STRUCTURAL MATERIALS TO 1800°F (STEEL AND TITANIUM)

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In choosing materials for applications in present and future weapon systems, design requirements are of prime importance. Without attempting to assess the relative importance of each, they are listed as follows: high strength-weight ratio, ductility and fracture toughness, stability, fabricability, and corrosion resistance. There are certainly many other factors of importance; however, many of these will be determined by the intended application and the type of environment envisaged. Since it is impractical to attempt to cover the entire spectrum of available materials, this discussion will be limited to steel and titanium alloys for applications at temperatures up to 1200°F.

Three broad categories of steel will be discussed: low alloy martensitic steels, hot work die steels (primarily H-11 types), and the stainless steels. One other class of materials to be considered are the iron base alloys containing 20 to 25 percent nickel. These alloys may or may not be classified as steels, depending almost entirely upon a matter of definition. Typical strengths currently available in steels from room temperature up to approximately 1200°F are shown in figure 1.

We turn our attention first to a discussion of steel and consider the low alloy martensitic steels, typified by such compositions as 4340, AMS 6434, and D6A. These steels exhibit tensile strengths in the 300,000 psi range with good ductility as measured in the uniaxial tensile test. These materials depend to a great extent for their strength upon the amount of carbon present. A wide variety of properties may be obtained, depending upon a judicious selection of heat treatment. Since materials with high strength-to-weight ratios are of considerable interest, it should be observed that most of these materials are tempered in the lower range (400-600°F) in order to achieve high strengths. It is therefore apparent that the application of these materials must be limited primarily to room temperature applications or very moderate elevated temperatures. It should also be observed that the carbon content in these steels, as well as others, plays a dual role: (1) contributing to high strengths; and (2) contributing to a decrease in ductility and toughness. The role of carbon is mentioned because of its significance and will be further related to material properties in the discussion. In summarizing, the low alloy martensitic steels provide very high strengths and are useful for room temperature and very moderate elevated temperature applications.

The H-11 steels form part of a class known as the hot work die steels. While there are several classes of hot work die steels, only the H-11 types will be discussed. The chemical composition range of this group of steels is C - .30-.40, Mn - .20-.40, Si - .80-1.20, Cr - 4.75-5.50, Mo - 1.25-1.75, and V - .30-.50. These steels are characterized by: (1) high strength to density ratios in the 1000°F range; (2) sufficient hardenability to permit air quenching; and (3) tempering temperatures in the 1000 to 1100°F range. These characteristics, and others, make them usable for many applications in aircraft and missiles. Some limitations of these steels are: (1) possible low transverse ductility; (2) sensitivity of mechanical properties to carburization or decarburization. The H-11 steels can be heat treated to strengths from 280,000 to 300,000 psi tensile, with reasonable ductility as measured in the uniaxial tensile test. Much attention is being given to this class of material as a candidate for many current and future weapon systems.

40

The stainless steels comprise a large group of materials from which a variety of properties may be obtained. Since some classes are of more interest than others in present applications, only a few will be mentioned here very briefly. The semi-austenitic precipitation-hardenable stainless steels offer yield strengths in the neighborhood of 200,000 psi and retain a usable proportion of their room temperature strength up to about 900°F. The limiting temperature depends upon the alloy, the application, and duration of exposure at elevated temperature. The austenitic precipitation-hardenable stainless steels have been used mainly in applications requiring exposure to temperatures of 900 to 1200°F. These materials retain a large proportion of their room temperature strength at temperatures in this range. Other types of stainless steels are the martensitic and austenitic types. The austenitic types are further subdivided into austenitic precipitation-hardenable steels and austenitic stainless steels deriving their strength through cold working of the alloy. The stainless steels as a group are a very important part of the materials spectrum and offer properties for applications from sub-zero temperatures up to temperatures slightly in excess of 1200°F.

In the discussion of steels to this point, it is fairly evident that a large number of compositions is available offering a range of properties over temperatures from cryogenic conditions to slightly above 1200°F. While emphasis previously was placed on strength and ductility, other properties such as creep-rupture, stability, fatigue, and corrosion resistance should be adequately provided for by making a judicious choice of materials for a particular application.

Since considerable emphasis has been placed on strength-weight ratios, what are the requirements in this area? The designers are presently asking for materials with yield strength to density ratios of 1,000,000 or higher. Yield strength to density ratios of some currently available steel and titanium alloys are shown in figure 2.

In checking the available conventional steels, it is apparent when considering usable properties, there are no steels presently that meet these requirements. What then are the possibilities of meeting these requirements?

With our present knowledge, materials with yield strengths to meet these requirements may be possible if we make use of exotic fabrication practices such as "ausworking", about which we have a limited knowledge. "Ausworking" is a process of deforming a steel within the lower austenitic bay of the TTT diagram followed by quenching and tempering. This process is applicable to certain low alloy martensitic steels and currently has accounted for tensile strengths in excess of 400,000 psi with yield strengths of at least 350,000 psi. There are certain other questions related to the properties of such materials, but these are also related to conventionally treated compositions and will be discussed more fully later in this discussion.

An ausworked steel such as H-11 with a yield strength of 360,000 psi would provide a yield strength/density ratio of approximately 1,300,000. This is approaching the properties for resin bonded glass fibers, used for pressure vessels, but it is postulating a nonexistent production technique. There appear to be other approaches that may produce similar results, one of which is the interaction of a shock wave with a metal. One case reported using the technique where tensile strengths of 600,000 psi in steel has been reported. No information relative to other properties was reported.

Another process known as "mar-straining" is being investigated, which should also produce increases in strength. This process consists of straining of tempered martensite followed by another temper. These illustrations are used to indicate that for yield

41

strength/density ratio, there are several current thermal-mechanical processes available whose further development may form the basis for obtaining yield strength to density ratios well over 1,000,000 in various steel compositions. Figure 3 shows projected yield strength to density ratios that may be possible in the very near future with the accomplishment of additional research.

Earlier in the discussion, the dual role of carbon content as related to mechanical properties of high strength steel was mentioned. In many of the current steels of interest, a major portion of the strength is derived from the carbon content. Since carbon has a deleterious effect upon ductility, the production of higher strengths by increasing the carbon content would not be the best approach since very low ductility accompanies any major increases in strength. Figure 4 shows the general effect of increasing carbon content on strength and ductility. With this information in mind, a new approach should be made to the development of steels which obtain strengthening by mechanisms, other than those based upon the presence of carbon in moderate amounts. Compositions presently under development indicate this achievement is not entirely futile.

The series of alloys under development are iron base alloys with low carbon and nickel content ranging from about 18 to 27 percent. Response to precipitation hardening is obtained from controlled additions of titanium and aluminum. These materials are hardened by solution treating at about 1500°F and aging at 800-950°F. A refrigeration treatment prior to the aging may be necessary to insure complete transformation. Yield strengths of over 260,000 psi with 6 percent minimum elongation are obtainable with present compositions. In addition, they give promise of excellent toughness with a notch strength ratio in excess of 1:1 even at yield strengths approaching 300,000 psi. Perhaps the good toughness characteristics can be associated with the low carbon martensite formed. The principle of low carbon martensites with additional strengthening by some other mechanism could be logically extended to the development of additional high strength steel compositions.

In the discussion of high strength steels, it was mentioned that certain other material properties would be discussed. Since these properties are also related to titanium alloys, it is proposed that they be further deferred until after a brief look at titanium alloys for application in present and future weapon systems.

Titanium is a light weight, corrosion-resistant, structural material which can be strengthened through alloying. Titanium alloys fall into three categories: (1) alpha; (2) alpha-beta; and (3) beta. Figure 5 shows typical strengths of these classes of alloys. Alpha alloys, such as Ti-5A1-2.5Sn, have medium strength at room temperature and maintain high strengths at temperatures from 800 to 1000°F. They are readily welded and are not heat treatable but maintain toughness to cryogenic temperatures. A wide range of properties is available in the alpha-beta alloys. Alpha-beta alloys can be heat treated to high strength levels; however, welding is considered a problem except in alloys containing small amounts of beta stabilizers, such as Ti-6A1-4V. The heat treatable beta titanium alloy Ti-13V-11Cr-3A1 is very ductile and formable and is capable of being heat treated to high strength levels. It becomes brittle at cryogenic temperatures but can be used for short time applications at temperatures up to 1000°F. For longer time elevated temperature applications, the temperature should not exceed 600°F. There are a number of titanium alloy compositions available; however, it is necessary for purposes of this discussion to limit the number under consideration.

By reason of extensive experience with 6A1-4V in aircraft and aircraft engines, one could call it the 4340 of titanium alloys available today. It can be readily forged, and in

42

the solution treated, quenched and aged condition, the alloy develops tensile minima of 155,000 psi yield strength, 170,000 psi tensile strength, and 5 percent elongation. There are certain indications that Ti-6A1-4V can be processed by cold rolling and aging to a yield strength of 160,000 psi. At a density of 0.161 lb per cu in., this gives a yield strength to density ratio of 1,000,000. In some forming methods, such as flow turning, considerable difficulty is anticipated with the Ti-6A1-4V and alpha-beta alloys in general due to their greater resistance to deformation as compared to the all beta alloys.

The beta titanium alloy B120VCA (Ti-13V-11Cr-3A1), is an extremely attractive material based on present property data. In the annealed condition, it is a medium strength (120,000 psi yield strength) very formable alloy. It can be hardened by an aging treatment to have yield strengths in excess of 180,000 psi. With a density of 0.174 lb/cu in., the alloy exhibits a yield strength to density ratio in excess of 1,000,000 psi/cu in. This is the only material discussed so far that in its present state of development has reached the magic number of 1,000,000. There is also reason to believe that the beta titanium alloy is capable of significantly higher yield strengths than the present 180,000 psi level. The achievement of this strength level would provide yield strength to density ratios somewhat in excess of 1,000,000. The beta alloy is one of the more promising titanium alloys; however, present experience indicates the need for much additional information about the alloy in order to utilize it.

Another titanium alloy worthy of mention is Ti-22.5Cb-12.5A1-5Hf, which is still in the experimental stage. The importance of this alloy does not stem from high yield strength to density ratios or application in the temperature ranges under discussion in this paper, but in the fact that the alloy shows the potential of greatly increasing the temperature range over that normally thought to be useful. Recent work with this alloy has indicated that it may have applications at temperatures up to 1800°F. This is really sensational for a titanium alloy, since they were believed to have reached their limit at considerably lower temperatures. The short time properties of this alloy at 1800°F are: 59,300 psi tensile strength, 49,000 psi yield strength, and 35 percent elongation. Figure 6 compares this alloy on a strength to density basis with other elevated temperature alloys. It should be emphasized that this alloy is still very much in the experimental stage and no predictions as to future use can be made. It is merely mentioned as a matter of interest.

Now that a cursory look has been taken at available steel and titanium alloys, consider briefly another characteristic of these high strength materials imposing a serious limitation, relative to their successful application in present and future weapon systems. This is the problem of fracture toughness, which has been referred to earlier in the discussion. It has been shown that insofar as strength, ductility, strength/weight ratio, etc. are concerned, there are many attractive alloy systems. When attempts are made to utilize these alloys in ranges approaching their maximum yield strengths, they fail to meet requirements primarily because of inadequate toughness. This failing is common to steel and titanium alloys alike and is of particular importance when applied to the production of thin walled pressure vessels. Fracture toughness is essentially concerned with the tolerance of materials to sharp flaws or cracks. Materials with inadequate toughness fail in many instances at stress levels far below the design strength in a brittle manner (100% cleavage failure). A realization of the importance of this parameter has led to considerable study in an attempt to understand better the phenomenon and find means of overcoming or alleviating its drastic effects. In order to speak briefly about the fracture toughness problem and methods of obtaining quantitative data, it is necessary to oversimplify the subject greatly.

In getting an index of the toughness of a material, values known as G_c and K_c are used where:

$$K_c^2 = EG_c = \pi\sigma^2 a \qquad\qquad G_c = \frac{\sigma^2 W}{E}\ Tan\left(\frac{\pi a}{W}\right)$$

For a more precise determination of G_c, the plastic zone correction should be used, giving rise to:

$$G_c = \frac{\sigma^2 W}{E}\ Tan\frac{\pi a}{W} + \frac{EG_c}{2W\sigma_y^2}$$

$a = \frac{1}{2}$ crack length

W = width of the specimen

σ = greatest principle stress

E = Young's modulus

K = stress intensity factor at point of instability

G_c = critical driving force per unit area fractured at the point of instability

Minimum G_c or K_c values, thought to be necessary for satisfactory performance in a pressure vessel were agreed upon after much experimental work. Work accomplished by various research groups indicate when K_c values of at least 150,000 psi/inch and yield strengths up to 220,000 psi are used to fabricate pressure vessels, satisfactory performance can be expected (G_c 750 in. lbs/in²). These figures are not absolute but tend to reflect to a degree the thinking of others who have accomplished work in this area.

In looking over the available high strength alloys (steel and titanium), it appears that G_c values show a decrease as the strength of the material increases. This represents quite a problem since to obtain yield strength/density ratios in excess of 1,000,000, it is necessary to utilize these materials at very high percentages of their yield strength. Figure 7 shows G_c values and yield strengths of a current material.

The role of carbon in high strength steels has already been mentioned. In an attempt to relate the carbon content of steels to fracture toughness, it is significant that high carbon contents have a detrimental effect on the fracture toughness. The advantages of low carbon martensites with some other type of strengthening mechanism are again apparent.

The difficulties related to fracture toughness and high strength metallic materials are of prime importance and the problem is receiving considerable attention. The Metals and Ceramics Laboratory is currently sponsoring work to make a detailed study of the initiation and propagation of cracks in high strength steels and titanium alloys. This program is being approached from a metallurgical viewpoint rather than that of pure fracture mechanics. Considerable emphasis is being placed upon fundamental studies of microstructure as related to crack initiation and propagation.

It should be noted that in addition to improving the fracture toughness of high strength materials, it is also necessary to improve fabrication and inspection techniques. Failures encountered in pressure vessels have originated at some flaw which is usually the result

of fabrication processes. Methods of detecting these flaws and means of reducing them to a minimum in both size and quantity is mandatory.

Assuming that it is possible to produce high strength steels and titanium alloys with adequate strength/density ratios and fracture toughness, there are other areas that will require more work.

High strength space age materials are difficult to fabricate. This is especially true of high strength steels. Cutting any steel at Rockwell C-50 or higher is difficult even for external surfaces and is even more difficult for internal boring, tapping, and end milling. Although there is little likelihood that machining in the heat treated condition can be eliminated, designers should consider the advantages of machining closer to the finish size while the material is still in the annealed condition. While conventional machining methods will not be abandoned completely, it is necessary to implement existing techniques with new approaches. Some of these may include sub-zero machining, flooding the part with CO_2 mist, grinding, chemical milling, spark arc processes, and electrolytic machining. The high strength metals present a challenge in the machining and fabrication area; however, it appears that they are not insurmountable and will be solved through perseverance and ingenuity.

With the use of high strength metals at high percentages of their yield strength, joining is a problem that must be faced. Certainly, in some materials conventional welding appears to be impossible since a loss of strength is imminent when the material is heated to the welding temperature. In some instances, it may be possible to alleviate the joining problem through careful design of the components. New brazing alloys and techniques may be useful in many applications. New unique approaches to joining, such as ultrasonics and explosive welding, may find certain applications. Certainly, more basic information relative to the welding process from the metallurgical viewpoint, such as directional solidification effects, effects of contaminants, gas metal reactions, and other factors, would provide long range benefits in the utilization of high strength steel and titanium alloys. There still remains the requirement for the optimization of welding parameters in particular cases where the process is applicable.

These constitute only a few of the areas where additional information concerning the properties and behavior of high strength steel and titanium is required for application in future weapon systems. Additional information is necessary in other areas such as the mechanical properties and behavior for long time applications up to perhaps 30,000 hours, stress corrosion characteristics of many of the steel and titanium alloys, the effects of surface conditions and coatings, to name just a few. All of these factors will certainly play important roles if the potential of high strength steel and titanium alloys is to be realized. The broad categories requiring additional research and information are listed in figure 8.

Great strides have been made in the production of high strength metals for applications up to 1200°F; however, an understanding of the various other factors necessary in their application has not kept pace. The importance of these factors is now realized and work is being done in these vital areas. A start in this direction has been made and future developments in these and related areas should contribute to a brighter outlook for the production and application of high strength steel and titanium alloys in future weapon systems.

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TENSILE STRENGTH vs. TEMPERATURE OF CURRENT STEELS

Strength Range Of Current Steels (Minimum Values)

Austenitic PH Steels

Ultimate Tensile Strength 1000 PSI

Temperature °F

Figure 1.

47
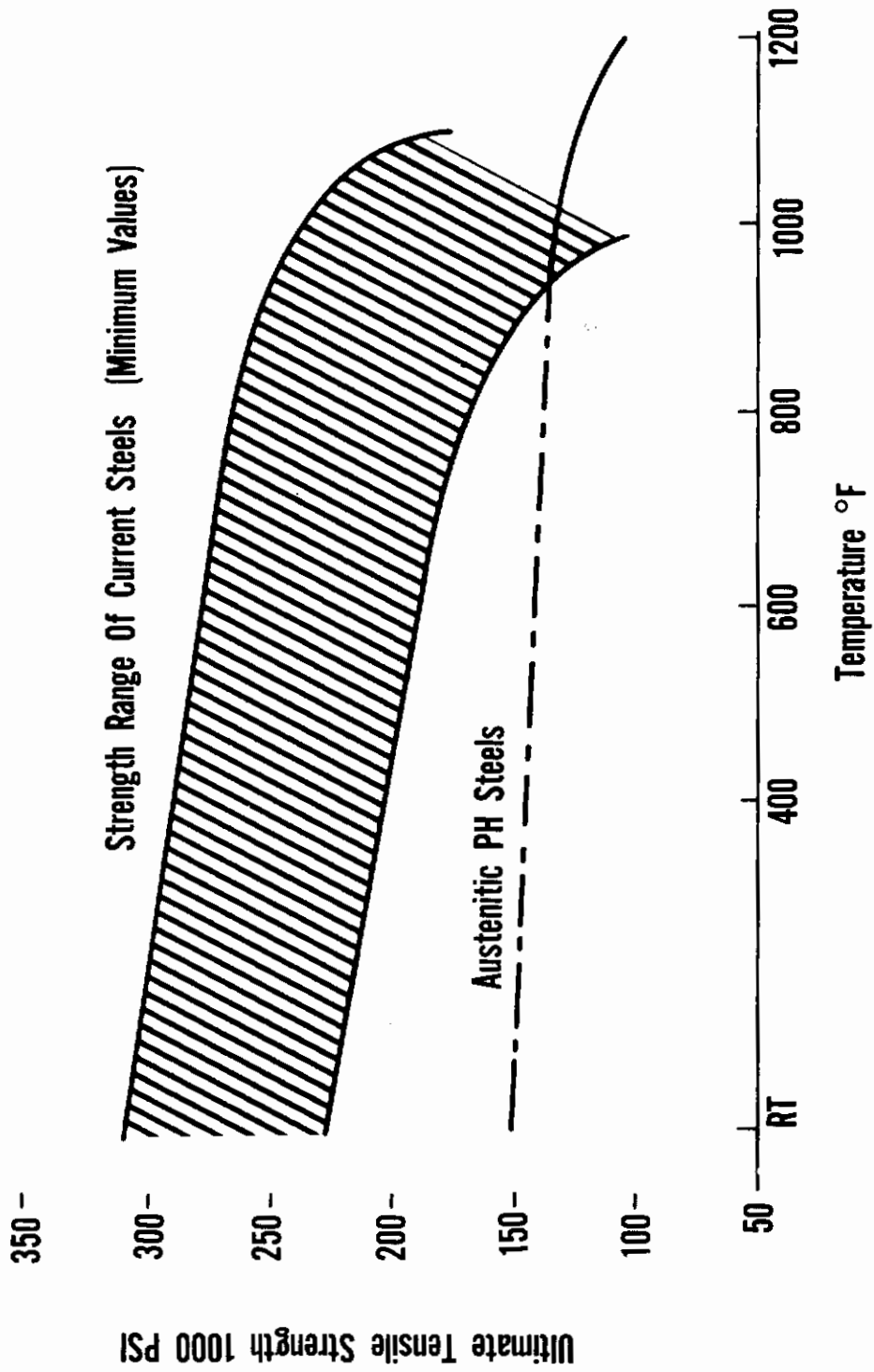
STRENGTH-WEIGHT COMPARISON OF CURRENTLY
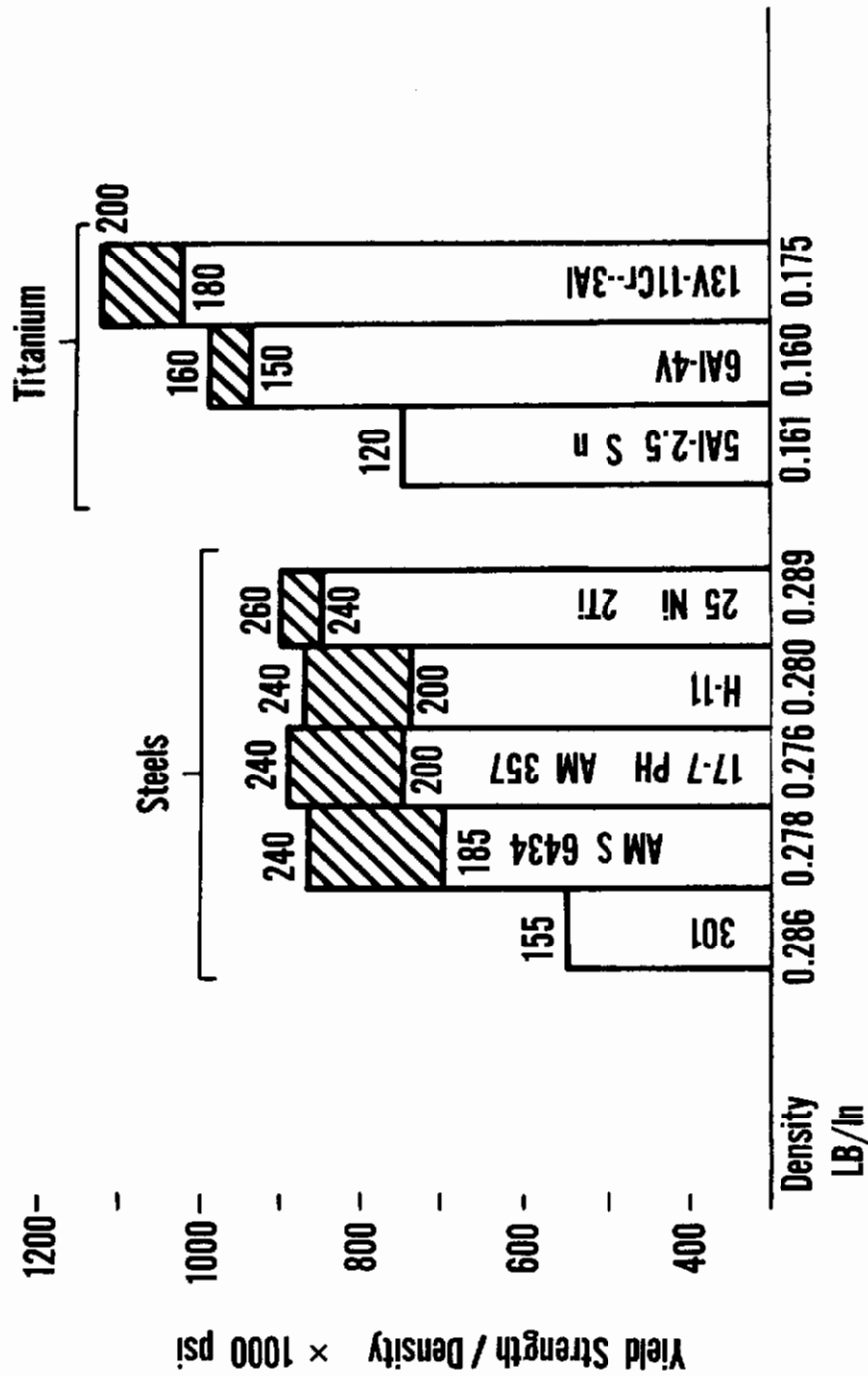AVAILABLE MISSILE CASE MATERIALS

Figure 2.

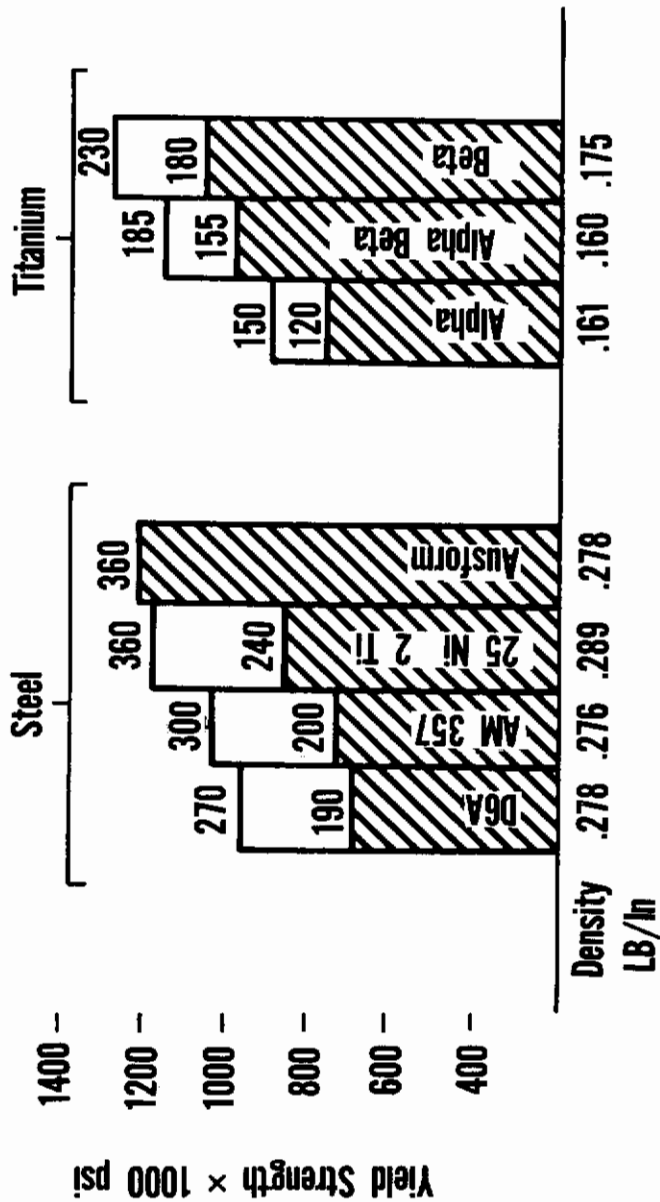# PROJECTED STRENGTH-WEIGHT COMPARISON
OF CURRENT MISSILE CASE MATERIALS

Figure 3.

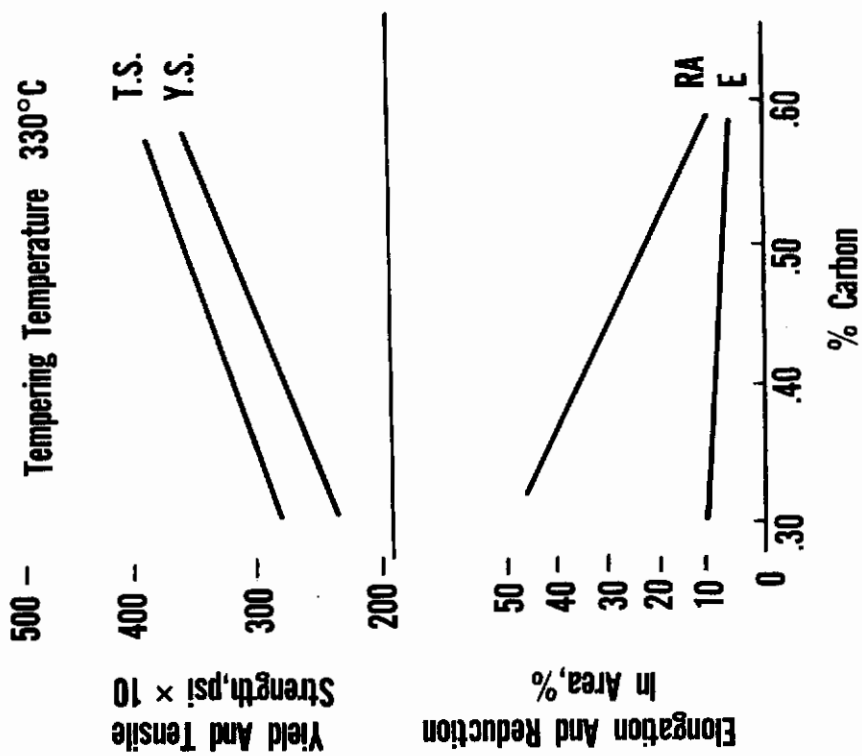# EFFECT OF CARBON CONTENT ON STRENGTH & DUCTILITY OF STEEL

Tempering Temperature 330°C

Figure 4.

TYPICAL STRENGTHS OF TITANIUM ALLOYS
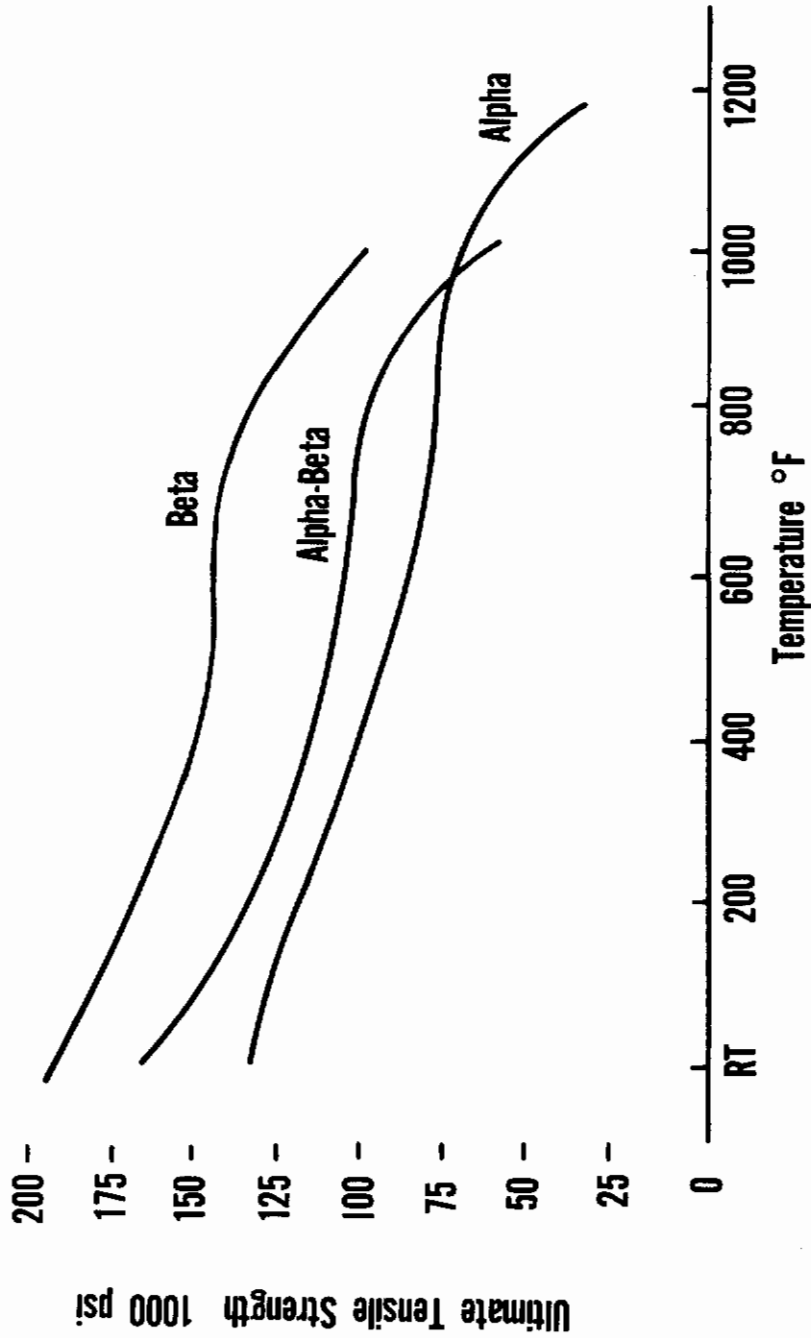
Figure 5.

TENSILE STRENGTH DENSITY RATIO
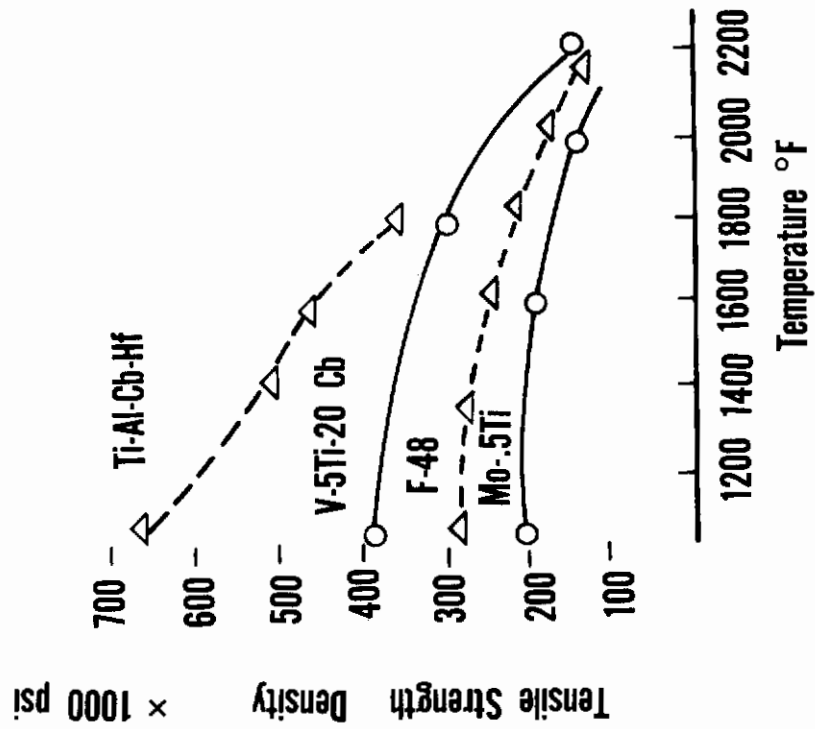
OF ELEVATED TEMPERATURE ALLOYS

Figure 6.
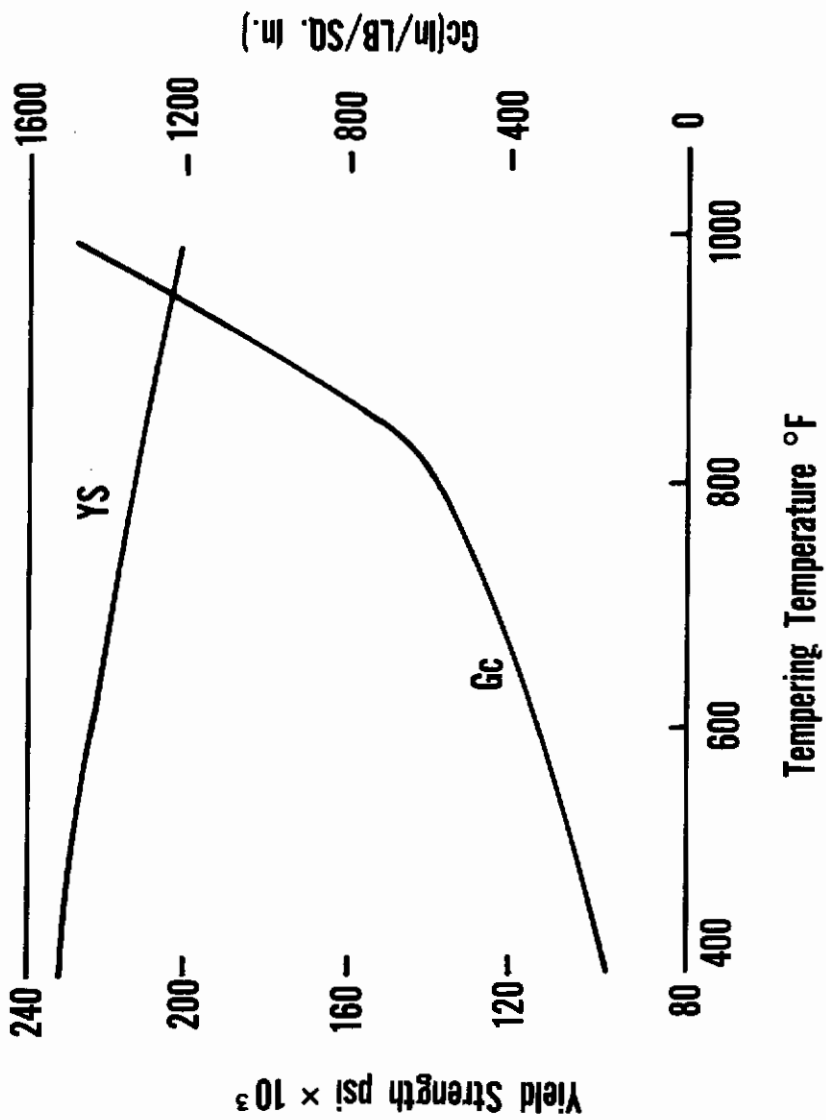
52

YIELD STRENGTH & TOUGHNESS OF LADISH D 6A STEEL

Figure 7.

53

AREAS REQUIRING ADDITIONAL INFORMATION STEEL & TITANIUM

- Strength And Ductility
- Alloy Development
- Joining
- Environmental Data
- Stress Corrosion Characteristics
- Surface Effects
- Improved Inspection Techniques
- New Maching Techniques
- Forming And Fabrication Studies

Figure 8.

54