BARRELLING IN SQUARE BILLETS OF ALUMINIUM DURING COLD UPSET FORGING UNDER DISSMILAR FRICTION

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ABSTRACT

In upset cold forging the existence of frictional constraints between the dies and the work piece directly affect the plastic deformation of the latter. The friction at the contact faces retards the plastic flow of metals and the surfaces and in its vicinity. A conical wedge of a relatively undeformed metal is formed suffers high strain hardening and bulges out in the form of barrel. This work has been taken up to generate data on the cold upset forging of square billets of annealed aluminium under dissimilar frictional conditions. Experiments were conducted by applying lubricant at one end of the square specimen and the other end with dry friction (with no lubrication). By the application of differential lubrication, a barrel and a truncated part near the unlubricated surfaces have been developed. The measured radius of curvature of the barrel was found to conform with the calculated value. The calculations were made on the assumption that the curvature of the barrel followed the geometry of circular arc. Relationship is established between the measured radius of curvature of the barrel and the stress ratio parameter.

1. INTRODUCTION

A series of investigations on cold upset forging of solid cylinders have been carried out by many investigators due to its technical potential in metal forming processes. A comprehensive review of the literature has been published by Johnson and Mellor¹. Another significant aspect of axisymmetric compression from the stand point of testing the mechanical manufacturing properties of metals is the estimation of their forming limits up to the plastic instability and fracture as explained by Shaw and Avery ².

In upsetting, the existence of frictional constraints between the dies and the work piece directly affect the plastic deformation of the latter. When a solid specimen (cylindrical / square billets) is compressed axially between the punch and the bottom platen, the work piece material in contact with their surfaces undergoes heterogeneous deformation resulting in “barrelling” of the specimen.

The friction at the faces of contact retards the plastic flow of metals and the surfaces and in its vicinity. A conical wedge of a relatively undeformed metal is formed immediately below it, while the rest of the cylinder metal suffers high strain hardening and bulges out in the form of a barrel. This demonstrates that the metal flows most easily towards the nearest free surface which is the point of least resistance. However, the use of lubricants reduces the degree of bulging and under the conditions of ideal lubrication, the bulging can be brought down to zero. Kulkarni and Kalpakjin ³ studied the arc of barrel as circular or parabolic, where as Sehey, et al ⁴ presented a comprehensive report on the geometrical factors that affect the shape of the barrel. Banerjee ⁵ and Narayanasamy, et al ⁶ showed
theoretically that the barrel radius could be expressed as a function of height strain and confirmed the same through experimental evidences. Yang et al \(^7\) developed an upper bound solution for the determination of forging load and deformed bulged profile during upset forging of cylindrical billets considering the dissimilar frictional conditions at flat die surfaces. Chen and Chen \(^8\) developed a theoretical solution for the prediction of flow stresses during a upsetting operation considering the barrelling effect. Gokler et al \(^9\) studied taper upset forging using elastic-plastic finite element analysis. Narayanasamy and Pandey \(^10\) studied the effect of barrelling in aluminium solid cylinders during cold upsetting. Malayappan and Narayanasamy \(^11\) studied the effect of barrelling of aluminium solid cylinders during cold upsetting using different lubricants. Malayappan and Narayanasamy \(^12\) also studied the effect of barrelling in aluminium cylindrical billets by considering the dissimilar frictional conditions at the flat die surfaces.

**SQUARE BILLET**

![Image of Square Billet](image1)

**INSTANTANEOUS BILLET**

![Image of Instantaneous Billet](image2)

**EXPERIMENTAL SETUP**

![Image of Experimental Setup](image3)

Fig. 1(a): Barreling under ideal condition.

Fig. 1(b): Barreling under Differential Friction Condition.
Earlier investigations have been made on solid cylinders to establish a relationship between the measured radius of curvature of barrel and the new geometrical shape factor arrived based on contact diameters, barrel diameters, initial height and height after deformation. The present investigation is aimed to establish a relationship between the measured radius of curvature of the barrel and the new geometrical shape factor arrived based on contact width, initial height and height after deformation of square billets under dissimilar frictional conditions. Most of square billets are being open die forged or upset before close die forging operation in aerospace industries.

2. EXPERIMENTAL DETAILS

Square Specimens having side length of 19.00 mm of varying lengths (aspect ratios namely 0.75, 1.00 and 1.25) were prepared from the annealed bar of commercially pure aluminium. The upset forging tests were conducted using the flat dies at room temperature and by applying different lubricants namely grease, zinc stearate, molybdinum-di-sulphide and SAE 40 oil on one side of the specimen and keeping the other end in dry friction. The upset forging tests were conducted using a 100 tonnes universal testing machine. Extreme care was taken to place the axis of the cylindrical specimen concentric with the axis of the ram. During upset forge testing, the Square specimen developed a barrel and a truncated part, as shown in Fig. 1b. For each test, ten specimens of the same dimensions were taken and deformed to different strain levels. The load used during each deformation was recorded from the dial indicator of the universal testing machine. After each test, the following parameters were measured.

1. Height of the deformed specimen (h_f)
2. Circumferential contact length of the specimen (l_c1, l_c2, l_c3, l_c4)
3. Circumferential bulged length (l_b1, l_b2, l_b3, l_b4)
4. Circumferential length along the top portion of the truncated pyramid (4l_p1)
5. Circumferential length along the bottom portion of the truncated pyramid (4l_p2)
6. Height of the bulged portion (h_b)
7. Height of the truncated pyramid (h_p)
8. Contact width of the specimen (l_cw)
9. Bulged width of the specimen (l_bw)
10. The radius of the barrel (R) and
11. Contact Area (A_c)

The barrel radius and circumferential lengths were traced using a profile projector and the values were measured using tablets (digitizers) in Auto CAD software and the rest of the dimensions were measured using digital micrometer.

3. RESULTS AND DISCUSSION

Figure 2 shows the plot drawn between the axial strain $\varepsilon_z = \ln(h_0/h_f)$ and the new hoop strain, eqn. B2. This plot is a straight line. The slope for all aspect ratios studied is almost equal. The hoop strain (eqn. B2) is calculated based on the following expression, which is derived in the Appendix-B:

![Graph showing relationship between axial strain and new hoop strain.](image-url)
\[ e_{0}^{m} = \ln \left( \frac{(2l_{b}^2 + l_{c}^2) h_{b} + (l_{p1}^2 + l_{p1}l_{p2} + l_{p2}^2) h_{p}}{3a^2 h_{f}} \right) \] (1)

Where:

- \( l_{b} \) - Bulged length \( \frac{(l_{b1}+l_{b2}+l_{b3}+l_{b4})}{4} \)
- \( l_{c} \) - Contact length \( \frac{(l_{c1}+l_{c2}+l_{c3}+l_{c4})}{4} \)

- \( a \) - Side of the square (mm)
- \( l_{p1} \) - Side length of the pyramid at the top
- \( l_{p2} \) - Side length of the pyramid at the bottom
- \( h_{f} \) - Height of the deformed specimen
- \( h_{b} \) - Height of the bulged portion
- \( h_{p} \) - Height of the truncated pyramid

Using the simple theory of plasticity stresses, namely hoop stress \((\sigma_{h})\), effective stress \((\bar{\sigma})\) and hydrostatic stress \((\sigma_{m})\) were calculated and plotted against axial strain \((\varepsilon_{x})\) as shown in figures 3(a) – (c). The computational procedure for the aforesaid stresses is shown in Appendix-A. The stresses namely axial

![Fig. 3(a): Stresses Vs Axial Strain.](image)

![Fig. 3(b): Stresses Vs Axial Strain.](image)

![Fig. 3(c): Stresses Vs Axial Strain.](image)
stress ($\sigma_e$), effective stress ($\sigma_0$), hoop stress ($\sigma_h$) and the hydrostatic stress ($\sigma_m$) increased with the increasing amounts of the strains. The hoop stress is tensile in nature because during compressive deformation, the bulged diameter expanded due to the action of secondary tensile stress. However, for any given deformation level, the increase in hoop stress due to loading was appreciably lower compared to the axial stress.

Figure 4 is drawn between the measured radius of curvature of the barrel and the calculated radius based on the principle of volume constancy during deformation, with the assumption that the barrel radius is circular arc. The calculated values of the radius of curvature are in close proximity with measured values. The plot of radius of curvature shows a straight line relationship and calculated values are in good agreement with the measured values. It is observed that the lubricant namely Molybdinum-di-sulphide is the most effective among the lubricants tested because the barreling is formed minimum in this.

The new geometrical shape factor developed is shown in Appendix-B. The power law relationship between barrel radius and new shape factor can be expressed as under:

$$R = CS^{-m} \quad (2)$$

Where:
- $R$ – Barrel Radius
- $S$ – New geometrical shape factor and
- $C$, $m$ – empirically determined constants

Figure 5 was drawn to establish a relationship between the barrel radius and the stress ratio parameter on a ln-ln plot. The straight line having same slope irrespective of aspect ratio is the manifestation of power law relationship between the barrel radius and the stress ratio parameter of the following form.

$$R = c_1 \left( \frac{\sigma_m}{\sigma} (h_o-h_f) \right)^{m_1}$$

Where:
- $\sigma_m$ – hydrostatic stress
- $\sigma$ – representative stress and
- $c_1$ & $m_1$ – empirically determined constants

Fig. 4 : Relationship between Measured Radius and Calculated Radius
Fig. 5 : Relationship between ln(Measured Radius) and ln(Stress Ratio Parameter)
CONCLUSIONS

The major findings of the present investigation are as follows:

1. Stresses, namely the hoop stress, the representative and hydrostatic, all found to increase with the increased level of deformation. The relationship between the new hoop strain and axis strain conformed to a straight - line behaviour.

2. The relationship between calculated and the measured radius of curvature of the barrel conformed to a straight-line behaviour.

3. It was found that the barrel radius could follow the following forms of power law equations.

\[ R = CS^{-m} \]
\[ R = C_1 [(s_m/s)(h_o - h_f)]^{-m_1} \]

Where:

- \( R \) - radius of curvature
- \( S \) - geometrical shape factor
- \( s_m \) - hydrostatic stress
- ‘s’ - representative stress
- \( h_o \) - initial height of the cylinder
- \( h_f \) - final height of the cylinder after deformation
- \( c, m, c_1 \) & \( m_1 \) - experimentally determined constants.

4. It was also found that all stresses were affected by the co-efficient of Friction. (different lubricants)

APPENDIX- A

As explained elsewhere[13], the representative strain can be calculated follows

\[ e = \left(\frac{2}{\sqrt{3}}\right) (1 + a + a^2)^{0.5} \varepsilon_z \]  

(A1)

Where,

- \( a \) - slope between hoop strain (eq) and the axial strain (\( \varepsilon_z \)). Since the radial stress (\( s_r \)) is zero at the free surface, it follows the flow rule that:

\[ s_q = \left[ 1/(2 + a) \right] \left[ 3(1 + a + a^2)^{0.5} \varepsilon_z \right] \]

(A2)

And the representative stress can be expressed as

\[ s^{' =} \left[ 1/(2 + a) \right] \left(3(1 + a + a^2)^{0.5} \varepsilon_z \right) \]

(A3)

The hydrostatic stress is given as follows

\[ s_m = (1/3)(s_q - s) \]

(A4)

APPENDIX-B

BARRELLING IN SOLID SQUARE BILLETS:

As explained elsewhere[14], the expression of bulging can be written as follows under the condition that this follows circular arc barrelling effect.

\[ \frac{p}{4}a^2h_o = \frac{p}{12}(2b_o^2 + b_o^2)h_b + \frac{p}{12}(l_{p1}^2 + l_{p1}l_{p2} + l_{p2}^2)h_p \]

(B1)

(Under volume constancy principle)

Where:

- \( l_b \) - bulged length \[ (l_{b1} + l_{b2} + l_{b3} + l_{b4})/4 \]
- \( l_c \) - Contact length \[ (l_{c1} + l_{c2} + l_{c3} + l_{c4})/4 \] and
- \( a \) - Side of the square (mm)
- \( l_{p1} \) - Side length of the pyramid at the top
- \( l_{p2} \) - Side length of the pyramid at the bottom
- \( h_f \) - Height of the deformed specimen
- \( h_b \) - Height of the bulged portion
- \( h_p \) - Height of the truncated pyramid
- \( h_o \) - initial height of the square billet

The above equation (B1) can be written as follows

\[ \frac{h_o}{h_f} = \left[ (2l_{b_o}^2 + l_{c}^2)h_b + (l_{p1}^2 + l_{p1}l_{p2} + l_{p2}^2)h_p \right]/3a^2h_f \]

(B2)

Taking natural logarithm on both sides, the equation becomes

\[ \varepsilon_z = \varepsilon_0 \]

(B3)
where:

\[ \varepsilon_{x} = \ln(h_{o}/h_{f}) \]

\[ \varepsilon_{0}^{*} = \ln\{[(2l_{b}^{2} + l_{c}^{2})h_{b} + (l_{p1}^{2} + l_{p1}l_{p2} + l_{p2}^{2})h_{p}]/3a^{2}h_{o}\} \]

From the Ref.[8], the expression for the radius of curvature of barrel is as follows

\[ X = R \cdot (R^{2} - h_{b}^{2}/4)^{0.5} \quad (B4) \]

Where: \( x = (l_{bw} - l_{cw})/2 \)

\( R \) is the radius of curvature of the barrel; \( l_{bw} \) is the bulged width; and \( l_{cw} \) is the contact width.

Simplifying the expression (B4), the expression for the barrel radius \( R \) can be obtained neglecting \( x^{2} \) term (because the quantity of the \( x \) is very less)

Therefore,

\[ R = h_{b}^{2}/8x \quad (B5) \]

Otherwise

\[ R = h_{b}^{2}/4(l_{bw} - l_{cw}) \quad (B6) \]

Multiplying \( h_{o} \) on both sides by the expression (B6), the following expression can be obtained:

\[ R^{0.50} = (h_{b}/h_{o})h_{o}[2(l_{bw} - l_{cw})^{0.5}] \quad (B7) \]

From the expression (B2) and (B7), the barrel radius becomes as follows

\[ R^{0.50} = (h_{b}/h_{o})h_{o}[\{3a^{2}h_{o}^{2}/(l_{bw} - l_{cw})^{1/2} + (l_{p1}^{2} + l_{p1}l_{p2} + l_{p2}^{2})h_{p}\}]/(2l_{b} + l_{c}^{2})h_{o} \quad (B8) \]

The logarithmic value of the right hand side of the equation (B8) represents the new geometrical shape Factor. Based on dimensional parameters one can determine the radius of curvature of the barrel

REFERENCES


