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METALS AND ALLOYS FOR ARCTIC USE

Prepared by the Staff of the
Physical Metallurgy Research Laboratories
(Edited by R.C.A. Thurston)

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FOREWORD

The essential role of the Physical Metallurgy Research Laboratories (PMRL) is to carry out fundamental and applied research on metals and alloys for the immediate and long-term benefit of the Canadian mining and metals industry. One of the important functions associated with this role is the provision of practical and consultative metallurgical services to the Armed Forces, to other government agencies and to Canadian industry at large. The present monograph was initiated in accordance with this function and was planned specifically with the objective of supplying guidance and data to those involved in the selection and application of ferrous and non-ferrous structural materials suitable for low-temperature operation, with particular reference to the Canadian North.

The expanding interest in the development of the northlands resulted in a proliferation of articles, presentations and publications dealing with the subject, but none has adequately fulfilled the requirements laid down for the monograph. Hence, the project was undertaken and completed by the staff of PMRL, and was based on a critical survey of technical information from internal and external sources. Every attempt was made to ensure that the data were reliable and as up-to-date as possible, and that sufficient references were included to enable the interested reader to investigate the characteristics and applications of a particular alloy in more depth than could be accommodated in the monograph. It is hoped that this monograph will serve as a useful handbook for those already engaged in or about to become engaged in the manufacture of engineering components and structures for the North, and will assist in enabling Canadian industry to maintain its competitive position in the world market.

AVANT-PROPOS

Le rôle principal des Laboratoires de recherche en métallurgie physique (PMRL) est d'effectuer de la recherche pure et appliquée sur les métaux et les alliages, dans l'intérêt, à court et à long terme, de l'industrie minière et métallurgique canadienne. Une des fonctions importantes associées à ce rôle, est d'assurer des services pratiques et consultatifs en métallurgie, aux Forces armées, aux autres organismes gouvernementaux ainsi qu'à l'industrie canadienne à l'étranger. Cette présente monographie a été préparée conformément à cette fonction et planifiée justement dans le but de fournir des conseils et des données à ceux engagés dans la sélection et l'application des matériaux structuraux ferreux et non-ferreux, appropriés à des opérations à basse température, surtout en ce qui concerne le grand nord.

L'intérêt, toujours grandissant, porté au développement des terres nordiques a donné suite à de nombreux articles, présentations, et publications concernant ce sujet, mais sans qu'aucun d'entre eux ne satisfasse les conditions requises pour la monographie. Par conséquent, le projet a été entrepris et complété par le personnel des Laboratoires de recherche en métallurgie physique, qui s'est basé sur une étude critique de l'information technique recueillie de sources internes et externes. Tout a été fait afin d'assurer des données aussi sûres et à jour que possible et afin de fournir assez de références pour faciliter la tâche du lecteur intéressé à enquêter, plus en profondeur que la monographie n'a pu le faire, sur les caractéristiques et les applications d'un alliage en particulier. Il est à espérer que cette monographie sera un guide utile pour ceux qui sont déjà engagés ou qui le seront bientôt, dans le processus de fabrication d'éléments et de structures industriels pour le grand nord, et qu'il aidera l'industrie canadienne à maintenir sa position compétitive sur le marché mondial.

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ABBREVIATIONS, SYMBOLS AND CONVERSION FACTORS

A - stress ratio in fatigue, S_a/S_m

DS - axial loading fatigue

E - elongation

FS - fatigue strength at 10^7 cycles, unless otherwise stated

K_t - theoretical stress concentration factor

K_c - critical stress intensity factor (plane stress)

K_{Ic} - critical stress intensity factor (plane strain) [K_c and K_{Ic} are fracture toughness parameters]

K_{ISCC} - critical stress intensity factor for stress-corrosion cracking

NDT - nil ductility transition temperature

NTS - notched tensile strength

PB - plane bending fatigue

Q - quenched

R - stress ratio in fatigue, algebraic value of S_{min}/S_{max}

RA - reduction of area

RB - rotating bending fatigue

RT - room temperature

S_a - one-half the range of stress

S_m - mean stress

S_{min} - minimum stress

S_{max} - maximum stress

Soln treated - solution treated

T - tempered

UTS - ultimate tensile strength

YS - 0.2% yield strength

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1 ksi = 6.895 MPa

1 ksi$\sqrt{\text{in.}}$ = 1.100 MPa$\cdot$m$^{1/2}$

1 ft lb = 1.356 Joules

1 lb/in.^{3} = 2.768 x 10^4 kg/m^3

METALS AND ALLOYS FOR ARCTIC USE

1. GENERAL INTRODUCTION

The northlands of Canada, which may arbitrarily be defined as the region north of 60°, can be regarded as a vast, but not inexhaustible, storehouse of mineral, oil and gas resources. These non-renewable resources exist in an area that is in a delicate state of ecological balance, the disturbance of which could lead to irreversible damage to the environment, with consequent detrimental effects for the inhabitants and the wild life of the north. The next decade will undoubtedly witness a marked upsurge in industrial activity associated with these resources, in spite of the difficulties imposed by the lack of easy accessibility and by the severe climatic conditions. It is, therefore, of manifest importance that such activity should proceed in an orderly and responsible manner with a maximum of safety, a minimum risk of pollution, and the optimum utilization of materials.

In order to facilitate the attainment of these objectives, appropriate technical information will be required on the characteristics of available engineering metals and alloys with respect to service in Arctic and sub-Arctic environments. The primary purpose, therefore, of the present monograph is to provide a review of such data based on an extensive survey of the published literature. The monograph should give guidance to the design engineer in his selection of suitable ferrous and non-ferrous structural materials and, at the same time, should be of some assistance to the construction and maintenance engineers.

The philosophy behind the format of this monograph may require some explanation. Data or technical information sheets covering a wide range of engineering alloys, wrought and cast, were obviously essential for the designer. However, it was considered desirable, in addition, to supply some background on the general characteristics of the various alloy systems, their advantages and disadvantages, on typical engineering applications, and on potential problem areas. The backbone of the monograph, therefore, consists of sections on irons and steels, aluminum, magnesium, titanium, copper, lead, tin, nickel and zinc alloys, each section being followed by individual data sheets on selected alloys plus appropriate references. Separate sections were included on those characteristics which were judged to be the most significant from a design point of view, namely fracture toughness, corrosion resistance, fatigue strength and weldability. The last of these deals also with welding at low temperatures and should be particularly useful to construction engineers.

The choice of a material for an application in a given environment is normally determined by a complex combination of technical, economic and aesthetic considerations which change only gradually from region to region. Thus most of the factors leading to the selection of a particular material for use in the North would be very similar to those in more southern regions. For example, the most obvious "special" condition associated with the North is the low ambient temperature. However, minimum winter temperatures in Alert, NWT (latitude 81°) are only about 11°C (20°F) lower than in Ottawa (latitude 45°) although the average value would naturally be much lower. Hence, only those material properties which deteriorate appreciably below, say, -34°C (-30°F) would warrant special consideration for Arctic service as compared to service in Ottawa.

Apart from the direct effect of low temperature on material characteristics, there are the associated human difficulties which should be taken into account for any engineering structure, such as a pipeline, which must be constructed by field welding. These will obviously exert some measure of control over the available construction periods, and may influence the techniques and materials used.

A second important factor is the general inaccessibility of the northern regions. As a consequence, the designer must pay more attention to such aspects as reliability, ease of maintenance and ease of transportation. Reliability is always of major condern, but owing to the difficulty of replacement, a given item of equipment for use in the Arctic may have to be designed to be more reliable than one to be used closer to large centres having ready sources of service and supply. The lack of easy access plus the severe climatic conditions emphasize the desirability of minimum maintenance. For example, regular painting of outdoor structures such as bridges will be more difficult and more expensive. Transportation problems will tend to place a premium on the lightness and compactness of equipment, and may swing the balance in favour of lower density and/or higher strength materials.

Other considerations associated with the remoteness of the areas concerned are the provision of temporary structures and the use of local labour. Many communities in the North have become "ghost towns" when a localized operation, usually a mine, has been closed down. In such cases, buildings and equipment that can be easily installed and removed would be advantageous. Lightness, recovery value and fabricability are involved. The last of these must also be borne in mind if assembly has to be carried out by the limited skilled labour available.

A third factor relates to pollution and environment control. From the metallurgical viewpoint, this concerns the disposal of discarded metal objects (containers, components, structures), and is affected by such aspects as scrap recovery value and rate of degradation. Ghost towns, mentioned above, are an obvious example but a far more prevalent one is the presence of thousands of abandoned oil drums. Corrosion resistance is normally regarded as a desirable characteristic, but in the case of objects of little recovery value, it is conceivable that this attitude should be reversed if environmental pollution is to be avoided.

With the foregoing considerations in mind, the alloys in the various groups were selected and the data sheets prepared. In view of the very large number of engineering alloys, both cast and wrought, that are available, the selection had to be somewhat arbitrary in order to keep the size of the monograph within reasonable limits. In general, only the more-widely used alloys have been included, and their choice was partially governed by the desirability of providing a range of properties suitable for most applications.

As regards the actual data sheets, an attempt was made to obtain reliable values for those properties considered to be of principal interest to the designer for room-temperature and low-temperature conditions. The lowest temperature recorded to date in the Arctic regions was about -62°C (-80°F), and it was therefore decided to set -73°C (-100°F) as the lower limit for the data. In some cases this involved justifiable interpolation from curves primarily intended to show cryogenic properties.

Since it was manifestly impossible to cover even the selected alloys for the various methods of manufacture (rolling, extrusion, forging), heat treatments and sizes, the data presented are related in general to a specific condition of the material. For more detailed information, the reader should consult the appropriate references which are listed at the end of each Section. Although every effort was made to ensure the reliability of the data, the values should be regarded as typical and not guaranteed. Grateful acknowledgement is extended to all those sources, government agencies, technical and professional societies, and alloy manufacturers, from whose publications the information presented in the data sheets was procured.

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2. DESIGN AND CONSTRUCTION FOR LOW TEMPERATURE

2.1 FRACTURE TOUGHNESS

L.P. Trudeau*

Notch toughness is a measure of the ability of a metal to flow plastically under high localized stresses, such as might occur at the root of a notch. Notches may be inherent in the design, may result accidentally from tool marks, shrinkage cracks, voids or cracks in welds, or electrical arcing, or may develop in service from fatigue or environmental effects. Low, or intermediate-strength ferritic steels, in particular, are susceptible to a marked decrease in notch toughness as the temperature is lowered through the transition range. The main complication in the interpretation of the strength significance of this transition arises because the notch toughness can be very much higher under slow strain rate loading that it is for impact rates. It is thus necessary to consider two notch strength parameters which may be called the static toughness and the dynamic toughness. The transition range is determined by an impact test of some type and is, therefore, concerned with a variation in dynamic toughness. Above this range, the energy absorption is relatively high and the fracture is predominantly by what is called "shear" and is fibrous in appearance; below, the energy absorption is low and the fracture crystalline, propagation being primarily by crystallographic cleavage. In the latter case, fracture is frequently sudden and catastrophic.

Because the static toughness is very much higher than the dynamic toughness for several tens of degrees below this transition, steels of ordinary section thicknesses, i.e., up to about 2 in., with small cracks (of the order of 1/2 to 1 in.) can develop yield strength on the net section in this temperature range

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*Research Scientist, Engineering Physics and Refractory Metals Section.

for ordinary, non-impact rates of loading. Cracked-strength tests of the proof-test type where the structural application is simulated as far as possible, are rather easy to do at ordinary strain rates, so the designer can determine whether the "average" cracked strength is adequate. Usually this strength will be adequate and an assessment must then be made of the consequences of a brittle failure versus the costs and other factors involved in the use of a steel with a lower dynamic transition temperature which would eliminate this possibility.

A failure possibility does exist at quasi-static loading rates because the "average" strength depends on exhausting the average ductility at the crack tip but, in manufacture, shipping or service, local ductility can be impaired by various causes such as mechanical damage from tool scrapes. The fast fracture of this brittle region introduces local dynamic loading and the continued propagation is opposed by the low dynamic toughness. For example, experiment has shown that under ordinary tension test rates of loading, a structural steel plate below the transition temperature and with a 5/8-in. deep edge fatigue crack, developed a net section strength of 40,000 psi, but failed at the same temperature at net section stresses as low as 16,000 psi, when the local ductility at a 1/2-in. deep edge-notch tip was impaired over microscopic distances.

While these exceptional low stress failures have been comparatively rare, the consequences have often been serious and various tests are used in attempts to assess the failure hazard by empirical correlation. The simplest and most commonly used test, and therefore the one from which most data are available, is the standard V-notch Charpy (CVN) impact test. Typical CVN values for the individual alloys have therefore been included in the data sheets. The selection of the actual design criteria for a specific application, however, is not so simple, and is generally based on experience, full-scale tests and/or failure analysis, and expressed in terms of the CVN test.

Code writing bodies have been particularly active as regards notch toughness considerations for the lower-strength steels used in ship structures, storage tanks, pipelines and bridges, and industry has moved towards standardizing on the CVN test for specification purposes. Requirements may be expressed in terms of a minimum energy absorption value at a specified temperature, or a transition temperature at which the fracture contains 50% shear. In field-erected structures of semikilled steels where no toughness specification exists and brittle failure is considered to be a problem, it is recommended that a minimum CVN value of 15 ft lb be specified at the lowest contemplated operating temperature. For killed plain-carbon steels and certain alloy steels, the available evidence indicates that a value of 30 ft lb or more may be required.

To give some guidance on this and other questions, the dynamic toughness of four Canadian structural steels (CSA G40.4, G40.11B, G40.12B and G40.18) has been measured as a function of thickness over the range 1/4 to 2 in. and over the temperature range from -75°C (-100°F) to room temperature. Some results are given in Figs. 2.1.a to 2.1.d which are reproduced from Ref. 15. From these graphs it may be noted, for example, that a dynamic toughness of 40 kpsi $\sqrt{\text{in.}}$ correlates with 9 to 10 ft lb Charpy in the semikilled structural steel G40.4, whereas it correlates with 45 to 50 ft lb in the low-alloy weathering steel G40.11B.

For high-strength steels (UTS >180 kpsi), the CVN test becomes less discriminating and less informative. Typical CVN values range between 15 and 30 ft lb, and decrease very gradually as the temperature is lowered. Hence, CVN data in general are not of much significance to the designer. Fortunately, however, linear elastic fracture mechanics (LEFM) theory can be applied for design purposes in this range, and is particularly successful at and above the 250 kpsi UTS level. Strain rate effects on toughness are not usually significant in this strength range and slow strain rate values are used.

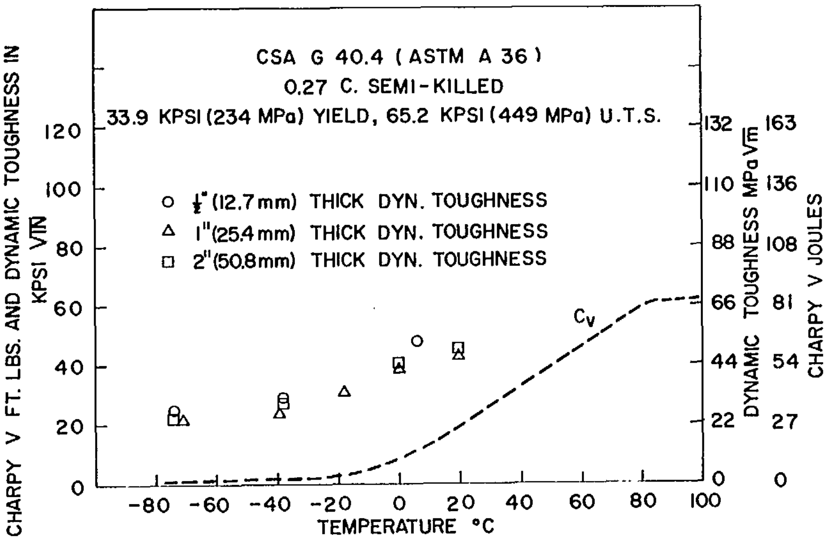

Fig. 2.1.a. CSA G40.4 (ASTM A 36) Steel. The 1-in. thick specimens are slightly below, and the 1/2-in. thick, slightly above the 2 in. This trend may result from chance or from differences in plate properties through the thickness.

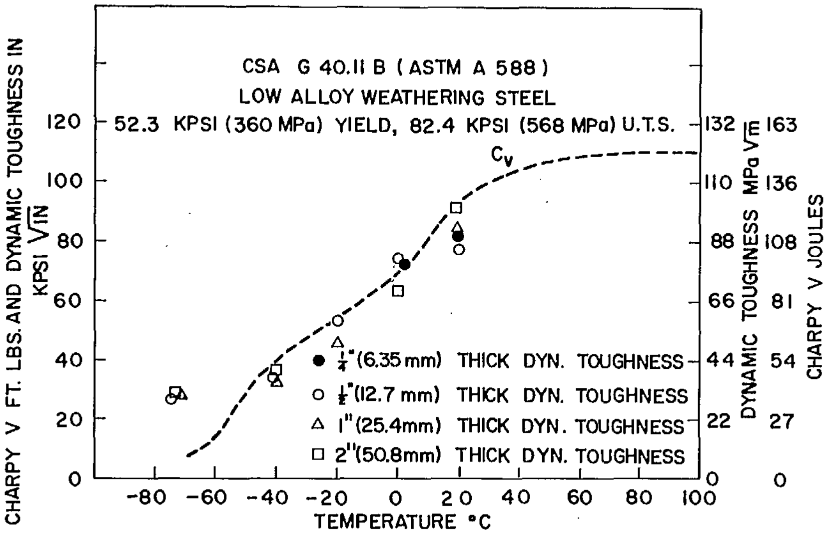

Fig. 2.1.b. CSA G40.11B (ASTM A 588) Steel. There is no consistent thickness effect on the stress intensity for fracture initiation.

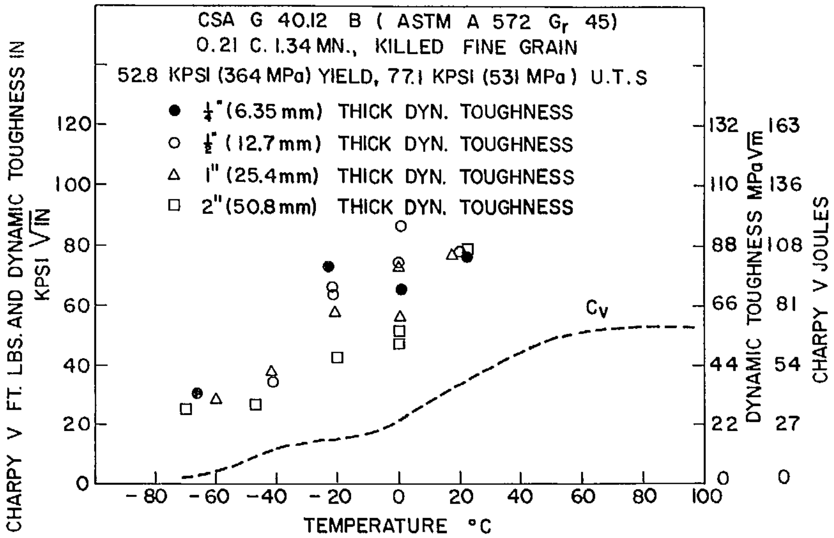

Fig. 2.1.c. CSA G40.12B (ASTM A 572) Steel. The scatter in test results is unusually high in the middle of the transition range for thinner specimens machined from the 2-in. thick plate. There was some consistent inhomogeneity in Charpy energies through the plate thickness but it is not known whether inhomogeneity is the major cause of this scatter.

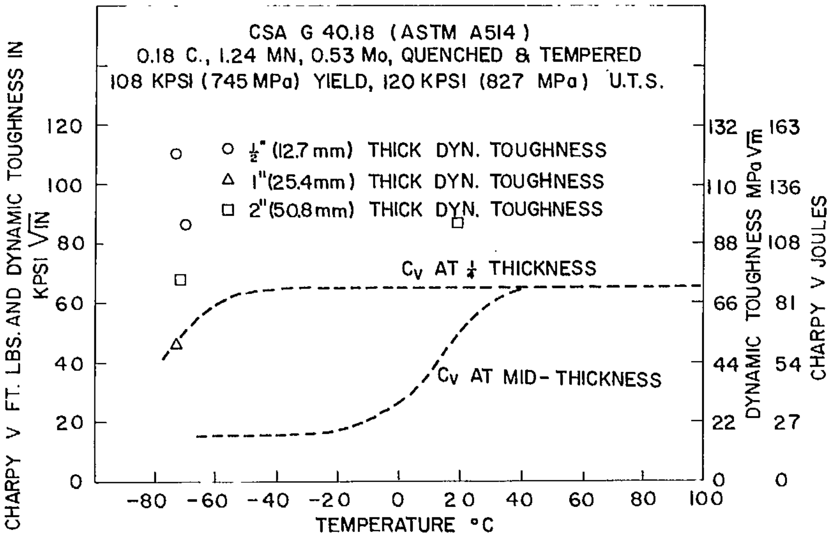

Fig. 2.1.d. CSA G40.18 (ASTM A 514) Steel. The properties at mid-thickness were poorer than near the surface but at -72°C the 2-in. thick plate still required a force of about 1/3 the peak value to propagate the fracture. The properties for thinner specimens depend on the thickness location from which they came so there was little point in an extensive series of tests. There was no load drop in the load-time trace for the 2-in. thick specimen at room temperature, so this data point is not quantitatively useful.

Essentially, the LEFM approach should enable the designer to calculate the maximum allowable flaw or defect size for a given material under known service conditions of stress and temperature. The calculation is based on the pre-determined value of the fracture toughness and, in turn, permits the establishment of realistic criteria for non-destructive inspection of the product. As in the case of the CVN transition temperature approach, the fracture toughness parameter also provides a useful yardstick for the initial selection of the most suitable alloy. While the application of LEFM principles has made remarkable advances during the last 20 years, the majority of the data available was obtained at room temperature and in many cases the fracture toughness values quoted are not valid by current standards. Information on the effect of temperature is limited, but indicates that steels, with few exceptions, show a decrease in the parameter as the temperature is lowered but non-ferrous alloys often do not exhibit the same trend.

The movement or distortion necessary to exhaust fracture propagation ductility is not automatically taken into account in using the LEFM approach. The implicit assumption is that strain energy release, i.e., an elastic unloading wave, can supply the necessary displacement as the fracture propagates. Generally, though, this is not the case so whether or not complete fracture ensues when the critical stress intensity is exceeded depends on the type of structure (see Ref. 15 for a fuller discussion). If the designer knows that the possible distortion in the structure is negligible, then a simple dynamic ductility sorting test such as the nil-ductility drop-weight test (ASTM E-208) may give an adequate basis for assessing freedom from catastrophic failure. A gas pipeline can need much more ductility because mechanical damage of the pipe may introduce both a hardened surface layer as well as denting, and the pressurized gas acts as a fast response load to cause finite displacements as the layer cracks and the dent tends to "iron out".

A larger-scale test where the fracture runs for several thickness lengths will allow a better assessment of the fracture behaviour than the Charpy test. This occurs because the fracture must run for a thickness length or more before it outruns the constraint of the starting notch and develops its own natural constraint which is a function of the propagation ductility. If the maximum freedom from fast fracture propagation is desirable, then one can use a dynamic tear test to ensure that propagation is largely or completely free from crystallographic cleavage at the lowest temperature and that the energy absorption in the test or in a supplementary Charpy test is representative of high steel quality. The dynamic tear test is under consideration for ASTM standardization and the data now available cover a wide range of materials and section sizes.

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2.2 WELDING AND WELDABILITY

Introduction

K. Winterton*

Weldability is a material characteristic as are the other topics dealt with in Section 2 of this Monograph, namely, toughness, corrosion resistance and fatigue strength. Welding, however, is a technique commonly used in fabrication and construction. It was considered desirable to discuss both the characteristic and the technique in order to give the designer an insight into the problems involved at low temperatures. Nevertheless, it is recognized that the information in this subsection will be of benefit primarily to the construction engineer.

Welding in cold weather has been a subject of interest to the Department of Energy, Mines and Resources for many years and several reports have been issued (1-3). A comprehensive survey (4) of the subject, at least in relation to the welding of steel, was made in 1963. A few additional papers of interest on the general subject (5-7) have appeared since that time.

Welding is a common source of geometrical and metallurgical flaws from which brittle cracks, stress-corrosion cracks and fatigue cracks can initiate. At the same time, welding usually provides fields of residual stress which encourage the initiation of cracking and support its extension and propagation. The continuity of welded construction has many advantages, but it has the disadvantage that it facilitates large-scale or catastrophic brittle failure.

To the extent that welding in Arctic regions must be used for construction and repair in the field, it is therefore important to know how low ambient temperatures may affect these special welding dangers, and to make proper use of the techniques that have been suggested or developed to avoid or minimize these dangers.

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*Head, Welding Section

Materials

Human and mechanical difficulties arise in welding at low temperatures, independent of the material to be joined, so that what is said under these headings is applicable for all materials.

Metallurgical difficulties can arise in welding at low temperatures, but in this case it is convenient to distinguish between ferrous and non-ferrous metals. Many irons and steels, when quenched rapidly from high temperatures, undergo a partial or complete transformation to martensite or other low-temperature-transformation products, with considerable hardening, and this is the source of most of the metallurgical difficulties that can arise in welding at low temperatures. There is no parallel for this in any of the non-ferrous metals that might be used as structural materials, except some of the titanium alloys.

Under the heading of metallurgical difficulties, therefore, almost all that will be said is applicable only to the hardenable steels (and irons).

Human Difficulties of Welding in Cold Weather

Manual welding requires that the eyes and hands should work together. Exposure to cold does not affect visual reactions, but it does remarkably reduce the dexterity and strength of the hands. The exact conditions under which this begins have not been determined, but it is clearly present within half an hour at -9 to -7°C (15 to 20°F). Wind seems to play a part, but this has not been systematically investigated. It seems most likely that in welding, impairment would usually take the form of difficulty with starting and maintaining the arc, rather than inaccuracy in locating the weld area.

It has been shown that the harmful effects of cold and wind can be reduced by wearing suitably designed heavy clothing. However, such clothing tends to interfere with the operator's ability to weld properly. In some tests carried out at Fort

Churchill, Manitoba (1), two highly skilled operators attempted to deposit welds with a controlled energy input at temperatures of -34, -29, -23 and -18°C (-30, -20, -10 and 0°F). They were shielded from the wind by a canvas enclosure, and wore Arctic clothing designed for the Canadian Armed Forces. Bulky felt inner mitts and heavy leather outer mitts destroyed their ability to make fine adjustments of arc length and electrode advance. Even when light woollen gloves were substituted and the work cycle was reduced to avoid excessive chilling, the extra clothing required for work at these low temperatures caused irregular deposition and resulted in a highly variable energy input. Resultant welds contained a much greater number of defects than did welds deposited by an automatic electrode feeder in a cold room (2).

It has been suggested that the problem of bulky clothing could be overcome either by using electrically heated suits similar to those used by aircrew, or by using lightweight suits heated by chemical canisters using breath moisture to generate heat.

At present the best that can be done is to protect the operator from the wind, provide warm clothing and regulate work shifts. One article, describing Russian experience with welding at -34°C (-30°F), stated that warmly clothed operators worked for two hours, and rested for two hours in a warm shelter. Conditions of temperature and exposure will vary with the nature of the work, and work periods should be fixed on the basis of experience.

Flaws associated with poor workmanship because of operator discomfort are particularly likely to occur in manual welding. However, a similar trend may occur even with semi-automatic and automatic welding, or because of the work done by the welder's helpers, inspectors or any other personnel connected with the operation.

Many standards specify or at least recommend that no welding shall be done if the welders are exposed to inclement conditions. The Canadian Standards Association Specification W59 requires that the welder and the work must be adequately protected against the direct effect of wind and snow, and all necessary steps are to be taken to enable the operator to work in reasonable comfort. This seems a logical approach. The shelters may be heated if necessary so that the "local" ambient temperature is high enough to permit the welder to make good-quality welds.

Useful practical information is contained in a booklet (8), published by the Defence Research Northern Laboratory of the Department of National Defence, Canada, for the guidance of personnel engaged in D.E.W. line construction.

Material and Mechanical Difficulties of Welding in Cold Weather

Those who drive a car in Canada already know much about the effect of cold on machines. For the project at Fort Churchill, previously mentioned, a supposedly "winterized" engine-driven motor generator was supplied. This was found to be unsatisfactory after exposure to temperatures of around -37°C (-34°F), and was abandoned in favour of a power source located in a heated room. Failure of an internal combustion engine to start and operate at low temperature can be caused by loss of battery efficiency, increased viscosity of lubricating oils and greases, changes in fit between bearings and shafts, and the reduced volatility of fuels.

The efficiency of a lead-acid battery is reduced at -40°C (-40°F) to a value of 10 to 25% depending upon the current drawn, compared with 100% at 27°C (80°F). Better efficiency, 40% at -40°C (-40°F), is obtained with silver-cadmium batteries, but the latter cost approximately ten times as much as lead-acid batteries. It is customary therefore to use lead-acid batteries in cold climates and to maintain their efficiency with electrical heaters or by storing them in a warm place when not in use.

Special lubricating oils and greases are required for operation under cold conditions. This is because the wax present in ordinary lubricating oils precipitates at low temperature to form semi-solid wax sponges which prevent oil from reaching the pump. The viscosity index applied to oils for normal temperature is not valid in the case of these newer oils, which must be considered on the basis of actual viscosity at the temperature extremes of operation. Gear lubricants that are too viscous at low temperatures tend to "channel" rather than to flow around the gears to provide a lubricating film. Greases for low-temperature service must have low enough viscosity to be delivered to the lubrication site and they must be fluid enough that the starting torque is not excessive. Low-viscosity petroleum oils, or synthetics such as di-esters, silicones and uncon fluids, are used as bases in these low-temperature greases.

The volatility of gasoline must be high for winter starting, and in order to prevent difficulties associated with high volatility, such as vapour lock and carburettor icing, these fuels must contain anti-icing compounds.

A change of fit or tolerance due to differential contraction may occasionally cause trouble. One investigator (2) reported difficulty with the steel shafts and bronze bearings in an automatic electrode feeder. At temperatures below -40°C (-40°F), the bronze bearings would bind on the steel shaft of the variable speed carriage. When the bronze bearings were replaced by roller bearings properly lubricated for the low temperature, the machine operated satisfactorily.

Welding helmets provide a problem for operators wearing warm headgear because of the limited adjustment allowance on existing headbands. More urgent is the problem of frosting of the lens due to condensation from the operator's breath. This can be prevented by battery-powered resistance heaters, but the battery replacement cost is high. Hand shields have been successfully used since the operator can adjust the distance of the shield from the face to prevent frosting.

The most widely used insulation on welding cable is a synthetic type of rubber, 5BR, which serves as an insulation and a jacket. This synthetic rubber is flexible down to -43°C (-45°F) and will pass a cold bend test at this temperature. However, at lower temperatures the cable insulation will become brittle and could fail after a sharp blow. It is conceivable that the operator would complain of the stiffness of the cable at -40°C (-40°F), simply because it would resist flexing. Maximum flexibility at -40°C (-40°F) can be obtained by using either a butyl-type insulation or a special low-temperature geoprene. Butyl will sustain a flame, whereas geoprene will not. Neither butyl nor geoprene is a standard item. Another possibility might be to use cable of slightly smaller size than that recommended for use at normal temperature. The heat generated should help maintain flexibility in the insulation without being enough to cause damage.

The adverse effects of wind during field welding are widely recognized, and it is clear that wind will aggravate the difficulties of welding at low temperature. However, few people have investigated directly the effect of wind and low temperature in combination. In one investigation (9) on the manual-arc welding of steel, it was found that effective welding could not be carried on with a wind velocity in excess of 20 mph, and the arc could not be maintained at all with wind velocity in excess of 30 mph. Although there was little effect on weld strength, ductility tends to decline with increasing wind velocity and the effect is more marked at the lower welding temperatures. The weld metal also showed poorer impact values when deposited with a wind velocity of 20 mph. For the manual-arc welding of steel, wind shields and shelters of various materials and of differing shape and complexity are often used. The inert-gas-shielded processes commonly used in the joining of non-ferrous metals are even more sensitive to wind and draughts, so that screens or shields are usually necessary.

The storage of electrodes under conditions of low temperature is not difficult. Since the moisture content of cold air is considerably lower than that of air at normal temperatures, storage at the working temperature will not harm ordinary electrodes. However, the danger of moisture precipitation when cold electrodes are brought into warm humid atmospheres must be considered. In the case of low-hydrogen electrodes, storage in sealed containers at work temperature or in a controlled-humidity cabinet would be necessary.

Acetylene may be needed for cutting and preheating. Carbide generators cannot, of course, be used below the freezing point of water, so that acetylene cylinders are generally used in cold weather. However, the pressure of acetylene dissolved in acetone in a cylinder is very sensitive to temperature changes. In one case, acetylene was charged to 250 psi at 21°C (70°F) in a cylinder containing 34.8% acetone by volume. If the cylinder were stored at a temperature of 49°C (120°F), the gauge pressure would rise to 440 psi, and if the temperature dropped to -45°C (-45°F), the gauge pressure would register only 20 psi. Under field conditions at low ambient temperature, acetylene cylinders should be located in enclosures heated to approximately the temperature of charging.

Published information concerning the over-all effect of low temperatures on man and materials is still sparse, but from the foregoing items of particular interest to welders, it is clear that there is room for development work in this area.

Metallurgical Difficulties of Welding in Cold Weather

A more comprehensive treatment of the metallurgical difficulties of welding steel in cold weather, and of the methods used to overcome these problems, will be found in a bulletin (4) issued by the U.S. Welding Research Council.

The metallurgical problems arise mainly in connection with the hardenable irons and steels, which tend to form hard, brittle martensite on quenching from high temperatures. The effect of low ambient temperatures is to increase the quenching rate, and so to increase the extent of this transformation. The principal concern is that cracking may occur, but brittleness associated with the martensitic structures may also be cause for anxiety.

One of the most important types of cracking that may occur is heat-affected zone (HAZ) cracking, which takes place in the coarse-grained part of the brittle martensitic zone adjacent to the weld in hardenable steels. Sometimes the cracks are so small that they can only be seen on polished sections with the aid of a microscope, but often they are opened up by welding stresses so that they can easily be seen by eye. When seen visually, they appear to run very close to the junction between the weld and the base metal.

When the hydrogen level is high, as it is with most of the stick electrodes used for manual welding, HAZ cracking will occur, once the cooling rate exceeds a critical level. When the hydrogen level is low, as with low-hydrogen electrodes, or even lower with many automatic welding processes, some external stress or restraint may be necessary to initiate cracking. The enhanced cooling rates, characteristic of welding at low temperatures, aggravate the problem by increasing the completeness of transformation, by trapping the hydrogen in the metal and not allowing its dispersement by diffusion, and by a tendency to increase the levels of residual stress.

Cottrell (10) used the Controlled Thermal Severity (CTS) test to investigate HAZ cracking, and showed that for any given plate-temperature combination, cracking would occur if the cooling rate at 300°C (570°F) exceeded a certain value. In one series of tests (11), Cottrell and Bradstreet found that 5% cracking occurred with the test plates at 20°C (68°F) and 72% cracking with the plate temperature at -50°C (-58°F). Cracking was initiated at approximately the same critical cooling rate, illustrating that the principal effect of welding at low temperatures was to increase the cooling rate. In Belgium, this kind of relationship is relied upon to such an extent that the weldability of a particular steel is sometimes gauged in terms of the lowest temperature at which the steel can be welded without sustaining HAZ cracking.

In tests at the Battelle Memorial Institute (12) simulated joints on pipeline sections using 5LX-52 steel showed that the percentage of cracked sections through root-pass welds increased from 0% at 21°C (70°F) to 19% at 13°C (55°F), to 34% (average) at 4°C (40°F), and to 37% (average) at -7°C (20°F). In complete welds, the extent of cracking can be reduced by minimizing the delay between the first and second welds, and by completing the whole joint in a 2-hr period. Preheat at 95°C (200°F), or alternatively the use of low-hydrogen E7016 electrodes, was effective in preventing cracking.

The production of fissures (minute cracks) in as-deposited weld metal has been a subject of interest to many since the discovery of the phenomenon by Flanigan (13) in 1947. It was known from the first that their formation was encouraged by high cooling rates. Since then, several authors have shown that the number of fissures increase with lower deposition temperatures.

Weld-metal cracks often result from an extension of these fissures. They appear to be caused by a combination of factors similar to those responsible for HAZ cracking, i.e., hydrogen level, high rates of cooling, hardenability (this time in the weld metal), and external stress or restraint. As before, and not surprisingly, the effect of low ambient temperatures is to aggravate this problem.

The Lehigh test has been used (2-3) to investigate the effect of ambient temperature on the tendency for weld-metal cracking. Agnew (2) confirmed that the number of fissures increases with lower deposition temperatures, but it appeared that there was a greater effect between 21°C (70°F) and -18°C (0°F) than from -18°C (0°F) to -62°C (-80°F). Good results (most welds uncracked) were obtained on some low-hydrogen electrodes tested at -62°C (-80°F) at full restraint, and there was a strong indication that no trouble would be encountered at lesser restraint or at slightly higher temperatures. Crack-free welds were also obtained at -62°C (-80°F) with inert-gas metal-arc deposits, using consumable electrodes.

Many authors have reported on the effect of low ambient temperatures on the mechanical properties of manual metal-arc welded joints. In general, tensile strength and yield strength are not much affected and, if anything, are increased somewhat. Ductility and impact strength, however, were sometimes adversely affected. The Tee-bend test has been used to evaluate the performance of welded joints; in one case it was concluded that low deposition temperature had a markedly deleterious effect on steels containing more than 0.20% C. Impact and bend tests carried out by Commission II of the International Institute of Welding showed that greater deterioration occurred in the range 20°C (68°F) to 0°C (32°F) than in the range 0°C (32°F) to -20°C (-4°F).

Data from U.S.S.R. sources has shown that when joining with submerged-arc welding and electro-slag welding, low ambient temperatures have a somewhat similar effect on the mechanical properties of the welded joints. However, because these are high-heat processes the impairment is less.

Means for Meeting the Problems of Welding Steel in Cold Weather

(a) Operational Control

For many years, very large structures such as bridges, buildings, cranes, nuclear-reactor spheres, storage tanks and pipelines have been welded in the field. In many countries, some of this work had to be done at low temperatures. Sometimes, very few special precautions have been taken.

An account (14) has been given of the successful winter construction (1936-37) in the United States of two siphon lines to pipe water across the Continental Divide and supply the city of Denver. Near West Portal, Colorado, the ambient temperature was in the range -37°C (-35°F) to -47°C (-52°F) during the day. The pipe joints were made in material conforming to ASTM A70-33, and the welding procedures were in accordance with paragraph U-69 of the Unfired Pressure Vessels Section of the ASME Boiler Code. This entails no restrictions or special precautions with regard to welding at low ambient temperatures.

Though full details are not always available, investigations into the brittle failure of large storage tanks (165,000-350,000 cu ft capacity) in the U.S.S.R. (15) suggest that low-temperature welding difficulties may have played a part. In one particular case, with ambient temperatures between -46°C (-50°F) and -57°C (-70°F), intersecting cracks in the form of a cross were produced as the arc was struck; these were usually 8 to 12 in. long and sometimes more.

Many codes and standards have taken the position, and some still do, that welding should be stopped altogether when the temperature falls below a certain value. Such standards prohibit or tend to prohibit welding when the primary steel temperature is below -18°C (0°F). The term "primary steel temperature" means the temperature of the steel resulting from exposure to the ambient conditions, as distinct from the temperature of the steel in a joint area resulting from local preheat and interpass control prior to and during welding.

During the last war, means had to be found to continue shipbuilding in cold weather, and since that time standards have increasingly reflected the view that welding can be continued in these circumstances if proper precautions are taken.

(b) Reduction in the Hydrogen Level

Low-hydrogen electrodes are preferable for welding in cold weather because they minimize those defects, such as HAZ cracking and weld-metal fissuring, which result from rapid cooling. Their advantages for low-temperature welding have been demonstrated, and their use has been advocated by numerous investigators. Precautions should be taken to keep these electrodes dry; for example, they should be issued in small lots and stored carefully, as otherwise they tend to pick up moisture in a few hours from a humid atmosphere to an extent that destroys their effectiveness. In the twenty-five years or so since they were first introduced, their usability characteristics, which at first were poor, have been greatly improved. It is unfortunate that none has yet been developed entirely suitable for the downhand root-pass welding welding used for the girth welds of transmission pipe. Nevertheless, they can be used for a multitude of other purposes.

Low hydrogen levels may also be secured by using certain automatic and semi-automatic processes, notably electro-slag welding, submerged arc welding, CO_2-shielded arc welding (for steel), metal-inert-gas welding (MIG), and tungsten-inert-gas welding (TIG). The hydrogen level associated with these processes is characteristically low, and may be so maintained with reasonable precautions, such as using carefully dried fluxes for submerged-arc welding, avoiding contamination with condensed moisture in gas-shielded processes, etc. On the other hand, it is worth noting that, with the flux-cored process, the hydrogen level is variable and may be high, as with the ordinary metal-arc electrodes.

For welding in cold weather, the simple substitution of low-hydrogen electrodes (or a low-hydrogen automatic welding process) for the ordinary metal-arc electrodes may bring the hydrogen level down to a value where cracking in the welded joint is no longer a problem. Under unfavourable circumstances, i.e., welding thick plates under heavy restraint, or when the carbon content is high, the reduction of hydrogen content alone may be insufficient to prevent cracking. In any case, it must be realized that the unilateral reduction of hydrogen content leaves untouched any problems arising from the hard, brittle HAZ that may result from the more rapid quench when welding at low temperatures. This hard zone may give problems in handling or in service because of the impaired notch-toughness, or it may be susceptible to stress-corrosion attack, or it may crack with the help of hydrogen resulting from later operations such as welding, pickling or plating, or hydrogen resulting from general corrosion attack.

(c) Thermal Control

Some welding processes are inherently less susceptible to the effect of low ambient temperatures, for the reason that the rate of energy input is high. These include submerged-arc welding, thermit welding, electro-slag welding, etc.

In Canada, and in the colder parts of the United States, the introduction of double-jointing techniques (and even triple-jointing) has made it possible for pipeline companies to continue some aspects of the work during the winter months. The method was used, for example, in trunk lines made from 5LX-52 steel in Manitoba and Alberta, with temperatures regularly around -34°C (-30°F) and occasionally as low as -44°C (-48°F). Double-jointing consists of joining the normal 40-ft lengths to make 80-ft lengths. By this means, 50% of the girth welding can be carried on when temperatures are low, under conditions rather better than are obtainable in the field. Semi-automatic submerged-arc welding is used with a joint geometry approaching a close-butted preparation, necessitating partial removal of the factory-made bevel on the pipe ends. Large propane burners are used to remove ice and snow from the pipe ends, the heating period required being in the order of half a minute. Since its introduction, the method has been improved by increased use of automatic methods, the elimination of tack welding, higher speeds, and increased efficiency. In addition, the double-jointing yard has become fully mobile. There seems little doubt that the high heat input characteristic of the method is the main factor responsible for the success. Trans-Canada Pipe Lines Ltd. have reported that a number of double-jointed section welds have been cut and tested. It was concluded that the process produces sound welds.

An old idea that still persists in some standards is the requirement that the starting point of the weld should be heated to a temperature "warm to the hand", when the primary steel temperature is in the range -18 to 0°C (0 to 32°F). This requirement is presumably based on the idea that the starting point of the weld is more susceptible to weld difficulties or defects when the steel is at a temperature below about 0°C (32°F). Apparently it is expected that once welding is in progress, the heat flow in front of the advancing weld will act in the same way as the local preheat at the start of the weld. This is not correct. Care should always be taken in preheating to heat a sufficiently large mass of metal along the path of the intended weld to prevent a premature drop in temperature, from that prescribed, before welding is completed.

Canadian workers (1) have suggested that long welds should be made in blocks so that the interpass temperature is maintained at a satisfactory level. From the same source comes the suggestion that, in some cases, welds could be laid on the plate surface just outside the welding groove for preheating purposes if auxiliary heating services are not available.

A rough rule used in the U.S.S.R. is that the specific heat input should be increased by 4% to 5% for each 10°C (18°F) drop in temperature below normal shop temperatures (apparently in the range 10 to 20°C (50 to 68°F) in the U.S.S.R). It was suggested that the increase should be made primarily by increasing the arc voltage. However, the reason for this is not known, and it would seem easier, normally, to make such adjustments by means of the welding current. Other calculations (4) indicate that the heat input should be increased by 7-8% for every 10°C (18°F) drop in temperature in order to maintain normal cooling rates.

Many standards require greater precautions as the plate thickness is increased. This is related, not only to the greater heat draw-off from a weld deposit, but also to the tendency for slightly higher carbon and/or manganese level in the thicker steel. Presumably the more rigid requirements for shapes and bars are dictated by the likelihood that these will have greater hardenability than will plates.

A system of weldability control proposed by Cottrell (10) was based upon the use of the CTS test. A weldability index letter from A to G was assigned to any particular steel after carrying out a prescribed schedule of testing. Bradstreet (16) later suggested that the weldability index for the steel could be calculated using a formula devised by Winterton (17):

$$\text{C.E.} = \text{C} + \frac{\text{Mn}\ \%}{6} + \frac{\text{Ni}\ \%}{20} + \frac{\text{Cr}\ \%}{10} - \frac{\text{Mo}\ \%}{50} - \frac{\text{V}\ \%}{10} + \frac{\text{Cu}\ \%}{40} .$$

The carbon-equivalent (C.E.) of the steel may be converted into a weldability index using a table provided by Bradstreet. In either case, whether the weldability index is determined by test or by calculation, the value can afterwards be substituted in a table to find the minimum plate temperature required for any particular joint, taking into account the electrode diameter and the joint severity (total plate thickness available for heat flow in 1/4-in. units). This data shows for example that steel with a weldability index of B can be welded in thicknesses up to 1/2 in. with electrodes of 6S.W.G. or larger (more than 0.92 in. diameter) at temperatures down to -50°C (-58°F).

Rather precise directions are given in British Standard Specification, B.S.2642-1965 (with amendments in 1966) - General requirements for the Metal-Arc Welding of Carbon Manganese Steels. For butt welds, graphs are provided which show the maximum run lengths to be made with an 18-in. long electrode (this is a convenient way of controlling the minimum weld size), for different combinations of total plate thickness, electrode size and plate temperature. Other graphs similarly make it possible to determine the minimum size of single-run fillet welds. The system of control incorporated in this Standard has been adapted (18) for CSA G40.12 steel (now designated in CSA Standard G40.21-1973 - Structural Quality Steels - as Grade 44W or 44T) which resembles UK steels to which B.S. 2642 applies. This system of control could also be applied to other carbon-manganese steels in G40.21.

(d) Present Trends

For a particular job, limited perhaps to one or two steels working in a certain range of plate thickness, it should not be too difficult to work out proper procedures with appropriate thermal control for welding, suitable for the lowest service temperatures expected, though it might be necessary to supplement any theoretical studies with a test program. Under these conditions it should be possible to continue welding work no matter how low the temperature falls. The experimental work that has been done certainly shows that the problems increase as the temperature declines, but there are no sudden changes, and therefore no support for the somewhat arbitrary cut-off temperature which are to be found in many specifications.

Steels for low-temperature service should be chosen to exclude or minimize the possibility of brittle failure. In addition, if welding construction or extensive repair by welding is to be done under low-temperature conditions, then weldability is another factor that should be given consideration in steel selection.

Metallurgical and practical problems of some magnitude will be encountered in constructing Arctic pipelines (19). Present Canadian codes require that for temperatures below 0°C (32°F), procedures must be qualified for the lowest ambient temperature to be encountered. For Arctic lines, more specific requirements will be laid down including specified notch-ductility properties for the welded joints.

Welding of Non-Ferrous Metals in Cold Weather

(a) Aluminum

Alcan International Limited report (20) that they have not encountered welding problems resulting from low ambient temperatures, other than the need to overcome chilling of the weld zone by surrounding metal. For example, some years ago an aluminum pipeline was installed in Alberta without preheat at temperatures down to -40°C (-40°F) using 4.5-in. diameter AA-6351-T4 pipe (0.188-in. wall thickness). The problems encountered were limited to equipment performance, operator comfort and the need to keep snow out of the weld zone. In MIG and TIG welding, trouble was encountered with hoses (for the supply of argon and cooling water) becoming stiff at low temperatures and interfering with the operator's freedom to manipulate the torch. One supplier was able to supply special hose with good low-temperature flexibility. Alcan (20) suggests that good practice with a water-cooled torch is to use a water recirculation system and to heat the water with an immersion heater. Anti-freeze should be added to the water for protection of the torch when the heater is not in use. For MIG and TIG welding, operator comfort is an important factor, yet the bulky clothing required for winter protection is an impediment to freedom of movement, so that frequently a successful job can only be done by surrounding the joint area with a heated enclosure. Snow trapped in a joint and melted by the welding heat is certain to introduce porosity in the welds, so that it is important to ensure that the joints are dry before welding. Even in mild weather, outdoor welding poses the problem of maintaining adequate shielding in a wind. Increased gas-flow rates and windbreaks may help, or for a variety of reasons a full enclosure may be preferred. Alcan warns that if such an enclosure is heated, the aluminum may have to be preheated to avoid contamination from condensed moisture.

From a metallurgical point of view, low temperatures per se do not lead to problems. In fact, due to the low humidity in the air and the fast freezing of the weld pool, MIG machine welding was appreciably easier and gave better quality joints in the cold weather than in the hot.

(b) Other Non-Ferrous Metals

In most cases, as with aluminum, there are no metallurgical problems in welding non-ferrous metals at low temperatures. Human and mechanical problems may be encountered and these are common to all metals. For joints of good quality in the non-ferrous metals it is now common to use the MIG or the TIG shielded processes. Shielding problems in the field are somewhat greater with these processes than with metal-arc welding. For these reasons, the problems of welding non-ferrous metals in the field and in cold weather are likely to be very similar to those already described for aluminum.

The titanium alloys might be thought to be exceptional in that metallurgical problems could result from excessive cooling rates. However, it is difficult to imagine making constructional or repair welds on titanium-alloy structures in a casual way. The rigorous requirements for shielding and care in welding required by these alloys means that all welding should be done under conditions approaching or simulating ideal indoor conditions.

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2.3 CORROSION

Introduction

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General information on the corrosion behaviour of metals is presented in a number of standard texts (1-4), while more up-to-date and specialized information is available in periodicals such as Materials Performance, Corrosion, and the Journal of the Electrochemical Society, and at the meetings of societies such as the National Association of Corrosion Engineers and the American Society for Testing and Materials.

A brief description of the more important forms of corrosion which might be encountered in Arctic environments follows.

Forms of Corrosion

Uniform Attack

Loss of metal is very nearly the same at all points on the surface. It may be observed in certain pickling solutions and can be approximated in atmospheric corrosion. Service life of components is easy to predict once corrosion rates have been established.

Pitting

This form of corrosion usually occurs in the presence of chlorides and is concentrated at certain well-defined areas where small holes called "pits", form. At areas that are not pitted, attack is uniform and takes place at a lower rate. It is difficult to predict both the location and depth of pits and penetration can cause failure of a component with relatively little total loss of metal. Hence, this is one of the more dangerous forms of corrosion attack.

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Crevice Attack

Alloys such as stainless steel, with excellent corrosion resistance in some aqueous solutions, may be severely corroded at localized areas where access of the bulk corrodent is difficult, e.g., within threaded joints, at laps, or under surface deposits. As with pitting, component failure may take place unpredictably with very little total loss of metal by corrosion.

Galvanic Attack

From tests in some common corrodent such as sea water, metals can be arranged in a "galvanic series". When two metals which are relatively far from each other in the series are linked electrically, the more active will corrode at an accelerated rate, while corrosion of the more noble is very nearly arrested. While unexpected galvanic corrosion can lead to difficulties, the effect is used in a positive way in cathodic protection, (e.g. corrosion of a zinc anode protects steel piping).

Erosion-Corrosion

This form of attack involves a high relative velocity between metal and liquid corrodent. For non-resistant metals, e.g., steel in sea water, high corrosion rates may be encountered.

Environmental Cracking (Stress-Corrosion Cracking)

This is observed for susceptible metals under tensile stress in a suitable corrodent. Though general corrosion is slight, at some locations fine cracks may develop and propagate until failure of a component occurs. Since propagation rates are usually rapid this can be an expensive and dangerous type of corrosion attack.

In many cases it has been shown that environmental cracking is caused by hydrogen entry into the metal, e.g., in cathodically protected high-strength steel.

Corrosion Fatigue

It is known that repeated stressing can cause the development of fatigue cracks which can propagate to component failure. In nearly all cases, the presence of a liquid corrodent will cause an increase in the propagation rate of fatigue cracks.

Arctic Corrosion

Atmospheric Corrosion

Corrosion of metals exposed outdoors will take place only in the presence of liquid water. However, in much of the Arctic, there are fewer than 40 frost-free days per year, with only about 2 to 4 in. (50 to 100 mm) of annual rainfall (5). This is consistent with low atmospheric corrosion rates, as is indeed evidenced by the relics of early Arctic explorers, still being found relatively intact today.

The only systematic atmospheric corrosion testing of structural and architectural metals in the Arctic has been carried out by the National Research Council of Canada at Norman Wells, N.W.T. Norman Wells is on the Mackenzie River, somewhat south of the Arctic Circle, and is representative of one of the warmer parts of the Arctic, with 60 to 80 frost-free days per year. Nevertheless, an ASTM survey showed atmospheric corrosion at Norman Wells to be the lowest of 46 sites (6). Based on State College, Pa. = 1.0 (Ottawa also happens to equal 1.0) the ASTM corrosion index at Norman Wells is given as 0.03 (7). The low SO_2 content of the air and the absence of marine conditions were other factors conducive to low corrosion rates at Norman Wells.

Atmospheric corrosion rates are characteristically most rapid on initial exposure of the clean metal; then, as corrosion product layers develop, they decrease until a steady state is eventually attained. In Table 2.3.a, extracts from the results of E.V. Gibbons (7,8) appear; corrosion rates are reported in terms of the average penetration per year calculated from the corrosion occurring during a 10-year period. It should be noted that the corrosion was in the form of pits in some cases and that a completely satisfactory service evaluation might necessitate knowledge of pit densities and pit depths.

As part of Gibbons' work, the effect of galvanic coupling of Alcan 3S-H14 aluminum alloy to each of copper, zinc and steel was investigated. For specimens exposed for ten years, galvanic effects were minor at Norman Wells, but more apparent at Ottawa. For example, when Alcan 3S-H14 was coupled to copper, the corrosion rate of the Alcan 3S-H14 was 0.022 mil/yr (0.56 micron/yr) at Ottawa, but only 0.002 mil/yr (0.051 micron/yr) at Norman Wells.

The National Research Council of Canada also tested the effectiveness of different metal coatings on steel at a number of sites (9). Included were cadmium and zinc electroplate, hot-dip aluminized and galvanized, and metallized zinc and aluminum. After fourteen years on test, there was no rusting of the substrate and little or no change in the appearance of specimens at Norman Wells. At Ottawa, pristine appearance was retained only by the zinc electroplate and the zinc and aluminum metallized coatings.

The results of Table 2.3.1 are indicative of the low corrosion rates obtainable in the Arctic and it is possible that even lower rates would be observed in the colder and drier parts of the extreme north. Conversely, higher rates might be observed where pollution, marine conditions or other adverse factors are present. As an example of the latter, in a limited-scale one-year test carried out by the writer at Tuktoyaktuk, N.W.T., at a site 200 feet (70 m) from the Beaufort Sea (Mackenzie River estuary), structural steels showed weight losses equivalent to an average penetration of 0.61 to 0.65 mil (15.5 to 16.5 microns). In view of the results obtained at Norman Wells and elsewhere (7) this was an appreciably higher corrosion rate than had been expected and suggests further testing is needed.

Because of the remoteness of most Arctic installations, maintenance and repair are difficult and expensive, and it would be prudent to choose structural materials which do not require painting (e.g., galvanized or aluminized steel) and which will retain their resistance to corrosion even if some local changes in conditions cause the atmosphere to become more corrosive. It is also an interesting possibility that certain metals, unusable in outdoor service in southern Canada, might be used in unpainted condition in at least some parts of the north. Examples might include high-strength steels and aluminum alloys which tend to fail by environmental cracking, and magnesium, mild steel and other alloys with relatively high atmospheric corrosion rates in southern Canada. It would be useful to perform atmospheric tests on such alloys, using stressed specimens when appropriate, to determine whether they might be used for outdoor structures. Because transportation costs are so high in the North, work should be concentrated on the alloys with the highest strength/weight ratios.

It should be noted that low atmospheric corrosion rates are not always advantageous as evidenced by the unsightly piles of discarded oil drums and other metallic wastes at Arctic settlements. Failing their use as scrap, some rapid and non-polluting means for their re-conversion to their ores might have to be sought.

Aqueous Corrosion

The temperature of sea water cannot fall below the freezing point of approximately 28.5°F (-1.9°C). This temperature is approached in southern Canadian waters, depending on the exact location, depth and time of the year (10). Nevertheless, sea-water temperatures in the Arctic will be lower, on the average, leading to the expectation of lower corrosion rates. Against this is the possible acceleration of corrosion because of increased oxygen solubility at or near the freezing point, and increased corrosion rates in splash zones have been explained on this basis.

The combined effect of these and other variables in the Arctic is not known. Through the agency of the Frozen Sea Research Group (Environment Canada), the writer was able to test specimens of G40.8 Grade B structural steel in the waters of D'Iberville Fiord, Ellesmere Island. On the basis of an 82-day immersion, the average penetration rate was only about 2.5 mils/yr (63 microns/yr) and no fouling was observable. This behaviour resembled that observed in the early stages of deep-sea testing carried out by U.S. workers (4) and is indicative of a low steady-state corrosion rate. However, no conclusions can be reached, and longer-term and more systematic testing in Arctic waters is needed to determine not only the general wastage rates of ordinary structural metals but also their pitting, crevice, galvanic and erosion-corrosion behaviour. Scanty laboratory data indicate that lowering of the temperature to the vicinity of the freezing point will bring about decreased corrosion-fatigue crack propagation rates (11-12) and decreased environmental cracking propagation rates (13-14). But these indicated trends need confirmation in appropriate laboratory and field tests on alloys of interest.

There is nothing to indicate that anti-corrosion schemes successfully used in more southerly waters, e.g., coating, coupled with cathodic protection, would not be effective in the north, with the qualification that damage by ice must be taken into account.

Pipeline Corrosion

The recent oil and gas discoveries in the Arctic lead to the probability that hundreds of miles of transmission pipe will be laid. For crude oil, product temperatures must be high enough to ensure sufficient fluidity for pumping. Corrosion behaviour should, therefore, resemble that observed in more southerly parts of Canada, e.g., there will be the possibility of both internal and external general wastage and pitting corrosion and environmental cracking (stress-corrosion cracking). However, well-proven conventional corrosion protection methods should be applicable, though there might be some novel difficulties related to the presence of permafrost.

For Arctic gas transmission lines, it has been proposed that the product be cooled below the freezing temperature of water, which would effectively eliminate the most common corrosion problems. However, with respect to the possible use of exotic high-strength alloys in this application, it deserves mention that hydrogen gas has been observed to induce sub-critical crack growth (14,15). The effect seems to be most pronounced near room temperature but remains significant far below the freezing point, indeed, at the lowest ambient temperature encountered in the Arctic. However, present-day line-pipe steels are not expected to be so affected by the hydrogen found in natural gases.

Undersea transmission lines should be able to benefit from the technology exploited successfully in the gas and oil fields of the North Sea, with the qualification that scouring of the ocean bed by ice masses must be taken into account. Perhaps this will necessitate burial of the pipe well below the scouring line.

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Table 2.3.a Atmospheric Corrosion Behaviour at Ottawa, Ontario and at Norman Wells, N.W.T. (7,8)

Alloy	Average metal loss in 10 years mil/yr (micron/yr)	
	Ottawa	Norman Wells
Aluminum-Alcan 57S-H34	0.006(0.15)	0.001(0.025)
" -Alcan 65S-T6	0.006(0.15)	0.0006(0.15)
" -Alcan 3S-H14	0.006(0.15)	0.0007(0.018)
Copper	0.023(0.58)	0.005(0.13)
61%Cu-39%Zn (Muntz Metal)	0.033(0.84)	0.003(0.076)
Lead (soft)	0.029(0.74)	0.009(0.23)
Magnesium AZ80X	0.34(8.6)	0.03(0.76)
ZK61X	0.80(20.3)	0.32(8.1)
66%Ni-32%Cu (Monel Alloy 400)*	0.0075(0.19)	0.001(0.025)
Steel - Low Carbon	0.41(10.4)	0.04(1.0)
- Low Carbon, Cu-bearing	0.41(10.4)	0.04(1.0)
- Low Carbon, Cu-Ni-bearing	0.21(5.3)	0.05(1.3)
Zinc	0.055(1.4)	0.005(0.13)

2.4 FATIGUE

R.C.A. Thurston*

Since fatigue is still responsible for the majority of service failures of engineering components, a knowledge of the effect of low temperatures on the fatigue behaviour of metals and alloys is of primary importance to the designer of equipment for use in the Arctic. Fortunately, all the available evidence indicates that the fatigue strengths of both unnotched and notched specimens tend to increase as the temperature is reduced. It is possible, therefore, to design for room temperature conditions (20°C, 70°F), for which the appropriate data are generally available, with reasonable confidence that fatigue failures will not result from operation at lower temperatures.

The reassurance contained in the foregoing is based on a survey of the literature covering numerous steels, nickel, copper, aluminum, magnesium and titanium alloys, as well as cast and nodular irons. In no case was a decrease in fatigue strength reported at temperatures down to -73°C (-100°F). A selection of the data is presented in Table 2.4.a, and further information can be found in references (9-11).

Examination of the data reveals a general tendency for the percentage increase in fatigue strength at the lower temperatures to be greater for the softer alloys than for the hard ones. This is particularly evident for mild steel, but a marked exception is the high-strength 17-7 PH alloy. The tensile strength also increases as the temperature is reduced, but not usually to the same extent as the fatigue strength. Of more practical significance is the behaviour of the notched fatigue strength. A trend was noted for the notch sensitivity to decrease at low temperatures for some aluminum and titanium alloys, and to increase for some steels, but in no case was the notched fatigue strength lower at low temperature than at room temperature. However, since many structural steels become susceptible to brittle fracture at low temperature, the possibility should not be overlooked of a brittle fracture starting from a small fatigue crack, which might otherwise require a much longer time for propagation.

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*Research Coordinator

Table 2.4.a Effect of Low Temperature on Fatigue Strength

Material	Condition	UTS ksi	Type of Fatigue Test	Fatigue Strength - ksi, Room temp	low temp	Reference
Monel	cold drawn	93.3	RB	± 36	± 38 (-40°C)	1
18/8 S.S.	annealed	88	"	± 33	± 42 (-40°C)	1
3 1/2% Ni Steel	heat-treated	128	"	± 61	± 68 (-40°C)	1
Cr-Mo Steel	" "	193	"	± 98	±101 (-40°C)	1
1020 Steel	" "	62.7	"	± 31	± 48 (-40°C)	2
3% Cr Steel	" "	185.2	"	± 94	±100 (-40°C)	2
0.25 C Steel	hot-rolled	-	"	± 30	± 35 (-60°C)	3
Mild steel	normalized	67.2	DS	± 28	± 35 (-60°C)	4
				± 11 (notched)	±12 (-60°C)	4
				0-47	0-49 (-60°C)	4
				0-16 (notched)	0-19 (-60°C)	4
En 25	Q. and T.	132	DS	±63	±63 (-60°C)	4
alloy steel				±15 (notched)	±15 (-60°C)	4
				0-102	0-106 (-60°C)	4
				0-28 (notched)	0-28 (-60°C)	4
K Monel	cold rolled and age hardened	182	PB	±58	±67 (-73°C)	5
17-7 PH	heat-treated	196	"	±83	±107 (-73°C)	5
Ti-6Al-4V	annealed	136	"	±50	±55 (-73°C)	5
70/30 brass	spring temper	95	"	±36	±50 (-73°C)	5
Berylco 25	heat treated	178	"	±60	±65 (-73°C)	5
1200 Al	H16 (3/4 hard)	20	"	±11	±13 (-78°C)	6
2024 Al	-	70	"	±26	±30 (-78°C)	6
6061 Al	T6	45	"	±20	±23 (-78°C)	6
7075 Al	-	84	"	±31	±35 (-78°C)	6
DTD 683	-	82	RB	±20	±22.5 (-40°C)	7
(Al-Zn-Mg)				±10 (notched)	±14 (-40°C)	7
DTD 364B	-	66	RB	±24	±25 (-40°C)	7
(Al-Cu)				±14.5 (notched)	±18.5 (-40°C)	7
Ti-150A	annealed	153	RB	±110	±120 (-78°C)	8
				±47 (notched)	±56 (-78°C)	8
RC-130B	annealed	149	RB	±84	±98 (-78°C)	8
				±44 (notched	±55 (-78°C)	8

RB - rotating bending
PB - plane bending
DS - axial loading

Note:
-40C = -40F
-60C = -50F
-73C = -100F
-78C = -110F

Very little information is available regarding the effect of low temperatures on crack propagation under repeated cyclic loading, but the indications again are encouraging. A Ni-Mo-V alloy steel (UTS 102 ksi) (12) gave increasingly higher endurance values in tension-tension loading as the temperature was reduced from room temperature to -73°C (-100°F), even though the crack length at failure steadily decreased. Actual measurements, using an ultrasonic crack-monitoring technique, confirmed that there was a significant decrease in the rate of crack growth as the temperature was lowered. Similar results have been reported for a Mn-V type structural steel (UTS 74 ksi (13). Low-cycle tension-tension tests over the range 0 to -75°C (32 to -103°F) showed a marked reduction in the crack length at fracture, but little change in the number of cycles to failure. However, a word of caution is desirable here. The toughness of most structural materials tends to decrease with temperature, i.e., the component or structure will not accommodate as serious a flaw or crack at lower temperatures. Hence the possibility of sub-critical crack growth, induced by cyclic loading and culminating in sudden brittle failure, must not be overlooked.

The published literature on the effect of low temperatures on the fatigue characteristics of weldments is equally sparse, (references 14-16). The studies involved various steels and welding processes, and in all cases the endurance increased as the temperature was reduced. For normalized niobium-containing steel plate, it was found that a reduction of 10°C (18°F) in the test temperature had roughly the same effect on the fatigue life as a 2% reduction in the cyclic load amplitude. A limited number of full-scale tests on 10-in. I-beam of rimmed or killed steel, rolled, riveted or welded, gave similar results. The welded beams had significantly longer lives at -40°C (-40°F) than at room temperature, though the improvement was not as marked as that of the rolled beams.

Some interesting work has been reported on the effect of low temperatures on the fatigue behaviour of press-fitted assemblies (17). Specimens of a 0.4% C axle steel (UTS 87 ksi), with or without surface rolling, were pressed into sleeves and tested at 20°C (68°F) and -60°C (-76°F). Apart from confirming the benefits of surface rolling in the presence of a stress concentration, the results showed a definite increase in fatigue life at the lower temperature for the two conditions. The S/N curves at -60°C (-76°F) were consistently superior to those at room temperature, although the endurance limits did not differ appreciably. The greatest difference was reported for the specimens without surface rolling in the low-cycle range.

Finally, information is also available on the effect of low temperatures on the rate of fatigue crack propagation in weldments of Ti-6Al-4V ELI alloy in a hydrogen environment (18). The material was in the form of solution-treated and aged (STA) forgings, and straight butt-type, fillerless welds were made by the gas-tungsten-arc process. The results established the fact that hydrogen accelerated the rate of fatigue crack growth in the parent metal and in the weld in the temperature range of ambient to -73°C (-100°F). In the case of the weld material, the effect was consistently less pronounced at low temperature. In the case of the parent metal, the effect decreased as the temperature decreased above a stress intensity range of about 12 ksi$\sqrt{\text{in}}$. Below this range, it is noteworthy that there was a definite tendency for the growth rate to be adversely affected as the temperature was lowered.

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3. STRUCTURAL MATERIALS AT LOW TEMPERATURES

3.1 IRONS

R.K. Buhr*

Characteristics and Applications

Cast irons are defined as iron-carbon-silicon alloys containing generally more than 2% C. These alloys are sub-divided into four broad categories, namely white irons, grey irons, malleable irons and nodular or ductile irons. Within each category, a wide range of properties is possible, depending upon the composition and/or heat treatment involved.

Whether an iron solidifies as white iron or as grey iron, or a combination known as mottled iron, depends mainly on the form in which carbon precipitates in the solidifying metal. This in turn is dependent upon the eutectic value of the composition and the cooling rate during solidification. In general, the faster an iron is cooled through the solidification temperature range, the greater is its tendency to solidify as a white iron, i.e., a large proportion of the carbon present will occur as metastable carbide (Fe_3C), known as cementite.

The eutectic composition of an iron-carbon alloy occurs at 4.30% C. When certain other alloys are present, this carbon content is lowered. A formula has been devised to take this into account, and the carbon equivalent (C.E.) is calculated as follows

$$\text{C.E.} = \frac{\%\ \text{Si} + \%\ \text{P}}{3} + \%\ \text{total carbon}$$

(In unalloyed cast iron, silicon and phosphorus are the elements which affect the eutectic value).

Thus, the eutectic composition is one with a C.E. = 4.30%. The lower the C.E. value of an iron, the more likely it is to solidify as white iron, and conversely, the higher it is, the greater is the likelihood of the formation of grey iron, i.e., the majority of the carbon present will be in the form of stable graphite flakes. In alloy cast iron, certain alloying elements may promote graphite formation and others may promote the formation of carbides.

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White Irons

Carbides are very hard and brittle. These properties are imparted to white iron castings, as they contain large quantities of carbides. Their application is generally confined to use where abrasive wear predominates, and impact requirements are low. Alloy white irons are being used to an increasing extent as marked improvements in wear resistance can be realized which more than offset the extra cost of the alloying elements, In addition, there is generally some increase in impact strength. The most common alloying elements are chromium, nickel and molybdenum. The mining industry is the major consumer of white iron castings, in the crushing and grinding of ores. Other applications are in agriculture and the ceramic industry, again in areas of high abrasive wear. Typical compositions and hardnesses of white iron castings are shown in Table 3.1.a (11).

Grey Irons

When the composition is such that it approaches or surpasses the eutectic composition, or if the rate of solidification is sufficiently slow, graphite will form in the alloy, and a grey cast iron results. The term grey is used because the fracture appearance is a dull grey colour.

The graphite occurs as flakes throughout the matrix and will occupy about 10% of the volume. The matrix in plain grey iron will be a mixture of ferrite and pearlite, and the overall hardness will be relatively low, generally below 250 BHN. This structure, although displaying somewhat more impact resistance than unalloyed white irons, is still brittle, due to the presence of the flake graphite.

The tensile properties obtainable vary considerably depending upon the C.E. of the composition and the section size of the casting (rate of solidification). Table 3.1.b (11) lists a number of compositions and sections to indicate the magnitude of these variables.

The effect of low temperature on cast irons has been investigated by Gilbert (1,2). Very little effect is shown on the mechanical properties of white or grey cast irons by lowering the temperature. In general, a small increase in the tensile strength is noted, which amounts to about 15%, whereas the impact strength decreases by amounts up to 30%. Since both of these types of cast iron are essentially brittle at normal temperatures, they should find applications at sub-zero temperatures similar to those they currently have at normal temperatures.

Malleable Irons

It has already been stated that cementite (Fe_3C) is the metastable form and graphite the stable form of the carbon in cast irons. It is possible, by appropriate heat treatment, to cause cementite to transform to graphite, the process being called malleablization, because the product is much softer. However, in this instance, the graphite precipitates as compact masses, referred to as temper carbon or spherulites, rather than the flake form which is found in grey cast iron. Because these compact graphite areas offer less interruption to the continuity of the matrix than is the case with grey cast iron, the iron's properties are more closely related to those of the matrix, which can be either pearlitic or ferritic, depending upon the heat treatment. The tensile properties of the irons display a yield point, as well as appreciable ductility and the materials also possess significant impact strength. In this respect they are similar to cast steels, and react to compositional and heat treatment variations in a similar fashion. Compositional and heat-treatment control can produce malleable irons with good impact resistance at low temperatures, and the use of these types of cast irons in Arctic service should be encouraged.

Table 3.1.a Typical Composition, Hardness and Microstructure of White Iron Mill Liners (11).

Table 4. Typical Composition, Hardness and Microstructure of White Iron Mill Liners

Item	C	Si	Mn	Cr	Ni	Mo	S	P	Bhn	Matrix
1	2.90	0.5	0.5	...	..	..	0.12	0.10	415 to 460	CP
2	3.50	0.5	0.5	1.0	..	..	0.12	0.30	444 to 477	CP
3	3.20	0.5	0.6	2.0	4.5	..	0.12	0.20	550 to 650	M,A
4	3.50	0.5	0.6	2.0	3.0	1.0	0.12	0.10	600 to 650	M,A
5	2.75	0.6	0.7	27.0	..	0.5	0.03	0.06	550 to 700	M,A
6	3.25	0.6	0.7	15.0	..	3.0	0.03	0.06	600 to 750	M,A

CP = coarse pearlite M = martensite A = austenite

Table 3.1.b Typical Compositions of Grey Iron Based on Strength and Section (11).

Type	Composition, %					Average carbon equivalent(a)	Metal section range, in.	Brinell hardness number	Transverse load, lb	Transverse deflection, in.	Tensile strength, psi
	TC	Si	P	S	Mn						
Class 20,............... light section, 0.875-in. test bar	3.50 to 3.80	2.40 to 2.60	0.20 to 0.80	0.08 to 0.13	0.50 to 0.70	4.58	Up to 0.50	160 to 200	900 to 1200	0.10 to 0.15	22,000 to 26,000
Class 20,............... medium section, 1.2-in. test bar	3.40 to 3.60	2.30 to 2.50	0.20 to 0.80	0.08 to 0.80	... ...	4.34	½ to 1	160 to 180	1600 to 2200	0.20 to 0.27	18,000 to 24,000
Class 20,............... heavy section, 2.0-in. test bar	3.10 to 3.30	2.20 to 2.40	0.20 to 0.40	0.08 to 0.13	0.50 to 0.80	3.98	1 and up	130 to 180	4500 to 6500	... ...	18,000 to 22,000
Class 25,............... light section, 0.875-in. test bar	3.30 to 3.50	2.20 to 2.40	0.20 to 0.50	0.08 to 0.13	0.50 to 0.80	4.20	Up to ½	160 to 180	950 to 1300	0.11 to 0.16	26,000 to 29,000
Class 25,............... medium section, 1.2-in. test bar	3.20 to 3.40	2.20 to 2.40	0.15 to 0.40	0.08 to 0.12	0.50 to 0.80	4.08	½ to 1	172 to 207	1800 to 2400	0.22 to 0.28	26,000 to 29,000
Class 25,............... heavy section, 2.0-in. test bar	3.00 to 3.30	1.90 to 2.20	0.15 to 0.25	0.08 to 0.12	0.50 to 0.80	3.82	1 and up	179 to 217	6000 to 7800	... ...	26,000 to 30,000
Class 30,............... light section, 0.875-in. test bar	3.20 to 3.40	2.10 to 2.30	0.15 to 0.30	0.08 to 0.12	0.50 to 0.80	4.03	½ to 1	179 to 228	1250 to 1500	... ...	30,000 to 34,500
Class 30,............... medium section, 1.2-in. test bar	3.10 to 3.30	2.10 to 2.30	0.15 to 0.25	... ...	... ...	3.92	... ...	... ...	....	... ...	....
Class 30,............... heavy section, 2.0-in. test bar	2.90 to 3.20	1.70 to 2.10	0.15 to 0.25	0.08 to 0.12	0.45 to 0.70	3.68	1 and up	207 to 228	6500 to 8200	... ...	30,000 to 34,500
Class 35,............... light section, 0.875-in. test bar	3.10 to 3.30	2.00 to 2.20	0.15 to 0.30	0.08 to 0.12	0.45 to 0.70	3.90	... to ½	179 to 228	1150 to 1450	... ...	36,000 to 40,000
Class 35,............... medium section, 1.2-in. test bar	3.00 to 3.25	1.80 to 2.10	0.15 to 0.25	0.07 to 0.12	0.46 to 0.70	3.77	½ to 1	207 to 228	2300 to 3000	0.25 to 0.35	35,000 to 39,000
Class 35,............... heavy section, 2.0-in. test bar	2.80 to 3.10	1.60 to 2.00	0.10 to 0.20	0.06 to 0.12	0.45 to 0.70	3.54	1 and up	183 to 217	7500 to 9000	0.32 to 0.38	35,000 to 38,000
Class 40,............... light section, 0.875-in. test bar	3.00 to 3.20	1.90 to 2.20	0.10 to 0.25	0.07 to 0.12	0.45 to 0.65	3.77	... to ½	212 to 241	1275 to 1550	... ...	42,000 to 46,000
Class 40,............... medium section, 1.2-in. test bar	2.95 to 3.15	1.70 to 2.00	0.10 to 0.20	0.06 to 0.11	0.45 to 0.70	3.65	½ to 1	207 to 241	2500 to 3400	0.25 to 0.35	40,000 to 47,000
Class 40,............... heavy section, 2.0-in. test bar	2.75 to 3.00	1.50 to 1.90	0.07 to 0.15	0.05 to 0.12	0.50 to 0.70	3.42	1 and up	180 to 217	8400 to 9800	0.30 to 0.38	41,000 to 45,000
Class 50,............... light section, 0.875-in. test bar	2.90 to 3.10	1.70 to 2.10	0.10 to 0.20	0.06 to 0.12	0.50 to 0.70	3.62	... to ½	228 to 269	1600 to 1800	... ...	51,000 to 55,000
Class 50,............... medium section, 1.2-in. test bar	2.70 to 3.00	1.70 to 2.00	0.10 to 0.20	0.06 to 0.11	0.60 to 0.80	3.45	½ to 1	228 to 269	3000 to 4000	0.28 to 0.34	50,000 to 57,000
Class 50,............... heavy section, 2.0-in. test bar	2.55 to 2.85	1.40 to 1.70	0.07 to 0.15	0.06 to 0.11	0.60 to 0.80	3.20	1 and up	207 to 241	10,000 to 12,500	0.38 to 0.48	50,000 to 54,000
Class 60,............... light section, 0.875-in. test bar	2.70 to 3.00	1.90 to 2.20	0.10 to 0.20	0.06 to 0.12	0.50 to 0.70	3.51	... ...	228 to 272	1750 to 2000	... ...	60,000 to 65,000
Class 60,............... medium section, 1.2-in. test bar	2.50 to 2.85	1.90 to 2.10	0.05 to 0.15	0.05 to 0.10	0.70 to 1.00	3.37	... ...	248 to 290	3400 to 4500	0.25 to 0.40	60,000 to 65,000
Class 80,............... heavy section, 2.0-in. test bar	2.50 to 2.80	1.20 to 1.50	0.07 to 0.15	0.05 to 0.12	0.50 to 0.80	3.09	... ...	212 to 248	11,500 to 13,500	0.35 to 0.50	60,000 to 64,000

(a) "Carbon equivalent" is calculated as percentage carbon plus 0.3 times the sum of percentage silicon and phosphorus. Some use carbon plus 1/3 silicon. Data in this table from "Handbook of Cupola Operation", AFS, 1946.

Currently, malleable irons find their widest use in the automotive field where they are used for many essential parts of the power train as well as for parts in the frames and wheels. They are also widely used in railway castings, agricultural equipment, ordnance material, electrical pole line hardware, hand tools and numerous other applications.

Nodular Irons

Shortly after the Second World War, it was found that the addition of small quantities of magnesium or cerium to grey cast iron caused the graphite to precipitate as nodules or spheroids, rather than the flake form. Like malleable iron, the matrix was no longer interrupted by long stringers of graphite, and the properties obtainable were similar to those found in malleable iron.

Since that time, the use of nodular or ductile iron, as it is called, has increased markedly, and has replaced many applications once served by mild steels. Ductile iron crankshafts, for example, are common in today's automobiles. Buried water and gas lines are often made of ductile iron, and a large amount of heavy machinery is produced from this type of iron, especially in the paper industry. Stamping dies are also being made from ductile iron to an increasing extent.

Impact properties are generally good, depending upon the composition and heat treatment employed, and transition temperatures can be as low as -75°C (-100°F). Consequently, greater use of nodular irons in the Arctic environment is to be anticipated, especially when one realizes that nodular irons offer similar properties to many cast steels but with improved castability as well as some economic benefit. It should be emphasized, however, that close control over the composition and quality of the castings is necessary, as with cast steel, if satisfactory use of nodular and malleable irons is to be made in the Arctic.

In all the foregoing, the discussion has centred around either unalloyed or low-alloy irons. With such compositions, the matrix phase has been alpha iron, a body-centered cubic structure.

If sufficient quantities of certain alloying elements (principally nickel) are present so that the stable room temperature phase is gamma iron, called austenite, the structure will be face-centered cubic. One of the many advantages of such a structure is a generally large increase in impact properties at low temperature (14). Thus, when considering alloys for use in low-temperature applications, austenitic alloys should also be investigated. Consequently, in the data sheets that follow, certain austenitic alloys will be listed, where sufficient information is available.

The data sheets which follow are directed into the four principal categories previously discussed for cast irons. In general, white and grey cast irons are almost completely brittle, and the applications for which they have been found suitable in normal climates will also hold true for Arctic conditions. Malleable and nodular (or ductile) iron exhibit significant ductility, and compositional control, heat treatment and freedom from defects all play an important role in determining their usefulness in low-temperature applications. Thus, more information is presented for the impact properties of these alloys than for the former two.

Mechanical Properties

White Cast Irons

The tensile properties of white iron castings are generally not of importance, except that there is a relationship between tensile strength and hardness. Generally speaking, unalloyed white irons range in tensile strength from 20,000 psi for high carbon white irons (3.75 to 4.00% C) to about (70,000 psi for lower carbon irons (2.50 to 2.60% C). Alloying could increase the strength to 90,000 psi. The compressive strength is suggested to be in the range 200,000 to 250,000 psi. Modulus of elasticity is between 24 and 28 x 10^6 psi.

Impact strength is very low, being about one third that of grey cast iron. Alloying results in some improvement. The hardness of white irons (unalloyed) ranges from about 375 BHN (54 Scleroscope) to 600 BHN (80 Scleroscope). Alloying can increase the hardness to about 700 BHN (90 Scleroscope).

The following table summarizes available data.

Table 3.1.c Types, Composition, Properties and Uses of Wear and Abrasion-Resistant, Chilled, Unalloyed and Alloyed White Irons (7,11,12).

PROPERTY	TYPES OF CAST IRON				
Analysis:	Unalloyed Chilled (1, 3)	Unalloyed White (1, 3)	Ni-Hard (5)	High Chromium (6, 8)	Molybdenum (7)
% Carbon.........	3.00-3.60	2.8-3.6	2.8-3.6	1.8-3.5	1.7-3.7
% Silicon..........	0.50-1.60	0.5-1.3	0.4-0.7	0.5-2.5	0.3-2.6
% Manganese......	0.25-0.70	0.4-0.9	0.2-0.7	0.3-1.0	0.2-1.5
% Nickel..........	....	....	2.50-4.75	0-5	0-5
% Chromium........	....	....	1.2-3.5	10-35	0-6
% Copper.........	Residual	Residual	....	0-3	0-1.5
% Molybdenum.....	....	....	....	0-3	0.3-12.0
Brinell Hardness No.......	350-575	300-575	525-600	250-700	350-700
Tensile Strength (in 1,000 psi).........	20-40	20-50	40-75	23-90	25-60
Transverse Test* Load-Lbs.............	2000-2800	2200-3000	4000-7000	2000-3500	1400-3200
Deflection-In............	.03-.12	.03-.15	.08-.12	.06-.15	.05-.15
Charpy Type Impact† Ft.-Lbs...............	3.5-8.0	3.5-10.0	20-55	10-35	10-25
Density-Lbs. per cu. in.....	.274-.280	.274-.281	.275-.280	.264-.280	.275-.285
Coefficient of Thermal Expansion at Room Temperature, 10^{-6} inches per °F...............	5.1-5.3	5.0-5.3	4.5-5.0	5.2-5.5	....
Electrical Resistivity Microhms/cc...........	5.0-5.3	5.0	80	....	....

* Standard 1.2" diameter bar loaded in center of 18" span.
† 1.2" diameter unnotched bar broken on 6" supports (Plain gray iron has 25-35 ft/lbs.)

TYPE	USES
Unalloyed White and Chilled Iron	Various abrasion resistant purposes, such as sludge pump liners, jaw crusher plates, grinding mill liners, grinding balls, abrasive handling equipment.
Martensitic Alloyed Iron (Ni-Hard)	Excellent wear resistance, used for grinding balls, mill liners, pulverizer rings and roll heads, slurry pump parts, elbows, metal working rolls, etc.
Martensitic Alloyed Iron (High Chromium) (Molybdenum)	Heat, abrasion and corrosion resistance, including augers, grinding balls, liners, shot blasting nozzles and blades, jaw crusher plates, rolls, valve seat inserts, plates, deep well pump, slurry pump parts, etc.

Grey Cast Irons

Flake graphite cast irons are normally brittle, due to the fact that an almost continuous path of graphite is present in the microstructure, leaving a small quantity of ferrite or pearlite to absorb this impact energy. The impact properties of these irons are therefore determined by the use of a special impact test specimen, the major departure being the elimination of the notch.

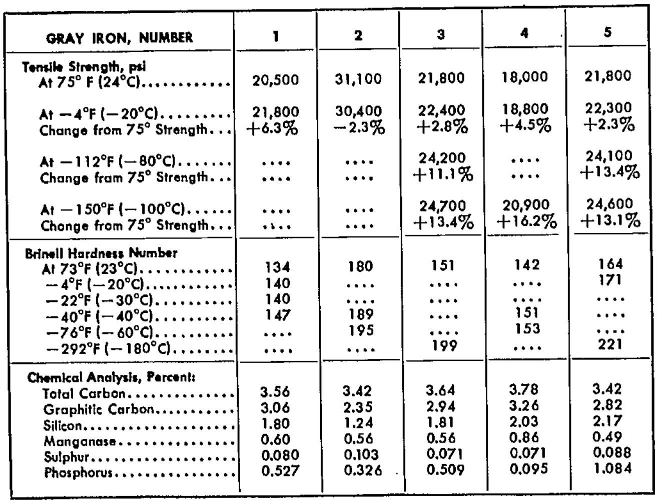
The fatigue properties of cast irons at low temperatures are not well established. A small amount of data indicates a slight but general increase in both notched and unnotched fatigue strength as the temperature is lowered to -40°C (-40°F). Since the flake graphite is, in effect, a notch in the specimen, little or no difference exists between notched and unnotched properties.

Rotating bending fatigue studies have shown a progressive drop in the endurance ratio of flake graphite irons from 0.46 to 0.34 as the tensile strength increased from 40,000 to 75,000 psi. The notch sensitivity was very low for the lower strength iron but followed a similar trend.

Table 3.1.d Physical and Mechanical Properties of Grey Cast Irons

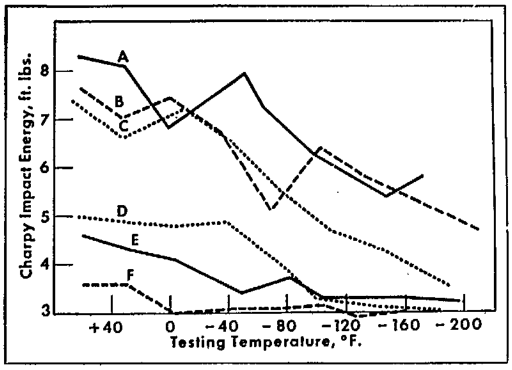
Density lb/in.^{3}	0.238/0.249	0.253/0.256	0.254/0.259	0.256/0.259	0.259/0.267
Coeff of thermal expansion,x 10^6/°F	Varies between 11 and 14 up to 1110°F				
Modulus of elasticity psi x 10^6	11 to 15	14 to 17	16 to 19	18 to 20	18 to 22
Tensile strength, psi	22,000	31,000	42,500	52,500	62,500
Comp strength, psi	83,000	109,000	140,000	164,000	187,500
Torsional shear strength psi.	26,000	40,000	57,000	73,000	88,500
Reversed bending fatigue limit, psi	10,000	14,000	18,500	21,500	24,500
Transverse strength, 1.2 in. diam bar, 18-in. span, lb	1,850	2,525	3,175	3,600	3,700
BHN	156	201	235	262	302

Table 3.1.e The Effect of Low Temperatures on the Tensile Strength Brinell Hardness of Five Grey Cast Irons



GRAY IRON, NUMBER	1	2	3	4	5
Tensile Strength, psi					
At 75° F (24°C)............	20,500	31,100	21,800	18,000	21,800
At −4°F (−20°C).........	21,800	30,400	22,400	18,800	22,300
Change from 75° Strength...	+6.3%	−2.3%	+2.8%	+4.5%	+2.3%
At −112°F (−80°C).......	....	....	24,200	....	24,100
Change from 75° Strength...	....	....	+11.1%	....	+13.4%
At −150°F (−100°C)......	....	....	24,700	20,900	24,600
Change from 75° Strength...	....	....	+13.4%	+16.2%	+13.1%
Brinell Hardness Number					
At 73°F (23°C)............	134	180	151	142	164
−4°F (−20°C)............	140	....	....	....	171
−22°F (−30°C)..........	140	....	....	....	....
−40°F (−40°C)..........	147	189	....	151	....
−76°F (−60°C)..........	....	195	....	153	....
−292°F (−180°C)........	....	....	199	....	221
Chemical Analysis, Percent:					
Total Carbon..............	3.56	3.42	3.64	3.78	3.42
Graphitic Carbon...........	3.06	2.35	2.94	3.26	2.82
Silicon....................	1.80	1.24	1.81	2.03	2.17
Manganase.................	0.60	0.56	0.56	0.86	0.49
Sulphur...................	0.080	0.103	0.071	0.071	0.088
Phosphorus................	0.527	0.326	0.509	0.095	1.084

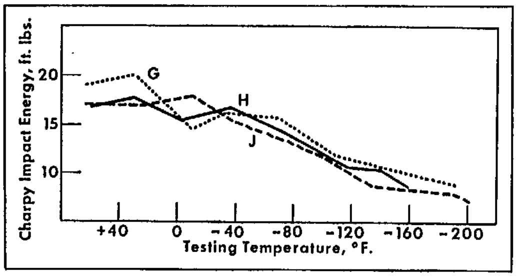
Figures 3.1.a and 3.1.b are graphs made from data by Gilbert and show the variation in impact properties with temperature for a number of different irons, using an unnotched Charpy impact specimen.



Chemical analysis (%)

Curve	TC	Si	Mn	S	P	Ni	Cr	Mo	Cu
A	3.20	1.90	0.69	0.03	0.04	...	...	...	...
B	2.91	1.57	0.87	0.10	0.04	0.16	0.10	0.57	0.11
C	2.89	1.68	0.54	0.06	0.04	2.13	...	...	...
D	2.79	3.06	0.63	0.02	0.04	...	...	...	...
E	3.13	2.31	0.69	0.14	0.17	...	...	...	...
F	3.12	1.92	0.90	0.08	0.58	...	...	...	...

Fig. 3.1.a The low-temperature impact resistance of unalloyed and low-alloy grey cast irons.



Chemical analysis (%)

Curve	TC	Si	Mn	S	P	Ni	Mo
G	3.03	1.60	0.55	0.03	0.03	2.32	0.35
H	3.17	2.11	0.50	0.03	0.03	1.59	0.75
J	3.06	2.18	0.46	0.04	0.04	3.10	0.54

Fig. 3.1.b The low-temperature impact resistance of alloy grey irons with an acicular matrix microstructure.

Nickel is widely used to improve the impact properties of ferrous metals. Table 3.1.f below, lists the impact properties of four cast irons and illustrates the effect of increasing nickel content. The impact properties were determined on unnotched 1.2-in. diameter specimens broken in an Izod impact testing machine.

Table 3.1.f Impact Tests on Cast Irons Containing Nickel

	Chemical composition (%)					Unnotched Izod impact -ft lb	
Material	C	Si	Ni	Cr	Cu	Ambient	-43°C (-45°F)
A	3.44	1.96				39	29
B	2.76	2.02	1.75			44	38
Ni resist*	2.73	1.59	13.76	1.95	6.00	55	50
Invar cast iron*	2.50	1.40	30.00	4.00		81	70

*These two alloys contain an essentially austenitic matrix.

References: 1-4, 7, 11-12, 16-17.

Malleable Cast Irons

Table 3.1.g Physical Properties of Malleable Irons

Density	0.253 to 0.261 lb/in.^{3}
Coeff of expansion	6.6 x 10^{-6}/°F
Modulus of elasticity	25 x 10^6 psi (approximate)

Table 3.1.h Specifications for Ferritic and Pearlitic Malleable Irons

Specification*	Grade	Min UTS, ksi	Min YS, ksi	Min Elong % in 2 in.
ASMT- A 47	32510	50.0	32.5	10
A 47	35018	53.0	35.0	18
A197	Cupola	40.0	30.0	5
A220	45010	65.0	45.0	10
A220	45007	68.0	45.0	7
A220	48004	70.0	48.0	4
A220	50007	75.0	50.0	7
A220	53004	80.0	53.0	4
A220	60003	80.0	60.0	3
A220	80002	100.0	80.0	2

*ASTM A47 and A197 are for ferritic malleable iron and ASTM A220 is for pearlitic malleable iron.

Table 3.1.i Typical Composition (%) Ranges for Ferritic and Pearlitic Malleable Irons

Element	Ferritic Malleable Iron		Pearlitic Malleable Iron
	Grade 32510	Grade 35018	
Total Carbon	2.30 to 2.65	2.00 to 2.45	2.00 to 2.65
Silicon	0.90 to 1.65	0.95 to 1.35	0.90 to 1.65
Manganese	0.25 to 0.55	0.25 to 0.55	0.25 to 1.25
Sulphur	0.05 to 0.18	0.05 to 0.18	0.05 to 0.18
Phosphorus	0.18 max	0.18 max	0.18 max

The impact properties of malleable iron are much higher than those of white or grey cast iron, and are determined either on the "V"-notched Charpy or Izod impact specimens used for steels, or on similar specimens, unnotched.

The notched impact strength of ferritic grade malleable iron is about 10 ft lb at 21°C (70°F), and drops to about 7 ft lb at -29°C (-20°F). For pearlitic malleable iron the figures are about 8 and 4 ft lb respectively, at the two temperatures.

Phosphorus has a marked effect on the impact properties of malleable irons. If good low-temperature properties are desired, the phosphorus content should be kept as low as possible. Table 3.1.j (5) illustrates the effect of phosphorus on the tensile properties at room temperatures and on the unnotched impact properties at temperatures, down to -80°C (-112°F) for three malleable irons.

The structural differences achievable in malleable irons can also affect the mechanical properties, both at room and low temperatures, as indicated by the data in Table 3.1.k.

The fatigue strength of ferritic malleable iron is 28,000 to 30,000 psi, giving an endurance ratio of about 0.5. For pearlitic malleable iron, the endurance limit is higher at about 40,000 psi, but the endurance ratio is lower at around 0.4.

References 1,5,6-7,11-12

Table 3.1.j Effect of Phosphorus on the Mechanical Properties of the Malleable Irons (5).

Mechanical Properties

Grade	%P	Tensile Strength UTS ksi	Elong, %	BHN	Unnotched Impact Values - ft lb			
					20°C (68°F)	0°C (32°F)	-40°C (-40°F)	-80°C (-112°F)
KCh 35.10	0.04	44.45	17.4	121	64.7	61.8	56	53.2
	0.15	47.6	13.0	149	46.7	43.1	39.5	36
	0.20	50.2	11.8	149	39.5	37.4	21.6	12.9
	0.35	50	7.0	159	18.0	10.8	7.9	7.2
KCh 50-4	0.04	65.8	4.9	187	37.4	36	33	30.9
	0.12	65.4	4.6	183	30.2	28.8	25.9	24.4
	0.19	62.35	5.0	189	18.0	14.4	9.3	5.8
	0.34	57.9	2.5	179	10.8	8.6	5	4.3
KCh 60-5	0.05	81.9	6.0	179	50.3	48.2	46.7	43.1
	0.12	83.3	4.2	183	28.8	27.3	23.7	20.1
	0.20	81	2.5	177	19.4	15.8	12.9	10.1
	0.32	71.1	1.5	177	12.2	11.5	9.3	5.8

Grade	Composition, (%)					
	C	Si	Mn	S	P	Cr
KCh 35-10	2.70	1.25	0.55	0.20	0.04 - 0.35	0.07
KCh 50-4	2.69	1.22	0.38	0.15	0.04 - 0.34	0.07
KCh 60-5	2.60	1.27	0.38	0.14	0.05 - 0.32	0.07

Table 3.1.k Mechanical Properties of Various Heat-Treated Malleable Irons at 20°C and -60°C (6).

		Mechanical Properties							
		20°C (68°F)				-60°C (-76°F)			
Iron Grade	Matrix Microstructure	UTS, ksi	Elong, %	Unnotched Impact ft lb	BHN	UTS ksi	Elong, %	Unnotched Impact, ft lb	BHN
KCh 50-4	Pearlite + 25% Ferrite	67.3	5.6	36	197	71.7	5.0	30	197
KCh 63-2	Pearlite	82.5	4.0	28.5	281	85.6	3.0	21.5	281
KCh 60-4	Sorbite*	85.1	6.0	43	229	87.6	5.4	34.5	229
KCh 70-3	Sorbite + troostite*	91.4	4.5	32.3	255	94.0	3.9	25	255
KCh 80-2	Troostite + Sorbite*	106.7	3.5	25	289	107.9	2.5	21.5	289
KCh 90-1.5	Troostite*	120.6	3.2	23	310	123.2	1.8	16.5	310

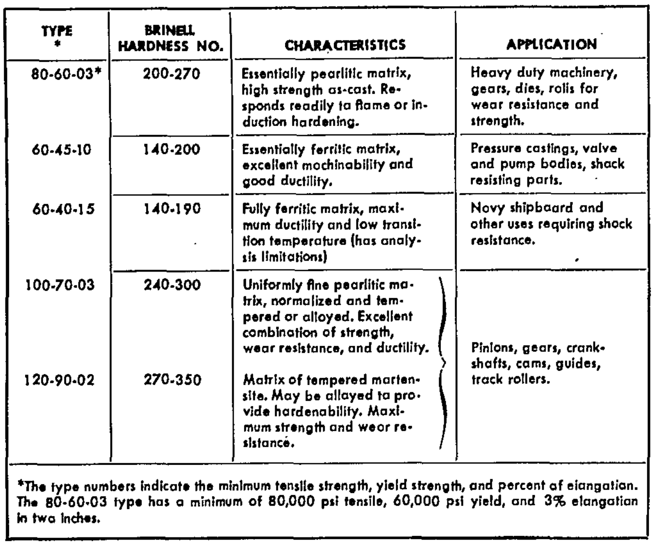
* These microstructures would be more correctly identified as tempered martensite. The terms sorbite and troostite are obsolete, and not used in most current Western literature.

Nodular Cast Irons

Table 3.1.ℓ Physical Properties of Nodular Cast Irons

Density	0.257 lb/in.^{3}
Coeff of thermal expansion (70°F to 400°F)	6.6 x 10^{-6}/°F
Modulus of elasticity	21 to 25 x 10^6 psi

Table 3.1.m Principal Types of Nodular Iron



TYPE *	BRINELL HARDNESS NO.	CHARACTERISTICS	APPLICATION
80-60-03*	200-270	Essentially pearlitic matrix, high strength as-cast. Responds readily to flame or induction hardening.	Heavy duty machinery, gears, dies, rolls for wear resistance and strength.
60-45-10	140-200	Essentially ferritic matrix, excellent machinability and good ductility.	Pressure castings, valve and pump bodies, shock resisting parts.
60-40-15	140-190	Fully ferritic matrix, maximum ductility and low transition temperature (has analysis limitations)	Navy shipboard and other uses requiring shock resistance.
100-70-03	240-300	Uniformly fine pearlitic matrix, normalized and tempered or alloyed. Excellent combination of strength, wear resistance, and ductility.	Pinions, gears, crankshafts, cams, guides, track rollers.
120-90-02	270-350	Matrix of tempered martensite. May be alloyed to provide hardenability. Maximum strength and wear resistance.	

*The type numbers indicate the minimum tensile strength, yield strength, and percent of elongation. The 80-60-03 type has a minimum of 80,000 psi tensile, 60,000 psi yield, and 3% elongation in two inches.

Table 3.1.n Typical Composition (%) Range for Unalloyed Nodular Iron

Total carbon	3.20 to 4.10
Silicon	1.80 to 2.80
Manganese	Up to 0.80
Sulphur	0.03 max
Phosphorus	0.10 max
Magnesium	0.03 to 0.07

The effect of low temperature on the tensile and impact properties of two unalloyed nodular cast irons is shown in Table 3.1.o. 3.1.o.

The silicon and phosphorus contents of nodular iron have been shown to have a pronounced effect on the impact transition temperature, as shown in Fig. 3.1.c and 3.1.d. The impact specimens used were oversize and give higher impact values. It was shown, however, that the impact transition temperatures were not affected by this specimen size, its effect being to reveal the transition more clearly.

The effect of microstructure and alloying elements on the nil-ductility transition (NDT) temperature of ferrite nodular iron is shown graphically in Fig. 3.1.e. Silicon and phosphorus are again shown to be detrimental and carbides are to be avoided if low NDT temperatures are to be achieved. The varying effect of nickel was unexpected, but similar effects were noticed with Charpy impact data. A fully ferritic microstructure is the most desirable for good low-temperature impact properties.

Table 3.1.o Effect of Low Temperatures on the Tensile and Impact Properties of Two Nodular Cast Irons (1)

Test Temp, °C (°F)	Ultimate Tensile Strength		Test Temp, °C (°F)	Unnotched Impact Strength	
	A ksi	B ksi		A ft lb	B ft lb
16 (61)	76.8	73.0	17 (63)	16.8	24.0
0 (32)	82.4	75.9	0 (32)	16.0	13.3
-30 (-32)	82.4	76.8	-21 (-6)	8.2	9.0
-48 (-51)	80.6	80.6	-45 (-49)	7.2	9.0
-75 (-103)	83.8	81.5	-60 (-76)	2.9	4.3
-91 (-132)	80.4	83.2	-75 (-103)	3.1	4.3

Iron	Composition (%)					
	C	Mn	Si	S	P	Ce
A	3.62	0.49	3.11	0.010	0.037	0.054
B	3.65	0.44	3.06	0.003	0.033	0.070

The fatigue strengths of nodular irons are higher than those of flake graphite irons of the same tensile strength, but the endurance ratio decreases similarly (0.59 to 0.46) as the tensile strength increases (53,000 to 90,000 psi). Nodular irons are, however, much more notch sensitive. Both plain and notched fatigue strengths tend to increase as the temperature is lowered, going from about 28,000 psi at room temperature to 32,000 psi at -78°C (-110°F) for unnotched bars.

Austenitic nodular cast irons have much better low-temperature impact properties. Table 3.1.p lists the mechanical properties of several austenitic nodular cast irons and includes impact data down to -73°C (-100°F).

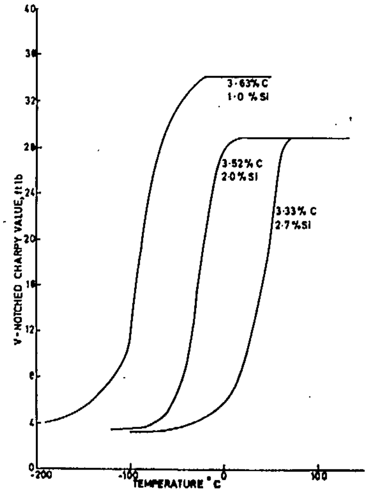


Fig. 3.1.c Effect of silicon on impact properties of ferritic nodular irons, V-notched specimens. BCIRA specimen 3/4 x 1/2 x 4 in.

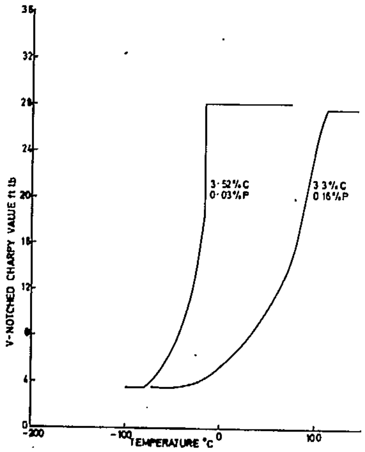


Fig. 3.1.d Effect of phosphorus on the impact properties of ferritic nodular irons, V-notched specimen BCIRA specimen 3/4 x 1/2 x 4 in.

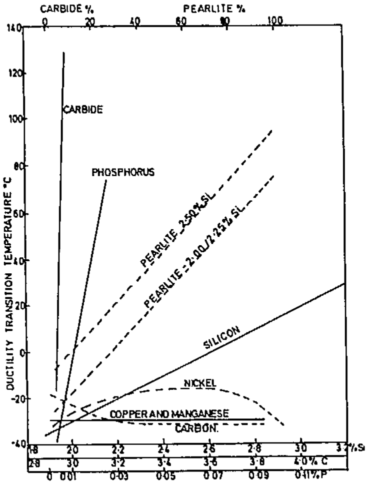


Fig. 3.1.e Effect of compositional and microstructural variables on the drop-weight transition temperature (19).

Table 3.1.p Composition and Mechanical Properties of Austenitic Nodular Cast Irons

Trade names (Type)	BS 3468/1962 designation	Equivalent ASTM designation	Composition, %						Tensile strength, tons/in²	Minimum 0·50% proof stress, tons/in²	Minimum elongation, %	Hardness, HB 10/3000	Charpy V-notch impact, ft lb			
			C	Si	Mn	P	Ni	Cr					+ 20 C	− 18 C	− 73 C	− 185 C
D2 S.G. *Ni-resist*	AUS: 202 Grade A	D-2	3·0 max.	1·0–2·8	0·7–1·5	0·08 max.	18·0–22·0	1·0–2·5	24·0	15·0	8·0	201 max.	12·5	11·5	10·0	4·5
D2B S.G. *Ni-resist*	AUS: 202 Grade B	D-2B	3·0 max.	1·0–2·8	0·7–1·5	0·08 max.	18·0–22·0	2·0–3·5	24·0	15·0	6·0	205 max.				
D2C S.G. *Ni-resist*	AUS: 203	D-2C	3·0 max.	1·0–2·8	1·8–2·4	0·08 max.	21·0–24·0	0·5 max.	24·0	15·0	20·0	170 max.	28·0	15·0	5·5	4·0
Modified D2C (D2M)	—	—	2·5 max.	2·2 max.	3·75–4·25	0·08 max.	21·0–24·0	0·5 max.	—	—	—	—				
S.G. *Nicro silal*	AUS: 204	—	3·0 max.	4·5–5·5	1·0–1·5	0·08 max.	18·0–22·0	1·0–2·5	24·0	15·0	10·0	230 max.				
D3 S.G. *Ni-resist*	AUS: 205	D-3	2·60 max.	1·5–2·8	0·5 max.	0·08 max.	28·0–32·0	2·5–3·5	24·0	15·0	7·0	201 max.	7·0	—	6·5	3·5
D3A S.G. *Ni-resist*	—	D-3A	2·60 max.	1·0–2·8	1·0 max.	0·08 max.	28·0–32·0	1·0–1·5	24·5	13·4*	10·0	131–193	14·0	14·0	13·0	7·5
D4 S.G. *Ni-resist*	—	D-4	2·60 max.	5·0–6·0	1·0 max.	0·08 max.	28·0–32·0	4·5–5·5	26·9	—	—	202–273				
D5 S.G. *Ni-resist*	—	D-5	2·40 max.	1·0–2·8	1·0 max.	0·08 max.	34·0–36·0	0·01 max.	24·5	13·4*	20·0	131–185	17·0	15·0	14·0	11·0
D5B S.G. *Ni-resist*	—	D5B	2·40 max.	1·0–2·8	1·0 max.	0·08 max.	34·0–36·0	2·0–3·0	24·5	13·4*	6·0	139–193	5·5	5·5	4·5	4·0

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3.2 STEELS

R.F. Knight*

Introduction

Ferrous products, both wrought and cast, make up the vast majority of the world's metallic utilization. It is natural, then, that for tonnage applications such as bridges, pipelines, transmission towers, rails and rolling stock, and drilling rigs, steels will be the material of choice in the development of the Arctic regions. The wide diversity of properties attainable in specialty steels will make their choice for many special applications attractive. Hence, a detailed knowledge of the effects of Arctic environment on steels is essential.

The vast number of combinations of compositions and treatments for ferrous materials precludes the preparation of anything approaching a comprehensive listing. The examples described in the following narrative and data sheet sections are intended to be illustrative of the type of low-temperature behaviour expected for the various classes of steels.

The specific metallurgical problem arising from the low-temperature application of ferrous materials would appear to be that of the brittle-fracture phenomenon, since steels become stronger and harder with decreasing temperature with, in general, predictable, proportional decreases in tensile ductility, i.e., without any transitional behaviour within the temperature ranges involved. Because of the inaccessibility of the regions in question, the strength-to-weight ratio of materials will be a significant parameter in the eyes of designers and may favour the use of ultra-high-strength steels in certain applications. However, it is essential to ensure optimum impact shelf energy, low-temperature impact strength and fracture toughness to preclude catastrophic failure.

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Classes of Steels

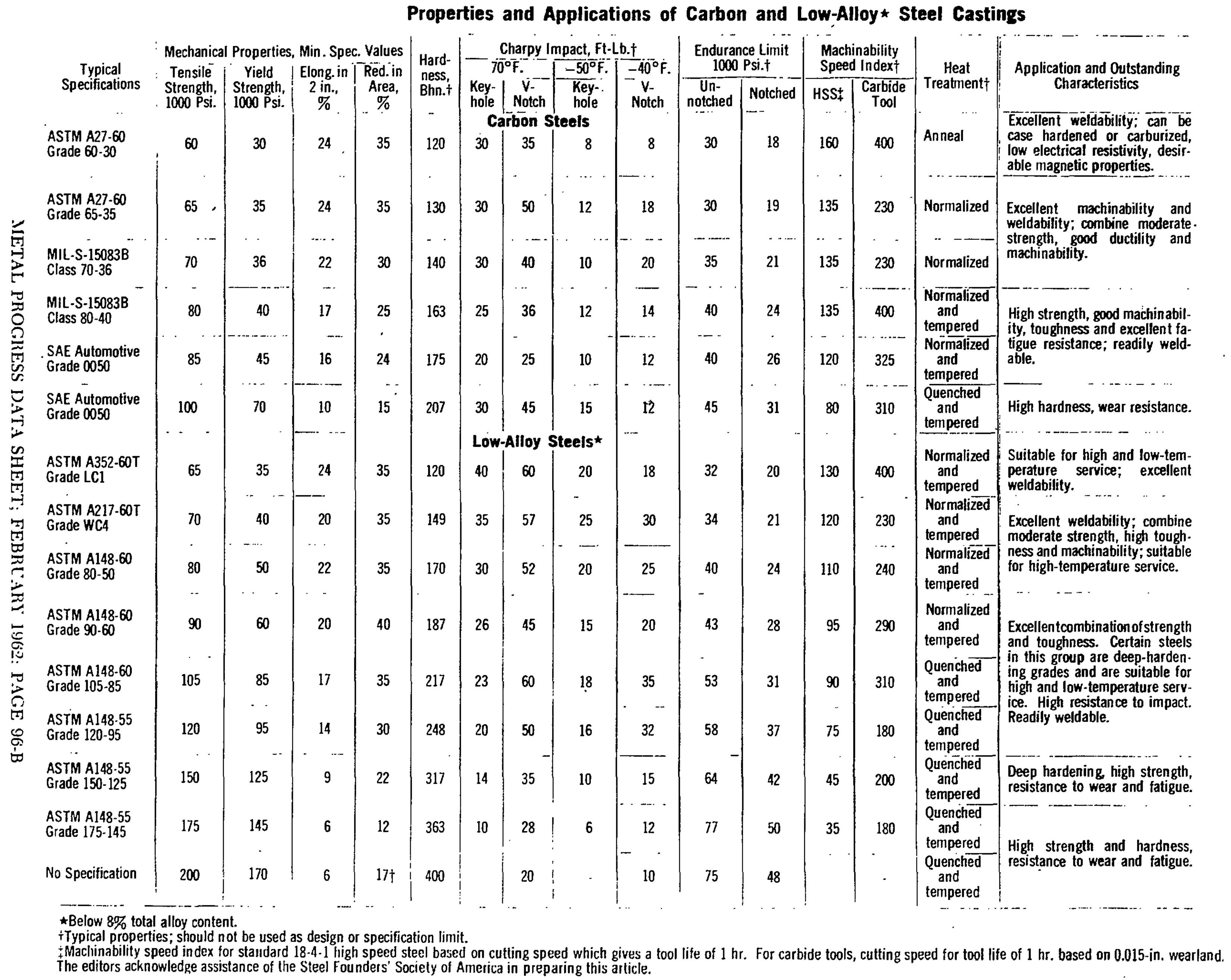
For the purposes of this report the properties of wrought materials are considered to be of practically exclusive interest. However, a compilation of data for carbon and low-alloy steel castings is reproduced in Fig. 3.2.a as an indication of the properties attainable for cast materials.

For convenience, steels are considered in this report as being in three separate categories, as follows:

- a - austenitic steels,
- b - steels that are ferritic after slow-cooling,
- c - air-hardening and precipitation-hardening martensitic alloys.

In general, the austenitic steels are not brittle-sensitive, and no special design problems are anticipated in their use in Arctic environment. However, in view of their high alloy content, the utilization of these materials would be expected to be limited to highly specialized applications.

The tonnage applications mentioned above will undoubtedly involve the use of ferritic steels. These become notch-sensitive at low temperatures to varying degrees dependent upon composition and treatment. The range of chemical composition for ferritic steels extends from the ordinary Bessemer grades, which are generally brittle in the Charpy test at room temperature, to the fine-grained, fully-quenched-and-tempered low-alloy grades, many of which still retain their notch-toughness down to -184°C (-300°F). Hence, the effect of composition is of primary concern in the selection of materials for low-temperature use. Since heat treatment provides control of the microstructure, it is one of the principal metallurgical factors affecting the low-temperature behaviour of steel.



METAL PROGRESS DATA SHEET, FEBRUARY 1962, PAGE 96-B

Properties and Applications of Carbon and Low-Alloy* Steel Castings

Typical Specifications	Mechanical Properties, Min. Spec. Values				Hardness, Bhn.†	Charpy Impact, Ft-Lb.†				Endurance Limit 1000 Psi.†		Machinability Speed Index†		Heat Treatment†	Application and Outstanding Characteristics
						70°F.		−50°F.	−40°F.						
	Tensile Strength, 1000 Psi.	Yield Strength, 1000 Psi.	Elong. in 2 in., %	Red. in Area, %		Keyhole	V-Notch	Keyhole	V-Notch	Unnotched	Notched	HSS‡	Carbide Tool		
						Carbon Steels									
ASTM A27-60 Grade 60-30	60	30	24	35	120	30	35	8	8	30	18	160	400	Anneal	Excellent weldability; can be case hardened or carburized, low electrical resistivity, desirable magnetic properties.
ASTM A27-60 Grade 65-35	65	35	24	35	130	30	50	12	18	30	19	135	230	Normalized	Excellent machinability and weldability; combine moderate strength, good ductility and machinability.
MIL-S-15083B Class 70-36	70	36	22	30	140	30	40	10	20	35	21	135	230	Normalized	
MIL-S-15083B Class 80-40	80	40	17	25	163	25	36	12	14	40	24	135	400	Normalized and tempered	High strength, good machinability, toughness and excellent fatigue resistance; readily weldable.
SAE Automotive Grade 0050	85	45	16	24	175	20	25	10	12	40	26	120	325	Normalized and tempered	
SAE Automotive Grade 0050	100	70	10	15	207	30	45	15	12	45	31	80	310	Quenched and tempered	High hardness, wear resistance.
						Low-Alloy Steels*									
ASTM A352-60T Grade LC1	65	35	24	35	120	40	60	20	18	32	20	130	400	Normalized and tempered	Suitable for high and low-temperature service; excellent weldability.
ASTM A217-60T Grade WC4	70	40	20	35	149	35	57	25	30	34	21	120	230	Normalized and tempered	Excellent weldability; combine moderate strength, high toughness and machinability; suitable for high-temperature service.
ASTM A148-60 Grade 80-50	80	50	22	35	170	30	52	20	25	40	24	110	240	Normalized and tempered	
ASTM A148-60 Grade 90-60	90	60	20	40	187	26	45	15	20	43	28	95	290	Normalized and tempered	Excellent combination of strength and toughness. Certain steels in this group are deep-hardening grades and are suitable for high and low-temperature service. High resistance to impact. Readily weldable.
ASTM A148-60 Grade 105-85	105	85	17	35	217	23	60	18	35	53	31	90	310	Quenched and tempered	
ASTM A148-55 Grade 120-95	120	95	14	30	248	20	50	16	32	58	37	75	180	Quenched and tempered	
ASTM A148-55 Grade 150-125	150	125	9	22	317	14	35	10	15	64	42	45	200	Quenched and tempered	Deep hardening, high strength, resistance to wear and fatigue.
ASTM A148-55 Grade 175-145	175	145	6	12	363	10	28	6	12	77	50	35	180	Quenched and tempered	High strength and hardness, resistance to wear and fatigue.
No Specification	200	170	6	17†	400		20	-	10	75	48		-	Quenched and tempered	

*Below 8% total alloy content.

†Typical properties; should not be used as design or specification limit.

‡Machinability speed index for standard 18-4-1 high speed steel based on cutting speed which gives a tool life of 1 hr. For carbide tools, cutting speed for tool life of 1 hr. based on 0.015-in. wearland.

The editors acknowledge assistance of the Steel Founders' Society of America in preparing this article.

Fig. 3.2.a. Reproduction of a portion of a Metals Progress Data Sheet showing the properties and applications of steel castings.

The best possible low-temperature properties obtainable from ferritic steels result from a fast cool from 816-871°C (1500-1600°F) and tempering at 538-649°C (1000-1200°F) (1). This treatment will normally give excellent toughness down to -129°C (-200°F), particularly if the fast-cool results in a martensitic microstructure. The tensile strength of such materials increases with decreasing temperature without any serious loss of ductility.

Most of these tonnage applications, however, present size and economic considerations which preclude the use of quenched materials. Generally, materials for such applications are used in the normalized condition or in the as-rolled condition, with or without controlled cooling from the rolling operation. These materials include carbon steels and various high-strength, low-alloy (HSLA) steels. Of particular interest from the latter group, in view of accessibility and maintenance difficulties in the Arctic, are the recently developed grades of "weathering steel".

The attractive properties of the more highly alloyed high-strength and ultra-high-strength steels will make them strong candidates for many specialty applications. These materials include the tempered-martensitic alloy steels and the highly alloyed, precipitation-strengthened low-carbon martensitic grades. It should be pointed out that these materials are expensive both by virtue of their high-alloy content and because of the fact that for optimum properties, particularly fracture toughness, vacuum melting or vacuum treatment of some type is essential.

a) Austenitic Steel

These highly alloyed steels, in general, present no special design problems at low temperature since they are tough, readily welded, and possess high strength and low thermal conductivity. The strength of these materials increases with reduced temperature, and the ductility values show a decrease commensurate with strength increase, with no severe transitional behaviour. These alloys are widely used for vessels operating at -157°C (-250°F) or lower.

The high strength of these alloys is provided by cold working, and hence their implementation is generally in the form of sheet, although casting grades are available. Although cold working lowers the overall notch toughness, it does not appear to affect sensitivity to temperature.

Data sheets appear in an Appendix for several typical austenitic stainless steels and for one grade of austenitic precipitation-strengthened steel.

Certain predominantly austenitic steels are temperature-sensitive, due in many cases to minor quantities of ferrite, sigma, carbides, and other precipitates in the austenite matrix. Certain sensitizing heat treatments, which simulate conditions that might occur on cooling after welding, can cause a deterioration of properties of some stainless austenitic steels.

In some cases nominally austenitic steels become embrittled at low temperatures without structural modifications. Type 201, a Cr-Ni-Mn steel developed as a low-nickel replacement for Type 301, shows a precipitous drop in impact properties between 10 and -18°C (50 to 0°F). The Hadfield manganese steels show a rapid decrease in impact values as well as a rapid decrease in both tensile strength and ductility. Austenitic precipitation-hardening grades have extremely low impact values even at room temperature.

b) Ferritic Steels

In general, those materials normally used in the as-rolled, annealed, or normalized conditions have low impact properties at the lowest limit of Arctic temperatures. As an illustration AISI 1040 may be considered. In the as-rolled condition, CVN values of 12 and 2 ft lb are obtained at 27 and

-73°C (80 and -100°F) respectively. For the normalized condition, comparative values are 23 and 3 ft lb (2).

Most of the HSLA steels are superior to carbon steels in low-temperature toughness, and, like the carbon steels, normalizing improves the properties as compared with the as-rolled condition. For applications such as air liquefaction plants, refrigeration installations, transport equipment, and containment vessels operating down to -46°C (-50°F) the steel normally must meet impact test requirements of ASTM A300 Class I specification, which calls for plate to be normalized and to meet a Charpy keyhole minimum of 15 ft lb at -46°C (-50°F). Potential materials are ASTM A516 Grades 55, 60, 65 and 70 and AARTC-128-Grade B at the 50 ksi minimum yield strength level (3). Other normalized steels specified for low-temperature service are ASTM A442-Grade 60 (to -46°C (-50°F)), ASTM A537-grade A (to -59°C (-75°F)), and nickel-bearing grades ASTM A203, Grades A and B (to -59°C (-75°F)) and Grades D and E (to -101°C (-150°F)).

As stated previously, the best possible low-temperature properties obtainable from ferritic steel result from quenching and tempering to obtain a tempered martensite microstructure. Although the impact properties attainable at particular strength levels are somewhat dependent upon composition, as illustrated by the appended data sheets for selected ferritic steels, they are also dependent upon the strength level, regardless of composition. This is illustrated by Fig. 3.2b which shows a graphical representation of the spread of all the data for quenched-and-tempered steels (4). It should be pointed out that these data include that of several higher-alloy steels which are discussed in the next section.

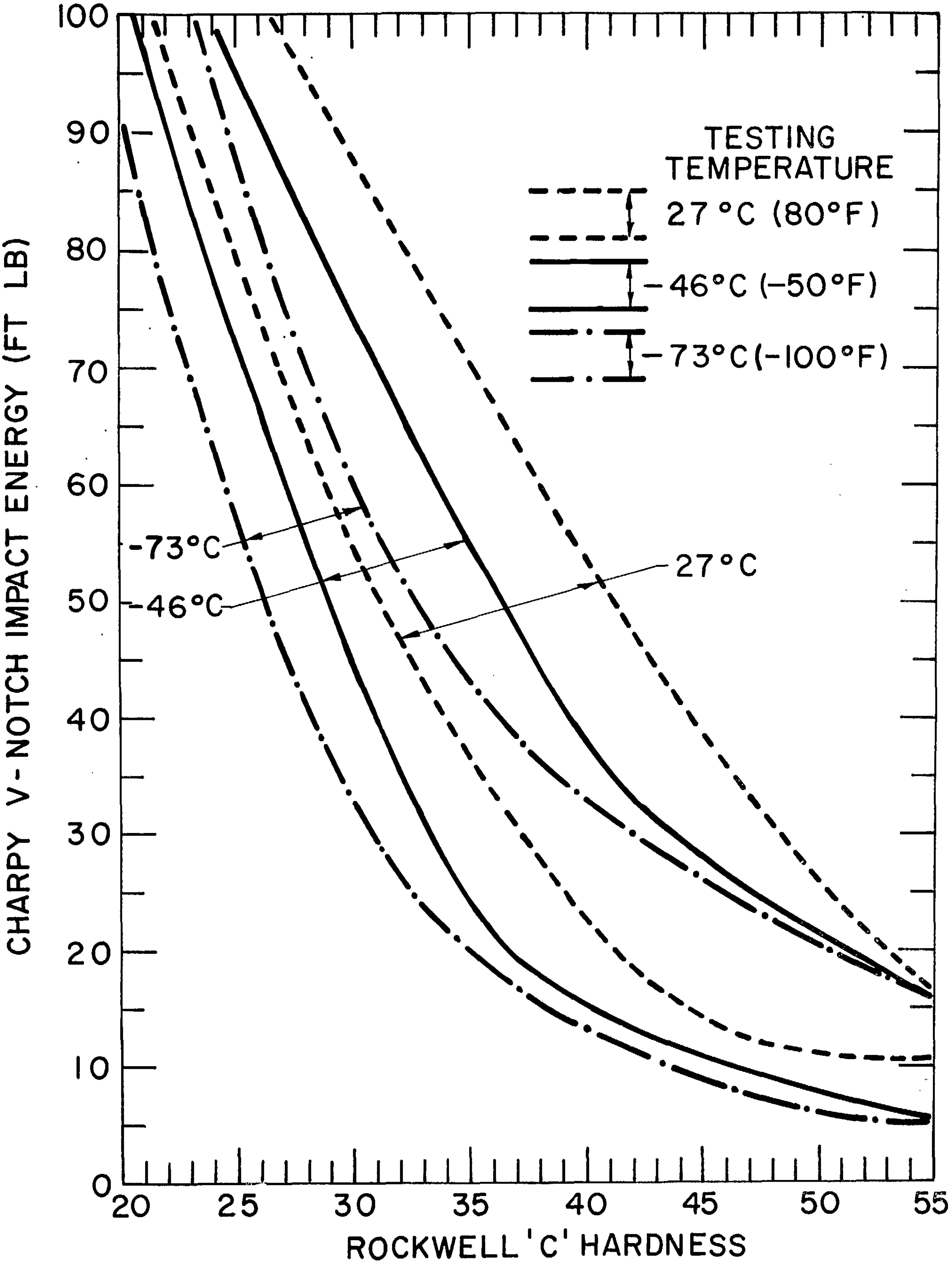


Fig. 3.2b Graphical presentation of spread of impact data for quenched-and-tempered steels.

c) Air-Hardening and Precipitation-Hardening Martensitic Steels

Many of the higher-alloyed steels and precipitation-strengthening steels, such as the various maraging grades, are capable of developing ultra-high-strength properties which, in view of the transportation problems involved in Arctic development, would make them attractive design possibilities. Their high relative cost, however, necessitates their use with a low safety factor, and hence it is most important that the knowledge of the effects of Arctic environment be thoroughly understood.

The appended data sheets summarize such relevant data as were available for air-hardenable quenched-and-tempered steels and for various low-carbon martensitic alloys which are strengthened by precipitation mechanisms.

Potential Problems

In order to provide adequate low-temperature toughness for Arctic installations it is probable that the bulk of the tonnage steel applications will be constructed of high-strength, low-alloy constructional steels. It is known that strain-ageing processes can cause embrittlement of many steels, and it is essential that the behaviour of the steels chosen under such conditions be known and accounted for in design.

Many of the materials used will be in the quenched-and-tempered condition. In certain steels under particular conditions of heat treatment, some degree of temper embrittlement can occur and it is important that the danger of this problem occurring be minimized by proper choice of materials and treatment.

In many of the steels that will be used at ultra-high-strength levels susceptibility to hydrogen embrittlement is found, in varying degrees. Processes must be controlled to minimize this problem.

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TYPE 301 and TYPE 302

Composition: 301 - 17 Cr, 7 Ni (0.15 C max)
302 - 18 Cr, 9 Ni (0.15 C max)

Physical Constants:

Density: 0.286 lb/in.^{3}
Modulus of elasticity: 28-30 x 10^6 psi
Modulus of rigidity: 12.5 x 10^6 psi
Thermal expansion (RT-400F): 8.2-9.4 x 10^{-6}/°F

Mechanical Properties:

301 Sheet - 40% cold rolled

	RT	-100F
UTS, ksi	190	225
YS, ksi	170	155
Elong, %	17	19
NTS, ksi (K_t=6.3)	200	216
NTS/UTS	1.05	0.96

301 Sheet - 60% cold rolled

	RT	-100F
UTS, ksi	224	253
YS, ksi	200	237
Elong, %	11	15
NTS, ksi (K_t=6.3)	240	250
NTS/UTS	1.07	0.99
Kc, ksi $\sqrt{\text{in.}}$	207	195

301 Sheet (UTS=241 ksi)

	RT	-110F
F.S.(P.B.)ksi	±80	≈±65

302 Sheet - 60% cold rolled

	RT	-100F
UTS, ksi	205	267
YS, ksi	180	195
Elong, %	3	13
NTS, ksi (K_t=6.3)	220	≈260
NTS/UTS	1.07	0.97

Comments:

Corrosion: Exceptional corrosion and oxidation resistance. Type 301 has a slightly lower corrosion resistance than 302.

Formability: Excellent formability in the annealed condition. Type 301 is a strongly work-hardening alloy, its austenite actually being unstable at room temperature, but too sluggish to transform without imposition of some other factor. Type 302 work-hardens less than 301, and is extremely well fitted to deep drawing operations and to almost every fabrication method.

Welding: For welded assemblies which are subjected to certain corrosive environments, low-carbon grades of the straight 18-8 steels may be satisfactory. High carbon leads to sensitization, and frequently the stabilized 18-8 steels, Type 321 and Type 347, are recommended.

General: Type 302 is by far the most widely used of any stainless steel. These steels are used primarily in the cold-worked condition, generally with a stress-relief treatment. Type 302 has a cast counterpart, CF-20.

References: 2,9-10

TYPE 304 and TYPE 304L

Composition: 19 Cr, 10 Ni (C-0.08 max-Type 304)
(C-0.03 max-Type 304L)

Alternate Designations: Cast - CF-8 and CF-3

Physical Constants:

Density: 0.287-0.292 lb/in.^{3}
Modulus of elasticity: 29 x 10^6 psi
Modulus of rigidity: 11.4 x 10^6 psi
Thermal expansion (RT-400F): 9.2-9.6 x 10^{-6}/°F

Mechanical Properties:

Annealed 304 bar

	RT	-100F
UTS, ksi	92	152
YS, ksi	35	35
Elong, %	62	55
RA, %	85	78
CVN, ft lb	120-155	90-130
FS(RB) ksi	±40	

Cast 304

	RT	-100F
UTS, ksi	68	127
YS, ksi	28	37
Elong, %	48	72
RA, %	49	61

50% cold-rolled sheet (ELC)

	RT	-100F
UTS, ksi	176	204
YS, ksi	158	190
Elong, %	6	3
NTS, ksi (K_t=6.3)	191	220
NTS/UTS	1.09	1.08

Full-Hard 304 bar (UTS-210)

	RT	
FS(RB) Plain ksi	±110	
FS Notched, ksi	± 23	(K_t=3.2)

Comments:

Corrosion: The slightly raised alloy content improves the general corrosion resistance somewhat.

Formability: Work hardening is minimized. The wrought forms of these grades possess very good formability.

Welding: These steels can be readily welded by all common methods. The low-carbon content minimizes the danger of sensitization.

References: 2,8,11-12

17-7 PH

Composition: 17 Cr, 7 Ni, 1 Al (0.09 C max)

Physical Constants:

Density: 0.276 lb/in.^{3}
Modulus of elasticity: 28 x 10^6 psi
Modulus of rigidity: ≈11 x 10^6 psi (dynamic)
Thermal expansion (70-400F): 6.5 x 10^{-6} /°F

Mechanical Properties:

Sheet TH1050 Condition

	RT	-110F
UTS, ksi	195	215
YS, ksi	180	195
Elong, %	11½	12
RA, %	26½	23
NTS, ksi (K_t=3)	235	235
NTS/UTS	1.21	1.09
K_{1c} (½-in.plate) ksi $\sqrt{in.}$	65-75	40-50
CVN, ft-lb (bar)	≈9	≈5
FS(PB) plain ksi	±81	≈±100
FS-Notched, ksi	±36 (K_t=3.61)	

Sheet RH950 Condition

	RT	-110F
UTS ksi	235	255
YS, ksi	225	240
Elong, %	7½	4
RA, %	17	3
NTS, ksi (K_t=3)	255	265
NTS/UTS	1.08	1.04
CVN, ft lb (bar)	≈ 6	≈ 4

Comments:

Corrosion: This age-hardenable, nearly austenitic stainless steel is superior in corrosion resistance to the chromium (martensitic) stainless steels and has oxidation resistance comparable to that of the austenitic stainless steels.

Formability: Can be formed readily in the annealed condition.

General: Special precautions are necessary when using the highest strength conditions or when using the alloy at subzero temperatures because of reduced crack propagation resistance.

References: 2,8,13,32

A533, GRADE B

Composition: 1.35 Mn, 0.5 Ni, 0.5 Mo (0.25 C max)

Mechanical Properties:

Plate (Q&T)

	RT	-100F
UTS, ksi	95	113
YS, ksi	73	91
Elong, %	25	25
RA, %	65	58
K_{1c}, ksi $\sqrt{in.}$	140	45-68
K_{1d}, ksi $\sqrt{in.}$	75	25

	RT	-80F
CVN, ft lb	105	16 (3-6 in.)
CVN, ft lb	70	7 (10-12 in.)

NDT temperature -28°F (3-6 in.)
-5°F (10-12 in.)

References: 5,6,7

NAX AC 9115

Composition: 0.75 Si, 0.6 Cr, 0.2 Mo, 0.1 Zr (0.14C)

Physical Constants:

Density: 0.284 lb/in.^{3}
Modulus of elasticity: 30 x 10^6 psi
Modulus of rigidity: 11.8 x 10^6 psi
Thermal expansion (70-200F): 6.5 x 10^{-6}/°F

Mechanical Properties:

Hot-Rolled bar

	RT	-100F
UTS, ksi	72	82
YS, ksi	53	60
Elong, %	38	38
RA, %	75	70
FS(RB), ksi	±46-50	

½-in. plate	RT	-60F
Charpy keyhole, ft lb	70	46

Comments:

Formability: Can be cold formed by standard procedures used for carbon steels with allowance for higher strength.

Machinability: It machines better than carbon steel of the same strength. The cold-worked condition is best for machinability.

Corrosion: Corrosion and oxidation resistance superior to those of plain carbon grades.

Weldability: Excellent.

Reference: 2

4130

Composition: 0.95 Cr, 0.2 Mo (0.3 C)

Physical Constants:

Density: 0.283 lb/in.^{3}
Modulus of elasticity: 30 x 10^6 psi
Thermal expansion (70-400F): 7.3 x 10^{-6}/°F

Mechanical Properties:

Normalized Bar

	RT	-100F
UTS, ksi	100	116
YS, ksi	76	94
Elong, %	15	16

Quenched, Tempered 800F

	RT
UTS, ksi	178
YS, ksi	150
Elong, %	19
RA, %	55

Quenched, Tempered 1200F

	RT
UTS, ksi	120
YS, ksi	96
Elong, %	25
RA %	70

FS(DS) normalized sheet (UTS ≈117)-plain ±42
- notched ±27 (K_t=2)

FS(RB)(UTS ≈ 140) ±70

	RT	-100F
CVN, ft lb (UTS 94)	110	30 (½-in. plate)
CVN, ft lb (UTS 131)	75	30 (½-in. plate)
K_{1c}(YS 158), ksi$\sqrt{\text{in.}}$	100	

Comments:

Corrosion: Coating or plating is required for corrosion resistance.

Formability: Good.

Machinability: Good.

Welding: Fusion-welded readily, but resistance welding is not recommended.

General: This material has low hardenability and poor impact properties at very low temperature, particularly in the normalized condition.

References: 2,14-15

4140

Composition: 1.0 Cr, 0.2 Mo (0.4 C)

Physical Constants:

Density: 0.283 lb/in.^{3}
Modulus of elasticity: $\approx 30 \times 10^6$ psi
Thermal expansion (0-200F): 6.3×10^6/°F

Mechanical Properties:

Q & T bar (½-1 in.) - T at 600F

	RT
UTS, ksi	230-250
YS, ksi	195-230
Elong, %	10
RA, %	40 - 45

Q&T bar (½-1 in.) T at 1075F

	RT
UTS, ksi	135-160
YS, ksi	120-150
Elong, %	18
RA, %	55

	RT	-100F	
K_{1c} (205 UTS) ksi $\sqrt{\text{in.}}$	70-110	40-60	
FS(RB)(237 UTS) plain ksi	±104		
notched ksi	± 62		(K_t=1.8)
FS(RB)(140 UTS) plain ksi	± 75		
notched ksi	± 40		(K_t=2)

	RT	0F	-100F
CVN, ft lb (T1075)	90-100	75-90	45-70

Comments:

Corrosion: Machinability, Welding - similar to AISI 4340.

General: Widely used where the higher hardenability and higher strength capability of 4340 is not required. It may be nitrided to improve wear and abrasion resistance.

References: 2,16,19

4330 V MOD (+ Si)

Composition: 1.8 Ni, 0.8 Cr, 0.4 Mo, 0.07 V (0.3 C, 1.5 Si)

Other Designations: AMS6427, 4330 V, 4330 V Mod, 4330 Modified
4330 V (Mod +Si)

Physical Constants:

Density: 0.283 $\mathrm{lb/in.}^3$
Modulus of elasticity: 30×10^6 psi
Modulus of rigidity: 11×10^6 psi
Thermal expansion (RT-200F): $\approx 6.7 \times 10^{-6}$/°F

Mechanical Properties:

T650F

	RT		
UTS, ksi	230		
YS, ksi	212		
Elong, %	11		
RA, %	50		
NTS, ksi (240 UTS) K_t=10	325		
NTS/UTS	1.35		
K_{Ic} (forging, 220/240 UTS)	52		(45 at -66F)
FS(RB)(250 UTS) plain, ksi	±90		
notched, ksi	±50	(K_t=8)	
CVN (3/4-in. bar)	28		(16 at -100F)

T 1050F

	RT		-100F
UTS, ksi (1-in. plate)	196		213
YS, ksi (1-in. plate)	172		187
Elong, % (1-in. plate)	16		13
RA, % (1-in. plate)	50		47
NTS, ksi (200 UTS) K_t=10	290		
NTS/UTS	1.45		
FS(RB) plain	±85		
notched	±40	(K_t=8)	
CVN, ft lb (T1000)	43		25

Comments:

Corrosion: Corrosion resistance similar to 4340 and 300-M.

Welding: Better welding and general fabrication characteristics than 4340 because of lower carbon content.

General: The addition of vanadium to this steel improves hardenability and provides some secondary hardening. The addition of silicon retards tempering so that higher strength can be maintained at higher tempering temperatures. The steel has better fracture toughness than 4340. Hydrogen embrittlement is a problem if the steel is heat treated to over 200 ksi UTS.

References: 2,18,33

4340, 4337

Composition: 1.8 Ni, 0.8 Cr, 0.25 Mo (0.38-0.43 C for 4340)
(0.35-0.40 C for 4337)

Physical Constants:

Density: 0.283 lb/in.^{3}
Modulus of elasticity: 29-30 x 10^6 psi
Thermal expansion (0-200F): 6.3 x 10^{-6}/°F

Mechanical Properties:

Tempered 800F

	RT	-100F
UTS, ksi	210-225	
YS, ksi	195-205	
Elong, %	15-20	
RA, %	40-55	
FS(RB&DS)plain, ksi	±120	
(10^6 cycles), notched, ksi	±38 (K_t=7.8)	
CVN, ft lb	12	9
K_{1c}, ksi $\sqrt{in.}$	≈90	30-55

Tempered 450F

	RT	-100F
UTS, ksi	270	280
YS, ksi	227	237
Elong, %	11	11
RA, %	39	40
NTS,ksi(K_t =3.2)	345	350
NTS/UTS	1.28	1.25
K_{1c}, ksi $\sqrt{in.}$	50-55	30-35
FS(RB&DS)(UTS 290)plain	±150	
(10^6 cycles) notched	±50 (K_t =7-8)	
CVN, ft lb	9-12	6-10

Comments:

Corrosion: General resistance is poor and corrosion protection is required. Hydrogen embrittlement becomes pronounced in material heat treated to above UTS 200 ksi when exposed to hydrogenating conditions.

Formability: Not well known, particularly in sheet form. Severe forming should require full or spheroidizing annealing. Straightening of parts should be performed cold. If heat treated parts are straightened, stress relief should follow.

Welding: Has good welding characteristics and parts can be joined by gas or arc fusion welds and resistance flash welding. Spot and seam welding is not recommended. Fusion or resistance flash welding of bar, forgings and tubing to be heat treated to UTS 260-280 ksi is not permissible.

Machining: Rough machining should be done in normalized and tempered condition. Finishing can be performed on material heat treated to all strength levels (followed by stress relieving for UTS >260).

Hardenability: 4337 is used only up to 1/8-in. diameter. 4340 through-hardens on oil quenching up to 3-in diameter.

References: 2,8,13,19,20,33

HY-TUF

Composition: 1.8 Ni, 1.5 Si, 1.3 Mn, 0.4 Mo(0.25 C)

Physical Constants:

Density: 0.281 lb/in.^{3}
Modulus of elasticity: 28.5 x 10^6 psi
Thermal expansion (RT-400F): 6.4 x 10^{-6}/°F

Mechanical Properties:

T 600F

	RT	-100F
UTS, ksi	230	
YS, ksi	194	
Elong, %	14	
RA, %	52	
NTS, ksi (K_t=9.5)	305	
NTS/UTS	1.32	
F.S.(RB) plain, ksi	±88	
notched, ksi	±46 (K_t=2.5)	
CVN, ft lb	30	21

Comments:

Corrosion: Similar to AISI 4340

Machinability: Comparable to other alloy steels of similar microstructure and hardness.

Welding: Easily welded by conventional methods using low-hydrogen electrodes of similar composition. Joint efficiencies are 92-95 per cent.

Reference: 2

T-1 and T-1A

Composition:

T-1 0.15 C, 0.8 Mn, 0.85 Ni, 0.53 Cr, 0.5 Mo, 0.32 Cu, 0.25 Si, 0.05 V (B)

T-1A 0.16 C, 0.85 Mn, 0.53 Cr, 0.2 Mo, 0.27 Si, 0.05 V, 0.02 Ti (B)

Physical Constants:

Density: 0.284 lb/in.^3

Modulus of elasticity: 30.5 x 10^6 psi

Thermal expansion (75-200F): 6.5 x 10^{-6}/°F

Mechanical Properties:

T-1 Plate (Q&T)

	RT	-100F
UTS, ksi	122	
YS, ksi	111	123
Elong, %	18½	
RA, %	62	
K_{Ic}, ksi $\sqrt{\text{in.}}$	≈140	83
CVN, ft lb (½-2 in)	52-58	24
FS(RB), ksi	±70	

Comments:

Corrosion: Resistance to atmospheric corrosion is considerably better than that of carbon steels.

Machinability: Readily fabricated.

Welding: Good Weldability.

General: T-1 is a low-carbon quenched and tempered low-alloy constructional steel with high yield strength and good toughness at moderately low temperatures. T-1A has somewhat lower toughness and hardenability. The minimum recommended service temperature is -50F, and these steels are not recommended for service conditions where tolerance for large plastic deformation is required under dynamic loads.

References: 2,21

300-M

Composition: 1.8 Ni, 1.6 Si, 0.8 Cr, 0.4 Mo, V (0.43 C)

Alternate Designations: Inco Ultra High Strength Steel, 4340M

Physical Constants:

Modulus of elasticity: 28.4×10^6 psi

Mechanical Properties:

Quenched and Tempered Bar

	75F	-110F
UTS, ksi	285	295
YS, ksi	240	257
Elong, %	12½	14½
RA, %	41½	42
NTS, K_t=3.0, ksi	387	395
NTS/UTS	1.36	1.34
K_{1c}, ksi $\sqrt{\text{in.}}$	40-60*	
CVN, ft lb	13-16	10-13 (at -100F)
FS(DS), ksi, plain	±120	
(10^6 cycles) notched	±70 (K_t-3)	

*Vacuum arc remelt, forging

Comments:

Corrosion: General corrosion resistance is poor and protection is needed. At high-strength levels this steel is very susceptible to hydrogen embrittlement, and the introduction of hydrogen by processes such as pickling, cathodic cleaning, and plating cannot be tolerated.

Formability and Welding: Can be formed, but welding is generally not recommended.

Machinability: Machining is best performed in the spheroidized condition.

General: This ultra-high-strength steel is being used primarily in the form of bar, tubing and forgings, heat treated to 270 to 300 ksi UTS.

References: 2,8,22,33

H-11 Mod

Composition: 5 Cr, 1.3 Mo, 0.5 V (0.4 C, 0.8 Si)

Other Designations: Type H-11 Modified Steel, 5 CrMoV Aircraft Steel, Modified AISI Type H-11 Steel, 5 Cr Ultra-High-Strength Steel, AISI No. 610, Type H-11.

Physical Constants:

Density: 0.280 lb/in.^{3}
Modulus of elasticity: 28.5 - 30 x 10^6 psi
Thermal expansion (70-400F): 6.8 x 10^{-6}/°F

Mechanical Properties:

Bar, T975

	RT	-110F
UTS, ksi	312	350
YS, ksi	236	267
Elong, %	6½	5½
RA, %	23½	9½
NTS(K_t=3.0), ksi	307	310
NTS/UTS	0.98	0.89

Sheet and Bar

	T1000		T1100	
	RT	-50F	RT	-50F
UTS, ksi	290-300	300-310	225-235	235-245
YS, ksi	240-245	250-255	190-195	195-210
Elong, %	10-15	10-15	10-15	10-15
RA, %	40	35	50	47
K_{1c}, ksi $\sqrt{\text{in.}}$	25	22	50-75	30-45

		RT	-100F
CVN, ft lb (T1060)		22	15
FS, ksi (UTS 260)	RB, plain	±130	
(T1025)	DS, plain	±90	
	DS,notched	±50 (K_t=3)	

Comments:

Corrosion: Corrosion resistance is low and surface protection is required. Hydrogen embrittlement may occur after hydrogenating treatments of the high-strength conditions.

Formability: Good in the annealed condition.

Welding: Since the steel is air-hardening, it requires preheating for welding, but it is readily welded and exhibits little distortion when heat treated.

General: Since the steel is of the secondary hardening type it requires tempering temperatures in excess of 900F.

References: 2,8,15,19

9 Ni-4 Co

Composition: 9 Ni, 4 Co, Cr, Mo, V
(0.20, 0.25, 0.30 and 0.45 C grades)

Physical Constants:

Density: 0.28 lb/in.^{3}
Modulus of elasticity: 28.3 x 10^6 psi
Modulus of rigidity: 10.9 x 10^6 psi
Thermal expansion (70-200F): 6.2 - 6.4 x 10^{-6}/°F

Mechanical Properties:

Grade 20,25 - 180-210 ksi UTS
Grade 30 - 220-240 ksi UTS
Grade 45 - 260-280 ksi UTS

Plate

	0.30C		0.25C	
	RT	-100F	RT	-100F
UTS, ksi	220	238	208	222
YS, ksi	199	215	188	212
Elong, %	15	14	16	14
RA, %	63	58	58	56
*NTS,ksi(.25C sheet,178YS)			235	246
K_{Ic}(.25C),ksi$\sqrt{\text{in.}}$			100-120	110 (at -75F)
CVN, ft lb(3/4-in. 0.25C plate)			35	28
(3-in. 0.25C plate)			46	35

0.20C, 204 UTS	RT
FS(RB),ksi,plain	±100
notched	±36 (K_t=3)

0.25C, 200 UTS	RT
FS(RB),ksi,plain	±110
notched	±35 (K_t=3)

(*1-in. wide, 60° edge notch, 0.35-in. minor width, r=0.002 max)

Comments:

Corrosion: General corrosion and oxidation resistance is superior to AISI 4340; however, coatings are necessary to protect it from atmospheric corrosion.

Formability: In general, hot working is somewhat more difficult than with 4340 due to high cobalt. The absence of aluminum in carbon deoxidized materials will result in rapid grain growth at temperatures above 2050F.

Machinability: Similar to 4340.

Weldability: The 0.20 C and 0.25 C grades can be welded in the fully heat-treated condition and achieve essentially 100 per cent joint efficiency without preheat or post heat treatment. There is little experience with the 0.30 and 0.45 C grades which are intended for use in forged parts not requiring welding.

General: This steel has high hardenability. All grades may be heat treated by conventional Q&T procedures, and fully bainitic structures can easily be produced in the 0.45 C grade.

References: 2,5,33

5 NiCrMoV

Composition: 5 Ni, 0.55 Cr, 0.47 Mo, 0.075 V (0.12 C max)

Other Designations: HY 130/140

Physical Constants:

Density: 0.285 lb/in.^{3}
Modulus of elasticity: 29.5 x 10^6 psi
Thermal expansion (80-1100F): 7.3 x 10^{-6}/°F

Mechanical Properties:

1-in. Plate, Q&T

	RT	-100F
UTS, ksi	155	165
YS, ksi	145	155
Elong, %	20	20
RA, %	65	70
K_{Ic}(2-in. plate)ksi $\sqrt{\text{in.}}$	≈250	100
FS(RB),ksi, plain	±73	
, notched	±45 (K_t=6)	

NDT temperature -120°F

2-in. Plate, 150 YS

	RT	-100F
CVN, ft lb	87	55

1-in. Plate, 137 YS

	RT	-100F
CVN, ft lb	100	85

Comments:

Corrosion: Resistance to general corrosion and stress Corrosion is slightly better than that of HY80.

Formability: The cold formability in the quenched and tempered condition is good.

Welding: Easily welded by inert gas and covered electrode processes.

General: This material through-hardens in 2-in. section.

References: 2,23,24,25

AM-363

Composition: 11.5 Cr, 4 Ni, 0.3 Ti (0.05 C max)

Physical Constants:

Density: 0.281 lb/in.^3
Modulus of elasticity: 27.9 x 10^6 psi
Modulus of rigidity: 10.6 x 10^6 psi
Thermal expansion (RT-400F): 7 x 10^{-6}/°F

Mechanical Properties:

Annealed and Aged Sheet

	RT	-100F
UTS, ksi	123	143
YS, ksi	107	125
Elong, %	15	17
NTS, ksi(edge notch, r<.001)	135	152
NTS/UTS	1.10	1.06
*FS(DS),ksi,A=0.2,plain	120	
notched	75 (K_t=3.5)	
A=0.8,plain	100	
notched	35 (K_t=3.5)	

$*A=\frac{\sigma a}{\sigma m}$

3/4-in. Bar

	RT	-100F
CVN, ft lb	180	5 (30 at -50F)

Comments:

Corrosion: Atmospheric corrosion resistance is comparable to Type 430 stainless.

Formability: Can be formed by all conventional methods.

Welding: Readily welded.

General: This is a low-cost, medium-strength stainless steel for structural applications. Solution annealing produces a low-carbon martensite which does not marage. It is comparable in strength with low-alloy structural steels.

Reference: 2

17-4 PH

Composition: 17 Cr, 4 Ni, 4 Cu (0.07 C max)

Physical Constants:

Density: 0.281 lb/in.^{3}
Modulus of elasticity: 28.5×10^6 psi
Modulus of rigidity: 10.5×10^6 psi
Thermal expansion (70-800F): 6.5×10^{-6}/°F

Mechanical Properties:

Bar

	RT	-100F
UTS, ksi (H900)	240	255
YS, ksi (H900)	180	195
Elong, % (H900)	15	17
RA, % (H900)	50	55
K_{Ic}(UTS 200 ksi)ksi $\sqrt{in.}$	42	28
FS(RB),ksi (H900)	±90	
(H1100)	±82	
CVN, ft lb(H925)	30	5
(H1025)	76	19

Comments:

Corrosion: Resistance is better than for martensitic stainless steels and compares favourably with that of austenitic stainless steels. Not susceptible to hydrogen embrittlement. Stress corrosion of high-strength condition may occur in certain media.

Machinability: Tool life approximately the same as for Type 416 stainless steel of equal hardness. Hot cutting or wheel cutting may cause cracking.

Welding: Preheating not required. Any arc-and resistance-welding processes suitable for austenitic stainless steels may be used.

General: Develops full hardening in all sections on air cooling.

References: 2,15,19

PH 15-7 Mo

Composition: 15 Cr, 7 Ni, 2.5 Mo (1.2 Al, 0.09 C max)

Physical Constants:

Density: 0.277 $lb/in.^3$
Modulus of elasticity: 29.5 x 10^6 psi
Modulus of rigidity: 11.3 x 10^6 (dynamic) psi
Thermal expansion (70-200F): 5.0 x 10^{-6}/°F

Mechanical Properties:

1/2-in. Plate-RH950 Condition

	RT	-100F
UTS, ksi	230-235	260-265
YS, ksi	205-208	220-230
Elong, %	10	11

0.064 in. Sheet-RH950

	RT	-100F
UTS, ksi	230	260
YS, ksi	210	240
Elong, %	8½	10
RA, %	28	27
NTS,ksi(K_t=3)	265	290
NTS/UTS	1.15	1.12
FS(DS)ksi,plain	160	
(R=0.6) notched	43 (K_t=3.5)	
CVN, ft lb	4	3
K_{1c},ksi $\sqrt{in.}$	45	30

TH1050, UTS 195

	RT	-100F
K_{1c}, ksi $\sqrt{in.}$	77	47

Comments:

Corrosion: General corrosion resistance is superior to that of martensitic stainless steels, but is not quite as good as Type 304. Hydrogen embrittlement may occur during plating with inadequate control.

Formability: Can be formed readily in annealed condition.

Welding: Easily welded by various methods.

Comments: (cont.)

General: This is a semi-austenitic precipitation hardening stainless steel that can be converted to martensitic by refrigeration or cold working before further hardening by thermal treatment.

References: 2,8,13,15,19

AM-350

Composition: 17 Cr, 4 Ni, 3 Mo (0.08-0.12 C)

Physical Constants:

Density: 0.282 lb/in.^{3}
Modulus of elasticity: 30×10^6 psi
Modulus of rigidity: 11.4×10^6 psi
Thermal expansion (RT-200F): $6.3 - 8.5 \times 10^{-6}$/°F, depending on condition

Mechanical Properties

0.064-in. Sheet-SC7850 Condition

	RT	-100F
UTS, ksi	192	215
YS, ksi	162	188
Elong, %	14	16
RA, %	27	26
NTS, ksi ($K_t \approx 3$)	210	230
NTS/UTS	1.09	1.07
K_c (0.025-in.sheet) ksi $\sqrt{\text{in.}}$	160-190	70-130
FS(PB)plain,ksi	±80	
FS(DS)plain,ksi(205 UTS)	0-100	
notched,ksi (205 UTS)	0-30 (K_t=3.2)	
CVN, ft lb	14	8

Comments:

Corrosion: Resistance comparable to austenitic stainless steels. It is severely susceptible to stress-corrosion cracking at 60-90 per cent of YS.

Formability: It has inferior forming characteristics to austenitic stainless steels because it strain-hardens rapidly.

Machining: Similar to austenitic stainless.

General: A sub-zero cool after solution annealing converts austenite to low-carbon martensite which is strengthened by ageing. It is intended primarily for light sections.

References: 2,8,26-27,32

18 Ni(250)Maraging

Composition: 18 Ni, 7.5 Co, 5 Mo (Ti,Al,>.03 C)

Other Designations: 18 Ni Maraging Steel, 18 NiCoMo, 18-7-5, Vasco Max 250 CVM, RSM250, ALMAR 18, Marvac 250

Physical Constants:

Density: 0.29 lb/in.^{3}
Modulus of elasticity: 25.5 - 27 x 10^6 psi(26.7-28.3x10^6 at -100F)
Modulus of rigidity: ≈10.2 x 10^6 psi
Thermal expansion (75-900F): 5.6 x 10^{-6}/°F

Mechanical Properties:

Typical Ranges:

UTS, ksi	YS, ksi	Elong, %	RA, %
240-270	230-265	4-10	30-60

	7/8-in. Bar		0.25-in. Plate	
	RT	-100F	RT	-100F
UTS, ksi	265	288	250	272
YS, ksi	257	282	242	268
Elong, %	9	8	8	9
RA, %	45	42		
CVN, ft lb	20-25	15-20		

FS(RB)(bar)plain,ksi	±115
notched,ksi	±55 (K_t=2.2)

	RT	-100F	
K_{Ic}(1-in.plate,259YS) ksi $\sqrt{in.}$	68.4		(23 tests)
K_{Ic}(1-in.plate,246YS) ksi $\sqrt{in.}$	100	70	

Comments:

Corrosion: Corrodes in atmospheric environments at about half the rate of normal high-strength low-alloy steels. Resistance to environmental assisted crack propagation is better than 4340 steel at an equivalent level of tensile strength. Hydrogen embrittles this steel, but it has a greater tolerance for hydrogen than conventional low-alloy steels.

Comments: (cont.)

Formability: Readily hot worked by conventional rolling and forging operations, and is easily cold worked by conventional procedures in the annealed condition. This alloy may be cold reduced by substantial amounts before intermediate annealing is required. Cold work prior to ageing will increase aged strengths but will reduce toughness.

Machinability: Most easily machined in the solution-annealed condition. After ageing its machinability is comparable to AISI 4340 at equal hardness levels.

Weldability: Weldable, using suitable precautions, in both the solution annealed and fully heat-treated conditions. Joint efficiencies from 90-100 per cent are attainable for aged welds in sheet and heavy sections. The toughness of the weld deposit is generally below that of the parent metal.

References: 2,25,28-29,31

18 Ni(200)Maraging

Composition: 18 Ni, 8.5 Co, 3 Mo (Ti,Al,>0.03C)

Other Designations: 18 Ni Maraging Steel, 18 NiCo-Mo, 18-8-3
Vascomax 200 CVM, RSM200, Almar 18

Physical Constants:

Density: 0.289 lb/in.^{3}
Modulus of elasticity: 26.2×10^6 psi
Modulus of rigidity: $\approx 10.2 \times 10^6$ psi
Thermal expansion (75-900F): 5.6×10^{-6}/°F

Mechanical Properties:

Bar, Aged 3 hr at 900F

	RT	-100F
UTS, ksi	215	≈235
YS, ksi	210	≈228
Elong, %	12	
RA, %	60	
NTS, ksi (K_t=6)	333	
NTS/UTS	1.55	
CVN, ft lb	30-40	25/30
FS(RB)ksi,plain	±90-110	
notched	±40-50 (K_t=2.2)	
K_{1c},ksi $\sqrt{\text{in.}}$	100-150	

Comments:

The hardenability, formability, machinability, weldability and corrosion resistance characteristics are similar for all the 18 Ni maraging steel series. (See 18 Ni(250) Maraging Data Sheet M-8).

References: 2,15,30-31

18 Ni(300)Maraging

Composition: 18 Ni, 9 Co, 5 Mo (Ti,Al,>0.03C)

Other Designations: 18 Ni Maraging Steel, 18 NiCoMo, 18-9-5, Vasco Max 300CVM, RSM300, Almar 18, Marvac 300

Physical Constants:

Density: 0.29 lb/in.^{3}
Modulus of elasticity: $\approx 26.5 \times 10^6$ psi
Modulus of rigidity: $\approx 10.2 \times 10^6$ psi
Thermal expansion (75-900F): 5.6×10^{-6}/°F

Mechanical Properties:

	7/8-in. Bar		0.25-in. Plate	
	RT	-100F	RT	-100F
UTS, ksi	290	315	300	320
YS, ksi	280	302	295	313
Elong, %	10	8	7	7
RA, %	43	40		
CVN, ft lb	14-18	10-14		

	RT	-100F	
K_{Ic}(plate & bar)ksi $\sqrt{in.}$	65-77	41-52	
K_{Ic}(1-in. plate)ksi $\sqrt{in.}$	51.8		(38 tests)
FS(RB),ksi, plain	±120		
notched	±55 (K_t=2.2)		

Comments:

The hardenability, formability, machinability, weldability, and corrosion resistance characteristics are similar for all the 18 Ni maraging steels. (See 18 Ni(250)Maraging, Data Sheet M-8).

References: 2,15,28,30-31

3.3. ALUMINUM ALLOYS

Introduction

W.A. Pollard*

Aluminum alloys, in common with most face-centered cubic metals, have no ductile-to-brittle transition, so that the effects of lower ambient temperatures on mechanical properties can usually be ignored. Some exceptions to this, involving very high-strength alloys will be mentioned later, but for all low, medium- and most high-strength alloys the structural design properties used in the North would be the same as those used in more temperate regions. In most alloys the toughness and strength increase as the temperature falls.

The special properties of aluminum alloys as they apply to possible uses in the North are best understood by reference to existing applications which will now be reviewed.

Applications

Transportation and Packaging

(a) General

In the recent trend to "containerization" in land/sea and land/air transportation, it is estimated that 80% of all containers are of aluminum. Transportation in the North would be expected to continue this trend, the land/air interface being especially important. Aluminum/balsa sandwich construction in shapes designed to fit aircraft are commonly used and no special difficulties appear to be associated with the Northern environment. Problems connected with high temperature and humidity gradients, similar to but less pronounced than those in building applications, may have to be considered.

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(b) Road, Rail

In areas such as truck bodies and hopper cars where aluminum competes with steel, the North would tend to favour the lighter metal.

Another application in the field of transportation is temporary pavements for roads and landing mats. These would be particularly important on permafrost, and the low emissivity and high thermal conductivity of aluminum would be important considerations in determining the stability of the roadbed.

(c) Sea, Air

Aluminum alloys are widely used in ships and aircraft, and applications in the North would be similar to those in other environments. The high ice loads of ships operating in the North would favour the use of aluminum superstructures to give increased stability under such conditions.

(d) Packaging

A possible advantage connected with the use of aluminum for packaging is the high scrap value of the metal compared with that of steel, for example. This would tend to give an economic incentive for collecting and returning used containers, thus reducing the garbage disposal problem which is already serious in some northern communities (e.g., Churchill).

In the transportation of liquid natural gas and liquid propane, aluminum alloys and 9% Ni steel compete on roughly equal terms. The light weight of aluminum might be a possible advantage in the North but in most cases is of secondary importance.

Building Construction

The chief advantages of aluminum over other building materials are lightness, ease of maintenance and stability of properties.

Aluminum alloy siding is a well-established material in residential and non-residential building practice in all climates. The use of aluminum in the form of sheet, formed-sheet and other shapes is covered in various publications, some of which are given in the References (1-3).

Special considerations connected with applications in Northern Canada are:

(a) High Wind-Loadings

These will require appropriate design consideration not limited to aluminum alloys of course.

(b) High Thermal Expansion and Contraction

The thermal expansion coefficient of aluminum and most of its alloys is roughly twice that of steel, and joints between aluminum and other materials therefore have to be designed with this in mind. However, the range of temperatures in service in the Arctic may be only marginally greater than that, say, in Ottawa, so that standard practices should be suitable in most northern locations.

(c) Condensation and Frosting

The use of any metal building material in locations of high thermal and humidity gradients raises the important question of condensation and frosting. This situation would be particularly severe in the Arctic owing to the long cold periods. The high thermal conductivity of aluminum also tends to aggravate the condition. Condensed water can lead to corrosion problems, particularly if contaminated with heavy metal or chloride ions, for example. Again, these problems are merely extensions of those found in more temperate climates and appropriate measures (such as insulation) have been developed to overcome them.

(d) General Remarks

Aluminum alloys are among the light-weight materials used for prefabricated building construction and the advantages of their use in the North are summarized in the following quotation from Mr. F.R. Francis, Chief Architect, DIAND ("North" Mar.-Apr. 1970, pp1-6).

"Thus building materials should be light and construction costs fairly low ...". They should be made from a "... number of basic prefabricated units made of a light material such as plywood or aluminum. This means that the houses could be erected with a minimum of skilled labour, which is scarce in the North, and thus could be erected quickly, a necessity in view of the short construction season ...". This author also emphasized the desirability of building structures which could easily be removed so that the familiar "Ghost Towns" could be avoided.

There are numerous examples of the use of aluminum structures in the North and considerable experience has been accumulated by the principal suppliers.

Pipelines

The use of aluminum piping in the North was covered thoroughly by various submissions to the "Petroleum-Aluminum Industry Arctic Technological Exchange Meeting", November 1970, at Calgary. These, of course, emphasized the advantages of aluminum; for example

Good service record in the petroleum industry.
Good low-temperature properties.
Low emissivity and high thermal conductivity.
Good weldability under Arctic conditions.
Light weight reduces transportation and handling costs.
Good fluid and gas flow characterisitcs.

These advantages are well documented and must be set against the obvious cost disadvantage of aluminum when it is compared with its principal competitor, steel. The availability of large sizes of aluminum alloy pipe is limited at present, although this is an economic problem rather than a technical one since there seems no reason why large sizes and amounts of aluminum alloy pipe could not be produced. At present, 12-in. diameter would seem to be the largest size readily available in Canada although experimental amounts of spiral and straight seam welded pipes in larger sizes have been made. Extruded pipe up to 24 in. in diameter has also been made. There seems to be no immediate prospect of aluminum competing with steel in pipelines of the order of 48-in. diameter.

There appear to be no special conditions in the North which would be detrimental to aluminum and most factors such as low temperatures, remoteness, transportation costs, etc., would tend to be favourable to its use in place of steel.

A well-publicized application of aluminum alloy pipe is the sewer and water installation in Alert, Ellesmere Island, the most northerly inhabited place in the world. Details of this and other installations are given by Jamieson, (4) who claimed that aluminum was specified because it offered the lowest installed cost.

In Alert, the water supply is heated at its source (a lake) to 16-18°C (60-65°F) before being pumped to the community. After two years in service it was found that the aluminum pipe was badly pitted in some areas. Investigation showed that the corrosion was caused by contamination of the water by copper pipes in the boilers at the lake; replacement of the copper pipes by stainless steel solved the problem. This case is an illustration of a secondary effect of low ambient temperatures; the necessity to heat the supply water created a corrosion problem which would be unknown in more temperate regions.

Petroleum Industry

In general, aluminum alloys have sometimes been substituted for the more conventional steel where the following advantages are sufficient to offset the added cost:

1. Light weight - handling and shipping.

2. High corrosion resistance, particularly to H_2S and CS_2 such as in "sour crude".
3. Smooth surface (in pipes) giving lower pressure drop and reduction of paraffin buildup.
4. Low modulus - more flexible than steel (may be an advantage when pipeline is laid over rough terrain).
5. Rapid welding using manual or portable machine techniques.

An example of "2" is the extensive use of aluminum alloys in storage tanks for "sour" gas and crude.

The low weight of aluminum pipe, as compared with steel of similar strength, has led to its use in portable equipment such as "fly-in" drilling rigs and piping. The initial cost premium for aluminum is offset by the lower moving costs.

It is claimed that aluminum alloy drill pipe and accessories are used although the amount seems relatively small. Aluminum drill pipe is lighter and allows deeper drilling and is also cheaper to transport and handle.

A considerable amount of aluminum is used in heat exchangers in petroleum refining (good thermal conductivity).

All of the above applications would be equally viable in the North and in most the environment would be less important than factors such as transportation costs and remoteness.

Electrical Transmission

Aluminum is the principal metal used for high-voltage transmission cables, and applications in the North would be similar to those in other climates.

As a material for the construction of transmission towers and sub-station structures, aluminum competes directly with steel. The principal advantage of light weight (aluminum alloy structures weigh 50-65% less than steel structures) has to be balanced against higher cost. Other factors such as corrosion resistance (giving ease of maintenance) may also be important in remote locations.

This subject is covered thoroughly in the Aluminum Association publication "Aluminum Transmission Towers and Substations" (5).

Owing to the recent high cost of copper, there has been increasing interest in the use of aluminum for domestic and industrial wiring. Use and applications in the North would be similar to those in other parts of Canada. Again, the lighter weight of aluminum wire would reduce transportation costs (see "Aluminum Building Wire Reference Book", The Aluminum Association (5).

Properties

In view of the very large number of aluminum alloys in use, a somewhat arbitrary selection of alloys had to be made in order to keep the size of the compilation within reasonable bounds. In general, only widely used alloys have been included and they represent a range of properties suitable for most applications and enable interpolations to be made for the properties of other alloys of the same class.

The four-digit Aluminum Association designation system used in this survey classes alloys according to the principal alloying elements. The wrought alloy groups are shown in the following table together with their characteristics.

Table 3.3.a AA4-Digit Designations for Wrought Aluminum Alloys with Principal Characteristics

Designations	Principal Alloying Elements	Alloy Characteristics
1xxx	>99.00 % Al	Low strength, high ductility, easy to form, high conductivity, good corrosion resistance.
2xxx	Cu	High strength, lower formability, lower corrosion resistance, not fusion weldable. Heat-treatable.
3xxx	Mn	Stronger than pure Al, corrosion resistant, good formability, weldable. Non-heat-treatable.
4xxx	Si	Welding and brazing material, limited architectural use.
5xxx	Mg	Good combination of strength, ductility and corrosion resistance. Weldable. Non-heat-treatable.
6xxx	Mn-Si	Good combination of strength, corrosion resistance and formability. Weldable. Heat-treatable.
7XXX	Zn	Highest strength, lower formability and corrosion resistance. Limited weldability. Heat-treatable.
8xxx	Other Elements	Miscellaneous alloys.

Generally, the wrought alloys can be divided into those which are strengthened by cold work and are termed "non-heat-treatable", and those which are strengthened by precipitation hardening - "heat-treatable". The strongest alloys (2000 and 7000 series) are in the latter class and have the disadvantages of lower weldability and corrosion resistance. With some exceptions these alloys are used for more critical applications where maximum strength-to-weight ratios are required. For most structural applications, alloys of the 5000 and 6000 series are used since these combine good strength, corrosion and forming properties with better weldability. The examples of cast alloys are limited to the two most common (356.0 and 355.0) in their strongest (heat-treated) conditions. Many other casting alloys are in use but for a detailed treatment the handbooks and publications listed in the References should be consulted.

As mentioned earlier, the mechanical properties of aluminum alloys generally remain the same or increase at temperatures down to -73°C (-100°F). However, there are some exceptions to this, and these are summarized in Table 2. It will be seen that in wrought alloys the deleterious effects are confined to the relatively high-strength alloys whose use is mainly limited to critical applications such as aerospace.

Table 3.3.b. Summary of Deleterious Effects of Low Temperatures on Properties of Aluminum Alloys.

Wrought Alloys (6)

Alloy	
2014-T6	Reduction in notch tensile strength (notch K_t ~30) from 65 ksi at 73°F to 60 ksi at -100°F.
2024-T4	Reduction in RA from ~15% at 75°C to ~5% at -100°F (no reduction in elongation).
7075-T6	Charpy V ~6 ft lb at 80°F to ~5 ft lb at -150°F. Notch Tensile (K_t ~17) ~65 ksi at 75°F to ~45 ksi at -320°F.
7079-T6	Charpy V ~4.5 ft lb at 75°F to ~3.5 ft lb at -100°F. Notch Tensile (K_t ~17) ~70 ksi at 75°F to ~60 ksi at -320°F.
7039-T61,T64	Notch Strength Ratio ~1.4 at 75°F to ~1.1 at -320°F. Fracture Toughness ~65 ksi $\sqrt{\text{in.}}$ at 75°F to ~55 ksi$\sqrt{\text{in.}}$ at -100°F (interpolated).

Cast Alloys (9)

	Effect
355.0-T71	Elongation ~3% at 75°F to ~2% at -112°F.

Notes on the Selection of Aluminum Alloys Included in Data Sheets

Alloy 6351 was included because, although it is not as generally used as some others, it is the principal alloy recommended in Canada for high-strength line-pipe applications.

Alloy 7005 was included as an example of a high-strength, weldable alloy suitable for large structures, and is produced in the U.S. where patented heat treatments give optimum properties. Also, the roughly equivalent alloy 7004, produced in Canada, was less well documented, particularly with regard to low-temperature properties.

Each alloy has usually been included in only one temper, normally the most representative or the one for which most data were available. It should also be noted that properties will usually vary with material thickness, direction of testing (longitudinal, transverse) and method of manufacture (e.g., rolling, extrusion, forging).

For these reasons more complete sources of information, such as those listed in the reference, should be consulted for detailed information in any specific design problem.

The machinability ratings, based on chip characteristics and surface finish, are from A - free cutting, excellent finish, to E - optimum tool design and machine settings required to give satisfactory chips and finish.

Alloy 2014

Composition (%): Al-4.5 Cu, 1 Mn, 1 Si, 0.5 Mg

Condition: T6

Physical Constants:

Density: 0.101 lb/in.^{3}

Modulus of elasticity: 10.6 x 10^6 psi

Modulus of rigidity: 4.0 x 10^6 psi

Thermal expansion: 12.8 x 10^6/°F

Mechanical Properties		Temperature (°F)	
		75	-100†
UTS, ksi	+	70	77
0.2% YS, ksi	+	66	70
Elong, %	+	11	12
NTS*, ksi	+	65	63
NTS/UTS ratio	+	0.93	0.82
CVN, ft lb	x	3	4.5
K_{Ic} - ksi$\sqrt{in.}$	‡	28(19 transverse)	
FS - RB ksi	x	24	
FS - RB (5 x 10^8) - ksi		18	
FS - RB notched (K_t=8) ksi		10	
FS - RB notched (K_t=8) 5 x 10^8 - ksi		9	
Machinability: B			

* Type of notch K_t ~30

† Interpolated

‡ 4-in. diameter forging (longitudinal)

\+ 0.125-in. sheet, longitudinal

x 0.500-in. plate, longitudinal

Comments:

This is a high-strength material available in all wrought forms and in Alclad sheet. It is not fusion weldable but is resistance weldable. In common with other alloys in the 2000 series, it does not have as good corrosion resistance as most aluminum alloys and under certain conditions may be subject to stress corrosion (corrosion resistance is good in the Alclad condition).

In the stronger tempers (e.g., T6, T4), its formability is limited but in the annealed (O) or freshly solution-treated (W) conditions, it has good formability.

References: 6,11,16

Alloy 2024

Composition (%): Al-4.5 Cu, 1.5 Mg, 0.6 Mn

Condition: T3

Physical Constants:

Density: 0.100 in./in.^{3}

Modulus of elasticity: 10.6×10^6 psi

Modulus of rigidity: 3.9×10^6 psi

Thermal expansion: 12.5×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		80	-100
UTS, ksi	sheet	68	71
0.2% YS, ksi	"	48	49
Elong, %	"	19	21
NTS*, ksi	"	61	61
NTS/UTS ratio	"	0.9	0.86
CVN ft lb	plate	5.5	5.5†
FS - RB - ksi		25	27 at -110°F
FS - RB (5×10^8) - ksi		20	
FS - RB notched (K_t=3.15) - ksi		10	
K_{Ic} - ksi$\sqrt{\text{in}}$.	plate extrusion	22 28	T851 temper
Machinability		B	

* Type of notch $K_t = 6.3$

† Interpolated

Comments:

As for 2014, except that 2024 is not commonly used in forgings.

References: 6,11,12,16

Alloy 3003

Composition: Al-1.2 Mn, 0.12 Cu

Condition: H14

Physical Constants :

Density: 0.099 lb/in.^{3}
Modulus of elasticity: 10.0×10^6 psi
Modulus of rigidity: 3.8×10^6 psi
Thermal expansion: 12.9×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	22	24
0.2% YS, ksi	21	22
Elong, %	16	18
RA, %	68	59
FS - RB (5×10^8) - ksi	9	
Machinability	D	

Comments:

This alloy is non-heat-treatable and is widely used as a general purpose alloy for moderate-strength applications requiring good formability. It has excellent corrosion resistance and has good weldability by all methods.

References: 7,11

Alloy 5052

Composition (%): Al-2.5 Mg, 0.25 Cr

Condition: H38

Physical Constants:

Density: 0.097 $lb/in.^3$

Modulus of elasticity: 10.2×10^6 psi

Modulus of rigidity: 3.8×10^6 psi

Thermal expansion: 13.2×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100
UTS, ksi	sheet	44	45
0.2% YS, ksi	"	35	36
Elong, %	"	8	12
NTS*, ksi	"	46	46
NTS/UTS ratio	"	1.1	1.1
K_{1c} - ksi$\sqrt{in.}$	"	12	12
FS - RB - ksi		22.5	
FS - RB (5×10^8) - ksi		20	
Machinability		D	

*Type of notch $K_t \sim 6.3$

Comments:

This is a medium-strength, non-heat-treatable alloy used in sheet form for roofing and siding, duct work, food and chemical equipment, etc. It has good formability and corrosion resistance and is readily weldable. (For "as-annealed" properties see following page).

References: 6,11

Alloy 5052 (continued)

Condition: O

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	28	29
0.2% YS, ksi	12	12
Elong, %	30	35
FS - RB (5×10^8) - ksi	16	

References: 6,7,11

Alloy 5083

Composition (%): Al-4.45 Mg, 0.6 Mn, 0.15 Cr

Condition: O

Physical Constants

Density: 0.096 lb/in.^{3}
Modulus of elasticity: 10.3×10^6 psi
Modulus of rigidity: 3.9×10^6 psi
Thermal expansion: 13.2×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	42	43
0.2%, YS, ksi	21	21
Elong, %	25	30
Machinability	D	

Comments:

A medium-strength alloy having good corrosion resistance and high "as-welded" strength as shown by the above "annealed" properties (the various work-hardened forms are correspondingly stronger). This alloy is available in most wrought forms but is usually used as sheet or plate. There is a risk of stress corrosion susceptibility if exposed to temperatures above about 140°F.

References: 7,11

Alloy 5454

Composition (%): Al-2.7 Mg, 0.8 Mn, 0.12 Cr

Condition: H34

Physical Constants:

Density: 0.097 lb/in.^{3}
Modulus of elasticity: 10.2×10^6 psi
Modulus of rigidgity: 3.8×10^6 psi
Thermal expansion: 13.1×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-112
UTS, ksi	sheet	46	42
0.2% YS, ksi	"	40	31
Elong, %	"	11	23
FS - RB (5×10^8)		19	
Machinability		C	

Comments:

This alloy has somewhat lower mechanical properties than 5083 but has superior resistance to stress corrosion under fluctuating elevated temperatures. It is easily welded and is widely used for tanks, pressure vessels and items in chemical processing equipment. It is mainly used in sheet form.

References: 7,11

Alloy 5456

Composition (%): Al-5.1 Mg, 0.8 Mn, 0.1 Cr

Condition: H343, H321

Physical Constants:

Density: 0.096 lb/in.^{3}
Modulus of elasticity: 10.3 x 10^6 psi
Modulus of rigidity; 3.9 x 10^6 psi
Thermal expansion: 13.3 x 10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100
UTS, ksi	+	58	60
0.2% YS - ksi	+	47	48
Elong, %	+	7	8
NTS* ksi	x	44	44
NTS/UTS ratio	x	0.87	0.78†
K_{Ic} - ksi$\sqrt{in.}$	+	15.9	16
FS - RB (5 x 10^8) ksi		23	
Machinability		C	

+ H343 0.063 in. sheet, longitudinal
x H321 0.125 in. sheet, longitudinal
† Interpolated
* Type of notch K_t ~17-20

Comments:

This alloy is non-heat-treatable and similar to 5083 but is stronger and somewhat more susceptible to stress corrosion if exposed to high ambient temperatures (>140°F).

References: 6,11,15

Alloy 6061

Composition (%): Al-1 Mg, 0.6 Si, 0.20 Cr

Condition: T6

Physical Constants:

Density: 0.098 lb/in.^{3}
Modulus of elasticity: 10.0×10^6 psi
Modulus of rigidity: 3.8×10^6 psi
Thermal expansion: 13.1×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100†
UTS, ksi	+	45	52
0.2% YS, ksi	+	41	44
Elong, %	+	14	18
NTS*, ksi	+	46	48
NTS/UTS - ratio	+	1.02	0.92
FS - PB (10^8) ksi		20	24
FS - RB (5×10^8) ksi		17	
CVN - ft lb		9	10
K_{Ic} - ksi$\sqrt{\text{in.}}$ (T651)		27	30
Machinability		C	

* Type of notch K_t ~17
\+ 0.125 in. sheet, longitudinal
† Interpolated

Comments:

This is a medium strength structural alloy which has been very widely used both as sheet and plate and in extruded shapes. It has a long history in furniture, handrails, transportation, industrial equipment and general structures. It is readily weldable, possesses good corrosion resistance, and has a high plane strain fracture toughness.

References: 6,11,13,16

Alloy 6063

Composition (%): Al-0.7 Mg, 0.40 Si

Condition: T6

Physical Constants:

Density: 0.098 lb/in.^{3}

Modulus of elasticity: 10.0×10^6 psi

Modulus of rigidity: 3.8×10^6 psi

Thermal expansion: 13.0×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	35	38
0.2% YS, ksi	31	33
Elong, %	18	20
FS - RB (5×10^8) ksi	10	
Machinability	C	

Comments:

This alloy has a good combination of extrudability and mechanical properties. It is widely used for all types of extrusion and responds well to all finishing methods. It has good corrosion resistance and is readily weldable.

References: 7,11

Alloy 6351

Composition (%): Al-1 Si, 0.6 Mg, 0.6 Mn

Condition: T6

Physical Constants:

Density: 0.098 lb/in.^{3}
Modulus of elasticity: 10.0×10^6 psi
Modulus of ridigity: 3.8×10^6 psi

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	45	50
0.2% YS, ksi	41	43
Elong, %	14	-
Machinability	C	

Comments:

This alloy is widely used for structural shapes as it has good mechanical properties, corrosion resistance and extrudability. It is used in general structures, architectural items, road vehicles and railway rolling stock, ships and pipelines for air, water, oil and gasoline.

Reference: 8

Alloy 7005

Composition (%): Al-4.6 Zn, 1.4 Mg, 0.5 Mn, 0.1 Zr, 0.1 Cr, 0.03 Ti

Condition: T53* (Extrusions)

Physical Constants:

Density 0.101 lb/in.^{3}
Modulus of elasticity: 10.5×10^6 psi
Modulus of rigidity: 3.9×10^6 psi
Thermal expansion: 13.2×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-112
UTS, ksi	+	60	68
0.2% YS, ksi	+	52	57
Elong, %	+	14	12
NTS, ksi	x	83	85
NTS/UTS ratio		1.4	1.3
FS - RB ksi		24	
FS - RB (5×10^8) ksi		20	
FS - RB notched - ksi		6	60° V notch, 0.075 in. deep, rad = 0.0005 in.
FS - RB notched (5×10^8) ksi		4	
Machinability		B	

x Type of notch $K_t \approx 17$; extruded bar
* Proprietary heat treatment - Alcoa
\+ 0.063-in. sheet

Comments:

This is one of a group of alloys designed for high-strength welded structures. Simple ageing at room or elevated temperatures after hot forming or welding will give good properties so that complete re-heat treatment is not necessary. The corrosion resistance while good in industrial and marine atmospheres is inadequate in sea water and saline road splash without protective coatings. Formability is good in the softer tempers or at high temperatures.

References: 6,11

Alloy 7075

Composition (%): Al-5.6 Zn, 2.5 Mg, 1.6 Cu, 0.3 Cr

Condition: T6

Physical Constants:

Density: 0.101 lb/in.^{3}
Modulus of elasticity: 10.4×10^6 psi
Modulus of rigidity: 3.9×10^6 psi
Thermal expansion: 13.1×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100†
UTS, ksi	+	82	88
0.2%, ksi	+	74	78
Elong, %	+	11	12
NTS*, ksi	+	68	55
NTS/UTS ratio	+	0.83	0.63
K_{Ic} ksi$\sqrt{in.}$	++	24.9	25.4
K_{Iscc} (3 1/2% NaCl) ksi$\sqrt{in.}$		19	
CVN- ft lb	x	6	5.5
FS - RB (10) ksi		17-28 (scatter band)	
FS - RB notched $(10^8$ ksi K_t >12		16-10 (scatter band)	
FS - PB (10^6) ksi		34	40
FS - PB notched $(K_t=3.2) 10^6$ ksi		17	22
Machinability		B	

* Type of notch $K_t \sim 17$
\+ 0.125 in. sheet-longitudinal
† Interpolated
x Bar stock
++ 1/2-in. plate in T651 condition (UTS 88 ksi)

Comments:

This is a high-strength alloy, not easily weldable and having lower corrosion resistance than most other wrought aluminum alloys. Used when maximum strength-to-weight ratio is required. Formable in soft tempers.

References: 6,11,13,14,16

356.0 Casting Alloy

Composition (%): Al-7 Si, 0.3 Mg

Condition: T6 (Sand Cast)

Physical Constants:

Density: 0.097 lb/in.^{3}
Modulus of elasticity: 10.3 x 10^6 psi
Modulus of rigidity: 3.8 x 10^6 psi
Thermal expansion: 11.5 x 10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	33	35
0.2% YS, ksi	24	25
Elong, %	3.5	3.5
FS - RB (10^8) ksi	6-14	scatter bands
FS - RB notched (10^8) ksi (60°V notch 0.075 in. deep, r<0.0001 in.)	4-10	
Machinability	C	

Comments:

This is a medium-high strength, heat-treatable casting alloy for general purposes. It has good castability and corrosion resistance. Typical uses include automotive transmission cases, housings, aircraft fittings, marine hardware, rail parts, truck axle housings. Weldability - good.

References: 6,9,10

356.0 Casting Alloy

Composition (%) : Al-7 Si, 0.3 Mg

Condition: T7 (Permanent Mould Cast)

Physical Constant:

Density: 0.097 lb/in.^{3}
Moludus of elasticity: 10.3 x 10^6 psi
Modulus of rigidity: 3.8 x 10^6 psi
Thermal expansion: 11.5 x 10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS - ksi	32	35
0.2% YS - ksi	24	26
Elong, %	6	6
FS - RB (10^8) ksi	8-17	scatter bands
FS - RB notched (10^8) ksi r<0.0001 in.)	4-11	
Machinability	C	

Comments

Properties are similar to those for this alloy in the sand cast condition. The T7 heat treatment gives maximum stability of properties and dimensions, but results in lower tensile properties than would be obtained in the T6 treatment.

References: 6,9,10

355.0 Casting Alloy

Composition (%): Al-5 Si, 1.25 Cu, 0.5 Mg

Condition: T71 (Sand Cast)

Physical Constants:

Density: 0.098 lb/in.^{3}
Modulus of elasticity: 10.2×10^6 psi
Modulus of rigidity: 3.8×10^6 psi
Thermal expansion: 12×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	35	37
0.2% YS, ksi	29	32
Elong, %	1.5	1.5
FS - RB (10^8) ksi	6-14	scatter bands
FS - RB notched (10^8) ksi (60° V notch, 0.075 in. deep, r<0.0001 in.)	4-10	
Machinability	C	

Comments :

Similar to 356.0 alloy but stronger, less ductile, and less corrosion resistant.

References: 6,9,10

355.0 Casting Alloy

Composition (%): Al-5 Si, 1.25 Cu, 0.5 Mg

Condition: T71 (Permanent Mould Cast)

Physical Constants:

Density: 0.098 lb/in.^{3}

Modulus of elasticity: 10.2×10^6 psi

Modulus of rigidity: 3.8×10^6 psi

Thermal expansion: 12×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-112
UTS, ksi	36	39
0.2% YS, ksi	31	34
Elong, %	3	2
FS - RB (10^8) ksi	8-17	scatter bands
FS - RB notched (10^8) ksi (60° V notch, 0.075 in. deep, r<0.0001 in.)	4-11	
Machinability	C	

Comments:

Similar to 356.0 alloy but stronger, less ductile and less corrosion resistant.

References: 6,9,10

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3.4 MAGNESIUM ALLOYS

Introduction

B. Lagowski*

Magnesium with a density of approximately 1.8 g/cc, is the lightest structural metal; some of its alloys can be even lighter, e.g., Mg-Li alloys with a density as low as 1.3 g/cc.

Magnesium can be extracted from minerals such as magnesite or dolomite, but the main source is sea water, and it is estimated that sea water alone contains approximately 1.92×10^{15} tons of magnesium metal. This means that every country with access to the sea can become independent of foreign supplies of this metal, which at the present time is an important factor. Canadian production of magnesium utilizes dolomite as a raw material, producing metal of very high purity (99.95%).

Because of its light weight and high strength-to-weight ratio, magnesium is used extensively where weight saving is of paramount importance, such as in aircraft and spacecraft applications. Other useful characteristics of magnesium are its high resistance to buckling; the best machinability of any metallic material; excellent casting properties which includes the ability to produce very complicated shapes; relative ease of fabrication by welding, rivetting, bolting and adhesive bonding [brazing and soldering, although possible, are not commonly used]; high damping capacity in some alloys; good thermal conductivity; and freedom from reaction in the molten state with the iron. The last two characteristics make the die casting process for magnesium very attractive.

Alloy Systems

Magnesium metal in its pure form is never used as a structural material due to its low strength, but it is used when alloyed with other elements. The alloys used in the cast and wrought form are generally divided into two main groups:

1. Alloys containing aluminum as a strengthening element, with the addition of manganese and, sometimes, zinc.

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*Research Scientist, Non-Ferrous Metals Section

2. Alloys containing zirconium as a grain-refining element with the strengthening element added, such as zinc, rare earth metals, thorium, silver, and a combination of these elements.

The first group is the oldest and is characterized by ease of preparation of the alloy, good foundry characteristics for cast shapes, and good working characteristics for wrought forms. Strength, however, is not very high, particularly at elevated temperatures.

The second group is characterized by high strength at room temperature and, in some alloys, at elevated temperatures.

Low-Temperature Trends

A summary of available data disclosed the following generalities for magnesium alloys at low temperatures.

1. Magnesium alloys have no ductile-to-brittle transition, therefore any changes in the properties are gradual.
2. Ultimate tensile strength in the majority of cases increases with decrease in temperature and this increase is more rapid than the accompanying increase in yield strength.
3. Ductility decreases slightly to approximately -70°C (-94°F). At much lower temperatures it decreases more rapidly.
4. Impact resistance decreases slightly at first and tends to increase slightly at very low temperatures (liquid nitrogen).
5. Notch sensitivity decreases slightly.
6. Hardness increases.
7. Endurance and modulus of elasticity increase.
8. Coefficient of thermal expansion decreases.

9. Specific heat decreases.
10. Thermal and electrical conductivity increases.
11. Weld efficiency decreases slightly.

Some property data sheets for the most commonly used cast and wrought alloys have been compiled and are attached.

Although low-ambient temperatures have some small effect on the properties of magnesium alloys as noted above, designers of structures for use under Arctic conditions may use room-temperature property data with reasonable confidence.

Possible Problem Areas

Resistance of magnesium alloys to corrosion is relatively low (compared with that of steel), and this characteristic may present some problems under Arctic conditions. During the winter months the low temperature and humidity should be beneficial to the resistance to corrosion. However in summer, when there are extremes in temperature during day and night, coupled with higher humidity, condensation in a structure may occur and could lead to corrosion problems. This possibility may be minimized by careful structural design to ensure proper drainage and proper surface protection.

Applications

Magnesium alloys, because of their light weight and high-strength ratio, can be seriously considered for use under Arctic conditions for structures which are to be transported by air.

Typical examples of engineering applications are snow shoes specified by the Army, sleighs, snowmobile components, supporting structures for portable tents, hangars, blowers, etc., housings for portable tools and radio-communication systems, and even parts for drilling rods.

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Alloy AZ91

Composition (%): Mg-9 Al, 0.7 Zn, 0.15 Mn

Condition: T6 (cast)

Physical Constants:

Density: 0.065 lb/in.^{3}

Modulus of elasticity: 6.5×10^6 psi

Thermal expansion: 14.5×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	42	45
0.2% YS, ksi	19	21
Elong, %	7	5
CVN, ft lb	1	1
(unnotched) ft lb	6	4.5
FS - RB (10^8) ksi	9.5-12	(scatter band)

Comments:

AZ91 is a heat-treatable casting alloy of the aluminum- and zinc-containing family, and combines relatively high ductility with good strength. It possesses good pressure tightness and is fully weldable, requiring stress relief after welding.

References: 2,3

Alloy AZ92

Composition (%): Mg-9 Al, 2 Zn, 0.15 Mn

Condition: T6 (cast)

Phsyical Constants:

Density: 0.066 lb/in.^{3}
Modulus of elasticity: 6.5 x 10^6 psi
Modulus of rigidity: 2.4 x 10^6 psi
Thermal expansion: 14 x 10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	42	43
0.2% YS, ksi	23	24
Elong, %	4	3
NTS/UTS ratio (K_t=2)	0.93	
FS - RB (10^8) ksi	15	
notched (K_t=2) ksi	9.5	
" (K_t=5) ksi	0.5	
CVN, ft lb	0.6	0.6
(unnotched) ft lb	5.6	4.7

Comments:

AZ92 is a heat-treatable casting alloy of the aluminum- and zinc-containing family. In this group, it has the highest yield strength combined with moderate elongation and good pressure tightness. It has good machinability and can be welded; stress relief after welding is required.

References: 2,3,6

Alloy ZK61

Composition (%): Mg-6 Zn, 0.8 Zr

Condition: T6 (cast)

Physical Constants:

Density: 0.066 lb/in^3
Modulus of elasticity: 6.5×10^6 psi
Thermal expansion: 14.5×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	46	50
0.2% YS, ksi	30	35
Elong, %	10	4
CVN, ft lb	3.5	2
(unnotched) - ft lb	18	
FS - RB (10^8) ksi	14.5	
FS - RB notched (10^8) ksi (K_t=2)	10	

Comments:

Alloy ZK61 has an outstanding combination of strength and ductility in the age-hardened condition, but its foundry characteristics are inferior to those of most other magnesium alloys. Its machinability is excellent, but its weldability is very poor. Like other magnesium alloys, it is subject to corrosion in industrial, marine and moist environments, and requires protection.

References: 2,3,8

Alloy QE22

Composition (%): Mg-2.5 Ag, 2.0 Didynium, 0.4 Zr

Condition: T6 (cast)

Physical Constants:

Density: 0.066 lb/in.^{3}
Modulus of elasticity: 6.5×10^6 psi
Modulus of rigidity: 2.4×10^6 psi
Thermal expansion: 14.8×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	41	47
0.2% YS, ksi	30	32
Elong, %	8	5
CVN, ft lb	1	1
(unnotched) ft lb	17	13
FS - RB (10^8) ksi	14.5	

Comments:

Alloy QE22 contains good mechanical properties with excellent foundry characteristics. It is readily weldable but, if possible, the welded part should be fully heat treated after welding.

References: 2,3,7

Alloy AZ31

Composition (%): Mg-3 Al, 1Zn, 0.2 Mn

Condition: F (rolled, forged or extruded)

Physical Constants:

Density: 0.064 lb/in.^{3}
Modulus of elasticity: 6.5 x 10^6 psi
Modulus of rigidity: 2.4 x 10^6 psi
Thermal expansion: 14 x 10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100
UTS, ksi	*	38	43
0.2% YS, ksi	*	28	37
Elong, %	*	12	10
CVN, ft lb	†	6	3.5
FS - RB (10^7) ksi	*	18-21	
FS - PB (10^7) ksi	*	19	23
FS - PB (10^7) ksi	‡	14	
notched K_t=2 (10^7)ksi		13	

* Extrusion (F)
† Plate (0)
‡ Sheet (0)

Comments:

This non-heat-treatable magnesium alloy has good mechanical properties together with excellent formability. It is fully weldable and should be stress relieved after welding to minimize stress-corrosion cracking. Corrosion resistance is similar to that of other magnesium alloys and surface protection is generally required.

References: 2,3,6,10,11

Alloy AZ61

Composition (%): Mg-6.5 Al, 1 Zn, 0.15 Mn

Condition: F (extruded or forged)

Physical Constants:

Density: 0.065 lb/in.^{3}
Modulus of elasticity: $6.3/6.5 \times 10^6$ psi
Modulus of rigidity: 2.4×10^6 psi
Thermal expansion: 14×10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	45	48
2.0% YS, ksi	32	38
Elong, %	14	10
CVN*, ft lb	4.5	3
FS - RB (10^7) ksi	20.5 (18-26)	
notched $K_t=2$ (10^7) ksi	11.5	
FS - DS (10^7) ksi	±13	

* Non-standard specimen; 0.5 in. wide.

Comments:

AZ61 is a non-heat-treatable alloy which is easily extruded. Toughness, cold formability and machinability are good, although the alloy has a tendency to harden when cold-worked. It is fully weldable and should be stress relieved after welding. Corrosion resistance is considered to be good.

References: 2,3,6,10,11

Alloy AZ80

Composition (%): Mg-8.5 Al, 0.5 Zn, 0.15 Mn

Condition: T5 (extruded or forged)

Physical Constants:

Density: 0.065 lb/in.^{3}
Modulus of elasticity: 6.5 x 10^6 psi
Modulus of rigidity: 2.4 x 10^6 psi
Thermal expansion: 14 x 10^{-6}/°F

Mechanical Properties	Temperature (°F)	
	75	-100
UTS, ksi	50-55	50-65
0.2% YS, ksi	34-40	38-50
Elong, %	5-7	3-5
NTS/UTS ratio (K_t=2)	1.0	
FS - RB (10^8) ksi	16-19	
FS - RB notched (10^8) ksi (K_t=2)	9.5	

Comments:

This heat-treatable alloy is one of the strongest for forgings and solid extrusion for service up to 300°F. It is fully weldable, but must be stress relieved after welding to avoid cracking.

References: 2,3,6

Alloy ZK60

Composition (%): Mg-5.5 Zn, 0.5 Zr

Condition: T5 (extruded or forged)

Physical Constants:

Density: 0.066 lb/in.^{3}

Modulus of elasticity: 6.5 x 10^6 psi

Modulus of rigidity: 2.4 x 10^6 psi

Thermal expansion: 15 x 10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100
UTS, ksi		53	64
0.2% YS, ksi		44	53
Elong, %		13	5
NTS (K_t=3) ksi	*	61	67
NTS/UTS ratio	*	1.34	1.16
CVN, ft lb	†	3	3
(unnotched)		34	45
FS - RB (10^8) ksi		17-23 (scatter band) extrusions	
FS - RB (10^8) ksi		16-18 (scatter band) forgings	

* UTS of 46 ksi at 75°F, and 57 ksi at -100°F

† Keyhole notch

(cont'd)

Comments:

This alloy has similar high-strength properties to AZ80, and its ductility and toughness are superior to those of any other magnesium extrusion and forging alloy. Weldability is poor, but it can be satisfactorily resistance welded, spot welding being generally used; stress relieve after welding.

References; 2,3,11

Alloy LA141

Composition (%): Mg-14 Li, 1.25 Al

Condition: T7 (stabilized - rolled, forged or extruded)

Physical Constants:

Density: 0.048 lb/in.^{3}
Modulus of elasticity: 6.2×10^6 psi
Modulus of rigidity: 2.3×10^6 psi
Thermal expansion: 22×10^{-6}/°F

Mechanical Properties		Temperature (°F)	
		75	-100
UTS, ksi	*	20-26	26-30
0.2% YS, ksi	*	15-20	20-24
Elong, %	*	13-24	11-16
CVN, ft lb	†	15	15
(unnotched) ft lb		32	30
FS - PB (10^8) ksi	*	15	

* Sheet
† Plate

Comments:

LaI41 is a more recently developed alloy with a very high stiffeness-to-weight ratio, good impact strength and good damping characteristics. It is fully weldable and should be stress relieved after welding. Formability is excellent at room temperature, but corrosion resistance is only moderate, and protective coatings are frequently required.

References: 2,9

3.5 TITANIUM ALLOYS

Introduction

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Probably over 80% of titanium mill products go into aircraft engines and airframes (both civilian and military), missiles and spacecraft and other military uses. The figure was 90% in 1965 and still about 83% in 1974, the consumption pattern having changed little in the interim (1-3,26). Projections suggest that industrial uses will consume 40% of mill products in 1980 and 50% in 1985 (26). Aside from the aerospace industry, titanium has found its greatest use in chemical and food processing equipment, power production, desalination plants and marine and ordnance applications (1-4,26). Types of items in current use include 1) condensers, heat exchangers, tank linings, piping systems filter pumps and valves in processing, power and desalination equipment and 2) deck hardware, plumbing, structures and hulls in both deep-diving submersible and surface craft.

Because of this application pattern for titanium alloys, the most immediate utilization problems in the Arctic environment will arise in connection with aircraft operation. Sheet, structural extrusions, fasteners and engine and undercarriage forgings may be subjected to the stresses of landing and take-off at temperatures as low as -60°C (-80°F). Although it is true that operation at high altitudes already necessitates the resistance of existing alloys to such very low temperatures, landing and take-off are normally carried out at the much higher ground-level temperatures of the more southerly latitudes. Turbine engine alloys normally operate at elevated temperatures, but dwell and start-up at the very low Arctic temperatures raises the question of the effect of such exposure on the subsequent elevated temperature properties particularly in the two-phase alloys. This survey of properties therefore is aimed primarily at aircraft alloys with some attention also being given to alloys exposed to salt water.

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Trends in Properties at Sub-Zero Temperatures

General

Titanium exists in two allotropic forms: alpha (h.c.p.) below 882°C (1620°F), and beta (b.c.c.) above this. The alloying elements commonly added to strengthen titanium are usually divided into three categories: the alpha stabilizers (Al), neutral (Zr, Sn) and the beta stabilizers (V, Mo, Nb, Ta). A sub-group of the latter category is less commonly used, the eutectoid or compound formers (Cu, Si, Cr, Mn, Co). Depending on the amount and proportion of alloy additions used, three broad categories of alloys are produced: 1) the alpha alloys which have moderate strength and good ductility, are relatively stable to elevated temperatures (600°C (1100°F)), are weldable, but are not heat treatable to high strength, 2) the alpha-beta alloys, which are heat treatable to high strength but are not weldable or are only marginally so, and 3) the so-called beta alloys which are highly formable, can be heat treated to very high strengths and under certain conditions possess fair to good weldability.

Although many of the mechanical properties of these different categories of alloys exhibit similar trends as the temperature is lowered, there are many differences between them. Alpha titanium has a greater abundance of possible slip and twinning systems than are provided by other common h.c.p. metals, such as Zn, Mg, and Cd. Consequently, it has good ductility at normal and low temperatures. However, as the temperature decreases, twinning becomes a more common mode of deformation, and there is evidence that this leads to fatigue damage that assists crack propagation at low temperatures (5). Although there are no published data as yet, such effects of deformation twinning are less likely in the beta phase as twinning is much less common in b.c.c. metals in this temperature range.

Generally speaking, despite the paucity of data, the indications are that all three categories of alloy undergo an increase in both yield and ultimate tensile strength when the temperature is lowered within the temperature range 40 to -75°C (100 to -100°F). At the same time, ductility usually remains unchanged or declines only slightly. Although increasing levels of interstitials (C, O, H, N) and Fe accentuate these trends, unless the levels are abnormally high, no ductile-brittle transition phenomenon is exhibited by the alloys under impact testing.

The strength/density and elastic modulus/density ratios of titanium are amongst the highest of any material. These could become important criteria for choice of material in instances where transportation costs are high.

In salt water, titanium alloys possess good corrosion resistance but most are susceptible to environmental cracking. Alloys have been developed especially for high-stress service in such an environment and currently are undergoing improvement.

Alpha Alloys

The alpha alloys are those with essentially an all-alpha structure including the commercial purity grades and the "near-alpha" or "super-alpha" alloys. The more commonly used compositions are:

Commercial purity Ti: Ti-40, Ti-55 and Ti-70
Ti-0.2Pd
Ti-5Al-2.5Sn
Ti-8Al-1Mo-1V
Ti-7Al-2Nb-1Ta
Ti-6Al-2Nb-1Ta-1Mo
Ti-7Al-12Zr

Although the data are sparse, the following property trends are indicated.

Ultimate tensile strength and yield strength increase markedly with decrease in temperature (6 - 8). At the same time, tensile ductility in terms of both elongation and reduction in area remain essentially unchanged.

With the exception of Ti-40, the most pure commercial grade of titanium, the impact energy decreases with drop in temperature, but no ductile-to-brittle transition temperature is encountered. The impact energy of Ti-40 increases to greater than 120 ft lb as the temperature is lowered to -75°C (-100°F).

The notched tensile properties of the commercially pure grades and Ti-5Al-2.5Sn under all notch conditions are favourable, as are those of the other alpha alloys under mild notch conditions. In these cases, the notched strength parallels the unnotched strength down to -75°C (-100°F) and this results in notched strength ratios that remain constant or decline only slightly.

For the more highly alloyed alpha alloys, data are both sparse and conflicting for all degrees of notch sharpness. It is evident, however, that unfavourably low notch strength ratios are possible (e.g., in Ti-8Al-1Mo-1V, single annealed, with a stress concentration factor $K_t = 8.0$ (6)).

In addition to being sparse, the fatigue and notch fatigue data available in the literature were produced under conditions which vary widely with the source. Only the behaviour of individual alloys in uncoordinated tests can be cited.

In fatigue, alpha titanium alloys exhibit an endurance limit in the range of 30 to 50% of the ultimate tensile strength (7). This has been shown in tests on Ti-55, Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V. The extra low interstitial (ELI) grade of Ti-5Al-2.5Sn ELI shows greatly increased fatigue strength, whereas Ti-8Al-1Mo-1V, although it exhibits a dramatic strength increase in low cycle fatigue, shows no change in its endurance limit. The presence of a mild notch reduces the fatigue strength of Ti-8Al-1Mo-1V by a factor of 2, and a sharp notch by a factor of as much as 10.

All of the alpha alloys are weldable, and provided that good welding practices recommended for titanium are observed, the weld joint strength and ductility are comparable with those of the parent metal. Post-weld stress relief of the high aluminum alloys below 700°C (1300°F) should be avoided when good ductility and toughness are important.

Although impurities such as the interstitial elements and beta-stabilizers (commonly iron) strengthen alpha alloys, they also are detrimental to ductility, impact strength and fracture toughness. Thus, the (ELI) grade of Ti-5Al-2.5Sn was specially developed as a material with good fracture toughness at sub-zero temperatures and commonly is used in cryogenic applications.

Alpha-Beta Alloys

Common alloys of this group include:

Ti-6Al-4V
Ti-4Al-3Mo-1V
Ti-7Al-4Mo
Ti-8Mn
Ti-6Al-6V-2Sn

Both allotropic forms of titanium are present in nearly all heat-treated conditions of these alloys. The properties are highly dependent on the microstructure, which can be varied widely. These alloys are age-hardenable by heat treating at about 480 to 650°C (900 to 1200°F) to precipitate fine alpha or beta phase. Prior solution treatment in the alpha plus beta range gives the optimum combination of strength and ductility in aged alloys; solution-treatment above the beta transus gives a coarse beta grain structure which results in poor ductility. Improved fracture toughness with lower tensile strength is achieved by heat treatment in the upper part of the ageing temperature range.

As with the alpha alloys, the ultimate tensile and yield strengths of alpha-beta alloys increase markedly with drop in temperature (6-8). The ductility, though characteristically low in most of these alloys, remains unchanged or declines only slightly down to -75°C (-100°F). These trends are true of both annealed and solution-treated- and -aged material. The content of interstitial impurities at normal levels and below appears to have little effect on these smooth tensile properties in this temperature range.

The notched impact strength which in most of the alloys is below 20 ft lb at room temperature declines moderately down to -75°C (-100°F).

The notched tensile properties of Ti-6Al-6V-2Sn are poor at low temperatures (7). The notched/unnotched strength ratio at room temperature is about 1.0 for the annealed condition, but less than 1.0 for aged material and decreases rapidly with decreasing temperature for both conditions.

Data available for other alpha-beta alloys, principally Ti-6Al-4V, indicate that, in general, for mild-notch conditions the notched tensile strength parallels the ultimate tensile and yield strengths for -75°C (-100°F), resulting in favourable notched strength ratios. However, under sharp-notch conditions, the notched tensile strength remains constant or declines somewhat with decrease in temperature.

Too few data are available on the fatigue properties of alpha-beta alloys to allow generalization. On the basis of some results for Ti-6Al-4V alone, the endurance limit of smooth specimens increases with drop in temperature as does the tensile strength (6). Under even mild-notch conditions, however, the notched strength at a given fatigue life drops to about 50% of the unnotched value at room temperature and shows negligible increase with decrease in temperature.

Forging of alpha-beta alloys above the beta transus temperature rather than in the alpha + beta range prior to heat treatment can give significant improvement in fracture toughness along with some increase in notched tensile strength; there is an accompanying drop in tensile ductility and a slight reduction in yield strength. Considerable care must be taken during beta forging to introduce adequate deformation and avoid excessive pick-up of interstitial elements (9,10).

Because of their response to heat treatment, the alpha-beta alloys are difficult to weld. Individual successes have been reported but no general means exists. The use of commercial titanium Ti-70 as filler rod rather than the parent composition appears to raise fracture toughness to more acceptable levels. The advice of titanium alloy producers should be sought before alpha-beta alloys are designed into weldable assemblies (7,8).

The alpha-beta alloy Ti-6Al-4V is the most widely used of all the titanium alloys and its properties best documented. No special precautions appear warranted in extending its use to sub-zero temperatures. Claims of superior toughness and ductility are made for the ELI grade, although these are not reflected in published data and graphs, and it is probably advisable to use this grade where toughness is critical.

Beta Alloys

The beta titanium alloys contain sufficient proportions of beta-phase stabilizers that 100% beta phase can be retained readily at room temperature. The alloys are metastable in this state and precipitate alpha titanium and possibly intermetallic compounds at suitable ageing temperatures.

The few beta alloys that have been marketed include Ti-13V-11Cr-3Al, Ti-11.5Mo-6Zr-4.5Sn (Beta III) and Ti-1Al-8V-5Fe. Low-temperature data are available for only Ti-13V-11Cr-3Al (6-8).

In the temperature range of 38 to -73°C (100 to -100°F), the ultimate tensile and yield strengths of Ti-13V-11Cr-3Al increase markedly with drop in temperature as do the strengths of all other titanium alloys. The ductility of fully aged sheet, which is low at room temperature, declines with drop in temperature. Ductility is much higher for the solution-treated condition throughout the same temperature range.

Impact strength is low at room temperature (in the order of 10 ft lb for Charpy V-notch tests) and drops with decreasing temperature. This holds true whether the alloy is solution treated and aged or just solution treated.

Ti-13V-11Cr-3Al is notch sensitive in the aged condition, the notched tensile strength at a stress concentration factor K_t = 4 being below the smooth tensile value at room temperature and declining further with drop in temperature. The notch sensitivity becomes more severe with longer ageing times, sharper notches and thicker sections. For the solution-treated condition the notch sensitivity is favourable even under sharp notch conditions; the notched tensile strength is a maximum at -75°C (-100°F) and the notched/unnotched tensile strength ratio approximately 1.0.

There is a problem of stability in this alloy after long-time exposure at temperatures above 200°C (400°F). This results in drastic reductions in room temperature tensile ductility and notched strength in solution-treated sheet. Severe reduction in the tensile strength of aged sheet by a notch has been reported at -80°C (-110°F), although no similar effect was observed in the room-temperature values.

Optimum fracture toughness at room temperature is obtained through use of low solution temperatures, short ageing times and low ageing temperatures. The fracture toughness declines moderately from 40 to -75°C (100 to -100°F).

For aged sheet, the fatigue ratio is about 0.3 to 0.5. A drop in temperature raises the endurance limit, but in low-cycle fatigue reduces the fatigue strength below room temperature values. A notched/unnotched fatigue strength ratio of 0.5 with K_t = 3 has been found for material in both aged and solution-treated conditions.

Room temperature properties of Ti-11.5Mo-6Zr-4.5Sn (Beta III) are comparable with those of Ti-13V-11Cr-3Al with the exception that the fracture toughness of Beta III plate is much superior. The ductility is much higher for Beta III rivet stock than for other forms of either alloy (8).

Both Ti-13V-11Cr-3Al and Beta III can be extensively cold worked even in processes such as spinning and deep drawing. Both are readily welded by techniques and practices recommended for titanium and yield good weld efficiency. Also, both alloys have higher tolerance for hydrogen than the alpha or alpha-beta alloys and are extremely resistant to sea-water corrosion.

No pertinent data were found for Ti-1Al-8V-5Fe but it would seem an unlikely candidate for sub-zero temperature service because of poor notch-strength properties at room temperature even when annealed and under mild-notch conditions (7).

Hydrogen Embrittlement

The solubility of hydrogen in α-titanium is very low, but increases rapidly with increasing temperature e.g., 0.002 wt % at 125°C (255°F) and 0.17 wt % at 325°C (615°F) (11). Beyond the solubility limit, platelets of titanium hydride precipitate to cause embrittlement. This embrittlement occurs at high strain rates in the alpha phase and is particularly manifested by a sharp decrease in impact ductility. Cracks develop along the interface of matrix and hydride. It is held that the hydride possesses sufficient ductility at low strain rates to accommodate the matrix deformation and, therefore, tensile properties of alpha alloys are relatively unaffected at low rates of deformation (12). Increased hydrogen content and the presence of notches increase the severity of embrittlement. Because the hydrogen solubility is decreased at low temperatures and the hydride precipitation consequently increased, the lowering of the temperature also increases the severity of embtittlement. Addition of the alpha stabilizer, aluminum, inhibits the formation of titanium hydrides, but precipitation can be initiated by small plastic strains and proceeds to completion rapidly (13). Low temperatures can only accentuate this phenomenon.

Hydrogen has high solubility in beta titanium which it acts to stabilize. It has a marked preference for solution in the beta phase in duplex alpha-beta alloys. In contrast to the "impact-embrittlement" of alpha alloys, hydrogen embrittlement of alpha-beta alloys occurs at low strain rates (11). Thus, particularly affected are tensile properties, especially ductility, whereas impact properties are unaltered. As segregation of hydrogen through diffusion is involved, low temperature tends to suppress low-strain-rate embrittlement. The critical hydrogen content varies widely from alloy to alloy. It appears to be a minimum at about room temperature and increases as the temperature is raised or lowered. The temperature range of the effect is -70 to 40°C (-95 to 105°F) (13). Such low-strain-rate embrittlement also has been found to occur in some single-phase alpha and beta alloys.

Hydrogen embrittlement of beta alloys currently is under debate and may vary widely with alloy composition. On the one hand, slow-strain-rate embrittlement has been observed; on the other, the hydrogen embrittlement characteristic of other b.c.c. metals does not occur and excellent tensile ductility has been found in certain high-molybdenum alloys containing high hydrogen (11-13).

In summary, hydrogen embrittlement is a potential danger in titanium alloys. In alpha titanium and alpha alloys its presence affects impact and notched properties and introduces a ductile to brittle transition which occurs at higher temperatures with increasing hydrogen content. In duplex alpha-beta alloys tensile properties are affected, especially ductility, the maximum effect occurring at room temperature.

The maximum hydrogen content cited by suppliers is usually about 0.015% by weight. This target is readily achieved but care must be taken during subsequent processing, particularly acid pickling, to keep hydrogen pick-up as low as possible.

Ti-40

Alternative Designations: A-40, RMI-40, RS-40, Ti-55A, HA1940, ASTM Grade 2.

Composition (%): 0.25 max O, 0.03 max N, 0.10 max C, 0.015 max H (commercially pure).

Physical Constants:

Density:	0.163 lb/in.^{3}
Modulus of elasticity:	15.5 x 10^6 psi
Modulus of rigidity:	6.5 x 10^6 psi
Thermal expansion:	5.3 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties	Temperature		
	Room	0°F (-18°C)	-100°F (-73°C)
0.010-in. sheet, annealed			
UTS, ksi	73	83	96
YS, ksi	52	60	70
Elong, %	29	34	40
NTS, K_t = 7.2, ksi	89	98	110
NTS/UTS, K_t = 7.2	1.22	1.18	1.15
CVN*, ft lb	> 60	50	36

* Plate or bar.

Comments:

The mechanical properties are highly dependent on impurities, especially interstitial elements (carbon, oxygen, nitrogen and hydrogen) and iron; the strengths are raised, the ductility and toughness lowered, by increased levels of impurities.

Commercial purity titanium is hardenable only by cold working. It is available in a wide range of mill shapes.

Most forming on sheet stock can be performed at room temperature. However, springback and power consumption can be reduced by warm forming.

The machining characteristics are similar to those of austenitic stainless steels. Rigid set-ups and sharp tools are basic conditions. The poor thermal conductivity of titanium necessitates use of good coolants, and the high work-hardening rate the use of heavy feeds, but slow speeds.

Commercially pure titanium is readily welded by techniques and procedures established especially for titanium and its alloys, namely gas-shielded arc-welding such as TIG or MIG. Welds possess strength, ductility and corrosion resistance equivalent to that of the parent metal.

Titanium possesses outstanding corrosion resistance to most media such as alkalis, organic salts and inorganic salts in all concentrations including, in particular, sea water. It is also good with most mineral acids. Exceptions are red fuming nitric acid, hydrofluoric acid and aluminum chloride. It is not susceptible to stress corrosion.

References: 6-8,14

Ti-55

Alternative Designations: A-55, RMI-55, RS-55, Ti-65A, HA1950, ASTM Grade 3

Composition (%): 0.35 max O, 0.05 max N, 0.10 max C, 0.015 max H (commercially pure)

Physical Constants: Same as for Ti-40

Mechanical Properties	Temperature		
	Room	(-18°C)	-100°F (-73°C)
0.025 in. sheet, annealed			
UTS, ksi	72	81	93
YS, ksi	57	64	77
Elong, %	21	27	34
NTS, $K_t = 13.6$, ksi	73	82	94
NTS/UTS, $K_t = 13.6$	1.01	1.01	1.01
CVN, ft lb *	47	42	38
FS - PB, ksi - plain *	41		
- notched	35 (K_t=2.7)		

* Plate or bar, annealed

Comments: See Ti-40

References: 6-8, 14-16

Ti-70

Alternative Designations: A-70, RMI-70, RS-70, Ti-75A, HA1970, ASTM Grade 4

Composition (%): 0.40 max O, 0.05 max N, 0.10 max C, 0.015 max H (commercially pure)

Physical Constants: Same as for Ti-40

Mechanical Properties	Temperature	
	Room	-65°F (-54°C)
UTS, ksi	97	123
YS (0.2%), ksi	84	111
Elong, %	20	
RA, %	40	
		-100°F (-73°C)
CVN, ft lb *	24	17.5
FS - RB, ksi - plain *	62	
ksi - notched	36 (K_t = 2.7)	

* Plate or bar, annealed

Comments: See Ti-40

References: 6-8, 14-16

Ti-5Al-2.5Sn

Alternative Designations: A-110AT, HA5137, RS-110C, Hylite 20, ASTM Grade 6

Composition (%): Ti-5 Al, 2.5 Sn

Physical Constants:

Density: 0.161 lb/in.^{3}
Modulus of elasticity: 16 x 10^6 psi
Modulus of rigidity: 7 x 10^6 psi
Thermal expansion: 5.3 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties		Temperature		
		Room	0°F (-18°C)	-100°F (-73°C)
Sheet and bar, annealed				
UTS, ksi		132	143	157
YS, ksi		125	135	145
Elong, %		15	15	14
RA, %		35	33	30
NTS, $K_t = 7.2$, ksi		170	173	183
NTS/UTS, K = 7.2		1.29	1.21	1.17
Weld TS, ksi		120	130	145
CVN, ft lb		20	18	15
FS - DS, ksi	plain	0-90		
ksi	notched	0-30 (K_t=3.5)		
FS - RB, ksi	plain	62		
ksi	notched	27 (K_t=3.2)		

Comments:

Ti-5Al-2.5Sn has the most favourable combination of strength, ductility and toughness of all the titanium alloys at cryogenic temperatures. It is a medium-strength all-alpha alloy used only in the annealed condition. It is not hardenable by heat treatment.

Annealing above 760°C (1400°F) appears to improve tensile and impact properties. Rapid cooling after annealing increases the toughness of sheet. Toughness is reduced by beta-phase stabilizing elements such as oxygen and iron, which consequently should be kept as low as possible for low-temperature use. The (ELI) grade is recommended for such applications.

Formability is good although inferior to that of commercially pure titanium. Warm working will reduce springback and power requirements.

Welding and machining considerations are similar to those for Ti-40. Brazing is not recommended.

Corrosion resistance of Ti-5Al-2.5Sn is comparable to that of Ti-40. The alloy is, however, susceptible to stress corrosion.

Under certain conditions, titanium and its alloys are extremely reactive in oxygen environments. In contact with liquid oxygen or oxygen gas at pressures as low as 50 psi and temperatures as low as -155°C (-250°F), impact loading or fresh fracture surfaces may result in burning and possibly explosion.

References: 6-8, 14-16

Ti-5Al-2.5Sn ELI

Alternative Designations: A-95AT, HA5137 ELI, RS-110C-L

Composition (%): Ti-5 Al, 2.5 Sn, 0.12 max O, 0.05 max N, 0.08 max C, 0.0175 max H, 0.15 max Fe

Physical Constants: Same as for Ti-5Al-2.5Sn standard grade

Mechanical Properties	Temperature		
	Room	0°F (-18°C	-100°F (-73°C)
0.020-in. sheet, annealed			
UTS, ksi	110	113	128
YS, ksi	102	105	118
Elong, %	17	16	15.5
NTS, K_t=8.0, ksi	144	150	163
NTS/UTS, K_t=8.0	1.31	1.33	1.27
Weld TS, ksi	104	106	117
0.40-in. plate, annealed			
CVN, ft lb	26	22	17

Comments: See Ti-5Al-2.5Sn

References: See Ti-5Al-2.5Sn

Ti-8Al-1Mo-1V

Alternative Designations: HA8116, RS-811X

Composition (%): Ti-8 Al, 1 Mo, 1 V

Physical Constants:

Density: 0.156 lb/in.^{3}

Modulus of elasticity: 18.5 - 19 x 10^6 psi

Modulus of rigidity: 6.7 x 10^6 psi

Thermal expansion: 5.0 x 10^{-6}/°F (RT to 400°F)

MMechanical Properties	Temperature		
	Room	0°F (-18°C)	-100°F (-73°C)
0.032-in. sheet, single annealed			
UTS, ksi	152	158	176
YS, ksi	144	154	172
Elong, %	17	17	17
NTS, K_t=8.0, ksi	150	130	122
NTS/UTS, K_t=8.0	0.98	0.82	0.69
Weld TS, ksi	151	154	170
FS - RB, (bar stock), ksi	82		
0.032-in. sheet, duplex annealed			
UTS, ksi	140	146	162
YS, ksi	132	138	150
Elong, %	17	16	15.5
NTS, K_t=8.0	160	160	165
NTS/UTS, K_t=8.0	1.14	1.10	1.02
Welds TS, ksi	137	144	160
Bar, hot-rolled		-40°F (-40°C)	
CVN, ft lb	17	12.5	
0.040-in. sheet, duplex annealed		-110°F (-79°C)	
FS - DS, unnotched, ksi	25±55	25±58 (extrapolated)	
notched, K_t=4.0, ksi	25±9	25±15 (extrapolated)	
K_{Ic} (1-in. plate) ksi$\sqrt{in.}$	67 (YS 138 ksi)		

Comments:

Ti-8Al-1Mo-1V is a high-strength, predominantly alpha alloy having the highest tensile modulus and lowest density of the titanium alloys. The fracture toughness of single annealed sheet is high at room temperature and above but deteriorates at low temperatures. Duplex annealing, which involves high-temperature annealing and rapid cooling, yields high-fracture toughness at sub-zero temperatures. This structure loses its high toughness if subsequently exposed to intermediate temperatures, 540 to 650°C (1000 to 1200°F).

Forming and forging characteristics and practices for this alloy are similar to those for other alpha-rich titanium alloys. The higher beta-transus temperature (1040°C (1900°F)) allows higher hot-working temperatures to be used. Sheet forming is more difficult than for Ti-6Al-4V.

Machinability is similar to that of Ti-6Al-4V.

The alloy can be resistance or fusion welded (TIG or MIG with parent metal rod) with resulting high joint efficiency and good ductility when proper precautions are taken to clean surfaces to be welded and to avoid contamination.

The corrosion properties are similar to those of other titanium alloys. It is susceptible to stress corrosion in the mill annealed (single annealed) condition to a greater degree than Ti-6Al-4V but less so than Ti-5Al-2.5Sn. Duplex-annealed thin sheet appears not to be susceptible.

References: 6-8,15,16,21,24

Ti-679

Alternative Designation: IMI-679

Composition (%): Ti-11 Sn, 5 Zr, 2.25 Al, 1.0 Mo, 0.2 Si

Physical Constants:

Density: 0.174 lb/in.^{3}

Modulus of elasticity: 15.5 x 10^6 psi

Thermal expansion: 5 x 10^{-6}/°F (RT to 200°F)

Mechanical Properties	Temperature	
	Room	-110°F (-70°C)
Forgings, duplex annealed		
UTS, ksi	148	170
YS, ksi	130	158
Elong, %	14	13
RA, %	44	41
NTS, K_t=3.9, ksi	205	
NTS/UTS, K_t = 3.9	1.38	
NTS*, ksi	104	90
NTS/UTS*	0.78	0.68
CVN, ft lb	15	
FS - DS (rolled bar) ksi	±55	
notched, K_t=3, ksi	±20	
K_{Ic} (forging, β processed) ksi$\sqrt{in}$.	31 (YS 141 ksi)	

* 0.750-in. diameter bar, 60° notch to 0.6-in. diameter, fatigue cracked to 0.37-0.50-in. diameter.

Comments:

Ti-679 is a high-strength, super-alpha alloy strengthened by both solution strengthening of the alpha phase and precipitation strengthening by a silicide. It is used almost exclusively in the duplex annealed condition. Quenching rather than air cooling can increase the tensile strength by up to 30 ksi upon subsequent ageing; there is an accompanying slight decrease in ductility.

There is some evidence that the fracture toughness of sheet is poor, but few data are available.

Machinability is similar to that of other titanium alloys.

Forgeability of this alloy is good, being comparable to that of Ti-8Al-1Mo-1V, but not as good as for Ti-6Al-4V or Ti-6Al-6V-2Sn.

Opinions on the weldability of Ti-679 differ and the ability to achieve suitable welded properties may depend on whether or not the welded piece can be heat treated.

Ti-679 is susceptible to stress corrosion.

References: 7,8,24

Ti-6Al-2Nb-1Ta-0.8Mo

Alternative Designations: Ti-621/0.8, Ti-621/1.0

Composition (%): Ti-6 Al, 2 Nb, 1 Ta, 0.8 Mo

Physical Constants:

Density: 0.162 lb/in.^{3}

Modulus of elasticity: 17.0 x 10^6 psi

Thermal expansion: 5 x 10^{-6}/°F (RT to 1200°F)

Mechanical Properties	Temperature	
	Room	-80°F (-62°C)
Plate, beta-processed		
UTS, ksi	120	
YS (tens., 0.2%), ksi	100	
Elong, %	12	
RA, %	30	
CVN, ft lb	30	25
FS - RB, ksi	45	
notched ksi	25 (K_t=3)	
K_{Ic} (estimated) ksi$\sqrt{in.}$	80-100	
K_{Iscc} (estimated) ksi$\sqrt{in.}$	80-90	

Comments:

Ti-621/0.8 is an all-alpha alloy of moderate strength. Although few data can be given for its low-temperature properties, it is included here because of its high toughness at room temperature and its favourable stress-corrosion resistance. It was developed primarily for marine structural applications.

Some reduction in load-carrying capability in sea water is indicated although there is no evidence of stress corrosion on the fracture surfaces. Sea water appears not to affect the notch fatigue properties.

This alloy is generally used as-fabricated or in the annealed condition. Ageing gives a small increase in strength but at a considerable loss of ductility and toughness.

Working is usually carried out in the beta-range. Processing in the alpha + beta range increases strength but at a sacrifice in toughness.

The machinability is comparable to that of other titanium alloys.

Ti-621/0.8 is weldable by fusion or resistance welding with resultant good ductility when appropriate titanium welding techniques are used. The weldability is excellent with the same ductility and toughness resulting in the weld metal as in the parent metal.

References: 7,8

Ti-4Al-3Mo-1V

Alternative Designations: C-115Mo V, RS-115

Composition (%): Ti-4 Al, 3 Mo, 1 V

Physical Constants:

Density: 0.163 lb/in.^{3}

Modulus of elasticity: 16.5 x 10^6 psi

Modulus of rigidity: 7.0 x 10^6 psi

Thermal expansion: 5 x 10^{-6}/°F (RT to 200°F)

Mechanical Properties	Temperature	
	Room	-100°F (-73°C)
0.063-in. sheet, soln treated and aged		
UTS, ksi	185	225
YS, ksi	163	197
Elong, %	6	5
NTS, K_t=6 ksi	165	175
K_t=12 ksi	95	95
0.5-in. plate, beta-annealed + soln treated + aged		-65°F (-54°C)
UTS (transverse) ksi	160	172
YS, " ksi	138	153
Elong, " %	8	7
RA, "	14	14
K_q* " ksi$\sqrt{\text{in.}}$	87	87

* surface crack tensile specimen, 4-in. wide, 0.5-in. thick, 0.2-in crack depth, 0.4 in.-crack length

K_{Ic}(0.5-in. plate) ksi$\sqrt{\text{in.}}$	63 (YS 161 ksi)
0.065-in. sheet, soln treated + aged	
FS - DS, R = 0.25, ksi	31-125
notched (K_t = 3.5) ksi	10-40

Comments:

Ti-4Al-3Mo-1V is an alpha-beta alloy capable of being aged to tensile strengths of 180 to 200 ksi. Treatments to give high strength or high toughness involve annealing above the beta transus prior to solution treating and ageing. This beta anneal is claimed to give good toughness and satisfactory salt water crack-propagation resistance, but with reduced ductility that gives poor formability. Omission of the beta anneal greatly improves formability.

Workability is good. Annealed material is used for extensive hot forming, in which a minimum bend radius of 2T can be achieved. Solution-treated material provides maximum formability and minimum bend radius at lower temperatures. Minimum bend radius at room temperature is 3.5T for thin sheet. Aged material can be modestly formed cold.

Machining considerations are the same as for other titanium alloys.

This alloy can be welded successfully by fusion techniques, both TIG and MIG, but extreme caution is necessary to avoid porosity and weld cracking. Resistance welding requires techniques and equipment similar to those used for stainless steels, and results in good weld properties. High strength, ductile spot and seam welds can be made in aged material. Resistance welding should never be followed by ageing or stress relief.

The corrosion resistance is similar to that of commercially pure titanium. It is galvanically similar to austenitic stainless steels and is considered insensitive to stress corrosion.

References: 7,8,15,16,23,24

Ti-6Al-4V

Alternative Designations: C-120AV, HA6510, RS-120A, Hylite 45, ASTM Grade 5

Composition (%): Ti-6 Al, 4 V

Physical Constants:

Density: 0.160 lb/in.^{3}

Modulus of elasticity: 15.5-18.0 x 10^6 psi

Modulus of rigidity: 6.1 x 10^6 psi

Thermal expansion: 5 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties	Temperature		
	Room	0°F (-18°C)	-100°F (-73°C)
0.040-in. sheet, annealed			
UTS, ksi	140	155	176
YS, ksi	127	142	160
Elong, %	11	12	13
NTS, K_t=7.2, ksi	170	186	203
NTS/UTS, K_t = 7.2	1.22	1.20	1.15
0.50-in. plate, annealed			
CVN, ft lb	17	15	13
K_{Ic} ksi$\sqrt{in.}$	68		65
0.072-in. sheet, annealed			
FS - PB (10^6 cycles) ksi	50		55
notched, K_t=6.4, ksi	25		26
0.065-in. sheet, soln treated + aged			
UTS, ksi	172	180	200
YS, ksi	162	167	184
Elong, %	6	6	6
NTS, K_t=6, ksi	155	167	180
K_t=12, ksi	120	110	108
0.5-in. plate, soln treated + aged			
CVN, ft lb	14	14	13
K_{Ic} (YS 150 ksi) ksi$\sqrt{in.}$	45-50		42-52

Comments:

Ti-6Al-4V is the most widely used of the titanium alloys. It is an alpha-beta type that can be heat treated to high strength levels; attention must be given to fracture toughness in design for these strength levels. The properties of annealed material are good for low-temperature applications although somewhat inferior to those of Ti-5Al-2.5Sn. The ELI grade is claimed to have improved ductility and fracture toughness and is preferred to the standard grade for low-temperature use. The one processing variable which is claimed to consistently improve the fracture toughness is termed a recrystallization anneal (RA). Plate with alpha-beta processing followed by the RA has shown an increase of about 20% in K_{Ic} with little change in tensile properties.

Annealed Ti-6Al-4V is one of the most difficult of the annealed titanium alloys to form. Severe forming can be accomplished by hot working. Parts to be aged should be formed in the solution-treated condition. Moderate deformation can be carried out on aged material.

Solution treatment requires water quenching prior to ageing and full properties may not be achieved in sections over 1 in.

Machinability is similar to that of titanium and other titanium alloys.

Ti-6Al-4V is weldable by both fusion and resistance-welding methods.

The corrosion resistance is similar to that of commercial purity titanium and of other titanium alloys. This alloy is sensitive to stress-corrosion cracking, although to a lesser degree than either Ti-5Al-2.5Sn or Ti-8Al-1Mo-1V.

References: 6-8,15,16,21,22,24,25

Ti-6Al-4V ELI

Alternative Designations: HA6510 ELI, RS-120A-L

Composition (%): Ti-6 Al, 4 V, 0.13 max O, 0.05 max N, 0.08 max C, 0.015 max H, 0.25 max Fe.

Physical Constants: Same as for Ti-6Al-4V standard grade

Mechanical Properties	Temperature		
	Room	0°F (-18°C)	-100°F (-73°C)
0.032-in. sheet, annealed			
UTS, ksi	140	150	162
YS, ksi	130	140	154
Elong, %	13	13	13
NTS, $K_t = 3.5$, ksi	161	168	175
$K_t = 8.0$,	160	147	142
NTS/UTS, $K_t = 3.5$	1.15	1.12	1.08
$K_t = 8.0$	1.14	0.98	0.88
Weld TS, ksi	140	144	162
0.032-in. sheet, soln treated + aged			
UTS, ksi	180	192	208
YS, ksi	165	178	198
Elong, %	9	7	6
NTS, $K_t = 3.5$, ksi	200	209	228
$K_t = 8.0$, ksi	195	152	142
NTS/UTS, $K_t = 3.5$	1.11	1.09	1.09
$K_t = 8.0$	1.08	0.79	0.68
Welds TS, ksi	166	182	193
0.5-in. plate, annealed			
CVN, ft lb	18.5	16.5	14
soln treated + aged			
CVN, ft lb	17.5	17	16

Comments: See Ti-6Al-4V standard grade

References: See Ti-6Al-V standard grade

Ti-7Al-4Mo

Alternative Designations: C-135A Mo, HA7146, RS-135

Composition (%): Ti-7 Al, 4 Mo

Physical Constants:

Density: 0.162 lb/in.^{3}

Modulus of elasticity: 16.5×10^6 psi

Modulus of rigidity: 6.5×10^6 psi

Thermal expansion: 5×10^{-6}/°F (RT to 400°F)

Mechanical Properties	Temperature		
	Room	-65°F (-54°C)	-105°F (-76°C)
Sheet and bar, annealed			
UTS, ksi	159		183
YS, ksi	153		174
Elong %, sheet	7		2.5
Elong %, bar	13		13
RA %, bar	38		31
NTS, $K_t = 11.2$*, ksi	143		151
NTS/UTS, $K_t = 11.2$*	0.90		0.83
*0.062-in. sheet, 45° notch, 30% depth, 0.5 in. between notches			
K_{Ic}- forging, mill annealed, ksi$\sqrt{\text{in.}}$	41 (YS 155)		
0.75-in. diameter bar, soln treated + aged			
UTS, ksi	200	200	
YS, ksi	180	200	
Elong, %	7	6	
RA, %	25	20	
11/16-in. diameter bar, annealed			
			-100°F (-73°C)
CVN, ft lb	16.5		16
soln treated + aged			
CVN, ft lb	13		12
Annealed bar			
FS - RB, ksi	97		
notched, $K_t = 3.9$, ksi	29		

Comments:

Ti-7Al-4Mo is a heat-treatable alpha-beta forging and extrusion alloy with somewhat higher strength than Ti-6Al-4V. Hardenability is the same as for Ti-6Al-4V.

Machinability is comparable to that of other commercial titanium alloys.

Welding of this alloy is not advised because of its age-hardening properties although it has been successfully flash welded.

It is comparable to commercial purity titanium in corrosion resistance but is susceptible to stress-corrosion cracking.

References: 7,8,15-17,21,24

Ti-8Mn

Alternative Designations: C-110M, RS-110A

Composition (%): Ti-8 Mn

Physical Constants:

Density:	0.170 lb/in.^{3}
Modulus of elasticity:	15.5 x 10^6 psi
Modulus of rigidity:	6.0 x 10^6 psi
Thermal expansion:	5 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties	Temperature	
	Room	-110°F (-79°C)
0.064-in. sheet, annealed		
UTS, ksi	140	175
YS, ksi	125	167
Elong, %	13	13
RA, %	15	19
NTS, K_t = 3, ksi	150	190
NTS/UTS, K_t = 3	1.07	1.09
FS - DS, ksi	21-85 (R=0.25)	

Comments:

Ti-8Mn is an alpha-beta type alloy that is heat treatable but used only in the annealed condition. There is very poor reproducibility of properties in the aged condition.

Formability is optimum with warm working but extensive hot or cold working is possible. Subsequent stress relief annealing is recommended.

Machinability is similar to that of other titanium alloys.

Welding of this alloy is not recommended.

Ti-8Mn is comparable to commercial purity titanium in corrosion resistance but is sensitive to stress-corrosion cracking.

References: 7,8,15,16,21

Ti-6Al-6V-2Sn

Alternative Designations: HA5158

Composition (%): Ti-5.5 Al, 5.5 V, 2.0 Sn, 0.7 Fe, 0.7 Cu

Physical Constants:

Density: 0.164 lb/in.^{3}

Modulus of elasticity: 15.5-16.5 x 10^6 psi

Thermal expansion: 5 x 10^{-6}/°F (RT to 200°F)

Mechanical Properties	Temperature	
	Room	-108°F (-78°C)
4.5-in. diameter bar, annealed		
UTS, ksi	150	171
YS, ksi	136	163
Elong, %	20	21
RA, %	40	39
NTS, $K_t = 11.8$, ksi	175	134
NTS/UTS, $K_t = 11.8$	1.17	0.78
soln treated + aged		
UTS, ksi	194	226
YS, ksi	184	218
Elong, %	8	4.5
RA, %	13.6	5.4
NTS, $K_t = 11.8$, ksi	98	89
NTS/UTS, $K_t = 11.8$	0.50	0.39
low-interstitial forging, annealed		
K_{Ic}, ksi$\sqrt{\text{in.}}$	70	55
soln treated + aged		
K_{Ic}, forging, ksi$\sqrt{\text{in.}}$	60	55
plate, ksi$\sqrt{\text{in.}}$	30-40	
plate, mill annealed (ELI)		
CVN, ft lb	14	11 1/2
soln treated + aged		
CVN, ft lb	8	7
annealed plate		
FS - DS, ksi	8-86	
notched, $K_t = 3.5$, ksi	2-26	
plate, soln treated + aged		
FS - DS, ksi	10-105	
notched, $K_t = 3.5$, ksi	2-28	

Comments:

Ti-6Al-6V-2Sn is a heat-treatable alpha-beta alloy having greater strength potential and hardenability than Ti-6Al-4V but at a sacrifice in toughness and weldability.

It is slightly more difficult to deform than Ti-6Al-4V. Hot working is most successful, but cold forming is possible although difficult.

Machining considerations are the same as for other titanium alloys.

Welds possess low ductility and low notch strength. Use of Ti-55 filler metal is advised as well as post-weld annealing to improve ductility and toughness. Solution treatment and ageing, however, leads to very brittle conditions.

The corrosion resistance is similar to that of commercial purity titanium. The alloy is susceptible to stress corrosion in aqueous chloride solutions.

References: 6-8,15,16,18,19,21,24

Ti-13V-11Cr-3Al

Alternative Designations: B-120 VCA, RS-120B, Beta Ti

Composition (%): Ti-13.5 V, 11 Cr, 3Al

Physical Constants:

Density: 0.175 lb/in.^{3}

Modulus of elasticity: 14-16 x 10^6 psi

Modulus of rigidity: 6.2 x 10^6 psi

Thermal expansion: 5.5 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties	Temperature Room	 0°F (-18°C)	 -100°F (-73°C)
Sheet, soln treated			
UTS, ksi	140	150	172
YS, ksi	130	142	165
Elong, %	22	-	-
NTS, K_t = 10, ksi	158	168	188
NTS/UTS, K_t = 10	1.13	1.12	1.09
Sheet, soln treated + aged			
UTS, ksi	192	210	218
YS, ksi	180	186	197
Elong, %	4	3 1/2	2 1/2
NTS, K_t = 3, ksi	196	202	192
NTS/UTS, K_t = 3	1.02	0.96	0.88
Bar, annealed and soln treated + aged			
CVN, ft lb	8		5
Bar and sheet, soln treated + aged			
K_{Ic}, ksi$\sqrt{in.}$	~30		~25
Sheet, annealed (UTS 138 ksi)			
		Room Temperature	
		R = 0	R = -1
FS - DS, ksi		0-63	±35
notched, K_t = 3.0, ksi		0-27	±19
Sheet, soln treated + aged (UTS 174 ksi)			
FS - DS, ksi		0-55	±38
notched, K_t = 3.0, ksi		0-27	±19

Comments:

Ti-13V-11Cr-3Al is a metastable beta alloy which is highly formable in the solution-treated condition and can be aged to strengths of 170 to 200 ksi. Extreme cold working prior to ageing can result in strengths as high as 300 ksi. Low solution-treatment temperatures favour improved toughness.

Although this alloy requires high work forces to form, in the solution-treated condition it is more amenable to cold forming than any other high-strength alpha or alpha-beta titanium alloy. Forming by all conventional methods is possible.

This alloy is more difficult to machine than alpha and alpha-beta alloys. Slower speeds are required. High-speed tool steels can be used for solution-treated material but carbide tools may be preferred for aged material.

Weldability of annealed material is excellent with strength and ductility of weldments about the same as those of the parent metal. Ageing of welds, however, can result in low ductility and toughness.

The corrosion resistance is similar to that of other titanium alloys. The alloy is susceptible to stress-corrosion cracking in aqueous chloride solutions.

References: 7,8,15,16,20,21,24

Ti-11.5Mo-6Zr-4.5Sn

Alternative Designations: Beta III, ASTM Grade 10

Composition (%): Ti-11.5 Mo, 6 ZR, 4.5 Sn

Physical Constants:

Density: 0.183 lb/in.^{3}

Modulus of elasticity: 15 x 10^6 psi

Thermal expansion: 4.5 x 10^{-6}/°F (RT to 400°F)

Mechanical Properties	Room Temperature	
	Solution treated	Solution treated & aged
0.063-in. sheet		
UTS, ksi	141	205
YS, ksi	128	191
Elong, %	17	7
RA, %	45	29
0.5-in. plate		
UTS, ksi	110-140	185-250
YS, ksi	90-125	170-195
Elong, %	10-30	5-10
RA, %	40-70	8-28
K_{Ic}, , ksi$\sqrt{in.}$		~60
soln treated + aged		
CVN, (1 1/2-in. bar) ft lb YS 176 ksi	14.5 at RT 13.0 at -40°F	
0.5-in. bar soln treated + aged		
FS - RB, ksi	80 (UTS 200 ksi)	
FS - DS, (R = 0.1) ksi notched, K_t = 3.3, ksi	15-150 (UTS 200 ksi) 4-40 (UTS 200 ksi)	

Comments:

Ti-11.5Mo-6Zr-4.5Sn, or Beta III, is a metastable beta alloy which precipitates a fine dispersion of alpha phase upon ageing to give strengths as high as 200 ksi with good ductility. It is hardenable to depths of 3 to 4 in.

In cold formability, Beta III is equivalent to Type 301 stainless steel and better than any other commercial titanium alloy. It is highly recommended for fastener and sheet applications.

This alloy has good weldability with ductility and strength of weldments equal to that of solution-treated material. Ageing gives high strength with good joint efficiency, reasonable weld ductility, and fracture toughness equal to that of parent metal.

Beta III is resistant to both oxidizing and reducing environments and has excellent stress-corrosion resistance.

References: 7,8,14,21

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3.6 COPPER, TIN AND LEAD ALLOYS

Introduction

A. Couture*

In an overall project to review the use and application of materials in the Arctic, it is apparent that many factors govern the selection of materials for this type of service. It is also obvious that greatest attention must be focussed on structural materials such as cast iron, steel, and aluminum, since these are the ones most likely to be operating outdoors in the severe environment.

The rationale concerning the choice of materials for service in the North has already been dealt with (Section 1) and, consequently, will not be repeated here. Copper, tin and lead alloys are not expected to serve as structural units, except perhaps in the case of copper alloy tube, valves, etc., but nevertheless they may well be exposed to arctic environment in the form of machine parts, bearings, electrical equipment, solder connections, etc.

This Section, therefore, indicates how the mechanical properties of copper, tin, lead and their alloys are affected by low temperatures. However, as pointed out by Pollard (1) the difference in minimum winter temperatures between Alert, NWT and Ottawa is only about 10°C (20°F). Thus, unless some property of the metal is much lower at say, 62°C (-80°F) (extreme lowest temperature recorded in Snag, NWT), than at -40°C (-40°F) (extreme lowest temperature recorded in Ottawa) - the effect of ambient temperature would cause no unusual restriction on the use of the material in the North. Other factors such as secondary effects of low ambient temperatures on thermal expansion and corrosion, reliability, ease of maintenance and transport, etc., have been discussed already and can be applied to the alloys referred to in this review.

As, in general, the mechanical properties of copper, tin and lead alloys increase with decreasing temperature, the

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designer does not have to worry about the effect of low temperature except in a few cases. The increase due to lower temperatures should not make him under-design however, because, in the first place, the improvement between normal ambient temperatures and -73°C (-100°F) is usually small and, in the second place, the part so designed would presumably have to operate at the higher temperatures of the long-day arctic summer. The present review will therefore be limited to the exceptions, which the designer should consider, i.e., the cases where some property or properties decrease appreciably with decreasing temperature.

Copper and Copper Alloys

The electrical resistivity of copper and copper alloys decreases with decreasing temperature (2,3,4). Camenisch (5) gives, for pure copper, values of 0.017 and 0.01 Ohm mm^2/m at 24°C (75°F) and -73°C (-100°F), respectively.

The thermal conductivity of pure copper does not vary much in the temperature interval covered here (2,5), but increases rapidly at lower cryogenic temperatures. The thermal conductivity of copper alloys decreases steadily with decreasing temperature (2,3,4). For example, that of 70-30 brass is 9.23 and 7.93 $W{\cdot}m/m^2{\cdot}°C$ per hour at 24°C (75°F) and -73°C (-100°F) respectively.

The mechanical properties - ultimate tensile strength and 0.2% yield strength, elongation, reduction of area and impact strength - of copper and copper alloys are in the vast majority of cases not detrimentally affected by decreasing temperatures, as indicated on pages 208 to 211 (2,3). The properties steadily increase with decreasing temperature or are not affected (2-10). However, a word of caution is in order concerning certain alloys which lose ductility at sub-zero temperatures, their elongation and/or impact strength sharply decreasing with decreasing temperature.

Howells and Lange (11) measured the impact strength at four temperatures, including 27°C (80°F) and -73°C (-100°F) of fifteen as-cast copper-base alloys in use by the U.S. Navy. The alloys were No. 836 (4A), 863 (8C), 865 (8A), 872 (12A), 875 (13B), 903 (1B), 922 (2A), 952 (9A), 953 (9B), 954 (9C), 955 (9D), as well as two tin-nickel bronzes and two phosphor bronzes. All alloys, with the exception of Alloy No. 922 (2A), the tin-nickel bronzes, Grade C phosphor bronze and Alloy No. 865 (8A), showed higher Charpy V-notch energy at 27°C (80°F) than at -73°C (-100°F). The maximum percentage drop in impact strength was experienced with as-cast Alloy No. 863 (8C) (high-strength manganese bronze), where the absorbed energy was 15 1/2 and 8 1/2 ft lb respectively at 27°C (80°F) and -73°C (-100°F). The highest impact values were those for Alloy 872 (12A) (silicon bronze) at 74 and 61 ft lb respectively, and the lowest were for Alloy No. 954 (9C) (aluminum bronze), where they were 4 and 2 1/2 ft lb respectively. However, the authors found that copper-base alloys have fracture characteristics different from steel in that copper-base alloys with Charpy V values as low as 3 ft lb will plastically deform even in the presence of a sharp notch. Of the alloys tested, only the high-tensile manganese bronze (Alloy 863 (8C)) approached a truly brittle condition and then only at temperatures below -100°C (-150°F).

Jaffee and Ramsey (12), investigating three cast aluminum bronzes of compositions corresponding roughly to Alloys No. 952 (9A) and 955 (9D) heat treated to various temper conditions, found that the Charpy impact strength decreases slightly between room temperature and -73°C (-100°F), whereas the hardness, elongation, yield strength and tensile strength increase. Other workers showed that in the case of sand-cast aluminum bronze, Alloy No. 955 (9D), the elongation in 4D drops from 11 to 9% and the absorbed energy from 10 to 8 ft lb over the same temperature range (7,8). For wrought products, the Charpy V-notch absorbed energy for cold-drawn Alloy No. 230 (red brass, 85% Cu - 15% Zn and Alloy No. 614 (aluminum bronze D)) annealed 0.75-in. diameter bars is quoted as 96 and 82, and 110 and 100 ft lb respectively at room temperature and -73°C (-100°F), and phosphor bronze Alloy No. 510 (cold drawn 85%) has values of 106 and 85 ft lb at the same temperatures (6,7,8). The other alloys reported (6,7,8), (Alloys No. 102, 122, 150, 220, 443, 464, 647, 655, 706 and 715) have at least as good an impact strength at low temperature as at room temperature.

Lismer (13) tested the following alloys: arsenical copper, 60:40 brass, cupro-nickels of 90:10, 80:20 and 70:30 compositions, kunifer alloys (cupro-nickel containing iron and manganese) of 5, 10 and 20% nickel contents and Superston 40 (manganese-aluminum bronze). The tensile strength of every alloy increased with decreasing temperature and the only alloys in which the Charpy V-notch impact strength decreased between 38°C (100°F) and -73°C (-100°F) were the 80:20 cupro-nickel and Superston 40. The impact strength increased to various degrees in the other cases, and no explanation was given as to why the 80:20 cupro-nickel had a different behaviour pattern from the 90:10 or 70:30 alloys, or from the similar 80:20 kunifer alloy.

As far as corrosion is concerned, the low temperature encountered in the Arctic should normally retard any corrosion process and, therefore, copper alloys should be at least as safe in such applications as they are in more moderate climates.

In summary, therefore, it can be stated that the electrical resistivity and thermal conductivity of copper decrease with decreasing temperature. The impact strength of some alloys, particularly cast high-strength manganese bronze and aluminum bronze, can be appreciably lower at -73°C (-100°F) than at 27°C (80°F), and this applies to a lesser extent to wrought products in the same alloys. Unlike some ferrous materials, such changes occur progressively over a range of temperatures rather than at a sudden transition temperature, and copper alloys are not considered to undergo a transition from ductile to brittle behaviour over the temperature range being considered.

Thus, it may be concluded that copper alloys which perform satisfactorily in winter in centres such as Ottawa, Winnipeg and Edmonton, would behave similarly in the high Arctic and could be used there without special design consideration on this account.

Tin, Lead and their alloys

As in the case of copper alloys, the mechanical properties of tin and lead alloys generally improve with decreasing temperature. However, here again the designer should be aware that certain exceptions exist.

The Charpy V-notch impact strength of pure tin drops very abruptly below 0°C (32°F) going from 35 ft lb just above -60°C (-75°F) to approximately 3 ft lb at -60°C (-75°F) (14). A tin-5% Sb alloy behaves similarly.

In the case of pure lead, the impact strength, tensile strength and elongation increase with decreasing temperature (15).

Investigators (16), who had tested a number of lead alloys (2.5 Ag-97.5 Pb; 5 Sn-95 Pb; 10 Sn-90 Pb; 15 Sn-85 Pb; 1.6 Ag-15 Sn-83.4 Pb and 50 Sn-50 Pb), found that the impact strength of alloys containing 95% Pb or more increases with decreasing temperature and that of the alloys containing 80 to 90% Pb was little affected by temperature. Kalish and Dunkerley (17) claim that tin-lead solders containing about 70% or less of lead would become brittle at temperatures below -160°C (-255°F), although no results are given to substantiate this point. They also say that solders containing about 70 to 80% lead should remain ductile down to temperatures near absolute zero (-273°C i.e., -458°F).

It appears that the tin-lead alloys which are the most affected by low temperatures are the common solders, 60 Sn-40 Pb and 50 Sn-50 Pb. Their impact strength and elongation decrease drastically with decreasing temperature (16,18). A summary of the mechanical properties of a range of solders at room temperature and -73°C (-100°F) is given in the Table.

Mechanical Properties of Selected Solders

Composition	UTS, ksi		Elong, %		CVN ft lb	
	24°C (75°F)	-73°C (-100°F)	24°C (75°F)	-73°C (-100°F)	24°C (75°F)	-73°C (-100°F)
Sn 95, Sb 5	5	10	60	70	43	3
Sn 1, Pb 97.5, Ag 1.5	4	5.5	30	28	24	26
Sn 5, Pb 95	3.5	6	50	33	14	17.5
Sn 10, Pb 90	3.5	5.5	50	45	8	7
Sn 60, Pb 40	7	13	60	54	17	4
Sn 50, Pb 50	4	10.5	110	45	15.5	4

Examination of Fig. 1 suggests that there is a transition temperature for tin alloys containing more than say, 40% tin. This diagram shows a very marked drop in the impact strength of these alloys at temperatures slightly higher than 0°C (32°F), this drop being displaced towards higher temperatures for ordinary solders when compared to tin or tin - 5% antimony. No explanation is offered for this loss of ductility. It should not be attributed to the phenomenon known as "tin pest" as it appears that only the ductility is affected and the tensile strength increases gradually with decreasing temperature over the range considered.

The tin pest phenomenon is worthy of comment. This is an allotropic change which can occur, when normal tetragonal white tin transforms to "grey" cubic tin at temperatures about 13°C (56°F), the most rapid rate of transition taking place about -40°C (-40°F). This transition is accompanied by an expansion of about 30% which results in disintegration of the article into a grey powder, or grey powder excrescences occurring on the surface depending on the completeness of the transformation. Certain elements and strain conditions promote the change while others inhibit it. Although this is a well-documented transition, it is difficult to initiate, and many of the impurities commonly found in tin, particularly lead and antimony, will inhibit the transformation (19,20). For these reasons, authenticated instances of the transformation taking place under natural conditions are extremely rare, and no instance of failure in tin materials containing more than 5% lead has been recorded (4). As a precaution however, solders designed specifically for refrigeration service contain 0.2-0.5% antimony to inhibit this transformation (see ASTM B32-66T Tentative Specification for Solder Metal). Similarly, although the problem is not acute, it may be desirable to specify such materials for joints subject to long-term exposure at Arctic temperatures.

Limited low-temperature data are also available (18) about a special class of solders, those containing indium. In the following alloys: 25 In-75 Pb; 50 In-50 Pb; 50 In-50 Sn; 90 In-10 Ag; 80 In-20 (Ag + Pb) and 25 In-75 (Pb + Sn), tensile strength increases with decreasing temperature, and impact tests indicate that the 50 In-50 Pb alloy is the best of the group for low-temperature service.

In summary therefore, it can be said that the properties of lead and lead-based alloys improve as the temperature decreases so that no problems should be encountered in Arctic service. However, tin and tin-rich alloys can show a drastic reduction in impact strength and elongation with decreasing temperatures. Thus, solders about the popular 50 Sn-50 Pb composition can suffer a four-fold reduction in impact strength between 24 and -74°C (75 and -100°F) which may give failures if joints are shock-loaded at the low ambient temperatures of the Arctic. Tin pest, the allotropic change from white to "grey" tin, seems very unlikely and can be prevented by alloying with antimony.

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Oxygen-Free Copper

Alternative Designation: CDA No. 102

Composition: Commercial purity

Physical Constants:

Density: 0.323 lb/in.^{3}

Modulus of elasticity: 17×10^6 psi

Modulus of rigidity: 6.4×10^6 psi

Thermal expansion: 9.8×10^{-6} in./in./°F (RT to 570°F)

Mechanical Properties	Room temperature	-100°F (-73°C)
0.75-in. bar, annealed		
UTS	32.2	39.1
YS, (0.1%) ksi	10.9	11.6
Elong, %	54	53
RA, %	86	84
CVN*, ft lb	53	57
0.75-in. bar, cold drawn		
UTS, ksi	52	57
YS, (0.1%) ksi	49	55
Elong, %	19	20
RA, %	75	79
FS - RB, ksi	~11 (annealed) ~19 (annealed)	

*1/2 thickness specimen

Comments:

The hot and cold workability are excellent, and the machinability index is 20 on the basis of free-cutting brass being 100. Soldering and brazing characteristics are also excellent, but the weldability varies from fair to good depending on the process. Resistance to atmospheric corrosion is high, though tarnishing will occur in the presence of sulphur compounds.

References: 2,8,21,22

Beryllium Copper

Alternative Designation: CDA No. 172, Berylco 25

Composition: Cu-1.9 Be, 0.2 Co

Physical Constants:

Density: 0.295/0.298 lb/in.^3

Modulus of elasticity: 18.5×10^6 psi

Modulus of rigidity: 7.3×10^6 psi

Thermal expansion: 9.3×10^{-6} in./in./°F (RT to 570°F)

Mechanical Properties	Room temperature	-100°F (-73°C)
0.75-in. bar, annealed		
UTS, ksi	69.9	74.9
YS, ksi	27.4	34.7
Elong, %	63	69
RA, %	80	79
Charpy U-notch, ft lb	102	98
0.75-in. bar, 1/2 H		
UTS, ksi	101.8	108.4
YS, ksi	96.7	100.1
Elong, %	19	23
RA, %	68	70
Charpy U-Notch, ft lb	37	40
.032-in. strip, 1/2 H		
FS - PB (10^8 cycles), ksi	34 (UTS 93 ksi)	
.078-in. sheet, 1/2 HT		
FS - PB (10^6 cycles), ksi	~60 (UTS 191 ksi) ~70	

Comments:

The workability of this alloy is considered good to excellent. As regards its joining characteristics, silver alloy brazing is rated good and soft soldering excellent; oxyacetylene is poor, but carbon arc and butt resistance welding are both excellent. Resistance to atmospheric corrosion is generally good, as it its resistance to weak acids and bases.

References: 2,8,22,24

70-30 Brass

Alternative Designation: CDA No. 260, Cartridge brass

Composition: 70 Cu, 30 Zn

Physical Constants:

Density: 0.308 $lb/in.^3$

Modulus of elasticity: 16×10^6 psi

Modulus of rigidity: 5.3×10^6 psi

Thermal expansion: 11.1×10^{-6} in./in./°F (RT to 570°F)

Mechanical Properties	Room temperature	-100°F (-73°C)
0.75-in. bar, annealed		
UTS, ksi	51	56
YS, (0.1%), ksi	28	27
Elong, %	50	60
RA, %	76	80
0.75-in. bar, 3/4 H		
UTS, ksi	95.2	100.8
YS, ksi	60.9	64.3
Elong, %	14	17
RA, %	58	62
CVN, ft lb	15	15
.032-in. sheet, annealed		
FS - PB (10^8 cycles), ksi	12.5(UTS 49.5 ksi)	
.040-in. sheet, CR and stress relieved		
FS - PB (10^6 cycles), ksi	33(UTS 95 ksi)50	

Comments:

The cold workability of the alloy is considered to be very good and the hot workability fair. As regards the joining characteristics, soft soldering and silver alloy brazing are rated excellent, and oxyacetylene and butt resistance welding good. Resistance to atmospheric corrosion generally good, but its resistance to weak acids and bases is only fair, and it is susceptible to stress corrosion cracking.

References: 2,8,22,23

Free-Cutting Brass

Alternative Designation: CDA No. 360

Composition: 61.5 Cu, 35.5 Zn, 3 Pb

Physical Constants:

Density: 0.307 lb/in.^3

Modulus of elasticity: 14×10^6 psi

Modulus of rigidity: 5.3×10^6 psi

Thermal expansion: 11.4×10^{-6} in./in./°F (RT to 570°F)

Mechanical Properties	Room temperature	-100°F (-73°C)
1-in. bar, annealed		
UTS, ksi	49	
YS*, ksi	18	
Elong, %	53	
RA, %	58	
1-in. bar, 1/2-hard		
UTS, ksi	58	
YT*, ksi	45	
Elong, %	25	
RA, %	50	
Charpy keyhole value:		
annealed, ft lb	14	16
cold-worked, ft lb	8.5	11
FS - RB, ksi	19 (UTS 60 ksi)	

*0.5% extension under load

Comments:

Free-cutting brass has the best machinability index of the copper alloys. Its cold workability is considered to be poor, and hot workability fair. As regards its joining characteristics, soft soldering is rated as excellent and silver alloy brazing good, but the weldability is fair to poor. Resistance to atmospheric corrosion (industrial), marine and naval) is good.

References: 3,4,22

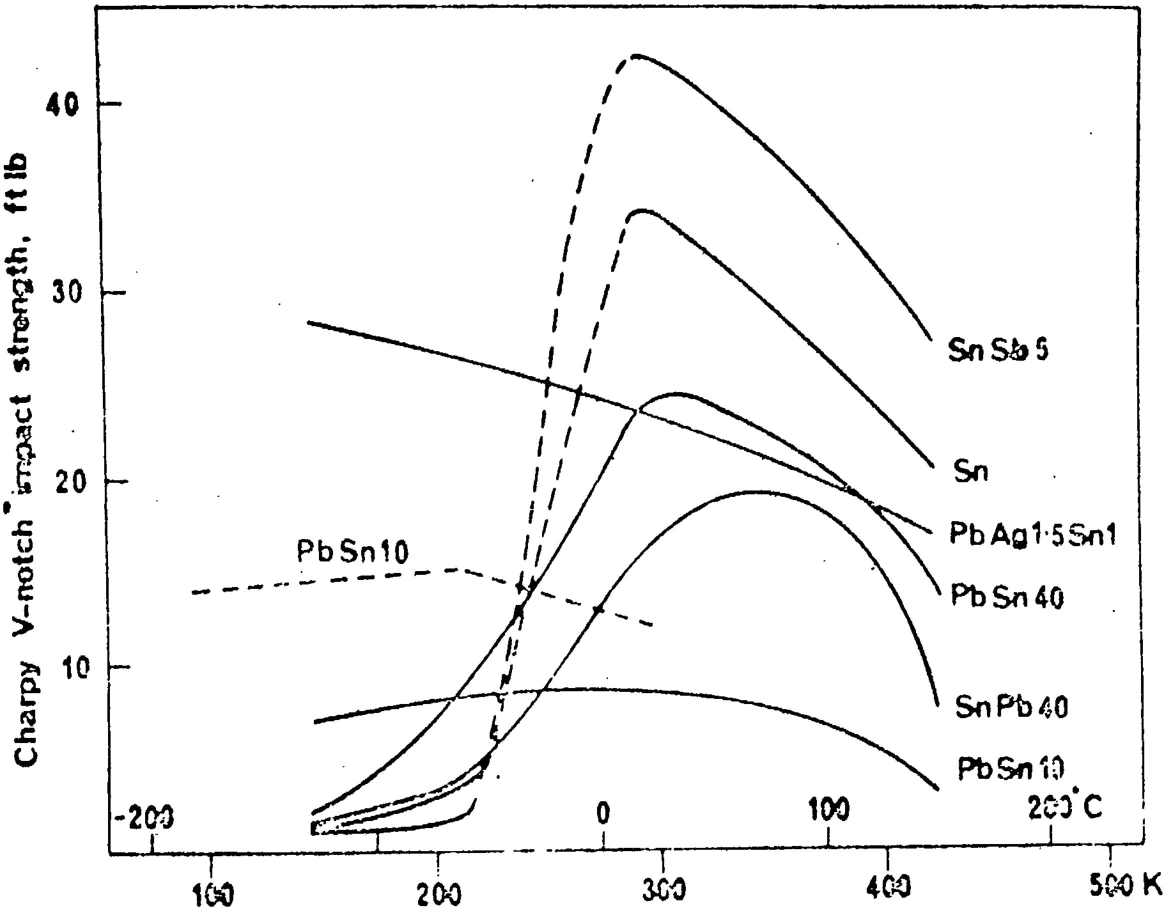

Fig. 3.6.a Influence of temperature on the impact strength of bulk solders (14).

3.7 NICKEL AND NICKEL ALLOYS

Introduction

N.S. Spence*

Although nickel is an important and essential alloying element in many ferrous and non-ferrous alloys, this section deals only with high-nickel content materials where nickel is the principal constituent.

In general, nickel and nickel-base alloys are noted for their high-temperature strength and resistance to oxidation as well as excellent performance and corrosion resistance at normal ambient temperatures. Nickel alloys have also found applications at cryogenic temperatures for equipment handling liquified gases, pressure vessels and in space vehicles. The strength, toughness, fabrication characteristics and freedom from ductile-brittle fracture transition of nickel alloys are all desirable properties of materials for extreme low-temperature use. Although Canadian Arctic conditions of temperature range are more severe than those in more temperate regions, the low end of the range -73°C (-100°F) is substantially above that associated with cryogenic conditions -240°C (-400°F), consequently nickel materials can be expected to perform equally satisfactorily in the Arctic. Whether it is necessary to use nickel and its alloys for any specific application will then depend on other considerations since there appears to be no unique feature of these materials which would make them singularly useful or attractive for Arctic use when compared to some other less expensive alloys. On the other hand, nickel and its alloys have found application in high performance, high reliability equipment such as aircraft, aero-engines, ordnance, electronics and instruments where any cost disadvantage is outweighed by considerations of dependability under severe operating conditions. Although the chief virtue of nickel-base alloys is resistance to degradation of properties by high temperatures and corrosion, this feature cannot be dismissed as of no relevance

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*Head, Nuclear and Powder Metallurgy Section to Arctic operations, where even simple equipment breakdown can be the ultimate disaster in the absence of repair facilities or spare parts.

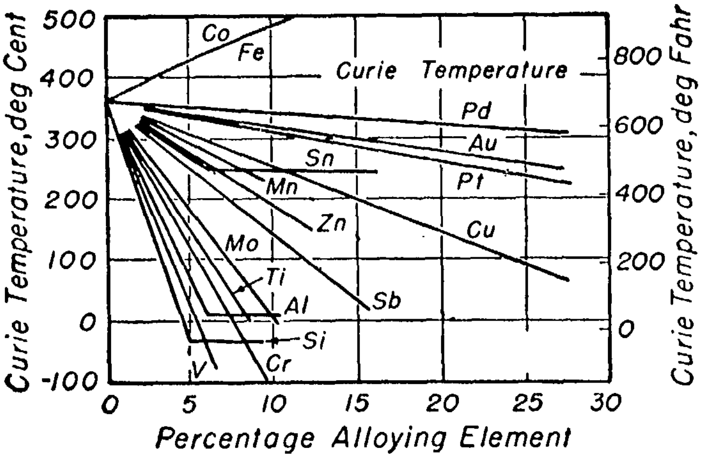
Although nickel finds its main application in the production of stainless steels, and as an important minor alloying element in many ferrous and non-ferrous alloys, high-nickel alloys and electroplating each account for about 15% of the annual consumption. The bulk of electroplated nickel is for decorative purposes, but this may be attributed to the better corrosion and wear resistance conferred on the base metal by the nickel deposit.

As mentioned above, high-nickel alloys are employed mainly for their excellent corrosion and heat resistance in marine (sea water) and hot gas environments (furnaces, reciprocating and jet engines, heat exchangers, etc.). Many nickel alloys can be cast, but in general the widest usage is in the form of wrought products such as plate, sheet, rod, tube and wire. Joining of nickel alloys is readily accomplished by soldering (soft and hard), brazing and most forms of welding including oxyacetylene, resistance and metal arc. Nickel is also available in the form of powder in several morphologies, for consolidation by pressing and sintering. Spherical powders of narrow size fraction range can be employed to produce controlled pore size sinterings for filter elements, electrode plates and the like where other properties of nickel are required.

It was suggested earlier that nickel and its alloys have no notably unique properties which have led to specific applications for use in Arctic service. Although this appears to be the case up to the present time, it may be interesting and perhaps useful to review some properties which are unique and which apparently have yet to be exploited.

Magnetic Characteristics

Nickel and many of its alloys are magnetic, but the effect of some alloying elements is to change the temperature of magnetic transformation, i.e., from being magnetic to being non-magnetic - the Curie point. The effect of alloying elements is shown in the chart below.



ASM Metals Handbook 1948 Ed. p1046.

Magnetostriction

Magnetostriction is a phenomenon displayed by nickel, manifest by a contraction in length of a specimen when subjected to a magnetic field; alternatively some iron-nickel alloys expand. Application of this behaviour would seem to be limited to electronics and electromechanics.

Thermal Conductivity

Thermal conductivity of nickel alloys ranges from low to very low, but that of pure nickel is substantially higher and is in the same range as some brasses, iron and aluminum alloys. Coupled with superior strength, high melting point, corrosion resistance and toughness, this moderately good thermal conductivity offers an opportunity for design advantage where heat transfer (input or output) is involved. Components in pure nickel suitably designed should run hotter or cooler as required compared with alloys of lower thermal conductivity.

The following Table lists the room temperature thermal conductivity of various nickel materials.

Alloy	Thermal Conductivity near room temperature cal/sq cm/cm/°C/sec
Nickel (99.95% Ni+Co) ...	0.22
"A" Nickel	0.145
"D" Nickel	0.115
Monel	0.062
"K" Monel	0.045
Inconel	0.036
Hastelloy B	0.027
Hastelloy C	0.03
Hastelloy D	0.05
Illium G	0.029
Illium R	0.031
60 Ni - 24 Fe - 16 Cr	0.032
35 Ni - 45 Fe - 20 Cr	0.031
Constantan	0.051

ASM Metals Handbook 8th Ed., Vol. 1 p55.

Coefficient of Expansion

A great many high-nickel alloys were developed to meet the need for engineering materials destined for severe service conditions. Additionally, there is a class of alloy which, although iron-based, owes its usefulness to a substantial nickel content, namely the Invar type which has very low or negligible coefficient of thermal expansion, coupled with moderately high strength and good toughness down to -253°C (-423°F). The 36% Ni Invar has good weldability and fabricating characteristics and has found application in cryogenics. The presence of a high proportion of nickel results in the alloy being austenitic in character which confers toughness and freedom from ductile-brittle fracture transition down to -240°C (-400°F). For applications where dimensional stability over wide temperature ranges is important, this type of iron-nickel alloy would offer attraction, particularly when alternative design compensation is difficult or impossible.

Property Data Sheets on Typical Nickel Alloys

The following sheets tabulate data for a cross-section of nickel-base materials and the interested reader is referred to the references cited for information on other compositions and conditions.

High-Purity Nickel

Alternative Designation   Nickel 200

Composition: Ni + Co = 99.0% min

Physical Constants:

Density: $0.321\ \text{lb/in.}^3$

Modulus of elasticity: 30×10^6 psi

Modulus of rigidity: 11×10^6 psi

Thermal expansion: $8.5 \times 10^{-6}/°F$ (77 to 212°F)

Mechanical Properties (hot rolled and annealed)	Room temperature	-100°F (-73°C)
UTS, ksi	67	72
YS, ksi	22	24
Elong, %	46	47
RA, %	64	66
CVN, ft lb	90	85
FS, ksi 0.021-in. sheet, annealed 10^6 cycles	50	60

Comments:

Corrosion - Good to high resistance in outdoor and marine atmospheres, natural and high-purity waters. Some attack in mine and sea waters. Good resistance in sulphur-free environments, hydrochlorine and phosphoric acids. Attacked by nitric and strong sulphurous acids.

Formability - Highly ductile, can be hot and cold worked.

Welding - Can be joined by the usual welding, brazing soldering processes common to industry.

Machining - Cutting speeds should be slightly slower and feeds lighter than for mild steel.

References: 1,2,3

Hastelloy B

Composition: Ni-26-30 Mo, 4-6 Fe, 2.5 Co, 1 C, 1 Si, 1 Mn

Physical Constants:

Density:	0.334 lb/in.^{3}
Modulus of elasticity:	31.1 x 10^6 psi
Thermal expansion:	5.6 x 10^6/°F (32 to 212°F)

Mechanical Properties (0.080-in. sheet, 20% cold reduced)	Room temperature	-100°F (-73°C)
UTS, ksi	143	159
YS, ksi	122	134
Elong, %	33	37
NTS, ksi (K_t = 3.5)	158	177
NTS/UTS	1.1	1.1

Comments:

Corrosion -	High resistance to hydrochloric acid, good resistance to sulphuric, acetic and phosphoric acids. Not recommended for strongly oxidizing acids or salts.
Formability -	Hot-working temperature range 980-1190°C (1800-2175°F). Good temperature control is important.
Welding -	All types of resistance welding are satisfactory.

References: 1,3,12

Monel 400

Composition: Ni-32 Cu, 1.25 Fe, 1 Mn

Physical Constants:

Density: 0.319 lb/in.^{3}

Modulus of elasticity: 26×10^6 psi

Modulus of rigidity: 10×10^6 psi

Thermal expansion: 7.7×10^{-6}/°F (77 to 200°F)

Mechanical Properties (cold drawn, annealed)	Room temperature	-112°F (-80°C)
UTS, ksi	82.7	95.3
YS, ksi	29.9	36.8
Elong, %	46.2	49.5
RA, %	74.0	72.2
CVN, ft lb	216	219
FS, ksi	-	-

Comments:

Corrosion - High resistance to atmospheric corrosion, fresh water and high-velocity sea water.

Formability - Can be fabricated by either hot or cold processes.

Welding - Joined by the usual welding, brazing and soldering processes common to industry.

Machining - Standard procedures.

References: 3,5,6

Inconel 625

Composition: Ni-22 Cr, 9 Mo, 4 Nb, 3 Fe

Physical Constants:

Density:	0.305 lb/in.^{3}	
Modulus of elasticity:	29.8×10^6 psi	
Modulus of rigidity:	11.4×10^6 psi	
Thermal expansion:	7.1×10^{-6}/°F	(70 to 200°F)

Mechanical Properties (cold-rolled sheet)	Room temperature	-110°F (-79°C)
UTS, ksi	155	167
YS, ksi	111	117
Elong, %	33	39
NTS, ksi ($K_t = 6.3$)	137	153
NTS/UTS	0.89	0.92
Charpy (keyhole), ft lb*	45-52	40-50
FS - RB, ksi†	93	-

* 0.5-in. hot-rolled plate

† hot-rolled and annealed bar

Comments:

Corrosion	-	High resistance to atmospheric corrosion, fresh water and high-velocity sea water. Resistant to many acids, dry gases and most alkalies.
Formability	-	Can be fabricated by either hot or cold processes.
Welding	-	Joined by the usual welding, brazing and soldering processes common to industry.
Machining	-	Standard procedures.

References: 3,5,6

Inconel X750

Alternative Designation: Inconel X

Composition: Ni-15 Co, 7 Fe, 2.5 Ti

Physical Constants:

Density:	0.298 lb/in.^{3}
Modulus of elasticity:	31 x 10^6 psi
Modulus of rigidity:	11 x 10^6 psi
Thermal expansion:	6.96 x 10^{-6}/°F (70 to 200°F)

Mechanical Properties (soln treated and aged bar)	Room temperature	-100°F (-73°C)
UTS, ksi	172	187
YS, ksi	101	115
Elong, %	26	23
RA, %	28	24.5
NTS, ksi*	197	200
NTS/UTS	1.1	1.1
CVN, ft lb	32	36
FS - RB, ksi	72	-
FS - PB, plain, ksi	~78 (10^6 cycles)	~90 (10^6 cycles)
soln treated + aged sheet, UTS, 177 ksi		
notched (K_t = 6.4)	~53 " "	~55 " "

* 60° V notch, 0.037-in. deep, 0.005-in. root radius

Comments:

Corrosion	-	High resistance to oxide and chloride-ion-induced stress corrosion.
Formability	-	Hot forging temperature 1800-2200°F.
Welding	-	Weldable. Riveting is also a suitable method of joining.
Machining	-	Has greatest machinability in the "as-equalized" condition.

References: 3,9,10,13,14

Incaloy 800

Composition: 30-35 Ni, 19-23 Cr, 1.5 Mn, 1 Si, balance Fe

Physical Constants:

Density:	0.287 lb/in.^{3}
Modulus of elasticity:	28.5 x 10^6 psi
Modulus of rigidity:	10.6 x 10^6 psi
Thermal expansion:	8.0 x 10^{-6}/°F (RT to 200°F)

Mechanical Properties (hot rolled and annealed)	Room temperature	-110°F (-79°C)
UTS, ksi	93.8	106.4
YS, ksi	37	42
Elong, %	37	39
RA, %	63.5	64
CVN, ft lb	130	136
FS - RB (UTS, 82 ksi) ksi	35	-

Comments:

Corrosion - Excellent resistance to oxidation and scaling at high temperatures.

Formability - Readily fabricated by both hot and cold working.

Welding - In the wrought or extruded condition, can be welded to itself or other wrought alloys.

Machining - Readily machined by standard procedures.

References: 1,6,14

Invar

Composition: 36 Ni, balance Fe

Physical Constants:

Density: 0.291 lb/in.^{3}

Modulus of elasticity: 20.5×10^6 psi

Modulus of rigidity: 8.1×10^6 psi

Thermal expansion: 1.1×10^{-6}/°F (-200° to 0°F)

Mechanical Properties (5/8-in. Sq. forged bar, annealed)	Room temperature	-100°F (-73°C)
UTS, ksi	65	85
YS, ksi	40	60
Elong, %	42	42
RA, %	79	70
NTS, ksi	88	120
NTS/UTS	1.4	1.4
CVN, ft lb (1/2-in. plate, annealed)	95	74
FS - DS, ksi (sheet, 5% CW)	21	30

Comments:

Corrosion - Resistant to atmospheric corrosion and to fresh and salt waters.

Formability - Cold rolling and drawing properties similar to those of nickel.

Welding - Can be welded by all conventional welding processes.

Machining - Machines best at a hardness of about Rc 20.

References: 1,3,4

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3.8 ZINC ALLOYS AND GALVANIZED COATINGS

Introduction

W.A. Pollard*

This Section deals with the factors relating to the use of cast and wrought zinc structural shapes in Canada's North, and to the behaviour of galvanized coatings. Most structural zinc is used in the form of die castings and, for these, only two alloys are in common use. Recently, some new wrought zinc alloys have been introduced and developments in this field will be described.

Zinc is unusual among non-ferrous metals in having a ductile-to-brittle transition. Some results for Charpy V-notch bars in unalloyed zinc are shown in Fig. 1 (1). The mechanical properties of zinc-based alloys appear to be mainly determined by the behaviour of the zinc-rich phase so that, although alloying (e.g., with aluminum) gives some improvement as detailed below, in any application of zinc alloys at low ambient temperatures this transition must be kept in mind.

Cast Alloys

Die Castings

Some of the low-temperature properties of the two standard die casting alloys (based on Zn-4% Al) are shown on pages 230 and 231. These values were determined on die cast specimens made under optimum conditions. Normally, mechanical properties are not included in die casting specifications because these castings are used for decorative or functional parts where strength is not a major consideration. Thus, in ASTM B86-71 "Zinc Alloy Die Castings" the tensile property values are given (for information only) and do not form part of the specification.

Zinc die castings could not, therefore, be considered for use in the North where impact strength is important but as the transition occurs between -18 and 0°C (0 and 32°F) this limitation would apply equally in most other parts of Canada.

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*Research Scientist, Non-Ferrous Metals Section

Other Castings

Recently, a Zn-12% Al alloy has been introduced for general gravity casting applications. It was developed under the sponsorship of the International Lead-Zinc Research Organization and is known as ILZRO 12 (a similar alloy is marketed as Korloy 2570). Typical properties for this alloy are given on p232. It will be seen that impact properties at room temperature are lower than those of the die casting alloys. There is a sharp transition to very low values at about 10°C (50°F).

Wrought Alloys

Wrought zinc alloys have had only limited application, although they were used extensively in Germany in World War II as substitutes for copper and aluminum alloys. Recently, several new wrought zinc alloys have been introduced in Canada as extrusions and forgings. These are based on two systems: the Zn-Al (14% Al), characterized by fairly high tensile strength but low creep strength, and the Zn-Ti alloys designed for higher creep strength.

The variation of tensile properties with temperature of an extruded Zn-Al alloy (Cominco Korloy 2573 (3)), is shown in Fig. 2, and it will be seen that there is no sudden decrease in elongation at low temperatures. However, the impact properties, though better than those of the cast alloys, show a ductile/brittle transition as illustrated in Figs. 3 and 4, and in this sensitivity to strain rate these wrought zinc alloys closely resemble mild steel. Earlier German work (4) showed similar curves for other wrought Zn-Al alloys so that it is considered that the curves shown in Figs. 3 and 4 may be taken as typical for this class of material.

The wrought Zn-Ti-based alloys have low impact properties at low temperatures, generally similar to those of the die casting alloys.

Applications

In addition to the numerous decorative and non-stressed applications of die cast zinc alloys such as automotive trim, ash trays, etc., more structural uses include housings of all kinds (e.g., automotive carburettors) levers, handles, parts of small mechanisms, locks, etc.

The wrought alloys show promise as replacements for brass in some applications, although little progress has so far been made in this direction.

Galvanized Coatings

Hot-dip galvanizing has long been recognized as the best method of protecting steel against corrosion attack. The advantages of low cost and long service combined with other useful properties not inherent in most coating systems has led to use of galvanized coatings in a myriad of applications under a wide variety of service conditions. Published information on low-temperature applications is, for all practical purposes non-existent, but galvanized coatings are used in Arctic service and performance experience has shown that the brittle fracture characteristics of the substrate material (steel), and not the galvanized coating, present the principal problem.

Particular service data are not available, but some typical applications serve to indicate that there are no known limitations on galvanized coatings usage under Arctic or equivalent low-temperature conditions. In Northern Sweden for example, thousands of galvanized pylons for electrical lines and radio towers exposed at -40 to -50°C (-40 to -58°F) have given long service without trouble. Galvanized transmission tower and sub-station structures have also been extensively used in electrical installations in Northern Ontario. The structural steel items are usually of ASTM A36, CSA G40.12, or even the old G40.4 catogory, together with some newer proprietary high-strength grades of 50,000 and 60,000 yield strength. In the case of the 550-mile Nelson River Transmission Project, the Northern Manitoba, ASTM A572, Grade 50 steel was specified and, again, with no particular limitations or reservations in so far as the galvanized coating applied was concerned.

Other less spectacular applications worthy of mention include the extensive use of continuous strip galvanized coatings in portable industrial, commercial and domestic housing. Galvanized sectional steel light standards, and spiral-welded pipe jackets for steam and other service lines, are additional examples.

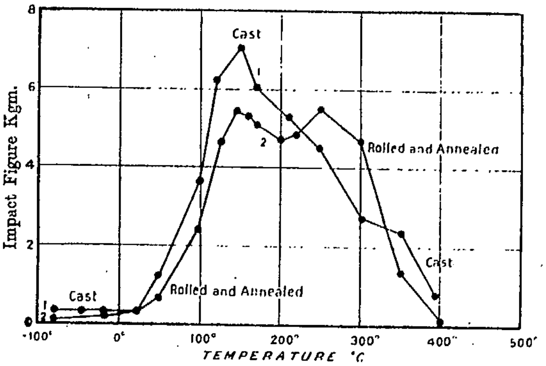

Fig. 1. Charpy V-notch impact transmission curves for cast and rolled zinc. (From Greaves and Jones (1)).

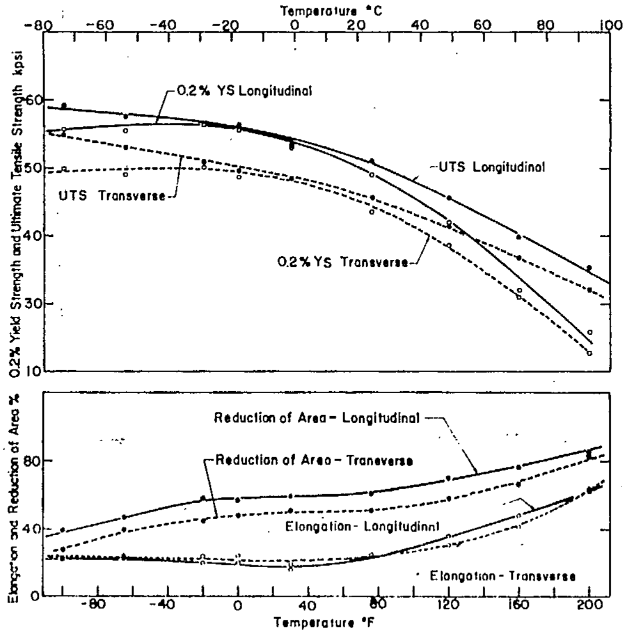

Fig. 2. Variation of tensile properties with temperature of an extruded zinc-14% Al alloy (3).

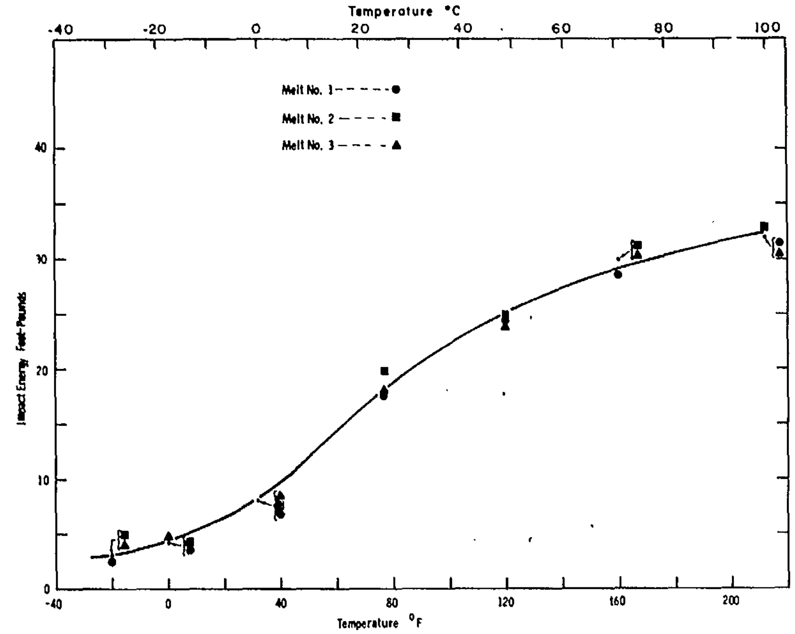

Fig. 3. Charpy V-notch transition curve for an extruded zinc-14% Al alloy (3).

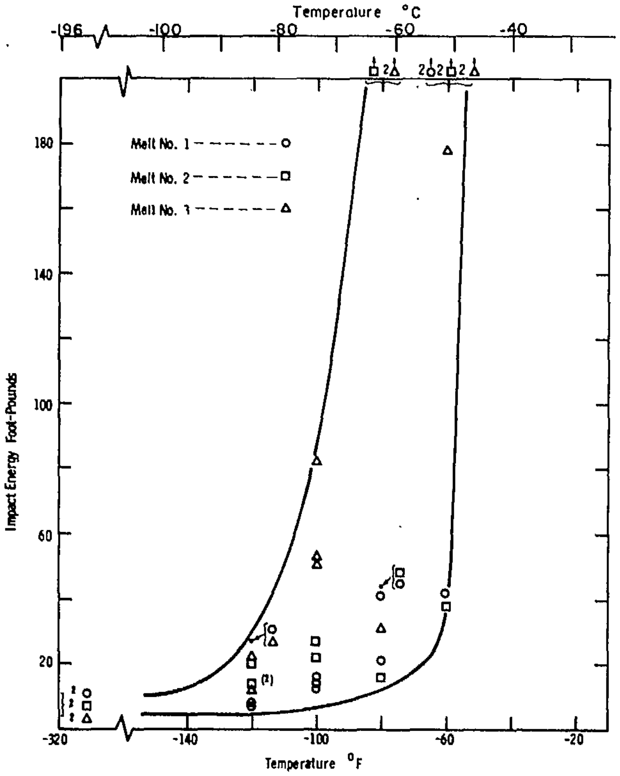

Fig. 4. Unnotched Charpy impact transition scatter band for an extruded zinc-14% Al alloy (3).

Alloy AG40A

Alternative Designation: Zamak-3

Composition: Zn-4 Al, 0.05 Mg

Condition: Die casting

Physical Constants:

Density: 0.24 lb/in.^{3}

Modulus of elasticity: *

Modulus of rigidity: *

Thermal expansion: 15.2×10^{-6}/°F (RT to 212°F)

Mechanical Properties	Room temperature	-40°F (-40°C)
1/4-in. diam bar		
UTS, ksi	41.0	44.8
Elong, %	10	3
Charpy impact value † ft lb	43	2
FS (10^8 cycles), ksi	6.9	

*Zinc alloys in general deform plastically under extremely low loads and exhibit no true elastic deformation.

†From unnotched 1/4-in. square bars.

Comments:

When zinc alloys are machined, they tend to form long chips so that sharp cutting tools and, in some cases, cutting fluids must be used to attain high speeds and good finishes. Resistance to atmospheric corrosion, metropolitan and rural, and to a variety of liquid media (see ref (6)) is very good. Die castings can be formed moderately, especially if warmed to about 100°C (212°F). They are amenable to soldering and welding, but for limitations see ref (6).

References; 5,6,7

Alloy AC41A

Alternative Designation: Zamak-5

Composition: Zn-4 Al, 1 Cu, 0.05 Mg

Condition: Die casting

Physical Constants:

Density: 0.24 lb/in.^{3}

Modulus of elasticity: } see Alloy AG40A

Modulus of rigidity: } see Alloy AG40A

Thermal expansion: 15.2 x 10^{-6}/°F (RT to 212°F)

Mechanical Properties	Room temperature	-40°F (-40°C)
1/4-in. diam bar		
UTS, ksi	47.6	48.9
Elong, %	7	2
Charpy impact value † ft lb	48	2
FS (10^8 cycles), ksi	8.2	

† From unnotched 1/4-in. square bars

Comments: As for Alloy AG40A

References: 5,6,7

ILZRO 12

Alternative Designation: Korloy 2570 (similar)

Composition: Zn-12 Al, 1 Cu, 0.03 Mg

Condition: Sand casting

Physical Constants:

Density:	0.22 lb/in.^{3}
Modulus of elasticity:	see Alloy AG40A
Modulus of rigidity:	
Thermal expansion:	6-13 x 10^{-6}/°F

Mechanical Properties	Room temperature	32°F (0°C)
UTS, ksi	42	44
Elong, %	3	2 1/2
Charpy impact value † ft lb	7	1 1/2

† From unnotched 1/4-in. square bars

References: 8

Zn-Al-Cu Alloy

Alternative Designation: Korloy 2573

Composition: Zn-14.5 Al, 0.7 Cu, 0.02 Mg

Condition: Extruded and stabilized at 480°F

Physical Constants:

Density: 0.21 lb/in.^{3}

Modulus of elasticity: } (see Alloy AG40A

Modulus of rigidity: }

Thermal expansion: $6\text{-}13 \times 10^{-6}$/°F

Mechanical Properties	Room temperature	-100°F (-73°C)
UTS, ksi	52	59
YS, ksi	51	56
Elong, %	24	22
RA, %	54	39
CVN, ft lb	19	3 (at -20°F)

Comments: As for Alloy AG40A

References: 3,7

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