Effect of Lubrication in Cold Upsetting Using Experimental and Finite Element Modeling

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Reference

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ABSTRACT

An effective lubricant will always enhance the formability of a material when applied at the die–billet interface in cold upsetting processes. High friction at the die–billet interface leads to adhesion of the cylindrical billets to the surfaces of the die, and barreling can occur. The present work focuses on the experimental and finite element investigation of the cold upsetting process of AA2014-T6 cylindrical billets under different friction conditions. The forces, stresses, and strains required for deformation were analyzed for different lubrication conditions using the finite-element-based software DEFORM 2D. The sliding velocity and sliding distance of the material are explained with the aid of computational results. The barreling radii determined from the computational techniques and analytical results were in close agreement. The influence of lubrication on stresses—namely, axial stress, hoop stress, and hydrostatic stress—was investigated. Finite element investigations were conducted for friction factors ranging from $m = 0$ to $m = 1$ to predict the effect of stresses on the formability of the billets.

Keywords

upsetting, friction, formability, barrel radius, adhesion

Introduction

Metal forming operations play a significant role in the manufacturing industry in the production of a wide variety of components. Metal forging as a primary operation has gained importance in the fields of automobile and aerospace engineering. This has led to a great amount of investigation on newer and harder materials regarding process improvement, material property development, formability improvement, etc. When experimental investigations are combined with finite element techniques, the extent of experimentation and cost can be considerably reduced. Kamaluddin et al.

[1] studied the upsetting process of age-hardened aluminum billets at room temperature. The flow behavior was analyzed using experimental investigations and finite element modeling. The geometry of billets compressed to different levels of deformation under lubricated and unlubricated conditions was examined using a machine vision system. Gupta and Khapre [2] developed algorithms for obtaining the solutions of metal forming problems. By treating the deformation process as two-dimensional axisymmetric and plane strain problems, the authors validated the predicted results with the results obtained from the finite element packages ANSYS and FORGE2. The geometry of the billets was found to change with the friction condition employed at the face of the cylindrical billet when the billet was compressed between the dies.

Malayappan et al. [3–5] conducted cylindrical upsetting tests with machine-turned, milled, and ground faces and also employed different lubricants on the faces. They developed the relationship between the barreling radius as well as new hoop strain, hydrostatic stress, geometrical shape factor, and stress ratio parameters. Barreling has also been a problem with square and rectangular billets. Keeping in view its importance in metal forging operations, Manisekar et al. [6–8] conducted research on square and rectangular annealed billets of aluminum by applying various lubricants on the faces of the billets. The authors noticed that the geometry of the billet after deformation seemed truncated when different friction conditions were involved. The barrel curvature was circular irrespective of the friction condition or the shape of the billet. A relationship between the barrel curvature and stress ratio parameters was established. Similar research was done by Narayansamy et al. [9,10] on truncated cone billets under unlubricated and lubricated conditions to prove that the barrel curvature was circular irrespective of any aspect ratio or lubrication condition. Further, there was a consistent relationship between the stress ratio parameters and the barrel curvature.

The coefficient of friction at the die–billet interface is not constant and changes with the type of lubricant employed at the interface. Sahin et al. [11] conducted ring compression tests to estimate the friction factor between the die and the billet. The surface roughness was measured for all lubrication conditions using a digital roughness meter. Using the Amontons–Coulomb friction law, Akira et al. [12] determined the coefficient of friction at the die–billet interfaces in cold upset forging processes. The authors used a finite element method to determine the normal and tangential stresses acting on the billets.

In the present investigation, we studies the role of lubrication during the upsetting process of solid cylindrical billets of AA2014-T6 aluminum alloy with various aspect ratios. Finite element analysis simulation studies were conducted with the commercially available finite element software DEFORM 2D. To analyze the capability and applicability of the simulation results, the experimental results were compared with the simulated values. The barreled profile was determined using computational techniques, which has been a limitation in other research. The flow pattern of the alloy during upsetting due to the increased frictional conditions is thoroughly explained in the present work.

TABLE 1 Experimental processing conditions used for upsetting.

Billet material	AA2014-T6
Aspect ratios h/d	1, 0.75, and 0.5
Temperature	32°C
Lubricants	Grease, molybdenum disulfide, and white grease

Experimental Details

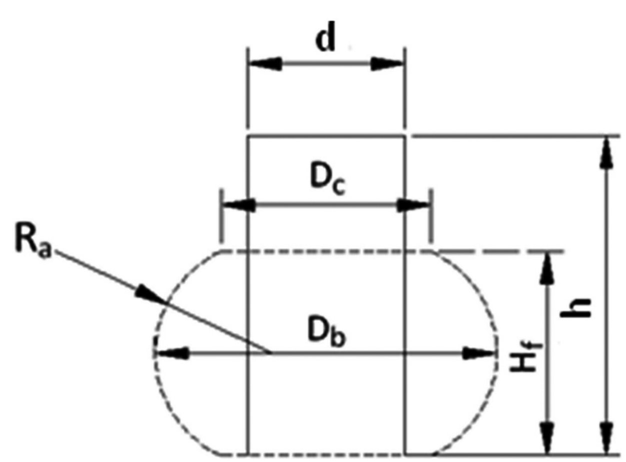
Solid cylindrical billets with various aspect ratios were upset between two rigid dies with the help of a 100-ton-capacity test machine. Different lubricants were employed on the faces of the billets (**Table 1**).

Extreme care was taken to position the billet at the center of the die and to properly apply the lubricant on the face of the billet. The geometry of the billet before and after upsetting is illustrated in **Fig. 1**. All billets were deformed to different strain levels, and at each and every stage of the deformation process, the following parameters were noted:

h = height of the cylinder before upsetting
d = diameter of the cylinder before upsetting
H_f = height after deformation
D_b = central bulging after deformation
R_b = bulged radius at the center of the billet
D_c = contact diameter at the die–billet interface
R_a = barrel radius after deformation

Ten sets of samples for each lubrication condition and aspect ratio were deformed plastically between the rigid dies with different lubricants applied on the faces. **Figure 2(*a*)** presents the surface expansion of the cylindrical billet, and **Fig. 2(*b*)** presents

FIG. 1 Geometry profile of the billet before and after deformation.



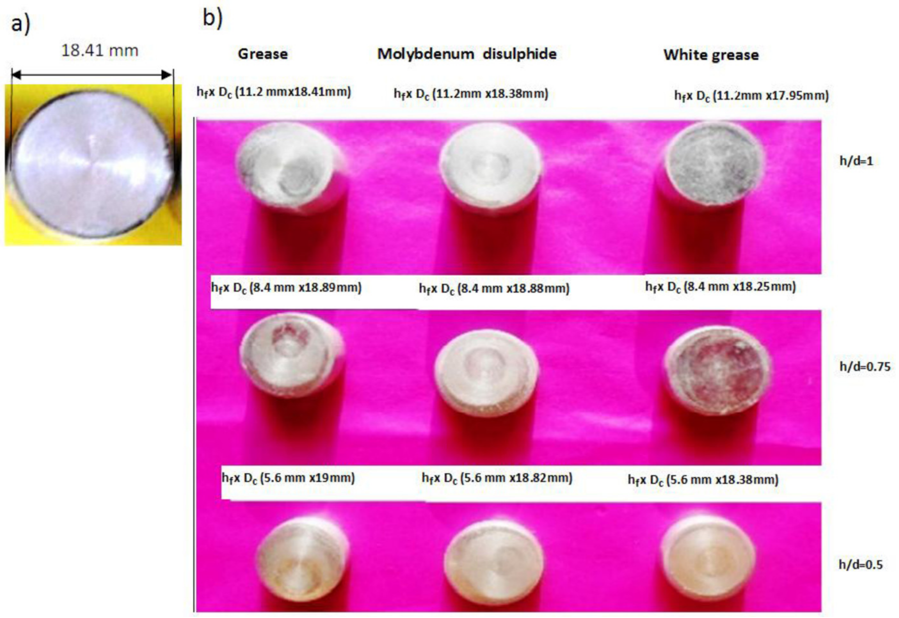


FIG. 2
(*a*) Top surface of the upset billet representing a cylindrical shape. (*b*) Preforms of 16-mm height and different aspect ratios upset with different lubricants applied on the faces.

deformed billets of different aspect ratios associated with different lubrication conditions.

Finite Element Simulation

To predict the accuracy of the finite element simulations, the billets were compressed between two rigid dies as illustrated in **Fig. 3**. The processing conditions for the upsetting process were given as per the data mentioned in **Table 2**. Flow stress equation 1 was given as input to the finite element software.

$$\sigma = 720\varepsilon^{0.22} \quad (1)$$

where:

σ = flow stress, and

ε = true strain.

The values of the friction factor corresponding to the lubricant applied were obtained from a standard ring compression test. Ring specimens with dimensions in terms of the ratio of outer diameter to inner diameter to height of 6:3:2 were deformed to different levels by employing different lubricants. The mean value of the ratio of change of the inner diameter to the height of the ring is considered as the friction factor m. The values of the friction factor obtained from the ring compression tests for different lubricants are mentioned in **Table 2**.

Results and Discussion

EFFECT OF FRICTION ON GEOMETRY

The barreled profile of the billet for $h/d = 1$ when grease was employed as the lubricant is illustrated in **Fig. 3**. The coordinates of the barreled curvature were measured from the post-processing data of the simulation software, and these coordinates were given to the drafting package AutoCAD 2D to

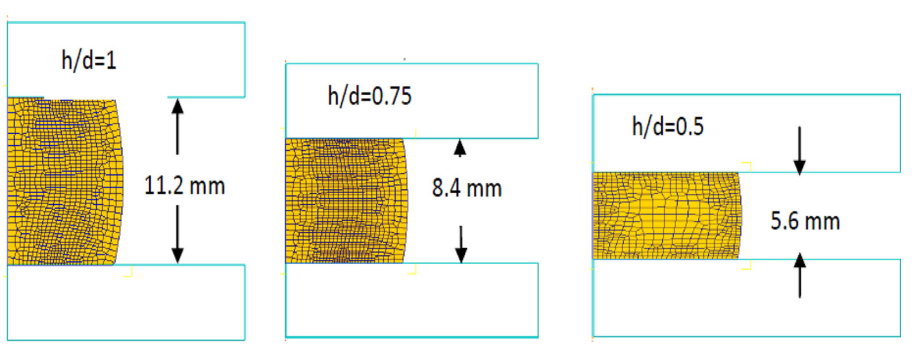


FIG. 3
Axisymmetric configuration of the billets reduced by 30 % in height.

TABLE 2 Material processing conditions using finite element modeling.

Billet material	AA2014-T6
Mode of deformation	Axisymmetric
Material behavior	Plastic
Dies	Rigid
Aspect ratios *h*/*d*	1, 0.75, and 0.5
Temperature	32 °C
Friction at the die–billet interface *m*	0.24 (grease), 0.29 (molybdenum disulfide), 0.44 (white grease)

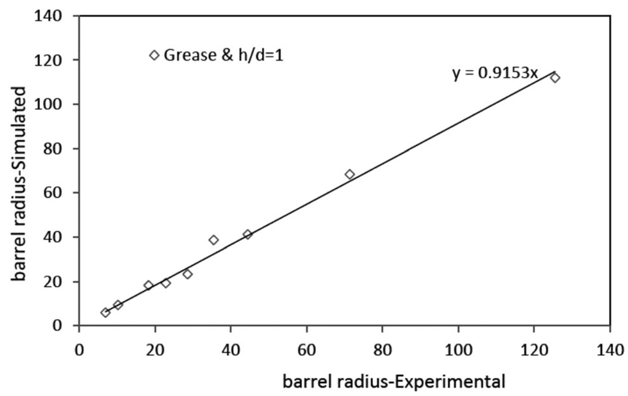
measure the barrel radius (**Fig. 4**). The barrel radius was measured using Eq 2, proposed by Narayanasamy and Pandey [13].

$$R_a = \frac{h_f^2}{4(D_b - D_c)} \tag{2}$$

To validate the experimental and finite element results and predict the accuracy, **Fig. 5** was plotted. From the trend line of **Fig. 5** and the data in **Table 3**, it can be noticed that the simulated results were in close agreement with the experimental results.

On examining the plot in **Fig. 6**, one can see that the increasing amount of axial strain increases the bulged diameter irrespective of the type of lubrication applied on the faces of the billet. For the same amount of strain, the bulged diameter achieved with white grease was greater than those noted with the other two lubricants. The rate of increase of the bulged diameter was greater with white grease than with molybdenum disulfide and grease regardless of the aspect ratio. The contact diametral expansion was greater when grease was used ($m = 0.24$) than with molybdenum disulfide ($m = 0.29$) or white grease ($m = 0.44$) under the same amount of axial strain (**Fig. 7**). The increasing amount of friction increases the sticking between the faces of the billet and the die, which restricts the flow of material in the radial direction. Because of this, the contact diameter will not expand more when white grease is used than it will with the use of other lubricants. This phenomenon is also responsible for the relatively larger bulging diameter at the middle observed with white grease than with molybdenum disulfide and grease.

FIG. 5 Comparison of barrel radius values (in millimeters) from experimental and simulated results.



The magnitude of the barreling radius decreased with increasing axial strain. This indicates that an increasing barrel radius makes the outer periphery more parabolic in nature, and a decreasing barrel radius makes it circular. From the trend lines in **Fig. 8**, it can be observed that when grease was employed, there was less barreling, but the barreling was greater when white grease was used. Similar behavior was observed for all aspect ratios when the same set of lubricants was employed on the billet faces.

ANALYSIS OF THE METAL FLOW BEHAVIOR IN THE BILLET

Figure 9 illustrates the velocity of the metal particles flowing in the radial direction near the contact surface of the billet with the die. This is important because of the adhesive nature of the billet with the die. It can be observed from this plot that the increasing friction factor reduces the flow velocity. The flow rate is greater with grease than with the other lubricants. This can also be explained with the aid of **Fig. 10**. This plot shows the relative displacement of the particles with increasing distance from the billet center. The relative velocity and relative displacement with respect to the billet center are shown for the top die movement of 0.2 mm/s and a stroke of 8 mm.

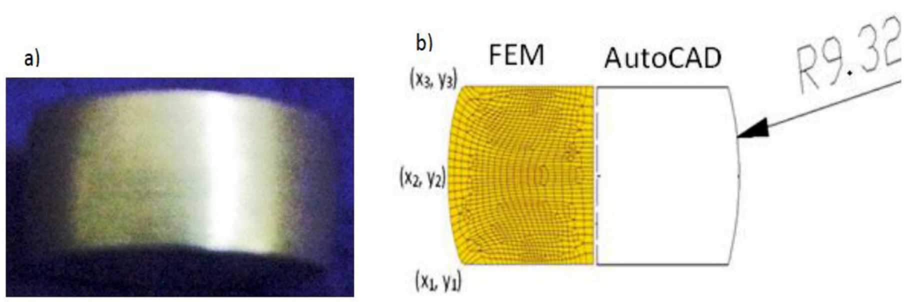


FIG. 4 Photographs of the deformed billet for h/d = 1: (*a*) experimental; (*b*) simulated.

TABLE 3 Comparison of experimental and finite element results for the barreled geometry.

Results	D_b, mm, (Error), %	D_c, mm, (Error), %	R_a, mm, (Error), %
Experimental	22.08	20.58	10.23
Simulated	22.57 (2.21)	20.21 (1.8)	9.32 (8.89)

Figure 11 illustrates the axisymmetric configuration of the billet with varying strain for different lubrication conditions. Grease, the best lubricant out of the three used, was associated with little difference in strain distribution when the strain at the center was compared to that at the periphery. The difference in the strain distribution was 0.23 [**Fig. 11(*a*)**]. When molybdenum disulfide was used as the lubricant, the difference in the magnitude of strain distribution at the center of the billet and at the equator was 0.34 [**Fig. 11(*b*)**]. The maximum difference in the strain distribution was 0.52 when white grease was applied as the lubricant [**Fig. 11(*c*)**]. The presence of a dead zone makes the strain distribution insignificant, and its value is close to zero at the top surface and near the axis of the billet.

IMAGE ANALYSIS FOR METAL FLOW BEHAVIOR

This is a technique that explains the intensity of the pixel distribution after a photograph is taken. The photograph is used as a source file in MATLAB software, and the processing is done according to the requirements. To analyze the metal flow behavior, an attempt was made to analyze the pixel intensity. One cylindrical sample deformed when white grease was applied as lubricant was taken and was cut along the axis. Later, a photograph of the section was taken and the image was converted to grayscale. A grayscale image is a data matrix in which values are represented by shades of gray. Integer values in the range of 0 to 255 represent the intensity of the pixels. As illustrated in **Figs. 12** and **13**, the pixel intensity was measured at the center of the billet and at the periphery, respectively. The (x,y) coordinate represents the distance moved by the pointer along the x- and y-axes. The first column in the pixel window represents the intensity variation measured at the center and along the axis of the billet (**Fig. 12**). When the pointer was moved to the periphery of the billet, a reduction in the intensity of the pixels was observed. A greater magnitude of the pixel intensity indicates a greater strain distribution, and lesser values of pixel intensities indicate a lesser strain distribution.

FIG. 6 Axial strain versus bulged diameter (in millimeters) for different aspect ratios: (*a*) h/d = 1; (*b*) h/d = 0.75; and (*c*) h/d = 0.5.

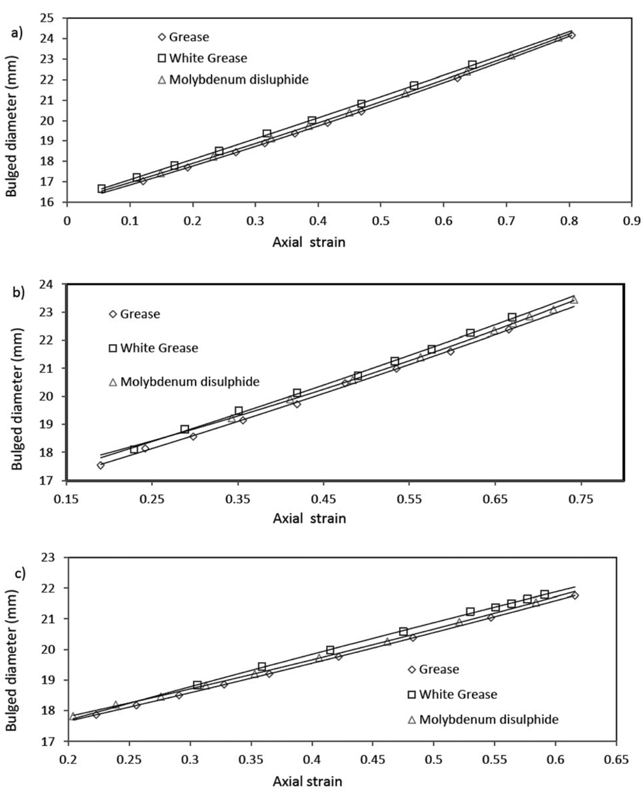
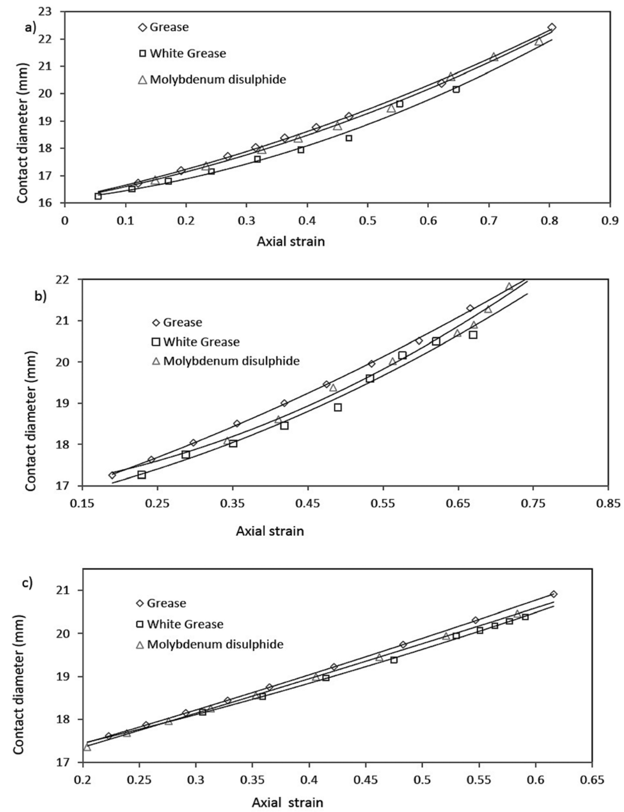


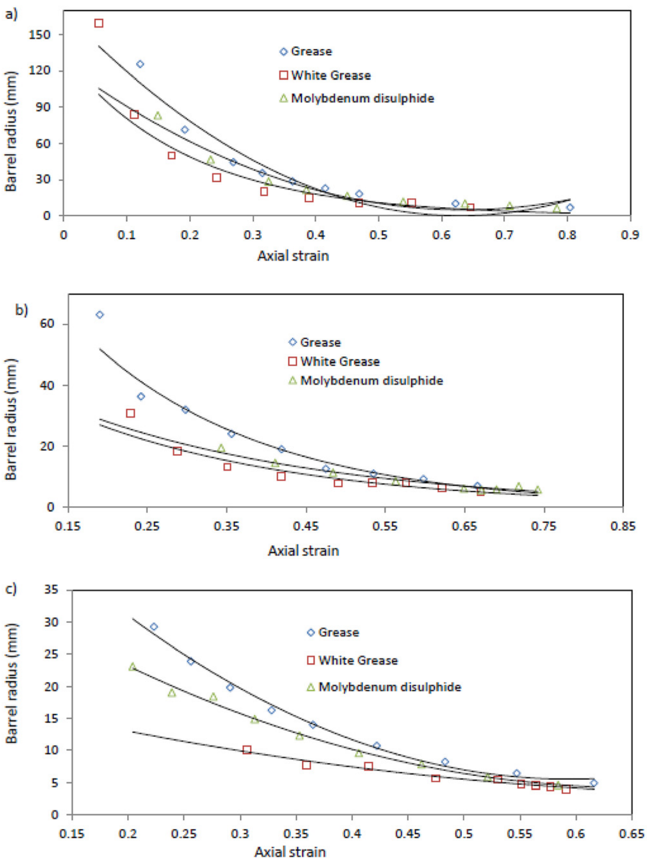
FIG. 7 Axial strain versus contact diameter (in millimeters) for different aspect ratios: (*a*) h/d = 1; (*b*) h/d = 0.75; and (*c*) h/d = 0.5.



EFFECT OF FRICTION ON FORCE AND STRESSES

With an increase in the level of deformation, the force required for further deformation also increases. The force required in order to deform the material plastically depends on the lubricant employed. This is because a high friction coefficent leads to

FIG. 8 Axial strain versus barrel radius (in millimeters) for different aspect ratios: (*a*) h/d = 1; (*b*) h/d = 0.75; and (*c*) h/d = 0.5.



sticking of the metallic billet and the die, and correspondingly, the force required for deformation also increases. **Figure 14** illustrates such behavior; an increase in the force was observed with white grease relative to other lubricants under the same amount of axial strain.

To determine the impact of effective stress on the axial force for different aspect ratios, a plot of the effective stress versus the axial force was constructed based on the results obtained

FIG. 9 Sliding velocity of the particles in the radial direction

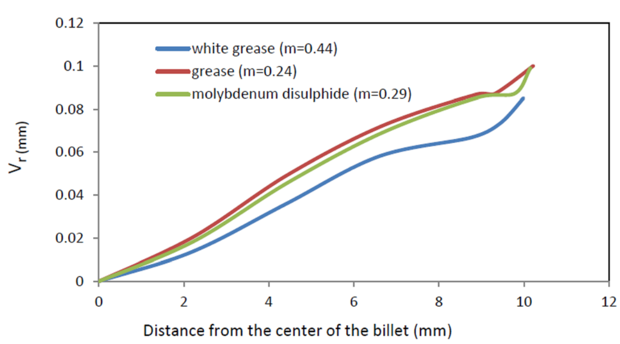
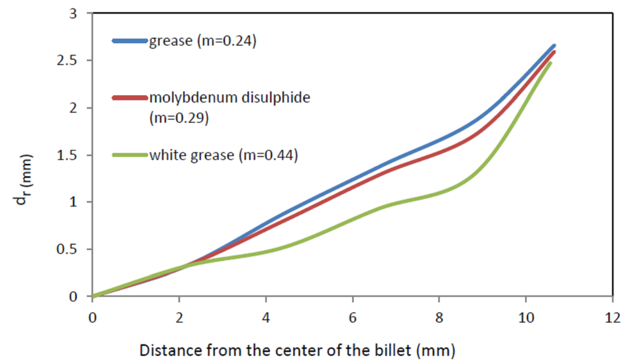


FIG. 10 Sliding distance of the particles in the radial direction.

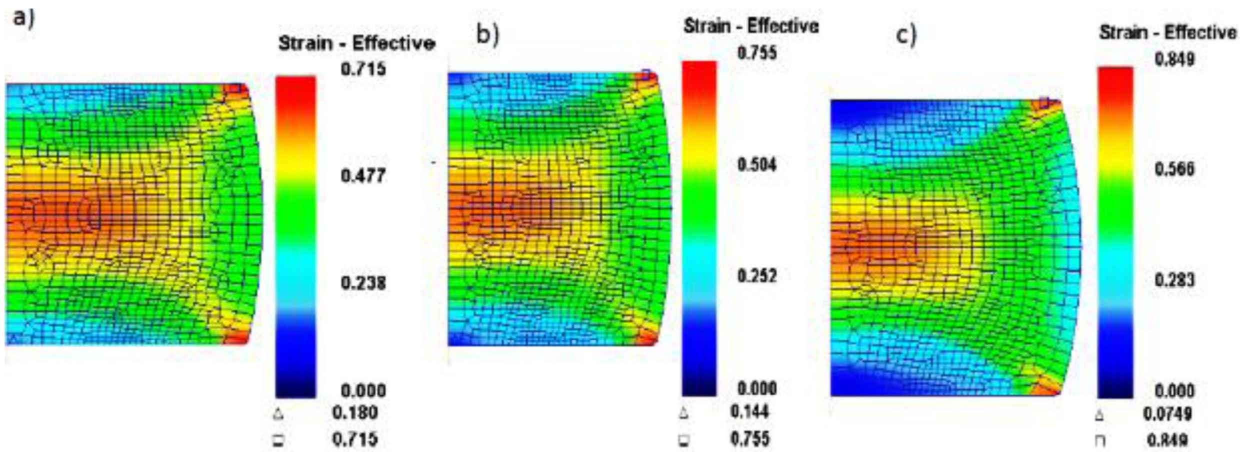


from the finite element modeling. The billets obtained after a 30 % height reduction for different lubrication conditions are illustrated in **Fig. 15**. It can be noted from **Fig. 15** that the effective stress was greater when white grease was used than with the molybdenum disulfide and grease. High stress was concentrated near the outer corners of the top and bottom surfaces. The stress concentration is comparatively low near the bulged portion of the geometry relative to the top and bottom surfaces because the material gets loosened near the bulged region.

An increasing force increases the effective stress, and the rate of change of the effective stress with respect to the force differs with the lubrication. This can be explained using **Fig. 15**. With high friction, the contact area of the surfaces will expand less than with low friction. An increasing force with a reduced contact area increases the amount of stress required in order to deform the billet to the same level of deformation (**Fig. 16**). From the investigations made, it can be noted that friction has a significant effect on the deformation force, effective stresses, and geometry of the billet.

To predict the effect of friction on the axial stress (σ_z), mean stress (σ_m), and hoop stress (σ_θ), simulations were conducted with different friction conditions corresponding to the lubricants used in the process. To compare the stresses for different friction conditions, **Fig. 17** was plotted. When the billets were subjected to the same amount of axial strain, the axial stress required for deformation was greater for white grease than for the other two lubrication conditions, but the rate of axial stress with respect to the axial strain declined when the axial strain reached a value of 0.57. This is because of the lower workability of the billet when a lubricant with higher magnitude of friction was employed at the die–billet interface. The tensile nature of the circumferential stress (σ_θ) and mean stress (σ_m) increases with an increase in the magnitude of the axial stress (σ_z). It can be noted from **Fig. 6** that an increase in the friction factor increases the value of the barrel curvature radius. This is because of the tensile nature of the hoop stress for the higher friction factor. A negative value of the hydrostatic stress

FIG. 11 Strain distribution for 30 % height reduction and different lubricant conditions: (*a*) grease; (*b*) molybdenum disulfide; and (*c*) white grease.



increases the formability of the material. The magnitude of the hydrostatic stress is relatively less in the case of $m = 0.4$ than in the other two friction conditions when the billets were subjected to same level of strain. This directly reflects the formability of the material.

In order to study the effect of stresses in different friction conditions, we subjected the billets to a height reduction of 50 %. **Figure 18** shows that the values of σ_z, σ_θ, and σ_m were different for different friction conditions. This is due to the tendency toward increasing barreling behavior of the billet for higher friction conditions relative to lower friction conditions. The value of σ_z is increasing at the beginning of the deformation process because of the initial strain hardening of the material and then gradually decreases because of the dynamic softening of the material. At the friction factor $m = 0$, the value of the axial stress is greater than in other friction conditions. This is due to the ability of the material to flow freely in the radial

FIG. 12 Pixel intensity measurement at the center of the billet.

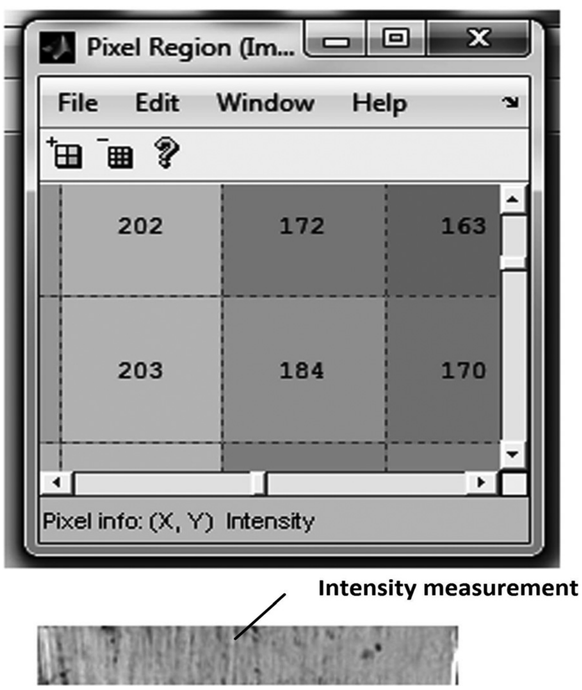


FIG. 13 Pixel intensity measurement at the periphery of the billet.

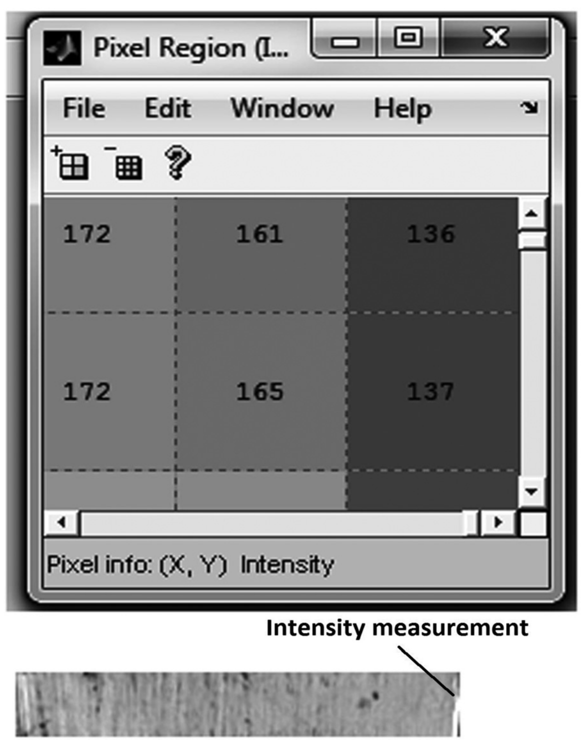


FIG. 14 Axial strain versus axial force (KN) for different aspect ratios: (*a*) h/d = 1; (*b*) h/d = 0.75; and (*c*) h/d = 0.5.

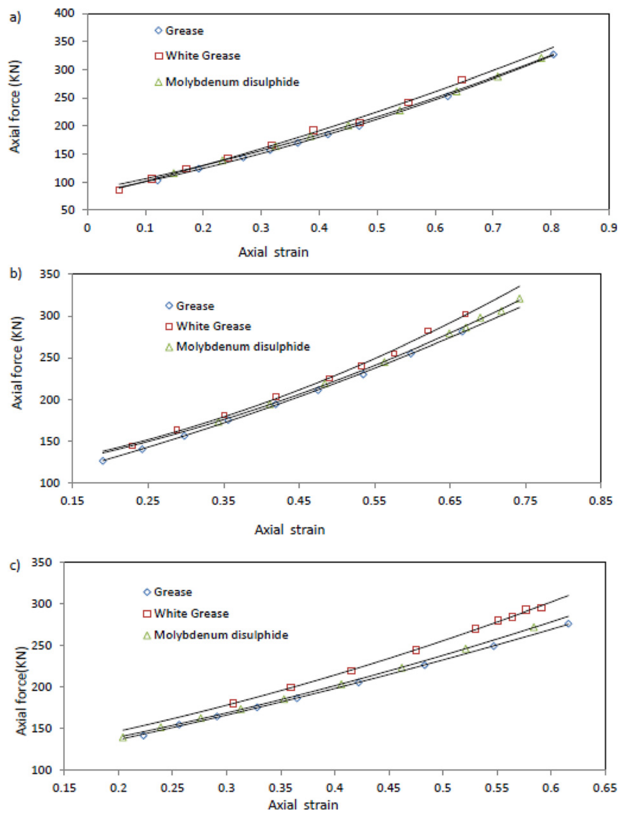
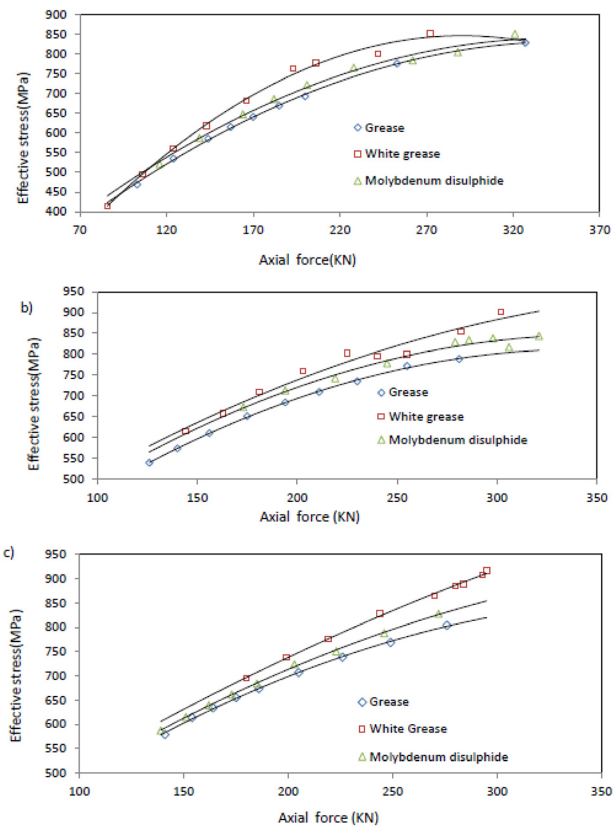


FIG. 16 Axial force versus effective stress for different aspect ratios: (*a*) h/d = 1; (*b*) h/d = 0.75; and (*c*) h/d = 0.5.



direction without barreling. The ability to absorb more deformation force increases when there is no friction, and failure of the material will not take place even at greater strains. This is not the case for other friction conditions; the barreling of the billet makes the billet crack, and the axial force required in order to deform the material further decreases, as does the axial stress. When the barreling of the billet becomes severe, the billet loses the ability to absorb the deformation force, and cracking initiates at the equator of the billet. This makes the hydrostatic stress become tensile. The hoop stress and the hydrostatic stress together promote surface cracks on the billet. In a zero-friction condition, the value of the hydrostatic stress is much greater than in the other friction conditions, and the value of the tensile hoop stress is zero, indicating better formability. The effective stress also increases with an increase in the friction factor.

FIG. 15

Stress distribution for 30 % height reduction: (*a*) grease; (*b*) molybdenum disulfide; and (*c*) white grease.

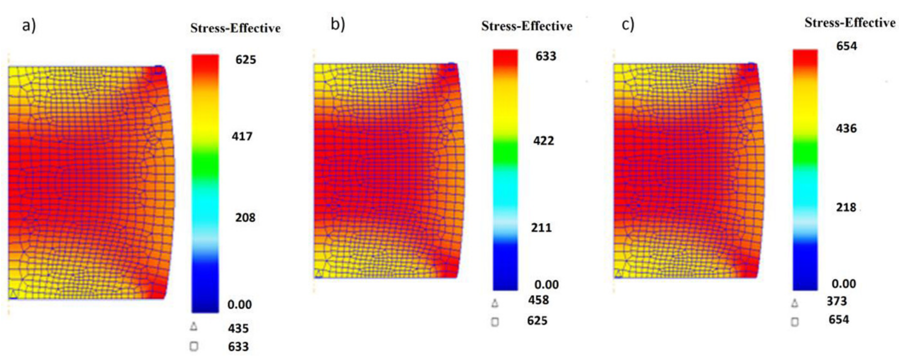


FIG. 17 Axial strain versus stresses with different lubricants.

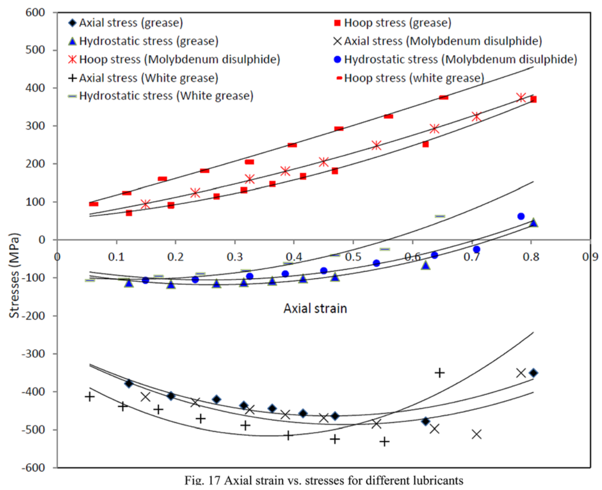
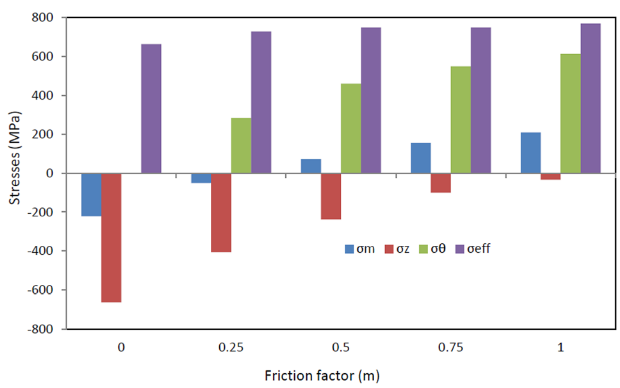


FIG. 18 Different types of stresses for varying friction conditions.



Conclusions

1. The barreling radius obtained from the computational techniques was in close agreement with the experimental results.
2. The friction factor is mainly responsible for the lack of difference in the strain distribution.
3. Grease was found to be more effective than the other lubricants tested in reducing the barreling curvature and nonuniformity in the geometry of the billet.
4. The image analysis technique adopted can explain the metal flow behavior in the billet and was in accordance with the strain distributions obtained from the finite element simulations.
5. For the same level of deformation, the hydrostatic stress may become tensile in nature, making the billet fracture in high-friction conditions.

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