconnecting porosity is closed. However, if the required mechanical properties of a part are less than those of a wrought part and greater than a normal P/M part, this process may find use.

Cold densification is similar to hot densification, but no attempt is made to reduce internal oxide layers or to eliminate trapped gas or air. The properties of a cold densified part will probably be lower than the same part hot densified, but for some uses may be adequate. Some work has been done on the cold forging of P/M preforms, but so far the economics seem to favour conventional forging.

Hot forging of P/M preforms seems to have aroused the greatest interest of all the newer forging developments. In theory, it has the possibility of forming forged parts of excellent mechanical strength with little or no scrap, including no final trim scrap. One possible deterrent to the rapid development of this process is the high tooling costs unless the preform tooling can be extremely simple. There is a vast amount of work to be done on this process before it becomes a viable production method, despite its obvious attractions.

252. Anon. "P/M - the fastest growing metal working industry", ibid, 42, 84.

This is part of the same survey (see previous reference) on the precision metal industries. Powder metallurgy has shown a growth rate which is far greater than any other metal working industry. If and when powder forging becomes a viable process the powder metallurgy industry should show a rate of growth little short of spectacular. According to T.W. Pietrocini (Gould, Inc.) most people are moving toward cold forming rather than hot forming. In cold forming, tolerances can be held more closely, tooling is less expensive, and the process fits more closely the presently installed equipment. Reheating is much too expensive. Pietrocini thinks that hot forming of powder compacts will not come as rapidly as people once thought - it will be three to five years before the average forge shop gets into the hot forming of powder compacts.

John Caputo (Norwalk Powdered Metals, Inc.) states that they have not seen any activity in the forging of powder metal parts, hot or cold. He believes that the basic principles have not been sufficiently developed yet.

253. Guest, T.L., Negm, M., and Davies, R. "Metal flow and densification in the die-forging of porous preforms", Powder Metallurgy, Vol. 6, No. 3, 314-326, Autumn 1973.

Preforms of a Ni-Mo steel were formed at 1130°C in lubricated closed dies, the ratio of die diameter to preform diameter varying between 1.0 and 1.37. Both the high-speed Petro-Forge and a crank press were used, and parameters such as forging load, energy, and density during the forging operation were measured.

Two conditions of deformation were studied:
(a) recompaction where the diameter of the preform is nominally the same as that of the die, and (b) closed upsetting where the die diameter is larger than that of preform. In each test the dimensions of the preform were the same, 38 x 38 mm diameter, and they were forged in dies of 37, 45 and 52.5 mm diameter. The compacts were sintered at 1130°C for 15 min and transferred to the press in about 5 sec and so were forged at close to the sintering temperature.

The results show that in the earliest stages of forging the deformation of the preform is largely in the pressing direction and the rate of densification is then at its maximum. In the intermediate stages the metal flow increasingly takes place in the radial direction. Deformation continues in a manner similar to that found in simple upsetting experiments, and barrelling takes place until the material reaches the die wall. Because of the porosity still present during this stage, deformation can still continue under comparatively low loads. Once the preform is in contact with the die wall the densities and the load increase more rapidly as in the recompaction experiments.

The danger of cracking of low-density preforms while forging outweighs the advantage of easy flow at low loads. Thus, the most effective way of using powder metallurgy is to produce a preform having intricate detail and close tolerances, to which a simple hot-coining operation can be applied in forging. One of the economic advantages of the powder-forging process lies in the elimination of multistage preforming operations with their operating costs and scrap losses. These advantages are reinforced when producing high-value forgings since the precision die is safeguarded from wear caused by high forging loads and from erosion by deforming powder masses. The use of detailed preforms is the most direct route to economic production.

254. Brown, G.T. and Steed, J.A. "The fatigue performance of some connecting rods made by powder forging", ibid, 405-415.

Powder-forged connecting rods were made from plain iron powder and the carbon content was raised to about 0.45% by the addition of graphite. Fatigue performance was investigated under alternating tensile and compressive stress using a 'push/pull'-type machine, standard drop-forged rods being tested for comparison. Tests were also made on parallel-sided test pieces of forged iron powder, and wrought bar stock analyzing 0.37% C, 1.32% Mn and 0.18% Si.

The connecting rods made by powder forging from the plain iron-carbon material had fatigue performance equivalent to that of conventionally drop-forged rods made from the wrought carbon-manganese steel. The results of fatigue tests on plain parallel-sided test pieces from the same materials indicated that the wrought steel should have the higher endurance limit. The reason for the discrepancy between component and test piece results is probably attributable to the following conditions in the drop-forged rods:

(1) endurance/elastic limit ratio was lower,

(2) 'grain flow' was exposed after trimming the flash,

(3) the surface finish was generally poor.

Shot-peening the powder-forged rods further improved their fatigue-endurance.

While a plain iron-carbon material may be suitable for small section components, a low-alloy material with higher hardenability will probably be advantageous, particularly in heavier sections or more highly stressed components.

255. Downey, C.L. and Kuhn, H.A. "Application of a forming limit concept to the design of powder preforms for forging". Paper presented at the Materials and Eng. Congress, Chicago, 1-4 Oct. 1973.
(See: Metal Powder Report, Vol. 29, No. 2, 38, Feb. 1974.)

Specification of preform shape, dimensions, and density are important in preform forging. Design of the preform should be such that subsequent plastic deformation during forging gives a defect-free, fully dense forging. Studies of the plastic deformation of sintered powders have shown that structure and properties of the forged material are improved by large amounts of lateral flow during forging. However, increasing the degree of lateral flow also increases the possibility of cracking. The preform can be designed to avoid fracture during forging. An example of the technique is given in the design of a preform for forging a pulley blank.

256. Moyer, K.H. "Properties of fully dense prealloyed and admixed Ni-Mo steel preforms". Paper presented at the Materials and Eng. Congress, Chicago, 1-4 Oct. 1973.
(See: Metal Powder Report, Vol. 29, No. 2, 38, Feb. 1974.)

The properties of fully upset preforms of mixed and prealloyed powders and the effect of processing conditions on the mechanical properties are given. The prealloyed and mixed powders were made to the compositions: 1.8% Ni-0.5% Mo-balance Fe and 0.5% Ni-0.5% Mo-balance Fe. Atomized powder of the latter composition was also mixed with 1.3% Ni powder. Graphite was added to give 0.2% C in the final forging. Preforms were compacted to a density of 6.2 g/cm^3. Sintering was done in dissociated ammonia at temperatures of 1120°C to 1260°C. Preforms were hot upset at 980°C to full density. Test specimens were heat treated to a hardness of Rc 20-25. Hardenability, tensile and impact properties were determined.

257. Creeger, G.A. and Smith, Y.E. "Carbide distribution in sintered 0.25% carbon alloy steel preforms". Paper presented at the Materials and Eng. Congress, Chicago, 1-4 Oct. 1973.
(See: Metal Powder Report, Vol. 29, No. 2, 38-39, Feb. 1974.)

The influence of composition and cooling rate on the size and distribution of carbides formed during cooling from sintering was evaluated. The powders studied ranged from an atomized iron powder to standard commercial and experimental prealloyed atomized powders containing up to 1.1% Mn, up to 1.5% Mo, up to 1.8% Ni, up to 0.4% Cu, and up to 0.4% Cr. The powders were blended with graphite and zinc stearate, pressed to

6.7 g/cm^3 density, sintered at 1120°C in a synthesized endothermic atmosphere and subjected to one of four cooling rates. The cooling rates ranged between 110°C/min and 7°C/min. Both the tendency to form coarse carbides and the maximum size of carbides increased as the cooling rate decreased. The greatest tendency to form massive carbides was found in the low-silicon and manganese powder without other alloying elements. In general, the addition of other alloying elements promoted the formation of finer carbides.

258. Gessinger, G.H. and Cooper, P.D. "Direct forging of Cr-Ni-W steel powder". Paper presented at 5th Int. Powder Metallurgy Conf., Dresden, Germany, 13 p, 23-25, Oct. 1973.
(See: Metal Powder Report, Vol. 29, No. 3, 67, Mar. 1974.)

A high-temperature Cr-Ni-W steel has been produced by direct forging of powder-filled cans. The powder was produced in high-purity argon by rotary atomization from the bar-stock material. Mechanical properties were determined from the as-consolidated powder and from 50% upset-forged billets and compared with the as-received bar-stock material. It was found that ultimate tensile strengths of the cold-worked powder material were significantly increased, but also that ductility decreased. The as-consolidated powder had lower tensile strength but higher ductility than the bar-stock material. The data were explained in terms of carbide microstructure.

259. Kotschy, Janina and Marciniak, Zdzislaw. "Cold forming of P/M preforms by the rocking die method", Int. J. Powder Met., Vol. 9, No. 4, 135-137, Oct. 1973.
(See also: "New Polish forging press suited to powder forging", Marciniak, Zdzislaw, Precision Metal, Vol. 32, No. 9, 28-31, Sept. 1974.)

Cold re-pressing of sintered preforms is hampered by two factors - a very high value of the true stress necessary to achieve full density and cracking of the preforms when conventional methods of cold pressing are applied.

The rocking die method is a new technique of cold forging, based on the tilting-action press-forging. A billet is forged between the lower die and the upper die or punch that is continuously rocking, while inclined at an angle to the vertical axis. At any moment of working only a small area of contact exists between the top punch and the workpiece. This method of pressing confines the material flow to the volume restricted to the region which is at any given moment subjected to the action of the migrating pressure.

Experiments carried out on iron and steel preforms proved that the method is very promising for cold forming sintered preforms into complicated shapes. The method is recommended for shapes having large diameter to thickness ratio.

260. Downey, Charles Lawrence. "Powder preform forging - an analytical and experimental approach to process design", Dissertation Abstracts International B, Vol. 34, No. 5, 172 p, Nov. 1973.

Research was undertaken to supply a complete understanding of a capability to control the deformation during forging to achieve full densification and defect-free products. A regular relationship was found between lateral flow (as represented by the plastic Poisson ratio) and relative density of the material. It was also found that the fracture behaviour of the porous materials could be described in terms of a fracture criterion developed previously for conventional, fully dense materials.

Results of the investigation were applied to design of the preform for a complex part involving the three modes of flow active in common forged shapes. The preform designed on this basis was shown to form the part successfully, while other preforms led to cracking during the forging process.

261. Mocarski, S. "New P/M alloy steels for critical components", Metals Eng. Quart., Vol. 13, No. 4, 21-27, Nov. 1973.

Alloying of hot-formed powder metal steels presents a problem because elements which are strong oxide formers tend to be preferentially oxidized during both water atomizing and subsequent processing. In recognition of this, the popular (modified) 4600 P/M steel is low in manganese (0.20% max) and silicon (0.01% max) in the interest of impact strength and ductility. During investigations into a substitute for expensive 4600 alloy, new P/M steels and modified 4600 were studied, resulting in two compositions of equivalent hardenability and one of slightly lower hardenability being tentatively established. In the course of the investigation, hardenability factors for Mo, Ni, Mn, and Cu were determined, and D_1 carbon graphs developed, which can serve as an aid to control the hardenability of hot-formed P/M parts. One P/M steel composition (Ford MDO-101: 0.35% Mn-0.45% Ni-0.60% Mo-balance Fe) has already found acceptance and is commercially available. The second alloy (Ford MDO-102: 0.45% Mn-0.35% Cu-0.25% Ni-0.65% Mo-balance Fe), though highly hardenable, will require upgrading of powder manufacturing facilities to ensure a consistent and larger percentage of active (unoxidized) manganese. The third alloy (Ford MDO-103: 0.40% Cu -0.40% Ni-0.70% Mo-balance Fe), with somewhat higher hardenability than modified 4600 P/M steel, contains alloying elements more noble than iron. High molybdenum prealloyed P/M steels were also investigated, but it was found that these steels, particularly the ones containing much oxygen and sulphur, can form carbides having a shape which can lower machinability and hardenability.

262. Henning, H.J. "P/M forging - courtship of the 60's and marriage of the 70's", New Perspectives in Powder Metallurgy, Vol. 6 - Forging of Powder Metallurgy Preforms, pp. 3-18. Edited by H.H. Hausner, K.H. Roll and P.K. Johnson. Published by MPIF, 1973.

This is a critical review article in which powder forging is compared with other processes such as conventional forging and casting. Most P/M forging studies conducted to date have been aimed at evaluating the technical-economic aspects of the process in comparison either with hot forgings or with more conventionally processed P/M parts. Comparisons with cold or warm forged components are rare, yet both of these processes frequently offer technical-economic advantages over hot forgings in the production of smaller parts. Warm and cold forging processes have made significant advances in the last decade for the production of symmetrical parts. The economics of forging cast steel preforms have not proven to be very attractive, partly because any flash-metal savings realized in forging are offset by the normal casting losses (sprues, runners, gates and risers).

Most of the developmental activity in powder forging is either in the powder metallurgy industry, in the automotive industry, or in prominent research centres, rather than in the custom-forging industry. According to a forging company representative, material accounts for roughly half the total cost of producing a conventional forging. In many cases the finished forgings weigh 25 to 40% less than the starting slug, with metal being lost to scale (2-5%), flash (15-25%), tong holds (5-10%), etc. If preforms can be prepared with accurately controlled volume, scrap losses should be reduced to less than 5%. Even if the powder preform would cost 30% more than the cut slug, it should be possible to reduce forging costs by increasing production rates and reducing the die wear otherwise encountered when flash is formed. This is where the powder preform appears to have its greatest promise. The author's opinion is that metal savings effected through powder forging must be of the order of 25% or more to offer an economically attractive alternative to more conventional hot-forging practices. Any precision part that must undergo considerable machining after casting or forging and that can be compacted into a preform is a potential candidate for the powder-preform forging process because of the potentially better tolerances and surface finishes obtainable.

Approximately 50% of the total cost of a conventional forging is in the material. The virtual elimination of scrap by use of metal-powder preforms would result in a reduction in the over-all cost of a forging. In addition, it is anticipated that only one forging step, and not three to five, will be required to form the desired part configurations. The additional quantity of parts to be produced by powder-preform forging could amount to 230,000 tons per year. However, more data are required on the following subjects: preform design guidelines, density requirements for best forgeability, properties of forged P/M parts, forging equipment, tooling design, and economics.

263. Durdaller, Cornelius. "The Hoeganaes powder forging laboratory", ibid, 35-43.

During the 1960's it became apparent that a substantial part of the future of the powder metallurgy industry resided in the use of metal powders to produce parts with densities much higher than those then available. Hoeganaes had been working for some time on the development of powders for forging, but it became clear that the effort was too small and that it was necessary to build a facility that could investigate the forging process itself. A decision was made in 1969 to have a major expansion in the laboratory by more than doubling the available space for research. The effort at Hoeganaes is directed toward obtaining basic information on the powder forging process in general.

264. Kawakita, Takao, Onoda, Mineo, Kuroishi, Nobuhito, Iwaki, Isao and Nagasaka, Yusuke. "Properties of forged super-high density sintered steel", ibid, 349-356. (See also: Sumitomo Electric Technical Review, No. 15, Aug. 1971.)

This paper compares the mechanical strength and fracture behaviour of forged sintered steel with conventional low-density sintered steel and cast wrought steel. The powder alloy was prepared by mixing the ingredients and had the composition: 2.0% Ni+0.3% Mo+0.2% Mn+0.35% C, balance iron.

The strength of the sintered steel was strongly affected by the number and shape of pores in the compact as they caused inferior ductility compared to cast wrought steel. Forged high-density sintered steel with a density greater than 7.7 g/cm^3 was almost equal to conventional wrought steel in strength and fracture behaviour.

265. Pietrocini, Thomas W., "Economics of P/M hot formed parts production", ibid, 385-388.

One of the main reasons why hot forming of powder preforms is competitive with more conventional methods, such as forging and casting, is that nearly 100% of the material is utilized. An important advantage accrues for the powder process when precision dimensions are required. Tool replacement is a significant cost factor and quite often determines the competitive position. If lateral flow of the preform during forging is eliminated, that is, process is one of "hot densification", then less pressure is required, with consequent increase in tool life.

266. Kuhn, H.A. and Downey, C.L. "Mechanics of forging sintered powder materials", Proc. North American Metalworking Research Conf., Vol. 1, Metal Forming, 205-220, 1973. (Abstracted in World Aluminum Abstracts, Vol. 6, 1973, Abs. No. 43-0047X.)

Factors to be considered in the design of powder forging preforms are discussed. Design involves establishment of process parameters such that full density and sound metallurgical structure are achieved. The design procedure is illustrated by considering the forming into discs of cylindrical preforms of 601AB aluminum powder alloy and 4020 ferrous powder alloy.

267. Dean, Trevor A. "High speed hot forging techniques from solid billets and metal powders", Tech. Paper No. MF 73-166, Soc. Manufacturing Eng., 20501 Ford Rd., Dearborn, Mich. 48128, 20 p, 1973.
(See Metals Abstracts, Vol. 6, p. 1684, Abs. 52 0807, Oct. 1973.)

The process of hot forging from solid billet stock and hot forging from sintered powder preforms have both been extensively developed using Petro-Forge high-speed (high-energy rate) machines. This paper describes some of the differences between, the two techniques and some of their similarities. Forged shapes are used as examples to illustrate where each form of manufacture may be most usefully employed.

268. Seeds, William E. "The design of preforms for precision forgings", Tech. Paper No. MF 73-176, Soc. Manufacturing Eng., 20501 Ford Rd., Dearborn, Mich. 48128, 20 p, 1973.
(See Metals Abstracts, Vol. 6, 1684, Abs. 52-0808, Oct. 1973.)

The fundamental philosophy of preform design for blade forgings for the gas turbine industry is discussed in relation to single- and double-ended blades, and to blades with midspan struts. The manner in which the basic design strategies are modified to suit the material of the blade to meet metallurgical and physical requirements is considered using Ni alloys, Cr steel and Ti alloys. The importance of the economically profitable concept of design relative to the more esoteric idealized solution is stressed.

269. Antes, H.W. "Forming metal powders", Manufacturing Eng. Trans. Vol. II, 137-145, 1973.

Indications are that atomized iron powder will be the most widely used for P/M forming. Formability of P/M preforms has been evaluated in terms of the results of a high-temperature torsion test. Flow has been found to be an important factor in developing optimum properties in P/M forged material. A 6.2 g/cm^3 preform provides the best impact properties for preforms deformed in a plane strain to near full density.

270. Bockstiegel, G. "Some technical and economic aspects of P/M hot forming", Hoeganaes AB PM Iron Powder Information, No. PM 73-7, Hoeganaes, Sweden, 46 p, 1973.

Examples of both power-transmitting and nonpower-transmitting automobile parts are discussed with respect to cost structure in P/M hot forming and in conventional forging. It is concluded that the economic feasibility of P/M hot forming such parts depends strongly on the amount of subsequent machining costs that can be saved. For some open-die forgings, the economy of P/M hot forming looks more favourable than others. Precision forgings will probably not be economically feasible as P/M hot-formed parts for a long time to come.

1974 (271-347)

271. Cook, J.P. "Manganese steels for P/M hot forming", The Int. J. of Powder Met. and Powder Tech., Vol. 10, No. 1, 15-19, Jan. 1974.

Both the hardenability and impact properties of manganese steels can be degraded by oxidation of the manganese during powder production or during preform sintering. The impact properties of oxidized material can be improved by increased deformation. However, high-temperature sintering can reduce the oxides and yield material with impact properties and hardenability equal to wrought steels. Increased usage of manganese steels is expected when high-temperature sintering becomes more commonplace since these P/M steels can offer savings over the presently available nickel-molybdenum steels.

272. Gaigher, H.L. and Lawley, A. "Structural changes during the densification of P/M preforms", ibid, 21-31.

This work is concerned with the structural changes accompanying the densification of a porous preform. Void morphology, grain structure, dislocation substructures and impurity distribution are characterized and correlated with the densification process in iron-powder preforms.

The densification process covers three steps: (a) an initial small increase in density at small levels of preform deformation occasioned by a decrease in the number of large pores, (b) a rapid densification from about 86% to about 94% of theoretical density at intermediate levels of deformation attributable to the flattening of cylindrical pores oriented roughly perpendicular to the load axis and (c) a saturation region due to the presence of cylindrical pores oriented approximately parallel to the load axis, which do not flatten.

Characterization of pore morphology coupled with the results of a concurrent experimental and model study provide a rationalization for the increase in the plastic Poisson's ratio with densification.

273. Donachie, S.J. and Church, N.L., "Effect of composition, temperature and crystal structure on the flow stress of P/M forged preforms", ibid, 33-41.

Alloy flow stress is an important parameter of the P/M hot forging process. Although the literature on the economics of P/M hot forging is limited, there is general agreement that one of the major factors influencing the cost of a P/M forged part is die wear. No extensive investigation into the mechanism of die wear has been reported. However, it is qualitatively known that die life is related to forging temperature and pressure. It is the intent of this investigation to define the conditions under which low flow stress alloys may be forged and to evaluate their effect in reducing forging pressures and thus, ultimately, increase die life.

The alloys selected for evaluation were based on commercially available compositions. The carbon content of a 4600 Type alloy (0.45% Mn-1.7% Ni-0.24% Mo-balance Fe) was varied from essentially carbon-free to 0.6%C. Two other carbon-free alloys were investigated, a low-nickel (0.5%) 4600 modification and an atomized iron powder.

It is concluded that the flow stress of P/M forging preforms is determined principally by phase balance and solid solution strengthening. Ferritic structures have lower flow stress than austenitic structures in the temperature range of interest. Molybdenum contributes strongly to solid solution strengthening.

The phase balance at which minimum flow stress will occur is dependent upon the flow stress of each phase, the slope of the flow stress-temperature curve for each phase and the rate of phase change with temperature.

The use of low flow stress alloys in P/M hot forgings may increase die life significantly without decreasing the density of the forged part.

274. Kuhn, H.A. and Downey, C.L. "How flow and fracture affect design of preforms for powder forging", ibid, 59-66.

A method is presented for the design of sintered powder preforms for forging. Design of powder preforms for forging must include consideration of densification, deformation and cracking during forging. Results of basic material tests provide the fundamental relationship for design. These can be used in a quantitative manner to establish broad design guidelines for a particular part, or they may be used along with plasticity analysis to give more refined preform dimensions and shape. As an example, the forging of a cylindrical preform into a disc is considered.

275. Lenel, F.V. "New processes for P/M components", Metals Eng. Quart.(ASM), Vol. 14, No. 1, 24-29, Feb. 1974.

This is a review of hot forging of powder metallurgy preforms and hot consolidation techniques for highly alloyed powders, mainly superalloy and high-speed steels.

The technology of hot forging of P/M preforms has become feasible because of the cost of steel compared to that of iron and steel powders. In 1967, iron powder for moulding parts cost 11 1/2¢ per lb and decreased to 9 1/2¢ per lb in 1972. During the same period, hot-rolled carbon steel bars increased from 7¢ per lb to 9¢ per lb. Similarly, the price of prealloyed steel powder approaches that of hot-rolled alloy steel bars. The author proceeds to give examples of preform forging techniques and products from references which have been covered in this survey.

The hot consolidation technique differs from preform forging in that the aim is to produce semi-finished products which must be further formed. Consolidation techniques have been developed in the last 10 to 15 years primarily for refractory metals, beryllium, and materials for nuclear fuel elements. They are now being applied to powders of nickel-bar superalloys and high-speed steels, which have been exclusively processed by fusion metallurgy for some time.

276. Lyle, J.P. and Cebulak, W.S. "Properties of high-strength aluminum P/M products", ibid, 52-63. (See also: Ref. No. 208.)

This article describes the properties of aluminum P/M products which have been made as large billets and then forged or extruded. Prealloyed atomized powder is used. Important steps in the fabrication are: (1) cold compacting, (2) preheating, (3) hot compacting, (4) hot working and, (5) solution heat treating and ageing.

P/M Al-Zn-Mg-Cu alloys, with and without additions of cobalt or iron-plus nickel, have exhibited outstanding combinations of strength, resistance to stress-corrosion cracking and resistance to exfoliation corrosion. Fatigue characteristics have been at least equal to those of 7075-T6 fabricated in conventional manner from cast ingots.

277. Anon. "New P/M process for superalloys", Materials Eng., Vol. 79, No. 2, 18, Feb. 1974.

This is a news item which describes a new process, developed by American Powder Casting Co., for the consolidation of superalloy powder metal preforms to almost full density without high temperature and pressure equipment. Nickel, cobalt, chromium-base powders, as well as beryllium, titanium and tool steels can be compacted by the process. The process is based on the removal of surface oxides and gas molecules, which may be absorbed by the powder particles. This is done by heat activation of particle surfaces causing an ionic or interatomic exchange between particles in intimate contact with each other and an electron donor compound of boric acid and alcohol.

The Company has produced 20-cm diameter billets weighing 27 kilos and the billets have been evaluated by aircraft engine manufacturers. Physical and mechanical properties conform to General Electric and Class B property specifications at room and elevated temperatures.

The process will enable economical production of superalloy P/M preforms by heating to temperatures below the solidus in standard heat-treating furnaces. Dimensional stability and production of complex shapes with internal cooling are possible.

278. Koczak, M.J., Downey, C.L., and Kuhn, H.A. "Structure/property correlations of aluminum and nickel steel preform forgings", Powder Metallurgy International, Vol. 6, No. 1, 13-16, Feb. 1974.

The alloys investigated were Alcoa 601 AB mixture (1.0% Mg+0.6% Si+0.25% Cu + balance Al) and prealloyed 4620 steel (0.20% C-0.55% Mn-0.28% Si-1.80% Ni-0.25% Mo). The aluminum preforms were supplied compacted and sintered by Alcoa. The steel preforms were isostatically compacted and then sintered in hydrogen at 1122°C for 30 min. The sintered compacts were machined into cylindrical preforms with height-to-diameter ratios ranging from 0.27 to 1.90. Preforms were forged at a maximum stress of 386 MPa (56 ksi) to give specimens 27 mm (1.06 in.) in diameter and 5.3 mm(0.21 in.) high. Densities of all forged discs were at least 99.7% theoretical. Miniature Izod impact specimens were machined from the forged discs.

For both aluminum and steel forgings, impact resistance increased with increasing flow or height strain in compression. In the 601 AB alloy, a brittle intergranular fracture was associated with low impact properties. With increased flow during forging, a ductile transgranular fracture was associated with improved impact properties. For 4620 steel, little or no flow during forging gave poor impact properties associated with microporosity. With increased flow and complete densification, an improvement in impact properties also occurred in the 4620 steel forgings.

279. Fischmeister, H.F., Olsson, L. and Easterling, K.E. "Powder metallurgy review 6. Powder forging", ibid, 30-40.

This is a comprehensive review of powder forging. Although "sinter-forging" can probably be traced back to World War II, it was the mid-sixties before interest was fully awakened. This followed an announcement, in 1964, that connecting rods forged from iron powder had been successfully tested by General Motors. That these connecting rods never came into full production was for economic reasons rather than technical. General Motors had just completed a foundry line for casting connecting rods from ductile iron.

The following advantages have been quoted by proponents of powder forging: (1) material savings, (2) forging to finished shape, dimensions and surface, (3) high precision, (4) one stroke forging, (5) reduced tool wear and, (6) favourable metallurgical structure.

Theories and experiments concerning the simultaneous deformation and densification of porous specimens are reviewed. The properties of sinter-forged steels are considered in relation to those of conventional wrought materials on the one hand, and to sintered steel on the other.

Areas requiring further development are die-wall lubrication, hydrostatic compaction of large preforms, and automatic production lines. Much remains to be done to establish rules for the design of preforms and tools in powder forging which would reduce the amount of trial and error work involved in the development of a powder forging. The rate of tool wear is a decisive factor in the economics of powder forging. The optimization of alloy compositions and alloying methods for steel powder forgings is another important problem area. Powder forging offers interesting technical possibilities such as the manufacture of parts with a controlled porosity gradient, or of composite shapes. The possible benefits of synthetic structures which may be produced by powder forging, such as steels with increased content of wear-resistant carbides, are still largely unexplored.

280. Krantz, T. "Development of low alloy steel powders containing molybdenum for forging applications", Materiaux et Techniques, Vol. 6, No. 3, 117-126, Mar. 1974.

The composition variables investigated were manganese, molybdenum, copper and nickel contents. The forgings were evaluated by density measurements, microexamination, hardenability testing, and determination of tensile properties and impact strength.

Results showed that nickel-free Mn-Mo steel forgings could be competitive with those made from AISI 4630 steel. When nickel was added to the Mn-Mo steel, hardenability and mechanical properties exceeded those of the 4630 steel.

281. Anon. "Coatings protect P/M preforms during sintering", Materials Eng., Vol. 79, No. 3, 55, Mar. 1974.

This news item describes two glass ceramic coatings which have been developed by A.O. Smith for the protection of powder metal forging preforms during sintering and forging preheat.

282. Abkowitz, S. "Cost savings in the application of P/M titanium and P/M aluminum alloys", Progress in Powder Metallurgy, Vol. 30, 85-101, 1974. National Powder Metallurgy Conf. Proc. 1974. Sponsored by Metal Powder Industries Federation and the American Powder Metallurgy Institute. Ed. by Richard F. Halter. Presented Apr. 9th and 10th, 1974, Boston, Mass.

This article makes brief mention of preform forging of titanium. The forging of P/M titanium and titanium alloy preforms to full density results in properties which are essentially equivalent to wrought products. Pressed and sintered preforms with an initial density of 94% of theoretical, when forged to full density, do not show substantial increases in strength, but do achieve substantially higher ductilities. Another unique advantage of P/M titanium is the ease with which it machines by comparison to wrought titanium which is relatively difficult to machine.

The powder preform approach for titanium and its alloys has a potentially strong economic advantage, particularly for high surface-area-to-weight-ratio forgings with poor material utilization. Preforms can eliminate the cost of wasted material, but more important, the preliminary forging operations and die costs.

283. Cook, John P. "The effect of sintering temperature and flow on the properties of AISI 4027 hot P/M formed material", ibid, 173-191.

A manganese-molybdenum low-alloy steel powder with an AISI 4027 composition (0.8% Mn-0.25% Mo) was water atomized and mixed with carbon to provide material with a final carbon content of 0.2%. The compacted powder was sintered in endogas at 1120°C and in dissociated ammonia at 1120-1260°C. Different degrees of deformation were applied to the sintered preforms - repressing with no laterial flow up to rolling with considerable lateral flow.

The effect of increasing the sintering temperature was to increase the hardenability by reducing the oxides and thereby increasing the amount of alloying elements in solution. Increased sintering temperature also increased the impact strength by reducing the number of crack initiating brittle inclusions.

The effect of increasing the amount of deformation was to increase the impact strength by eliminating any residual porosity, prior particle boundaries, and to break up and elongate the inclusions.

Wrought "H" band hardenability was achieved by sintering at 1200°C or 1260°C in dissociated ammonia. Material sintered in endogas at 1120°C had ductile room temperature impact properties when it was fully upset (lateral strain ε=0.9), whereas material sintered in dissociated ammonia at 1120°C had ductile failure even in the re-press condition (no lateral strain).

284. Moyer, Kenneth H. "The effect of sintering temperature (homogenization) on the hot formed properties of prealloyed and admixed elemental Ni-Mo steel powders", ibid 193-205.

Two alloy steels were studied: 1.8% Ni-0.5% Mo and 0.5% Ni-0.5% Mo. The alloys were prepared in three ways: (a) by mixing nickel, molybdenum and graphite powder with iron powder, (b) by mixing nickel and graphite powder with a 0.5% Ni-0.5% Mo-balance iron prealloyed powder (partial prealloying) and, (c) by mixing graphite powder with a completely prealloyed powder. Carbon content ranged from 0.16 to 0.25% in the hot-formed material.

The preforms (51 mm x 51 mm x 127 mm) were cold-die compacted to density of 6.2 g/cm^3. Sintering was carried out at 1120°C to 1260°C for one hour prior to hot forming. After sintering, the preforms were hot upset to full density at 980°C or 1120°C.

When the prealloyed material is sintered at 1120°C it gives tensile properties equivalent to those of wrought AISI steels. The hardenability falls within the upper region of the AISI 4620 H band. Impact properties are improved by sintering at higher temperature because at higher temperatures the kinetics for reduction of oxides are more favourable.

The properties of the admixed elemental material are generally lower than the prealloyed material. At a sintering temperature of 1120°C the nickel does not diffuse completely into the iron matrix. At a sintering temperature of 1260°C the tensile properties are similar to those of the prealloyed material, and the room temperature impact strength approaches that of the prealloyed materials. Hardenability, regardless of sintering temperature, remains lower than that of the prealloyed material.

The impact strengths of admixed powder materials at low test temperatures do not improve as the sintering temperature increases. Since it is virtually impossible to achieve a uniform martensitic structure on quenching admixed powder material, the toughness of this material should be inferior to prealloyed material in the quenched and tempered condition.

To match the properties of the prealloyed materials either a finer nickel powder would be necessary or higher sintering temperatures and longer time would be required to diffuse the nickel into the iron matrix. Finer nickel powders are more expensive and even a sintering temperature of 1260°C in conventional sintering furnaces is considered impractical by many.

Partially prealloyed materials, on the other hand, show more promise for matching the properties of prealloyed materials at lower sintering temperatures, especially if the molybdenum is prealloyed. Molybdenum makes the greatest contribution to hardenability. Tensile strength and impact strength of partially prealloyed materials also behave similarly to those of prealloyed materials, and partially prealloyed materials can be processed at reasonable sintering temperature.

Hardenability, tensile properties and impact properties of high-nickel-molybdenum materials are all higher than those of the low-nickel-molybdenum materials.

285. Lyle, J.P. and Cebulak, W.S. "Approach for control of microstructure and properties in high-strength aluminum alloys", Met. Trans., Vol. 6A, No. 4, 685-699, Apr. 1974. (See: Metal Powder Report, Vol. 30, No. 6, 186-187, June 1975.)

High-strength products made from atomized Al-Zn-Cu-Co alloy powders have good combinations of strength, ductility, resistance to stress-corrosion cracking and fracture toughness. P/M methods produce fine metallurgical structures and compositions which cannot be produced by ingot metallurgy methods. Some characteristics of metallurgical structures of extrusions and forgings are shown and related to the structure of atomized powder and the fabricating process.

286. Brown, G.T. "Properties of structural powder-metal parts - over-rated or under-estimated", Powder Metallurgy, Vol. 17, No. 33, 103-125, Spring 1974.

In this paper, the properties of compacted-sintered materials as well as powder-forged materials are compared with wrought steels. Costs are also considered.

One of the difficulties of powder forging is controlling density in all parts of the component. Also, it is necessary to remove the last small traces of porosity to achieve properties directly comparable to those of wrought materials. The high Ni-Mo prealloyed steels are much favoured on account of the easy reducibility of the oxide film formed at various stages of processing powder and preform. There is little point in powder-forging development using highly alloyed materials for through-hardening applications if leaner compositions will perform the same function. There is good reason to suppose that many general applications can be fulfilled with straight Fe-C materials or very much leaner steels than reported to date. High molybdenum contents may cause some machinability problems and should be treated with caution.

Some of the views expressed by about 40 personalities and organizations involved in powder metallurgy contained the following suggestions for further work:

a) automatic dry-bag isostatic pressing, particularly of large pieces for subsequent powder forging

b) the sinter-forging process itself.

The powder-forging process can extend the use of powdered metal into the field of higher-stressed parts and large-volume components. An overriding conclusion is that uniformity of both tolerance control and properties should be studied as a separate subject vital to the generation of customer confidence.

287. Bockstiegel, G. and Björk, U. "The influence of preform shape on material flow, residual porosity and occurrence of flaws in hot-forged powder compacts", ibid, 126-139.

In the hot forging of powder compacts into items of complicated shape, proper preform design is critical. In particular, in cases where items having sections of different lengths in the forging direction are to be produced in tools with undivided punches, the risk of cracking, overlapping or residual porosity in one or several of the sections is great.

Model experiments were carried out with iron powder compacted to a green density of 6.5 g/cm^3 and presintered for 30 min at 1120°C in dry hydrogen. After presintering, the cylinders were machined into asymmetrical bodies of various shapes. The compacts were then reheated to 1100°C and forged with the same cylindrical die and flat lower punch, but the upper punch varied according to the final shape desired.

Guided by the information obtained from the model experiments, various types of ring-shaped preforms were prepared for experimental forging. The interesting result here was that two simpler preform shapes, deviating considerably from the shape of the tool cavity, yielded forgings which were fully densified in all sections at reasonably low forging pressures, whereas the more complicated preform shapes, closer to the shape of the tool cavity, could not be fully densified in their highest section even at forging pressures 50% higher than in the case of simpler preform shapes. A simplified explanation of this is that it is easier to move material from one section of the preform to another before too much pressure and surface friction have been built up in these sections. However, this conclusion must not be generalized, since in other cases, somewhat more complicated preform shapes may be required in order to avoid flaws of various types.

288. Griffiths, T.J., Jones, W., Lundregan, M. and Bassett, M.B. "Pilot study of preform design for sinter forging", ibid, 140-156.

The purpose of this study was to produce some guidelines to assist in designing preforms for sinter forging. This was done by the production and study of a component suitable for P/M forging which at present is produced by conventional forging. The forging was 95 mm diameter and 5 mm thick, with a central boss 10 mm high. The diameter of the preform was varied to give different amounts of lateral flow and relate this to the onset of peripheral cracking. Iron powder premixed with 1% graphite (to allow for loss of carbon) and 1% zinc stearate lubricant was sintered at 1120°C for 20 min in an endothermic atmosphere. The preforms were coated with "Berkatekt" to prevent scaling during preheating, which was carried out at 900°C for 20 min.

From a visual inspection of the forgings it became evident that those produced from the denser preforms gave consistently better results with freedom from cracking and other surface defects. As expected, peripheral cracking was particularly evident in those preforms of the smallest diameter.

A more uniformly dense component would have resulted if the preform shape had more closely followed the shape originally evolved by calculation, rather than the simplified shape derived from this. The problem of chilling also emphasizes the need for adequate preheating of dies.

289. Brown, G.T. and Steed, J.A. "A comparison of the mechanical properties of some powder-forged and wrought steels", ibid, 157-177.

Brown and Steed found that most of the powder-forged materials have properties at least as good as those of the transverse properties of wrought steel; the best of the powder-forged materials have properties that approach the best obtained from longitudinally-tested wrought bar. If a direct comparison is made between the properties of powder-forged and wrought steel, the precise nature of the wrought steel must be clearly defined and allowance made for the expected divergence in relation to the degree and direction of working.

The properties of powder-forged materials have been shown to be sensitive to non-metallic inclusion content. Good ductility, reasonable impact strength and high fatigue performance can be obtained by appropriate material selection.

The hardenability of powder-forged steels appears to respond to the well understood variables of composition and grain size. In controlling the hardenability of steels alloyed primarily with nickel and molybdenum, the level of manganese also present has been shown to be critical.

Higher-manganese powder-forged steels and similar types of wrought steel have similar hardenability but the former tend to contain more non-metallic inclusions than lower-manganese alternatives; their ductilities are reduced in consequence but are still adequate for many purposes.

Powder-forged steels should offer advantages in service because they are not subject to directionality of properties.

290. Antes, H.W. and Stockl, P.L. "The effect of deformation on tensile and impact properties of hot PM-formed nickel-molybdenum steels", ibid, 178-192.

Hardenability, tensile, and impact properties were determined for two Ni-Mo powder-formed steels. The compositions of the two steels were Fe-1.8% Ni-0.5% Mo and Fe-0.5% Ni-0.6% Mo; carbon contents studied for both materials were 0.2, 0.3 and 0.4%. Preforms were hot-formed to full density by upsetting (plane strain) at 980°C or by re-pressing (uniaxial strain) at 1040°C. Jominy end-quenched tests were made to determine hardenability. Triplicate tests were made in the as-formed as well as the quenched and tempered conditions.

The additional flow provided by upsetting gave higher tensile and impact strengths than re-pressing. Tensile ductility was the same for both processing conditions. Tensile yield strength increased with increasing carbon content for the slack-quenched material and levelled off for fully martensitic structures. Room temperature impact strength also increased with increasing carbon content owing to a decrease in the amount of ferrite in the slack-quenched structure. Increasing carbon content caused a decrease in impact strength once fully martensitic structures were achieved.

Impact strength at -40°C ranged from about 20 to 40J. Room temperature impact strength ranged from about 20 to 50J. These properties were obtained for materials heat treated to approximately 850 MPa (124 ksi). At the lower carbon contents the hardenability curve was found to fall within the AISI 'H' band for 4620 wrought steel. At the higher carbon level (0.4% C) the Jominy curves were close to the lower limit of the 'H' band for the 4640 wrought steels.

291. Fischmeister, H.F. and Larsson, L-E. "Fast diffusion alloying for powder forging using a liquid phase", ibid, 227-240.

This paper is concerned with attempts to use a pre-mixed powder rather than a prealloyed powder for powder forging which mainly uses the latter. Objections to using a pre-mixed powder are the difficulty of obtaining a homogeneous product and the problem of oxide formation on such additions as manganese.

The authors propose a way of overcoming the objections to pre-mixed powder that involves mixing in with the powder a low-melting master alloy which can reduce diffusion times. The master alloy chosen, after considering various possibilities, was 50% Mn-50% Cu. Since only small amounts of master-alloy powder are required, 'solid-liquid alloyed' plain iron powders appear to offer great flexibility in alloy composition at a cost substantially below that of conventional prealloyed powders.

It was shown that sufficient homogenization was obtained with heating times as short as 2 min at 1200°C which should be quite compatible with induction heating, or 12 min at 1100°C -- well within the range of normal furnace heating.

Using solid-liquid alloying, it should be possible to replace prealloyed steel powders for hot compaction by plain iron powders, which would substantially reduce material costs in powder forging. Alternatively, solid-liquid alloying could be used to 'spice' a prealloyed base powder, reducing the number of prealloyed grades that would have to be produced and yet allowing greater flexibility in adapting compositions to the hardenability required by the user.

292. Moyer, Kenneth H. "Thermal-mechanical processing improves properties of dense steel powder preforms". Metal Progress, Vol. 105, No. 5, 105-107, May 1974.

High-temperature (1200°C) sintering plus upsetting to assure lateral flow produces powder forgings of Ni-Mo steel with tensile and impact properties equivalent to those of conventional AISI 4620 steel.

Toughness of the preform forging depends upon the amount of flow which the preform receives in forming and the non-metallic inclusions it contains. Flow provides a shearing action, which increases toughness by fragmenting surface impurities on the powder particles and promotes metal-to-metal contact between the powder particles. Non-metallic inclusions are known to provide nucleation sites for fracture and paths for failure in conventional steels. Careful atmosphere control during processing can prevent oxidation or reduce existing oxides in the preform.

293. Gessinger, G.H. and Cooper, P.D. "Direct forging of high-temperature steel powder", Powder Met. Int., Vol. 6, No. 2, 87-89, May 1974.

This article is concerned with the direct forging of prealloyed powder which is vacuum sealed in a steel can and then forged to nearly full density. A high-temperature Cr-Ni-W steel was processed by this method. The powder was produced in high-purity argon by rotary atomization from bar-stock material. Mechanical properties were determined for the as-consolidated powder and for 50% upset-forged billets and compared with the as-received bar-stock material. The as-consolidated powder had lower tensile strength but higher ductility than the bar-stock material. The ultimate tensile strength of the cold-worked consolidated powder material increased significantly, whereas the ductility decreased. Low ductility values seem to follow the general behaviour of materials containing fine dispersions. A possible increase in ductility might be expected by using a lower combined carbon content which would decrease the carbide volume fraction.

294. Bartos, J.L., Allen, R.E., Thompson, V.R. and Moll, J.H. "Development of hot-isostatically pressed and forged P/M René 95 for turbine disc application". Presented at 6th Annual Spring Meeting of Metallurgical Soc. AIME, Pittsburgh, Pa., May 20-23, 1974.

Argon-atomized René 95 powder was used. After investigating several variables such as powder characteristics and forging conditions, a process was selected in which -60 mesh powder was consolidated to full density by hot-isostatic pressing at a temperature above the γ^1 solvus temperature. Subsequent forging below the γ^1 solvus temperature developed the required partially recrystallized microstructure. The properties of the resulting product exceeded specification requirements.

295. Gessinger, G.H., and Bomford, M.J. "Powder metallurgy of superalloys", Int. Met. Reviews (ASM and MS), Vol. 19, 51-76, June 1974.
(See also: Ref. No. 347.)

This is a comprehensive review of the production of superalloy powders, various methods of consolidating them, and their properties. Direct forging of canned powders is a simple technique to hot-consolidate superalloys. Forging is commonly used as a shaping operation of extruded or hot-isostatically pressed bar stock. It is also possible to convert the preform into a state capable of superplastic deformation and also to isothermally forge into complex shapes. The application of pressure during sintering, such as vacuum hot pressing or hot-isostatic pressing, can produce parts of 100% density.

Research and development over the last ten years has shown that powder metallurgy methods are a feasible way to manufacture superalloy components. Now that pressing procedures have been devised, some attention will be given towards production of superalloys by powder metallurgy of compositions which would be difficult to produce by more conventional means. Another prospect is the manufacture of composite components.

296. Brown, G.T. "Powder-forging: properties related to sintered and wrought steels", Metallurgia and Metal Forming, Vol. 41, No. 6, 172-173, 175-178, June 1974.

Pilot- and full-scale production facilities for powder-metal forging are now in operation. The powder-forging process is not a low cost one, particularly because the powder cost is relatively high. The economics rely on developing a shape such that all machining operations can be eliminated. It is expected that as more powder is used the ratio of powder to billet steel price will be a favourable factor in encouraging powder forging.

The essential difference between the established press and sinter and the powder-forging route is that an extra hot-compacting operation is used to eliminate porosity and produce what are essentially homogeneous metallurgical structures with properties more closely resembling wrought steel than sintered steel. Atomization of molten alloys is more favoured than mixing of ingredients for preparation of alloys.

The results quoted show that although it is possible to make a comparison between sintered properties, powder-forged properties, and wrought steel, the conditions under which the properties are determined need to be considered and if the data are to be used for component design, then test-piece results obtained by powder forging may have more relevance than specification data developed for wrought steel.

At present, ranges of steels are being developed for both through-hardening and carburizing applications and it appears that adequate ranges of fatigue performance, tensile strength, and ductility are available in powder-forged materials for the vast majority of general engineering components.

The application of powder forging is controlled primarily by the economics, it being possible to produce finished, or more nearly finished, shapes than is possible by conventional drop-forging practice using wrought steel bar as the raw material.

297. Maclean, M.S., Campbell, W.E. and Dower, R.J. "An insight into the mechanical properties of powder metal forgings as a function of processing route". Dept. of Industry, National Eng. Lab., U.K. Report No. 566, July 1974. (See also: Proc. 4th Int. Powder Metallurgy Conf.,Czechoslovakia, Vol. 1, 309-321, Oct. 1-3, 1974.)

An investigation into the effect of the processing route on the final properties of powder forgings is reported. Parameters investigated were powder type, sintered and non-sintered preforms, forging temperature, and amount of deformation in forging. The composition of the powders used was 1.7% Ni+0.51% Mo+0.12% Mn, balance iron, and 0.45% Ni+0.55% Mo+ 0.35% Mn, balance iron. Carbon (0.4%) was mixed with the powders and the combined carbon content of the forgings was 0.25% except for the forgings heated to only 950°C.

Conclusions were as follows:

a) Powder metal preforms can be hot forged to give mechanical properties fully comparable to those of normal wrought material.

b) Residual oxygen in powder forgings critically affects these properties, especially ductility and impact strength.

c) It is possible to obtain reasonable mechanical properties, including impact strength, without resorting to full sintering, as long as the forging temperature is sufficiently high.

d) For maximum impact strength, full sintering (1 hr at 1150°C) must be employed. At lower temperatures it is necessary to hot-sinter forge to achieve maximum impact strength; at higher temperatures, hot forming (re-striking) is adequate.

e) If very high sintering temperatures are used, it would seem that quite short sintering times could be used.

298. Allen, G.J. and Weston, P.R. "New directions for sintered components", Metals and Materials (Metals Soc., U.K.), Vol. 8, Nos. 7-8, 371-377, July/Aug. 1974.

This review paper deals mainly with the conventional powder metallurgy method of compacting and sintering with variations of that method designed to give stronger sintered products. However, it mentions briefly 'hot consolidation', 'sinter forging' or 'powder forging' as being the most exciting of recent developments. It is only beginning to be commercially available in the U.K. The authors state that it is doubtful whether a component produced by such a technique should be regarded as a P/M part at all; for all intents and purposes it is a close-tolerance forging, with full characteristics of wrought steel.

299. Anon. "Automated production and advanced designs spur P/M growth", Product Eng., Vol. 45, No. 8, 22-23, Aug. 1974.

Gleason Works (Rochester, New York) has introduced a new integrated system to convert metal powder to a finished shape in three steps: isostatic dry bag compacting, high temperature (1315°C) sintering and final hot forming. The equipment is designed for precision powder forming of high-strength parts such as bevel and hypoid gears that are manufactured by Gleason. Sintering times are 3 to 5 min rather than 20 to 30 min as with conventional sintering furnaces.

300. Bockstiegel, G. "Technical and economic aspects of P/M-hotforming - Part 1: Technical problems". Powder Metallurgy Int., Vol. 6, No. 3, 116-120, Aug. 1974. (See also: Ref. No. 316.)

This paper discusses technical and economic aspects of a successful utilization of preform forging. Interest is focussed mainly on parts for the automobile industry, where the greatest potential for preform forging can be expected. Parts for a European car which may be potentially suitable for preform forging are: connecting rods, wheel hubs, gears and synchronizing rings, rear axle end flanges, differential side gears, pinion gears, differential ring gears, driving flanges, clutch hubs, and ball-joint cups. All the parts except one have already been made on an experimental or pilot scale as preform forgings.

The exception is the wheel hub. Specific experience from the production-scale and large pilot-scale runs of powder-forged parts has shown that the flashless type of hot forming yields far longer die life than conventional hot forging. This can be explained by the fact that due to the absence of flash, forming pressures and die-friction are much smaller in preform forging.

The occurrence of Mn and Cr oxides in the particle surface of atomized Mn- and Cr- alloyed steel powders cannot entirely be avoided without substantial increases in powder manufacturing costs. There are however two alternatives which separately or in combination can counteract the disadvantage of having residual surface oxides on the powder particles. The first alternative is to reduce the oxides in the preform state by sintering them at 1200°C in dry hydrogen by taking advantage of the presence of carbon in the preform. The other alternative is to let the preform undergo substantial macroscopic flow during hot forming to break up and elongate the inclusions in the direction of material flow.

Small additions of sulphur in elemental or in prealloyed form, should have a beneficial effect on the machinability of preform forgings.

Of the three kinds of hot forming the simplest and probably the cheapest is that which excludes presintering of preforms and is likely to be useful in the non-power-transmitting automobile parts. The second kind includes sintering of preforms and is probably the most suitable for power-transmitting parts. The third concept, which combines a sintering and reheating furnace in one unit, is probably too complicated and inflexible to be a good solution for any kind of part.

301. Gurganus, T.B. and Turnbull, G.K. "Hot isostatic compaction is key to quality titanium parts", Metal Progress, Vol. 106, No. 3, 83-84, 86, 88, Aug. 1974.

Alcoa has performed tests with several of the more common titanium powder metallurgy techniques to isolate important processing variables and their effect upon microstructures and mechanical properties. These findings were then extended to hot isostatic methods.

Powder metallurgy offers potential economic advantages over wrought titanium products if attention is directed toward microstructural and interstitial control to satisfy the rigid requirements demanded by the aerospace industry. Microstructural refinement and typical wrought property levels could not be achieved in sintered materials without a subsequent subtransus forging operation. Sintering followed by extrusion developed reasonable properties but failed to meet microstructural requirements.

Only the simultaneous application of high subtransus temperature and pressure through hot isostatic compaction produced acceptable microstructures and typical wrought-product mechanical properties without subsequent subtransus processing.

Use of this technique should permit the production of parts close to net configuration with properties equivalent to those of wrought products with economic benefits through increased material utilization and decreased machining costs.

Chips of Ti-6% Al-4% V were produced from a low-oxygen billet and converted to powder, using rigid processing controls to achieve low interstitial oxygen levels.

The hot-isostatic compaction concept offers excellent potential. Mechanical properties were comparable to those of typical wrought materials, and microstructures showed no evidence of overheating. Additional subtransus work further refined the structure but was not necessary for mechanical property development.

302. Wallace, W., Dunthorne, H.B. and Sprague, R.A. "Microstructures and mechanical properties in a turbine disc fabricated from Astroloy powder", Can. Met. Quarterly, Vol. 13, No. 3, 517-527, Sept. 1974.

Powder metallurgy processing of nickel-base superalloy turbine discs is described. The discs were prepared from hot-isostatically pressed Astroloy powder preforms by a single-stage forging operation, followed by machining. The forgeability, machinability, tensile and stress rupture properties of the powder fabricated material were better than, or equivalent to, those of cast material. The fatigue lifetimes obtained in laboratory push-pull tests and the lifetime obtained in a disc exposed to engine testing and ambient temperature spin-rig testing were also good. However, the lifetimes obtained from crack detection to final failure were short, indicating either poor resistance to fatigue-crack propagation or poor fracture toughness. The fatigue-crack propagation resistance and/or fracture toughness are believed to be degraded by the presence of carbide networks on powder particle boundaries and possibly by the presence of platelets of a sulpho-carbide. These problems might be avoided by the use of pressing and forging operations carried out below the γ^1 solvus. Forging deformations and forging temperatures must be sufficient to cause complete recrystallization and the dispersal of any deleterious precipitates or inclusions.

303. Lefer, Henry. "Developments in titanium, aluminum P/M technology", Precision Metal, Vol. 32, No. 9, 44, 47-8, Sept. 1974.

Dynamet Technology has been pushing the limits of practical titanium and aluminum metallurgy to points which surprise the experts. Using its proprietary powder techniques, the Company has been producing a variety of pressed and sintered parts, forging preforms, extruded shapes and tubing and controlled porosity parts.

Where the higher toughness of the wrought product is required, 94% dense titanium alloy preforms can be hot-forged to 100% density. The resulting tensile properties are comparable to conventional wrought materials. With the P/M preform, forging to final size usually requires only one die. This can eliminate as many as six dies in conventional forging and the attendant reheat operations. One customer reports that, although the preforms are more expensive than billets previously used, finished part cost was about 70% less.

304. Olsson, L.R., Lampe, V. and Fischmeister, H.F. "Direct forging of high-alloy steel powders to bar stock", Powder Metallurgy, Vol. 17, No. 34, 347-362, Autumn 1974. (See also:Ref.No. 306.)

A method for the powder-metallurgy fabrication of tool-steel bar stock has been developed that requires neither isostatic compaction nor low-oxygen powders. The work reported was carried out on hot-work tool steel with nominal analysis of 0.28% C-0.60% Si-0.40% Mn-11.50% Cr-9.5% Co-7.5% W-0.55% V - balance iron. This steel is used mainly for inserts in die-casting tools. It was felt that this composition would exemplify the whole range of problems to be encountered in the powder processing of tool steels. In particular, the high-chromium content of this steel would bring out the problem of surface deoxidation. The powder was made by atomizing with nitrogen.

The powder is heated in sealed steel tubes and step-forged to 99.5% density. Further reduction by rolling raises the density to 100%. A reducing agent (e.g., carbon) and an oxygen getter (e.g., titanium) are enclosed in the container, together with the powder, for reduction of particle surface oxides. This makes initial evacuation of the containers unnecessary and allows powders with high-oxygen contents to be used.

The step-forging process requires no heavy investments, neither in furnaces nor in presses. Most steel works and forging departments already have the necessary equipment. The process is suitable for small-scale production as well as for larger quantities.

305. Pilliar, R.M., Ladanyi, T.J., Meyers, G.A. and Weatherly,G.C. "Study of metallurgical factors on fracture toughness of powder forged steel". Proc. 4th Inter. Powder Metallurgy Conf., Czechoslovakia, Vol. 1, 233-249, Oct. 1974. (See: Metal Powder Report, Vol. 30, No. 2, 45, Feb. 1975.)

Powder-forged alloy steels heat treated to give yield strengths greater than 1000 MPa have been evaluated by plane-strain fracture-toughness tests. This parameter has proved extremely sensitive to structural features in the powder-forged parts. Two steels were investigated, namely: a Cr-Mn and a Ni-Mo steel.

306. Fischmeister,H.F. et al. "Hot consolidation of metal powders - selected problems and solutions", ibid 293-308. (See: Metal Powder Report, Vol. 30, No. 2, 46, Feb. 1975 and Ref. No. 304.)

Basic studies of the deformation of porous preforms are aimed at providing guidelines for design of preforms. A model for the compaction of spherical powders and studies of the lateral spreading, densification and cracking of preforms during compaction are described. A method of rapid diffusion alloying has been developed for the preparation of low-alloy steels. A process for continuous hot compaction of tool-steel powders is described which requires neither isostatic compaction nor highly oxygen-free powders. It is based on the step-forging of powder-filled tubes provided with a getter for in-situ reduction of particle surface oxide. Grain size control in powder-forged superalloys is achieved by strain-induced grain coarsening. The production of tungsten-reinforced, nickel-base composites by powder forging is described.

307. Suzuki, K. and Shimamura, K. "Mechanical properties of P/M hot forged iron preforms via HERF process", ibid, 323-336. (See: Metal Powder Report, Vol. 30, No. 2, 47, Feb. 1975.)

Iron powder preforms made from reduced and atomized powders were densified by a Dynapak forging machine with flat, open dies and with closed dies at temperatures from 900 to 1200°C. Forgeability of sintered preforms was measured by the dimensional change before and after deformation. Tensile, impact and density measurements were made on the hot-forged billets. Relationships between hot-forging conditions and mechanical properties are discussed with respect to the ferrite grain size and forged density of specimens. Optimum forging conditions in the HERF process are determined for each iron preform.

308. Siergiej, J.M. "P/M complex shapes by hot extrusion and the prospects for mammoth P/M extrusions and forgings", ibid, 359-372. (See: Metal Powder Report, Vol. 30, No. 2, 48, Feb. 1975.)

Current and developing processes for the fabrication from metal powders of structural shapes of complex cross-sections and/or extremely long lengths, some with continuous taper or composed of two or more metallurgically bonded metals, are reviewed. Examples of beryllium and titanium products of this type are presented. The advantages of the P/M approach in the preparation of billets or preforms for subsequent forming and the advent of the very large isostatic-pressure vessels and large presses now coming into existence are reviewed relative to the prospects of having huge P/M components in the near future.

309. Arén, B. "Material flow in the powder forging of a gear-profile as a function of preform shape", ibid, 123-139. (See: Metal Powder Report, Vol. 30, No. 2, 58, Feb. 1975.)

Powder preforms of unalloyed iron with different shapes were forged to gear-profile form. The preforms, of 82% density, were preheated to 900°C and forged under plain strain conditions in a closed preheated (200°C) die. The influence of tooth height vs total height of the preforms on the localization of remaining porosity in the forgings, the risk of stress cracking and the tendency for folding were investigated. Density changes during different stages of forging up to 94% relative density were studied by hardness testing and metallography. The results are discussed in relation to the fundamental flow behaviour of porous materials. They indicate concentrations of compressive stresses as well as shear flow under hydrostatic pressure, resulting in local densification.

310. Bocksteigel, G. "Some technical and economic aspects of P/M hot forming", ibid, 48 pp. (See: Metal Powder Report, Vol. 30, No. 2, 60-61, Feb. 1975.)

The problems of designing preforms and hot-forming tools have turned out to be less difficult than first believed. The heating and handling of preforms prior to hot forming still seem to constitute an engineering problem, especially where complicated shapes are involved.

The elimination from hot-formed materials of oxide inclusions harmful to impact strength, fatigue strength and hardenability, although possible on a laboratory scale, still constitutes a problem on an industrial scale.

Examples of both power-transmitting and non-power-transmitting automotive parts are discussed with respect to cost structure in P/M hot forming and in conventional forging. It has been concluded that the economic feasibility of P/M hot forming such parts depends strongly on the amount of subsequent machining costs that can be saved. For some open-die forgings, the economy of P/M forging looks more favourable than for others. Precision forgings will probably not be economically feasible as P/M forging parts for a long time to come.

Prices for steel billets and castings can, for various reasons, be expected to increase faster than powder prices. Since in many cases the competitiveness of P/M forging with respect to conventional forging (or casting) depends critically on the ratio between steel billet price (or cast iron price) and powder price, this tendency is going to favour P/M forging more and more.

311. Anon. "New property data for titanium P/M grades", Metals News, Materials Eng., Vol. 80, No. 5, 64, Oct. 1974.

This is a brief news item which mentions that high-purity, inexpensive titanium and titanium alloy powders produced by chemical reduction can save money in the production of forging preforms. The pressed and sintered preform approach for titanium and its alloys is well suited to high-surface-area-to-weight ratio forgings, which normally have poor materials utilization. The information comes from Dynamet Technology of Burlington, Mass.

312. Kuhn, H.A. "Overcoming cracking problems during forging of aluminum alloy powder preforms". Paper presented at ASM/AIME Materials Science Symposium, Detroit, Oct. 21-24, 1974. (See: Metal Powder Report, Vol. 30, No. 6, 187, June 1975.)

Previous studies have shown that the mechanical properties of forged aluminum-alloy powder preforms are enhanced if large deformations are incorporated along with densification during the forging process. Large deformations involve an initial period of unconstrained lateral flow; this, combined with the relatively low ductility of the sintered powder material, may lead to severe cracking during forging. In general, the low workability of powder materials limits the range of shapes that can be forged, and thus limits the breadth of application of forged powder parts. The degree of deformation to fracture during forging of complex parts can be increased, however, by careful control of local stress and strain states through improved die design, preform design, or lubrication. The key element of the technique is a ductile-fracture criterion involving linear relationship between total surface strain at fracture. Use of the method is demonstrated through design of the preforms for a complex axisymmetric part forged from 601AB aluminum alloy powder.

313. Cook, J.P. "Effect of sintering temperature and flow on the properties of Ni-Mo steel hot P/M formed material". Paper presented at Automobile Eng. Meeting, Toronto, Canada. SAE Paper No. 74 0982, 12 p, Oct. 21-25, 1974.

Water-atomized Ni-Mo alloy (0.5% Ni-0.5% Mo) powder was blended with graphite to give 0.4% C and pressed into preforms. The sintering temperature and atmosphere and the degree of metal flow were varied, and the preforms were hot-formed to full density. Increased deformation increased the impact strength by eliminating particle boundaries and elongating the inclusions. High-temperature sintering reduced the oxygen content and improved impact strength by reducing the number of crack-initiating inclusions.

314. Rifai, M.A. "Effect of lateral flow on cold forged powder preforms". Paper presented at 1974 Annual Meeting of the Powder Metallurgy Group, Eastbourne, England, October 28-30, 1974.
(See: Metal Powder Report, Vol. 29, No. 12, 373-374, Dec. 1974.)

During cold forging of powder preforms, pores offer resistance to deformation. This resistance can be differently affected by the way and type of loading. The rearrangement of preform particles by free and restricted lateral flow and the effect of different types of loading (compressive, shear, tensile) at different stages of densification are studied.

315. Steed, J.A. "Effect of iron powder contamination on the properties of powder forged low alloy steel", ibid.
(See: Metal Powder Report, Vol. 29, No. 12, 373, Dec. 1974.)

The effects of moderate amounts of plain iron powder contamination on the tensile properties of a through-hardened low-alloy steel powder are not significant provided that the carbon content is maintained at the design level. The fatigue endurance limit is lowered for a given strength level although the ratio of fatigue endurance to elastic limit remains constant. If the carbon content is not maintained there is a degradation in the hardenability of the material, resulting in lower tensile strength for a given heat treatment cycle. The fatigue endurance limit is also lowered although, again, the fatigue endurance/elastic limit ratio remains constant.

316. Bockstiegel, G. "Technical and economic aspects of P/M-hotforming. Part 2: Comparative cost analyses", Powder Metallurgy Inter., Vol. 6, No. 4, 172-178, Nov. 1974. (See also: Ref. No. 300.)

A comparison is made between costs of preform-forged parts and parts produced by other processes. Three automobile parts were selected for cost analysis:

a) a differential ring-gear, chosen as a representative for power-transmitting parts with high demands for hardenability, fatigue, and impact strength, which have to be made from an expensive type of powder. The ring-gear has to be made by hot forming, including sintering, but expensive machining operations can be saved.

b) a gear-box gear picked as another representative of power-transmitting parts, but one for which preform forging cannot offer substantial savings on machining operations (because of the helical teeth on this part). This part must compete not only with conventional forging but also with automatic transfer-forging on Hatebur presses. (These automatic presses are capable of producing rotational-symmetrical blanks with diameters up to 120 mm at a rate of 4-5,000 pieces per hour, with only 5-10% scrap, and dimensions much closer to final shape than possible in open-die forging.)

c) a hexagonal nut with the function of locking a roller-bearing on the rear-axle of a truck. This was chosen as being representative of non-power-transmitting parts which can be made from inexpensive powder and by a simple hot-forging process without presintering, and where expensive machining operations can be saved.

The following points arise from the data presented:

a) Powder costs are dominating in all cases, especially in the case of the ring-gear, where powder costs vary from 77-80% of total preform forging cost, depending on shape and weight of the blank. For the hexagonal nut, which is made from a cheaper powder, powder costs are less at 40 to 48%.

b) Compacting and hot-forming costs are relatively independent of the part weight while sintering cost, as can be expected, increases with the part weight. An interesting consequence of these relationships is that, for the heavier ring-gear blank, sintering costs are approximately as large as compacting and hot-forming costs together, whereas for the lighter gear-blank sintering cost is lower than either of the two pressing costs.

c) Capital costs are comparatively small (approx. 10%) for the heavy ring-gear blank, and comparatively large (approx. 40%) for the much lighter hexagonal nut. The explanation for this surprising dependence of capital cost percentage on blank weight is found in the dominating influence of powder cost. Leaving out powder cost, the distribution of capital cost, labour cost, tooling cost and energy cost is roughly independent of blank weight.

d) Total preform forging cost per blank weight-unit increases moderately with decreasing blank weight.

The following points are also brought out:

a) In the case of the gear box, P/M hot forming is not at any state competitive with conventional open-die forging and even less competitive with Hatebur forging. This is mainly due to the circumstance that, in this case, preform forging cannot eliminate any substantial amount of subsequent machining.

b) In the case of the ring gear, both conventional forging cost and P/M hot forming cost, are only approx. 10% of the total cost for the conventionally made finished ring-gear. In the best alternative, P/M hot forming saves only about 2% of total conventional cost as a consequence of reduced material cost, but about 21% as a consequence of eliminated machining operations.

c) In the case of the hexagonal nut, P/M hot forming saves, in its best alternative, 6% of total conventional cost as a consequence of reduced material cost, and about 37% as a consequence of eliminated machining operations.

On the basis of his analysis the author states that preform forging cannot compete favourably with conventional forging unless the following condition is satisfied:

$$\frac{\text{powder weight}}{\text{slug weight}} < \left(1 + \frac{\text{saved processing costs}}{\text{slug cost}}\right) \times \frac{\text{billet price}}{\text{powder price}}$$

Prices for steel billets and castings can, for various reasons, be expected to increase faster than powder prices in the future. Since, in many cases, the competitiveness of preform forging to conventional forging (or casting) depends on the ratio between steel billet price (or cast iron price) and powder price, this tendency is going to favour preform forged parts more and more.

317. Gessinger, G.H. "Recent developments in powder metallurgy", Metal Science, Vol. 8, No. 11, 394-396, Nov. 1974.

This is a brief review of recent developments in powder metallurgy in which preform forging is discussed.

Of the various possible kinds of preform forging the one that gives some degree of lateral flow has been most developed. The main emphasis is on processing development, i.e., to find the most economic set of preform presses, preheating systems, and forging presses. Powder-forged parts are mainly economic for components where large amounts of subsequent machining costs can be saved. P/M hot-forging of steels is gradually finding acceptance, and tool steels and highly alloyed superalloys for aircraft turbine discs have become important powder metallurgy applications. The high prices of inert-gas-atomized powder continue to be a problem for new applications in the special alloys field, especially where low volumes are concerned.

318. Brady, Brian D. "Where forging and stamping in Australia stands today in the face of current technologies". Status of the drop-forging industry relative to rival processes. A forum held held at 8e Congrès International de l'Estampage de la Forge, Nice, June 1974; Metallurgia and Metal Forming, Vol. 41, No. 11, 324-325, Nov. 1974.

The traditional work load of the Australian forging and stamping industries is continually kept under pressure and has seen some erosion of its tonnage due to improvements in techniques of other metal processes, among them sinter forging. The powder metallurgy technique as it has developed, has had more of an adverse effect on components produced by casting and machining or machining off the bar. The author considers that the sinter-forging process will be used for several automotive components, but that it also has a big potential for components used in consumer durables, such as washing machines, refrigerators and other household appliances.

319. Hollingworth, Arthur. "The position of the drop-forging industry in the U.K. relative to rival processes", ibid, 325-326.

Of all the developments that have taken place in the drop-forging industry during the last two decades, the powder-forging process is the most promising. The ability of the process to produce virtually "finished" components requiring little machining, has particular merit, but this must not lead to a disproportionate increase in cost. The price of powder is a vital factor and this criterion will, of course, govern its development. The process is still being developed in the U.K., but indications are that successful commercial exploitation is not too far away.

320. Anon. "Prototype P/M service aids designers, custom producers", Precision Metal, Vol. 32, No. 11, 43, Nov. 1974.

A very brief article describes a company, Powder-Tech Associates, that will produce discs of hot-forged materials for evaluation.

321. Antes, H.W. "P/M hot formed gears", Metals Eng. Quarterly (ASM), Vol. 14, No. 4, 8-15, Nov. 1974.
(See also: "Gear Manufacture and Performance", Proc. of Metalworking Forum held at Troy, Mich., Oct. 29-31, 1973, Sponsored by ASM Mechanical Working and Forming Division.)

This is a review article which describes the different powder-forming processes and the advantages and disadvantages of each process. The effects of variables such as sintering temperature, forging pressure and temperature on the properties of the forgings are discussed.

Of the three principal types of ferrous powders available - sponge, electrolytic and atomized - the last is preferred because of its low cost, relative cleanliness, and the fact that a large variety of prealloyed compositions can readily be made.

Three variations of the basic P/M forming process have evolved: hot repressing, confined-die flashless forging, and closed-die limited flash forging. Hot repressing utilizes a precision preform made by die pressing to a shape very similar to the final forging, so there is little metal movement apart from closure of pores. In confined-die flashless forging the preform weight must be controlled accurately. The closed-die limited flash process does not require careful control of preform weight; lateral flow occurs but no parting line flash is formed because confined or "trap" dies are used.

Examples of powder-forged components that have been made are differential pinion gears, bevel gears, input gears for automatic transmissions, and differential and side ring gears. The most publicized is the differential pinion gear. This gear has been made from a variety of materials including Ni-Mo, Cr-Ni-Mo, and Mn-Mo low-alloy steels. Most of the work has been concentrated on two Ni-Mo steels, containing 1.7% Ni-0.5% Mo and 0.5% Ni-0.5% Mo.

Properties of powder-forged components are as good as, if not superior to, conventionally forged components.

322. Brown, G.T. and Smith, T.B. "The relevance of traditional materials specifications to powder metal products". Modern Developments in Powder Metallurgy, ed. Henny H. Hausner and Walter E. Smith, Vol. 7, P/M Forging and Copper P/M, Proc. 1973 Inter. Powder Metallurgy Conf. MPIF and APMI, 9-31, 1974.

The development of powder forging has widened considerably the range of mechanical properties obtainable from powder products. The purpose of this paper is to reveal the danger of relying upon quality-control properties relating to wrought steel billets and bars to specify properties for components manufactured by powder forging. The properties used in this comparative study are tensile and fatigue strengths, ductility, and impact strength. The results show that powder-forged steels are capable of producing mechanical properties of approximately the same level as those of conventional wrought steel. It is shown that traditional wrought steel specifications are of little use in estimating the probable performance of powder-forged materials in engineering components since the specifications are mainly for quality control and have little relevance to component design.

323. Wisker, J.W. and Jones, P.K. "The economics of powder forging relative to competing processes - present and future", ibid, 33-49.

This paper reviews the factors which help decide whether or not a given component should be made by powder forging. A powder-forged part may be considered as an economic substitute for a part made conventionally for the following reasons: machining savings, simplified forging route, improved material utilization, improved weight control, and uniformity of properties. Now that commercial production of powder forgings has commenced at the authors' plant (GKN Forgings Ltd.), and elsewhere, it is possible to make realistic economic comparisons with competing processes, such as conventional drop forging and casting.

A powder-forged differential side gear ring, although more expensive than a conventional forging, is very attractive for the customer because expensive machining operations are eliminated. Considerable development effort has been expended by GKN on the development of powder-forged connecting rods. Samples have been engine and fatigue tested entirely satisfactorily, and rods have been manufactured for customers in pre-production quantities.

In conventional drop forging, material cost normally represents about half the finished part cost. The corresponding figure for powder forgings is somewhat lower (30-40%), but is still a very significant percentage. Every movement in powder price towards that of steel means that another group of components becomes economically attractive as powder forgings. It is felt that the rate of powder price escalation in the future should be lower than the rate of steel price escalation.

The authors suggest that the following development areas could be particularly rewarding economically:

a) increased production rates

b) improved die materials

c) fully carburized powders which have good compacting properties

d) reliable wall lubrication for compacting dies

e) extension of induction heating techniques to complex shapes such as connecting rods

f) induction sintering techniques.

A description is given of GKN's facility for producing powder forgings. Plans for another larger plant to be built on a new site are at an advanced stage.

324. Pilliar, R.M., Bratina, W.J. and McGrath, J.T. "Fracture toughness evaluation of powder-forged parts", ibid, 51-72.

This paper reports on a comparison of the mechanical properties of powder-forged and wrought low-alloy, high-strength steels. The investigation was concerned mainly with plane-strain fracture toughness, but Charpy impact and tensile strengths were determined also. The alloy compositions were (a) Ultimo 200: 0.34% C-0.36% Si-1.54% Cr-0.61% Mn-0.32% Mo-balance iron. (b) modified 4640: 0.43% C-0.25% Mn-1.79% Ni-0.51% Mo-balance iron, (c) 4600 V: 0.39% C - 0.18% Mn-1.83% Ni-0.51% Mo-balance iron.

The importance of non-metallic inclusions on particle bonding and fracture toughness for powder-forged, high-strength steels was demonstrated. The extent and nature of these non-metallic inclusions depend on the alloy powder system. For powder-forged materials containing detrimental non-metallic inclusions, improvements in plane-strain fracture toughness can be achieved by mechanical working and/or diffusion anneals of the full density alloy. Corresponding improvements in impact resistance and tensile ductility will occur.

325. Avitzur, B. and Blum, P. "Forging and extrusion of P/M preforms", ibid, 73-90.

This article reports a study of the forming process for P/M preforms in terms of the parameters: preform density, amount of deformation, and environmental pressure. Although the title mentions "forging" all of the data given are from extruding experiments.

326. Bockstiegel, G. "Some technical and economic aspects of P/M-hotforming", ibid, 91-135.

This article discusses some of the technical and economic aspects upon which successful industrial utilization of powder forging may depend. Considerable detailed facts and figures are presented. The author points out that it has been shown in the past 3 or 4 years that powder forging of complicated machine parts is technically feasible. Contrary to earlier belief, the design of preform shape and of suitable tools for hot forming have not posed any great problems. More serious difficulties have arisen in the search for acceptable solutions to the problem of proper heating and handling of preforms prior to hot forming and in attempting to match requirements for high hardenability and toughness in economically acceptable ways. The applications considered are mainly parts for the automobile industry, e.g., connecting rods, ball joint cups, wheel hubs, clutch hubs, gears and synchronizing rings, driving flanges, rear axle end flanges, differential side gears, pinion gears and differential ring gears. Most of these parts have already been successfully made as powder forgings on an experimental or pilot scale.

The following are some of the conclusions made:

(a) The elimination from hot-formed materials of oxide inclusions harmful to impact strength, fatigue strength and hardenability, although possible on a laboratory scale, still constitutes a problem on an industrial scale.

(b) Major efforts are required by equipment makers to find acceptable solutions to the problems of heating and handling of preforms.

(c) The economic feasibility of powder forging some automotive parts depends strongly on the amount of subsequent machining costs that can be saved.

(d) In many cases, the competitiveness of powder forging with respect to conventional forging or casting depends on the price of steel billets or castings compared to the price of powder. The tendency for the price of billets and castings to increase faster than that of powder will favour powder forgings more and more.

327. Halter, Richard F. "Recent advances in the hot forming of P/M preforms", ibid, 137-152.

This paper reports on work conducted on three aspects of the powder forging process: lubrication, tool temperatures, and induction sintering.

The "ring compression test" was used for lubricant evaluation. Of the 37 lubricants evaluated, best lubrication was obtained with graphite-based materials. Acheson Delta 31 was rated the best. A mathematical analysis for the tooling-temperature distribution caused by the hot forming of simple shaped preforms was shown to be feasible. The surface temperature of the hot-forming tools instantaneously exceeded the tempering temperatures for most tool steels. These temperatures occur in production runs of preforms at 815°C (1500°F). There is a need for higher-temperature tooling materials for precision powder forging. A totally automatic induction sintering and forming system capable of high production is now feasible.

328. DiGiambattista, Vincent N. and Reilly, William E. "Pressureless process for manufacture of P/M preforms", ibid, 153-173.

Details are given of a new patented process for the compaction of superalloy and tool-steel powders to 99+% of theoretical density without the need for high temperature and pressure equipment such as hot-isostatic presses. The process is based upon the removal of all surface oxides and gas molecules which may be absorbed by a given particle of powder, with subsequent activation of the particle surfaces by heat and in the presence of an electron donor.

Minus 100-mesh superalloy powder is placed in a vacuum retort and saturated with a solution of boric acid in methanol. The mixture is heated to 425°C (800°F) under vacuum. After cooling, the powder is vibrated in a standard borosilicate pyrex glass container which is made to the configuration required for the preform. The container is vibrated under vacuum and then heated under vacuum to 425°C (800°F). While under vacuum, the pyrex container is sealed. The container is then heated by steps to 1230°C (2250°F) and held at that temperature for about 5 hr. The container is next cooled in air, which causes the pyrex glass to spall off, leaving a preform with a density of 99+% of theoretical. The powder preform is forged at 1150°C (2100°F), being reduced about 30%, to give a forged density of 100% theoretical.

Large-diameter René-95 billets produced by the process from Federal Mogul Powder have been evaluated by General Electric Co's. Flight Propulsion Division and found to conform to all class "B" physical and mechanical properties specifications at room and elevated temperatures. Billets of IN-100-X849 produced by the process are being evaluated by Pratt and Whitney Aircraft.

329. Eloff, P.C. and Wilcox, L.E. "Fatigue behavior of hot formed powder differential pinions", ibid, 213-233.

This paper describes development work undertaken to establish process guidelines for an integrated system to isostatically compact, induction sinter for 1 to 6 min at 1150 and 1290°C, and hot-forge powder preforms. The part chosen for production in this way, and subsequent evaluation, was an automotive differential pinion. Two prealloyed powders were used: Anchorsteel 4600V (1.67% Ni-0.46% Mo-0.18% Mn-balance Fe) and Anchorsteel 2000 (0.50% Ni-0.48% Mo-0.23% Mn-balance Fe). Graphite was mixed with the powder to give 0.15-0.20% C. Fatigue and impact tests were conducted on the actual forged part.

It was concluded that differential pinions having fatigue and impact behavior equal or superior to conventionally produced pinions can be made from metal powder by a process using isostatic compaction, short-cycle high-temperature sintering, and hot forging with sufficient metal flow to obtain full density. The data indicated that longer sintering times, up to 6 min, promoted more uniform fatigue lives. It was also concluded that the Anchorsteel 2000 Type of alloy shows definite promise for applications requiring high impact and fatigue resistance. This is especially important to the over-all economics of the powder metal forming process, since this type of alloy contains lower amounts of nickel than the 4600 Type and is therefore less costly.

330. Moyer, Kenneth H. "A comparison of deformed iron-carbon alloy powder preforms with commercial iron-carbon alloys", ibid, 235-254.

The object of this study was to determine the mechanical properties of cold-formed Fe-C alloy preforms compared to commercial steels, and to determine if embrittlement similar to that observed in hot-formed steel occurs also in cold-formed material. The powder used was atomized iron to which sufficient graphite was added to provide 0.4% combined carbon after processing.

Tensile specimens tested in the as-cold upset, re-sintered or quenched and tempered condition had strength properties and elongations similar to commercial 1040 steel. Impact strength of cold-upset mild steel powder preforms was lower than that of commercial mild steels, because a continuous carbide network was precipitated at the ferrite grain boundaries.

Upset powder preforms containing 0.2% or less carbon have room temperature impact strength similar to commercial mild steels with the same carbon content. When carbon content was greater than 0.2% however, the room temperature impact strength was less than for commercial mild steels with the same carbon addition.

331. Badia, F.A., Heck, F.W. and Tundermann, J.H. "Effect of compositional and processing variations on the properties of hot-formed mixed elemental P/M Ni steels", ibid, 255-284.

Nickel additions, particularly in the 2-3% range, have a beneficial effect on the mechanical properties of mixed-elemental, hot-forged steel powders containing 0.2-0.35% C and ≤0.25% Mo. Higher sintering temperatures are beneficial to properties because of homogenization, but a sintering temperature of 1120°C (2050°F) appears adequate if sulphur and phosphorus contents are kept to low levels (50 ppm or less). The hot forming of mixed-elemental nickel-steel preforms to practically full density (≥7.81 g/cm^3) is readily done at forming temperatures of 815-1040°C (1500-1900°F). The forming loads required for a mixed-elemental 4600 Type steel are about 14-31% less than for its commercial prealloy counterpart. Dies heated to about 260°C (500°F) are beneficial in that they allow increased metal flow and greater toughness. A high degree of metal flow is desirable in improving toughness.

332. Lindskog, Per, and Grek, Sven-Erik. "Reduction of oxide inclusions in powder preforms prior to hot forming", ibid, 285-301.

The presence of oxides in porous sintered steels is not serious because the porosity is much more harmful than the inclusions. However, oxides can seriously lower the mechanical properties of dense material and so must be minimized or avoided in forging preforms. The oxidation problem in powder forging has limited the range of alloying elements to those that have a low affinity for oxygen, for example, nickel. Unfortunately, these elements are expensive and it would be a significant advantage if less expensive elements, such as manganese and chromium, could be used instead. This paper discusses how oxide inclusions in atomized, prealloyed powder can be reduced during sintering. The alloys investigated contained various amounts of nickel, molybdenum, manganese, chromium, carbon and oxygen.

It was found that with high enough sintering temperature, 1100-1300°C (2010-2370°F), and available carbon, oxidation could be prevented and oxides reduced, even MnO and Cr_2O_3. There was no significant variation of tensile strength, yield strength and elongation with oxygen content but reduction of area and impact strength were lowered as oxygen content increased. Hardenability was also adversely affected with increasing oxygen content because manganese and chromium present as oxides do not contribute to hardenability.

333. Mocarski, S. "Influence of process variables on properties of mod. 8600 and manganese-nickel-molybdenum low-alloy hot-formed P/M steels", ibid, 303-321.

The properties of Ford MDO-101 (0.35% Mn-0.45% Ni-0.60% Mo-balance Fe) and modified 8600 (0.4% Cr-0.4% Ni-0.4% Mo-balance Fe) prealloyed powders were determined using different sintering conditions and forging with and without lateral flow. The carbon was added as graphite powder, in the range of 0.2 to 0.5%. It was concluded that oxygen adversely affects hardenability, ductility and impact strength. High-temperature sintering at 1205-1230°C (2200-2250°F) in low-oxygen-potential atmospheres results in excellent mechanical properties and provides maximum hardenability. The chromium oxide in modified 8600 preforms and some manganese oxide in MDO-101 are apparently reduced at temperatures of 1230°C (2250°F) to chromium and manganese in solution, thereby increasing hardenability. If the highest levels of tensile properties and impact strength are desired, high-temperature sintering might be economically justified. Where parts are for use in applications not requiring high impact strength, powder preforms hot formed without any sintering could probably provide adequate service performance.

334. Morimoto, K., Ogata, K., Yamamura, T., Yukawa, T., Saga, T., Yamada, N. and Sekiguchi, N. "Transmission spur gear by powder forging", ibid, 323-339.

A transmission spur gear for motorcycles was chosen for development work on powder forging for the following reasons:

(1) The gear has a complicated shape and if satisfactory results were obtained other types of gears could be made with less difficulty.

(2) The tolerance for motorcycle gears is not as close as automobile tolerances.

(3) An economic advantage for powder forging this kind of shape can be expected as compared with more conventional methods.

Prealloyed, atomized powder to the following composition was used: 1.86% Ni-0.42% Mo-balance Fe. An addition of 0.25% graphite was mixed into the powder.

The impact properties of the powder forging were found to be better than those of conventional wrought products. The fatigue properties of the powder forging were as good as those of the conventional product. The results showed that the powder-forging process was feasible for this application although it was considered that further work would be required to increase die life and to permit the use of smaller forging loads.

335. Donachie, S.J. "Low flow stress hot forming of ferrite", ibid, 341-358.

This paper deals with the forming response and mechanical properties of a prealloyed ferrous powder IN-0300 (<0.005% C-0.88% Ni-2.0% Cu-0.13% Mo-balance Fe). Comparison tests were carried out on a prealloyed, steel powder made to the composition of 4640 steel (1.7% Ni-0.25% Mo+0.4% C mixed in -balance Fe).

The IN-0300 steel powder can be hot formed at 815°C (1500°F) as readily as can conventional (4640) powders at 1040°C (1900°F). This should result in increased die life. The basis for the development of good low-temperature formability in IN-300 is to maintain a stable ferritic structure at temperatures in the range of 760-815°C (1400-1500°F). This is accomplished by achieving low carbon contents through the use of decarburizing atmospheres during preform preparation. It is anticipated that use of IN-0300 alloy will also reduce the degree of oxidation of the preform during transfer to the forming die. It is also expected that distortion will be eliminated and cost of post-forming heat treatment reduced by substitution of an age-hardening steel for steels strengthened by quenching and tempering.

336. Stockl, P. L. and Antes, H. W. "Formability of low alloy and plain carbon steel P/M preforms", ibid, 359-383.

A high-temperature torsion test was developed to evaluate the formability of P/M preforms. The materials tested included atomized iron with sufficient graphite added to yield 0.4% combined carbon, and two low-alloy steels (0.5% Ni-0.6% Mo and 1.8% Ni-0.5% Mo) with 0.2, 0.4 and 0.6% C.

The torsion tests revealed that formability of the carbon and low-alloy steel preforms increases as preform density, temperature and nickel content increase. Formability also increases slightly with increasing carbon content for austenitic material. Ni-Mo steels exhibit lower formability than plain iron for the same carbon level. Exposure of preforms to air decreases formability. Most of the loss of resistance to deformation, resulting from exposure oxidation, occurs within the first 30 sec of exposure.

337. Tsumuki, C., Niimi, I., Hasimoto, K., Suzuki, T., Inukai, T., Ushitani, K. and Yoshihara, O. "Connecting rods by P/M hot forging", ibid, 385-394. (See also: C. Tsumuki, et al. "In hot forging, iron powder may be the answer", Metal Progress, Vol. 104, No. 6, 96, 98, Nov. 1973.)

The authors point out that despite the extensive research and development work on powder forging in recent years, no company is actually using it in a mass-production line. The reason for this appears to be that companies have been trying to substitute alloy powder forgings for conventional forgings rather than develop powder forgings for the application. The following problems exist with alloy powder-forged parts: the types of prealloyed powder available on the market are limited and expensive; quality of prealloyed powder is unsatisfactory; it is difficult to case-harden these alloy powder-forged parts without distortion because the carbon content is not controlled accurately during sintering. The authors decided to study the possibility of applying the process to the production of connecting rods from plain carbon steel. The powder consisted of iron powder (reduced from mill scale) mixed with 3% Cu, 0.6% C and 0.3% S. The following results were obtained in a comparison with conventional forgings: hardenability about the same; machinability of powder product much superior; fatigue and tensile strength about the same; impact strength and elongation of powder product inferior. The powder forgings showed a reduction of about 30% in a manufacturing cost over conventional forgings. Plans were being made to apply the process to actual production.

338. Pietrocini, T.W. "Hot formed P/M-applications", ibid, 395-410.

This is a review of applications for powder forgings. Parts considered are gears, clutch components, hydraulic components, magnetic parts, fasteners and bearings.

Resistance to wear can be provided by parts having a density of 7.5 g/cm^3 through-hardened to 55 Rc. A molybdenum steel powder is preferred since it provides good hardenability. A typical composition would be 0.5% Mo-0.5% Ni-0.5% C-balance Fe.

Good impact resistance is attained in parts having a density of 7.8 g/cm^3. These are generally carburized to ensure a good combination of a wear-resistant surface with a tough core. A typical composition would be 0.5% Mo-2.0% Ni-0.25% C-balance Fe. However, composition and density do not in themselves result in good impact strength. Processing parameters are equally important.

339. Nakagawa, T., Amano, T. and Nagase, M. "Cold forging and extrusion of green metal powder", ibid, 411-422.

Simple forging tests were carried out on green compacts of iron and aluminum powders. Forging consisted of simple compression (upsetting) of a cylindrical green compact. Attempts were also made to cold-forge a green gear-shaped compact. No conclusions were drawn from the forging experiments, but it is obvious that the technique as reported in this article is not practicable.

340. Obara, Kunio, Nishino, Yoshio and Saito, Yuichi. "The cold forging of ferrous P/M preforms, ibid, 423-440. (See also: K. Obara, et al. "Cold forging shows promise with both iron and steel", Metal Progress, Vol. 104, No. 7, 81, 84, Dec. 1973.)

Although hot forging of powder preforms has resulted in mechanical properties superior to those of sintered products, some problems exist, such as comparatively low dimensional accuracy, rapid wear rate of dies, and somewhat low production rate. According to the authors, the most feasible way to solve these problems is by developing the cold forging process. An investigation was made of factors which affect the cold forgeability of ferrous preforms, such as powder properties, heat treatment after sintering and preform density.

Three kinds of iron powder were used: reduced mill scale, electrolytic and atomized. Steel preforms were also made from mixtures of reduced mill-scale powder with nickel, chromium, molybdenum and graphite powders, and from atomized steel powder.

It is concluded that cold forging of sintered iron preforms can be successfully carried out. The higher the density of the preform, the better the cold forgeability. A spheroidizing treatment of the sintered steel preforms greatly improves cold forgeability. A proper annealing treatment after cold forging the steel preforms gives high strength and sufficient ductility.

341. Hirschvogel, M. and Aldinger, F. "Hot forging of pure and coated beryllium powders", ibid, 441-455.

The two main factors that have delayed wide industrial application of beryllium are high production costs and relatively low ductility. The high amount of waste produced during fabrication is one reason for the high cost of beryllium parts, particularly if complex structures are required. Practically all beryllium produced today in any form is by P/M techniques, and the powder forging method should offer economic advantages.

Recent studies have shown that the ductility of beryllium can be increased by coating the powder with a ductile metal prior to forging at temperatures low enough to prevent formation of intermetallic compounds. Silver has been used for the purpose. The authors have compared the forging of beryllium with four beryllium-silver alloys made from coated powders. It is demonstrated that even relatively complex shapes can be produced by forging a differential pinion gear.

342. Hoefs, Ralph H. "Manufacturing and economic aspects of hammer forging of P/M preforms", ibid, 457-484.

A comprehensive assessment is made of the individual elements that constitute the P/M forging process in order to make a preliminary judgment of its technical and economic feasibility. P/M forging is defined as the substitution of P/M preforms for the bar stock as the raw material used in conventional closed-die forging. It is also pointed out that the process called P/M hot forming, or P/M hot re-pressing, is not being considered. These processes use punch-and-die type of tooling, which is completely different from the tooling for closed-die forging. P/M hot re-pressing turns out dimensionally precise parts, whereas P/M forged parts must be machined for dimensional precision, the same as conventionally forged parts.

The author concludes that there are no major obstacles to the establishment of a P/M forging industry in which P/M preforms are substituted for bar stock in forging. Know-how in preform design can be developed with a little experience. Properties of P/M forged parts are a function of the powders used and also of the processing cycles. P/M cold forging as well as P/M hot forging should be considered.

It is probable that P/M forging will start in the automotive industry and spread to the independent forge shops. The role of P/M fabricators will be to serve as the source of preforms, particularly to the smaller independent forge shops.

The cost analyses for P/M forging looks favourable.

343. Ferguson, B.L. and Lawley, A. "Impact properties of forged aluminum alloy preforms", ibid, 485-501.

The technology for forging aluminum alloy P/M preforms is new and incomplete. It is anticipated that P/M forging technology will integrate with areas utilizing aluminum P/M parts, with the important advantages that the higher property levels and reduced costs should greatly expand market potential. Primary potential applications for aluminum P/M forgings include gears, pistons, and connecting rods.

The preforms were made of a 601 AB blend of nominal composition: 0.25% Cu-0.6% Si-1.0% Mg-1.5% lubricant-balance Al. The preforms were 25.4-mm diameter by 25.4-mm height. They were sintered at 605°C for 30 min in a nitrogen atmosphere having a dew point of -40°C. Two levels of preform density were utilized, 80% and 90% of theoretical. The preforms were heated to 385°C for a minimum of 20 min in an open tube furnace and forged in uniaxial compression between flat dies. In order to achieve frictionless conditions, teflon sheet (0.13 mm thick) was placed between the preform and the upper and lower die faces.

Two sets of forgings were prepared - one with a range of 97.4% to 98.6% of theoretical density and the other from 93.6% to 99.1% of theoretical density. Forging rings were used in the latter case to control height strain.

The authors found that densification of 601 AB P/M preforms by hot forging gave an increase in impact strength. Relative impact values were higher in test pieces notched perpendicular to the forging direction than in test pieces notched parallel to the forging direction.

344. Buchovecky, K.E. and Hurst, A.L. "Fabrication and properties of cold-formed aluminum P/M parts". Modern Developments in Powder Metallurgy, ed. Henry H. Hausner and Walter E. Smith, Vol. 8, Ferrous P/M and Special Materials. Proc. 1973 Inter. Powder Metallurgy Conf. MPIF and APMI, 189-207, 1974.

This paper discusses parameters for cold-forming aluminum P/M alloys, relates forming variables to properties and examines cost-saving features for a specific application.

Sintered preforms of 201 AB, 202 AB, 601 AB and 602 AB P/M alloys were cold formed in closed dies to determine safe limits of height reduction and to establish the effect of cold working on densification and on resulting strengths in the as-forged temper and after different heat treatments. The alloys investigated were mixtures containing various amounts of Cu, Si and Mg.

Cold forming of precision P/M parts is a viable process. It offers a simple, flexible method of processing for producing finished P/M parts. The process can be readily automated. Production cost factors make cold forming of aluminum P/M parts competitive with those of small aluminum parts produced by other metalworking processes and with P/M parts produced from other base metals.

Applications for cold-formed aluminum P/M parts will be primarily those that require some feature of aluminum, such as light weight, corrosion resistance, electrical and thermal conductivity, good machinability and finishing. Currently, two prototype aluminum P/M connecting rods are being tested as replacements for cast 380 alloy connecting rods.

345. Swain, M.P. and Butera, E.L. "The market for aluminum P/M parts and forgings", ibid, 281-300.

Since the beginning of significant development activity in aluminum powder metallurgy, in the 1960's, there has been a need for detailed information on the market for aluminum P/M parts. The recent introduction of information on hot and cold deformation of aluminum P/M preforms has opened up a new area of potential applications to consider, based on the higher-strength levels now available with aluminum P/M parts. With several aluminum P/M parts now in commercial production, numerous case histories are available which provide actual cost comparison information and can be used to demonstrate the potential for aluminum powder metallurgy in specific markets.

Aluminum P/M forgings are in a unique position of providing strengths similar to wrought forgings, but at considerably lower costs. Aluminum powder metallurgy has progressed to a point where useful information on markets and applications for aluminum P/M parts and forgings can now be developed, based on actual production experience and operating cost data.

This is a very practical paper that gives costs and properties data.

346. Downey, C.L. and Kuhn, H.A. "Application of a forming limit concept to the design of powder preforms for forging", ASME Publ. No. 74-WA/Prod.-11, 5 p, 1974.

The soundness of the metallurgical structure and the associated strength of a forged powder preform material increase with increasing lateral flow during the forging process. Unconstrained lateral flow, however, enhances the possibility of fracture during deformation. A preform design technique is presented that provides the preform shape and dimensions for forging a part to full density with a sound metallurgical structure but without fracture. The basis of the approach is a forming limit concept developed previously for cold forming processes. Application of the technique is demonstrated through design of a preform for forging a pulley blank consisting of a flange, rim and hub in aluminum alloy 601 AB.

347. Gessinger, G.H. and Bomford, M.J. "Modern methods of powder metallurgical processing of superalloys". High-Temperature Materials in Gas Turbines. Proc. Symposium on high-temperature materials in gas turbines, Brown, Boveri & Co. Ltd., Baden, Switzerland, 1973. Published by Elsevier Scientific Publishing Co., Ed. by P.R. Sahm and M.O. Speidel, 345-382, 1974.
(See also: Ref. No. 295.)

Powder metallurgical processing of superalloys overcomes to a great extent the segregation inherent in their conventional cast and wrought counterparts. The advantages of powder metallurgical superalloys can include improved workability, a better balance of properties and a possibility of economic savings.

Forging is a technique which should enable the production of large-shaped bodies. Two advantages generally claimed for this technique are:

(a) superior mechanical properties resulting from metal flow and the development of preferred crystallographic texture, and

(b) low material losses since components can be produced which are closer to the final shape.

Forging has to be performed on sealed cans which is a limiting factor with regard to possible shapes. Due to the finer grain size of the material, the forging pressure for PM preforms is considerably lower than that for wrought material.

/sg

AUTHOR INDEX

SUBJECT INDEX

POWDERS

PRODUCTS (cont.)

PRODUCTS (cont.)

PROPERTIES

CANMET REPORTS

Recent CANMET reports presently available or soon to be released through Printing and Publishing, Supply and Services, Canada (addresses on inside front cover), or from CANMET Publication Office, 555 Booth Street, Ottawa, Ontario, K1A 0G1.

Les récents rapports de CANMET, qui sont présentement disponibles ou qui ce seront bientôt, peuvent être obtenus de la direction de l'Imprimerie et de l'Edition, Approvisionnements et Services, Canada (adresses au verso de la page couverture), ou du Bureau de Vente et distribution de CANMET, 555 rue Booth, Ottawa, Ontario, K1A 0G1.

76-20 The Director-General's Annual Review, Revue annuel du directeur général; Dr. D.F. Coates;
Cat. #M38-13/76-20, ISBN 0-660-00675-8; Price: $.75 Canada, $.90 other countries.

76-24 MINES MEMO 1976;
Cat. #M31-12/1976; Price: $2.00 Canada, $2.40 other countries.

76-25 Fly Ash for Use in Concrete Part 1 - A Critical Review of the Chemical, Physical and Possulamic Properties of Fly Ash; E.E. Berry;
Cat. #M38-13/76-25, ISBN 0-660-00689-8; Price: $2.25 Canada, $2.70 other countries.

76-28 Pilot Plant Thermal Hydrocracking of GCOS (Great Canadian Oil Sands) Bitumen: 1. The Effect of Heavy Oil Recycle on the Plant Operation; C.P. Khulbe, B.B. Pruden, J.M. Denis and W.H. Merrill;
Cat. #M38-13/76-28, ISBN 0-660-00690-1; Price: $1.75 Canada, $2.10 other countries.

76-29 Mining Technology in 1974; R.J.R. Welwood;
Cat. #M38-13/76-29, ISBN 0-660-00578-6; Price: $1.50 Canada, $1.80 other countries.

76-30 Heat of Reaction and Vaporization of Feed and Product in the Thermal Hydrocracking of Athabasca Bitumen; B.B. Pruden and J.M. Denis;
Cat. #M38-13/76-30, ISBN 0-660-00691-X; Price: $1.25 Canada, $1.50 other countries.

76-31 1976 Catalogue of CANMET Publications, Catalogue des publications de CANMET; Technology Information Division;
Cat. #M38-13/76-31, ISBN 0-660-00657-X; Price: $3.50 Canada, $4.20 other countries.

76-32 Effect of Thermal Hydrocracking on the Distribution of Compound-Types in Athabasca Bitumen; A.E. George, R.C. Banerjee, G.T. Smiley and H. Sawatzky;
Cat. #M38-13/76-32, ISBN 0-660-00652-9; Price: $.75 Canada, $.90 other countries.

76-33 Thermal Hydrocracking of Athabasca Bitumen Reduction of Reactor Fouling; B.B. Pruden, R.B. Logie, J.M. Denis and W.H. Merrill;
Cat. #M38-13/76-33, ISBN 0-660-00692-8; Price: $1.25 Canada, $1.50 other countries.

76-34 A Technical Review of Ore Dressing Investigations on Canadian Titaniferous Ores Conducted at CANMET from 1950 to 1975; D. Raicevic;
Cat. #M38-13/76-34, ISBN 0-660-00760-6; Price: $2.50 Canada, $3.00 other countries.

76-35 Preliminary Studies on the Denitrogenation of Distillates Obtained from Thermally-Hydrocracked Bitumen; R. Ranganathan, J.M. Denis and B.I. Parsons;
Cat. #M38-13/76-35, ISBN 0-660-00693-6; Price: $1.00 Canada, $1.20 other countries.

76-36 SY-2, SY-3 and MRG-1 Report on the Collaborative Analysis of Three Canadian Rock Samples for Use as Certified Reference Materials - Supplement 1; Sydney Abbey;
Cat. #M38-13/76-36, ISBN 0-660-00676-6; Price: $1.00 Canada, $1.20 other countries.

76-39 Technical Review of Ore Dressing Investigations on Canadian Chromite Ores Conducted at CANMET from 1918 to 1976; D. Raicevic;
Cat. #M38-13/76-39, ISBN 0-660-00759-2; Price: $1.75 Canada, $2.10 other countries.

76-40 Evaluation of Canadian Commercial Coals: Nova Scotia and New Brunswick - 1975; T.E. Tibbetts and W.J. Montgomery;
Cat. #M38-13/76-40, ISBN 0-660-00769-X; Price: $2.00 Canada, $2.40 other countries.

76-41 Evaluation of Canadian Commercial Coals: Saskatchewan, Alberta and British Columbia - 1975; T.E. Tibbetts;
Cat. #M38-13/76-41, ISBN 0-660-00770-3; Price: $2.00 Canada, $2.40 other countries.

76-42 Evaluation of Peat Samples as Part of a Peat Fuel Inventory in the Province of Newfoundland; T.E. Tibbetts;
Cat. #M38-13/76-42, ISBN 0-660-00771-1; Price: $1.25 Canada, $1.50 other countries.