Non-Ferrous Metals Casting, History and Forecast

Jerzy W. Meier
Ottawa, Canada

Department of Energy, Mines and Resources, Ottawa
August, 1970

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A Contribution to the History of Metals Casting

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Cover: "Early Mesopotamia and Iran", M.E.L. Mallowan; pub. McGraw-Hill Co., New York, 1965.

Cover:

Bronze casting of Sumerian King, probably Sargon of Agade (ca. 2370 BC) found at the ancient remains of Nineveh. The head shows typical Semitic characteristics of the Akkadian dynasty ruling in the 24th century BC. At present in the Iraq Museum in Baghdad.

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Foreword

In any study of the development of civilization, the adaptation of metals to man's use, for better or worse, is an essential component of the fabric of history. From primitive tools and adornments to computer parts and hardware for the space age, metals have contributed to the achievements of mankind's necessities and aspirations. It is, therefore, of great interest to trace the development of non-ferrous metals casting through the ages, since this is both a fascinating subject in itself, as well as the foundation of further progress in the future.

The author, Dr. J.W. Meier, has a long professional career of academic, industrial and research work in all phases of non-ferrous physical metallurgy, both in Europe and, for the last 29 years, in Canada. This background has prepared him particularly well to deal with the past and consider the future of non-ferrous metals casting.

Canada is a major producer of most non-ferrous metals—with the exception of tin—and they constitute an essential segment of the Canadian economy, especially in the field of foreign trade. The history of metals in North America is relatively brief and cannot be compared with that developed in the ancient civilizations of the Near East, Europe or the Orient.

Nevertheless, it is essential to establish the beginnings of our metallurgical past and to compile information on the early development of our metallurgical industries. A start has been made on iron castings*, and this should be followed up by a similar treatise on early non-ferrous castings. The present volume constitutes excellent background material for such a study.

John Convey,
Director,
Mines Branch

Ottawa, March 1970.

*Harry Miller: *Canada's Historic First Iron Castings* — Mines Branch Information Circular IC209 (December 1968).

Avant-propos

Dans toute étude de l'évolution de la civilisation, l'adaptation des métaux à l'usage de l'homme constitue, pour le mieux ou le pis, un élément essentiel de la trame de l'histoire. Des outils et ornements primitifs aux pièces d'ordinateur et au matériel de l'ère spatiale, les métaux ont contribué à répondre aux besoins et aux aspirations de l'humanité. Il est, par conséquent, très intéressant de retracer l'évolution du moulage des métaux non ferreux à travers les temps puisque c'est à la fois un sujet fascinant et un gage de vastes progrès futurs.

L'auteur, M. J.W. Meier, possède une longue expérience professionnelle dans l'enseignement, l'industrie et la recherche, embrassant toutes les phases de la métallurgie physique des métaux non ferreux; il a d'abord exercé en Europe, puis au Canada depuis 29 ans. Sa formation l'a particulièrement bien préparé à traiter du passé et à analyser l'avenir du moulage des métaux non ferreux.

Le Canada est un important producteur de métaux non ferreux (à l'exception de l'étain); ces métaux constituent un secteur essentiel de l'économie du pays, et surtout de son commerce extérieur. L'histoire des métaux en Amérique du Nord, relativement courte, ne peut être comparée à celle des civilisations anciennes du Proche-Orient, de l'Europe ou de l'Orient.

Néanmoins, il est essentiel de retracer nos premiers progrès dans le domaine de la métallurgie et de recueillir des renseignements sur les origines de nos industries métallurgiques. Une première étude a été effectuée sur le coulage de la fonte*, et elle devrait être suivie d'un traité semblable sur les débuts du coulage des métaux non ferreux. Le présent volume constitue une excellente documentation de base pour une telle étude.

John Convey,
Directeur,
Direction des mines.

Ottawa, mars 1970.

*Harry Miller: *Canada's Historic First Iron Castings,* Mines Branch Information Circular IC209 (décembre 1968).

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Abstract

The history of non-ferrous metals casting is reviewed, tracing the art of founding since the fifth millennium BC and illustrating the excellent achievements of early civilizations in moulding and casting. Ancient metallurgy was born in the Middle East and spread very early throughout Europe, the Far East and Africa. Independently, the art of casting was discovered by the pre-Columbian Indians in Middle and South America.

In Europe, the peak of artistic casting development was reached in Classical Greece. After the Middle Ages, when founding was confined mainly to the production of bells, guns and ornamental castings, came the Renaissance and the splendid castings of Cellini and other artist-founders.

The coming of the Industrial Age and the discovery of new metals, especially aluminum, magnesium, nickel and zinc, considerably increased the output of castings. The concept of internal casting quality was introduced and with it the need for adequate mechanical properties for proper performance. A brief account of present trends in "premium-quality" castings and some recent improvements in casting techniques is included.

Considerations of the future of non-ferrous metals are based on statistical surveys of growth figures of world outputs analyzed by geographical distribution, volume versus weight, price and per capita consumption. United States casting production figures illustrate the trend of shifting from sand casting to die casting.

The future of the non-ferrous castings industry depends on the consistent production of highest-quality castings, which can compete with wrought products and other competitive materials, as well as on further automation and mechanization of all foundry equipment and procedures, using mechanical robots and modern computers.

*Principal Metallurgist (Non-Ferrous Metals), Physical Metallurgy Division, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada. (Retired 31 March 1970).

Résumé

L'auteur passe en revue l'évolution de la coulée des métaux non ferreux, retrace l'art de la fonderie depuis le V^e millénaire avant J.-C. et analyse les excellentes réalisations des premières civilisations dans les domaines du moulage et de la coulée. La métallurgie antique a vu le jour au Moyen-Orient et s'est étendue très tôt à l'Europe, à l'Extrême-Orient et à l'Afrique. Les Indiens de l'ère précolombienne de l'Amérique centrale et de l'Amérique du Sud ont aussi découvert l'art de la fonderie.

En Europe, le moulage artistique des métaux a atteint son sommet dans la Grèce classique. Après le Moyen Âge, alors que la fonderie demeurait restreinte à la production de cloches, de canons et de pièces ornementales, vint la Renaissance et les superbes pièces coulées de Cellini et autres artistes fondeurs.

Avec l'ère industrielle et la découverte de nouveaux métaux, en particulier de l'aluminium, du magnésium, du nickel et du zinc, la production de pièces coulées a considérablement augmenté. La notion de qualité interne des pièces coulées a pris naissance et, avec elle, le besoin de propriétés mécaniques suffisantes pour obtenir les rendements désirés. L'auteur donne un bref compte rendu des tendances actuelles dans la fabrication des pièces coulées de première qualité et de quelques améliorations récentes dans les techniques de moulage.

Les hypothèses sur l'avenir des métaux non ferreux sont fondées sur des relevés statistiques des chiffres de croissance de la production mondiale analysés selon la répartition géographique, le volume en fonction du poids, le prix et la consommation par habitant. Les chiffres relatifs à la production de pièces coulées aux États-Unis montrent la tendance à substituer au moulage en sable le moulage sous pression.

L'avenir de l'industrie du moulage des métaux non ferreux dépend de la production uniforme de pièces coulées de la plus haute qualité susceptibles de concurrencer les produits ouvrés et autres matériaux compétitifs, ainsi que de l'automatisation et de la mécanisation perfectionnées de l'équipement et des techniques de fonderie, à l'aide de robots mécaniques et d'ordinateurs modernes.

*Métallurgiste principal (métaux non ferreux), Division de la métallurgie physique, Direction des mines, ministère de l'Énergie, des Mines et des Ressources, Ottawa, Canada.

Non-Ferrous Metals Casting, History and Forecast

Introduction

Most metallurgists consider themselves too busy to relax and enjoy the casual study of the history of metals and of casting, a history as ancient as the history of civilized man. It is a pity, because this history is not only merely interesting, it is fascinating reading. It seemed, therefore, that the invitation to present the Charles Edgar Hoyt Memorial Lecture* was an opportune occasion for a very short look at the beginnings of our metallurgical profession and at some future developments. This paper is an expanded version of the Hoyt Memorial Lecture, based on a broad literature survey as indicated in the appended list of sources and references.

It would, of course, be impossible to completely cover, in a presentation like this, as vast a subject as the whole history of non-ferrous metals or of their casting processes, and it would be at least as difficult to see very far into the future. Therefore, only some highlights are given to illustrate the theme. This paper cannot, of course, deal with all non-ferrous metals (there are some 74 of them), and has to be confined to the major metals used today.

This paper is divided into three parts: a short recapitulation of the past, exemplified by a number of outstanding castings of earlier times; a brief account or some recent trends, illustrated by a few statistics of present metal production and consumption; and some considerations of the future.

The list of sources from the literature, although it looks extensive, should not be considered complete; there are hundreds of other books and articles connected with the theme of this paper; only those are listed which were actually used by the author.

It is hoped that further study of archeological literature and examination of museum exhibits of castings from the ancient past will allow the author to elaborate on some of the more detailed aspects of early metallurgy (archeometallurgy) and primitive foundry techniques.

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*The 32nd Charles Edgar Hoyt Memorial Lecture was presented by the author at the 73rd Annual Meeting of the American Foundrymen's Society, held in Cincinnati, Ohio, on 7 May 1969 (publ.) *Trans. AFS* 77 (1969), pp. 97-112; *Modern Casting* 55 (June 1969), pp. 97-112)

Part 1
Past

Prehistory

Mankind is at least a million years old (13). Most of this immense stretch of time, in fact, some 99% of it, has been called the "food-gathering" phase. During this time, men or their man-like ancestors (hominids) relied for their living entirely on hunting, fishing, and collecting wild berries, nuts, roots and what other plant food they could find. In this nomadic and cave-dwelling period, men had to live in small groups, without permanent shelter, and had to be ready to follow wherever their food supply moved.

The history of man started when he began to *use* tools (e.g., naturally shaped stones); the next and most important evolutionary stage came when the primitive savage began to *make* tools by intentional shaping of stones, wood, bones or sea shells. The creature that certainly was modern man, *Homo sapiens*, first appeared between 30,000 and 40,000 years ago.

The second phase in man's history, called "food-producing", began when he discovered how to control his food supply by cultivating plants and breeding animals. In the Near East this happened only about 10,000 years ago and started the Neolithic (or New Stone) Age, which began the most important economic revolution in human history, the beginning of settled life and primary village-farming communities. Some 5,000 years later, urbanization followed, introducing religious and social organization of the people and all that we call civilization.

The third phase in man's history, called "industrialization", started only 200 years ago and is still progressing at an amazing and accelerating speed.

It should be noted that the above phases in the development of mankind were occurring in different geographic zones at different times. The neolithic revolution, which started the second phase, came in northern and western Europe and the Far East thousands of years later than in the Near East. There still are some primitive aborigines in out-of-the-way parts of the world who remain in the first, "food-gathering" phase. And there are billions of people in less-developed countries who have not yet entered the third phase, "industrialization".

So much for the background of prehistory.

It was at least 8,000 years ago that man first encountered metal*. This was still in the Neolithic (New Stone) Age, some time after he developed the earliest forms of agriculture, succeeded in domesticating some farm animals, and learned to make crude fully-fired pottery. It is believed that this first farming economy was developed in the uplands that fringe the Arabian, Syrian and Iranian deserts.

The first metals were all non-ferrous. Indeed, gold, copper, silver and lead were used for at least 4,000 years before the introduction of iron smelting.

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*According to Çambel and Braidwood (169) the earliest evidence of man's use of metal was recently found at Cayönü Tepesi in south-eastern Turkey: fragments of native copper tools, from just before 7000 BC, which were shaped by abrading and hammering.

Native Metals

Au ☉

Gold was the first metal to attract the attention of primitive man. Looking for stones suitable for making his crude weapons and household implements, he detected in the river gravel some shiny yellow nuggets. To his disappointment he found out that gold was too soft to be used for defence or as a tool; however, it was found to be malleable and could be easily hammered into various shapes, and serve as attractive ornaments and decorations. The yellow metal could be gathered from alluvial deposits in the beds of many mountain rivers throughout the ancient world. That gold was once essentially valueless in the eyes of primitive man, because it was not usable for the production of tools and weapons, is demonstrated by the fact that natives of Colombia used gold for fish hooks.

Cu ♀

When searching for gold, the prehistoric savage picked up other, larger lumps of dark stone, that when hammered looked like gold. Native *copper* is more difficult to recognize, because its surface is oxidized, but when scratched or rubbed it shows its characteristic reddish colour. When hammering native copper to make ornaments, man learned his first metallurgical lesson: hammered copper hardened and could, therefore, be sharpened into weapons and tools. At once the red "stone" became more useful than the yellow one.

Native copper had been used in the Near East since the seventh millennium BC. Later, about 5000-4000 BC, man discovered that native copper could be annealed (softened by heating) and made plastic; by subsequent hammering it could be formed into a much more extensive range of objects. The possibility of hammering two or three heated lumps into a single mass by forge-welding was also discovered, and so the first industrial metal was born. It is believed that hot working of copper—a most important discovery—was introduced in the Near East about 5000 BC.

Forging and, somewhat later, casting of metals, mark the beginning of the science known today as metallurgy.

Ag ☽

The third native metal to be discovered was *silver*, which, like gold, was at first useless and disregarded; gradually it was used for ornamental purposes. In the Near East silver was much scarcer than gold and, therefore, in the earliest times it was much higher priced; at one period, in Egypt, it had twice the value of gold. There was also a native alloy, called "electrum", which contained a mixture of gold and silver. It has been found in relative profusion in ancient remains, but always in smaller quantities than gold. The pale, whitish-yellow colour of electrum depended, of course, on the silver content of the alloy.

The era of the use of the three native metals, and some rather negligible amounts of meteoric iron, is sometimes called the "Chalcolithic" (Copper-Stone) period. During this time, man used the native metals in much the same way as he had used stones, bone or wood for many millennia; it seems that he looked at metals as a sort of malleable stone.

Copper Age

The real Metal Age did not begin until man learned, by accident, how to *cast* metals, that is to melt them and to pour the molten metal into moulds of prearranged shapes. How this happened nobody knows, but this event marks the birth of the casting industry and must be considered a major achievement in man's cultural development. This started the Copper Age, the earliest period of the Metal Age. In the Near East it happened some time during the fifth millennium BC, probably first in Mesopotamia, and shortly after that in Egypt.

It was, however, somewhat later that man discovered, probably around 4000 BC, how to obtain copper by *smelting* from its ores. According to Gowland (48) this occurred when he used, by chance, some copper ore (carbonate, oxide or both) to protect his campfire for the night, and discovered in the ashes the next morning some gleaming copper beads, which were reduced from the ore by the charcoal in the fire.

Aitchison (1) disputes this, claiming that neither the proper high temperature nor the necessary reducing atmosphere could be obtained in a primitive campfire. Coghlan (23) demonstrated that both proper temperature and reducing atmosphere is attainable in two-tier pottery furnaces which were already in use in the fifth millennium BC. He suggests that inadvertent leaving of malachite (copper carbonate) within the baking chamber of a pottery kiln could readily be explained because the ancient potters made regular use of this mineral as an ingredient in decorative glazes.

The availability of man-made copper drastically changed the supply of the hitherto rather scarce metal and made it possible to use it more generally for all kinds of weapons and implements. The development of smelting, even more so than simple fusion, marks one of the great turning points in the history of man, comparable to the discovery of artificially-produced fire. It seems probable that smelting was first practiced in the Trans-Caspian regions (today's northern Persia).

Pb ♄

Lead must have been known to man soon after he found silver, because these two metals are closely associated in nature. Although lead was known at a fairly early date, certainly about 3500 BC, no lead has been found in the earliest archeological remains. This is probably because its properties were of little value for prehistoric applications. During the late Bronze Age it became more important as an alloying addition to bronze.

Silver became more plentiful because it was recovered as a by-product in lead-smelting from galena (sulphide of lead), but its use was confined to ornaments and decorations. In the early excavations of Ur even tools, such as a saw, adzes and chisels, were found (97) made of gold, silver and electrum, but these were probably used as ornamental parts of the burial ensemble, because they would be unsuitable for practical service.

Bronze Age

Another important step forward in prehistoric metallurgical art was the discovery of *alloying* or blending materials. This started the Bronze Age. Alloying began, probably again by chance, either by smelting of some complex ore containing both copper and tin (which is very doubtful), or by the use of some tin ore mixed accidentally with the copper ore. The primitive metallurgist found that the resulting alloy was harder than pure copper, was easier to melt, and had a superior castability.

The production of bronze started very early. The Sumerians cast bronze products well before 3000 BC; somewhat later, the knowledge of bronze-founding spread to Egypt and subsequently to Europe and China. Bronze, of course, is a copper alloy to which tin has been added *intentionally*.

It should be understood that the various phases of the Stone and Metal Ages do not refer to definite calendar periods throughout the world, but were cultural development phases in each particular region or country; sometimes they overlapped. This can best be illustrated by the cultures of pre-Columbian America: the North American Indians were still living in the late Stone Age (perhaps, more exactly, in the Chalcolithic period); the Mexican Aztecs were already in the Copper; and the Incas of Peru had just entered the Bronze Age. In spite of the fact that the Iron Age in Europe, Asia and Africa had already existed for some 3,000 years, the American natives did not know iron until the European conquest. This is why it is so important to state the geographical region when discussing archeological periods.

The first bronze castings were made by the addition of tin ore (cassiterite or tin oxide) to copper ore when smelting. The tin content of such "bronzes" was, of course, low and very erratic; in most cases it would be difficult to call the alloy a true tin bronze. Much later, tin ore and charcoal were added during the melting of metallic copper, in order to obtain the desired alloy. The final phase in bronze-making was the addition of metallic tin (after reducing tin oxide with charcoal) to the metallic copper charge in the melting pot.

By 2000 BC, the alloy made by mixing one part of tin with nine parts of copper seemed to have become the standard bronze composition for castings. Actual analyses of bronze products found in ancient remains show an amazing regularity of chemical composition, in spite of the fact that no chemical controls existed. In antiquity the composition of bronzes was evaluated by tone, colour, hardness and castability (fluidity).

Copper deposits in the Middle East and in Europe were relatively small, by today's standards, but were large enough to meet the demands in pre-industrial times for weapons, tools, utensils and ornamental work.

There were sometimes difficulties in obtaining tin (or tin ore), and substitutes for tin were sought; lead was used in some regions, and in Hungary antimony bronzes were found containing up to 20% antimony. Analyses of some early Chinese bronzes show considerable amounts of lead present (25) in otherwise standard tin bronzes, probably because of the increase in fluidity, important in art work. Small amounts of various "impurities" or "modifiers" were found to improve the castability of copper and to increase its hardness slightly. In Egypt arsenic was found to play this rôle; in Germany, it was nickel; in India, zinc, and in some Central European countries, antimony. But copper so treated should not be considered as a bronze, since these additions—in many cases accidental—hardly amounted to one or two per cent of the composition.

Sn ♃

Tin ore (tinstone or cassiterite) was known very early, but *metallic tin* was not recognized as a separate metal for a considerable time. The Greeks considered it as "dirty silver", the Romans as a kind of lead (the Latin word "plumbum" means both lead and tin). It is believed that comparatively pure tin was first produced around 1500 BC, probably in northwestern Persia. During the later periods of antiquity, tin ore came mainly from Spain, the Danube basin and the British Isles.

Other alloys besides bronze were fortuitously produced. Examples were the Chinese alloys of "paitung" (our cupro-nickel) and "paktong" (our nickel silver or nickel brass). These came from a complex ore, found in the Yunnan province of China, containing both copper and nickel. To obtain a more pleasing colour the cupro-nickel was mixed with calamine (zinc carbonate ore). The earliest records of the use of cupro-nickel appear in the third century BC. In 235 BC, the King of Bactria (at present Russian Turkestan) issued coins that contained 78% Cu and 20% Ni; the alloy was probably imported from China*. Thus, these alloys were produced nearly 2,000 years before nickel was discovered as a separate metal.

The discovery of bronze was a great achievement, especially as an alloy having casting characteristics superior to any other metal or alloy. Although bronze is much harder than the previously used copper, it should be noted that Homer mentions that the warriors at Troy had to pause during their battles—to straighten their bronze swords!

Fe ♂

The Bronze Age in the Near East came to an end in the period 1400 to 1000 BC, when iron smelting became more generally known and the Iron Age began. This, of course, did not put an end to the use of bronze. Indeed, during the Iron Age bronze production increased at a greater rate than ever before.

The erection, in prehistoric times, of huge monoliths and of structures of large stones in Egypt and Middle America, for example, took place in a period when the use of iron and steel was unknown. The magnificent Maya culture in Guatemala and Yucatan was entirely neolithic and no metal tools were known. Stone was quarried, shaped, and sculptured with stone tools, made from either basalt or diorite (51). Megalithic monuments in northwestern Europe (e.g., Stonehenge in England (57)) and the more recent ones on Easter Island (Polynesia) were built without the use of any metal tools.

How the Egyptians built the pyramids remains largely a mystery to modern man. Recent archeological evidence shows that, even during the First Dynasty (about 3000 BC), they possessed excellent copper tools, including saws and chisels, which were capable of cutting any kind of limestone. The methods employed in the Pyramid Age for quarrying granite and other hard stones are still a subject of controversy (41).

Tubular copper drills and saws were aided by a wet abrasive material, such as moistened quartz sand (plentiful in Egypt), or emery powder (plentiful in the Aegean Islands). In prehistoric Tiryns (Greece, about 1500 BC) the cutting of hard stones was apparently done by a copper blade in which emery teeth were inserted, as evidenced by a fragment found in a saw-cut.

Early Casting Techniques

The campfire may be regarded as the first *metallurgical hearth* and the forerunner of today's sophisticated melting installations. The first step was to make a hole for the collection of the molten metal; this hole, sooner or later, was lined with fire-resisting clay;

*According to Wulff (168), native copper in the Anarak district of Persia contains varying amounts of nickel, in some cases up to 50%. Bactrian coins could, therefore, have been of Persian origin.

the clay would keep the metal clean. Later still, the hole in the floor of the hearth was enclosed by stones, which were arranged in the form of a wall, and so a primitive furnace evolved (80).

The primitive metallurgist soon noticed that the wind caused his fire to burn more freely, and thus the effect of *draft* was discovered. First, fans of tough grass or rushes may have been used; later the furnace was placed on the windward side of the hill and some kind of chimney was built by digging a trench in the hill slope. Finally, forced blast, first by blowpipes and then bellows, was introduced.

To transfer his molten metal from the campfire to the mould, the early foundryman—who already had considerable experience in making pottery—prepared *crucibles* of heat-resistant clay. The earliest crucibles were very small, resembling a large tea cup, but were large enough to hold the metal necessary for one small casting.

At first, there were no suitable tools for lifting the crucible out of the fire while the metal was still molten and, after cooling down, the metal had to be removed and shaped by hammering. Next, a pair of green sticks was put around the sides of the crucible and in this way the crucible with molten metal could be removed and the metal poured into the mould. *Tongs,* in the modern sense, were not known much before 1200 BC, although by 3000 BC, two bow-shaped copper or bronze rods had replaced the green sticks (1).

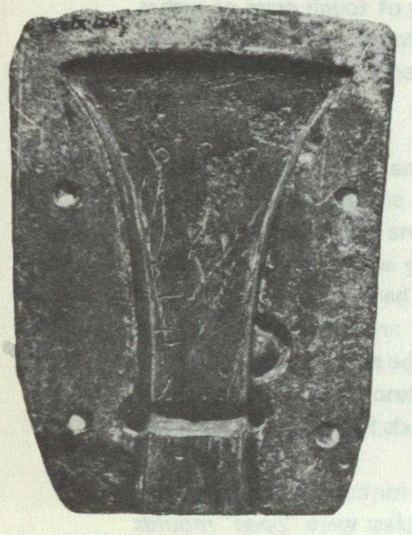
The next step of the early founders was to prepare *moulds* for casting their primitive products, mainly simple tools and weapons; the earliest and simplest were *"open" moulds* of sand or clay that roughly shaped one side of the artifact. The other side of the casting was left exposed and was flattened subsequently by hammering to complete the shaping. When many similar castings were to be made, the mould cavity was made in hard baked clay. Moulds carved in stone of uniform grain (schist, soapstone or fine-grained sandstone) were employed from very early times. After metal had been poured into these primitive permanent moulds, it cooled, the subsequent contraction leaving the metal intact. Usually all four surfaces of a stone were cut for different objects. This practice, of course, did not indicate a shortage of stone, but need of portability. Many bronzesmiths were itinerant and economy in weight was, therefore, important.

Figure 1.
Open stone mould for bronze axes

Figure 1 shows (120) such an open mould, used for casting bronze axes. It was found in Ireland and dates from the first half of the second millennium BC. The rough castings, before the cutting edges were hammered to harden them, were four inches wide at the broad end and one inch wide at the butt, the blade being about six inches long. The mould itself is two and three-quarters inches deep. This open stone mould is typical of those used in various regions throughout the earlier periods of antiquity.

The next improvement in casting techniques was the double cavity mould—the two halves of the object being joined after casting. Further refinement was achieved by closing the "open" mould by a movable flat cover (a flat stone) to prevent excessive oxidation of the cooling metal. The cover was so placed over the cavity before casting as to leave a space at one end into which metal could be poured.

The disadvantage of the "open" mould was that only very simple shapes could be cast, since any undercut would prevent the removal of the casting from the mould. They were used for a long time to cast coin-blanks and ingots for sheet-metal production.



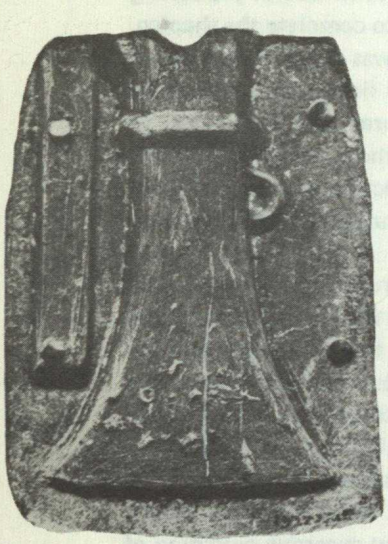


Figure 2. Two-piece closed stone mould for bronze axes

Sectional moulds (piece-moulds), made up of three or four pieces, had been used in Ur before 2600 BC. *Figure 2* shows (121) a two-piece mould, in mica schist. This was used in the middle bronze period for casting looped socketed axes. The mould was found in southern Scotland. Sectional moulds were first used tied together, but were later fitted together by dowels.

Piece-moulds were carved in stone or made in refractory clay. Clay moulds were prepared around a model, made of wood or clay, and carefully joined for proper fitting of all mould pieces. Metal piece-moulds were not used until much later; they had to be cast themselves in piece-moulds, generally of refractory clay.

Sectional moulds were generally made deeper than the intended casting; the additional height was to hold a small cup (sprue, gate) which was filled to avoid piping. Some moulds show also narrow channels (vents) for the displacement of air and gases, although normally the mould materials were porous enough and the mould sections ill-fitting enough to make this provision unnecessary (61).

The early founder discovered that if copper was cast in a closed mould it blistered and, therefore, became unserviceable; but when he began to add some tin or other modifying agents (Pb, Sb, As, Zn or Ni) much better castings resulted. Even today copper is considered a difficult metal to cast in the pure state; most of its alloys have much superior casting characteristics. But numerous cast copper products found in early excavations seem to show that it should have been quite within the ability of Copper Age foundrymen to make good pure metal castings in a closed mould. How many castings were discarded and remelted in this connection nobody knows—but this happens even today in some foundries having poor quality control!

For more complex or hollow shapes, piece-moulds with a "false core" were used, e.g., for socketed tools and weapons. The core was generally made of refractory clay, which was initially made to fill the whole space of the casting. The clay was then removed and pared down by the thickness of the metal required. Frequently the false core and the sprue-cup were made in one piece and channels (runners) for the metal were cut between the cup and the hollow of the mould (61).

Cored castings do not seem to have been made before about 2000 BC. Cores were made of clay and charcoal, or sand, and were sometimes strengthened and made more permeable with the aid of dry chopped straw, dung, or finely broken brick.

According to Hodges (122),

"In the casting of very complex shapes, such as statues, by means of the false core, the procedure was often somewhat different. The shape to be cast was first modelled in refractory clay, and onto this model was built up the piece-mould. If there were many undercuts the number of pieces might be so great as to demand a further outer mould piece, the mother-mould or case-mould, to hold them all in register. When the piece-mould was complete it was removed and the model pared down to provide the core. After the metal had been cast the core might be removed, but was more commonly left in place. The rough casting would, of course, carry a number of flashes corresponding to the interfaces of the various pieces of the mould, but in high-quality work these would all be removed in final planishing.

"An alternative and somewhat simpler method of producing complex castings was to use the lost-wax *(or cire perdue) method. Over a core of refractory clay the object to be cast was moulded in wax, the thickness of the wax corresponding to the thickness of the metal required; and over this a*

single outer mould of clay was built up, incorporating the sprue cup and any runners, risers or vents needed. The whole was then heated and the wax allowed to run out, so providing the space into which the metal was ultimately to be cast. The core, however, needed to be held in register, or, once the wax was melted, it would inevitably shift, and to achieve this the core usually incorporated a number of protruding rods or wires of metal, the chaplets, the free ends of which became embedded in the other mould. Being usually of the same metal as the casting, the chaplets ultimately became incorporated in it, the protruding ends being removed. The mould, of course, had to be broken away in order to get at the casting and hence could not be re-used, while the core was sometimes left in place. In most high-quality work, however, a space was left through which the core could be raked out.

"Very similar hollow castings could be produced by both the false-core and lost-wax methods, and while the presence of residual flashes on the one hand and chaplets on the other are indicative of the two processes, these have generally been removed. A very great disservice can be done to the study of the history of technology by assuming that either method of casting was used without any genuine evidence. The observation that an object appears to have been modelled in wax, for example, is a subjective one that has no real validity, and a far more critical examination should be made before any final conclusion is drawn."*

The lost-wax process had been invented by the Sumerians early in the third millennium BC; the Egyptians learned to use it about 2500 BC. The lost-wax process was used, generally, for castings of intricate shapes which would be difficult to mould in sand or carve in stone, and also for hollow vessels, but in many cases the process was used simply to save costly metal, because much thinner walls could be produced. Understandably, this method could be applied only in making relatively small castings. The lost-wax process was quite recently "rediscovered" and is used today not only by jewellers but also in the manufacture of gas turbine blades and many other modern products of refractory metals.

The normal *pattern* material for clay moulds was wood. However, evidence exists showing that sometimes lead was used as a pattern material; in these cases, lead patterns were cast in bronze moulds.

Early Castings

Following this very sketchy review of the earliest metals and casting methods, the development of castings is illustrated by discussing some of the more famous examples of the ancient art of casting.

Today's foundrymen might assume that castings produced by their early predecessors in the past 6,000 years of metallurgical history left much to be desired from the quality point of view. As is seen in the illustrations that follow, they would be wrong.

Bronze was, in ancient times, the major material for castings, both for works of art and for countless utilitarian applications. Unfortunately, metal possesses the disadvantage

*See also the findings of N. Barnard (9) noted in the discussion of ancient Chinese bronze vessels, p. 14.

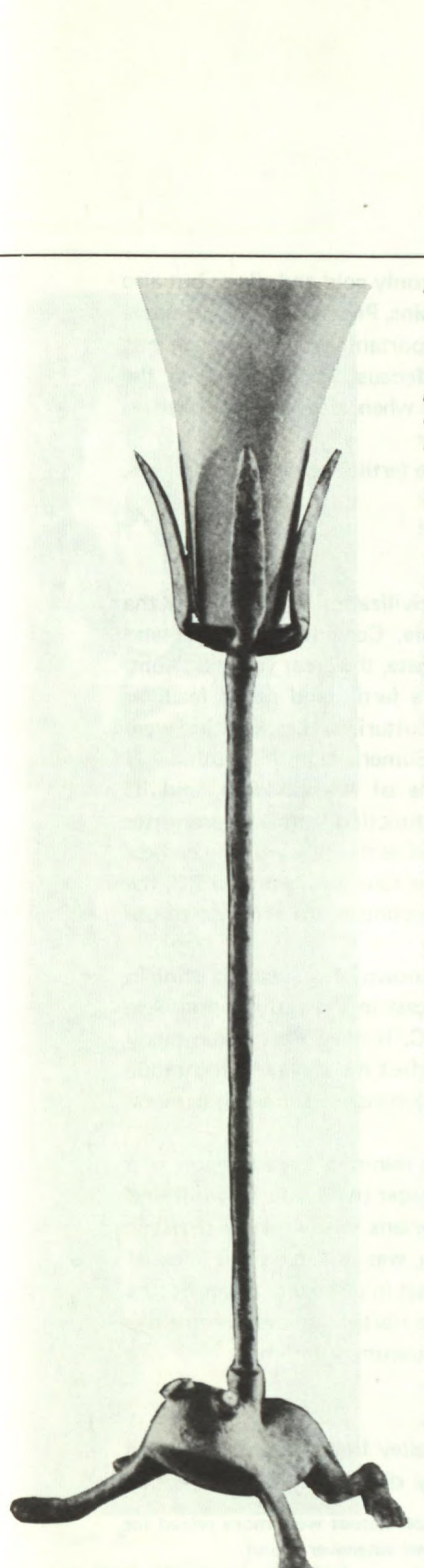


Figure 3.
Copper cup holder, oldest known casting (ca. 3200 BC)

Figure 4.
Cast silver rein-ring from Ur (ca. 3000 BC)

that it can be melted down and used again*. This is why not only gold and silver, but also bronze, objects are comparatively rare in archeological remains. Phoenician traders drove a thriving business in scrap-bronze, and many of the important bronzes, which had survived from the ancient world, were melted in the holocaust which followed the capture of Constantinople by the Crusaders in AD 1204, when statues were piled in churches to await consignment to the foundry (82).

The three most ancient urban civilizations emerged in the fertile basins of great rivers, the Tigris-Euphrates, the Nile and the Indus.

Sumerian Heritage

According to available archeological evidence, the oldest civilization originated in the valley system of the Tigris and Euphrates in Mesopotamia. Considerable effort and planning were necessary to clear and drain, and later to irrigate, the great valley bottom, but once brought under cultivation these flood plains were fertile and could feed far greater numbers than the upland fields of the early agriculturists. Large cities were erected in the valley; the most powerful were created by the Sumerians in the south.

The Euphrates thoroughfare has been the very life-line of Mesopotamia, and its ancient name Uruttu or Urudu, "copper" river, signifies its function both as transmitter of the raw material from the northern hills of Asia Minor and as the valley of the earliest Sumerian copper-smiths (74c). Excavations show that, by the fourth millennium BC, the Sumerians were already well acquainted with metals and casting, were the first to use bronze and invented the lost-wax technique of casting.

Figure 3 shows (123) what is believed to be the oldest known casting still existing in the world. This copper cup holder, shaped like a frog, was cast in the early Copper Age by the Sumerians in Mesopotamia, probably about 3200 BC. It must have taken many centuries of experimentation before primitive man could perfect the tools and technique to make a casting of this complexity; the competent workmanship shows that metal casting was already well established.

Figure 4 depicts (124) a casting of the same era, a silver rein-ring from the pole of a chariot** of Queen Shub-ad, with a "mascot" figure of an onager (wild ass). It was found at Ur in southern Mesopotamia (97) and cast by the Sumerians in their early dynastic period (ca. 3000 BC). The rein-ring, five and a half inches high, was cast in a silver alloy of 93.5% Ag and 6.1% Cu, while the figure of the donkey was cast in electrum. Silver occurs rather rarely in Sumerian findings and probably came from the northern mountains of this part of southwestern Asia. The casting is now in the British Museum, London.

Land of the Pharaohs

The ideas of civilization may have been brought to the Nile valley from Mesopotamia, but they matured very fast and soon assumed their own highly distinctive form. Egyptian

*For a long time after the decay of the ancient civilizations, bronze statues were more prized for their metal than for their aesthetic value and hence were melted down whenever found.

**Chariotry using wild asses was introduced by the Sumerians and inspired an almost superstitious terror in their enemies. Horses were, at that time, not known in the Middle East.

civilization as a whole was as unlike Sumerian as hierogliphic was unlike cuneiform writing (56).

There is abundant evidence to show that Egypt was the first in the field of artistic bronze casting, and objects produced at least as early as the third millennium BC are in existence. Most prominent also were many castings in precious metals, some of them on a very large scale, such as the two obelisks (40) made of electrum (a native gold and silver alloy). They weigh 40 tons each and were erected by Pharaoh Tutmosis III (1501-1447 BC) at Karnak. They were removed by the Assyrian King Ashurbanipal as war booty after he sacked Thebes in 661 BC.

Another Egyptian gold casting is shown in *Figure 5* (125). This is the inner coffin of Tutankhamen, who died around 1350 BC (40). According to Aitchison (125), the coffin (about one-eighth in. thick, weighing 242 lb) was cast in solid gold and then finished by tooling. It provides a life-size portrait effigy of the young pharaoh and is a magnificent example of the high technical skill and art appreciation of the goldsmiths of 3,300 years ago.

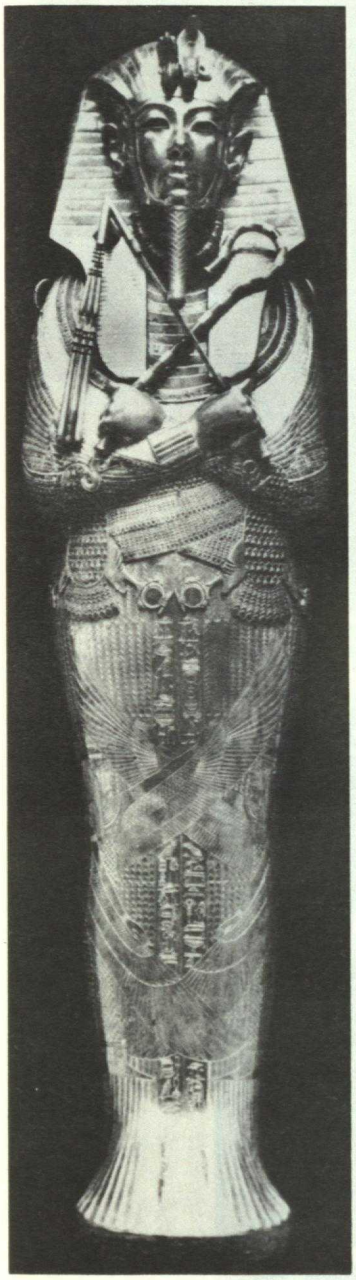


Figure 5.
Cast gold coffin of Pharaoh Tutankhaman (ca. 1350 BC)

Indian Subcontinent

By the middle of the third millennium BC another great river valley, the Indus, became the seat of a highly developed civilization, brought eastwards from Mesopotamia. The earliest settlements, from the fourth millennium BC, were found in the northwest, in Baluchistan and Sind. The "Indus Valley Civilization", with its great urban centres in Harappa and Mohenjo-daro, flourished for about a thousand years before it collapsed, around 1500 BC, under invasion by the Aryans, descendants of Indo-Europeans from the region of the Caspian Sea and southern Russian steppes.

The ancient bronzes of the Indus Valley reveal an excellent knowledge of metalworking, and the skill of the Indian people as bronzeworkers has survived until the present day in villages, where the casting of statuettes is still a village craft (82).

The "Ganges Civilization" was the second phase of Indian development in the late Bronze Age (1000-500 BC) and early Iron Age (after 500 BC), based on the two-river country of the Ganges-Jamuna rivers called the Doab. The Aryan invaders came in chariots, which is evidence of a fairly high level of metalworking, to be found among most nomadic tribes of the time, and they used bronze swords and other weapons. Little has survived from this period, however (82).

Figure 6 shows the "Dancing Girl", the earliest known Indian bronze figurine. This remarkable statuette was found in the excavation of Mohenjo-daro and was cast in the third millennium BC, probably by the lost-wax process. The casting, four and a half inches high, is in the National Museum of India, New Delhi (77).

Chinese Bronzes

The Chinese traditionally believe that metal and metallurgical techniques came from the West. To understand certain parallels in the development of early alloying and casting methods used in the Near East and in distant China, it should be realized that there were

Figure 6.
Dancing girl, the earliest Indian bronze figure (3rd millennium BC)

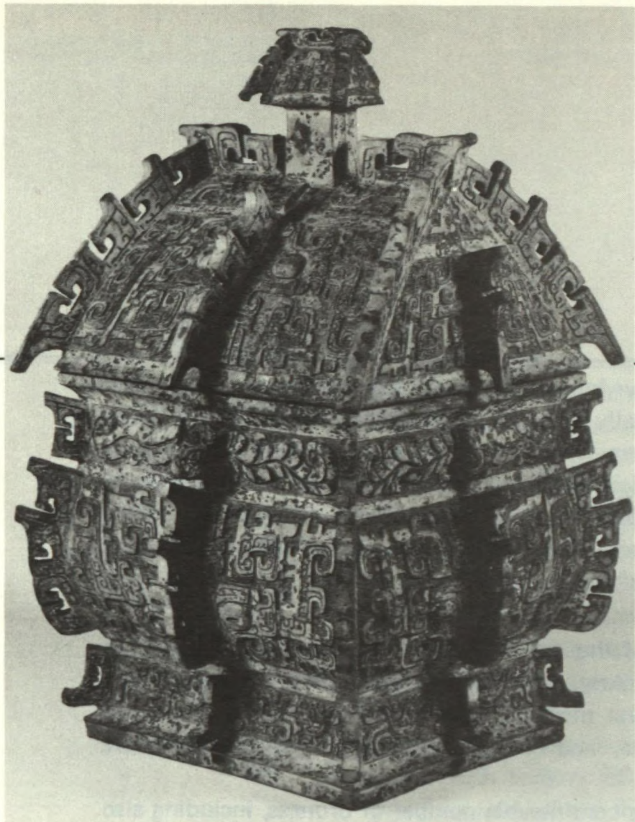


Figure 7.
Ancient Chinese bronze casting (11th century BC)

two fairly easy trade routes, one through Lake Balkash and the Altai mountains, and the other through Turkestan and Tarim.

The great Central Plain was the cradle of the Chinese civilization. Again, as in Mesopotamia, Egypt and India, it was a river-valley civilization created in the lower course of the Yellow River. Here arose the high Bronze Age culture of the Shang period.

The Chinese entered the Bronze Age much later than the Middle East countries, probably in the second half of the third millennium BC. In China an advanced bronze technique appears to have sprung up unheralded by a related, more primitive stage. It seems that bronze technology, introduced from western Asia, was absorbed at once and used to produce castings of refined form and elaborate ornament. Metallurgical knowledge came from the West, but the artistry and technical skill are wholly Chinese.

The art of the Shang (1523-1027 BC) and Chou (1027-249 BC) dynasties finds its fullest expression in the bronze vessels. They are hardly to be matched for beauty of form and skill of execution by castings of any other time or place in the ancient world.

The bronze alloys used differ from western compositions, not only by greatly varying tin contents, but also by considerable additions of lead; the lead was added to improve the castability of the alloy and to obtain better detail of fine ornaments. The beautiful green and blue patination, highly prized by western collectors, was acquired when buried for centuries in the soil.

Figure 7 (126) illustrates one of the famous Chinese bronze castings. This is a temple-shaped ritual wine vessel from the late Shang dynasty period (probably from the eleventh century BC) and has a 188-character inscription recounting sacrifices offered to gain victory. The bronze vessel is at present in the Freer Gallery, Smithsonian Institution, Washington, D.C.

Until recently, it was thought that all the exquisite bronze vessels from the Shang and Chou periods were cast by the lost-wax process. The fine surface conditions and the difficulty of observing any joins on the complicated shapes of the castings led to this belief.

Recently N. Barnard in his very interesting book (9) claims that thorough examination of hundreds of archeologically documented bronze castings from the Shang and Chou eras revealed that all of them were cast in piece-mould assemblies formed around baked clay vessel-models. He claims that the lost-wax method was unknown in China before the Han dynasty period (206 BC - AD 220), because no bronze cast by the lost-wax method has yet been unearthed under scientific excavation from any pre-Han site. He presumes that the lost-wax technique was introduced from India, some time between 200 BC and AD 300.

Additional archeological evidence of the use of sectional moulds was established in the comparatively recent excavations at Anyang, the oldest of the Shang capitals and an important foundry centre, where several model fragments admidst a pile of broken moulds were found; all are made of clay and during the process of construction were fired.

In his book, N. Barnard examines a considerable number of bronzes, including also the wine vessel casting shown in Figure 7, and shows how the mould pieces were arranged and the ingenious way of cunningly concealing the joins of piece-moulds. He also suggests that such evidence exposes later counterfeits of early bronze vessels, because, according to him, authentic antique castings could not have been made by the lost-wax method.

Another hypothesis of Mr. Barnard appears to be less credible, and without real evidence: he believes that the art of bronze casting was independently discovered in China and not through any contemporary Western influences.

Aegean Culture

European civilization was born in the Aegean area. As early as the third millennium BC, Crete entered the Bronze Age and became the seat of the brilliant *Minoan* culture, which spread to the Greek mainland and throughout the Aegean isles to the western shores of Asia Minor. At the height of Minoan expansion (1580-1480 BC) its metropolis at Knossos* became the centre of an international power, the first in Europe, and held virtual control of trade in the eastern Mediterranean. Around the middle of the 15th century BC, Crete suffered a destructive blow, one of the mysteries of ancient history which may never be solved**, and in a relatively short time the Minoan culture collapsed and was overtaken by the Achaeans in southern Greece.

Around 2000 BC the original, non-Greek, neolithic tribes of the Greece mainland were overrun, in a number of waves, by barbaric Indo-European invaders from the North,

*Knossos was the first large city of Europe with an estimated 80,000 population in the 15th century BC.

**It is now believed that the cause of the destruction of the Minoan civilization was the enormous volcanic eruption, about 1450 BC, on the island of Thera (Santorin), some 70 miles off the north coast of Crete. Recent publications (171, 172) on this event also explain, quite convincingly, the ancient legend of "The lost continent of Atlantis", first told by the Greek philosopher Plato (427-347 BC). Velikovsky (174) claims that this and many other cataclysms which occurred in the middle of the second millennium BC, were caused by a near-collision of the comet Venus (which later became a planet) with the earth.

the Greek-speaking Achaeans. After they settled, they created their own culture, called after their most important city-state *Mycenaean,* based generally on the earlier Minoan model. The Achaeans who took over Crete about 1450 BC, inherited the wealth of the old Minoan empire and became the leading marine power in the Mediterranean with colonies from the Syrian coast to Italy. This was the legendary "pre-Hellenic" history of Greece, the heroic world of Homeric epics, the Iliad and Odyssey (the legendary battles at Troy are dated at about 1200 BC).

The brilliant Aegean Bronze Age came to an end shortly before 1000 BC with the complete destruction of all Mycenaean centres by the barbaric Dorian invaders from the north. The Dark Ages of Greece (1100-700 BC) followed, when even the art of writing was lost.

Figure 8 shows a Minoan statuette of a bull and an acrobat, cast in solid bronze in the 16th century BC in Crete, now in the British Museum, London. The sculpture depicts a scene from the dangerous "bull-leaping" sport, a famous pastime of Minoan Crete, probably connected with a religious cult, in which acrobatic athletes vaulted between the horns of the bull, turned a somersault and vaulted off over his tail. The representation of violent movement, both of the animal and of the acrobat, is unequalled in ancient art (60).

Figure 8. Bull and acrobat, Minoan bronze (16th century BC)

Figure 9. Capitoline wolf (6th century BC)

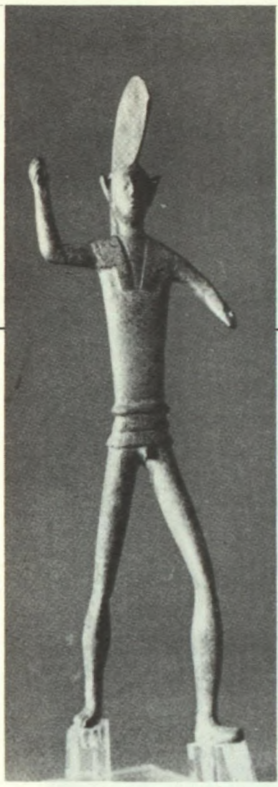
The bronze is a small masterpiece of ingenuity and its casting must have been extremely difficult and elaborate, because the "lost-wax" technique was not known to the Minoans (18). The technical feat of showing the acrobat, who is in the middle of a somersault, having let go the horns in order to land with his feet on the bull's neck, has been achieved by the use of his long hair as a support of the acrobat's head. It seems that this bronze was not cast using a double mould, because there is no ridge marking the join and the Minoans never eliminated such detail (65), leaving the castings rough and untouched, as they came from the mould.

Etruscan Sculpture

Next, the Etruscans should be mentioned; a mysterious people living during the first millennium BC in Italy, between the Tiber and the Arno, to the north of Rome, whose non-Indo-European language is still a puzzle to archeologists. The brilliant peak of their culture (600-475 BC) came when Rome was still a primitive town of wattle-and-daub huts and whose civilization they were to influence profoundly.

Etruria's wealth came from her copper and iron mines. Etruscans were known as excellent bronze-founders and metalworkers; they excelled in fine large-scale bronze work, like the famous Chimaera of Arezzo or the Capitoline Wolf, but their minor masterpieces in bronze deserve mention also, especially the statuettes whose attenuated bodies appeal strongly to modern taste (68).

Figure 9 depicts the "Capitoline Wolf", an Etruscan bronze from the sixth century BC. The figures of the twins are thought to be a Renaissance addition, although some ancient medals show the figures of Romulus and Remus, the legendary founders of



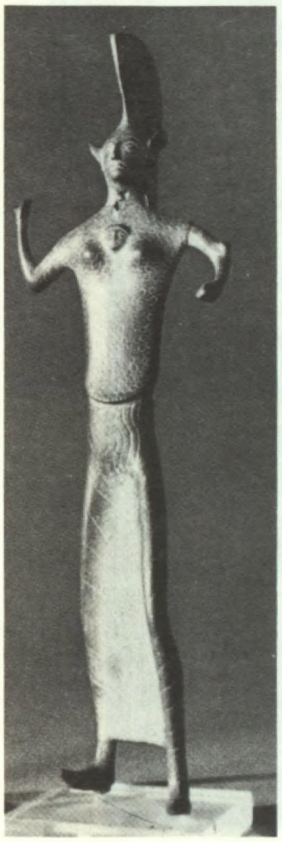


Figure 10.
Etruscan bronze figures (5th century BC)

Rome. It is possible that the original figures of the twins disappeared over the centuries and had to be replaced.

Figure 10 (79) shows two Etruscan bronze figures from the fifth century BC; at the top, a warrior; at the bottom, the goddess Athena. The elongated form of these figures shows the characteristic influence of the geometric period of early Greek art.

Classical Greece

After the cultural twilight which followed the invasion of Greece and Crete by the barbaric Dorians, the ancestors of the "classical" Greeks and those of today, and after the considerable progress during the Archaic period (700-500 BC), came the golden age of Greek arts and crafts. Classical Greek bronze sculptures of the fifth and fourth centuries BC have never been surpassed. Unfortunately, only comparatively few of these bronzes escaped the many centuries of destruction by remelting for cannons or church bells. They show the incomparable genius of their creators–Phidias, Myron, Polyclitus, Praxiteles, Lissipus or Scopus, to name only the greatest–and are still admired throughout the world.

One of the most famous works was Phidias' towering statue of Athena, entirely of gold and ivory, which stood 40 feet high, in the inner sanctuary of the Parthenon in Athens. Lissipus, the favourite sculptor of Alexander the Great, made the enormous number of 1,500 statues, nearly all in bronze; unfortunately, none of them remain, although many are known from coins (86).

To illustrate the incomparable art and the excellent foundry skill of Classical Greece, the following examples of the small number of authentic original large bronzes are reviewed, two in the "severe style" of the Early Classical period (500-450 BC) and the others from the less-rigid Hellenistic period (323-31 BC):

Figure 11 (10) shows the Charioteer of Delphi, a bronze cast about 470 BC, at present in the Museum of Delphi. Only the figure of the charioteer survives of a bronze chariot with four horses offered to the sanctuary of Delphi by Polyzalus, the tyrant of Gela, to commemorate his victory at the Pythian Games of 474 BC. The statue, about six feet high, was cast by the lost-wax process in seven parts–head, torso, lower half and the four limbs–and the joints concealed by edges of drapery.

Figure 12 depicts "Zeus" of Artemisium (archeologists have still to agree if this is Zeus hurling a thunderbolt, or Poseidon throwing his deadly trident). This superb bronze figure was found in the sea off Cape Artemisium, is over life-size (almost seven feet high) and probably a later work of the renowned and prolific sculptor Onatas from Aegina. It was cast about 460 BC and is now in the National Museum in Athens. The statue is an excellent example of great art and also of extraordinary skill of the foundryman.

Figure 13 shows the statue of a Hellenistic Prince, from a much later period in Greek art. This powerful bronze figure, almost eight feet high, was cast about 160 BC and is at present in the Museo delle Terme in Rome. It seems that it was inspired by Lissipus' lost statue of Alexander the Great bearing a lance. The subject is probably Demetrius I Soter, King of Syria (162-150 BC).

Figure 11. Charioteer of Delphi (ca. 470 BC)

Figure 14 presents the bronze statue of the Seated Boxer, which bears the signature of the sculptor Apollonius of Athens, and was cast probably in the first century BC. The statue is somewhat over four feet high and is now in the Museo delle Terme in Rome. It seems that this sculpture had been made for some Roman patron and shows the brutal gladiatoral figure from the Roman amphitheatre: the head is that of a professional boxer, face scarred, nose flattened, cauliflower ears and knocked-out front teeth. The casting of this statue must have been quite difficult.

Unfortunately, the rather voluminous literature on Greek sculpture is mainly focussed on the artistic values of the bronzes and sometimes on their historical or cultural background. Very little is reported on the casting methods used, the foundry equipment, moulding materials and preparation, or finishing procedures. It is known that the lost-wax process was used extensively, but older castings—especially of larger size—show that they

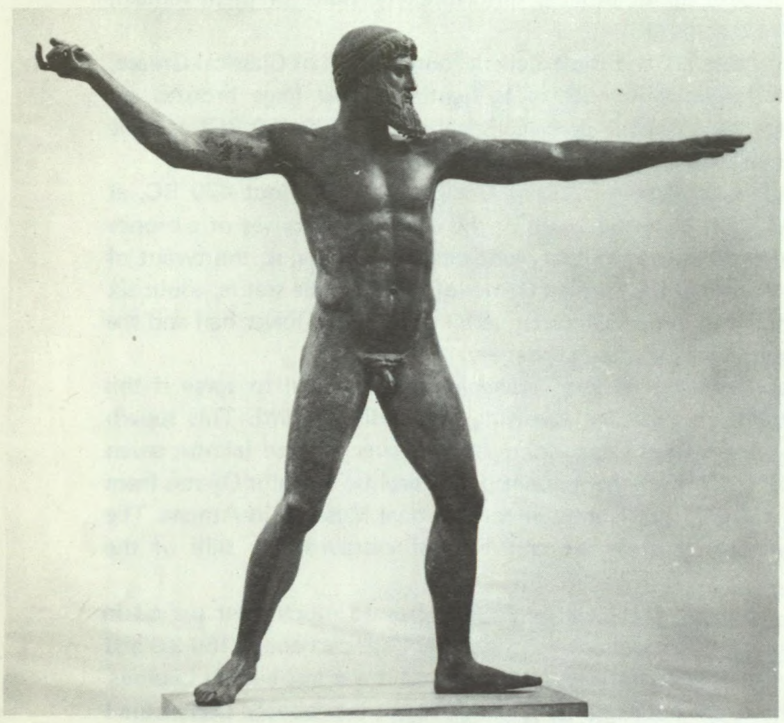


Figure 12. Zeus of Artemisium (ca. 460 BC)

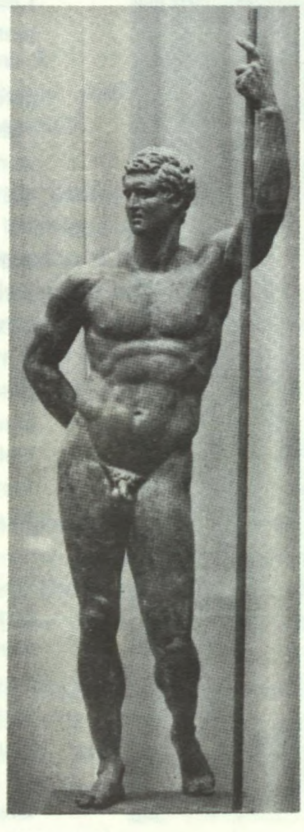


Figure 13 Hellenistic prince (ca. 160 BC)

Figure 14.
Seated boxer (1st century BC)

were made by the use of wooden models, sand or clay moulds, and clay cores. S. Casson describes (18) some of these methods and states that it would not be easy to get a very exact fitting for the core (in large castings) and this is why the thickness of metal in some early castings is extraordinary. As such an example he quotes the Charioteer of Delphi (shown in Figure 10). He says that:

". . . . no large bronze statue in antiquity either in the Greek or Roman period was ever cast in one whole; it was composed of different pieces soldered together. Heads, arms and legs were almost always separately made.

"The surface of a bronze statue was never left in the condition in which it came from the foundry. The whole surface was filed, scraped, smoothed and prepared for subsequent treatment with graving tools by the master himself."

The casting of the Artemisium Zeus (shown in Figure 11) marked, according to Casson

". . . . the highest point to which Greek foundry-work attained as well as the highest point to which it could reasonably hope to attain. That statue is as perfect an example of fine casting as any period in the history of art can show."

Colossal Castings

According to Casson the invention of bronzes of large-scale, or even more than life-size, must inevitably be attributed to the Greeks. It began in Samos, in the second half of the sixth century BC.

One of the greatest achievements of Greek foundrymen was the enormous Colossus of Rhodes, classed as one of the seven man-made wonders of antiquity. *Figure 15* (127) shows an artist's conception, prepared according to medieval traditions, of the figure standing with one foot on each side of the harbour entrance. Although this drawing obtained some "official" approval (the Greek Post Office issued, in 1949-51, stamps showing this design), old writings of Philon of Bizantium and Pliny, as well as some modern authors (33, 69) assert that the statue had the legs together and was located on one side of the harbour entrance.

In any case, it was an enormous collection of bronze castings, erected, 292-280 BC, on the Dodocanese island of Rhodes by the renowned Greek sculptor Chares of Lindus, a pupil of the famous Lissipus, to honour Apollo-Helios, the Sun God patron of the island. The statue was 70 cubits (105 feet) high, a little over two-thirds the size of Bartholdi's Statue of Liberty in the harbour of New York, and weighed about 360 tons. According to Pliny (AD 24-79), the figure was so big that only few men could encircle the thumb with their arms and the fingers were larger than most statues.

Figure 15.
Drawing of Colossus of Rhodes, enormous bronze casting (280 BC)

Philon of Bizantium describes (146 BC) how Chares, having first made a model of the statue, cast the parts separately in bronze and, as each was fitted into position, the next part above it was cast and fitted, and so on until the Colossus was completed (33). The whole structure was supported from within by an iron scaffolding and reinforced by blocks of stone placed inside the hollow legs, and was equipped with a winding staircase.

Unfortunately, it stood only 56 years, because it was toppled in 224 BC by an earthquake. The broken statue lay in the harbour for a further 900 years, still admired for its immensity and beauty, until the Arabs conquered Rhodes in AD 672 and sold the fallen giant to a scrap dealer, who obtained 900 camel loads of bronze from it.

This is not the only example of large monumental bronze castings of antiquity. Much earlier, Hiram of Tyre, a Phoenician and the first legendary foundryman known by name, produced the famous bronze pool for King Solomon (around 1066 BC). The bowl was fifteen feet in diameter, seven and a half feet deep, having a wall thickness of 9 inches, and weighing 45 tons; it was mounted on eight bronze oxen, cast separately. As mentioned in the Old Testament, the same Hiram of Tyre also cast the twin bronze pillars for King Solomon's splendid temple at Jerusalem; they were 27 feet high, 6 feet in diameter, about 3 inches thick, and weighed about 200 tons.

According to Pliny, the Greek sculptor Zenodorus, after having made a colossal bronze statue of Hermes in Gaul, was summoned to Rome and there cast a 110-feet high statue* of Emperor Nero, later dedicated to the sun. This huge bronze monument was finally removed by order of Emperor Hadrian with the assistance of 24 elephants (82). There were many other "colossal" (over 20 feet high) Greek bronzes which we know only from ancient descriptions or reproductions on coins.

Some other colossal castings are shown in Figures 18 and 19 (Russian) and in Figures 23 and 24 (Japanese); some of the methods used in the casting of the statues of the Great Buddha are illustrated in Figures 25, 26 and 27.

Roman Empire

After the Greek period came the era of the Roman Empire. The Romans did not add very much to the metallurgical arts. They took over the old mines in the Near East, in the Danubian basin, in Spain, and later in Britain, and, by means of their recognized organizing abilities and engineering genius, considerably increased the mining output of all the then-known non-ferrous metals. This was necessary to satisfy the huge requirements of the Roman legions, to maintain trade with the Far East, and to obtain the various luxuries of their way of life.

The Romans were connoisseurs of bronze. The alloy "Corinthian bronze" was more highly valued than silver, its legendary origin stemming from the savage burning by the Romans of Corinth in 146 BC**, when innumerable statues and vessels of bronze, gold and silver, fell victim to the ferocious Roman wrath and, melted by the heat, had run together

*This gave the name "Colosseum" to the Flavian Amphitheater, when it was built nearby (70 AD) by Emperor Vespasian (82).

**The burning of Corinth in 146 BC by Mummius was in revenge for an outburst of exuberance on the part of the populace, who emptied their chamber-pots over the heads of Roman ambassadors (82).

to form a new alloy (82). It is an interesting but little known fact that the ancient (even then) Chinese Shang bronzes imported by the old silk trades routes (15) were held in very high regard by the Romans.

One important contribution of the Romans was the first manufacture of brass. There were some brass products made before 500 BC, and a Greek writer mentions "white copper" being made by the Mossynoeci on the shores of the Black Sea*. Other ancient brass products, called "Bidri ware", were produced in India, but in Europe and the Near East brass was not made before the Roman era.

Zinc as a separate metal was unknown in earlier times; in fact as late as the 16th century it was not known in Europe, although it seems that the Chinese were acquainted with it a few centuries earlier. There were only two known occurrences of ore containing both copper and zinc, one in Bidar (India), the other in France. Normally, brass was made by the addition of calamine (a zinc carbonate ore) to metallic copper and charcoal, a method still used in some foundries in Britain as late as 1850, because "calamine brass" was considered superior to brass made with metallic zinc. The Romans used brass first for coins (since AD 20). The full development of brasses had to wait until the 18th century AD.

The word "brass" in translations of classical literature, such as the Bible, is often misleading, because it was loosely used for copper and bronze products. Until modern times the terms "bronze" and "brass" have always been confused with one another, and most ancient languages did not differentiate even between bronze and copper.

Another Roman achievement was the important increase in the use of lead because of the Roman's predilection for proper water supply and plumbing. Unfortunately, as Aitchison (128) reports,

"lead poisoning is a disease that strikes even clean people, and the sterility which afflicted the people of Rome during the third and fourth centuries AD has been in a great measure attributed to lead poisoning consequent upon the wide use of lead piping."

This statement might be difficult to prove, but it seems that the Romans understood the danger of lead poisoning. The Roman naturalist Pliny wrote about metal workers wearing face masks made from goats' bladders to protect themselves from dust and lead fumes (129). Today, the use of lead in domestic drinking vessels, water pipes, etc., is prohibited.

The wide use made of cast bronze for statuary in the Greek-Roman era is noted by Pliny (AD 24-79) when he reported that two thousand bronzes were brought from *one* Etruscan city (82). Emperor Nero ordered extensive depredations in Greece and Greek colonies in Asia Minor to replace work destroyed during the great fire in Rome of AD 64. Five hundred bronzes were removed from Delphi, and a like number from Olympia. In spite of this, comparatively few original statues survive to our times.

Figure 16 shows the Capitoline Brutus, an Etruscan or Roman bronze casting from the third century BC, which is at present at the Palazzo dei Conservatori in Rome. It is believed that this magnificent bust represents L. Junius Brutus, who according to

*According to Wulff (168) brass was made very early in Persia by alloying copper and calamine (called "tutti" by Marco Polo (95)), from whence the process spread to India and China.

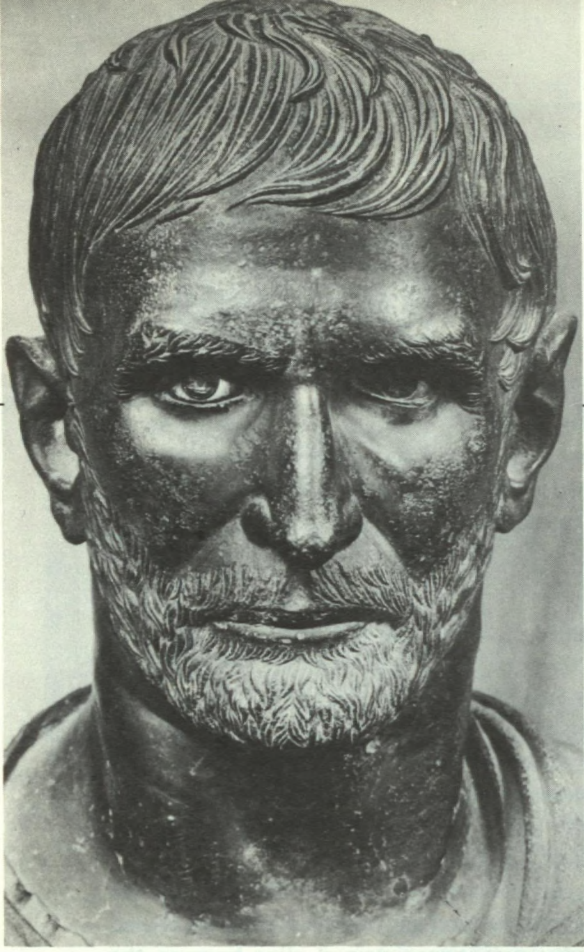


Figure 16.
Capitoline Brutus (3rd century BC)

tradition liberated Rome from the Etruscan yoke in 509 BC and became first consul of the Republic. The fine detail and the excellent craftmanship are notable.

The only specimen of large Roman bronze sculpture, which survived (almost miraculously, because the early Christians believed it to represent Emperor Constantine the Great) is shown in *Figure 17.* It depicts the large equestrian statue of Emperor Marcus Aurelius (AD 161-180), which was cast ca. AD 170-180 and probably adorned a triumphal arch. In 1538, it was placed by Michelangelo at the centre of Piazza del

Figure 17.
Emperor Marcus Aurelius (ca. AD 170-180)

Campidoglio in Rome, where it still stands. The statue of the philosopher-emperor stands about 17 feet in height and was gilded*. It has been repaired on several occasions, the last time in 1836 by the Danish sculptor Thorvaldsen (82). The influence of this statue on later Renaissance equestrian monuments was considerable.

Europe's Dark Ages

During the five millennia commonly called antiquity (4500 BC to AD 400), only seven metals came to light: gold, copper, silver, lead, tin, iron and mercury. For the next thousand years of the so-called Dark Ages, no new metals were discovered. Up to about the beginning of the 15th century AD, more copper and copper alloys were produced than any other metal, but thereafter copper took second place to iron.

Two important applications of cast non-ferrous metals that should be mentioned, but cannot be discussed here in detail, are coins (gold, silver, electrum, copper, bronze, cupro-nickel, lead, tin, brass) and mirrors (bronze, speculum metal).

After the fall of Rome (AD 476) and the conquest of Western Europe and the northern African coast by various barbarian tribes, cultural and technical progress ceased for many centuries. Some small-scale foundry activities remained alive because the warring conquerors needed weapons.

The tradition of bronze sculpture survived in Byzantium, although very little evidence was left after the sacking of the city by the Crusaders in AD 1204. With the incursion of the armies of Islam into the Near and Middle East, and later into North Africa and the Iberian Peninsula, new influences were born in Western Europe.

Bell and Gun Founders

With the diminishing of political chaos by the ninth century AD, metallurgy emerged again, showing certain characteristics connected with church patronage and the erection of large cathedrals and monasteries.

European bellfounders became the most important keepers of foundry traditions and metallurgical knowledge. Their guilds and confraternities controlled the quality and prices of castings. Larger castings than had been used in earlier times were needed to produce the large cathedral bells, and this need led (131) to the discovery of the first real moulding tools, the strickle board and sweep moulding, still in use today. Pit moulding too was developed. This technique called for deep pits dug directly in front of the furnace, thus simplifying the pouring process. Moulds too large for convenient floor moulding are still made in pits today. The most generally used bell metal composition is, and has been for many centuries, a bronze containing about 24% tin.

According to Simpson (131), the entire success of bell casting was

"dependent on the tone. True, a certain amount of chipping could improve the tone when the bell was tuned, but bellfounders, unwilling to leave tone to chipping or chance, sought for the relationship between tone and the size, shape, metal composition and thickness of a bell. Thus the standard bell

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*Legend has it among the people of Rome that when the gilding of the horse becomes bright again, the world will end (130).

Figure 18.
"Tsar-bell" in Moscow, a 220-ton bronze casting (AD 1733)

scale came into being—perhaps the first instance on record of the foundryman and the engineer combining their skills for the production of perfect castings. Biringuccio, again the diligent engineer-foundryman, was responsible for this scale of metal thicknesses, which still is employed in the production of cast bells.

"Thus bells, the great contribution of the church to the foundry art, were responsible for two important and progressive steps in foundry progress, aside from loam moulding and reverberatory furnaces. The greater exactness called for in bellfounding brought about the use of a precision tool (the strickle board) in moulding, and established a relationship among design, metallurgy, foundry practice and the final product—a relationship we refer to today as 'casting engineering' ".

Normal weight of the more famous bells in England was 5 to 20 tons. The Russians, of course, had to cast the largest bell. *Figure 18* (132) shows the "Tsar Kolokol" (King of Bells), a giant bronze casting weighing about 220 short tons, 19 feet high and 22 feet in diameter of the rim, with a wall thickness of up to two feet. Moulding for this bell required three years, and four reverberatory furnaces had to be built to melt the necessary metal. The bell was re-cast in 1733 from an earlier bell made in 1653 on order of Tsar Alexy Mikhailovits. It was never rung because a fire destroyed its supports and its fall broke an 11-ton piece from its side. It is now a curiosity for visitors to Moscow's Kremlin. There is another bell in Moscow which weighs "only" 110 tons.

American bells of fame should be mentioned, although, of course, these were not cast until about the end of the 18th century: the Liberty Bell in Philadelphia, cast in London and weighing about one ton, and the bell which hung in the Old North Church in Boston, cast by the prominent patriot Paul Revere.

Bellfounders also became gunfounders, later on. The first guns were cast in bronze in 1313 by a monk in Ghent, Belgium. The first actual use of guns was probably by the English in the battle of Crécy (1346). Cast bronze guns were used exclusively until they were replaced by iron around 1500. The first large-scale use of cannons for siege purposes occurred during the Turkish assault on Constantinople in 1453. Because it was difficult at that time to transport heavy cannons, they were cast directly on the battlefield.

Figure 19 (132) shows the "Tsar-Pushka" (King of Cannons), cast in bronze in 1586, which is exhibited in Moscow. It weighs 45 short tons, has a barrel diameter of 3 feet and barrel length of almost 18 feet. It was used to fire balls weighing 4,000 lb. The casting of such a large piece of ordnance was a considerable achievement for the technical skills of the bronze founder.

Figure 19.
Bronze "Tsar-cannon" in Moscow (AD 1586)

Figure 20.
Gloucester candlestick, gilded bronze casting (ca. AD 1100)

Later Middle Ages

Besides producing bells, cannons, various weaponry and implements, the bronze founders again revived the ancient art of creating sculptures and ornaments. Some remarkable castings survive from the Romanesque and the Gothic periods, most of them produced for religious purposes, such as fonts, reliquaries, candlesticks, crosses, censers (thuribles), sanctuary rings or door knockers, various tomb ornaments and other church furniture.

Figure 20 shows (133) an early European bronze casting from the so-called Dark Ages. This "Gloucester Candlestick" is considered to be the work of Anglo-Norman metalworkers and is a particularly fine example of combining art with excellent craftmanship. Standing about 22 inches high, it was cast in England about AD 1100, in bronze, by the ancient lost-wax process. It was made in three sections—foot, stem, and drip-pan—the parts being held together by a central iron rod terminating in the pricket (82). After casting and cleaning, the candlestick was gilded throughout.

It is interesting to compare this famous piece of art with the almost contemporary Indian casting, shown in *Figure 21* (133). This beautiful bronze statuette represents the Hindu god Siva Nataraja as Lord of the Dance. Cast during the Chola period, probably in the 11th or 12th century AD, using the lost-wax process, it is 35 inches high and is a magnificent example of oriental metalwork. Both of these castings are at present in the Victoria and Albert Museum in London.

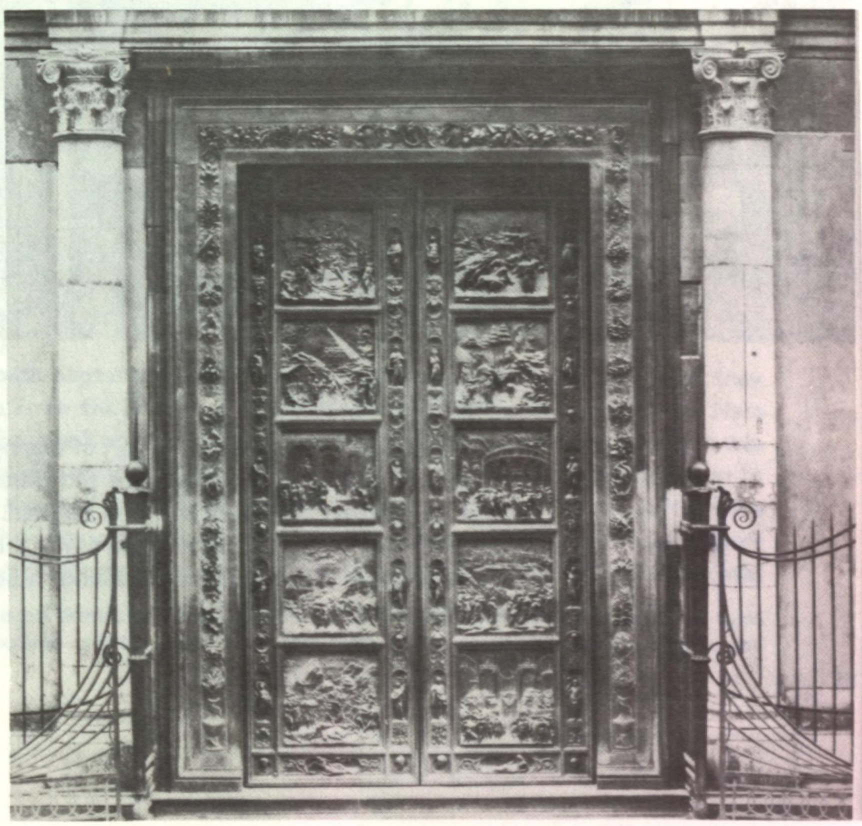
Building embellishments were another form of artistic casting. Bronze doors for the famous church of Sancta Sophia in Byzantium were cast in the days of Emperor Justinian (AD 527-565). The earliest post-Roman Italian doors, such as those at the Benedictine monastery of Monte Cassino (AD 1087), were produced by the famous bronze-founder Staurachios in Byzantium (82).

From the early years of the 12th century, the Italians developed their own production of elaborate bronze doors for their cathedrals; the most famous of which are the three pairs of doors of the Baptistry of St. John the Baptist in Florence, one of which is shown in *Figure 22* (134). Each door contains five panels which were cast in bronze by the renowned Italian sculptor Lorenzo Ghiberti and finished in 1452. Because of their splendour, Michelangelo called them "The Gates of Paradise". As Aitchison remarks, "the technical excellence of the doors, judged purely as bronze castings, is most impressive".

One important innovation, in the later Middle Ages, was the emergence of mechanical energy in the form of water-power, which had a profound effect on the mining and metallurgical practices, based hitherto only on manual labour. Aitchison (135) calls these developments in the 13th and 14th centuries "the first—the mediaeval—industrial revolution".

Figure 21.
Hindu god Siva Nataraja, bronze casting (ca. AD 1100)

Figure 22.
Cast bronze doors of Baptistry in Florence (AD 1452)



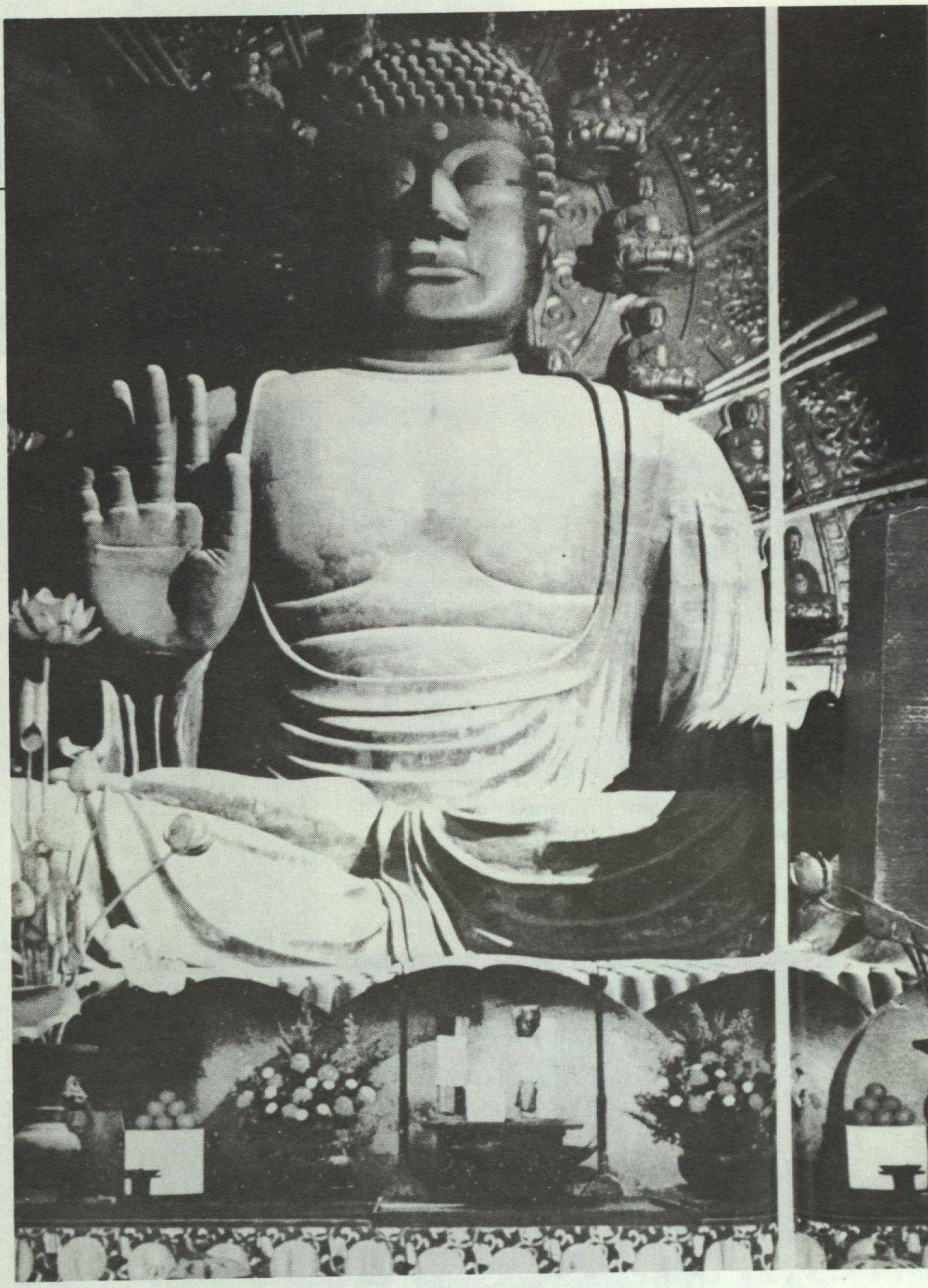


Figure 23.
Great Buddha at Nara, world's largest bronze statue (AD 749)

Japanese Bronzes

From China, through Korea, the art of casting was brought to Japan about 300 BC. The first bronze castings were weapons and ritual bells. First open stone moulds were used, but the lost-wax technique was soon adopted. The introduction of Buddhism, in the sixth century AD, created a golden opportunity for the growth of the bronze foundry industry to take care of the numerous castings needed for religious statues and various ritual articles.

Figure 24.
Great Buddha at Kamakura (AD 1252)

The most spectacular bronze castings are the statues of the Great Buddha. The oldest of these is the Asuka Great Buddha, originally completed in AD 605 (but later rebuilt). Its height is about 10 feet with a wall thickness of 0.4 inch and it weighs about 18 short tons (54).

Figure 23 (136) shows a partial view of the 53-foot-high bronze statue* of the Great Buddha (Daibutsu) cast in AD 749 in Nara, at that time the imperial capital of Japan. This is the largest of the Great Buddhas, the outside circumference of the pedestal measures 126 feet, the wall thickness is over 2 inches and it weighs about 275 short tons. The length of Buddha's hands is about 10 feet and there are 966 pieces of hair curls (each having a diameter of about 5 inches and length of about 8 inches), cast separately and then inserted into the cast head.

Figure 24 (138) depicts the Great Buddha (Daibutsu) in Kamakura, near Tokyo. Erected in AD 1252, it is the second largest bronze statue in Japan, having a height of 38 feet, a wall thickness of over 2 inches, and weighing about 120 short tons. The hair curls on the statue were cast integrally with the head, as may be seen from the fragment shown in *Figure 25* (139).

The casting of such huge statues could, of course, not be performed in one piece; they were cast in layers from the bottom to the top, as shown in *Figure 26A* (for the Nara casting) and *26B* (for the Kamakura figure) (140). The skeleton of the statue in Nara was made of wooden pillars, bamboos and ropes, and this was covered by moulding sand to build up the basic shape of the figure; to finish this inner mould, the outer surface was pared down by the required wall thickness of the casting. The outer moulds were prepared in segments (piece-moulds). For each consecutive layer of the casting a bank was

*A full view of this largest bronze statue in the world cannot be made, because it is enshrined in an enormous wooden temple and the pillars and other parts of the dome construction obscure the picture (137).

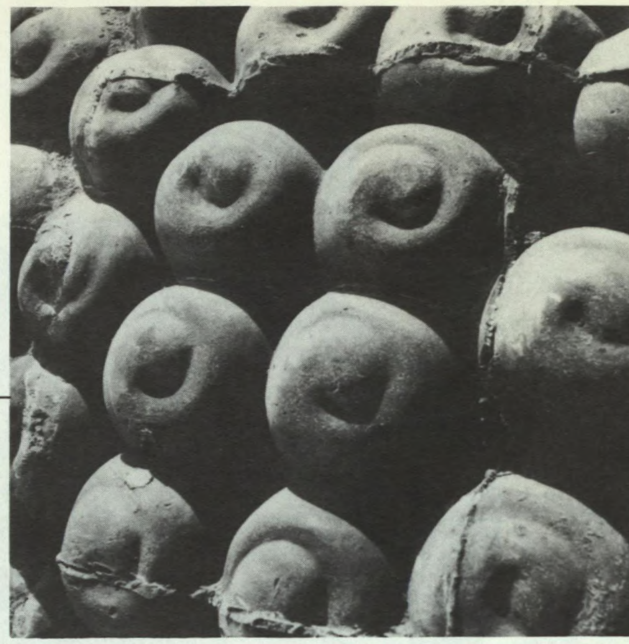


Figure 25. Fragment of integrally cast curls, Great Buddha at Kamakura

built around the moulds for the melting furnaces and casting was done directly in the mould cavities.

For the Kamakura statue a wooden model was prepared and then the inner and outer mould pieces were made separately and thoroughly baked. As shown in Figure 26B, casting was carried out in segments from the bottom up.

The various segments in the two statues were joined by a special casting technique, called Igaraguri (140). For the Kamakura statue, cast 600 years later than the Nara, this joining technique was improved. *Figure 27* shows three methods of joining used in Kamakura.

The first method (A) is the simplest (used also almost exclusively in Nara), and was employed mainly for the flat sections of the body. The edges of the two pieces are simply over-lapped and joined, whereby some extent of welding occurs due to the hot metal flowing in.

In the second method (B) the molten metal is poured into a hole provided in the earlier cast segment and acts, after the flattening of the head of the bolt, like a rivet. This more complicated method was used sometimes for joining mould pieces located at right angles (e.g. knee).

The third method (C) is the most complicated and was used for sections under heavy load, such as the curved part of the shoulder.

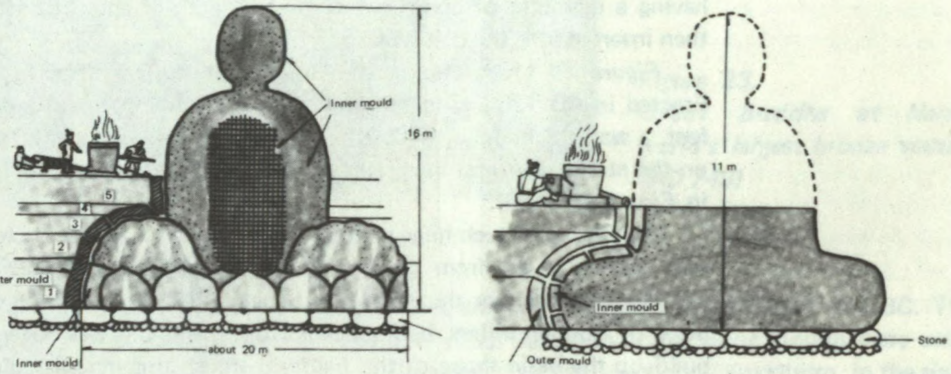


Figure 26A. (left) Casting method of Nara statue; B (right) casting method of Kamakura statue

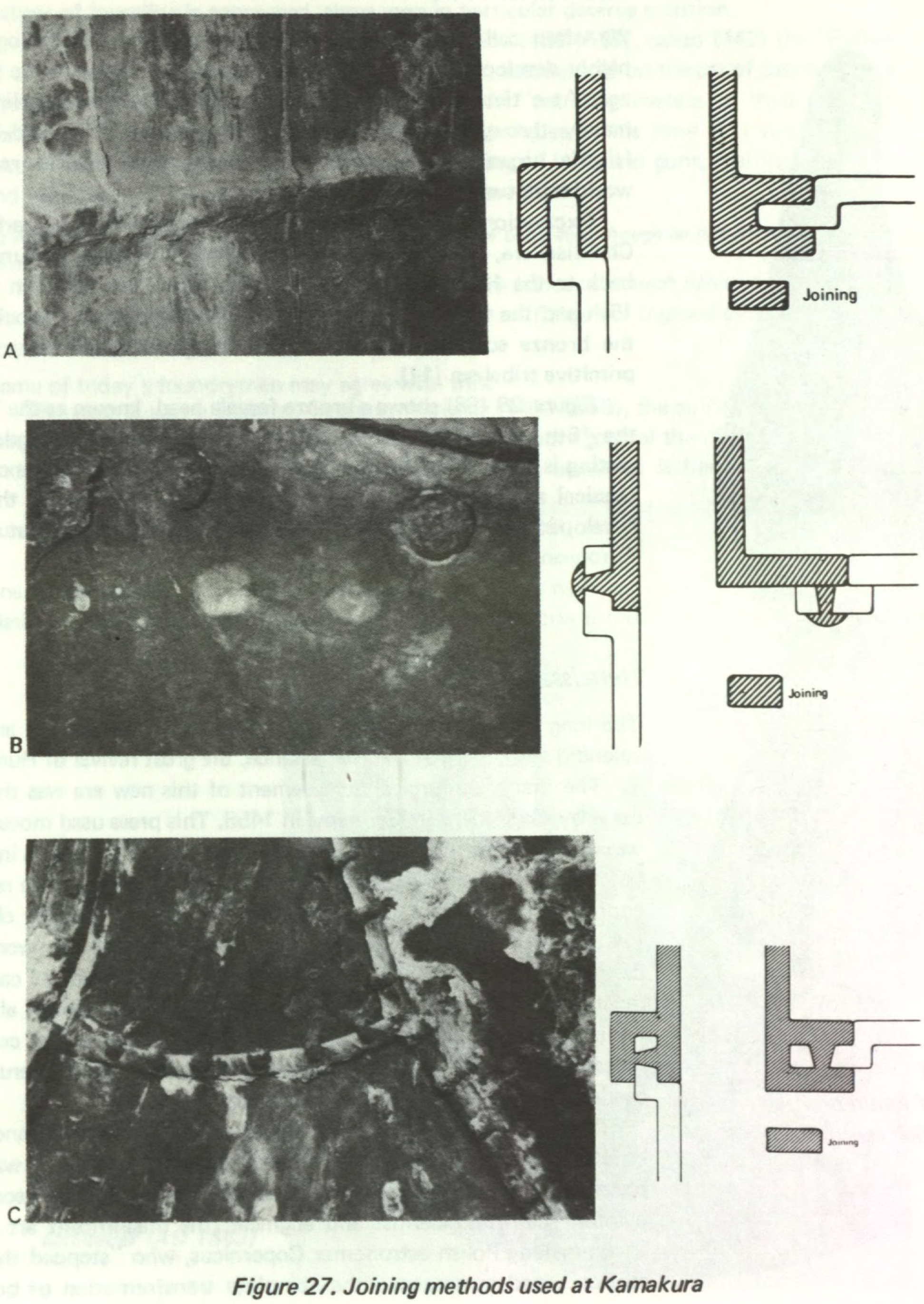


Figure 27. Joining methods used at Kamakura

West African Art

We often call Africa the "Dark Continent", but archeological excavations show that highly developed civilizations existed there, at least in some of its parts, many centuries ago. At a time when West Africa had only the slenderest links with the outside world, mainly through Arab slave traders, the peoples of Ife and Benin, in today's southern Nigeria, began to produce beautiful bronzes, some of which rank with the masterpieces of world sculpture (86).

Excavations so far show lively terracottas from the early Nok culture, before the Christian era, followed by lost-wax bronzes of the Ife culture, whose earliest objects go back to the 12th century AD, and those from the Kingdom of Benin, cast between the 15th and the 17th centuries AD. The still rare finds from ancient Africa, and particularly the bronze sculpture of the Yoruba Kingdom, show us a world very different from primitive tribalism (11).

Figure 28.
Princess of Benin bronze casting (16th century AD)

Figure 28 (86) shows a bronze female head, known as the "Princess of Benin", cast in the 16th century AD by the lost-wax process in the Kingdom of Benin, Nigeria. The casting is a memorial head of a dead queen used in a royal ancestral cult. It has an almost classical style and shows excellent technique. It is one of the proofs that Black Africa developed highly organized cultures and a sophisticated naturalistic art long before the Europeans arrived.

How and when the lost-wax process was introduced in ancient Nigeria is not known, but it was already used there when the Portugese explorers first visited Ife in 1484.

Renaissance

The long millennium of the Dark and Middle Ages drew to an end and gave way to the splendid awakening of the Renaissance, the great revival of Humanism.

The first metallurgical achievement of this new era was the invention of the printing press by Gutenberg in Germany in 1456. This press used movable, cast lead alloy type. It was not so much that the type was movable which made this invention so very important, but that the type was a form of *metal casting* which could be reproduced identically at an enormous rate and possessed excellent inking and wearing characteristics. As Simpson (141) mentions, "type founders are merely foundrymen working with cast alloys and permanent moulds". This great achievement in the art of casting metals, probably the most important since the discovery of melting and bronze alloying, had a considerable impact on our civilization and made possible today's vast communication industry. It should also be added that the printing press was an early forerunner of another important casting development, the modern die-casting machine.

One of the characteristics of the splendid era of Renaissance was the great number of outstanding men, in almost all fields of human endeavour. It was a time of many giants in philosophy, art and science, such as, the brilliant Italian Leonardo da Vinci, renowned painter, sculptor, scientist and engineer; the magnificent art creator Michelangelo; the epoch-making Polish astronomer Copernicus, who "stopped the sun and set the earth in motion", and commenced the complete transformation of both celestial and terrestial physics; and, of course, the great religious leaders of the 16th century. In so far as the history of founding is concerned, three men in particular deserve mention.

The first was the Italian Vannoccio Biringuccio (1480-1539), called (142) the "Father of the Foundry Industry" and author of the first textbook (4) on the art of casting, *De la Pirotechnia* (1540). His definition of casting is "reducing metals to their ultimate perfection". He describes in great detail the techniques of his time that were used in preparing sand mixes, the lost-wax process, casting of bells and guns, melting practices, and furnaces, etc. He points out that a foundryman—

"is required to have great endurance of mind as well as of body even though he himself may be a great genius of the art".

However, such labours and inconveniences *"are borne with such pleasure and to such an extent that those who practice the said art are as if they are trapped by it and cannot escape." (142).*

Some of today's foundrymen may agree with this.

The second was a German, Georgius Agricola (1494-1555), the author of an excellent metallurgical book (5) *De Re Metallica* (1556). It is more general than Biringuccio's text, and also contains information on smelting methods (some of it literally copied from

Figure 29.
Cellini's gold salt-cellar (AD 1543)

Biringuccio's book, without giving any credit). Agricola's book gives a very lucid description of metallurgical know-how in the late Middle Ages, including also some knowledge of the practical alchemists, and gives factual information on various aspects of the existing industrial practices and economies.

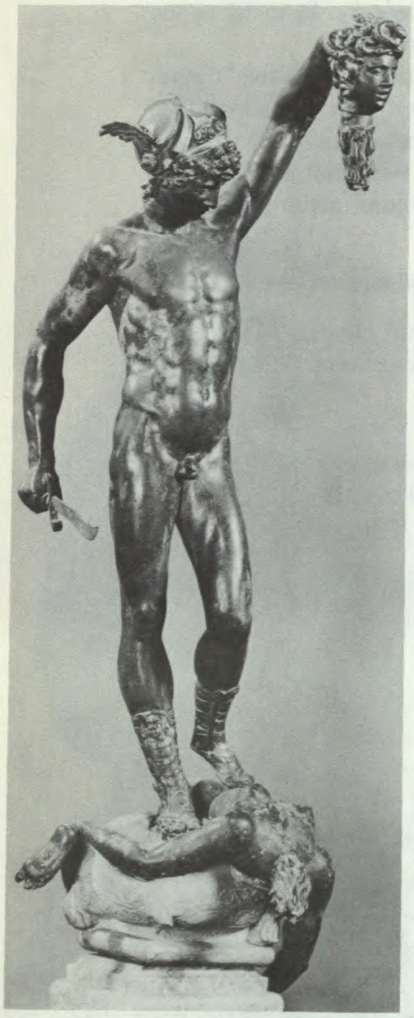


Figure 30.
Cellini's cast bronze statue of Perseus (AD 1553)

The third was again an Italian, Benvenuto Cellini (1500-1571), who was both a great artist and an accomplished founder. A typical child of the Renaissance, he described (6) in his *Autobiography,* published in 1568, not only his rather stormy life, but also many detailed descriptions of his casting procedures. Unfortunately, very few examples of his exquisite sculptures have survived. The best illustrations of his great talents as a sculptor, a goldsmith and a founder are two of his famous castings, the gold salt-cellar and the bronze Perseus statue.

Figure 29 shows (143) the famous gold "Salt-Cellar", cast in 1543 by Cellini for King Francis I of France. It weighs 15 lb, measures about 10 by 13 inches, and is justly ranked as the greatest example of the goldsmith's art. It depicts (144) Tellus, the Goddess of Earth, and Neptune, the Sea God, who sit with intertwined feet to symbolize the union of the two elements. The miniature triumphal arch (Ionic temple) holds pepper; salt is held in a boat-shaped receptacle on the opposite side. At present the salt-cellar is in the Kunsthistorisches Museum in Vienna, Austria.

Figure 30 shows the splendid bronze statue of "Perseus with the Head of Medusa", cast by Cellini for Duke Cosimo dei Medici of Florence, and completed in 1553. The statue, over life size, stands in the Loggia della Signoria in Florence, and was cast by the lost-wax method; it is an excellent example of its maker's artistry and foundry skill. His training as a goldsmith is revealed in the refined modelling and in the abundant ornament covering the base between the small bas-relief. Cellini tells in his *Autobiography,* in great detail, of the troubles (145) he encountered in the casting of Perseus, which may be of interest to all foundrymen. Simpson (146) summarized the tale:

"how he completed the mould, vented it, drew out the wax and lowered the mould into the pit for pouring; how he started his furnace and charged pigs of copper and bronze scrap. From these exertions he became violently ill with fever and retired to his home, leaving his "faithful" moulders in charge.

"At home he awakened from a terrible dream and with a premonition that something was wrong, rushed to his foundry. In his absence, due to neglect, the roof of the foundry had caught fire and, to make matters worse, a high wind had blown in all the windows of his little shop. While he and his helpers put out the fire and hung rugs in the windows, his fire went down in the furnace and the melt began to "freeze".

"Cursing his melters for ignoramuses, Cellini built up the fire and threw in his remaining pigs of metal."

At this point, a sudden explosion of the furnace took place—the cover of the furnace had blown up. Cellini opened the mould gates and started pouring, but found that the metal was not fluid enough (175). He threw in, therefore, all available pewter plates and dishes (some 200 pieces in all) in the melt and finally succeeded in filling the mould.

"Perseus was completed, and the result was a world-renowned casting. Perhaps there is some solace here for all modern foundrymen, who have a great many troubles, all at one time, but who generally produce good castings in spite of all obstacles."

(See also note on page 59)

Pre-Columbian America

Historically the most far-reaching achievement of the Renaissance era was the discovery of the New World by the Genoese explorer Christopher Columbus in 1492 and the subsequent Spanish conquest of the amazingly high cultures of the Aztecs, Maya and Incas.

European explorers were astonished to find the *Indians* of North America still living in the Neolithic Age, comparable to the cultures of the Middle East in the fifth millennium BC. The Indians in North America were just emerging from the Stone Age, but were not yet in the Copper Age. They used some hammered gold, copper and silver, but only when found as native metals, because the arts of melting metals or smelting them from their ores were still unknown to them. They possessed no tools for mining and were, therefore, restricted to the use of pieces of copper set free by weathering and decomposition of rock, although some traces of very primitive mining attempts were found in the Lake Superior copper region.

In Mexico, the *Aztecs* were already in the early Copper Age but still had no knowledge of the wheel; they had just learned to melt gold, silver and copper, and cast them into ornamental shapes, using moulds carved in stone, and, later, also the lost-wax technique. They were using native copper, but still did not know how to produce bronze or how to extract metals from ores, and iron was unknown to them.

In Middle America (southern Mexico, Guatemala and Honduras) the great culture of the *Maya* was almost entirely neolithic. At the end of their New Empire (10-13th century AD), they used some gold, copper, silver and copper-gold alloy objects, some of them cast, but exclusively for personal adornment or for ceremonial use; no metal tools were known (47).

In Peru, the empire of the *Incas* was slightly in advance of the Mexican Aztecs and had already entered the Bronze Age. The Incas were smelting copper from ore; were casting gold, silver and copper; and were doing practical welding and soldering. They learned, a short time before their conquest by the Spaniards, to produce bronze castings, using Bolivian tin, but still did not know iron.

The *Quimbayas* (ca. AD 1000-1300) and the *Chibchas* (ca. AD 1300-1438) of what is now Colombia, were outstanding artists and technicians in the lost-wax casting method, their ornaments and ritual objects being made of an alloy of gold, silver and copper, called tumbaga (77).

The principle of the wheel, the use of beasts of burden and the plow were unknown in any of the above pre-Columbian civilizations. Metals never supplanted the primary dependence of the Indians upon stone implements; they found few uses outside ornamentation (47).

It is amazing that the metallurgical discoveries of melting and smelting, of casting and the lost-wax process, bronze alloying, welding and soldering, etc., were made in the New World entirely independently from Europe and Asia. If one were to agree with Barnard (9) that the discovery of the art of bronze casting in China was independent of any western influence, and considering the high skill required in the lost-wax casting of bronzes in West Africa, before the Portugese explorers arrived, it seems that early man's inventions were made at different times and in widely separated geographical areas just as soon as he became developed enough for urban civilization.

Modern Metals

It has already been said that at the end of antiquity mankind knew only seven metals; between 1500 and 1700 another three were discovered; in the 18th century 14 more were found, and since 1801 another 51 have been isolated. The most important of these new metals were zinc, nickel, magnesium and aluminum (in the sequence of their discovery).

Zinc, although used for almost two millennia in the production of brass and nickel silver ("paktong"), was not recognized as a separate metal. Its first name, given by the Greek Strabo (first century BC) was "false silver". Zinc was first isolated by oriental alchemists before about the 12th century AD and used in China and India*. In Europe, the name "zinc" was first mentioned by Paracelsus (1490-1541), but the metal itself was not isolated until 1743, by the German chemist A. S. Marggraf. In the foundry today, zinc is the base for an important group of die-casting alloys and a valuable alloying addition to many aluminum, copper and magnesium casting alloys.

Nickel was also used for almost two millennia in the Chinese cupro-nickels and nickel silvers, but was not isolated until 1751 by the Swedish scientist Cronstedt. Although nickel is a non-ferrous metal and is used as an alloying element in many non-ferrous alloys, its main importance is as a steel addition.

Magnesium was discovered by Davy in 1808 and isolated in 1828 by Bussy. The metal was not used industrially until some 60 years ago. The first magnesium casting alloys of importance were developed on a practical scale in the 1920s. World War II requirements caused a boom in magnesium foundry operations and in the period of 1942-45 almost 120,000 tons of incendiary bomb castings alone were made. Great progress in the development of high-strength magnesium casting alloys and premium-quality castings has been achieved in the last two decades. Today's magnesium production is still comparatively small, but its future seems bright. The greatest single use of magnesium alloy castings, which recently exceeded 40,000 tons yearly, is the 28-lb crank-case and other die-cast engine parts in the German Volkswagen.

Aluminum compounds have been used for at least 7,000 years in producing pottery, but metallic aluminum was not separated until 1825, by the Danish scientist Oersted. The first industrial method for producing the metal was introduced in France by Sainte-Claire Deville, in 1854. Today's electrolytic process was discovered, simultaneously, by the American Hall and the Frenchman Héroult, in 1886. The meteoric rise of aluminum consumption in the last 50 years is dealt with later. In the last decade aluminum has become the most important non-ferrous metal and it seems that its consumption will, in the near future, be higher than that of all other non-ferrous metals taken together.

In speaking about aluminum and magnesium, *age-hardening* of their alloys should be mentioned. The discovery of this important heat treating process, by the German scientist Alfred Wilm in 1906, was, as are most discoveries, accidental. During his aluminum alloy

*See footnote on page 22.

development work, some test specimens were quenched and were awaiting hardness testing. Since it was Saturday and Wilm was an enthusiastic sailor, he told his assistant, a Pole by the name of Jablonski, to make the hardness tests before leaving work. But Jablonski was a young man and he had a date. When he went to work especially early the following Monday morning, to make the tests before his superior arrived, he was surprised to obtain hardness results much higher than expected. He confessed the whole story to Wilm, who realized the significance of the new data, repeated the experiment, and discovered age-hardening. In short, romance is not only confined to "Boy meets Girl" but can lead to scientific discoveries! (147). Wilm was unable to explain the mechanism of age-hardening, and this was not achieved until 1919 by Paul D. Merica and his associates at the U.S. National Bureau of Standards in Washington. The discovery of precipitation-hardening in aluminum and magnesium alloys opened up immense possibilities of developing a whole range of lightweight, high-strength alloys, and this, in turn, had an enormous impact on the growth of the aircraft industry and the use of light alloys in many other fields where strength-to-weight ratios are important.

Modern Castings

To complete the review of outstanding metal castings, some more recent examples of prominent foundry work are illustrated.

The next two illustrations present castings made of pewter, a tin alloy with additions of lead, antimony, copper, and sometimes some bismuth.

Figure 31 depicts (148) the sarcophagus of Emperor Francis I and Empress Maria Theresa in the vaults of the Capucin Church in Vienna, Austria. The magnificent tomb

Figure 31. Cast pewter sarcophagus in Vienna (ca 1775)

Figure 32.
Modern replicas of medieval pewter dish and ewer

was designed and cast in pewter by Balthasar F. Moll ca. 1775. As a spectacle this baroque-style tomb is without equal: the scale is larger than life, and the complication of the masses of ornaments is unique.

Figure 32 shows (149) a pewter dish and ewer by Briot. They were reproduced in a permanent mould by Chaumette in Paris. The exquisite perfection in detail is amazing.

Figure 33 shows one of the oldest aluminum castings, Sir Alfred Gilbert's famous statue of Eros in London's Piccadilly Circus. This statue was cast in commercially pure aluminum, which had been produced chemically, none being available from the electrolytic process (150). The statue was made in 1893 in London as a memorial to Lord

Figure 33.
Aluminum casting of Eros in London's Piccadilly Circus (1893)

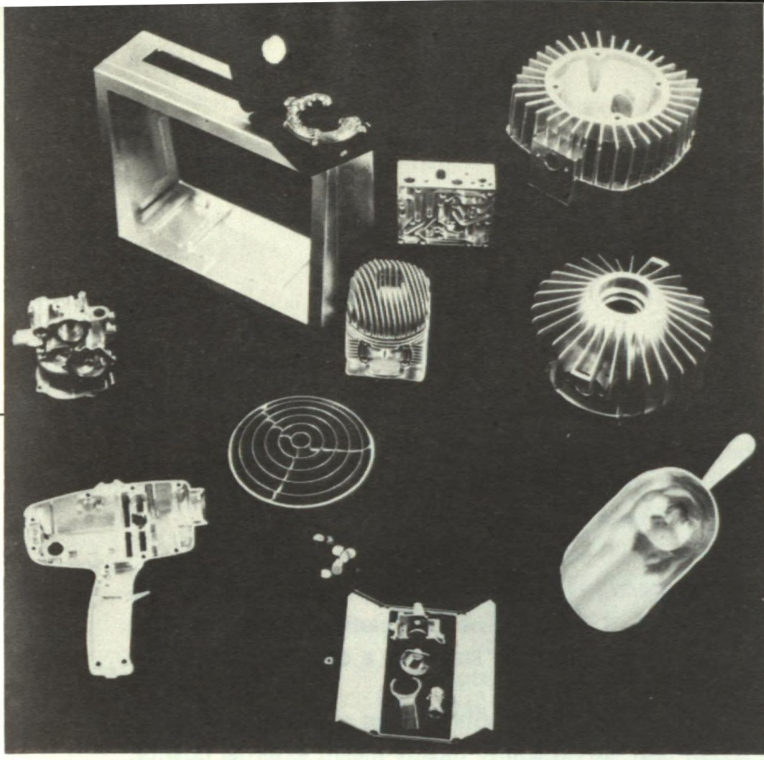


Figure 34.
Assembly of aluminum and zinc alloy die castings

Shaftsbury. In spite of exposure for 77 years to London's proverbial smog, the statue shows little sign of corrosion, although no surface protective treatment was used.

Figure 34 presents (151) an assembly of aluminum and zinc alloy die castings. The picture shows the intricacy of design and excellent surface quality of modern die castings.

Figure 35 depicts (152) a large tanker propeller during the course of chipping. The finished weight of the casting is 65 short tons and the diameter 29 feet. This propeller transmits 32,400 h.p., and the material is Nikalium (a strong aluminum bronze).

Figure 36 is (152) another propeller for the new British liner "Queen Elizabeth II". It weighs 35 short tons, its diameter is 19 feet and it transmits 55,000 h.p.—the largest power ever on a single propeller. The vessel, of course, has twin screws. The material in this case is Superston 70 (a high-strength aluminum-manganese bronze).

Both of these huge bronze castings are remarkable examples of today's casting skill, and show that the experience of ancient bronze founders has not been lost.

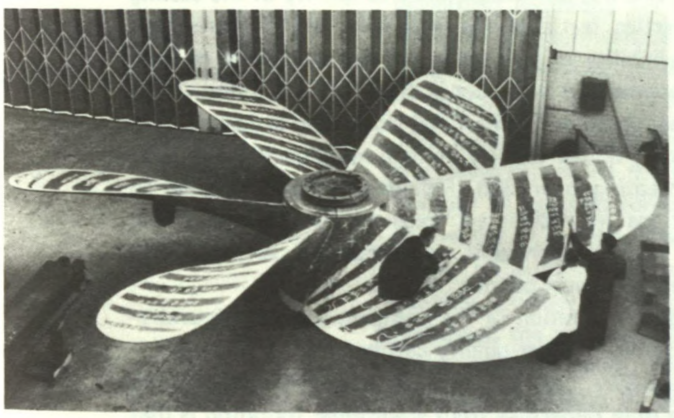


Figure 35. Modern bronze propeller for large tanker

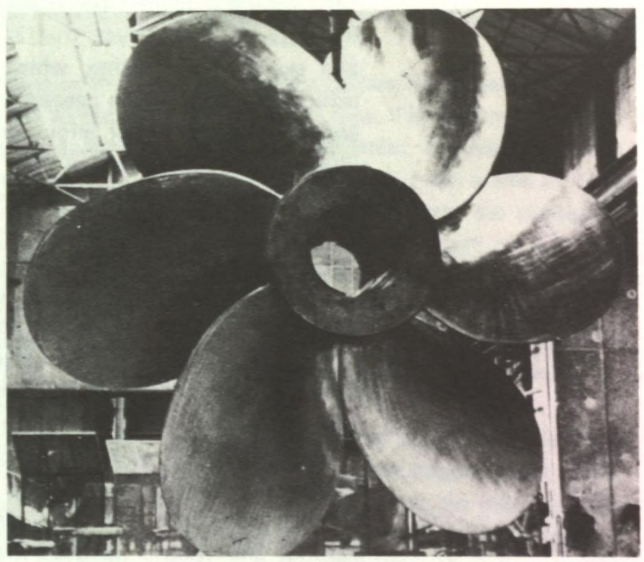
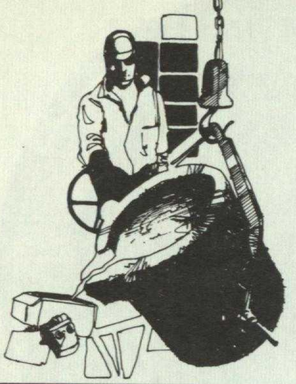


Figure 36. Bronze propeller of British liner Queen Elizabeth II



Part 2
Present

Casting Quality

Before considering the future of the non-ferrous casting industry, a brief review of the present state of the art is necessary, confined to some aspects of casting quality and some of the newer casting processes. This will help set the stage for a consideration of the future.

It was always the founder's job to produce serviceable castings at minimum cost. In ancient times and in the more recent past, serviceability mostly meant external quality; that is, acceptable standards of surface finish and dimensional tolerances. It is only comparatively recently that the importance of internal quality in certain kinds of castings has been recognized, and that this quality could only be achieved by requiring that the castings comply with specified mechanical property criteria.

The increasing engineering importance of "premium-quality" castings has brought about a gradual change in attitude, especially during the last decade or so. The idea of a foundry practicing a craft based on centuries of experience has almost completely given way to the concept of the foundry as a modern industry using methods founded on rigorous scientific principles.

It has not been easy for many foundrymen to change attitudes that have been based on "quantity" production; to abandon a reluctance to guarantee the properties of their castings; and to adapt their production to the requirements of "premium-quality" and "zero-defects" concepts.

What is "premium-quality"? (153). It is not only better internal quality of the casting with resultant higher mechanical properties, but also—the most important feature—high integrity of the product; that is, the reliability of properties in designated areas of each and every single casting, which are guaranteed with confidence by the foundry. To achieve this, it is often necessary to use higher purity of metal stock than is usually used and to maintain closer alloy composition limits. Quality control must be strict in each individual melting, casting and heat treating operation. Moulds must be designed to obtain optimum solidification conditions in designated areas of the casting. Metal soundness and mechanical properties must be carefully evaluated, and surface finish requirements and tight dimensional tolerances must be met.

"Casting engineering", that is, close cooperation of the designer, user and foundryman, is very important for the manufacture of highest-quality castings.

In the production of premium-quality castings, conventional equipment and manufacturing techniques are used; the only departure from traditional founding is that each foundry operation has to be carefully studied and, once established, strictly controlled. The most important problem is the appreciation and understanding of all the many factors (154) affecting the soundness of the casting and its mechanical properties.

Premium-quality castings are, of course, more costly than ordinary commercial castings and should be used mainly in highly stressed parts for service under severe conditions, or be substituted for parts fabricated from wrought alloys, where the highest strength-to-weight ratio is essential. However, taking into consideration that castings can be made to almost any final shape and to reasonably close tolerances, the higher material cost of premium-quality castings can often be offset by elimination of machining and other fabricating costs associated with wrought products.

The economic stimulus to survive has given the non-ferrous foundry industry its main reason for adopting scientific techniques. Many new materials—such as plastics of all kinds, other forms of non-metallics, high-strength steel castings, various wrought metal products, powder metallurgy components, and the most recent composite materials—are available to the designer and user. The competition is often very keen, and only highest quality and superior performance of a material assures success.

Casting Processes

So much for casting quality; now a few remarks on the various casting methods. Besides the ancient and time-honoured sand, permanent mould, lost-wax and slush casting processes, non-ferrous metals and their alloys are cast at present into shell moulds, various plaster moulds, ceramics, graphite, semi-permanent moulds, unbonded sand, floor and pit moulds (with green or dried sand, loam or cement-bonded sands). Metals are cast by gravity, counter-gravity, centrifugal force, low or high pressure, and under vacuum. The variety of moulding materials and casting methods seems to be almost unlimited; and their use depends on the number and kind of castings to be made, and on the requirements on casting quality and surface characteristics. Product cost, of course, remains the main consideration.

Three of these processes should be discussed in more detail, because they were developed especially for non-ferrous metals and will have considerable bearing on the future of the non-ferrous castings industry. These processes are die casting, low-pressure casting and extrusion casting.

Die casting (119) had its origins in the printing industry, where in the middle of the 19th century several inventors tried to obtain rapid casting of type. This led eventually to the development of the linotype machine by Ottmar Mergenthaler. In this machine a number of metallic forms or matrices were assembled automatically, and a line of type the width of a newspaper column was cast. The metal was forced into the mould by means of a piston and a cylinder immersed in liquid metal. At the start of the 20th century, Doehler patented the first commercially successful die casting machines, which embodied the principle of the first linotype machine in that it had a submerged plunger and a pump to force molten metal into the mould. First, tin and lead die castings were produced, followed in 1907 by die castings in zinc alloys, in 1915 in aluminum alloys, and later in brass and magnesium alloys.

In the development of the die-casting process some of the most important milestones were: the introduction in 1929 of high-purity zinc alloys; later the introduction of the cold-chamber process; and more recently, the use of more heat-resistant die materials; the automatic ladling and pouring devices; vacuum die casting; the intensification of pressure after the metal injection; thermal analysis of dies; the availability of proper instrumentation for process control; and the latest equipment used in the improved hot chamber method for aluminum alloys.

Pressure die casting is recognized for its suitability to mass-produce castings with very close tolerances and good surface finish, but die castings are not distinguished, as yet, for their internal soundness or reliably high mechanical properties. Considerable research is being directed to this end.

It would be much too early to predict that premium-quality castings can be consistently produced by this process, but—taking into consideration the rapid progress in automation and the possibility of computer coordination of metal flow, heat extraction and proper solidification conditions, pressure and die evacuation—it seems a reasonable prospect for the not too distant future.

Today, non-ferrous alloy die castings in the United States amount to almost a million tons yearly, which is more than half the total of all non-ferrous metals castings, and the trend is for more.

Low-pressure casting of aluminum alloys, similar to casting into partly evacuated moulds, was used during World War II for some aircraft castings, in order to obtain greater dimensional accuracy, fine detail in very thin sections, and better casting soundness. In the past few years a number of low-pressure (counter-gravity) casting installations have been in use and they show great promise for the future. This should not necessarily be regarded as a die casting process, because moulds of different materials may be used, not only metal dies.

In a typical low-pressure casting unit, the inverted mould is mounted above an electrically heated holding furnace and the metal is forced up by air pressure of 5-15 psi through a feed tube into the mould cavity. In general, the casting soundness, dimensional tolerances and surface finish produced by this method are excellent, comparable to or better than those obtained in permanent mould casting, and the elimination of risers and reduction of gating allows very high metal yields (85-99%). The process lends itself to full automation.

D. A. Linderman (155) lists some of the advantages of the low-pressure casting method as: adaptability to very intricate shapes with thinner sections than are possible with sand or permanent mould castings (sections down to 0.060 in. have been cast); low initial cost; denser castings and higher mechanical properties than with sand or die castings. Observing good casting practice and die design, this process will consistently produce premium-quality castings.

The low-pressure casting process has been used with various alloys, such as brass, aluminum bronze, nickel and magnesium alloys, although in each case a lot of development work was necessary; there is no reason to believe that other materials could not be cast in this way

Extrusion casting (156), pierce forging (157), ultra-high pressure die casting (158), auto forge (159), squeeze casting (160) and similar processes are representative of a combination of casting and metal forming under pressure, where the solidifying metal is additionally treated by pressing, forging or extrusion to obtain a very dense and sound casting with high mechanical properties.

Metal Statistics

To illustrate some present and future trends in metal production and consumption, a few statistics are necessary.

Table 1 shows the relative abundance of the major industrial metals and that of gold and silver. The table depicts the availability of these metals in the upper ten miles of the earth's crust, as estimated by the United States Geological Survey in 1924. To make it easier to compare the occurrence of commercially important metals, this table is calculated (161) with reference to aluminum, the most abundant metal, designated 100 instead of 8.13%, which is its actual calculated weight percentage in the earth's crust. The table shows that some of our oldest and best known metals are rather rare in comparison with the light metals and iron. It should be realized that for each ton of aluminum available in the earth's crust, only 2 lb of copper, 1 lb of zinc, a half lb of lead, and one-third oz. of tin exist.

It seems obvious that in the future we shall have to face some decrease in the availability of zinc, lead, tin, and perhaps also copper. This doesn't mean that we can foresee a complete depletion of these metals, but they will be more difficult to obtain and may be much more costly.

Figure 37 shows graphically the considerable progress in the world production of the four major non-ferrous metals. The very rapid growth of aluminum is remarkable. There

TABLE 1

Abundance of Metals

In the upper 10 miles of Earth's Crust (with reference to Al, the most abundant metal, designated 100, instead of 8.13%)

100	ALUMINUM
62	IRON
25	MAGNESIUM
8	TITANIUM
0.25	NICKEL
0.12	COPPER
0.05	ZINC
0.025	LEAD
0.001	TIN
0.000,01	SILVER
0.000,001	GOLD

(Source: Clarke and Washington, The Composition of the Earth's Crust, U.S.G.S., Washington, 1924; and Meier, How to Select and Use Non-ferrous Metals and Alloys, Canadian Metals 12(8), 8-11, 24-25, 35-38; (9) 12-15, 1949.)

is also an interesting reversal in the quantities produced. Although it does not show in Figure 37, at the end of the 19th century lead held the first place, then zinc, and finally copper. At present the reverse is true, with aluminum overtaking all three of these metals.

Table 2 shows the growth in world consumption of major non-ferrous metals during the past decade. Aluminum and nickel showed increases much above the totals for other

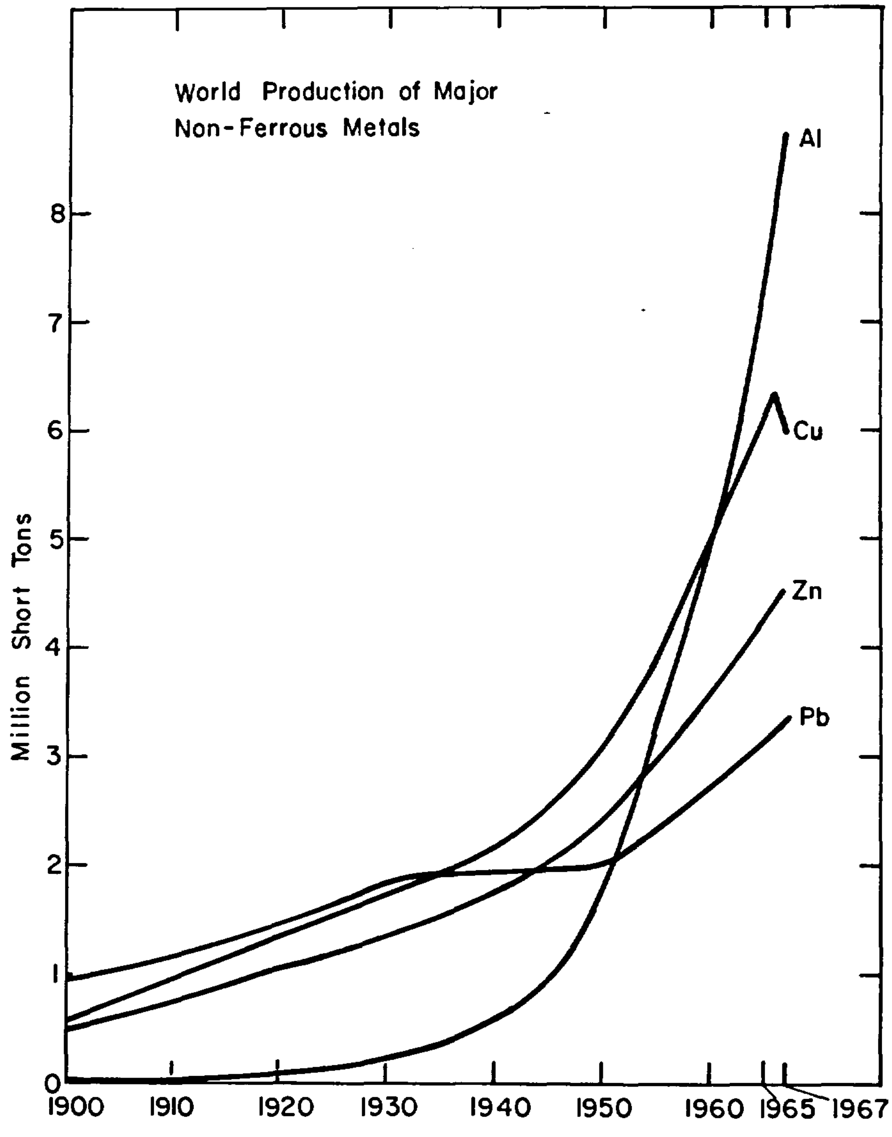


Figure 37. World production of major non-ferrous metals. (Source: Year Book, Am. Bur. Metal Stats, New York, 1968)

non-ferrous metals and for pig iron. Copper, zinc and lead have increased more slowly, but well above the rate of the population increase. Tin and magnesium show very little increase. The ratio of pig iron consumption to the total of non-ferrous metals is very slowly decreasing, being—by weight—around 15; by volume it is 11.8 for 1956 and 9.4 for 1966. The same ratio in the United States amounts at present to only 11.3 by weight and 6.5 by volume.

The comparison of the per-capita consumption of the metals, both on a world wide scale and in the United States, shows a great difference in favour of the latter, which consumes 5.6 times more non-ferrous metals and 4.1 times more pig iron than the world average.

TABLE 2

World Consumption of Major Non-Ferrous Metals

Metal	World Consumption (in 1000 short tons)		Increase %	1966 Consumption lb per capita	
	1956	1966	1956-66	World	U.S.A.
Aluminum	3,545	8,320	135	5.2	36.6
Copper	4,365	7,055	62	4.4	23.7
Zinc	2,935	4,660	59	2.9	14.2
Lead	2,455	3,645	48	2.3	9.0
Nickel	250	505	104	0.3	1.9
Tin	195	245	26	0.1	0.7
Magnesium	160	175	11	0.1	0.8
Total Non-Ferrous Metals	13,905	24,605	77	15.3	86.9
Pig Iron	221,900	383,000	73	237.9	979.7
Ratio: $\frac{\text{Ferrous}}{\text{Non-Ferrous}}$	15.9	15.6	–	15.6	11.3

Population (millions)			
	1956	1966	Increase %
World	2,734	3,220	18
U.S.A.	166	197	19

(Source: Metal Statistics, Metallgesellschaft A.G., Frankfurt, W. Germany, 1965-68; and Minerals Yearbook, U.S. Bur. Mines, Washington, 1956-67.)

Table 3 details the geographical distribution in the world consumption of the major non-ferrous metals. The disparity between the per-capita figures for North America and that for the underdeveloped countries of the rest of the world is striking, even if the Communistic countries are added to the latter figure.

TABLE 3

World Consumption of Major Non-Ferrous Metals*

	1966 Consumption*		
	1000 short tons	% World Total	lb per capita
U.S.A.	8,475	34.5	86.1
Canada and Australia	1,040	4.3	56.5
Western Europe	7,150	29.5	40.3
Japan	1,595	6.5	32.6
Communistic Countries	4,945	20.2	9.7
Rest of the World	1,225	5.0	1.5
WORLD TOTAL	24,430	100.0	15.2

*Al, Cu, Zn, Pb, Ni, Sn.

(Source: Metal Statistics, Metallgesellschaft A.G., Frankfurt, W. Germany, 1965-68.)

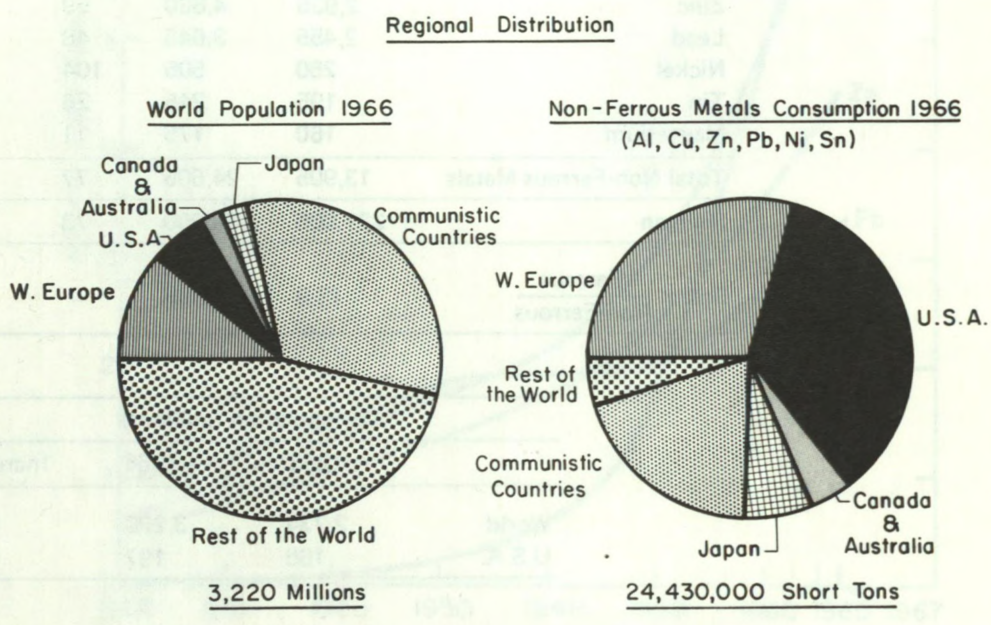


Figure 38. Regional distribution of non-ferrous metals consumption.
(Source: Metal Statistics, Metallgesellschaft A.G., Frankfurt, W. Germany, 1965-68)

Figure 38 illustrates graphically the regional distribution in non-ferrous metals consumption compared with the distribution of world population. It demonstrates that the western world (including Australia and Japan) is inhabited by only 21% of the world population but consumes 75% of the total non-ferrous metals, whereas the Communistic countries, with 32% population, consume 20% and the rest of the world, with almost half of the population (47%), consume only 5%. It is quite obvious that some equalization of this disparity will have to occur, and either a considerable increase in world production of non-ferrous metals or a decrease of the consumption in western countries would have to be expected in the future.

Figure 39 compares the world production of the major non-ferrous metals on the basis of weight and volume. The metals trade traditionally conducts its business by weight, but the user of castings is often more interested in the volume. It is shown here that two-thirds of the total world production of non-ferrous metals by volume are light metals. This figure emphasizes the present and future trend in metals towards aluminum and away from the heavy base metals.

Another aspect of future trends is the price of metals. This is illustrated in *Table 4,* on both a weight and volume basis. Trading by volume would be cumbersome, but the foundryman produces castings of a certain volume, rather than weight. As would be expected, the prices of pig iron and steel are the lowest, but the differences in prices per volume for steel and the light metals are very small when compared with the heavier non-ferrous metals. On a volume basis, copper tends towards the semi-precious metals group.

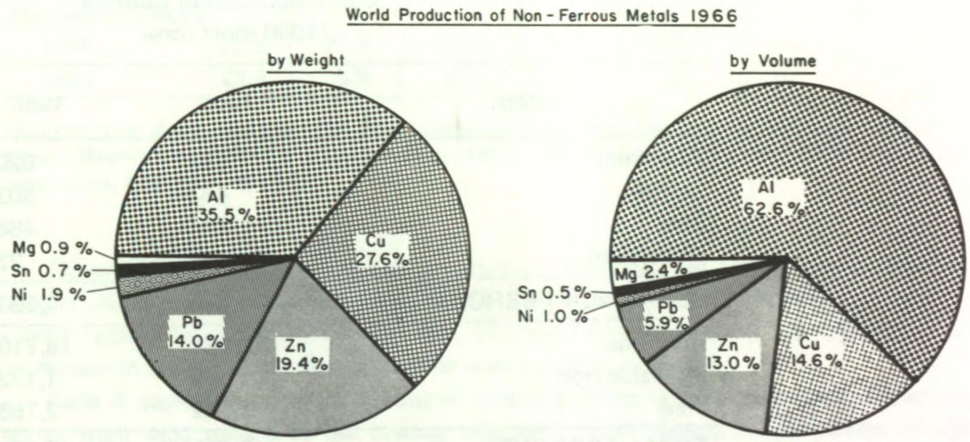


Figure 39. World production of non-ferrous metals by weight and by volume. (Source: Year Book, Am. Bur. Metal Stats, New York, 1968)

Table 5 shows the increase in United States castings production during the last decade and compares it with the increases in population and gross national product for the same period. Again, aluminum grows the fastest, much above the GNP increase. Copper is stagnant (which really means a per-capita decrease). Production in the other two base metals shows much higher growth than for ferrous castings, which increase more or less in

TABLE 4

U.S. Prices for Major Metals by Weight and Volume
(19 January 1970)

Metal	Price per weight (Ingot f.o.b. New York)	Price for 10 cu. in. metal	Metal volume for $1.00
	cents/lb	cents	cu. in.
Magnesium	35.25	22.14	45.16
Aluminum	28.00	27.30	36.68
Zinc	16.00	41.25	24.25
Lead	16.50	67.60	14.79
Copper	60.00	194.40	5.15
Titanium	132.00	216.48	4.62
Nickel	128.00	412.16	2.46
Tin	182.50	481.25	2.16
Pig Iron	2.95	7.67	130.51
Steel	7.26	20.61	48.48

(Source: Iron Age, **205** *(4), p. 76, 22 Jan. 1970.)*

TABLE 5

U.S. Production of Castings
(1000 short tons)

Metal	1956	1966	% Increase 1956-66
Aluminum	397	820	107
Copper	483	503	4
Zinc	347	488	41
Magnesium	18	22	22
TOTAL NON-FERROUS:	1,245	1,833	47
Grey Iron	13,861	15,716	13
Malleable Iron	952	1,132	19
Steel	1,932	2,156	12
TOTAL FERROUS:	16,745	19,004	13
Ratio: $\frac{\text{Ferrous}}{\text{Non-Ferrous}}$	13.5	10.5	–
U.S. Population in millions	169	197	15
U.S. GNP in billions $	419	743	77

(Source: Foundry Mag., Metal Casting Industry Census, 1968.)

line with the population growth, but at a slower rate than the GNP. The ratio of ferrous to non-ferrous castings in the United States by weight, came down from 13.5 to 10.5. In terms of volume (i.e., number of castings) these ratios reduce to 8.8 for 1956 and 5.9 in 1966, respectively. It should be mentioned here that 53% of the 1966 total of all non-ferrous metal castings by weight were pressure die castings.

TABLE 6

U.S. Production of Light Alloy Castings
(in 1000 short tons)

Year	Total	Sand Castings	Perm. Mould Castings	Die Castings	Sand Castings	Perm. Mould Castings	Die Castings
					% of Total		
Aluminum Alloys							
1945	186	98	54	34	52.5	29	18.5
1966	820	145	202	463	18	25	57
Magnesium Alloys							
1945	25.5	21.2	3.4	0.8	83.5	13.5	3
1966	22.4	6.5	6.3	9.6	29	28	43

(Sources: Year Book, American Bur. Metal Statistics, New York, 1968; Minerals Yearbook, U.S. Bur. Mines, Washington, 1956-67; Foundry Mag., Metal Casting Industry Census, 1968; Magnesium Association, New York, 1945-60.)

Figure 40 shows the United States non-ferrous metals castings production for 1966 by weight and by volume. Again the importance of light metals (72% by volume), and aluminum in particular (69%), is brought out. This last figure emphasizes the importance of aluminum in the foundry industry, and its future growth potential.

Table 6 depicts the gradual shifting of casting methods for aluminum and magnesium alloys from sand casting to die casting, with only small changes in permanent mould castings. Sand casting has been the traditional major casting process, but modern developments, made possible by automation and mass-production methods, have resulted in a systematic move towards die casting. A comparison between the production data for 1945 and 1966 indicates a dramatic switch in the percentages of sand and die castings produced. The position has almost exactly reversed. In copper alloys, however, sand castings still predominate with 92% of the total, while permanent mould castings amount to 5% and die castings to only 3% (1966).

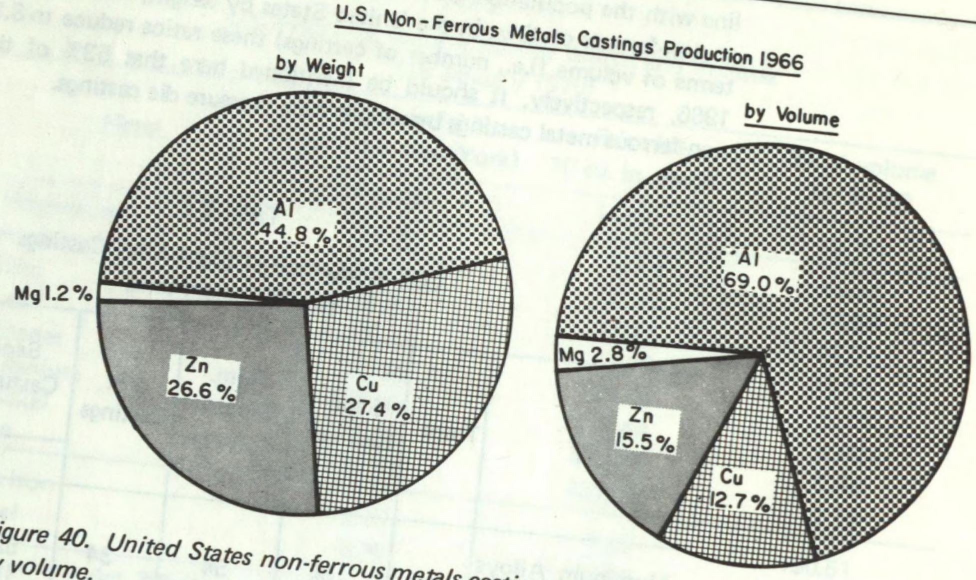
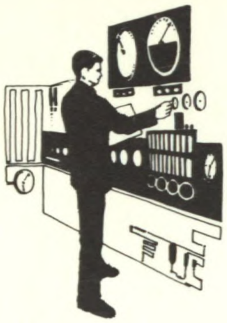


Figure 40. United States non-ferrous metals castings production for 1966, by weight and by volume.
(Source: Foundry Mag. Metal Casting Industry Census, 1968)



Part 3
Future

What tomorrow has in store for us must, of course, be essentially guesswork, even where there is a basis for extrapolating present trends. This is especially true in this era of rapid change, of new materials, of new technologies being created and others rendered obsolete.

Metals

As the statistical tables have shown, the future of non-ferrous metals generally, and of non-ferrous castings in particular, appears bright. There should be no danger of exhausting ore reserves for many years to come, and the source material for light metals is virtually inexhaustible. There may be some changes in the economics of heavy non-ferrous metals, especially of copper* and tin, which have already tended to become semi-precious metals. The tremendous rise in the production and consumption of aluminum will continue; magnesium also should gain in importance as a casting metal. The ratio of ferrous to non-ferrous metals will further decrease, although iron consumption will always predominate.

A very important factor affecting the demand for non-ferrous metals will be the industrialization of the less-developed countries of South America, Africa and south-eastern Asia, as well as the Communistic countries. Even a moderate increase in their metals consumption will double or treble the world requirements for non-ferrous metals.

Casting Quality

The main factors in future development of the non-ferrous foundry industry will be (a) improved casting quality, (b) superior alloys, (c) modernization of foundry equipment and processes, and (d) competitive economics.

We know that a casting is superior to any form of fabrication for innumerable applications, but we have to sell this idea to the designer and user, and we have to make a quality casting which is equal to or better than, as well as cheaper than, any competing product.

Essentially there are two kinds of castings: a quantity grade, and a high-quality grade. Even in so-called quantity castings, what was once acceptable is no longer so. The days are gone when metal was alloyed by colour or shape of the scrap, and when temperatures were "estimated" by so-called "specialists". I remember in many instances, when handling trouble-shooting jobs, the only conclusion to come out of an investigation of casting defects was to recommend the installation of proper temperature-measuring devices.

In this day and age of fierce competition from alternative materials, castings can no longer be considered as just simple shapes. All castings, even those made from the cheapest materials, will eventually have to be designed to optimize weight, serviceability, aesthetic appeal, and cost, if the foundry industry is to survive.

High-quality castings should not only be designed for maximum properties in areas required for high-stress service applications, but have to be produced to obtain optimum

*To illustrate the changing economics of copper, it should be understood that the average grade of copper ore mined in the United States has declined from about 3% in 1880 to about 2% in the 1906-10 period, to 1% in the 1941-50 period, and to 0.72% in 1960 (110).

casting quality (grain size, gas content, proper solidification conditions, and careful casting procedures). The tonnage involved is still relatively small, but it will grow, as designers in other industries take advantage of the benefits which the air- and space-craft industries now derive from premium-quality castings.

The quality concept should be developed. But it should be realized that this concept includes product design and engineering, as well as manufacturing design and processing. Quality-control testing is important, and the trend in this field is toward more sophisticated nondestructive methods. There are a host of these, including radiographic and fluoroscopic examination with image intensification, the use of radioactive isotopes and tracers, sonic and ultrasonic testing, as well as eddy currents, liquid penetrants, microwaves, electrical conductivity, stress coat, pressure testing, etc. Quality controllers, of course, should be properly qualified and trained to avoid over-zealous interpretation of test results, which could prove costly to the foundry.

Better Alloys

The development of better alloys is another factor. The mechanical properties to be expected in light alloy castings in the near future, if present trends in alloy research continue, are summarized in *Table 7*. The properties of the strongest commercial aluminum and magnesium alloys now available in premium-quality castings, the results achieved in recent experimental work, and the expectations for the near future, are all compared with the mechanical properties of premium-quality steel castings. It is apparent that the strength-to-weight ratios of the light alloys compare very favourably with those of cast steel. Work on improvements of copper- and zinc-base casting alloys also has been started, but very few results are as yet available.

Automation

A third factor in the equation for progress is the modernization of foundry equipment and processes. It is inevitable that the casting industry, to remain competitive, must eventually automate all phases of its casting operations. Since faulty workmanship is the largest single cause of poor product quality, and labour is becoming more difficult to hire and is a fast-soaring cost factor, it seems logical to assume that, in the not distant future, manual labour will rarely be used in foundries.

Full automation of melting, casting, trimming, finishing and testing operations is now under way in the die-casting industry, but similar methods are also being introduced in permanent mould casting (e.g., low-pressure and counter-gravity casting), and even in sand foundries (sand preparation and moulding). By instantly relating detailed work instructions, processing data and quality-control-test results, the computer will play a vital role. The use of computers will open new horizons for the production of highest-quality, lowest-cost castings with guaranteed properties.

We are, of course, living in the "Second Industrial Revolution". In the 19th century the first industrial revolution replaced some manual labour by machines; now we are replacing the labour of human brains by computers. To quote from a recent popular book (162):

TABLE 7

Comparison of Strength-to-Weight Ratios of Casting Materials

Casting Material	UTS kpsi	0.2% YS kpsi	El %	Strength-to-Weight Ratio* kpsi	
				UTS	0.2% YS
Aluminum Alloys					
commercial	60	50	10	22.2	18.5
experimental	70	60	10	25.9	22.2
future	80	70	10	29.6	25.9
Magnesium Alloys					
commercial	46	32	10	24.9	17.3
experimental	52	40	10	28.1	21.6
future	60	50	10	32.4	27.0
Steel Castings					
MIL-S-46052 (MR)	180	160	8	22.9	20.4
"	225	175	5	28.7	22.3
"	260	210	3	33.1	26.7

*(Densities: 2.70 for aluminum, 1.85 for magnesium, and 7.85 for steel.)

TABLE 8

U.S. and Canadian Non-Ferrous Metal Foundries

	Al	Cu	Zn	Mg	Exclusive N.F. Plants	N.F. Departments	Total N.F. Producers
1961	3,326	2,397	984	222	3,265	951	4,216
1967	3,020	2,048	898	188	3,083	749	3,832

(Source: Foundry Mag., Metal Casting Industry Census, 1968.)

"The imagination, ingenuity and inspirational qualities of the human being, in partnership with the vast memory and infallible calculation capability of the computer, together make up a strikingly new intellectual factor in our environment. We are only beginning to see where its possibilities can lead us."

"We are in the process of compressing time and space in a way that was inconceivable ten years ago. Even more importantly, we are learning how to intensify human experience through centralized information and instant communication. This is a new world, one filled with adventure and risks."

Full automation of foundry procedures will integrate computer control of all casting variables together with completely mechanical handling. Computer control of the casting operations will involve automatic error compensation through feed back from error detection devices (163).

Of course, conveyors of all kinds are already in use in foundries, but their use will have to be developed much more extensively to replace labour requirements. Operations will be in the hands of electromechanical, computer-controlled robots. Some of them are already used in the die-casting industry. They perform virtually all basic hand movements, but with the difference that the movements are performed again and again consistently, unerringly, without need for stopping and without fatigue. The industrial robot can work 24 hours a day, seven days a week, if desired (164).

The major reasons for full automation are increased productivity and improved casting quality. It is obvious that automation will be easier to apply in large operating units, be it long die-casting runs or large sand-preparation systems.

As an example of full automation, Beswick (165) foresees the future die-casting operation as follows: Present tedious die design and manufacture will be replaced by

"programming information into a computer which controls and records the activities of a sophisticated three-dimensional electronic device used for design and analysis of all new dies. Another electronically-controlled machine automatically fabricates the die components, with the ultimate in accuracy, repeatability and high speed.

"Each die-casting machine is completely automatic, with a 'brain bank' of advanced instrumentation consisting of high-gain small servo-loops which adjust every variable of machine operation to form a high-performance system producing 'perfect' castings. Each casting is removed from the machine, undergoes a series of tests, and is conveyed through a mechanized trimming and machining operation."

A trend exists to fewer but larger foundries; *Table 8* shows a decrease in the number of North American non-ferrous foundries during the period of 1961-1967. The trend is quite obvious for all non-ferrous metals (all 1967 figures are lower than those for 1961), in spite of the fact that United States production of non-ferrous castings rose by 72% during this time.

In so far as foundry equipment is concerned, it seems certain that modern electric furnaces will in the future replace all other melting and heat-treating facilities.

Competition

Another factor in the future development of the foundry industry is price competition. For the most part, in the past, competition existed largely within the foundry industry itself, although latterly there has been an increasing impact from fabricated products:

extrusions, forgings, stampings and weldments. Today, the most aggressive competition comes from plastics (there are currently some 50 different competitive ones), and this trend will probably intensify. To overcome this and other forms of competition the foundryman must offer high-quality castings (be it dimensional accuracy and excellent surface finish, or high strength-to-weight ratio) at reasonable prices. Automation will help in both cases. Computerized cost estimation, as already available (166) for the die caster, will be another tool of the future foundry.

Future Materials

As for the more distant future I would like to add a few remarks made in a paper some five years ago (153).

Prospects of entirely new cast products from the foundry of the future lie in the general area of novel material systems. This covers the field of unconventional combinations of cast metal and one or more added structural phases which may be metallic, intermetallic compound, ceramic, or gas. Such products include dispersion-strengthened alloys made, not by the usual solution and precipitation route, but by such techniques as interaction between dissimilar melts at the instant of pouring, mechanical dispersion by impressed energy or by electrodynamic melting. Is it asking too much to speculate that metallurgical processes analogous to those now applying to colloidal chemistry or to the development of metallurgical surface active agents, may not make possible the economic production of useful cast materials at present completely unimagined?

Going from the microscale to the macroscale, the application of high-strength metallic or non-metallic fibre reinforcements in castings offers intriguing prospects in the creation of unique materials, just as, for example, the deliberate and controlled addition of gas porosity has led to the creation of foamed metals, combining durability with lightness and ease of working and handling.

Concluding Remarks

The future is already upon us and holds the promise of many interesting and useful developments in the adaptation of cast metals to the service of mankind. It should never be forgotten that such progress will be founded on our heritage of the experience and knowledge of past generations, dedicated to developing the metal industry of which the foundry is the cradle.

I would like to close this paper with a quotation from a recent editorial by Jack Schaum (167):

"The future is impossible. But history proves that we will produce impossible castings with impossible properties, using impossible processes. While the scientist is still discovering what is, the engineer continues to create what never was. Doing the impossible has become a way of life for the metalcasting industry."

I also join Jack Schaum in saying:

"My hat off to the adventurous, imaginative foundrymen of the past and of the future, who have had, or will have, the courage to risk failure while proving it is possible to do the impossible."

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**Note at press time: A rather convincing explanation of the difficulties encountered by Cellini with obtaining the proper melt temperature and fluidity was recently offered by Bruno Bearzi, a renowned Italian foundryman, who restored the slightly damaged statue after World War 2. Chemical analysis of a sample taken from the head of Perseus revealed that the tin content of the bronze was only 1.7%, instead of the usual 10%. Old records of the Medici family, still available, show clearly that Cellini received enough tin for about a 12% content. It seems that Cellini sold most of the expensive tin and tried to cast the statue with almost pure copper, a practically impossible feat.*