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