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Warm Compression Tests of Aluminum Alloy

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Compression tests of aluminum alloy were experimentally investigated at specified temperatures ranging from 30 °C (room temperature) to 250 °C under a constant strain rate of 0.2 × 10^{-3}/s using powdered graphite as a lubricant throughout the tests. The effective stress method is found to show a significant fall in stress values beyond the barreling point, indicating a serious shortcoming over the barrel correction factor method within the tested temperature range. The compression curves obtained using the barrel correction factor method and the Bridgman remachining technique (no barreling allowed during the test) are found to have close values, even at higher temperatures. The true-stress versus true-strain curves and the barrel sizes obtained follow empirical power laws, even at higher test temperatures.

Keywords barreling, power law, true strain, true stress, warm compression

1. Introduction

Compression tests or simple axial upsettings are commonly used to determine mechanical properties such as yield strength and metal flow patterns in order to analyze metal-forming processes such as forging and extrusion operations, which can be undertaken either at cold or hot working conditions. During the forming process, the mechanical properties and metal flows are essentially influenced by strain-hardening, strain rate, temperature, prior deformation, and forming equipment and tooling factors, such as deformation speed, tool-workpiece interface friction, tool temperature, and tool materials. Several investigators have determined the true-stress versus true-strain curves and shapes of the deformed workpiece (i.e., barreling effect) occurring under these factors.

Several methods (Ref 1, 2) have been applied in analyzing compression tests, in order to determine the effective stress versus true-strain curves for different working metals.

Compression test results were analyzed using the barrel correction factor derived by Ettouney and Hardt (Ref 1) to account for barreling effect, which indicated agreement with results obtained by the Bridgman remachining method (Ref 2) used to eliminate the barreling effect. This process involved performing compression tests in stages, just before barreling was about to occur. After each stage, the specimen was machined back to original proportions (i.e., same diameter-to-height ratio), resulting in a continual decrease in absolute specimen size.

Kulkarni and Kalpakjian (Ref 3) studied the arc of barrel as circular or parabolic, while Schey et al. (Ref 4) presented a comprehensive report primarily on the geometrical factors that affect the shape of the barrel, such as diameter-to-height ratio, reduction ratio, and diameter of the specimen. Banerjee (Ref 5) and Holzer (Ref 6) further investigated experimentally the shape of barrel for different aspect ratios of an initially cylindrical specimen at the end of each intermittently incremental loading, under dry as well as lubricated compression tests. The effective stresses in compression tests were also analyzed by the average stress method (Ref 5).

The aim of the present investigation is to provide additional experimental data and information on the effects of tool temperatures on the shape changes in the upsetting of solid aluminum cylinders of a given unity aspect ratio, which previous investigators (Ref 1, 3, 6, 7) have restricted solely to room temperature tests. The research work further analyzes the effective stress versus true-strain curves for aluminum specimens at various temperatures under a constant strain rate, using the barrel correction factor (Ref 1), the average stress method (Ref 5), and the Bridgman remachining method (Ref 2). This is aimed at assessing the applicability of the three methods in analyzing compression tests at higher test temperatures.

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2. Theoretical Analysis

Figure 1 shows the original position and barreling effect of the specimen as compression of the specimen (placed between platens) reduces its height from h_0 to h. In ideal compression tests (i.e., in the absence of friction), the stress distribution is uniform, and assuming a perfectly plastic material, the effective stress is equal to the uniaxial compressive stress of the current applied load (Ref 2):

$$\sigma = (\sigma_z)_a = 4L/\Pi d^2 \quad \sigma_r = \sigma_\theta = 0 \qquad \text{(Eq 1)}$$

where σ is the effective stress; $(\sigma_z)_a$ is axial compressive stress; σ_z, σ_r, and σ_θ are the axial, radial, and hoop principal components, respectively; L is the current load; and d is the current diameter.

The natural or true strains at a particular stage of the test are:

$$\varepsilon_z = -1n(h/h_0),\ \varepsilon_r = \varepsilon_\theta = \varepsilon_z/2 \qquad \text{(Eq 2a)}$$

where ε_z, ε_r, and ε_θ are axial, radial, and hoop principal strains, respectively; and h_0 and h are the initial and current heights of the cylindrical specimen, respectively.

The effective strain, ε, is given as (Ref 2):

$$\varepsilon = -\varepsilon_z = \ln(h_0/h) \quad \text{(Eq 2b)}$$

The test strain rate, $\dot{\varepsilon}$, is given as:

$$\dot{\varepsilon} = V/h_0 \quad \text{(Eq 3)}$$

where $\dot{\varepsilon}$ is the strain rate and V is the velocity of deformation (i.e., press speed).

A barrel correction factor for determining effective stress that takes barreling into account, as derived in Ref 1, is given as:

$$\bar{\sigma} = (\sigma_z)_a[(1 - 4R/d_2) \ln (1 - d_2/4R)]^{-1} \quad \text{(Eq 4a)}$$

where $\bar{\sigma}$ is the effective stress and

$$(\sigma_z)_a = 4L/\Pi d_2^2 \quad \text{(Eq 4b)}$$

and where R is the radius of curvature of the barrel and d_2 is the maximum diameter of a barreled specimen.

The correction barrel factor, C, is given as:

$$C = [(1 - 4R/d_2) \ln (1 - d_2/4R)]^{-1} \quad \text{(Eq 4c)}$$

The radius of curvature of barreling, R, is given as (Ref 2):

$$R = h^2 + (d_2 - d_1)^2/4\,(d_1 - d_2) \quad \text{(Eq 5)}$$

where d_1 is the minimum diameter of a barreled specimen.

The average stress method for determining the effective stress is derived and given as (Ref 5):

$$\sigma = \frac{8L}{\pi(3h_0 d_0^2/h - d_2^2)} \quad \text{(Eq 6)}$$

where d_0 and h_0 are the original diameter and height of specimen, respectively.

3. Experimental Procedure

3.1 Material and Test Rig Used

The aluminum alloy used was composed of 1.0% Si, 0.8% Mg, 0.5% Cr, and the remainder Al. Figure 2 shows the initial microstructure of the sand-casted aluminum specimen, showing particles of impurities in the matrix solid solution of aluminum. The sand-casted aluminum alloy billets were machined into cylindrical specimens of 25 mm in diameter and 25 mm in height to provide a diameter-to-height ratio of unity.

The test rig consisted of a mild steel container with an outer diameter of ~124 mm, a concentric inner hole diameter of 50 mm, and a height of 87 mm. Three equally spaced 25 mm diameter holes were drilled into the test rig container in order to accommodate three 100 watt electric rod heaters used for heating the test rig. The punch and bottom dies were carefully threaded, so as to accommodate a specially designed screw that contained the thermocouple used for monitoring the temperature of the specimens during the compression tests. A temperature-control thermostat was also incorporated into the test rig to set and regulate the desired test temperatures of the rig. The rig was well-lagged with fiberglass, to reduce heat loss.

3.2 Experimental Set-Up

The test rig was carefully positioned centrally on the platen of an Avery-Denison (Avery Export Limited, Worcestershire, UK) hydraulic press, with the punch in proper position. Various position settings of the temperature control thermostat were initially calibrated by using a Chromel-Alumel type K thermocouple (Hoskins Manufacturing Company, Hamburg, MI) inserted at the rig die base into the test rig's internal hole portion. The thermocouple was connected to a chart recorder through a cold junction. The test-rig temperatures obtained and used were fairly constant to within ±1 °C of the set temperatures. This was achieved through careful and proper lagging of the test rig.

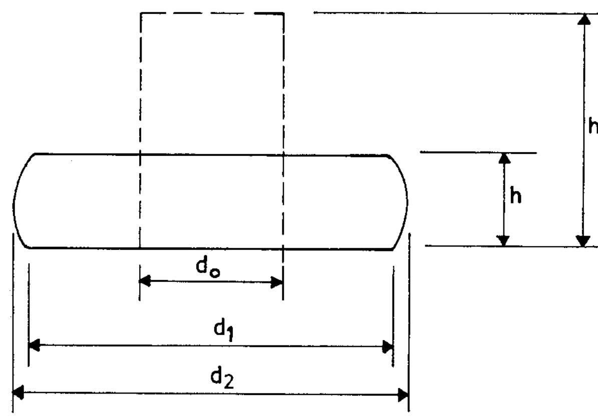

Fig. 1 Initial and barrel positions of compressed aluminum specimen

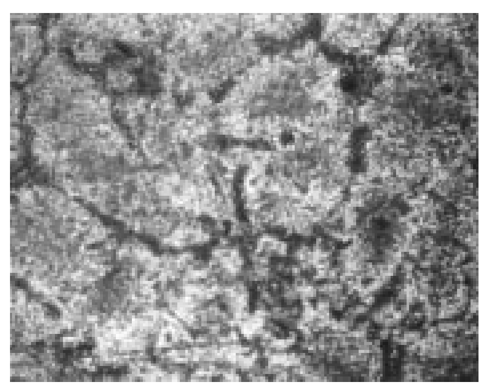

Fig. 2 Initial microstructure of the as-cast aluminum specimen. Etchant: 2% NaOH (400×). (Art has been enlarged 127% of its original size for printing.)

3.3 *Compression Tests*

The compression tests were carried out using two methods: the barrel correction factor method (Ref 1) and the Bridgman remachining method (Ref 2).

Barrel Correction Factor Method. The test rig, along with the punch and die, were heated until the test temperature was attained. The compression tests were conducted using graphite powder as a lubricant between the contacting surfaces of the specimen and the die and punch platens. The test specimens were preheated to a temperature of ~10 °C above the test temperature, using a separate electric furnace. The ends of the specimens were also sprayed with graphite powder before being positioned in the center of the die platen of the test rig. To achieve this quickly and accurately, concentric circles were inscribed on the surface of the die platen beforehand, to guide the positioning of the test specimen. The test specimens were allowed to soak until the desired test temperature was attained. Before the compression tests were started, the compression dial gauge indicator on a magnetic base was properly zeroed, while in contact with the press ram.

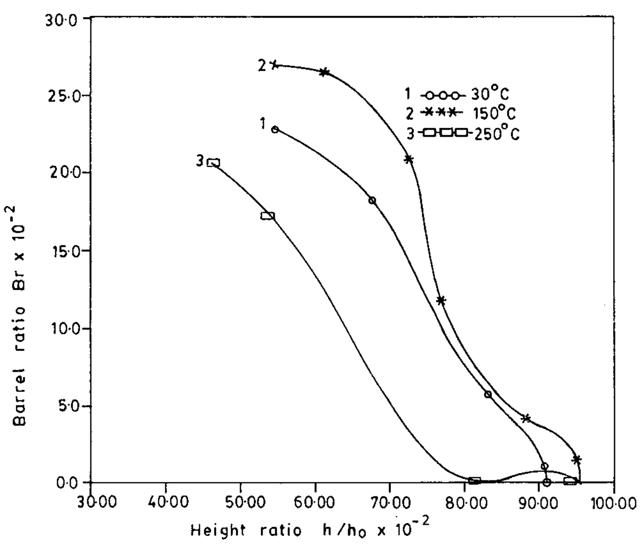

Fig. 3 Barrel ratio versus height reduction ratio

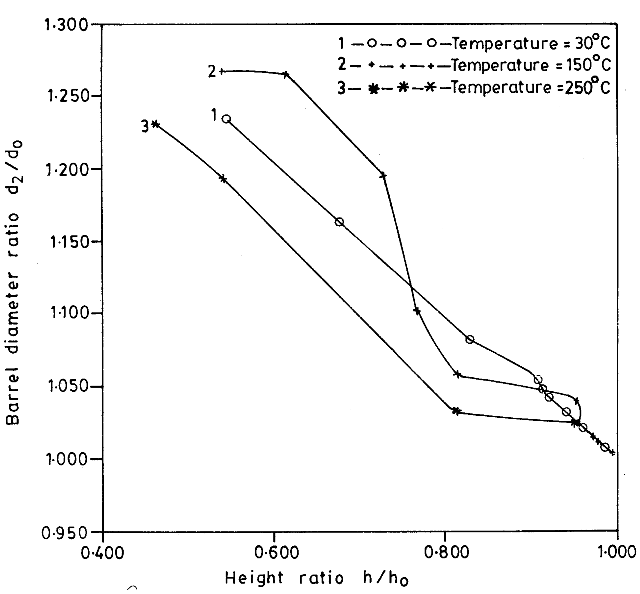

Fig. 4 Barrel diameter ratio versus height ratio with $d_0/h_0 = 1.0$

The test specimens were deformed at a set constant strain rate of 0.2×10^{-3}/s throughout the test. By using the Denison hydraulic press strain rate pacer, the current loads were manually taken at every 0.1 mm dial gauge travel, until barreling was beginning to occur. As the barreling stage was reached, further compressions of the specimens were conducted by increasing the loads beyond the preceding load value.

The maximum barrel diameter, d_2, the contact diameter, d_1, and the current height, h, were carefully measured with a vernier caliper after each load increment. The recorded values were based on an average of at least three readings taken on each specimen. The effective stress versus true-strain values were then computed, using a computer program written in BASIC language, to take barrel correction factor into account and using the average stress method. (See Eq 4a and b.)

The entire procedure was repeated at higher temperatures of 150 °C and 250 °C. The compression tests in these cases, however, required constant interruptions after barreling, in order to take the test specimen dimensions. The test specimens were relubricated and then allowed to soak to achieve the set temperature of the test rig before further loadings of the test were continued. Repeated tests at room temperature, 150 °C, and 250 °C were performed to check that the effective stresses calculated were within ±5% of the previous values.

Bridgman Remachining Technique (Ref 1, 2). This method is similar to Bridgman's correction factor method, except that no further compression is continued once barreling occurs. With this method, the compression of the test specimen was carried out up to the point when barreling was about to occur. The applied load was then removed, and the test specimen was remachined to reduce both the height and diameter so as to maintain its cylindrical shape and the aspect ratio (initial diameter-to-height ratio) of unity, before the test was continued. The current loads were taken manually at every 0.1 mm compression of the test specimen, until barreling was about to occur.

The above procedure was repeated for four loading cycles by carrying out successive remachining operations to different sizes, maintaining the initial aspect ratio of unity. This method was performed at a test-rig temperature of 150 °C so as to determine the true stress-strain curve to be used for comparison with the true-stress versus true-strain curve obtained by Bridgman's correction factor method.

4. Discussion of Results

4.1 *Barreling Dimensions*

Figures 3 and 4 show plots of barrel ratio, $B_r = A_1 - A_2/A_2$ (Ref 6), and barrel diameter ratio, d_2/d_0, respectively, with current height reduction ratio, h/h_0, over a test temperature range of 30 °C to 250 °C; where A_1 is the maximum barrel cross-sectional area, and A_2 is the area of the compression specimen in contact with the polished die. Figure 3 clearly shows that the barrel ratios, at all height reduction ratios, are highest for a temperature of 150 °C and are lowest for a temperature of 250 °C. In Fig. 4, the barrel diameter ratios are lower at a temperature of 250 °C than at room temperature (30 °C). At 150 °C, the barrel diameter ratios indicate initial irregular behaviors at height reduction ratios of up to 0.75, before indicating higher barrel diameter ratios than the 30 °C values. The initial irregularities of barrel diameter ratios occurring at a temperature of 150 °C indicate the deficiency of using the barrel diameter ratios, d_2/d_0, instead of the barrel ratios, B_r. The higher values of B_r obtained at 150 °C may be attributed to higher platen-specimen friction and strain-hardening effects, while the lower values of B_r, at 250 °C, can be attributed to lower platen-specimen friction and lower strain-hardening effects on the barrel dimensions.

By using the least square regression fit method (Ref 8) written in a Quick BASIC computer program, the barrel diameter ratio, d_2/d_0, with current height reduction ratio, h/h_0, can be fitted to the power law relations in the form of $d_2/d_0 = A(h/h_0)^{-p}$, where A is a constant and p is an exponential number. For a temperature of $T = 250$ °C with a coefficient of correlation $r = -0.986$, the empirical relation is given as:

$$d_2/d_0 = 0.9950\ (h/h_0)^{-0.28018} \quad \text{(Eq 7)}$$

At a temperature of 150 °C, $r = -0.940$, the relation is:

$$d_2/d_0 = 1.0053\ (h/h_0)^{-0.41668} \quad \text{(Eq 8)}$$

and at a temperature of 30 °C, $r = -0.998$, the relation is:

$$d_2/d_0 = 1.0220\ (h/h_0)^{-0.31786} \quad \text{(Eq 9)}$$

From the empirical power law relations, the values of constant A and exponential number p are functions of end restraint, dictated by friction and temperature. The values of A, as indicated by Eq 7 to 9, are found to decrease with the increase of temperature, while the values of p attained a minimum turning value at 150 °C.

4.2 True Stress Versus True Strain Curves

Accounting for Barreling. Figure 5 shows the true stress-strain curve values obtained by the barrel correction factor method of Eq 4 and 5 and the average stress-true strain curve of Eq 6 for test temperatures of 30 °C, 150 °C, and 250 °C, under a constant strain rate of 0.2×10^{-3}/s. The values of the true stress and the true strain obtained from the investigation are analyzed according to the empirical equation:

$$\bar{\sigma} = K\bar{\varepsilon}^m \quad \text{(Eq 10)}$$

where $\bar{\sigma}$ is the true stress, $\bar{\varepsilon}$ is the corresponding true strain, K is the ultimate yield strength coefficient, and m is the strain-hardening exponent.

The values of constants K and m are obtained using a computer program of least square regression fit analysis written in Quick BASIC, as follows (Ref 8):

For a temperature of 30 °C, with $r = 0.867$, the relation is:

$$\bar{\sigma} = 1803.82\bar{\varepsilon}^{0.8083} \quad \text{(Eq 11)}$$

At a temperature of 150 °C, with $r = 0.853$, the relation is:

$$\bar{\sigma} = 932.21\bar{\varepsilon}^{0.7123} \quad \text{(Eq 12)}$$

and at 250 °C, with $r = 0.855$, the relation is:

$$\bar{\sigma} = 718.90\bar{\varepsilon}^{0.7118} \quad \text{(Eq 13)}$$

It is observed, however, that the ultimate yield strength coefficient, K, and the strain-hardening exponent, m, are functions of temperature and are found to decrease with the increase of temperatures, within the range of temperatures considered.

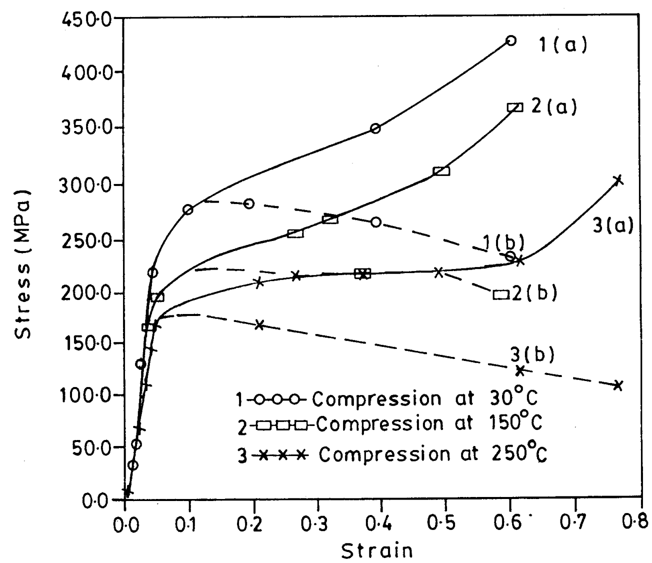

Fig. 5 True stress-strain curve at constant strain rate 0.01426/min. (a) Bridgman's correction factor method (d_0/h_0 = 1). (b) Average stress method (d_0/h_0 = 1)

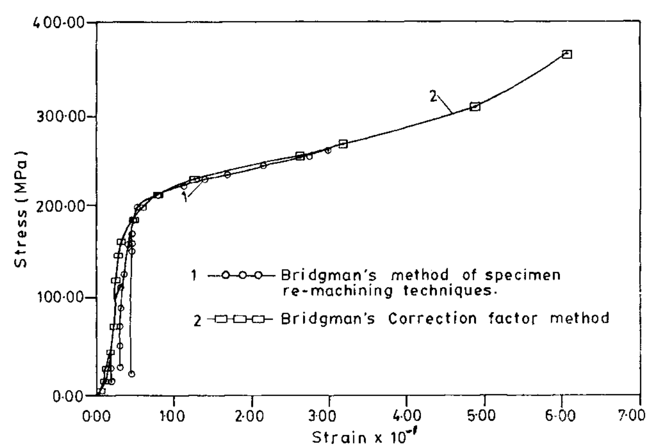

Fig. 6 Comparison between ideal and non-ideal test at a working temperature of 150 °C at a constant strain rate of 0.01426/min with d_0/h_0 = 1

Furthermore, there is a conformity between the effective stress-true strain curve using the barrel correction factor, and the average stress-true strain curve, up to the point where barreling begins. Thereafter, the two curves deviate from each other at various test compression temperatures, though the barrel correction factor method was found to be more accurate in comparison to the remachining method.

Bridgman Remachining Method. Figure 6 shows the comparison of the true stress-true strain curves using the ideal test (i.e., the Bridgman remachining method) and the barrel correction factor, at a working temperature of 150 °C. The two curves indicate that the true stress values from the compression test that were analyzed using the barrel correction factor are closer to the values obtained by the remachining method, even at the higher temperature of 150 °C. The deviations of the two curves are within a stress difference value of ±10 MN/m^2. This shows that the barrel correction factor method can be accurately used for true stress-true strain curves, even at higher test temperatures.

5. Conclusions

The following conclusions are made from the experimental compression tests:

- The barrel size can be fitted to a power law of the form $d_2/d_0 = A(h/h_0)^{-p}$ where A is a constant and p is the exponential value.
- The true stress-true strain values can be fitted to the empirical equation of the form $\bar{\sigma} = K\bar{\varepsilon}^m$ where K is the ultimate yield strength coefficient and m is strain-hardening exponent, which are functions of temperature.
- The barrel correction factor method is recommended for analyzing the effective or true stress during compression tests, even at high temperatures.

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References

1. O. Ettouney and D.E. Hart, A Method for In-Process Failure Prediction in Cold Upset Forging, *(Trans. ASME), J. Eng. Ind.,* Vol 105, 1983, p 161-167
2. P.W. Bridgman, *Studies in Large Plastic Flow and Fracture,* McGraw-Hill, 1952
3. K.M. Kulkarni and S. Kalpakjian, A Study of Barrelling as an Example of Free Deformation, *(Trans. ASME), J. Eng. Ind.,* Vol 91, 1969, p 743-754
4. J.A. Schey, J.R. Venner, and S.L. Takomana, Shape Changes in the Upsetting of Slender Cylinders, *(Trans. ASME), J. Eng. Ind.,* Vol 104, 1982, p 479-483
5. J.K. Banerjee, Barreling of Solid Cylinders under Axial Compression, *(Trans. ASME), J. Eng. Mater. Technol.,* Vol 107, 1985, p 138-144
6. A.J. Holzer, Specimen Geometry and Friction in Dynamic Compression, *Annals of the CIPR,* Vol 29 (No. 1), 1980, p 136-139
7. J.K. Banerjee and C. Gerardo, Numerical Analysis on the Barreling of Solid Cylinders under Axisymmetric Compression, *(Trans. ASME), J. Eng. Mater. Technol.,* Vol 107, 1985, p 145-147
8. J.S. Gunase Kera, et al., The Effect of Specimen Size on the Stress-Strain Behaviour in Compression, *(Trans. ASME), J. Eng. Mater. Technol.,* Vol 104 (No. 4), 1982, p 274