THE TENSILE FRACTURE CHARACTERISTICS OF METALS UNDER HYDROSTATIC PRESSURES TO 23 KILOBARS*

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The effect of superposed hydrostatic pressures to 23 kb on the ductility of two b.c.c. and three h.c.p. metals, generally classified as brittle at atmospheric pressure, was examined. All the metals exhibited increases in ductility at sufficiently high pressures. Abrupt increases over narrow pressure ranges were observed for magnesium, zinc, tungsten and as-quenched carbon steel. In the case of cobalt, the increase in ductility showed an asymptote. The ductility, as a function of pressure over the temperature range of −55 to 175°C, is also presented for magnesium.

The observed changes in fracture characteristics as a function of pressure are analyzed in terms of a model offered in explanation of the pressure effect upon the ductility of metals. Consistent with the model, which is based on the stress state sensitivity of the various types of fracture mechanisms, it was observed in magnesium that pressure initially retarded intergranular fracture at room temperature and below and cavities above room temperature. The abrupt increase in ductility in magnesium after a region of near linear pressure dependency corresponded to the fracture converting to a shear type along intense deformation bands.

CARACTERISTIQUES DE RUPTURE PAR TRACTION DE DIFFERENTS METAUX SOUS DES PRESSIONS HYDROSTATIQUES POUVANT ATTEINDRE 23 KILOBARS

Les auteurs ont étudié l'influence d'une pression hydrostatique pouvant atteindre 23 kb sur la ductilité de deux métaux c.c. et de trois métaux h.c. généralement classés comme fragiles à la pression atmosphérique. Tous ces métaux ont montré une amélioration de la ductilité, pour autant que la pression appliquée soit suffisamment élevée. Pour le magnésium, le zinc, le tungstène et l'acier au carbone fraichement trempé, on a observé une amélioration rapide de la ductilité dans un domaine de pressions relativement étroit. Dans le cas du cobalt, l'accroissement de ductilité présente une asymptote. Les auteurs ont également étudié l'évolution de la ductilité en fonction de la pression pour le magnésium, dans une gamme de températures de −55 à + 175°C.

Les auteurs analysent les modifications de ruptures ainsi observées en fonction de la pression, à la lumière d'un modèle expliquant l'influence de la pression sur la ductilité des métaux. En accord avec ce modèle, qui est basé sur l'idée que les différents mécanismes de rupture sont sensibles à l'état de contraintes, on a observé dans le magnésium que l'application d'une pression retarde la rupture intergranulaire à la température ambiante et au-dessous de cette température, et retarde la formation de cavités au-dessus de la température ambiante. L'augmentation rapide de ductilité dans le magnésium, après une région dans laquelle celle-ci varie de manière presque linéaire avec la pression, correspond au fait que la rupture devient une rupture par cisaillement le long de bandes très fortement déformées.

DIE DEHNUNGSBRUCHEIGENSCHAFTEN VON METALLEN UNTER HYDROSTATISCHEN DRUCKEN BIS ZU 23 KILOBAR

Der Einfluß eines hydrostatischen Druckes bis zu 23 kb auf die Duktilität von zwei k.r.z. und drei hexagonalen, bei Atmosphärendruck als spröde klassifizierten Metallen wurde untersucht. Bei genügend hohem Druck zeigten alle Metalle eine Zunahme der Duktilität. Plötzliche Zunahmen in einem engen Druckbereich wurden für Magnesium, Zink, Wolfram und abgeschreckten Kohlenstoffstahl beobachtet. Bei Kobalt verlief die Duktilitätskurve asymptotisch. Die Druckabhängigkeit der Duktilität wird für Magnesium im Temperaturbereich −55°C bis 175°C angegeben.

Die beobachteten Änderungen der Brucheigenschaften mit dem Druck werden analysiert auf Grund eines Modells für den Druckeinfluß auf die Duktilität von Metallen. Das Modell basiert auf der Abhängigkeit vom Spannungszustand der verschiedenen Bruchmechanismen. Konsistent damit ist die Beobachtung an Magnesium, daß der Druck anfänglich bei und unterhalb Raumtemperatur den Korngrenzenbruch verzögert und oberhalb Raumtemperatur die Hohlraumbildung unterdrückt. Die plötzliche Duktilitätszunahme im Magnesium nach einem Bereich nahezu linearer Druckabhängigkeit entspricht einem Übergang des Bruches zum Schertyp entlang starker Verformungsbänder.

INTRODUCTION

The effect of a superposed pressure upon the ductility of materials has been studied by several investigators including Bridgman,[1,2] Pugh,[3] Galli and Gibbs,[4] Beresnev *et al.*,[5] and Bobrowsky.[6] These investigators have observed that, in all instances, ductility, as defined by either natural strain to fracture or reduction in area, is increased by a superposed hydrostatic pressure, but to drastically different degrees. For example, Bridgman and Beresnev *et al.* have observed that numerous metals exhibit a linear relationship between pressure and the natural strain to fracture with each metal having a characteristic slope. The latter investigators also proposed that in some cases ductility will not continuously increase with increasing pressure, but that at some characteristic pressure, the slope decreases and the ductility shows no further increases.

In contrast to other investigators, Pugh observed that the ductility was not a linear function of pressure for many metals other than certain steels. He reported for the case of copper and aluminum an initially linear region with a positive increase in slope at some characteristic pressure. In the case of zinc and bismuth, he observed little pressure effect upon ductility up to a given level of pressure. Then, over a very narrow pressure region, the ductility abruptly increased to very large values. Bobrowsky[6] and Galli and Gibbs[4] observed a similar phenomenon in tungsten and molybdenum respectively.

Explanation of why pressure so markedly affects

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ductility and particularly why the effects of pressure can vary so radically from material to material has not been investigated in detail. It has been generally proposed that the increase is due to the hydrostatic compressive stress counteracting the normal tensile stress applied to the sample while not affecting the shear stress which is responsible for deformation. This, however, cannot in itself explain the difference in the pressure effect between materials.

In explanation of the abrupt discontinuities in ductility he observed in zinc and bismuth which might be appropriately designated pressure-induced brittle–ductile transitions, Pugh proposed that its occurrence depended upon the strain hardening characteristics of the material in the following manner. Those metals having a low strain hardening coefficient would exhibit such discontinuities whereas high strain hardening coefficients would result in a linear dependency of ductility upon pressure. In contrast, Galli and Gibbs(4) observed that the brittle–ductile transition temperature for molybdenum is progressively lowered by increasing the pressure which represents another possible explanation for the occurrence of some pressure-induced discontinuities in ductility.

It seems to the present authors that a more complete explanation of how and why pressure affects the ductility of metals can best be derived from an understanding of how pressure affects the basic fracture process. In this current work, ductility as a function of pressure is examined for a series of b.c.c. and h.c.p. metals classified as brittle at atmospheric pressure. In explanation of these and the data of other investigators, a model based on the stress state sensitivity of the fracture mechanism is proposed. The fracture mechanism in polycrystalline magnesium as a function of pressure is examined. The observations are correlated with observed effects of pressure upon the ductility and interpreted in terms of the proposed model.

Proposed model

The fracture of metals can classically be divided into an initiation and a propagation stage. The initiation stage involves the formation of micro-cracks or voids as a result of shear strain or, in some instances, a combination of shear strain and diffusion. The propagation stage involves the extension of these voids or cracks by normal tensile stresses, or shear strain, or a combination of both.

In an ideal material, an external hydrostatic pressure does not introduce shear stresses but only normal compressive stresses. It has been shown by prior investigations, however, that in some instances internal shear stresses can be induced by an external pressure in real polycrystalline metals.[7,8] The occurrence of such shear stresses depends upon the degree of anisotropy of the linear compressibility. In metals exhibiting isotropy in the linear compressibility, which is the case for all cubic metals, no internal shear stresses will result from an external pressure. In contrast, in some non-cubic polycrystalline metals, viz. zinc, cadmium, bismuth, tin, shear stresses at grain boundaries exceeding the flow stress can occur at sufficiently high pressures. However, since such shear stresses are confined to anisotropic non-cubic metals, and also since their effect will be small and then limited to the shear strain dependent initiation stage of fracture, it will be assumed for the purpose of following discussion that a hydrostatic pressure will introduce no shear stress. Thus, by considering whether the various stages or types of fracture are dependent upon shear strain and/or normal tensile stress, one can develop a qualitative model of how a superposed pressure will affect the fracture mechanisms and thus ductility.

Listed in Table 1 are several of the classic types of fracture, which are subdivided into their respective initiation and propagation stages and the mechanism for each stage.[9] Also shown for each stage is whether the specific mechanism is predominantly dependent upon shear strain or normal tensile stress and the expected effect of a superposed hydrostatic pressure.

The initiation stage for brittle cleavage and intergranular fracture involves the formation of microcracks in the cleavage plane or grain boundary as a result of dislocation pile-up or intersection, or twin band intersection, all of which are shear-strain processes.

In the case of ductile fibrous or shear fracture, micro-discontinuities or voids form in deformation bands by dislocation pile-up or dislocation or twin intersection processes as in the brittle fracture modes and possibly also due to inclusion fracture or inclusion-matrix interface separation.

In the classic high-temperature rupture, intergranular cavities are formed as a result of grain-boundary sliding and diffusion controlled processes although some contribution by those mechanisms cited for ductile fibrous and shear fracture might also be anticipated. In any event, the initiation stage of high-temperature rupture is also a process dependent upon the occurrence of shear strain.

Since a superposed pressure does not introduce shear stresses, it will not affect the initiation stage of the various types of fracture cited except for a small

TABLE 1

Fracture type	Initiation Mechanism	Initiation Requirement	Pressure effect	Propagation Mechanism	Propagation Requirement	Pressure effect
A-Brittle						
(1) Cleavage	Dislocation or twin intersection or dislocation pile-up	Shear strain	Nil	$\sigma^2 > \alpha \dfrac{\gamma_s E}{c}$	Normal tensile stress	Decrease σ
(2) Intergranular	Dislocation pile-up or twin intersection at grain boundary	Shear strain	Nil	$\sigma^2 > \alpha \dfrac{(\gamma_s - \gamma_B)E}{c}$	Normal tensile stress	Decrease σ
B-High temperature rupture						
	Cavitation due to grain boundary sliding	Shear strain	Nil	Cavity growth and link-up	Shear strain	Retard cavity growth
C-Ductile						
(1) Fibrous	Void formation in deformation bands	Shear strain	Nil	Void extension in deformation bands	Shear strain + normal tensile stress	Retard void growth and extension, decrease σ
(2) Shear	Void formation in deformation bands	Shear strain	Nil	Void sheet formation in deformation bands	Shear strain	Nil

if not negligible effect upon dislocation formation and motion.

Consider the propagation stage: in the case of cleavage and intergranular fracture, propagation occurs when the strain energy released due to crack extension equals the increase in energy associated with the formation of new crack surfaces. This energy balance results in the basic Griffith relationships shown in Table 1 where σ is the applied normal tensile stress and γ_s and γ_B the surface and grain boundary energies respectively, and "c" the crack size. The effect of a superposed pressure then will be to decrease the normal tensile stress by the magnitude of the pressure, thus impairing, if not preventing, crack propagation by cleavage or intergranular modes.

The propagation stage of high-temperature rupture and fibrous fractures involves the growth and extension of voids requiring shear strain in combination with some normal tensile stress and, in the former case, vacancy diffusion at low strain rates. The effect of pressure then will be to reduce any normal tensile stress contribution and to resist the growth of voids.

One can estimate the effect of pressure on retarding void growth by considering the parallel case of the yielding of a hollow sphere of infinite wall thickness under an external pressure.[10] From elasticity theory and assuming either a maximum shear stress or the Von Mises–Hencky yield criteria, collapse of the sphere will occur at a pressure equal to two-thirds the yield stress. Thus, one would not expect to see spherical void growth at pressures above two-thirds the yield stress at the test condition. Similar elastic solutions are also available for the ellipsoidal cavity case.[11]

Ductile shear fracture propagation is by means of void-sheet formation in severe deformation basis. Being primarily a shear-strain process, it is relatively unaffected by pressure.

In summary then, the proposed model is that pressure has little or no effect upon the initiation stage of fracture; its principal effect is in the propagation stage where it retards those mechanisms requiring normal tensile stresses or the growth and extension of large voids. Its effect then will be to retard those propagation mechanisms associated with brittle or low ductility type fractures, thus favoring those involving shear strain and high ductility.

EXPERIMENTAL PROCEDURE

Apparatus

The 30-kb Bridgman–Birch type hydrostatic pressure system used in this work has been previously described in detail.[7] It will suffice to say that this system is a piston–cylinder device having a high pressure cavity of 0.75-in. dia. with an 8-in. working length and 4-in. piston stroke. Pressure measurement is by means of a manganin wire transducer used in conjunction with a Foxboro recorder. The estimated error in pressure measurement is ± 2 per cent.

The fixture utilized for the conduct of the tensile tests under pressures to 23 kb is shown in Fig. 1 along with a typical specimen. This fixture consists of 4 segments or legs, two of which are stationary and bear against the bottom closure of the pressure cavity. The remaining pair of legs are movable and are driven downward by the advance of the main piston into the pressure cavity, thus inducing a tensile force in the specimen.

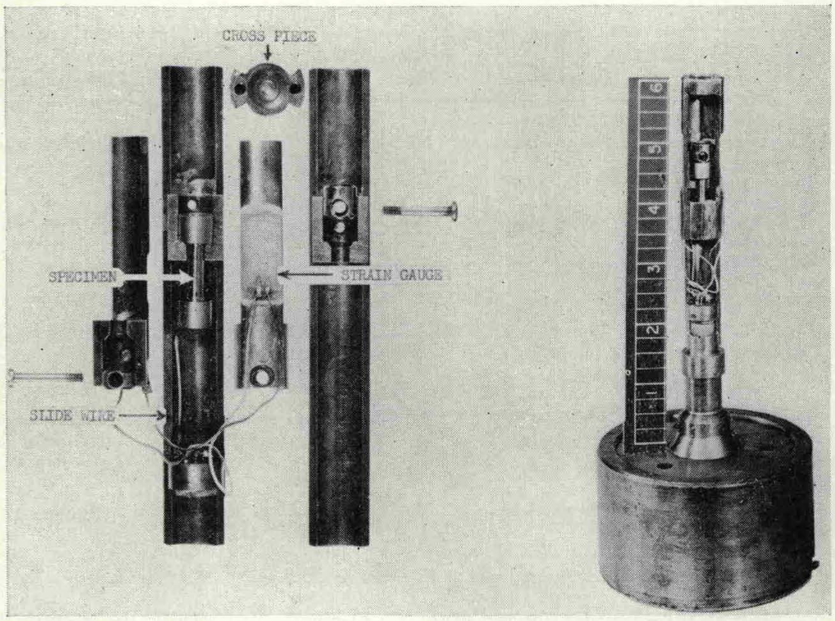

Fig. 1. High-pressure tensile specimen holder.

Materials and specimen configuration

The following materials and material conditions were utilized in this investigation:

Material	Purity %	Condition	Grain size (mm)
Magnesium	99.98	Hot extruded	0.08
Zinc	99.99	Hot drawn	0.08
Cobalt	99.9	Hot swaged	0.03
Tungsten	99.9	Pressed and sintered	0.09
1045 Steel	Alloy	Water quenched from 843°C. 61 R_c	0.07

In the pressure range of this investigation, these metals do not undergo any abrupt changes in electrical resistance nor in volume indicative of an allotropic transformation.[12]

The specimen configuration, as can be seen in Fig. 1, has a length of 9/16 in. as measured between the shoulders and section diameters of 0.160 in. for magnesium, zinc and cobalt, and 0.070 in. for the 1045 steel and tungsten.

Procedure

Since the actual straining of the specimen while under pressure was accomplished by the motion of the main piston, an increase in pressure occurred during the conduct of the test. The actual pressure change observed during the conduct of a test depends upon the ductility of the material being tested. For materials in their brittle form, little displacement of the piston is required and the pressure increase is quite small. In the case of ductile materials, or at pressures above brittle–ductile transition where the ductility can be quite high, the pressure variations during testing can be large. However, in the initial stages of the brittle–ductile transition, which is of principal concern in this investigation, the pressure change during the test is relatively small viz. 0.5 kb for magnesium at 4 kb, and 0.1 kb for steel at 18.5 kb. The fact that large changes occur above the transition pressure, particularly in the case of magnesium and zinc, has little bearing on the results or on the conclusions drawn therefrom since it is beyond the pressure region of major concern. For the purpose of reporting the data, only the final pressure, i.e. the pressure at fracture, is plotted.

The strain rate used throughout this investigation, as measured from the displacement rate of the high-pressure piston, was maintained at 0.05 in/min.

The tests for all materials except magnesium were conducted at ambient temperature. For the studies on magnesium at elevated temperatures, i.e. 100°C and 175°C, the outer restraining jacket of the pressure system was removed and the entire high-pressure cylinder was wrapped with a heating tape. For the tests conducted at —55°C, the high pressure cylinder was immersed in a dry ice–acetone bath.

Temperatures within the high-pressure cylinder were measured by the calibrated resistance change of an annealed platinum wire. The estimated error in the temperature measurement was ± 3 per cent.

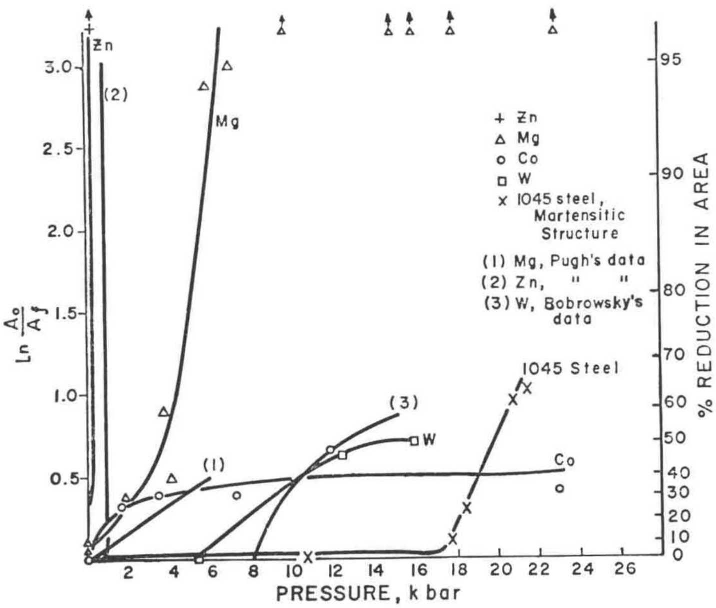

FIG. 2. Effect of pressure upon the ductilities of various metals.

The metallographic preparation of the fracture surfaces of magnesium was standard except for the vapor deposition of a layer of chromium on the fracture surface to prevent edge rounding. Mechanical polishing was used. The etchant consisted of 20 parts acetic acid, 60 parts ethyl glycol, 1 part nitric acid, and 19 parts distilled water.

RESULTS AND DISCUSSION

Effects of pressure on ductility

Ductility in terms of natural strain to fracture and reduction in area as a function of pressure at ambient temperature is summarized in Fig. 2 for the metals investigated. In the case of zinc, an abrupt brittle–ductile transition occurred at 0.1 kb where the ductility increased from 23 to 100% reduction in area. In comparison, Pugh observed the occurrence of the transition at 1 kb. The difference between the two results can be readily accounted for by the lower purity (99.8%) material used by Pugh as compared to that of the current investigation.

Initially, magnesium showed a nearly linear region and then a sudden increase in ductility to effectively 100% at 4 kb. In comparison, Pugh observed a linear region up to 6 kb although it is likely that he would have observed a similar transition in ductility had he gone to somewhat higher pressures. The difference in results may be attributable to a large difference in grain size and processing history.

Both tungsten and 1045 steel exhibited similar results consisting of a pressure insensitive region with an apparent brittle–ductile transition at 6–10 and 17 kb respectively. A similar observation for tungsten was recently reported by Bobrowsky.[6]

In contrast to the other metals, cobalt exhibited an initial increase in ductility up to 4 kb with no further pressure effect up to 23 kb.

Figure 3 summarizes the effects of pressure upon the ductility of magnesium at several temperatures. Each curve shows an initial region over which the ductility increases somewhat linearly with pressure until a point is reached at which the ductility goes effectively to 100% over a narrow pressure region. The relationship, if any, between this type of pressure-induced brittle–ductile transition and the commonly known temperature-induced transition at atmospheric pressure is currently under investigation and will be reported separately.

Macroscopic fracture appearance

Among the metals investigated, steel, cobalt and tungsten exhibited a planar or flat type of brittle fracture at atmospheric pressure, and a cup–cone type at high pressure. In terms of the nomenclature in Table 1, the flat portion of the cup–cone is fibrous or a combination of fibrous fracture and cleavage, and the inclined portion shear type ductile fracture. With increased pressure, the area of the fibrous fracture decreased with an associated increase in ductility, which is consistent with the proposed model. Zinc necked to a point above the transition pressure. In contrast, magnesium exhibited a drastically different behaviour. However, since magnesium was studied in great detail, its macroscopic fracture appearance will

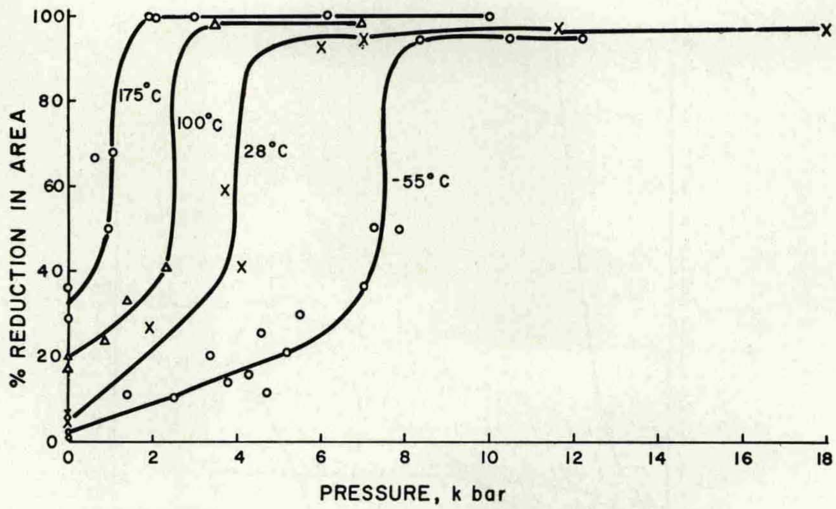

FIG. 3. Effect of pressure upon the ductility of magnesium at various temperatures.

be subsequently described in conjunction with the observed effects of pressure on fracture mechanism.

Fracture of magnesium

Atmospheric pressure. The macroscopic and microscopic fracture characteristics of magnesium at atmospheric pressure and various temperatures are shown in Figs. 4 and 5 respectively. The macrofracture appearance is brittle at low and ambient temperatures, progressively changing to a ductile rupture at higher temperatures. The associated ductility increased continuously with no apparent brittle–ductile transition over the temperature range of −55°C to 175°C. The microstructure in a plane parallel to the tensile axis, as shown in Fig. 5, shows predominantly intergranular fracture at −55°C with lesser amounts at room temperature, which is in agreement with the results of Hauser *et al.*[13] One can readily see the intergranular fissures which formed behind the fracture surface particularly at −55°C. At 70°C, voids started to form which increased in size and propensity at 175°C. As is typical of high temperature rupture, these voids formed at grain-boundary triple-points and grew into spherical

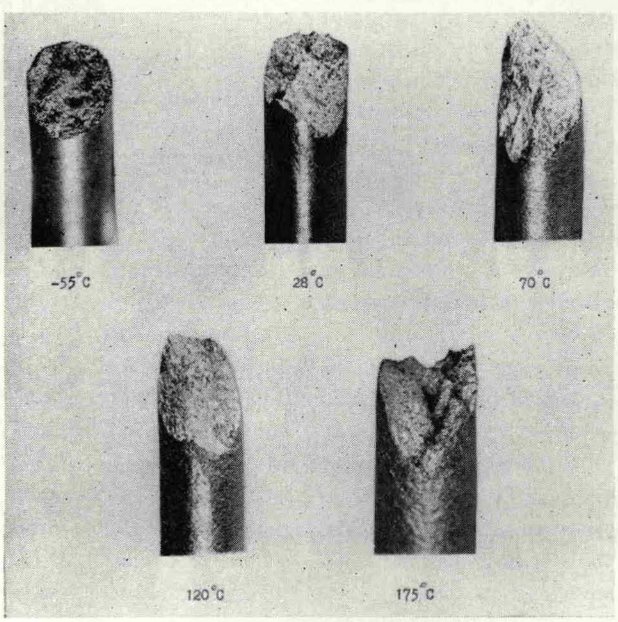

FIG. 4. Fracture appearance of magnesium as a function of temperature at atmospheric pressure.

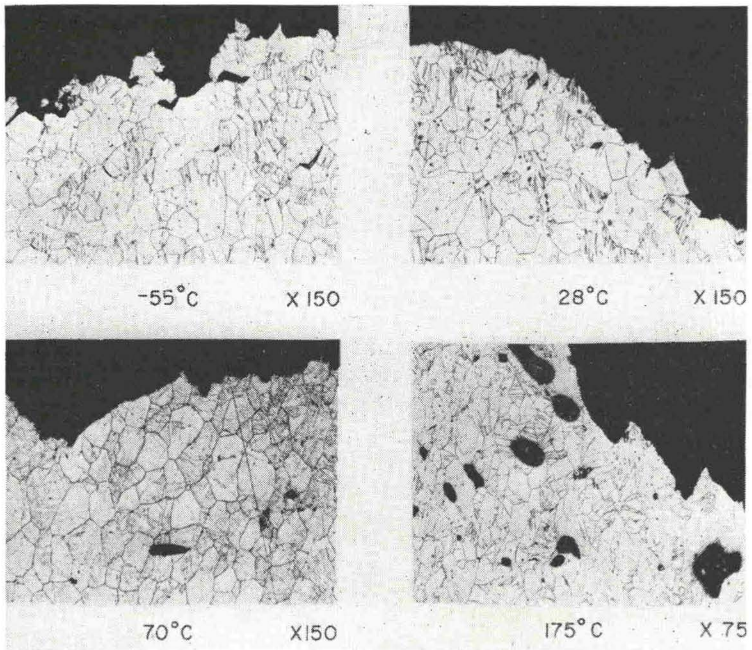

FIG. 5. Microstructure of magnesium near fracture surface at various temperatures, atmospheric pressure.

cavities which either linked together or reduced the actual load carrying cross-section to the point where rupture occurred.

Low temperature. The macroscopic fracture appearance for magnesium, as a function of pressure at −55°C, is shown in Fig. 6. Initially, one sees a progressive increase in the amount of necking along with a retardation of the brittle fracture appearance and finally the onset of shear and fibrous fracture. The abrupt discontinuity in ductility shown in Fig. 3 corresponds to the fracture appearance connecting to the shear or gliding type along the shear plane as shown in the latter two photographs of Fig. 6. Above the transition pressure, no further change in fracture appearance occurred. At room temperature, the fracture appearance was much the same as at −55°C.

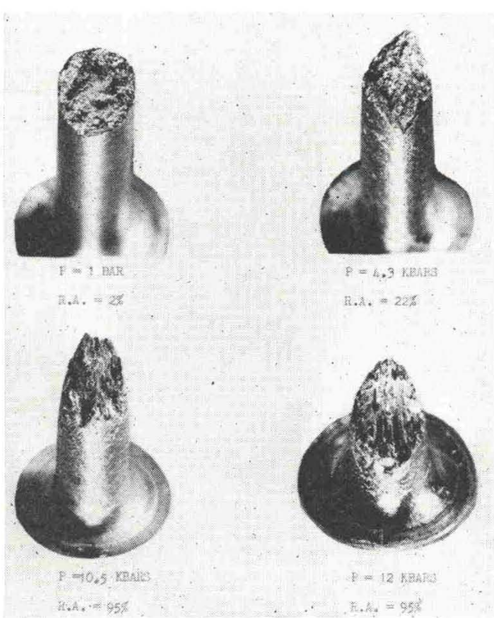

FIG. 6. Fracture appearance of magnesium as a function of pressure at −55°C.

Figure 7 shows a longitudinal plane through the center of a specimen above the transition pressure with the test being interrupted just prior to fracture. As can be seen, the specimen glided along the shear plane which, due to the constraint of the tensile fixture, introduced bending stresses of sufficient magnitude to severely bend the sample. The final stage of fracture involved the formation of external cracks around the periphery which penetrated inward. The crack in the center of the remaining cross-section actually was a crack initiating on the hidden surface. Since cracks do initiate at the surface at low temperatures, the gliding cannot proceed indefinitely, but still reductions in areas of 95% or greater were obtained.

The microstructural aspects of the fracture, as a function of pressure at −55°C, are summarized in Fig. 8. At this low temperature, the initial pressure effect is to progressively retard intergranular fracture

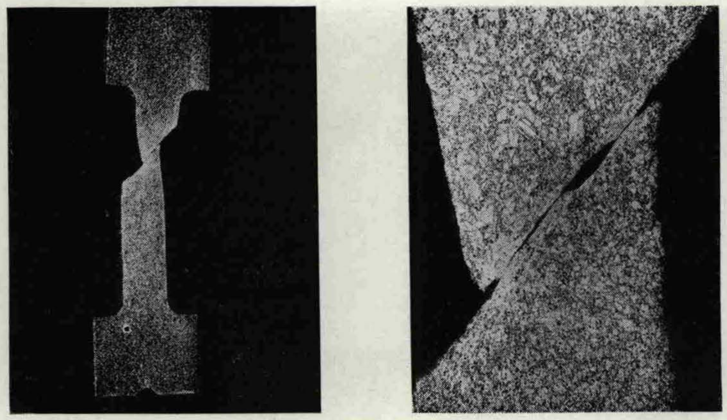

FIG. 7. Gliding type of fracturing at high pressures $-55°C$.

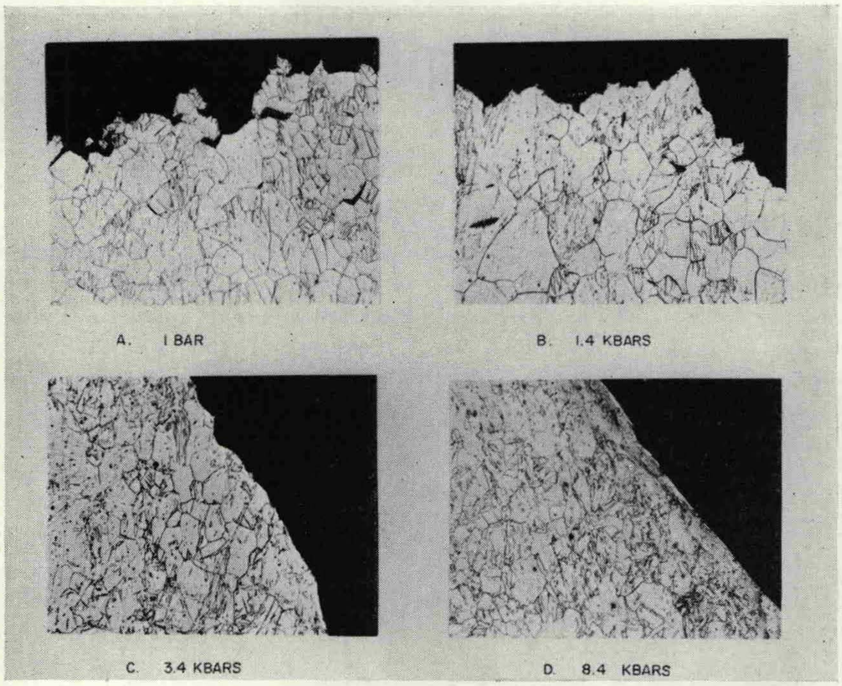

FIG. 8. Effect of pressure on fracture of magnesium at $-55°C$. $\times$ 150

as shown in Figs. 8(A–C), driving the fracture mechanism towards a transgranular process similar to the fibrous type. This then corresponds to the initially linear region of the pressure–ductility curve of Fig. 3. In the region of the transition and above, the fracture is total shear along a severe localized deformation band as shown in D. When this occurs, the structure adjacent to the fracture cannot be defined.

Electron fractographs for the atmospheric pressure fracture surface shown in Fig. 8(A) and for the high pressure surface in Fig. 8(D) are shown in Figs. 9(A–B) and (C–D) respectively. The fracture direction is towards the lower right-hand corner of each fractograph, except C, in which it is toward the lower left-hand corner. In the case of the atmospheric pressure fracture, one can see intergranular fracture A as well as dimpling B. The high-pressure fractographs (C and D) show large regions of regular ridges similar in appearance to the serpentine glide found in torsional fracture in magnesium[14] as well as large "featureless" areas. No intergranular fracture is evident. Also, there is an absence of dimples as is

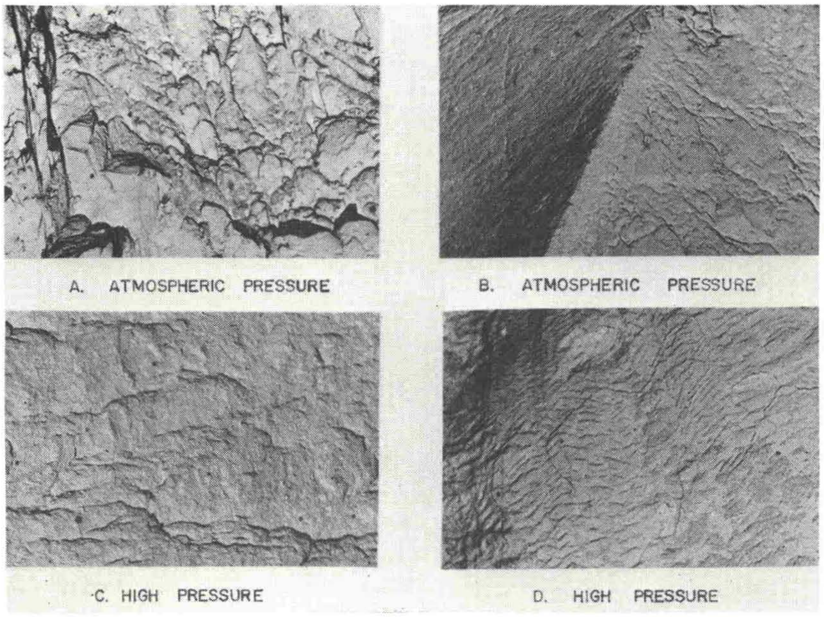

FIG. 9. Electron fractographs of magnesium fractured at −55°C. ×6,500

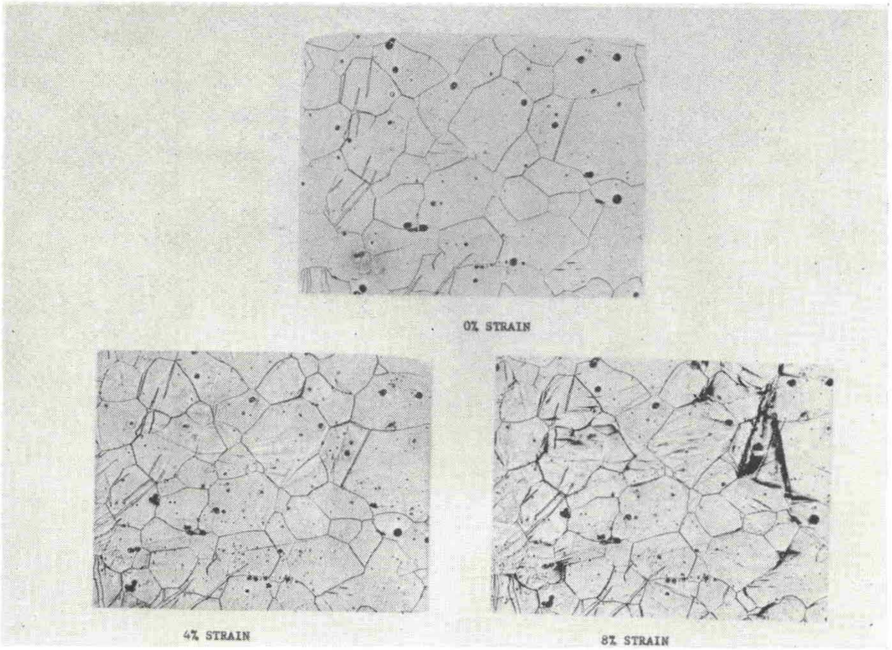

FIG. 10. Microstructures of magnesium after various values of tensile strain, 6 kb, 28°C. ×150

characteristic of normal ductile fracture. Dimples are associated with voids, thus one can deduce that since no dimples occur, the superposed hydrostatic pressure has prevented the formation of voids.

Figure 10 shows the initiation of the shear fracture occurring above the transition pressure at room temperature. In this case, the sample was metallographically prepared prior to being tested. The original structure is shown in A. After 4% elongation one sees mechanical twinning, basal slip, and grain-boundary shear, all of which also occur at atmospheric pressure.[13] At 8% strain, a shear-type fracture has occurred along a localized deformation band through one of the grains. There is no evidence of multiple slip.

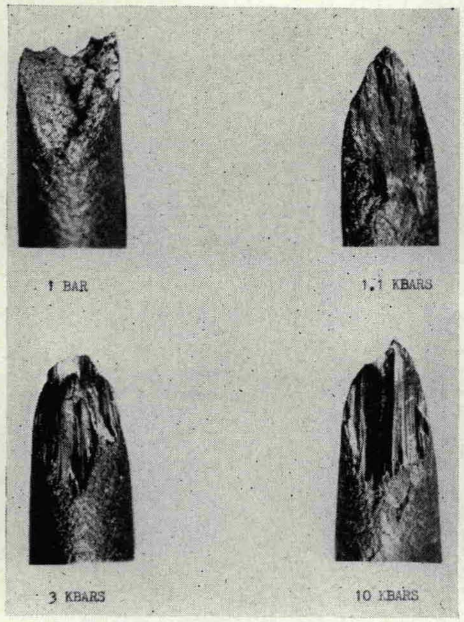

FIG. 11. Fracture appearance of magnesium as a function of pressure at 175°C.

High temperature. The macroscopic fracture appearance, as a function of pressure, at 175°C is shown in Fig. 11. Initially, one sees the elimination of the large voids characteristic of the atmospheric pressure fracture with an associated increase in necking and ductility. At slightly higher pressures, the fracture converts to the gliding type approximately along the shear plane. As in the case of the low-temperature fracture, above the transition pressure, no further change in fracture appearance occurred with increasing pressure.

An interrupted fracture above the transition pressure is shown in Fig. 12. In contrast to that observed at low temperature, no external or internal cracks were evident and the fracture occurred by gliding along a plane of intense and localized shear strain. Even in view of the high bending stresses tending to separate the surfaces, the gliding continued until the surfaces separated at a point with reductions in areas approaching 100%.

The microstructural aspects of the fracture process at high temperature are shown in Fig. 13. One first

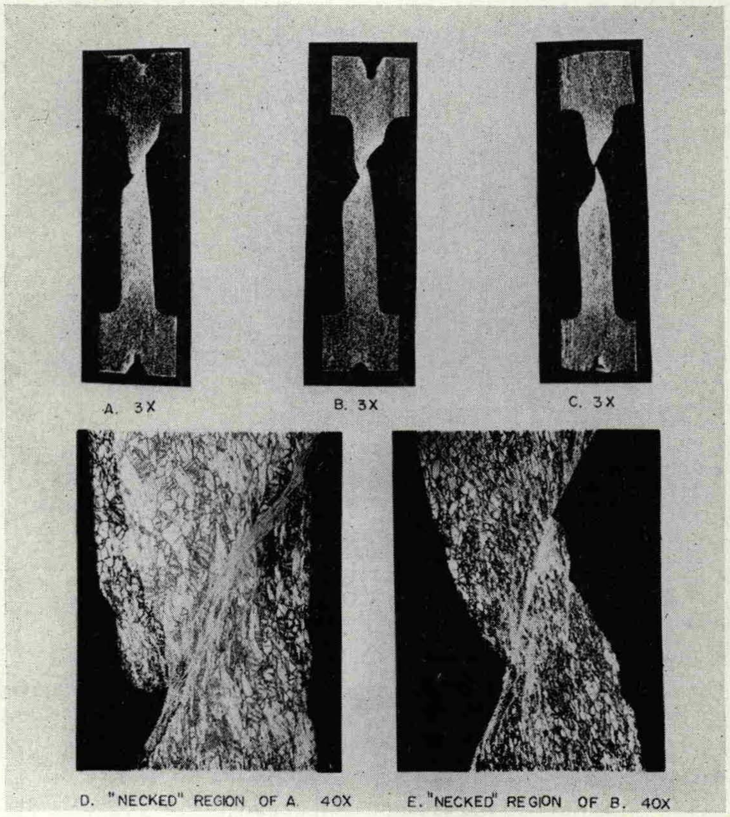

FIG. 12. Gliding type of fracturing at high pressures 175°C.

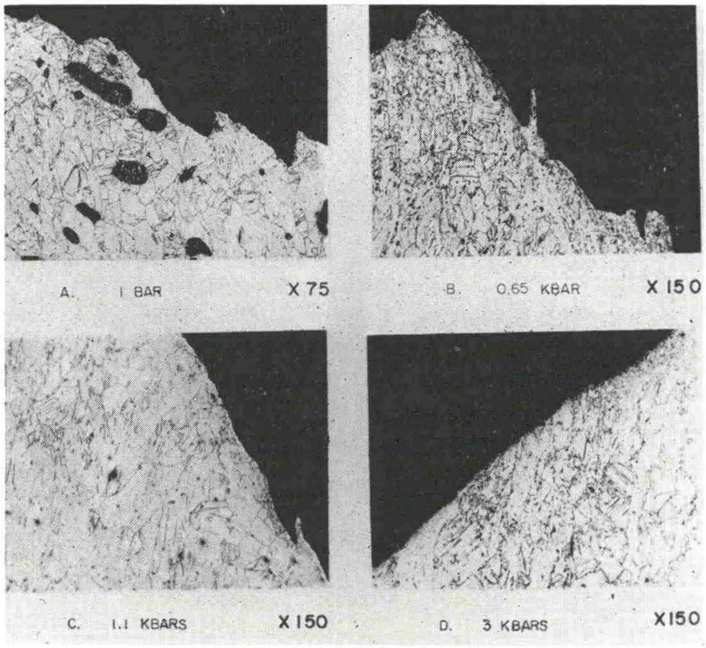

FIG. 13. Effect of pressure on fracture of magnesium at 175°C.

observes that at pressures as low as 0.65 kb (B), the large cavities characteristic of atmospheric pressure fracture (A) are no longer apparent. Theoretically, the hydrostatic pressure that will collapse a spherical void is two-thirds the yield strength. In the case of magnesium at 175°C, this comes out to be equivalent to 0.22 kb, which is in agreement with the metallographic observations on longitudinal sections of specimens tested at 0.20 and 0.45 kb; at 0.20 kb, small rounded voids could still be seen behind the fracture surface, while at 0.45 kb, no internal voids were discernible. At approximately 1 kb, the fracture becomes the shear type (C) along an intense deformation band with no further change at high pressures (D). Again, as in the case of the low-temperature shear fracture occurring above the transition pressure, the structure near the fracture surface cannot be readily resolved. It is likely, particularly at 175°C, that considerable recrystallization has occurred adjacent to the fracture surface due to the high and localized strains.

SUMMARY AND CONCLUSIONS

Superposed hydrostatic pressures to 23 kb enhance the ductilities of magnesium, zinc, cobalt, tungsten, and the martensitic phase of 1045 steel. The pressure–ductility curve of cobalt has an asymptote. The remaining metals initially exhibit nearly linear pressure dependence or pressure insensitivity followed by an abrupt and large increase in ductility over a narrow pressure range.

The observed change in fracture characteristics as a function of pressure is consistent with the model offered in explanation of the effects of pressure upon ductility. This model proposes that pressure will retard those fracture types having a propagation stage dependent upon normal tensile stresses (cleavage, intergranular) or the growth of voids (fibrous, high temperature rupture) thus favoring those dependent principally upon shear strain.

In magnesium, the initial nearly linear dependency of ductility upon pressure corresponds to the retardation of intergranular fracture at and below room temperature and to the prevention of cavities above room temperature. The abrupt increase in ductility after the linear region corresponds to the fracture converting to the shear type along intense deformation bands.

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