FRENCH-IE 73-0016

TENSILE FRACTURE OF FREE MACHINING BRASS AS A FUNCTION OF HYDROSTATIC PRESSURE*

I. E. FRENCH†, P. F. WEINRICH† and C. W. WEAVER†

The effects of hydrostatic pressures in the range 0.1 to 600 MPa on the tensile fracture of a free machining brass have been studied. In agreement with the results of earlier workers, the natural strain to fracture was found to increase rapidly with pressure for pressures up to 300 MPa, but to increase less rapidly at the higher pressures. The rapid increase in ductility under confining pressures up to 300 MPa is shown to be due to the suppression of void development, by the pressure, until later stages of deformation. The decrease in slope of the fracture strain pressure relationship above 300 MPa pressure was found to coincide with the localization of void formation to a narrow region at the centre of the neck.

ÉTUDE DE LA RUPTURE PAR TRACTION DU LATION NON USINÉ EN FONCTION DE LA PRESSION HYDROSTATIQUE

Les auteurs ont étudié l'influence de la pression hydrostatique (entre 0,1 et 600 MPa) sur la rupture par traction du laiton non usiné. Les auteurs trouvent que la déformation naturelle à la rupture augmente rapidement avec la pression, jusqu'à 300 MPa, mais augmente moins rapidement pour les pressions plus élevées, ceci étant en accord avec les résultats obtenus antérieurement par d'autres chercheurs. Les auteurs montrent que l'accroissement rapide de la ductilité pour des pressions comprises entre 0,1 et 300 MPa est dû à la suppression du développement des cavités par la pression, jusqu'aux derniers stades de la déformation. Les auteurs trouvent que la décroissance de la pente de la relation existant entre la pression et la déformation à la rupture pour les pressions supérieures à 300 MPa coincide avec la localisation de la formation des cavités dans une région étroite située au centre de la zone de striction.

DAS BRUCHVERHALTEN VON BEARBEITETEM MESSING IM ZUGVERSUCH UNTER HYDROSTATISCHEM DRUCK

Der Einfluß eines hydrostatischen Druckes zwischen 0,1 und 600 MPa auf das Bruchverhalten von bearbeitetem Messing im Zugversuch wurde untersucht. In Übereinstimmung mit Ergebnissen früherer Arbeiten ergab sich eine starke Zunahme der Bruchdehnung mit dem Druck bei 300 MPa. Die Zunahme war bei höheren Drucken geringer. Die rasche Zunahme der Duktilität unter dem Einfluß des hydrostatischen Druckes bis zu 300 MPa ist eine Folge der Verschiebung der Hohlraumbildung in ein späteres Verformungsstadium durch den Druck. Die geringere Abhängigkeit der Bruchdehnung vom Druck oberhalb 300 MPa tritt gleichzeitig mit der Beobachtung einer Hohlraumbildung in einem kleinen Bereich in der Mitte des Bruchhalses auf.

INTRODUCTION

Voids or cavities frequently form at inclusions or grain boundaries in ductile metals under axial tensile stress at an advanced stage of straining during necking. With increasing strain in the necked region the voids grow and coalesce to form a transverse cavity which, with only a small additional strain leads to rapid failure of the material by shear tearing.(1–3) The form of the stress state during plastic deformation has a substantial effect on the ductility of metals. During tensile tests under ambient pressure, the triaxial tensile stress developed in the centre of the necked region is such as to assist the growth of voids. However, the stress distribution in the presence of an external hydrostatic pressure is initially compressive,(4) and the formation of voids is delayed until a sufficiently large tensile component of stress is introduced. The greater the external pressure the greater the degree of necking required to overcome the compressive stress (within the neck) which counteracts the formation of voids and hence the greater the strain which can be withstood before fracture.

The natural strain to fracture of many metals subjected to tension under an external hydrostatic pressure has been found to increase linearly with pressure at a rate which is a characteristic of the particular metal. The work in this field has been reviewed recently by Brandes.(5) However, some metals are anomalous as regards their ductility–pressure characteristics in that, above a critical pressure the rate of increase of ductility with pressure may decrease, or the ductility may even be unaffected by further increase in pressure.(6,7) Brass is of particular interest in that the critical pressure is relatively low compared to that of steels. Yajima *et al.*(7) attribute this to the rapid reduction of stacking fault energy of the Cu–Zn and Cu–Ge alloys with increasing alloy content. However, since void formation is an important component of the fracture process, this aspect of the problem deserves closer attention.

In an attempt to find an explanation of the anomaly a series of tensile tests under pressure was made on a commercial free-machining brass which contained

---

* Received January 16, 1973.

† Australian Defence Scientific Service, Department of Supply, Defence Standards Laboratories, Melbourne, Australia.

lead inclusions. A scanning electron microscope (SEM) was used to examine both the fracture surfaces and the void populations in polished longitudinal sections of the brass specimens. The dimensions of the necks formed under pressure at increasing degrees of strain were also measured and the stresses in the neck regions calculated. A brass material containing a fine dispersion of lead particles was chosen in order to provide a structure having a large population of cavity nuclei.

EXPERIMENTAL

Material

Tensile test specimens of 10 mm gauge length and 4 mm diameter with threaded ends were machined from an 8 mm diameter rod of composition—57.5 wt % Cu, 39.6 wt % Zn, 2.9 wt % Pb, plus trace impurities only. All specimens were annealed at 600°C for one hour, the ultimate tensile strength being 390 MPa.

Equipment

The high pressure straining apparatus consisted of a pressurized chamber and associated gear drive, as designed by Heard.(8) Minor modifications were made to this equipment, notably in the use of 0-ring seals, in the method of housing the linear transducer on the load column, and in the addition of a tensile straining attachment.

The pressure chamber had a 15 mm diameter × 60 mm long work space, fitted with a hollow load column at one end (effectively, an internal load cell) and a movable piston sliding through an O ring seal at the other. Threaded adapters were fitted to the ends of the piston and the load column to accommodate the test specimen. The movable piston was connected to a gear train driven by a variable speed motor. The pressure medium was ethanol. Pressures were maintained to better than 0.5 per cent of the indicated pressures in all tests, as monitored by a Manganin gauge. The load on the specimen was continuously recorded by a Sanborn linear transducer mounted in an Invar housing (to minimize thermal effects) on the load column assembly.

Test methods and procedures

The tensile specimens were screwed into the threaded adapters on the load column and the top piston, care being taken to prevent damage by prestraining of the specimens during assembly or during pressurization. The strain rate in all tests was 1 mm/min. Continuous records of load against time were made during the experiments.

The experiments carried out can be classified into two series. Series I consisted of straining samples to fracture at various pressures within the range 0.1 MPa (atmospheric pressure) to 600 MPa. Series II consisted of straining samples by increasing amounts to just below the fracture strain at pressures of 200 MPa and 500 MPa.

With Series I specimens the minimum neck diameter was measured and the fracture surface of one part of the specimen was examined using an SEM. The other part of the specimen was sectioned longitudinally, polished, and examined optically and with the SEM. With Series II specimens the minimum neck diameter and the radius of curvature of the contour of the neck were obtained from tracings made of projections of the neck contours at magnifications of × 10 or × 50. These specimens were then sectioned longitudinally, polished and examined in the SEM. The metallographic preparation of longitudinal sections of specimens was such as to try to prevent microstructural features such as voids from being obscured (see Samuels(9)).

RESULTS

(a) *Series I*

The natural strain at fracture (ε_f) of the specimens fractured whilst under various hydrostatic pressures was calculated using the formula

$$\varepsilon_f = \ln \frac{A_0}{A_f} \tag{1}$$

where A_0 is the original cross-sectional area and A_f the final cross-sectional area at the neck. In Fig. 1 the ε_f values are plotted against hydrostatic pressure. This

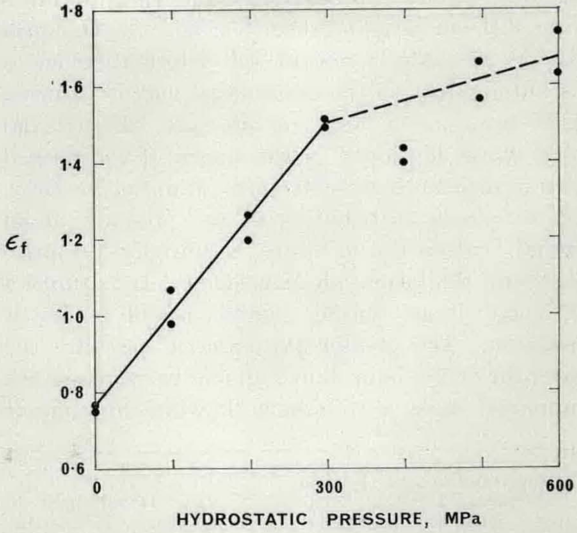
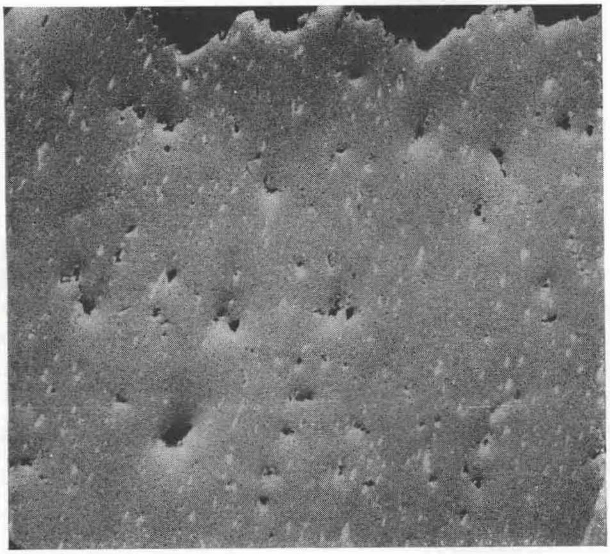


FIG. 1. The variation of natural strain to fracture (ε_f) with hydrostatic pressure.

figure shows that ε_f increases linearly with hydrostatic pressure for pressures up to approximately 300 MPa but increases much less rapidly at pressures above this.

When longitudinal sections of the specimens fractured at the pressures shown in Fig. 1 were examined the number and distribution of voids in the necked region was found to be strongly pressure dependent. Figure 2 shows SEM micrographs of regions near the fracture surfaces of specimens fractured at 0.1 and 500 MPa. The lighter regions in these micrographs represent lead inclusions, and the voids, which are black, can be seen to be associated with these. Table 1 gives the approximate numbers of voids visible at a magnification of ×500 and the distances from the fracture surfaces to which void formation extended, for a series of specimens fractured at pressures of 0.1, 300, 400 and 550 MPa. This shows that the specimens fractured at 0.1 and 300 MPa contained many voids, which occurred in a zone about 1 mm deep beneath the fracture surface. The specimens fractured at 400 and 550 MPa however contained only a few visible voids, which were confined to a small distance beneath the fracture surface. The conditions under which void formation was restricted therefore appear to correspond to those which produced the reduction in slope of the curve in Fig. 1.


(a)

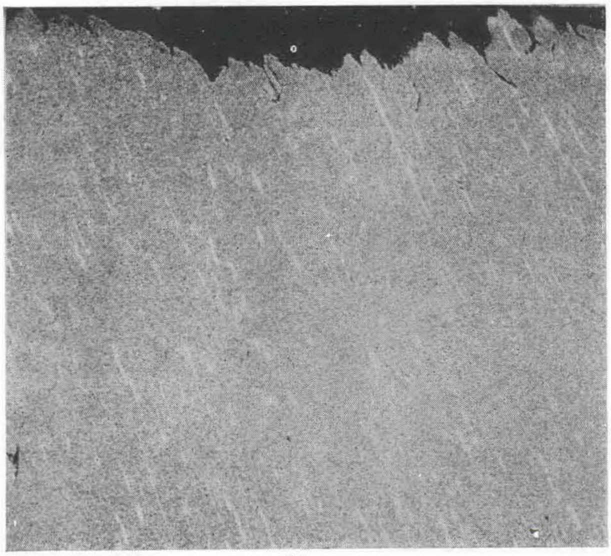

(b)

FIG. 2. Scanning electron micrographs of longitudinal sections of regions near the fracture surfaces of specimens fractured at (a) 0.1 MPa and (b) 550 MPa. ×200.

TABLE 1.

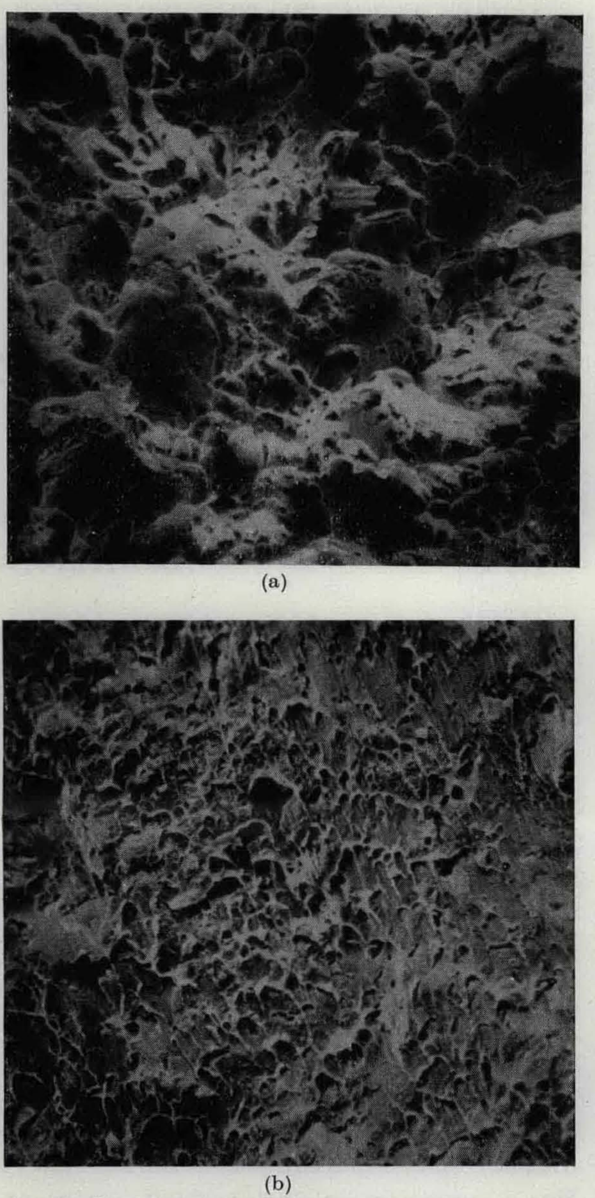
Hydrostatic pressure (MPa)	Total number of voids (Approx)	Maximum distance voids from fracture (mm)
0.1	100	1.3
300	40	0.7
400	15	0.2
550	10	0.1

SEM examination of the fracture surfaces of specimens fractured at all pressures showed that these surfaces were made up of two distinct regions: a central region of rough appearance as shown in Fig. 3(a), and an outer region of smoother appearance as shown in Fig. 3(b). The appearances of the surfaces of these regions were similar for all pressures. The structure of the central region is usually attributed to void coalescence while that of the outer region is attributed to shear tearing.[10] The principal effect of pressure on the fracture surfaces was in the area occupied by the central region. This area decreased considerably as the pressure of the test was increased from atmospheric pressure to 300 MPa but above 300 MPa the area remained approximately constant.

(b) *Series II*

(i) *Tests at* 200 *MPa*. Specimens were strained to a number of points on the load–extension curve. Measurements of the minimum neck radius (r), the radius of curvature of the contour of the neck (R) and the final load for each specimen are given in Table 2. When longitudinal sections of the specimens were examined it was found that visible voids were present only in the specimen taken to the highest strain (ε value of 1.0).

(ii) *Tests at* 500 *MPa*. Specimens were again strained to a number of points on the load-extension curve and Table 2 gives the value of r, R and load obtained. Examination of longitudinal sections of the


(a)

(b)

FIG. 3. Scanning electron micrographs of (a) the central region and (b) the outer region of the fractured surface of a specimen fractured in tension. ×560.

necked regions of these specimens revealed that very little visible void formation had occurred up to the highest strains obtained.

The stress system at the centre of the neck of a specimen undergoing tensile deformation whilst subjected to an external hydrostatic pressure can be calculated using the equations derived by Bridgman.(4) Bridgman showed that the stress system is made up of a hydrostatic or triaxial component H plus a longitudinal tensile component T. These components being approximately given by

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

and

$$T = F, \tag{3}$$

where

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

and P is hydrostatic pressure. These equations were used to find the resultant triaxial and tensile stress components in each of the specimens tested at 200 and 500 MPa. The results of these calculations are shown in Table 2 together with the natural strain for each specimen. The calculated H values for the tests at both pressures are plotted against natural strain in Fig. 4. These curves show that the resultant triaxial components of stress eventually become positive (tensile) for tests at both pressures. The values of natural strain at which these stresses become tensile increases markedly with pressure however. It should be noted that equations (2) and (3) refer only to the point at the centre of the minimum diameter of the neck. Since this is the point of maximum triaxial stress component this stress will decrease with distance from this point. Also, the equations assume a homogeneous material and are therefore not strictly applicable if a significant number of voids are present.

TABLE 2.

Pressure MPa	r (mm)	R (mm)	Load (Kg)	ε	H MPa	T MPa
200	1.63	44.0	513	0.41	−178	1175
200	1.50	14.7	506	0.58	−135	1306
200	1.43	7.3	463	0.67	−84	1239
200	1.39	5.7	481	0.73	−47	1325
200	1.23	1.78	388	0.95	+124	1104
500	1.61	31.0	525	0.43	−469	1218
500	1.51	20.4	494	0.56	−453	1281
500	1.45	5.6	481	0.64	−353	1207
500	1.24	3.05	400	0.95	−268	1271
500	1.14	2.34	375	1.13	−201	1349
500	0.975	0.81	312	1.44	+58	1169

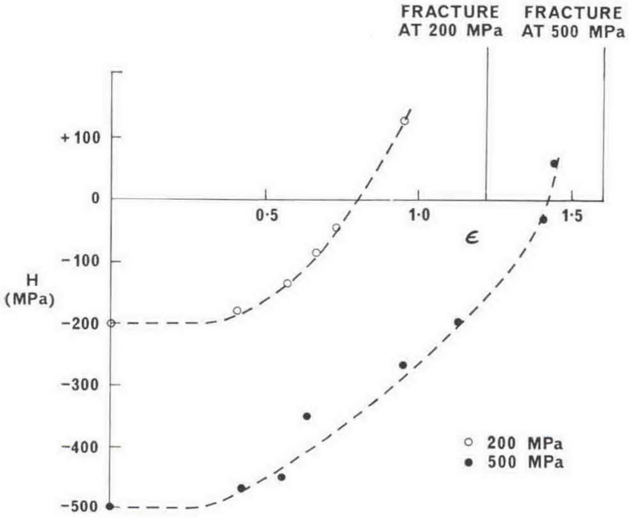


FIG. 4. The variation of resultant triaxial stress component at the centre of the neck (H) with natural strain (ε) for specimens strained at 200 and 500 MPa.

DISCUSSION

The plot of natural strain to fracture against hydrostatic pressure (Fig. 1) is in general agreement with the results of Beresnev *et al.*[(6)] who used a 60/40 brass, thus confirming that for this material the steeply rising relationship between pressure and fracture strain holds only up to pressures of about 300 MPa. This increase in fracture strain with hydrostatic pressure is strongly dependent on the formation and growth of voids in the neck, which is controlled by the value of the resultant triaxial stress component. The presence of voids weakens the material in the necked region and reduces ductility. As the hydrostatic pressure is increased, the formation of voids is suppressed to later stages of deformation until the resultant triaxial stress in the neck region reaches the necessary tensile value for void formation. Thus for pressures up to 300 MPa the fracture strain increases rapidly with increasing external hydrostatic pressure because of the increasing suppression of voids.

Above 300 MPa pressure the pressure sensitivity of the fracture strain is much reduced. This behaviour appears to be connected with the localisation of voids to a region very close to the fracture surface. The experimental results suggest the following explanation to account for this low sensitivity to pressure. At these pressures the resultant triaxial stress component (H) does not become tensile until very late in the deformation, when a highly developed neck exists in the specimen. Voids can therefore only develop in the narrow region near the centre of the neck. Under these circumstances very little further deformation can occur after macroscopic voids exist. This is confirmed by Fig. 4 which shows that the strain interval between the triaxial stress component becoming tensile and fracture at 500 MPa pressure is 0.18 whilst that at 200 MPa pressure is 0.41. Thus the decreased pressure sensitivity of the fracture strain–pressure relationship at pressures above 300 MPa occurs because little further deformation occurs after large scale void formation at higher pressures.

CONCLUSIONS

(i) The natural strain to fracture of leaded 60/40 brass increases rapidly with hydrostatic pressures up to 300 MPa but increases much less rapidly at higher pressures.

(ii) The numbers of voids present, and the distance from the fracture surface to which void formation extends, decreases markedly with increasing pressures in the range 0.1 to 300 MPa. At higher pressures however, the few voids present are restricted to a zone close to the fracture path.

(iii) The resultant triaxial stress component at the centre of the neck of specimens tested at pressures of both 200 and 500 MPa are tensile immediately prior to fracture. The strain interval between this stress becoming tensile and fracture however, decreases markedly with increasing pressure.

(iv) The reason for the decreased slope of the fracture strain–pressure relationship at pressures above 300 MPa is that voids develop only in a narrow region very late in the deformation at these pressures and are thus less effective in influencing ductility.

REFERENCES

1. K. E. PUTTICK, *Phil. Mag.* **4,** 964 (1959).
2. H. C. ROGERS, *Trans. Am. Inst. Min. Engrs.* **218,** 498 (1960).
3. J. GURLAND and J. PLATEAU, *Trans. A.S.M.* **56,** 422 (1963).
4. P. W. BRIDGMAN, *Large Plastic Flow and Fracture.* McGraw-Hill (1952).
5. M. BRANDES in *Mechanical Behaviour of Materials under Pressure*, edited by H. PUGH. Elsevier (1970).
6. B. I. BERESNEV, L. F. VERESHCHAGIN, YU. N. RYABININ and L. D. LIVSHITS, *Some Problems of Large Plastic Deformation of Metals at High Pressures.* Pergamon Press (1963).
7. M. YAJIMA, M. ISHII and M. KOBAYASHI, *Int. J. Fracture Mech.* **6,** 139 (1970).
8. H. HEARD, *J. Geology* **71,** 162 (1963).
9. L. E. SAMUELS, *Metallographic Polishing by Mechanical Methods.* Pitman (1971).
10. D. MCLEAN, *Mechanical Properties of Metals.* John Wiley (1962).