THE EFFECT OF HYDROSTATIC PRESSURE ON THE TENSILE FRACTURE OF α-BRASS*

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A detailed study has been made of the effects of hydrostatic pressures in the range 0.1–600 MPa on the tensile fracture strain of an α-brass. Fracture strain has been found to increase linearly with pressure up to 350 MPa, to decrease between pressures of 350 and 375 MPa and to then increase to a constant value at pressures greater than 450 MPa. The abrupt change from linearity of the fracture strain–pressure relationship at a pressure of 350 MPa was found to coincide with the suppression of large scale void development. At pressures below 350 MPa, fracture was found to occur by the conventional mechanism involving void coalescence whereas at higher pressures fracture occurred entirely by a shear process. Calculations of the increase of the resultant triaxial stress component in the necked region of specimens with strain have shown that, at pressures up to 350 MPa, fracture occurs when this stress reaches a critical value of about 325 MPa.

INFLUENCE DE LA PRESSION HYDROSTATIQUE SUR LA RUPTURE PAR TRACTION DU LAITON α

On a étudié en détail l'influence des pressions hydrostatiques (de 0,1 à 600 MPa) sur la déformation à la rupture par traction d'un laiton α. La déformation à la rupture augmente linéairement avec la pression jusqu'à 350 MPa, puis décroît entre 350 et 375 MPa et enfin augmente et atteint une valeur constante pour les pressions supérieures à 450 MPa. Le changement brutal dans la relation entre la pression et la déformation à la rupture, observé à 350 MPa, coïncide avec l'arrêt du développement des cavités. Pour les pressions inférieures à 350 MPa, la rupture est produite par le mécanisme habituel de coalescence des cavités, alors qu'aux pressions plus élevées elle est produite uniquement par un processus de cisaillement. Les calculs de la variation des composantes triaxiales de la contrainte résultante en fonction de la déformation dans la zone de striction montrent que, pour les pressions alllant jusqu'à 350 MPa, la rupture se produit quand cette contrainte atteint une valeur critique de 325 MPa environ.

EINFLUß DES HYDROSTATISCHEN DRUCKES AUF DEN BRUCH VON ZUGVERFORMTEM α-MESSING

Der Einfluß des hydrostatischen Druckes im Bereich 0,1 bis 600 MPa auf die Bruchspannung von α-Messing wurde ausführlich untersucht. Die Bruchspannung nimmt mit dem Druck bis 350 MPa linear zu, zwischen 350 und 375 MPa wieder ab und schließlich bei höheren Drucken wieder zu, bis sie bei 450 MPa einen konstanten Wert erreicht. Die abrupte Abweichung des Zusammenhangs zwischen Bruchspannung und Druck von der Linearität bei einem Druck von 350 MPa erfolgt gleichzeitig mit der Unterdrückung der Entstehung großer Hohlräume. Bei Drucken unterhalb 350 MPa erfolgt der Bruch durch den konventionellen Mechanismus (aneinanderlagern von Hohlräumen). Bei höheren Drucken ist jedoch ein Scherprozeß der bestimmende Mechanismus. Eine Berechnung der Zunahme der resultierenden triaxialen Spannungskomponente im Bereich des Bruchhalses der Proben als Funktion der Spannung zeigt, daß bei Drucken bis 350 MPa der Bruch erfolgt, wenn diese Spannung einen kritischen Wert von etwa 325 MPa erreicht.

INTRODUCTION

The increase in fracture strain of various brasses when strained in tension under increasing external hydrostatic pressures has been shown to be a substantially linear relationship with pressure up to a critical pressure of 300–400 MPa.[1–3] This increase in fracture strain is due to the effect of external hydrostatic pressure on the stress system in the necked region of tensile specimens.[4] In tests under ambient pressure conditions a tensile triaxial stress is produced in the necked region of the specimen and this enhances void development which leads to fracture. However, in tests in the presence of external hydrostatic pressure the triaxial stress in this region of the specimen will be compressive until the neck is well developed, thus retarding the development of voids and allowing the necking to proceed further before fracture occurs.

At pressures above the critical pressure the fracture strain of brasses either increases much less rapidly with pressure[3,5] or is constant.[1,2] This type of behaviour (also found to occur in copper–germanium alloys[2]) has been attributed to a number of causes. Yajima *et al.*[2] suggested that, in metals with low stacking fault energy such as brasses, the process of ductile fracture might be dominated by the shear stress rather than by the triaxial stress component. Beresnev *et al.*[5] have suggested that in two phase brasses the behaviour may be related to changes in phase composition due to pressure. French, Weinrich and Weaver[3] have found that, in a leaded two phase brass at pressures above the critical pressure, void development occurs only in a narrow region of the neck of the specimen very late in the deformation process. They therefore suggest that the decrease of pressure sensitivity of the fracture strain is attributable to the suppression of void development.

As far as is known, the only previous work on the effects of pressure on the fracture of single phase

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brasses was done by Yajima *et al.*[2] However, no detailed examination of the effects of pressure on void development or calculations of the stress conditions in the neck regions have been made for such brasses. Accordingly, for the purpose of studying further the anomalous behaviour of fracture strain with increasing pressure, a single phase brass of low inclusion content was used. In seeking an explanation for the variation of fracture strain with pressure, void distributions in fractured specimens were measured and the stress situations in the central neck regions of specimens strained to varying degrees in the pressure range 0.1–600 MPa were calculated.

EXPERIMENTAL

Tensile test specimens of 10 mm gauge length and 4 mm dia. with threaded ends were machined parallel to the rolling direction from one piece of 13 mm thick rolled brass plate of composition 70.1 wt.% Cu, 29.9 wt.% Zn plus trace impurities only. Prior to testing all specimens were annealed at 600°C for 1 hr; the ultimate tensile strength was 310 MPa and the mean grain dia. 0.07 mm. The high pressure apparatus and method of use have been described previously.[3] All tests were made at room temperature using ethanol as a pressure medium, at a deformation rate of 1.7×10^{-2} mm/s.

Two types of experiment were carried out. In the first type specimens were strained to fracture at pressures within the range 0.1–600 MPa and their minimum neck diameters measured. The fracture surfaces of these specimens were examined using a Scanning Electron Microscope (S.E.M.) and polished longitudinal sections through the fractures were examined optically. The second type of experiment involved straining specimens by various amounts to just below the fracture strain at a number of pressures. Measurements of the minimum neck diameter and radius of curvature of the contour of the neck of each of these unfractured specimens were obtained from tracings made of projections of the neck contours at magnifications up to ×50.

RESULTS

(a) *Fracture experiments*

Specimens were strained to fracture at pressure intervals of 50 MPa between atmospheric pressure and 600 MPa with duplicate tests being made at pressures of 0.1, 300, 400 and 500 MPa. The natural strain to fracture (ε_f) of the specimens was calculated from the relationship $\varepsilon_f = \ln A_0/A_f$ where A_0 and A_f are the initial and final minimum cross-sectional areas of the specimens. The resulting variation of ε_f with pressure is shown in Fig. 1. This figure shows that ε_f increases linearly with pressure for pressures up to about 350 MPa. At pressures between 450 and 600 MPa, the fracture strain is approximately constant. The experiments at a pressure of 400 MPa yielded lower ε_f values than those for specimens tested at either 350 or 450 MPa. To check the extent of this effect further experiments were carried out at pressures of 375 and 425 MPa. The fracture strain values from these experiments were also lower than expected as shown in Fig. 1.

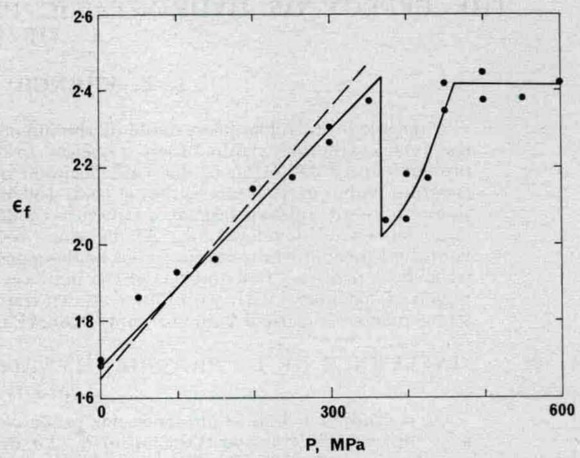


FIG. 1. Variation of natural strain to fracture (ε_f) with pressure (P).

Metallographic examination of longitudinal sections through one part of these fractured specimens showed that voids were present near the fracture surfaces of specimens fractured at pressures up to 350 MPa but that no voids could be seen in specimens fractured at higher pressures. The average area fraction of voids in the longitudinal sections of the regions of these specimens close to the fracture surfaces was determined using a Quantimet Image Analysing System. This was done by measuring the average area fraction of voids and inclusions near the fracture surface then subtracting the average area fraction of inclusions in the undeformed material. The resulting values of area fraction of voids are plotted against pressure in Fig. 2. This figure shows that the area fraction of voids decreases with increasing pressures up to about 350 MPa and is zero (within the limits of measurement) at higher pressures.

The surfaces of specimens fractured at pressures up to 350 MPa were made-up of a rough central region caused by void coalescence and a smoother outer region caused by shear tearing (see Fig. 3a). The fracture surfaces of specimens fractured at pressures above 350 MPa were found to consist entirely of the

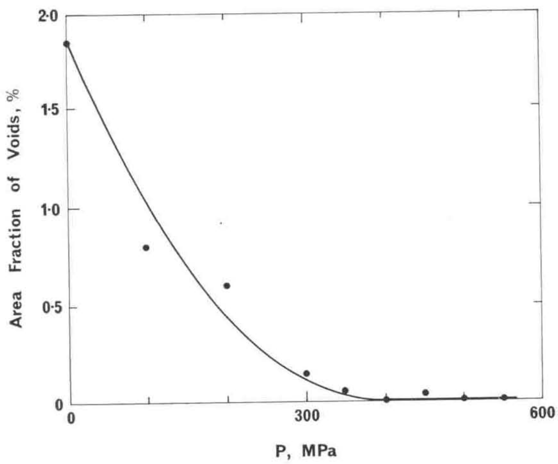


FIG. 2. Variation of area fraction of voids with pressure (P).

smoother surface characteristic of shear tearing (see Fig. 3b).

(b) *Non-fracture experiments*

Series of experiments were carried out at hydrostatic pressures of 0.1, 200, 300, 400, 500 and 600 MPa. At each pressure a number of specimens were strained by varying amounts up to almost the fracture strain. Measurements were made of the minimum neck dia. ($2r$), the radius of curvature of the contour of the neck (R) and the final load for each specimen. From these measurements the resultant triaxial stress component (H) at the centre of the neck of each specimen was calculated using the following equation originally derived by Bridgman.[(4)]

$$H = -P + F \ln \frac{(r^2 + 2rR)}{(2rR)} \qquad (2)$$

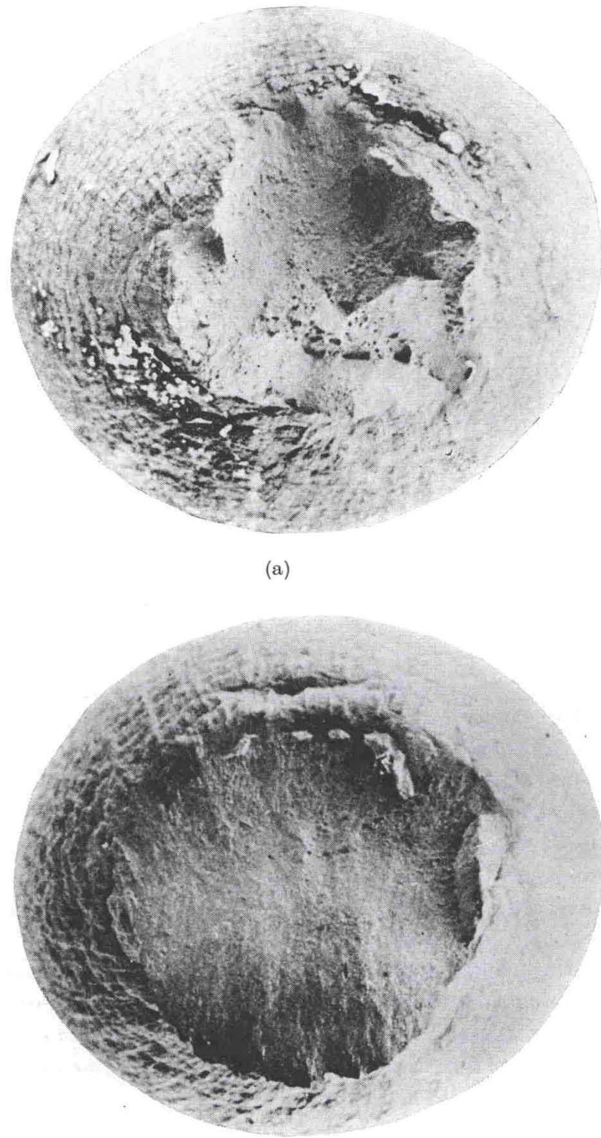
where

$$F = \frac{1}{(1 + 2R/r) \ln (1 + \frac{1}{2}r/R)} \times \frac{\text{Load}}{\pi r^2} \qquad (3)$$

and P is hydrostatic pressure. The H values calculated in this way are plotted against the corresponding natural strains in Fig. 4. The approximate H value for fracture at each pressure was obtained by extrapolating the H against ε plots to the fracture strain, as indicated in the figure. The main features of these plots are:

(1) H becomes positive (tensile) during the deformation at all pressures used but the natural strain at which this occurs increases with pressure.

(2) At all pressures H increases approximately linearly with natural strain between the strain at which necking begins and fracture.



(a)

(b)

FIG. 3. Scanning electron micrographs of the fracture surfaces of specimens fractured at pressures of (a) 350 MPa and (b) 400 MPa. $\times 20$.

(3) The plots of H against ε for the various pressures are approximately parallel.

(4) The H values at fracture of specimens tested at pressures of 0.1, 200 and 300 MPa are approximately constant and equal to 325 ± 25 MPa.

(5) The H values at fracture for specimens tested at pressures of 400, 500 and 600 MPa are significantly lower than the values obtained at the lower pressures and tend to decrease with pressure.

It should be noted that the extrapolation of the H against ε plots to give a H value for fracture is only a convenient approximation to the real situation at

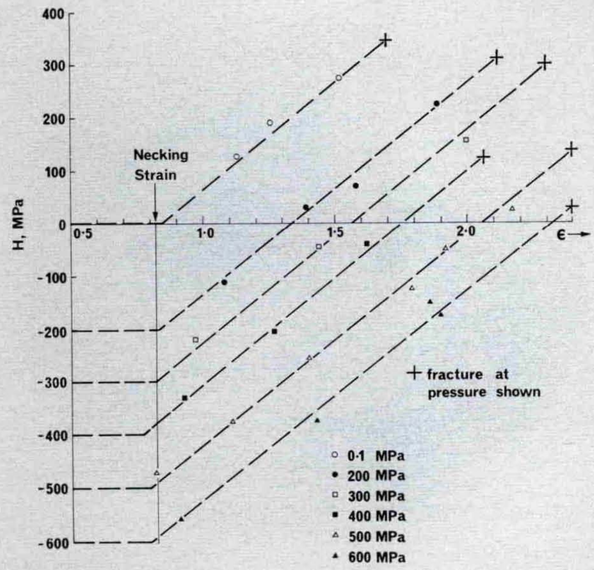


FIG. 4. Plots of the variation of the triaxial stress component (H) at the centre of the neck with natural strain (ε) for the pressure shown.

fracture at the lower pressures. This is because calculations of H based on equations (2 and 3) break-down when macroscopic voids are present in the material as they are late in the necking process since the true load-bearing area is then unknown. Also, the H values calculated for very high strains at pressures of 500 and 600 MPa are subject to some uncertainty. This is because an assumption made in deriving equations (2 and 3) was that the contours of the necked regions of specimens are circular but these contours for specimens taken to natural strains greater than 2.0 were not good approximations to portions of circles so that there was some uncertainty in measuring R.

DISCUSSION

The variation of fracture strain with hydrostatic pressure can conveniently be divided into two pressure regions: the behaviour at pressures between atmospheric pressure and 350 MPa and the behaviour at higher pressures.

(a) *Pressures up to* 350 *MPa*

Figure 1 shows that the fracture strain increased approximately linearly over this pressure range as noted previously by other workers.[2] The studies of the area fraction of voids and of the appearance of the fracture surfaces revealed that the formation of macroscopic voids was progressively suppressed over this pressure range—the suppression being complete at a pressure of about 350 MPa. Thus the conventional tensile fracture mechanism involving the formation then coalescence of voids in the central portion of the neck of a specimen can operate in this pressure range. The variations of H with ε which are plotted in Fig. 4 showed that fracture occurred at an approximately constant H value for pressures in this range.

These experimental facts suggest an explanation of the relationship between fracture strain and pressure in this pressure range. This explanation is based on the fact that fracture occurs when H reaches a critical value of approximately 325 MPa. Figure 4 shows that the relationship between H and ε from the beginning of necking to fracture can be written

$$H = m(\varepsilon - \varepsilon_n) - P \quad (4)$$

where m is the gradient of the H against ε plots, ε_n is the strain at which necking begins and P is the external hydrostatic pressure. Also from Fig. 4 it can be seen that m and ε_n are constants with $m = 400$ MPa and $\varepsilon_n = 0.82 \pm 0.04$. An expression for fracture strain (ε_f) as a function of pressure can be obtained by rearranging equation (4). This expression is

$$\varepsilon_f = \frac{P + H_f}{m} + \varepsilon_n \quad (5)$$

where H_f is the H value at fracture. To test the applicability of the suggested fracture criterion the line given by equation (5) with the values of H_f, m and ε_n found above was drawn on the same graph as the experimental results. The resulting plot is shown in Fig. 1 as a dashed line. The line obtained using this criterion can be seen to be in reasonable agreement with the experimental results.

The criterion for ductile fracture suggested by the present results is not one of the criteria tested by Bridgman.[4] Such a criterion has however been proposed previously by Yajima *et al.*[2] based on the work of Takase[6] and of Kolmogorov and Shishmintsev[7] who showed that the ductility of steel was a simple function of the hydrostatic component of stress. Yajima *et al.* showed that this criterion explained the variation of ductility with pressure of a number of pure metals and some plain carbon steels. However their results were based on assumed rather than measured neck contours and the critical triaxial stress value was not found.

(b) *Pressures above* 350 *MPa*

Optical and S.E.M. examinations showed that large scale voids were not present in specimens fractured at pressures above 350 MPa. Fracture at these pressures occurred entirely by a shear process. The plots of H

against ε in Fig. 4 showed that above 350 MPa pressure the H values at fracture were significantly lower than those at lower pressures. These facts suggest that at pressures in excess of 350 MPa failure occurred by shear tearing before the resultant triaxial stress component in the neck of the specimen became large enough for large scale void development to occur.

The fracture strains of specimens tested at pressures 375, 400 and 425 MPa were found to be significantly lower than those of specimens tested at slightly lower or higher pressures. This effect has not been previously reported, although some suggestion of its existence may be found in the variation of fracture strain with pressure of a leaded 60/40 brass studied previously.[3] No entirely satisfactory explanation of this unusual behaviour has been found as yet. The main difficulty in explaining the behaviour of fracture strain in this pressure range is that fracture appears to occur by a shear process but the shear fracture occurring at the higher pressures results in fracture strains which are insensitive to pressure.

CONCLUSIONS

1. The approximately linear increase in fracture strain with hydrostatic pressures between 0.1 and 350 MPa in α-brass was found to be accompanied by the progressive suppression of macroscopic void formation within the necked regions of specimens. In this pressure range fracture was found to occur at a constant value (H_f) of the triaxial component of stress at the centre of the neck. The relationship between fracture strain (ε_f) and pressure (P) for pressures up to 350 MPa was found to have the form

$$\varepsilon_f = \frac{P + H_f}{m} + \varepsilon_n$$

where ε_n is the strain at which necking begins and m is the gradient of the H–ε relationship.

2. Pressures in excess of 350 MPa were found to suppress macroscopic void development in the necked region and specimens tested at these pressures fractured by a shear mechanism. The fracture strains of specimens tested between pressures of 350 and 450 MPa were lower than expected whilst fracture strains were approximately constant for pressures between 450 and 600 MPa. The reason for the unusual variation of fracture strain with pressures between 350 and 450 MPa appears to be connected with the fact that the fracture mechanism changes at a pressure of about 350 MPa.

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