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A COMPARISON OF THE BRITTLE BEHAVIOR
OF METALLIC AND NONMETALLIC MATERIALS

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
COLUMBUS 1, OHIO

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A COMPARISON OF THE BRITTLE BEHAVIOR OF METALLIC AND NONMETALLIC MATERIALS*

G. T. Hahn and R. I. Jaffee**

INTRODUCTION

Only a small number of metals and alloys are truly ductile. The great majority of potentially useful structural materials, metals, alloys, intermetallics, ceramics, and plastics are brittle under some conditions. These brittle materials frequently possess unique mechanical and physical properties. In the face of expanding material requirements imposed by our technology, there is, consequently, growing incentive to utilize brittle materials in load-bearing structures. Metals, ceramics, and plastics once regarded as too brittle are today being used or considered for use in structural applications. This trend is evident in the development of gas turbines, rocket casings and nozzles, and re-entry vehicles.

The concept of using brittle materials in structures is by no means new. Brittle materials such as stone, brick, and mortar have been used successfully for centuries. Cast iron has and is still making important contributions to our technology. The more effective utilization of brittle metals, ceramics, and plastics depends to a large part on the proper recognition of the strengths and the limitations of these materials. Clearly, the properties defining response to the various loading conditions encountered in service must be understood. Methods of measuring and interpreting these properties are, in some cases, still in the developmental stage; only a relatively few brittle materials have been examined in detail.

Most of the design experience for structures subject to tensile loading has been obtained with metals that fail in a ductile manner. Also, there has been a significant amount of experience with metallic structures subject to brittle behavior. Up to the present, nonmetallic materials normally have not been used in tensile structures. However, many new applications now require consideration of these materials, even though they may be quite brittle. It is the purpose of this memorandum to compare the nature and properties of brittle metallic and nonmetallic materials to see whether a common basis for design of tensile structures might be adopted.

BASIC INFLUENCES

The strength and ductility parameters used by design engineers are derived from the deformation and fracture characteristics of a material. Deformation and fracture depend both on the elastic properties and the

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**Division Consultant, Metals Science Division, and Technical Manager, Department of Metallurgy, respectively, Battelle Memorial Institute.

movement of lattice defects; these, in turn, depend on the electron bond, the crystal structure, and the degree of order. To some extent, these basic influences, bonding, structure, and order, are interrelated. Although their effects on ductility are complex and not well understood, some generalizations can be made and are appropriate. These are summarized in Table 1 and discussed in this section.

Electron Bond

Metals are distinguished from nonmetals by the fact that their valence electrons are "free" and shared equally by all atoms. As indicated in Table 1, materials possessing this type of bonding appear to be the most ductile. The metallic-type orbitals usually are a maximum of four, the most typical metals possessing the least metallic electrons. In transition metals, the electron shell just below the valence shell is incomplete, and additional bonding of the resonating covalent type becomes possible. This type is established only between the atom and its nearest neighborhood, and the bond is not so random as that of a pure metallic. The greater the number of unpaired electrons participating in the resonating covalent bond, the less ductile seems to be the behavior at low temperatures. Thus, the transition metals of Group VI-A, tungsten, molybdenum, and chromium, possessing the maximum of five unpaired d-electrons also exhibit the most brittle behavior.

Ionic bonding, possessed by materials such as NaCl, LiF, and MgO, appears to be the most ductile of nonmetallic bonds. In this case, electrons are transferred from the electropositive donor-type atoms to the electronegative acceptor-type atoms. The most ductile behavior seems to occur in AB-type ionic compounds, where only one electron is transferred. Increasingly brittle behavior results when greater numbers of electrons are transferred.

The most brittle of the electron bonds appears to be the covalent bond, where the valence electrons are shared by the atom and its nearest neighbors. This type of bonding is found in diamond, silicon, and germanium, as well as in carbides, nitrides, and organic polymers, for example. These bonding orbitals are relatively fixed and, while characterized by great strength, are not easily re-formed once broken. In many covalent systems, for example, graphite, selenium, and tellurium, covalently bonded atoms are arranged in planes, chains, or pairs, and these, in turn, are held together by weak Van der Waals' forces. Van der Waals' bonds break and re-form readily, providing materials such as graphite and polymers with a mechanism for plastic deformation and ductility.

Crystal Structure

Crystal structure is a factor in determining the number of active slip systems, and, consequently, the ease with which deformation can occur. The symmetry of crystals also influences the possible type of embrittling defects (for example, dislocation pile-ups) produced by slip. Slip seems more difficult in crystals of lower symmetry, to the point where, in amorphous

TABLE 1. BASIC INFLUENCES ON BRITTLE BEHAVIOR^(a)

Electron Bonding	Crystal Structure	Degree of Order
Metallic	Close packed face-centered cubic	Random solid solution
Resonating covalent	Hexagonal	Ordered solution
Ionic	Body-centered cubic	Intermetallic compound
Covalent-Van der Waals	Rhombohedral	Ionic compound
Covalent	Less symmetrical (through triclinic)	Covalent compound
	Amorphous	

(a) Arranged in order of increasing effect in promoting brittleness.

materials such as glass, no crystallographic slip is possible. Amorphous materials thus tend to be extremely brittle at all but relatively high temperatures, where thermally induced local atomic rearrangements contribute to a "viscous" type of deformation.

In general, the high-symmetry close-packed structures are the most ductile. The (close-packed) face-centered cubic metals do not seem to undergo brittle cleavage fracture under any circumstances. In the case of ionic crystals, the rock-salt structure, which may be considered as face-centered cubic with four sets of atoms forming an interconnecting cubic network, exhibits ductility. Slip can occur on (110) planes without altering the relative position of the two types of ions. Hexagonal close-packed structures also possess good ductility, particularly when the c/a ratio is less than ideal for close-packed spheres, 1.633. In this case, additional slip on prismatic and pyramidal planes can supplement the basal-slip characteristic of hexagonal structures. The body-centered cubic structure possessed by many metallic materials is subject to low-temperature brittle cleavage fracture. Metals with less symmetrical structures are increasingly more brittle, although some of the low-melting metals with tetragonal symmetry, like white tin, have good ductility at temperatures relatively high on a homologous T/T_N scale. In nonmetallic materials, the less symmetrical structures also correspond to greater brittleness.

Degree of Order

Generalizations indicated in Table 1 for the degree of order may have their source in the nature of the electron bond. However, it is instructive to relate the ductility with the degree of order. For example, random solid solutions of metals seem to be the most ductile. Local ordering tends to enhance hardness at the expense of ductility, while completely ordered intermetallics such as CuAu and Fe_3Al tend to behave in a brittle manner. Since the ionic crystals are also ordered electrostatically, deformation is restricted to slip that does not alter the relative positions of ions. Atoms displaced to positions where they are opposite like-charged neighbors may be considered to be electrostatically faulted and act as a source of brittleness. Covalently bonded crystals are the most brittle and also the most strongly ordered, since, in this case, order depends not only on the relative position of the atoms but also on the relative position of the bonds themselves.

Interrelations

The basic influences on brittle behavior just discussed are interrelated to a considerable degree. Respective contributions to the resulting behavior are difficult to isolate. The average material is not typically metallic, ionic, or covalent, but must be regarded as a hybrid - a mixture of metallic, ionic, and covalent bonding. For example, the elements in Group IV-A of the periodic table, lead, tin, germanium, silicon, and carbon, present different degrees of metallic and covalent bonding, with metallic

bonding increasing with atom number. In the transition elements, bonding must be looked upon as gradations from strongly metallic to strongly resonating covalent. Similarly, the effect of a favorable crystal structure may be outweighed by unfavorable bonding or order. Sharp differences in behavior from one type of material to another need not be expected. However, in the extreme cases, large differences in ductile-brittle behavior do exist.

PROPERTIES

Properties of brittle materials important for design include elastic, plastic deformation, fracture, notch sensitivity, energy absorption, fatigue, and thermal-shock resistance. In this section, these properties of metallic and nonmetallic materials subject to brittle behavior are compared.

Elastic

Metals and ceramics exhibit comparable elastic properties. As shown in Tables 2 and 3, Young's modulus and Poisson's ratio values for metals and ceramics occupy the same range. The temperature dependence of the modulus, shown in Figure 1, for these two classes of materials is also similar. Composite materials, such as Fiberglas laminates and filled plastics, are intermediate on the modulus scale, while organic polymers characteristically possess low elastic moduli.

The elastic energy stored in structures loaded to comparable stress levels is inversely proportional to the elastic modulus. Since this energy is the driving force for unstable fractures, low modulus values (leading to high elastic energies) can contribute to the brittle behavior of materials, such as organic polymers.

Plastic Deformation

Under suitable conditions, metals, ionic single crystals, and organic polymers all undergo plastic deformation. Some typical stress-strain curves are reproduced in Figure 2. The stress-strain curve for steel at room temperature is characteristic of ductile behavior. Initial yielding is followed by work hardening to a maximum load and necking. After extensive deformation, the steel sample fractures by shearing across entire grains or between pores formed at brittle interfaces such as inclusions. At -200 C, the same steel fractures by grain cleavage after a small amount of plastic yielding at a much higher flow stress. The stress-strain curve of the ionic MgO single crystal shown in Figure 2 is an example of behavior considered "ductile" by ceramists. At room temperature, this crystal (like the steel at -200 C) fails by cleavage after a small amount of plastic yielding. It is apparent that the low-temperature behavior of steel - "brittle" by the metallurgists' standards - and the "ductile" ceramic are

TABLE 2. YOUNG'S MODULUS OF ELASTICITY VALUES FOR VARIOUS MATERIALS AT ROOM TEMPERATURE

Material		Modulus of Elasticity, 10 ⁶ psi
Metals ⁽¹⁻³⁾	(Fe, Mo, W, Cr, Be)	30 - 60
Ceramics ^(4,5)	(Al ₂ O ₃ , MgO, SiC, ThO ₂ , TiO ₂)	20 - 45
Composites ⁽⁷⁾	(Fiberglas laminates, filled phenol-formaldehyde compounds)	1 - 5
Organic polymers ⁽⁷⁾	(Plexiglas, nylon, Vinylite, polystyrene, polyethylene)	0.02-0.06

TABLE 3. POISSON'S RATIO FOR VARIOUS MATERIALS AT ROOM TEMPERATURE

Material	Poisson's Ratio
Fe	0.29
Mo ⁽⁸⁾	0.32
W ⁽⁹⁾	0.29
Be ⁽²⁾	0.01-0.2
BeO ⁽¹⁰⁾	0.38
Al ₂ O ₃ ⁽¹⁰⁾	0.32
MgO ⁽¹¹⁾	0.36
ThO ₂ ⁽¹²⁾	0.28
ZrO ₂ ⁽¹¹⁾	0.29

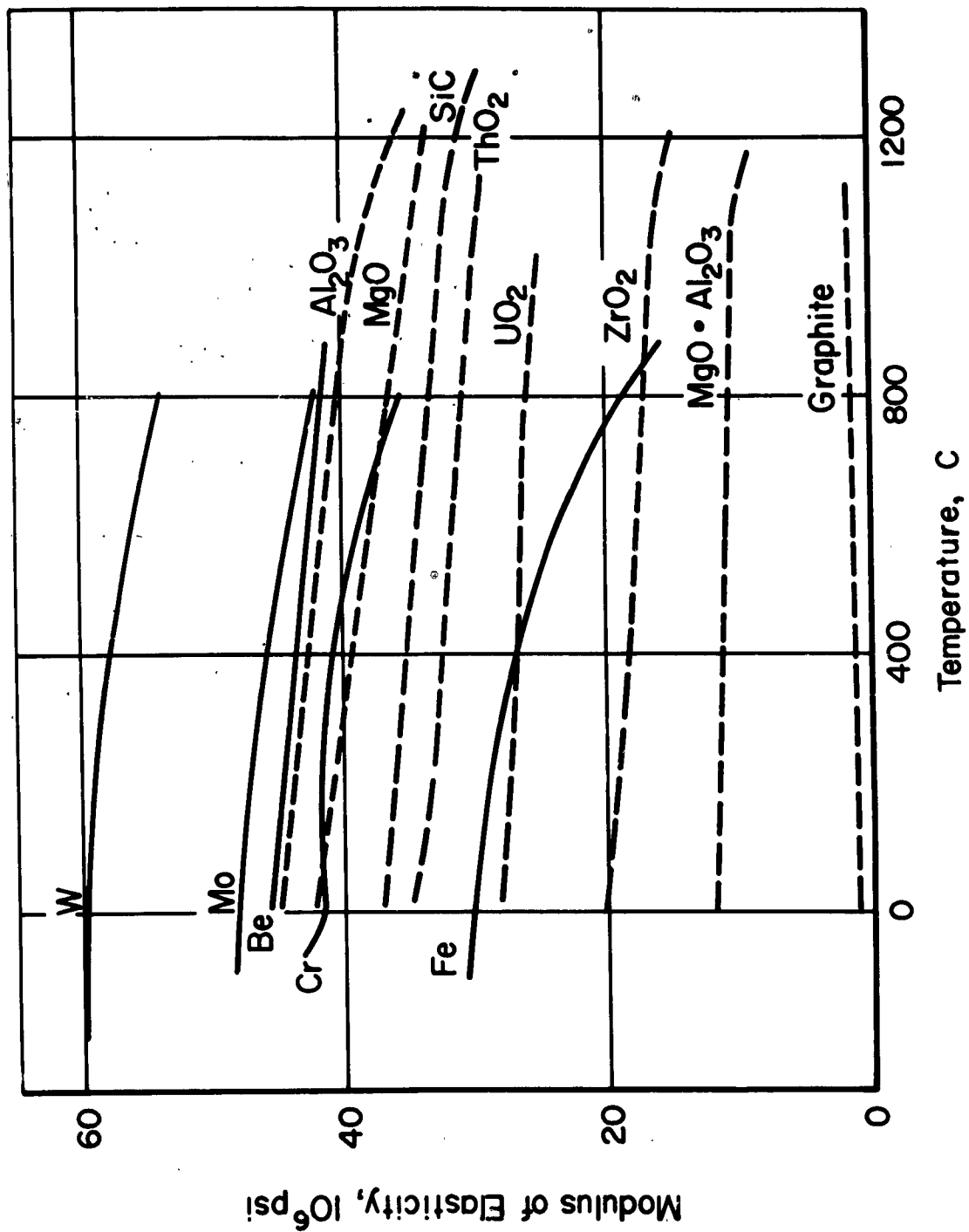


FIGURE 1. MODULUS OF ELASTICITY VALUES FOR VARIOUS MATERIALS(1-6)

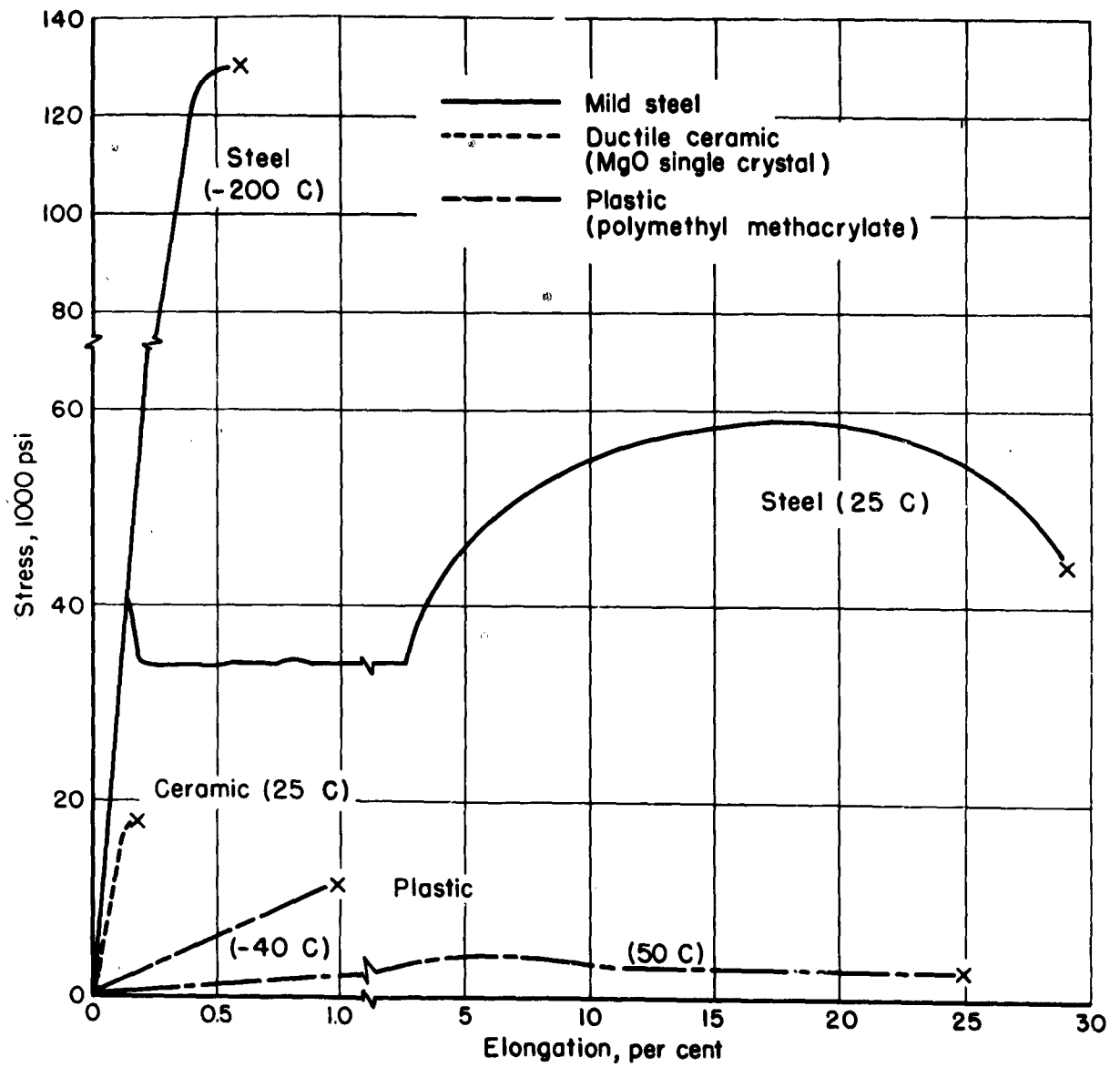


FIGURE 2. TENSILE PROPERTIES OF VARIOUS MATERIALS⁽¹³⁻¹⁵⁾

are comparable. Properties of the polymer plastic are also influenced by the temperature. Before breaking at 50 C, the plastic suffers an extension equivalent to that of ductile steel; at -40 C little deformation precedes fracture.

The deformation characteristics of metals, ceramics, and organic polymers have several common features. Heat treatment, alloying, and strain rate affect the strength of ionic crystals much in the same manner as they influence the strengths of metallic crystals. Figure 3 shows that the strength of MgO single crystals can be lowered by annealing and raised by alloying with iron, and the ductility lowered and flow stress increased by elevating the strain rate. This illustration also effectively demonstrates that the ductility of MgO in compression is much greater than that in tension. In all cases, resistance to flow increases as the temperature is lowered. This is illustrated for iron single crystals loaded in tension and MgO single crystals in compression (Figure 4). The flow characteristics of metals and ceramic crystals are quite similar, probably because dislocation mechanisms operate in both cases. The yield-strength values for the metal and ceramic single crystal appear to be comparable and considerably higher than those of organic polymers. Thus, there appear to be no major differences in metal and ceramic deformation behavior other than in degree.

Fracture Behavior

Body-centered cubic metals, notably iron, molybdenum, tungsten, and chromium, and also organic polymers, exhibit an abrupt change or transition from ductile behavior at elevated temperatures to brittle behavior at low temperatures. Data for metal single crystals and an organic polymer are given in Figure 5; results for polycrystalline metals are given in Figure 6. Ductile behavior in ceramic materials has, so far, been observed only in ionic single crystals of cubic symmetry. As shown in Figure 5, these crystals exhibit a very gradual transition from ductile-to-brittle behavior as the temperature is lowered.

In metals, the change from ductile to brittle, characterized by a "transition temperature", is related to a change in the mechanism of fracture. Above the transition temperature, rupture by a shear mechanism occurs only after yielding and extensive deformation. Below the transition temperature, fracture is propagated by cleavage cracks or, in some cases, by grain-boundary failure. Both cleavage and the grain-boundary fracture require little or no prior deformation. For example, in the case of mild steel, just below the transition temperature, cleavage cracks are formed and propagate shortly after the onset of yielding. The mechanisms underlying the transition in organic polymers are not understood. Ceramic single crystals described in Figure 5 do not undergo a change in mechanism but fail by cleavage throughout the entire range of temperature. The fracture of ductile ceramic single crystals is thus analogous to the fracture of body-centered cubic metals below their transition temperature.

Results for iron, molybdenum, and tungsten in Figure 6 illustrate that the increased ductility obtained on raising the temperature is accompanied by a marked loss of strength. A similar loss of strength of polycrystalline ceramic materials above 1000 C is not accompanied by enhanced

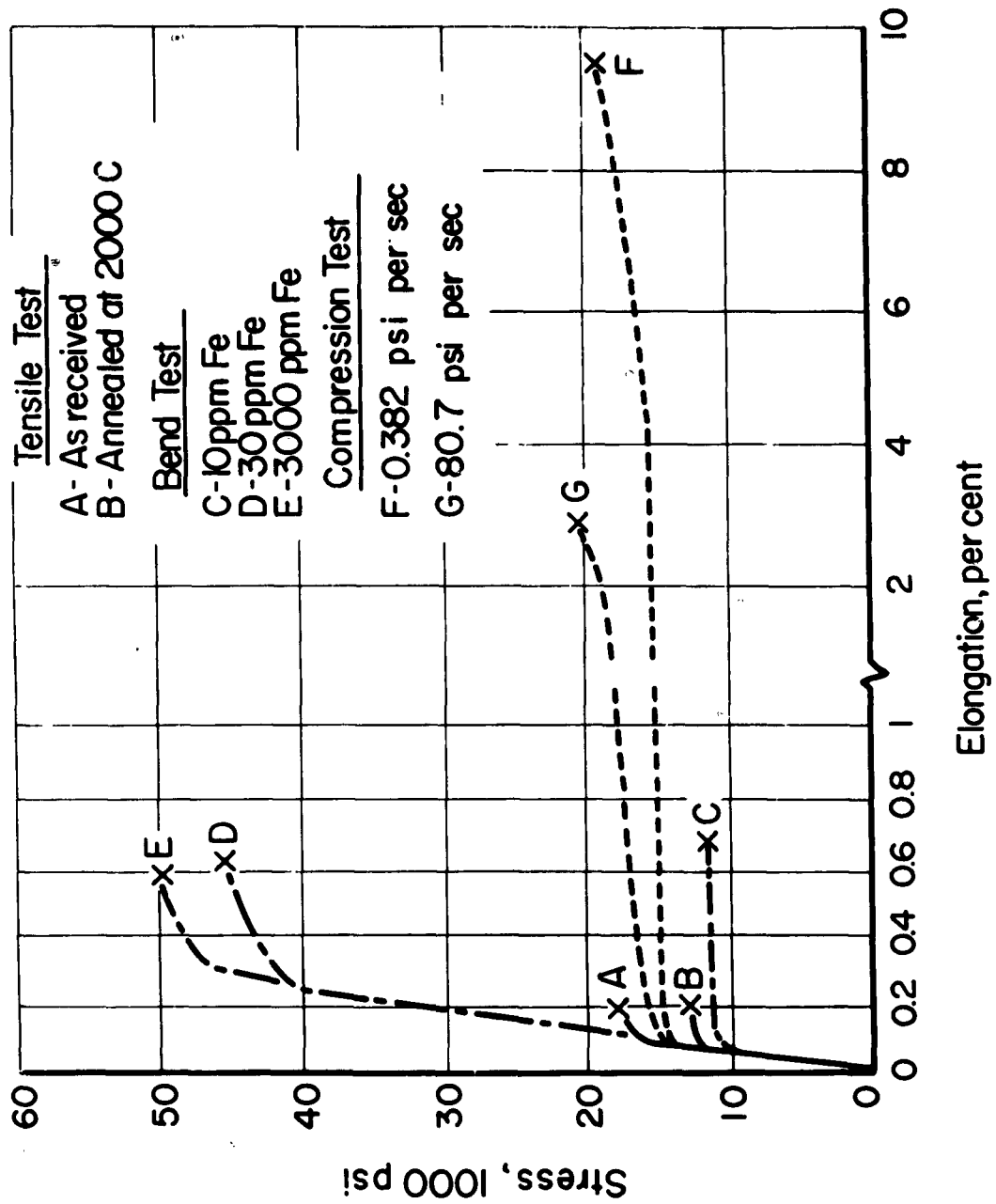


FIGURE 3. STRESS-STRAIN CHARACTERISTICS OF MgO SINGLE CRYSTALS (14,16)

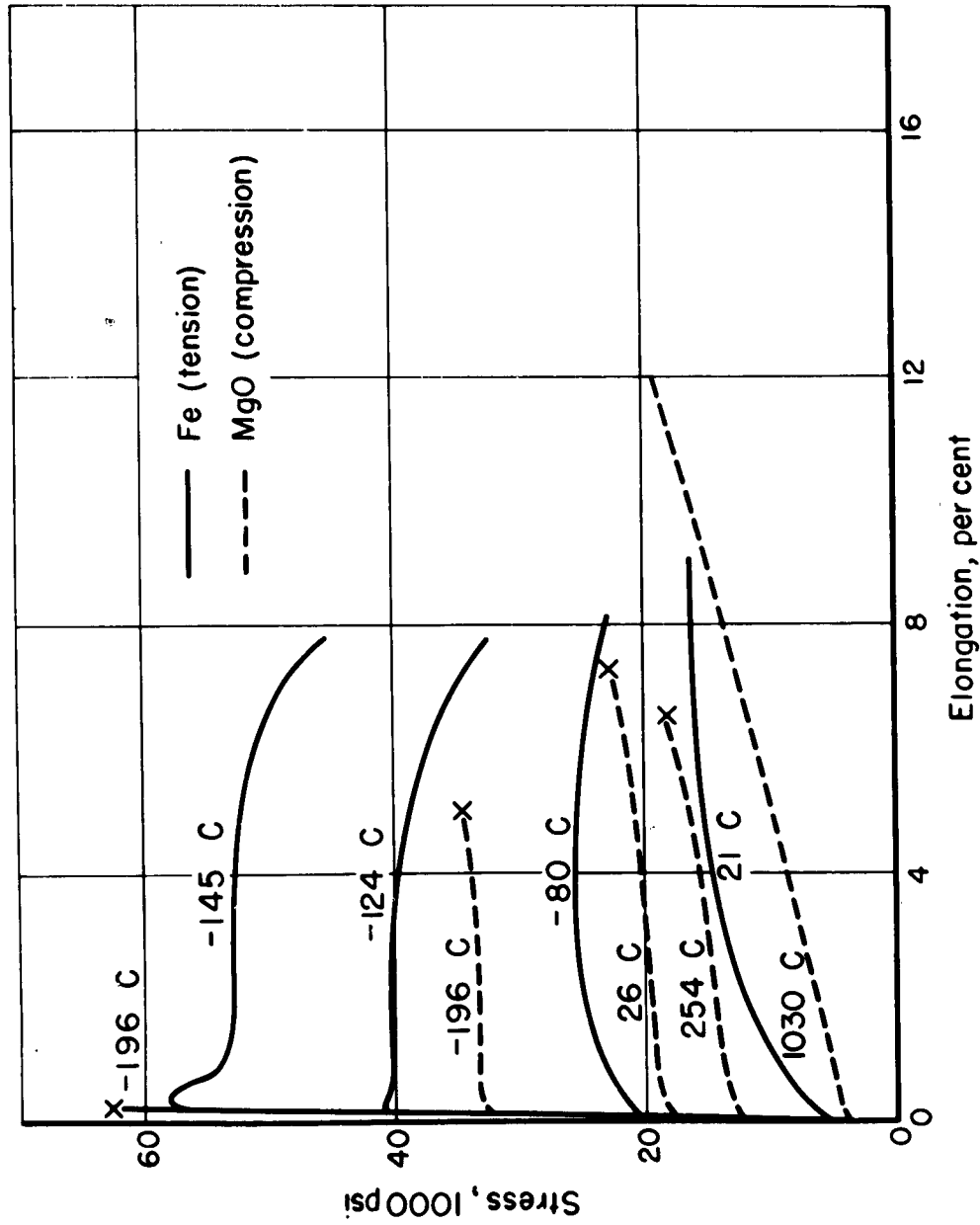


FIGURE 4. FLOW CHARACTERISTICS OF Fe AND MgO SINGLE CRYSTALS (16-19)

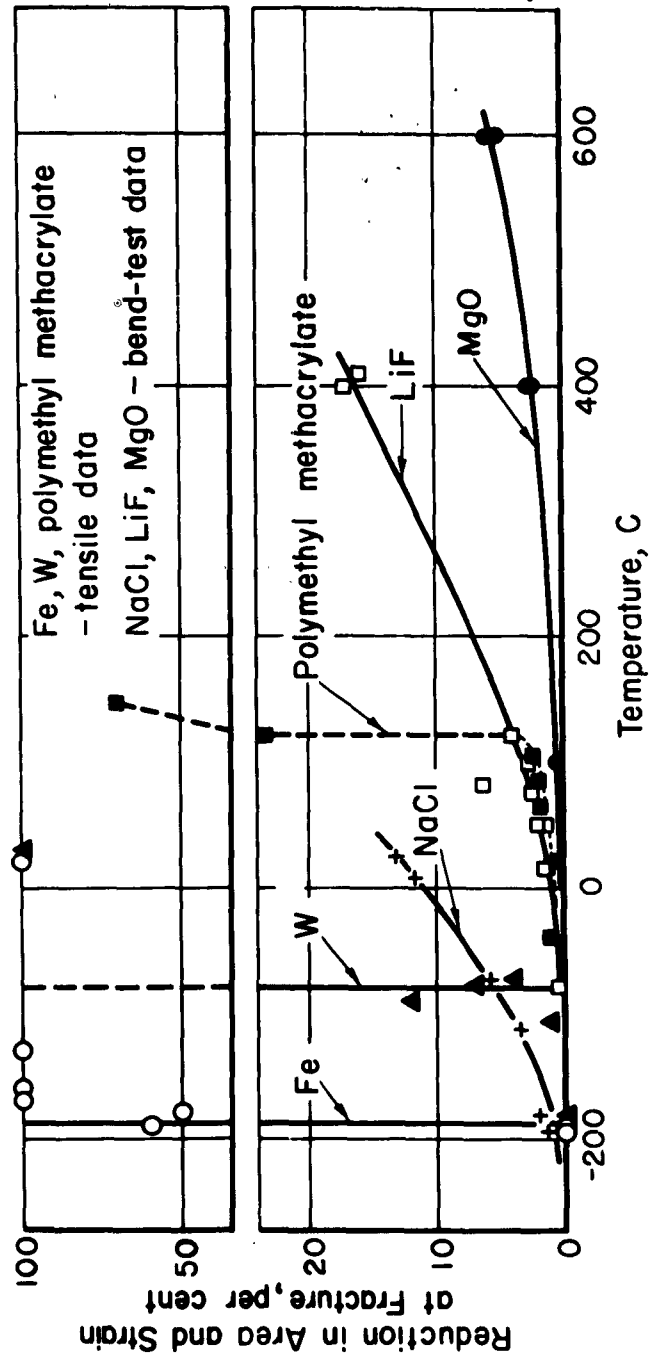


FIGURE 5. DUCTILITY TRANSITIONS FOR Fe, W, NaCl, LiF, AND MgO SINGLE CRYSTALS, AND POLYMETHYL METHACRYLATE(19,27-29)

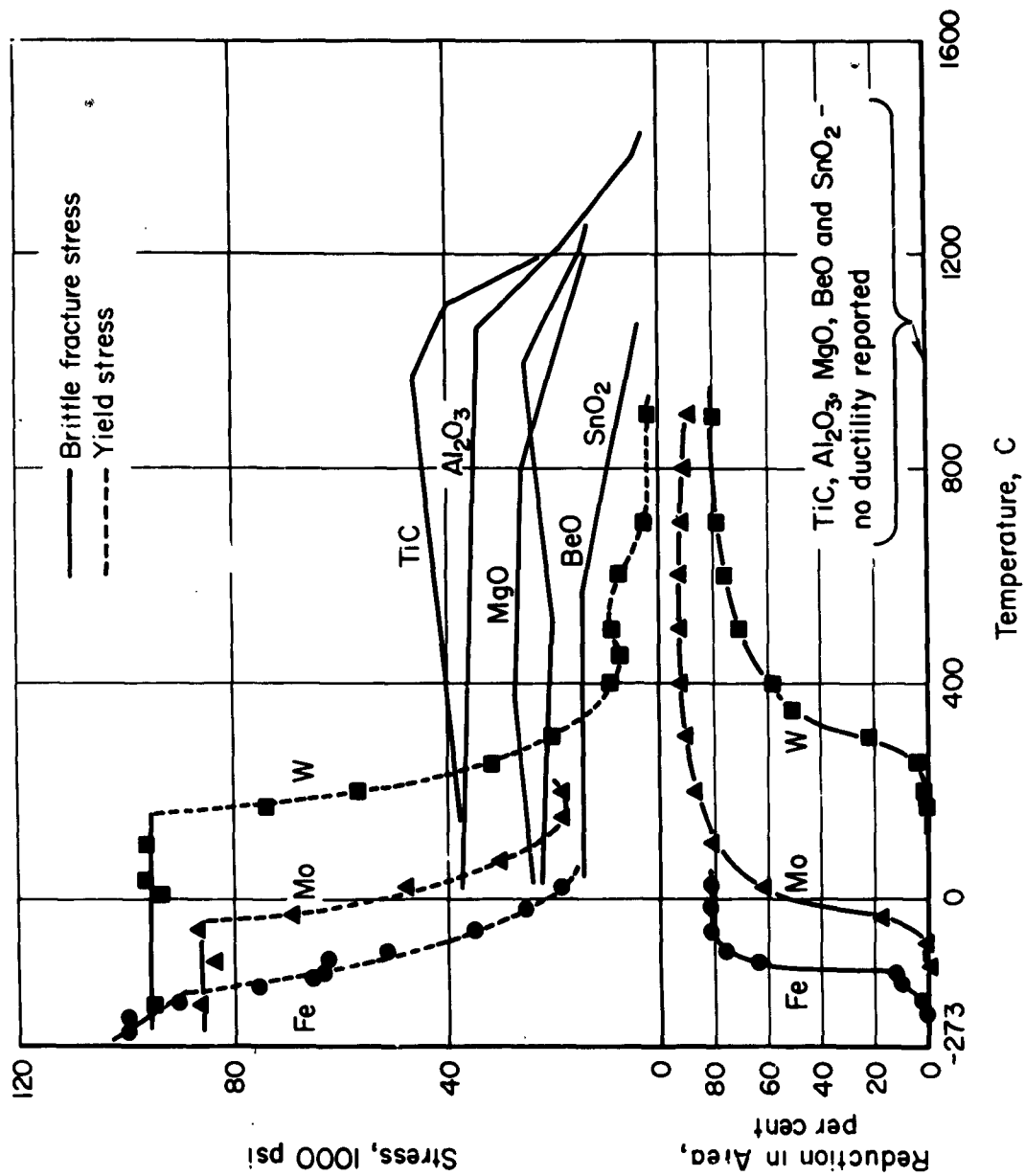


FIGURE 6. FRACTURE BEHAVIOR OF VARIOUS MATERIALS (4,20-26)

ductility. In this case, the loss in strength appears to be related to a change from cleavage to grain-boundary fracture.

Common ductile metals are relatively insensitive to surface damage. However, surface condition can have a marked effect on the fracture of brittle metals and ceramics. Cracks and possibly other forms of damage are produced at the surface of ceramics in the process of cleaving or simply by mechanical contact with a hard rough object. To avoid premature brittle fracture, the damaged surface layers must be removed. Figure 7 illustrates that good ductility is observed for NaCl crystals only when the surface damage introduced by cleaving is removed by a chemical polish. This effect is not restricted to ionic crystals. As shown in Table 4, surface condition influences the fracture behavior of covalently bonded germanium.

There are several other embrittling effects associated with the surface. Coherent crystalline deposits at the surface of NaCl crystals can cause cracking and brittleness. A similar effect may be the source of brittleness in polycrystalline ionic materials. Defects accumulating at the surface during plastic deformation may impede this location movement and cause hardening. Finally, absorption of gas atoms can lower surface energy and may thus reduce the fracture strength in the presence of flaws.

The ductility and fracture strength of both metals and ceramics are influenced by strain rate, composition, and microstructure. Figure 4 shows that strain rate influences the ductility of ceramic crystals. Increasing the strain rate raises the transition temperature of both metals and ceramics. The results presented in Figure 8 illustrate this effect and suggest that the transition from ductile to brittle may be more strain-rate sensitive in the case of ceramics. Figure 9 shows a similar effect of grain boundaries in tungsten and NaCl. In both metals and ceramics, increasing the grain size and porosity favor brittleness. In some metals, notably molybdenum and tungsten, large amounts of prior cold work enhance ductility. This effect, illustrated for recrystallized and wrought (cold worked) tungsten in Figure 10, is thought to be related to a change in the orientation of grain boundaries relative to the stress axis.

Notch Sensitivity

Plastic deformation provides a mechanism for relaxing and redistributing stresses concentrated at a notch, crack, or other discontinuity. Thus, strengths become progressively more sensitive to notches as the ability to deform is reduced. Figure 10 illustrates, for steel, molybdenum, and tungsten, that the decrease in ductility at low temperatures (measured by the reduction in area of unnotched samples) is accompanied by a loss in notch strength (shown by the ratio of notched-to-unnotched ultimate strength). Notch sensitivity is influenced by all the various factors that affect ductility. The influence of temperature and notch geometry* is illustrated in Figure 10. These results show that notched-to-unnotched strength ratios as low as 0.2 are obtained for steel tested under extreme conditions. Similar data for ionic and covalent ceramics or for refractory metals well below their transition temperature are not

*For steel samples having $K_t = 10.8$ and $K_t \gg 10$ notches, the latter tested at a higher strain rate. K_t is the calculated elastic stress-concentration factor.

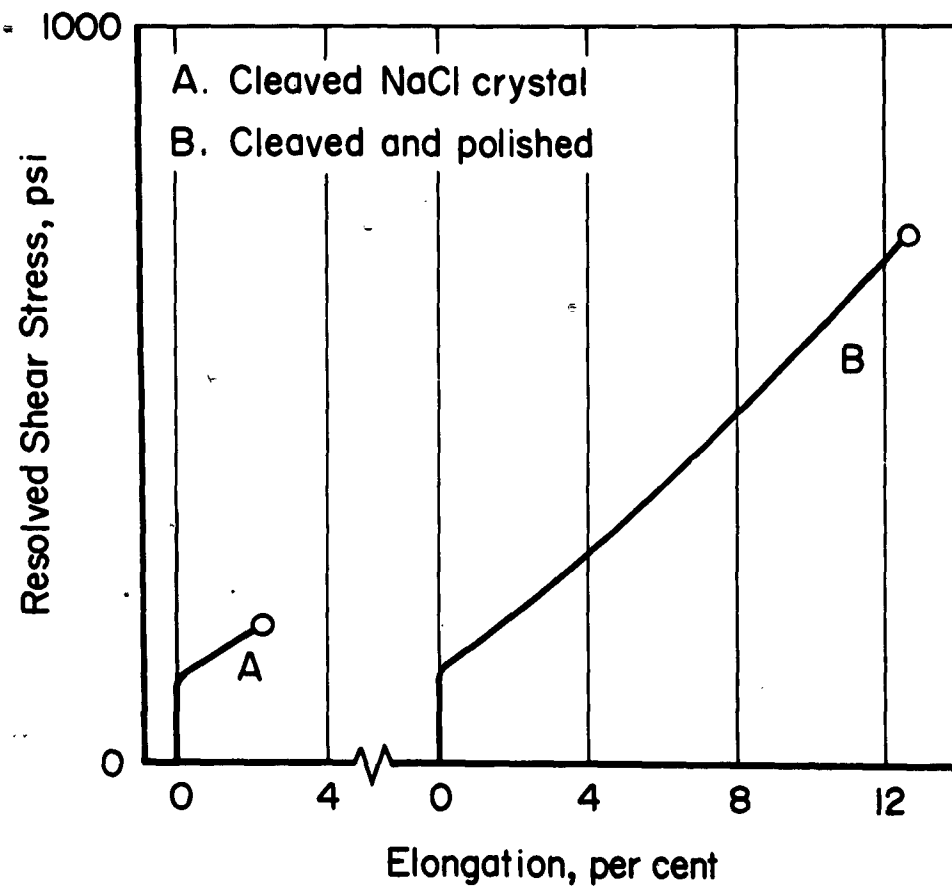


FIGURE 7. INFLUENCE OF SURFACE CONDITION ON THE DUCTILITY OF NaCl SINGLE CRYSTAL(30)

TABLE 4. INFLUENCE OF SURFACE CONDITION ON THE
STRENGTH OF GERMANIUM CRYSTALS(31)

	Breaking Stress, psi
Tested in air	9,500
Tested in HF-HNO ₃	68,000
Tested in CP-4 etchant	430,000

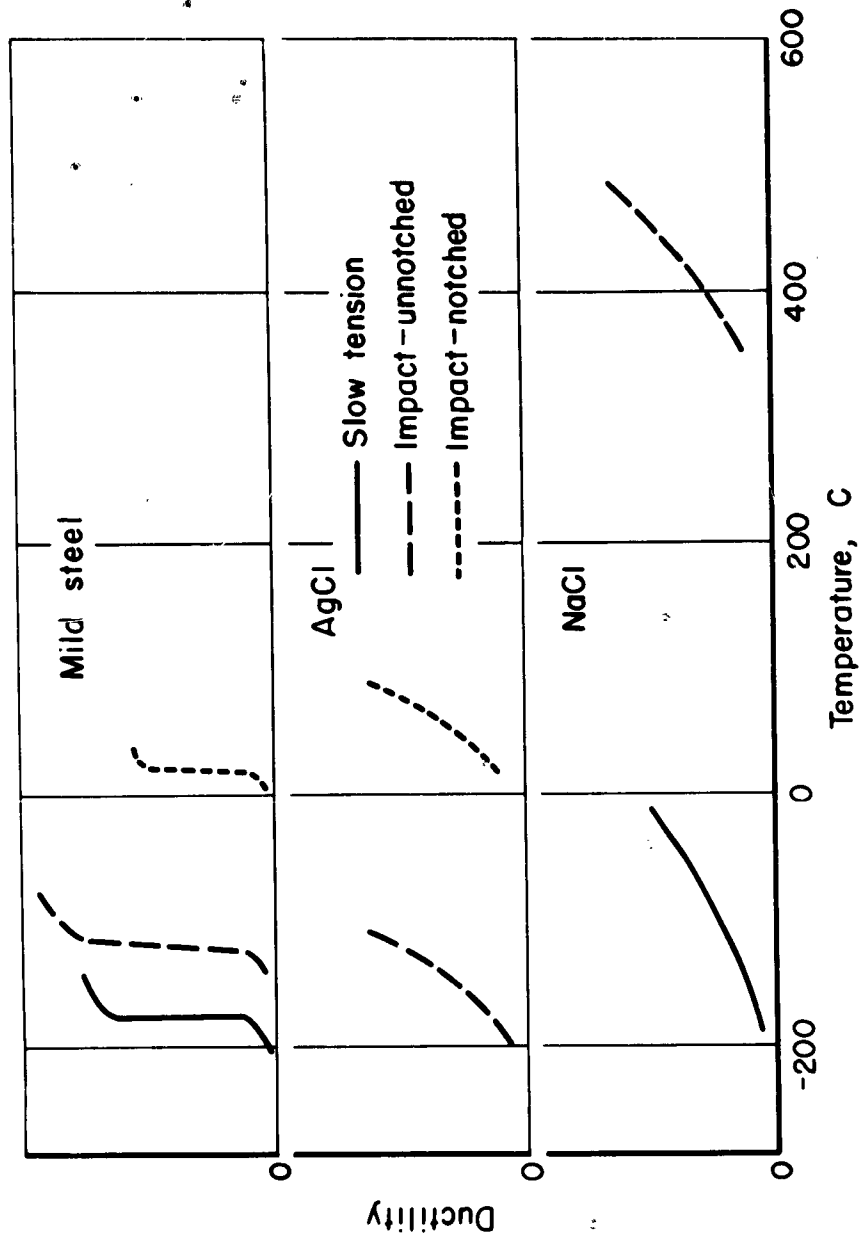


FIGURE 8. INFLUENCE OF STRAIN RATE ON THE DUCTILITY OF MILD STEEL, AgCl, AND NaCl(13,32-34)

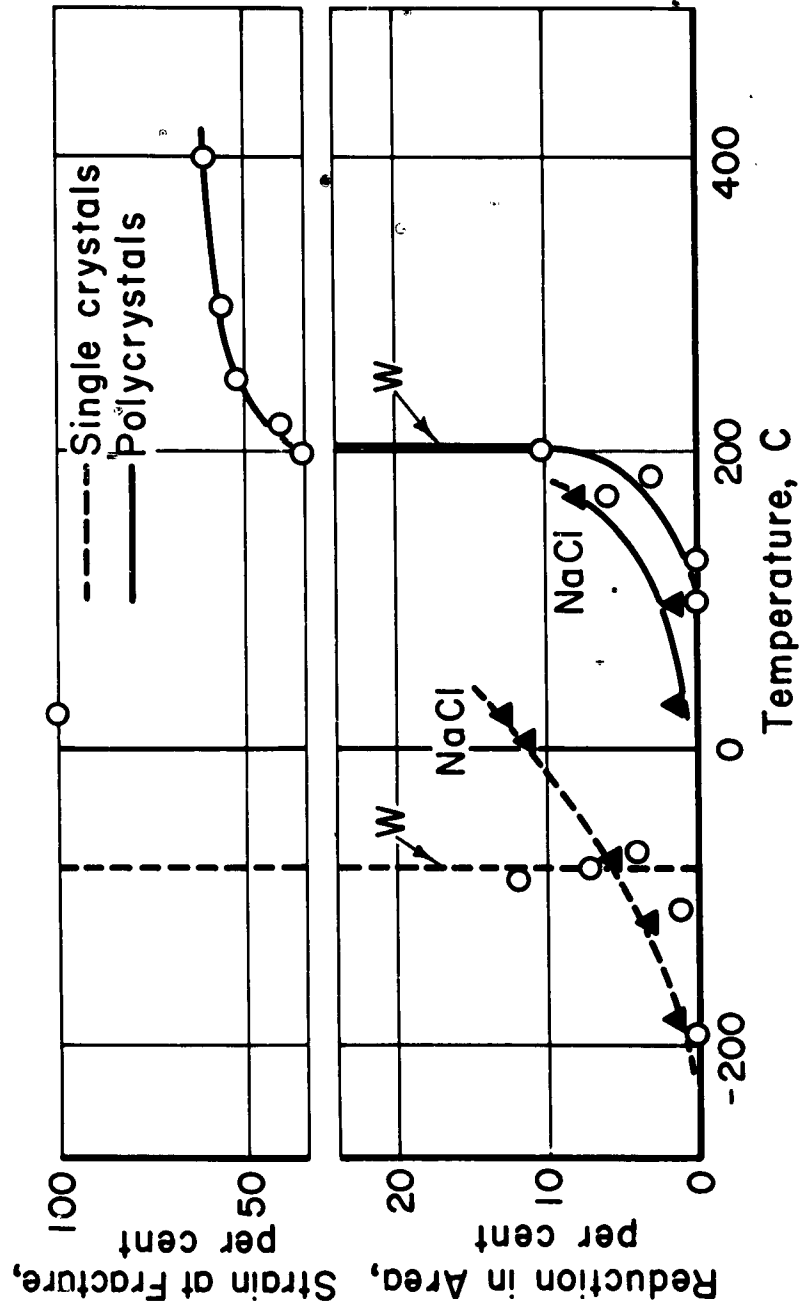


FIGURE 9. EFFECT OF GRAIN BOUNDARIES ON THE DUCTILITY OF W AND NaCl SINGLE CRYSTALS(27,34)

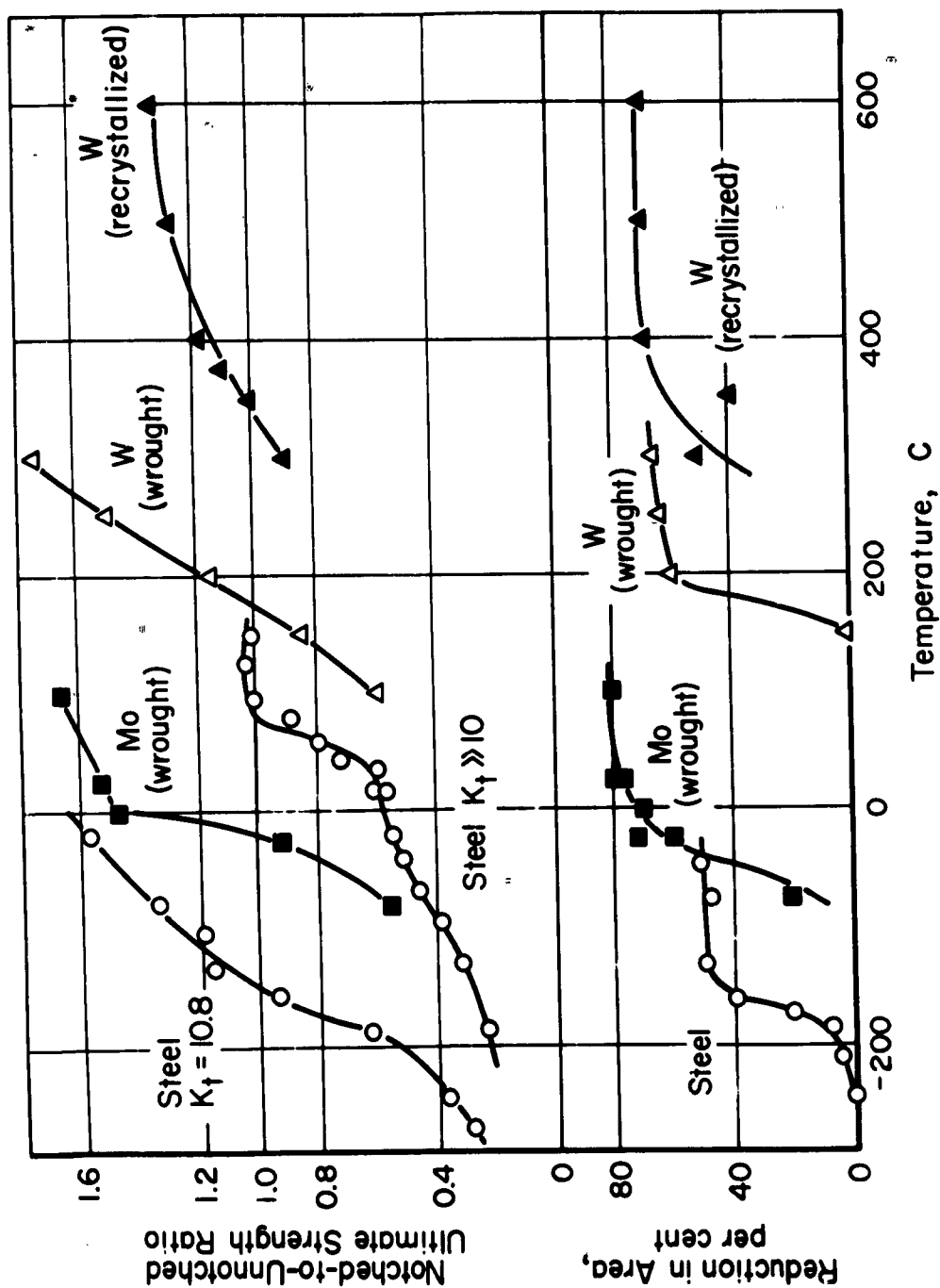


FIGURE 10. NOTCH TENSILE PROPERTIES OF UNALLOYED MOLYBDENUM ($K_t = 3$) AND TUNGSTEN ($K_t = 3$) AND A COMMERCIAL FORGING STEEL ($K_t = 10.8$, $K_t \gg 10$) (35,36)

available. Since these materials have limited capacity for plastic deformation, low notch strengths and a high degree of notch sensitivity may be anticipated.

The fracture toughness, G_c , is another useful notch-sensitivity parameter. This term represents the energy required to propagate a sharp crack the moment the crack becomes unstable. The term G_c provides a quantitative measure of crack-propagation resistance and notch sensitivity under severe loading conditions. The magnitude of G_c is influenced by notch and sample geometry, and, as shown in Figure 11, by the temperature. Approximate values of G_c for various classes of materials, given in Table 5, reflect the fracture toughness at temperatures where these materials are normally regarded as brittle. No experimental data are available for ceramics. In this case, the main contribution to the fracture toughness is probably the specific surface energy of the crack. The values listed for ceramics in Table 4 were estimated from the surface energy. The G_c values in Table 5 indicate that there are significant differences in the crack-propagation resistance of nominally brittle materials. The fracture toughness of ionic and covalent ceramics may be considerably less than for brittle metals and plastics.

Energy Absorption

The energy required to cause fracture under impact conditions is another measure of brittleness. Energy-absorption characteristics of various materials are summarized in Figure 12. It should be noted that the same sample or test procedure was not used in every case. However, in view of the wide variation in the energies recorded, corrections for sample size would not significantly alter the relationships indicated.

In general, metals exhibited the highest energy values; polymers are intermediate; ceramic crystals and particularly the polycrystalline ceramics exhibit the lowest energy values. Even in the brittle condition, the metals shown in Figure 12, with the exception of beryllium, exhibit much higher energy-absorption values than do ceramics. Energy values usually quoted for "brittle", gray cast iron, about 40 in-lb, may be compared with the values obtained for polycrystalline MgO and Al_2O_3 , about 1 in-lb at room temperature.

Metals, polymers, and ceramic single crystals undergo a transition from high energy absorption to low energy absorption as the temperature is lowered. In the case of metals, high energy values above the transition are associated with shear-type fractures; low energies below the transition, with cleavage. Ionic single crystals fractured only by cleavage. Above the transition temperature, the ionic-crystal samples fail by deforming rather than by fracture, and it is not known whether these crystals are capable of shear-type fractures. In contrast with the other materials, polycrystalline ceramics become slightly tougher as the temperature is lowered. The increase in fracture energy noted for polycrystalline MgO and Al_2O_3 samples below 1000 C seems to be related to the change from a grain-boundary to a cleavage fracture mechanism.

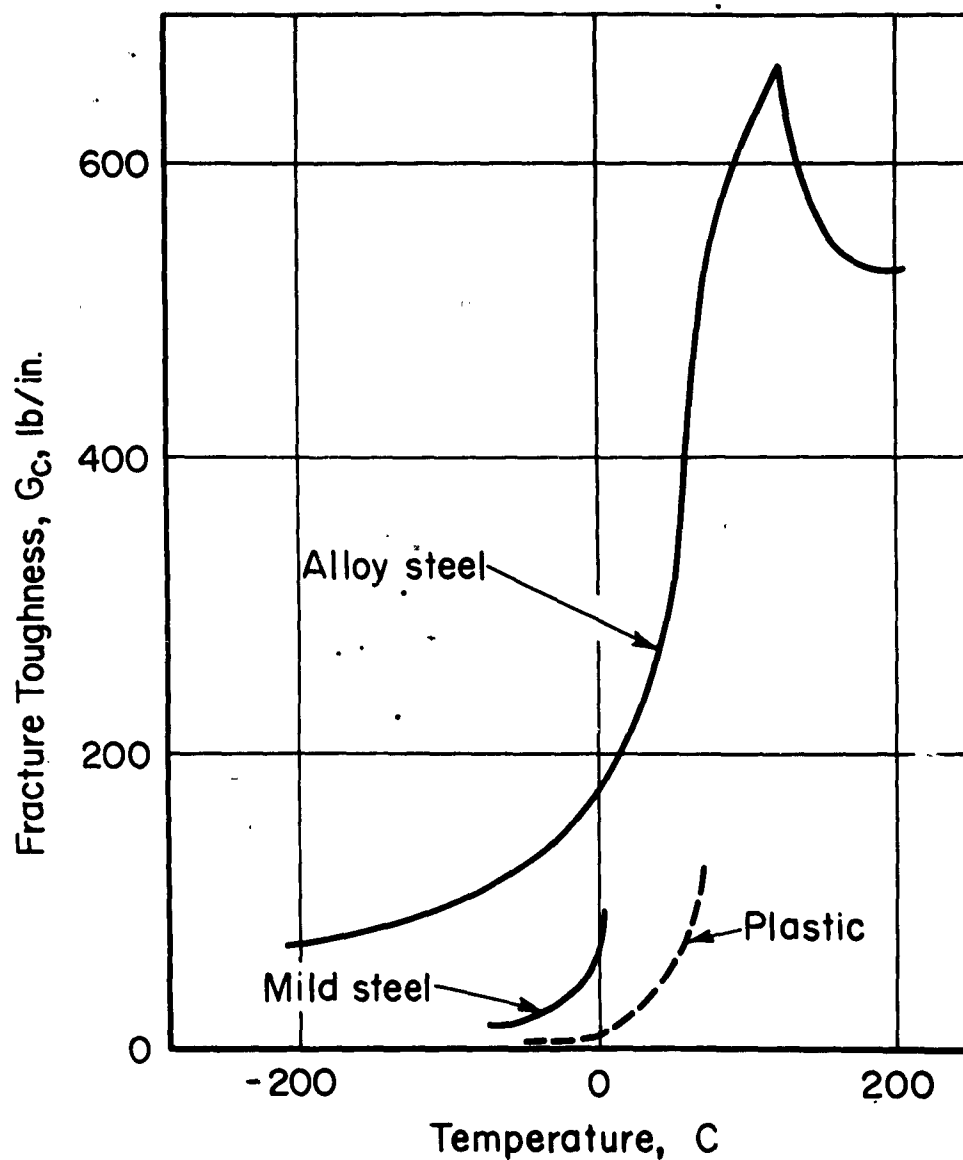


FIGURE 11. FRACTURE TOUGHNESS, G_c , OF A COMMERCIAL ALLOY FORGING STEEL, MILD STEEL (SHIP PLATE), AND AN ACRYLIC PLASTIC(37-39)

TABLE 5. ESTIMATES OF THE FRACTURE TOUGHNESS, G_c , FOR VARIOUS MATERIALS IN THE BRITTLE CONDITION

Material	G_c , in-lb/in. ²
Heat-treated steel ^(37,40)	100
Mild steel ⁽³⁸⁾	10
Organic polymer ⁽³⁹⁾	1.0
Ceramic ^(a)	0.05

(a) Estimated from the specific surface energy, γ , assuming $G_c \approx 5 \gamma$. According to Gilman⁽⁴¹⁾, γ values for a variety of ionic and covalent crystals range from 0.003-0.017 in-lb/in.² (500-3000 ergs/cm²).

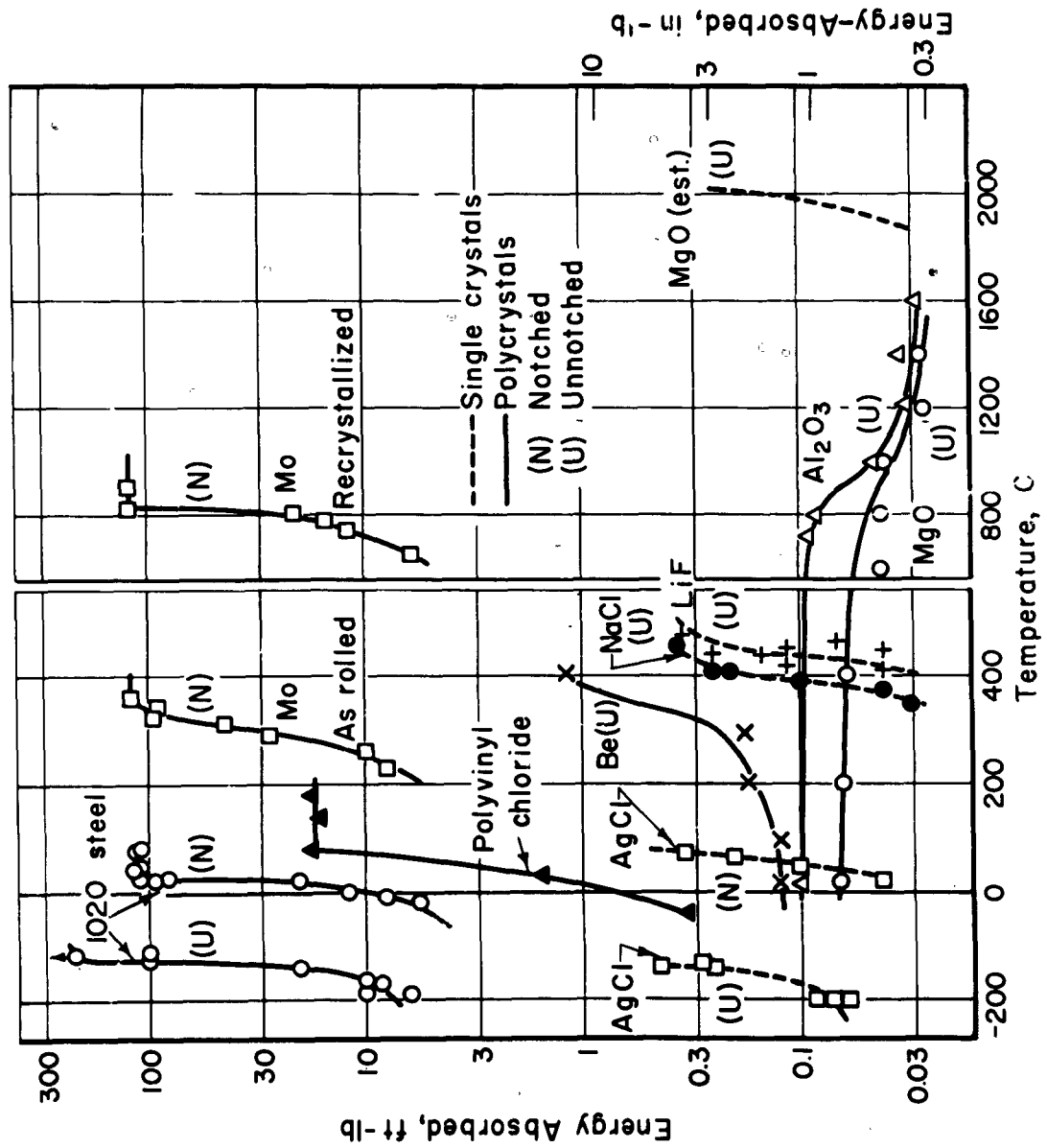


FIGURE 12. ENERGY-ABSORPTION CHARACTERISTICS OF METALS, CERMICS, AND A PLASTIC(32,33,42-45)

Fatigue

The load-carrying capacity of materials subject to either cyclic or sustained stress may deteriorate with time in the absence of obvious outward manifestations. Deterioration under cyclic stress or cyclic fatigue is the more familiar process. Table 6 illustrates that this type of fatigue is not restricted to metals. The cyclic fatigue characteristics of ceramics and polymers must also be considered when these materials are subjected to cyclic stress or vibrations.

An important consideration in designing with ceramic oxides and glasses is the deterioration of load-bearing capacity with time under sustained stress. This effect, illustrated in Table 7, is frequently referred to as "static" fatigue and is similar to the process of "delayed cracking" encountered in metals, notably steel and titanium when contaminated with hydrogen. As indicated in Table 7, static fatigue is related to the action of moisture or other constituents in the atmosphere at the surface of the material. In contrast, delayed cracking is thought to involve diffusion processes in the interior of the metal. In either case, strength values derived from short-time tests do not reflect the sustained load-bearing capacity of the materials.

Thermal Shock

Temperature gradients and the resulting differential thermal expansion and contraction generate residual stresses in materials. These "thermal" stresses can cause fracture, particularly in brittle materials, since the relaxation of the stress by plastic flow is not possible. The magnitude of the stresses produced by a particular heat flux in the absence of plastic deformation is a function of the thermal conductivity, the modulus of elasticity, and the coefficient of thermal expansion. As shown in Table 8, these factors can be combined into a useful parameter descriptive of the resistance to thermal-stress development. The table illustrates that metals and some ceramics are more resistant to thermal-stress development. The oxides MgO and Al₂O₃, mainly because of low thermal conductivity, offer characteristically poor thermal-shock resistance.

DESIGN PHILOSOPHY

This presentation of properties serves to illustrate many similarities among metals and nonmetallics subject to brittle behavior. Elastic properties are comparable in many cases. Both metals and nonmetallics are capable of plastic deformation. In both instances, ductility and fracture behavior can depend on composition, microstructure, temperature, and other test conditions. Finally, neither group is immune to fatigue or thermal shock. Significant differences also exist. Ductility, notch sensitivity, and energy-absorption data suggest that nonmetallics are more susceptible to cracking and fracture than brittle metals.

TABLE 6. CYCLIC FATIGUE STRENGTH OF VARIOUS MATERIALS

Material	Temp, C	Tensile Elongation, per cent	$\frac{S_f^{(a)}}{S_{ult}}$	$K_f^{(b)}$
SAE 4340 ⁽⁴⁶⁾	25	12	0.39	1.8
(230,000 psi)	-196	4	0.42	3.5
Molybdenum ⁽⁴⁷⁾	25	26	0.86	1.6
(unalloyed)	-40	0.06	1.05	1.6
Lucite ⁽⁴⁸⁾	25	-	0.18	0.8
Fiberglas ⁽⁴⁹⁾ laminate	25	0	0.35	1.0
Al ₂ O ₃ ⁽⁵⁰⁾	25	0	0.72	-
Glass ⁽⁵⁰⁾	25	0	1.00	-

(a) S_f/S_{ult} - endurance limit-to-ultimate tensile strength ratio.

(b) K_f - ratio of unnotched-to-notched endurance limit.

TABLE 7. STATIC FATIGUE STRENGTH OF VARIOUS MATERIALS

Material	Breaking Stress, psi	
	1 Sec	100 Days
Annealed glass ⁽⁵⁰⁾		
In air	16,000	7,000
In vacuum	25,000	23,000
Al_2O_3 ⁽⁵⁰⁾ (in air)	36,000	28,000
SAE 4340 ⁽⁵¹⁾		
Notched and charged with H_2	300,000	125,000
Uncharged	300,000	275,000

TABLE 8. THERMAL-SHOCK RESISTANCE OF VARIOUS MATERIALS⁽⁵²⁾

Material	$K/E\alpha \cdot 10^5$ (a)
Mo	180
W	160
Be	45
SiC	65
BeO	25
MgO	5
Al ₂ O ₃	7

(a) K = thermal conductivity (Btu/ft²/sec/F)
 E = elastic modulus, psi
 α = coefficient of thermal expansion per F.

The question of design must be examined in the light of these similarities and differences. Specifically, can design philosophy developed for metals subject to brittle behavior be applied to nonmetallics? Three separate cases are considered in the following paragraphs.

Transition-Temperature Philosophy

Metals subject to brittle behavior have been used successfully by restricting service to temperatures above the transition from ductile to brittle. Under these conditions brittle behavior is excluded; the metals deform extensively before breaking and are insensitive to material and design flaws. This philosophy may have value for some polymer plastics. Covalent and ionic materials do not exhibit a well-defined transition, nor do they possess, at any temperature, the ductility characteristic of metals above the ductile-brittle transition. Thus, the transition temperature concept is not expected to be useful for the ionic or covalent ceramics.

Crack-Propagation Philosophy

Semibrittle metals have been utilized successfully by maintaining stresses below the level required for crack propagation. This philosophy has been applied to ultrahigh-strength steel and titanium alloys in rocket motor casings and other applications exposed to temperatures below the ductile to brittle, where the metal is notch sensitive and subject to brittle fracture. Designs are based on the known level of notch sensitivity or fracture toughness and a knowledge of the largest crack or flaw in the structure likely to escape detection. It should be noted that this approach has so far been applied only in cases where some plastic deformation precedes fracture. The "ductile" ceramic single crystals also undergo some plastic deformation before breaking, and undoubtedly possess a high degree of notch sensitivity and low fracture toughness. A crack propagation philosophy may, thus, be appropriate for ceramic single crystals. However, notch sensitivity and fracture-toughness data, information not presently available for these crystals, must first be obtained.

A Brittle-Material Philosophy

Entirely brittle metals, those fracturing without prior plastic deformation, have not been used in tensile structures. For example, even brittle cast iron exhibits some flow and relatively high energy absorption on breaking. There is, therefore, no experience for metallic materials comparable to that for the brittle polycrystalline ionic or covalent ceramics. It is possible that the crack-propagation philosophy for semibrittle materials can be extended to brittle materials. However, it seems more likely that a design philosophy unique to brittle ceramics will have to be developed. In the interim, more information on the properties of brittle nonmetallics, particularly notch sensitivity, fracture toughness, and short- and long-time strength is clearly desirable.

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