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Forming of 7075-T6 Aluminum in High Pressure Environments

Plates of 7075-T6 Aluminum have been folded along a major axis in pressure environments of atmospheric, 20,000 psi, and 40,000 psi. A finite element computer program is used to determine the stress state in the plates at various loads. Tension and compression tests conducted in pressure environments up to 70,000 psi were used to construct models using effective stress, effective strain, and pressure as parameters to predict the behavior of the material under various stress conditions. A prediction of the occurrence of fracture in the folded plate was possible using the computer results and the pressure dependent model. As better finite element stress analysis programs become available, both the forming operation and the test specimen can be analyzed to provide more accurate data that can be coupled with tension and compression data to predict the performance of metalforming operations under pressure.

Introduction

THERE are a number of investigators that have contributed to the study of metalworking under pressure. Bobrowsky [1, 2, 3]¹ has been effective in helping to identify and report on the progress being made in this field, and his writings will serve to acquaint the unfamiliar reader.

The papers of Alexander [4], Pugh [5], Green [6], and Schmehl [7] are also quite helpful in describing the type of high pressure metal-forming work being conducted in university, government, and industrial laboratories, respectively. The particular forming operation to be discussed in this paper is the folding, or bending, of plates while immersed in controllable high pressure fluid environments. Certainly this is not a new operation in that Bobrowsky reported [8] in 1964 the bending of beryllium sheet in pressure environments up to 400,000 psi. The increased ductility that is brought about by an increase in environmental pressure is utilized to extend the degree to which a plate can be folded without the initiation of fracture. In the beryllium specimens, a fracture was initiated at very small bend angles (less than 10 deg) when tested in ambient pressure whereas a 150 deg bend angle (over a one thickness radius) could be achieved without fracture when immersed in a pressure of 400,000 psi.

The pressure induced ductility can, and has been, used to enhance the forming of materials into various shapes by use of extrusion, flanging, rolling, and other operations conducted in con-

trolled high pressure environments. A considerable saving in time and effort could result if the designer of a forming operation for a new material could use the data extracted from the testing of tension and compression specimens in high pressure to predict the soundness of the end-product. For example, if a designer wanted to roll and fold a particular material of limited ductility, it would be easier to conduct tension and compression tests under pressure and use this data to predict (if possible) the required environmental pressure in the rolling and folding operations rather than performing scale model tests of both rolling and folding.

The purpose of this paper is to illustrate that the data obtained from tension and compression tests in controlled pressure environments can be used to predict (using the effective stress-pressure-effective strain model described in reference [9]) the initiation of fracture in 7075-T6 aluminum plates. The mechanics of comparing equivalent stress states in tension, tension under pressure, tension necking, notched tension, compression, etc. is also very well described in references [1 and 10].

Experimentation

All of the tests which were performed under pressure were performed in a pressure vessel rated at 125 ksi. Oil was used as the pressurizing medium and a pump rated at 125 ksi was used to pressurize the vessel. Strain gages were used as load cells as well as for measuring specimen strains. The vessel was placed in a 300 Kip capacity Riehle compression tester, fluid pumped to the desired pressure level, and load exerted through a one-in. dia ram made of S-7 tool steel. The ram passed through pressure seals to the internal test chamber. This chamber was cylindrical, 12 in. long by 3-in. dia. Loads in all three tests (tension, compression, and bending) were obtained by downward movement of the ram. Pressure was measured using both a 100 ksi Bourdon pressure gage and a manganin pressure cell. At 40 ksi environmental pressure the pressure fluctuation during a test

¹ Numbers in brackets designate References at end of paper.

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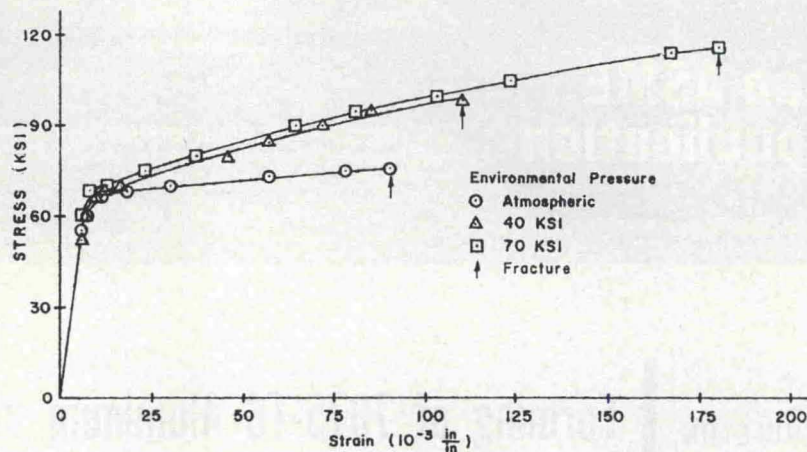


Fig. 1 Tension test (7075-T6 aluminum)

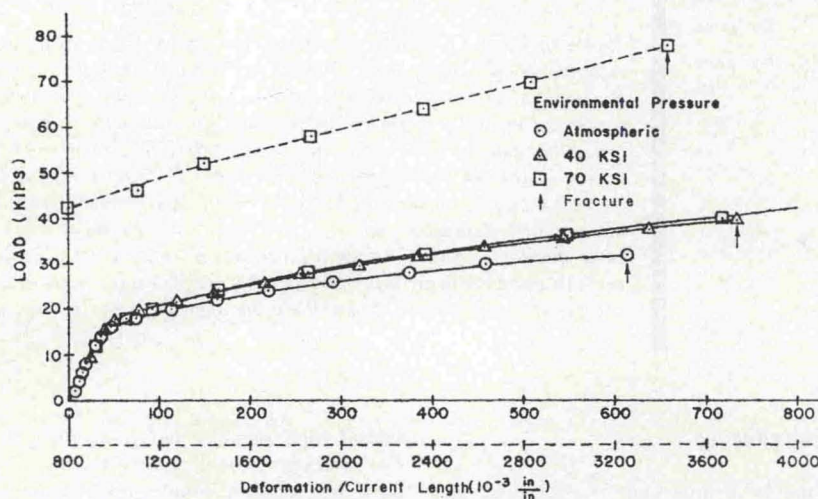


Fig. 2 Compression test (7075-T6 aluminum)

was only 3 to 5 ksi, and was considered negligible. At higher environmental pressures the fluctuation increased. For example, in a test conducted at a nominal pressure of 70 ksi the test was initiated at 65 ksi and terminated at about 75 ksi.

The downward travel of the ram lent itself naturally to running compression tests. A self-centering module was constructed to fit the test chamber, and the compression specimens (0.5-in. dia by 1.5-in. long) rested on a cylindrical load cell. No lubrication other than the oil environment was used. The L/D ratio for all reported compression tests was 1.5. This was the largest L/D for which buckling did not occur prior to fracture in the aluminum compression specimens.

To convert the downward movement of the ram into a tensile specimen load a special tensile yoke mechanism was constructed. Each tensile specimen was seven inches long by one-half in. dia with conical ends. The tensile yoke is composed of two opposing hollow cylindrical cages that are designed with sector-shaped prongs and openings that permit each cage to pass partially through the other. The conical-end tensile specimen is secured (via conical wedge blocks) to the base of each cage and a compressive axial load is applied to the protruding prongs (via end caps) of the cages. This action moves the cages apart thus generating a tensile load on the specimen. Load cell strain gages were placed on the outer cylindrical cage, and the assembly was placed in the 3 in. diameter by 12 in. high test chamber.

For the bending test a rectangular plate $2 \frac{13}{16}$ in. high by 3 in. long was tested. (The plates have thicknesses of $\frac{1}{8}$ and $\frac{3}{16}$ in.) In the bending test it was necessary to convert the vertical ram

displacement into a lateral line load on the plate. This was accomplished as follows:

As the fluid in the vessel was increased the ram was held just above an open cylinder located at the top of the bending apparatus. When the desired environmental pressure was reached in the pressure chamber, the ram was lowered into the cylinder passing through two O-ring seals. As the ram traveled downward additional hydraulic pressure was induced in the cylinder and was transmitted to two double telescoped pistons which expanded horizontally. A loading rod, fitted across the two pistons, impinged on the plate. As the telescoping pistons advanced, the plate was loaded with the desired line load. Strain gages located on the cylinder were used as the load cell. After normal debugging all three systems of loading worked very well.

Results

Tension and compression tests were conducted with 7075-T6 aluminum specimens in pressure environments up to 70,000 psi. The stress-strain and load-deformation per unit height curves for tension and compression are shown in Figs. 1 and 2, respectively. Load-deformation data are presented for the compression tests since these are the actual parameters monitored during the test, and the calculation of stresses in a barrelled compression specimen are questionable. Mehta and Girijarallabhan [11] have provided a means for assessing the stress state in a cylindrical compression specimen if the barreling is small; however, little appears to be available for the large deformation problem. The

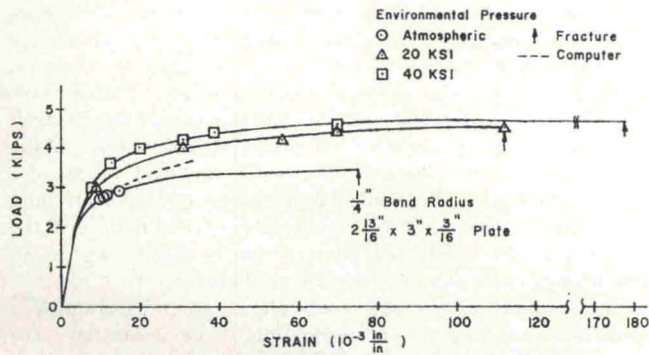


Fig. 3 Bending test (7075-T6-aluminum)

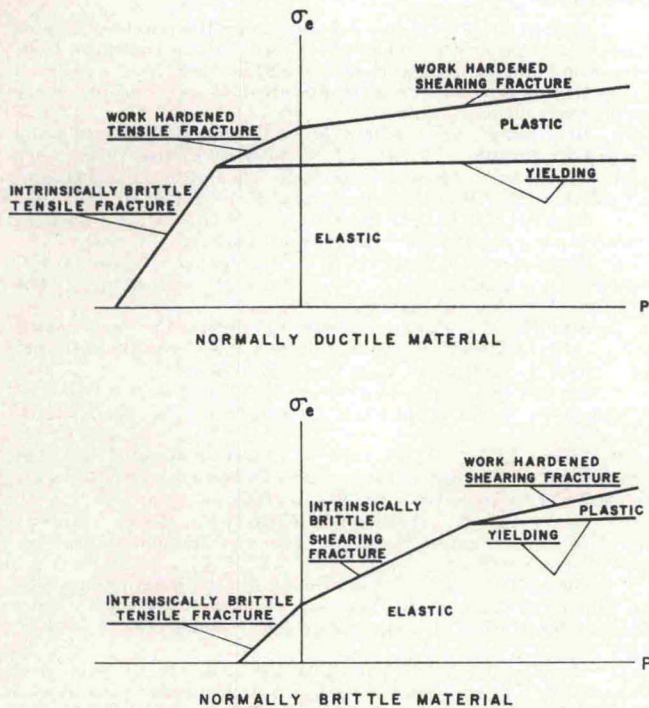


Fig. 4 General representations of effective stress-pressure relations

results shown in reference [12] certainly indicates that the stress distribution across a wafer-shaped ($L/D < 1$) compression specimen is not uniform. The primary effect of pressure is to increase ductility; however, the tension data also suggest that the fracture strength is likewise increased.

The results of bending a $3/16$ -in. 7075-T6 aluminum plate over a $1/4$ -in. bend radius are shown in Fig. 3. It is worthy to note that immersing the plate in a pressure of 40,000 psi results in a $2\frac{1}{2}$ -fold increase in the plate bend angle at fracture. These results alone suggest that the superposition of modest hydrostatic stress components can be an effective means of increasing the formability of 7075-T6 aluminum.

Strain gages were mounted on the tension side of the plate and were effective up to the point of fracture. The strain at fracture was found to correspond to the expression $\epsilon = y/\zeta$ where ϵ is the strain, y is the distance measured from the neutral axis, and ζ is the radius of curvature. A finite element program was used to analyze the plate bending to provide an assessment of the stress state in the plate during bending. To illustrate the accuracy of the finite element computer solution, load-strain values from the computer results were plotted with the experimental data.

The parameters of effective stress (σ_e) and pressure (P) have been found useful for describing material response under various stress conditions. The effective stress and pressure correspond

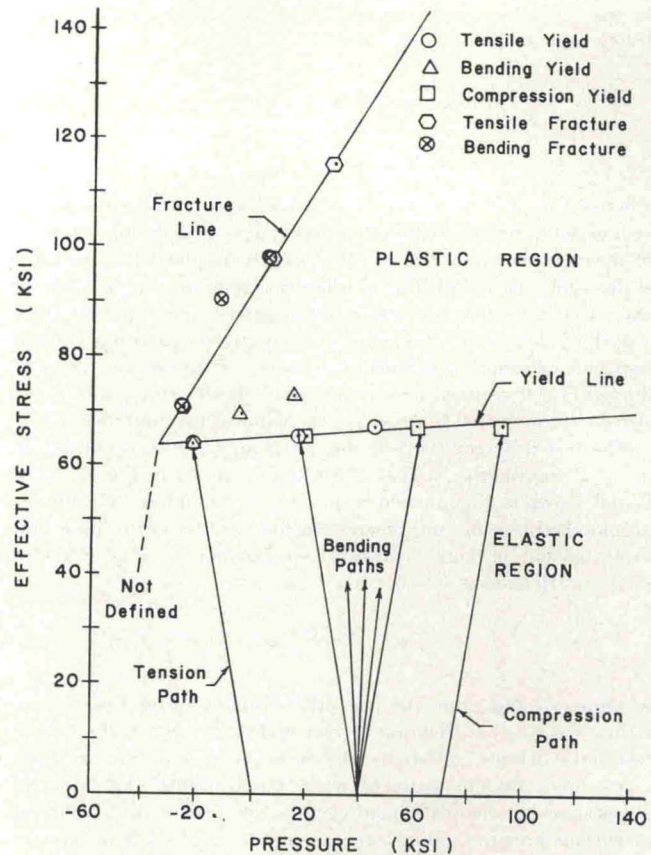


Fig. 5 Effective stress versus pressure

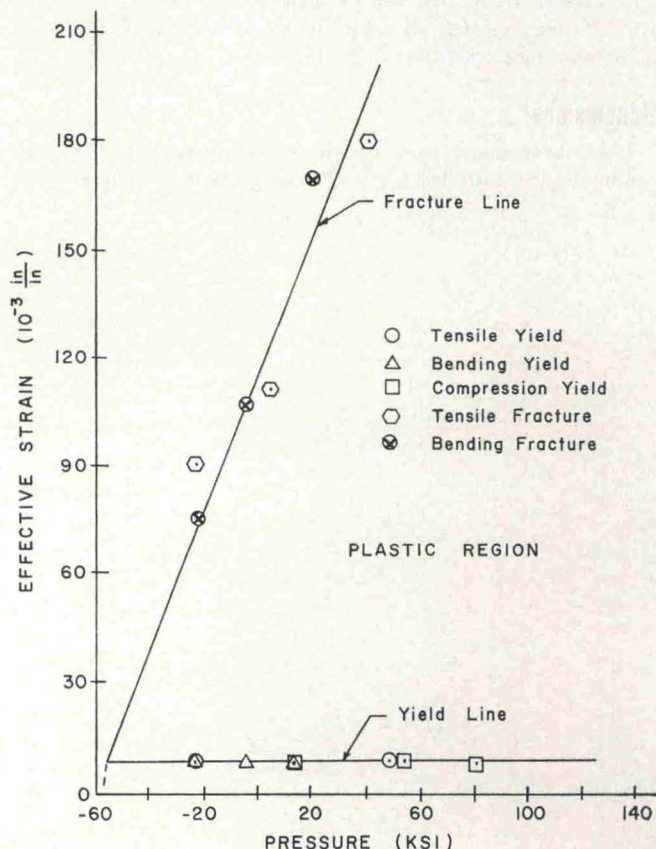


Fig. 6 Effective strain versus pressure

to the second and first invariants of the stress tensor, respectively, and are defined as

$$\sigma_e = \frac{1}{\sqrt{2}} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

$$P = -1/3(\sigma_1 + \sigma_2 + \sigma_3)$$

where σ_1 , σ_2 , and σ_3 are the principal stresses. The materials investigated in reference [9] indicate that $\sigma_e - P$ diagrams often are of the form shown in Fig. 4. If σ_e and P are plotted to the same scale, then the definitions of these parameters can be used to show that a tension test will generate stress states that lie along a path of slope -3 . Likewise, torsion stresses are on a vertical path, compression on a path of $+3$, etc. If these tests are conducted in a fluid pressure environment, the starting point of the stress path is shifted from zero to the value of the fluid pressure.

The test data collected in this program have been plotted on $\sigma_e - P$ coordinates, and the results are shown in Fig. 5. The model shown in Fig. 5 could be made more complete by conducting notched tension and biaxial tension, and by performing uniaxial tension in higher pressure environments. The effective strain (ϵ_e) defined as

$$\epsilon_e = \frac{\sqrt{2}}{3} [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{1/2}$$

where ϵ_1 , ϵ_2 , and ϵ_3 are the principal strains, can be used to construct the $\epsilon_e - P$ diagram shown in Fig. 6. Since the tensile test data defines essentially the same yield and fracture lines (these lines become surfaces when mapped into the principal stress space) as the plate bending data, the tension data collected in various pressure environments could be used to define the response of the plate specimen.

As better finite element stress analysis programs become available, both the forming operation (in the project, plate bending) and the testing specimen (tension necking and compression barrelling) can be analyzed to provide more accurate stress and strain distributions that can be used to construct $\sigma_e - P$ and $\epsilon_e - P$ diagrams that are useful for predicting the performance of metalforming operations under pressure.

Conclusions

It has been shown that tension and compression tests can be conducted in controlled pressure environments to generate ma-

terial response data which is used to construct effective stress-pressure and effective strain-pressure diagrams. These diagrams were, in turn, shown to be suitable for predicting the performance of plate bending in various pressure environments. To generalize this procedure, one would conduct sufficient uniaxial and biaxial tests under pressure to allow for the complete construction of the $\sigma_e - P - \epsilon_e$ model. The critical stresses occurring in a particular forming operation (finite element programs would help here) could be located on the $\sigma_e - P - \epsilon_e$ model which would indicate if the material at that particular point in the workpiece was in an elastic or plastic state, or if fracture would occur.

Future work on this project will include the application of a finite element program for evaluating (more accurately) the stress-strain states in necked tension and barrelled compression specimens.

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