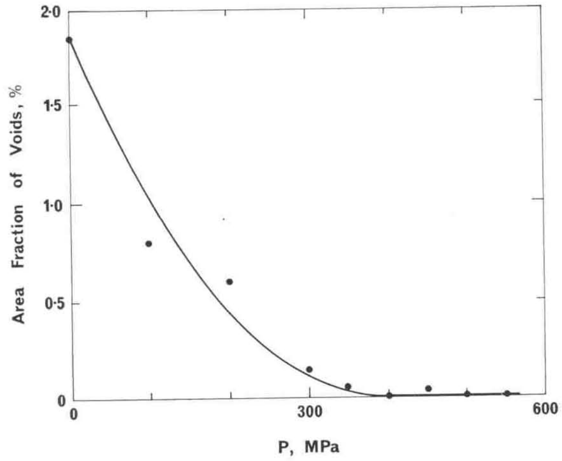


FIG. 2. Variation of area fraction of voids with pressure (P).

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)

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

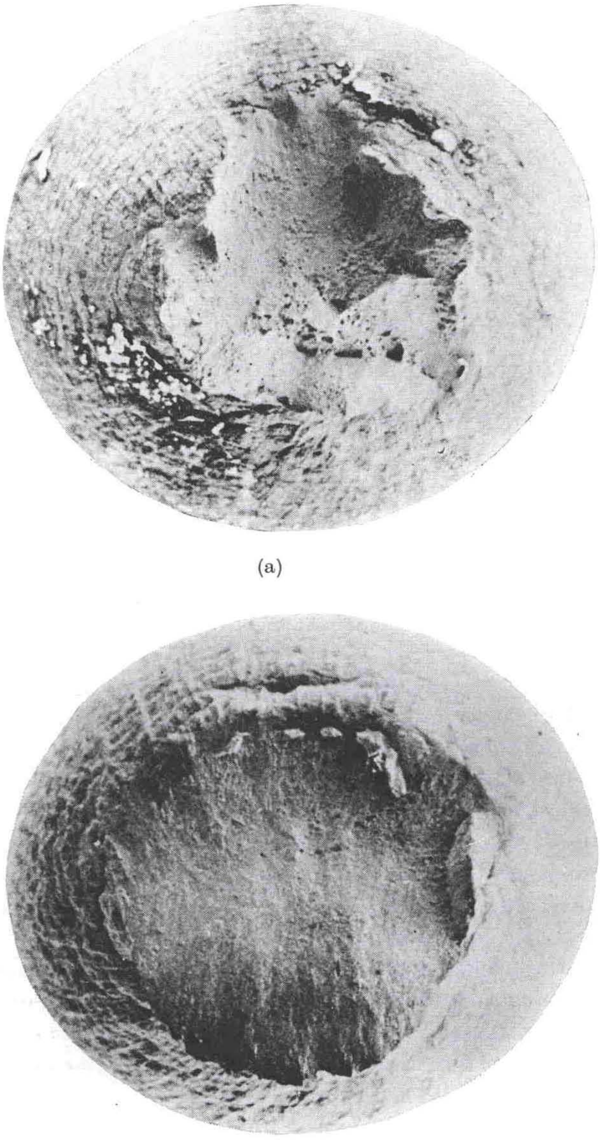
where

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

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. ×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

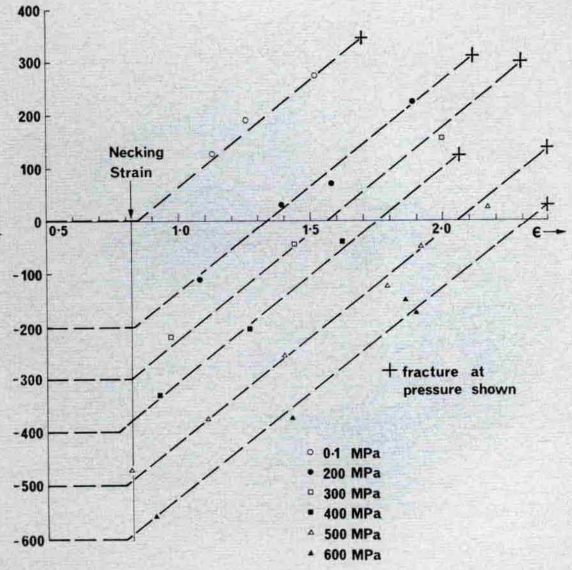


FIG. 4. Plots of the variation of the triaxial stress component (H) at the centre of the neck with natural strain (ε) for the pressure shown.

fracture at the lower pressures. This is because calculations of H based on equations (2 and 3) breakdown 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

$$H = m(\varepsilon - \varepsilon_n) - P \tag{4}$$

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

$$\varepsilon_f = \frac{P + H_f}{m} + \varepsilon_n \tag{5}$$

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