Comparison of barreling in unlubricated truncated cone billets during cold upset forging of various metals

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Received 4 July 2005; accepted 6 March 2006

Experiments have been carried out to generate data on cold upset forging of unlubricated annealed commercially pure aluminium, copper and zinc solids of truncated cone billets. The measured curvatures of the barreled truncated cone billets of all the three metals are found to closely conform to the calculated values on the assumptions that the shape of the barrels is in the form of a circular arc. It is further found that the measured radius of curvature of barrels exhibited a linear relationship with a geometrical shape factor irrespective of the aspect ratios of the truncated cone billets. Further, an empirical relationship has been established between the measured radius of curvature of the barrels and stress ratio parameter. A comparative study of barreling behaviour of aluminium, copper and zinc, during upset forging operation in unlubricated condition is presented in this paper.

IPC Code: B21J17/00

Investigations have been going on in cold upset forging of solid cylinders due to its relevance in metal forming applications. Earlier researchers have published a comprehensive review of literature. Shaw and Avery explained the aspect of axisymmetric compression, which is the estimation of forming limits and fracture. During upsetting the existence of frictional constraints between the dies and workpiece directly, affect the plastic deformation of the latter. When a solid specimen (cylindrical of truncated cone) is compressed axially between the punch and bottom platen, the workpiece material in contact with the surfaces undergoes heterogeneous deformation that results in barreling of the specimen.

Friction at the contact faces retards the plastic flow of metals on the surface and in its vicinity. A conical wedge of a relatively undeformed metal is formed immediately below the contact zone while the rest of the cylindrical metal suffers high strains 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 pints of least resistance, a well known principle in plastic deformation. However, the use of lubricants reduces the degree of bulging and under ideal lubrication, bulging can be brought down to zero. Earlier researchers examined the arc of barrel assuming it circular or parabolic, whereas Schey and his co-workers presented a comprehensive report on the geometrical factors that affect the shape of the barrel. Narayanasamy et al.\textsuperscript{1} showed theoretically that the barrel radius could be expressed as function of axial strain and confirmed this through experimental verification. Yang et al.\textsuperscript{2} developed an upper bound solution for the determination of forging of cylindrical billets considering the dissimilar frictional conditions at flat die surfaces. Chen\textsuperscript{3} developed a theoretical solution for the prediction of flow stresses during an upsetting operation considering the barreling effect. The barreling aspects during upsetting of unlubricated truncated cone type copper billets and aluminium cone type billets have been reported elsewhere\textsuperscript{4,5}.

Earlier investigations on open die forging have been made only on solid cylinders to establish a relationship between the measured radius of curvature of the barrel and a geometrical shape factor developed based on contact diameters, barrel diameters, initial height, and height after deformation. There seems to be no comparative study on open die forging of various metals. The investigation is aimed at establishing a new relationship between the measured radius of curvature of the barrel and geometrical shape factor arrived based on contact diameters, initial height and height after deformation using unlubricated truncated cone billets of aluminium, copper and zinc, and compare the barreling behaviour.

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Experimental Procedure

Truncated cone specimens of 10° taper with 0.5, 0.75, 1.00 and 1.25 aspect ratios were prepared from annealed rods of commercially pure aluminium, copper and zinc. The initial height of the specimen \( (h_0) \), the initial top contact diameter \( (D_{0t}) \) and the initial bottom contact diameter \( (D_{0b}) \) were measured before deformation. Upset forging tests were carried out under unlubricated conditions at room temperature using flat dies. The axial upsetting tests were carried out using a universal testing machine of 100 tonnes capacity. Form each test, 10 specimens of same dimensions were taken and deformed to different axial strain levels. After each test the following parameters were measured: (i) height of the deformed specimen \( (h_f) \), (ii) bulge diameter \( (D_{B av}) \), (iii) top contact diameter \( (D_{TC}) \), (iv) bottom contact diameter \( (D_{BD}) \) and (v) radius of curvature of barrel \( (R_m) \).

The load used during each deformation was recorded from the dial indicator of the universal testing machine. Extreme care was taken to align the axis of the truncated cone specimen with the axis of the die and platen. The incremental compressive upset cold forging was carried out up to a true height strain \( \ln \left( \frac{h_0}{h_f} \right) \) of approximately 1.0. The barrel radii were recorded using a profile projector and other dimensions were measured using a digital micrometer. The shapes of the sample before and after deformation are shown in Fig. 1.

Results and Discussion

Figure 2 shows the plot between the axial strain, \( \varepsilon_z = \ln \left( \frac{h_0}{h_f} \right) \) and the hoop strain \( \varepsilon_\theta \). The plot is a straight line with a slope of unity irrespective of aspect ratio for all the three metals namely aluminium, copper and zinc. Hoop strain, \( \varepsilon_\theta \) is calculated based on the following expression:

\[
\varepsilon_\theta = \ln \left[ \frac{2D_{B av}^2 + D_{C av}^2}{3D_{0 av}^2} \right]
\]

where \( D_{B av} \) is the bulge diameter at the centre

\[
D_{0 av} = \frac{D_{0t} + D_{0b}}{2}
\]

Fig. 1—Shape of the specimen before and after deformation
Applying the simple theory of plasticity, hoop stress ($\sigma_\theta$) and axial stress ($\sigma_z$), effective stress ($\bar{\sigma}$) and hydrostatic stress ($\sigma_m$) were calculated and plotted against effective strain ($\varepsilon$) as shown in Figs 3-5. The computational procedure is given in Appendix A.

Figure 6 is drawn between the measured radius of curvature of the barrel and the calculated radius based on the principle of volume constancy during deformation. On the assumption that the barrel radius fits a circular arc, the calculated values of radii of curvature agree with the measured values. The measured radius of curvature of barrel is plotted against the new geometrical shape factor as shown in Fig. 7.

The new geometrical shape factor is explained in Appendix B. The effect of hydrostatic stress on the measured barrel radius is shown in Fig. 8. Fig. 9 was drawn to establish a relationship between barrel radius and stress ratio parameter on an ln-ln plot.

The various stresses namely axial stress ($\sigma_z$), effective stress ($\bar{\sigma}$), hoop stress ($\sigma_\theta$) and the hydrostatic stress ($\sigma_m$) increased with the increasing amount of strain due to work hardening as shown in Figs 3-5 and then became almost constant for all the three metals. Hoop stress is tensile in nature because the diameter expands during deformation.
Figure 3 shows the variation of the hoop stress \((\sigma_\theta)\) and the axial stress \((\sigma_z)\) with the effective strain. The above stresses increase with the increase of effective strain due to work hardening but the maximum value is observed in the case of aluminium, a lesser value in the case of copper and the lease value in the case of zinc. At an effective strain of 0.2, the hoop stress values obtained are 400 MPa, 355 MPa and 220 MPa for aluminium, copper and zinc respectively. The axial stress values are 500 MPa, 425 MPa and 275 MPa respectively for aluminium, copper and zinc. This shows the order of work hardening due to upset forging for a given frictional condition.

Figure 4 clearly indicates the variation of representative stress \((\overline{\sigma})\) with representative strain \((\overline{\varepsilon})\). The representative stress \((\overline{\sigma})\) increases with an increase of representative strain \((\overline{\varepsilon})\) which is observed in all the three metals namely aluminium, copper and zinc; but the maximum values reached in all the cases are the same. Stresses are found to be 1130 MPa, 1000 MPa and 600 MPa for aluminium, copper and zinc respectively at an effective strain of 0.2 for a taper angle of 10°. The order of work hardening is aluminium, copper, and zinc during cold upset forging.
The hydrostatic stress ($\sigma_m$) also increases with an increase in effective strain ($\bar{\varepsilon}$) as shown in Fig. 5; but the maximum value reached is in the case of aluminium followed by copper and zinc. The values are 33 MPa, 27 MPa and 16 MPa respectively for aluminium, copper and zinc for a taper angle of 10°.

Figure 6 is drawn between the measured radius of curvature of the barrel and the calculated radius based on the principle of volume constancy for the above metals. This plot is a straight line with different slopes for the three metals. The assumption that the radius of curvature of barrel fits a circular arc has been proved because the calculated values closely match the measured radius of curvature for all the three metals tested under study. This is shown in Fig. 6.

The measured values of radius of curvature of the barrel are plotted against the new geometrical shape factor as shown in Fig. 7. It shows the ln-ln plot between the barrel radius and a geometrical shape factor. The straight line behaviour suggests a power law relationship between the barrel radius and the geometrical shape factor for all the three metals:

$$R = C_S S^m$$

where $R$ is the barrel radius, $S$ is a geometrical shape factor; $C$ and $m$ are empirically determined constants.

The straight-line relationship further proves that the barrel radius follow the circular arc of curvature. The rate of change of the barrel radius with respect to the new geometrical shape factor is different for the three metals. The slope values are 3.00, 2.42, and 1.94 for aluminium, copper, and zinc respectively.

The behaviour of barrel radius with hydrostatic stress is shown in Fig. 8. The radii of curvature of barrel which has been plotted against hydrostatic stress ($\sigma_m$) is a straight-line relationship irrespective of aspect ratios as shown in Fig. 8.

The radius of curvature of the barrel decreased exponentially with increasing values of the three metals as shown in Fig. 9. It was drawn to establish a relationship between the barrel radius and the stress ratio parameter on an ln-ln plot. The straight line behaviour is the manifestation of a power law relationship between the barrel radius and the stress-ratio parameter of the following form for all the three metals.

$$R = C_1 \left( \frac{\sigma_m}{\bar{\sigma}} \right) (h_0 - h_f)^{-m_1}$$

where, $\sigma_m$ is the hydrostatic stress, $\bar{\sigma}$ is the effective stress and $C_1$, $m_1$ are empirically determined constants.

The rate of change of barrel radius with respect to the stress ratio parameter exhibited different behaviour for different metals tested, due to different work hardening behaviour of metals.

**Conclusions**

The following conclusions can be drawn from this study:

(i) The relationship between the new hoop strain and axial strain conformed to a straight-line behaviour with a slope of unity. This is observed in all the three metals tested.

(ii) Stresses namely the hoop stress, the axial stress, the representative stress and the hydrostatic stress were found to increase with increase in the level of deformation and then become almost constant in all the three metals tested but maximum value is observed in the case of aluminium, a lesser value in the case of copper and lease value in the case of zinc. This is the order of work hardening behaviour of metals during cold upset forging.

(iii) The calculated and measured radii of curvature of barrel are in good agreement for all the three metals.

(iv) It was found that the barrel radius follows a power law relationship with new geometrical shape factor in all the three metals, viz.
\[ R = CS^m \]

where \( R \) is the barrel radius, \( S \) is a geometrical shape factor; \( C \) and \( m \) are empirically determined constants. However, the rate of change of barrel radius for different metals is different for the three metals tested.

(v) It was found that the barrel radius follows a power law relationship with the stress ratio parameter in all the three metals, viz.

\[ R = C_1 \left( \frac{\sigma_m}{\bar{\sigma}} \right) (h_0 - h_f)^{-m_1} \]

where, \( \sigma_m \) is the hydrostatic stress, \( \bar{\sigma} \) is the effective stress and \( C_1, m_1 \) are empirically determined constants. But the rate of change of barrel radius is different for the three metals tested.

References

APPENDIX A
As explained elsewhere\(^6\), the effective strain can be calculated as follows, assuming the metal is isotropic and Poisson’s ratio is 0.5.

\[ \bar{\varepsilon} = \frac{2\varepsilon_0}{\sqrt{\alpha}} (1 + \alpha + \alpha^2)^{0.5} \]

where \( \alpha \) is the slope between the hoop strain \( \varepsilon_0 \) and the axial strain \( \varepsilon_z \). Since the radial stress \( (\sigma_r) \) is zero at the free surface, it follows from the rule that

\[ \sigma_r = \frac{1 + 2\alpha}{2 + \alpha} \sigma_z \]

and effective stress can be expressed as

\[ \bar{\sigma} = (0.5 + \alpha) \left[ 3(1 + \alpha + \alpha^2)^{0.5} \right] \sigma_z \]

The hydrostatic stress is given as follows

\[ \sigma_h = \frac{1}{3} (\sigma_n - \sigma_z) \]

APPENDIX B
As explained elsewhere\(^7\) the expression for bulging can be written as follows, under the condition that this follows circular arc (barreling effect) under volume constancy principle.

\[ \frac{\Pi}{12} (2D_{B_{av}}^2 + D_{C_{av}}^2) h f = \frac{\Pi}{4} D_0^2 h_0 \]

\[ h_0 = \frac{2D_{B_{av}}^2 + D_{C_{av}}^2}{3D_{o_{av}}^2} \]

Taking natural log on both sides,

\[ \varepsilon_z = \varepsilon_{o_0} \]

\[ \varepsilon_z = \ln(h_0 / h_f) \]

\[ \varepsilon_{o_0} = \ln \left[ \frac{2D_{B_{av}}^2 + D_{C_{av}}^2}{3D_{o_{av}}^2} \right] \]

From Ref. [6], expression for radius of curvature of barrel \( (R) \) is as follows

\[ X = R' \left[ R^{2/3} \right] h f \]

where,

![Fig. A1 — The relationship between \( R \) and \( R' \)]
Simplifying the expression (B.4), the expression for barrel radius ($R'$) can be obtained neglecting $X^2$ term (because the quantity of $X$ is very small).

Therefore,

$$R' = \left[ \frac{h_f^2}{8X} \right]$$  \hspace{1cm} \text{(B.5)}

$$R'=\left[ \frac{h_f^2}{4(D_{B,av}-D_{C,av})} \right]$$  \hspace{1cm} \text{(B.6)}

$$R'^{1/2} = \frac{(h_f/h_b)h_c}{2(D_{B,av}-D_{C,av})^{0.5}}$$  \hspace{1cm} \text{(B.7)}

From Eqs (B3.1) and (B.7), the following is obtained:

$$R'^{1/2} = \left[ \frac{h_f}{2(D_{B,av}-D_{C,av})^{0.5}} \right] \left[ \frac{3D_{B,av}^2}{2D_{B,av}^2 + D_{C,av}^2} \right]$$  \hspace{1cm} \text{(B.8)}

From Fig. A1

$$R = \frac{R'}{\cos \theta}$$  \hspace{1cm} \text{(B.9)}

$$R'^{1/2} = \frac{R'^{1/2}}{\sqrt{\cos \theta}}$$  \hspace{1cm} \text{(B.10)}

Therefore, the Eq. (B.10) becomes

$$R'^{1/2} = \left[ \frac{h_f}{(D_{B,av}-D_{C,av})} \right] \times \left[ \frac{3D_{B,av}^2}{2D_{B,av}^2 + D_{C,av}^2} \right] \frac{1}{\sqrt{\cos \theta}}$$  \hspace{1cm} \text{(B.11)}

Taking natural logarithm on both sides of the Eq. (B.11),

$$\ln R'^{1/2} = \ln \left[ \frac{h_f}{(D_{B,av}-D_{C,av})} \right] + \ln \left[ \frac{3D_{B,av}^2}{2D_{B,av}^2 + D_{C,av}^2} \right] - 0.5 \ln(\cos \theta)$$  \hspace{1cm} \text{(B.12)}

Simplifying Eq. (B.12),

$$\ln R = 2 \ln \left[ \frac{h_f}{(D_{B,av}-D_{C,av})} \right] + 2 \ln \left[ \frac{3D_{B,av}^2}{2D_{B,av}^2 + D_{C,av}^2} \right] - \ln(\cos \theta)$$  \hspace{1cm} \text{(B.13)}

We know that $R = C_s^{-\pi}$ where $S$ is the shape factor.