AN ALTERNATIVE METHOD TO PREDICT FRICTION IN METAL FORMING

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SHIVANTHA MAHADEVA
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INTRODUCTION

Metal forming process has been one of the oldest technologies known to prehistoric man, who used cold forging process to fabricate weapons, tools for his use. Since then, metal forming has come a long way, with an exponential type of growth, to the present times, which are dominated by computer based applications. It is essential for the processing scientist to know about the metal properties, and the factors affecting the metal forming processes. In the recent years, new types of equipment and special processes for new materials with special properties and applications have been developed. The optimum utilization of these materials, has greatly benefitted from new knowledge of temperature effects, deformation speed, special kinds of dies, frictional effects on the basic characteristics of metals and the effects of metal flow by these parameters.

Deformation usually proceeds as a relative motion between dies and workpiece. This movement may influence velocity differences or it may develop as a consequence of the deformation itself, or may be a result as a combination of both. This relative motion is opposed by friction, which can be simply, described by assigning an average frictional shear strength to the interface. When this value reaches the shear flow strength of the deforming material, it is energetically more favorable for deformation of the
workpiece, to take place by internal shearing within the body of the workpiece. Movement at the interface ceases, and this condition is known as sticking friction, although this term does not imply actual sticking or adhesion between die and workpiece. This explanation alone is not sufficient, if the sources of friction and mechanism are to be understood. To the microscopic eye, both die and workpiece surfaces show minute asperities, peaks, and valleys. The directional magnitude of this surface conditions also play a major role in creating friction, and also the ability to sustain the lubricant film designed to influence the frictional effects.

In order to predict interface pressures, deforming forces, energy requirements, the magnitude of a friction factor has to be known. Following Coulomb classification of frictional constant \( \mu \), is the ratio of frictional force to the normal force of the surface, or the frictional stress to the normal stress

\[
\mu = \frac{\text{Frictional force}}{\text{Normal force}} = \frac{T_f}{p}
\]

It is possible that \( T_f \) has a linear relationship with \( p \) and \( \mu \) may reach any constant value. However, \( \mu \) cannot rise indefinitely, because sticking friction begins when \( \mu \cdot p > k \), in fact it can be shown that \( \mu \) can be only up to 0.5 because,

\[
k = 0.5 \cdot \sigma_f
\]

This coefficient of friction becomes meaningless when \( \mu \cdot p > k \),
since the relative movement at the interface ceases. This has led to the definition of a new interface factor known as $m$, $\tau_f = m k$. Since, $\tau_f$ is directly related to workpiece material property, which is known beforehand (unlikely as in case of $\mu$ where pressure has to be known), the use of $m$ favorably simplifies calculation, especially those based on upper bound theory or other numerical methods.

It is desirable to have a very precise knowledge of this interface shear factor $m$, for any specific lubricant system, and die workpiece material combination. Especially, for predicting the behavior of metal flow using numerical computer simulation in order to reduce experimental casts, and improve the quality of products.

The most widely known method of measuring friction is the ring compression test [ref 1]. This test can be used to characterize the lubricant system and die, workpiece material, but the validation of this test has certain restrictions, which will be discussed in the following chapters. The main aim of this thesis is to establish an alternative and better method to the ring compression test.

Extrusion Forging operation is the simple upsetting of a cylindrical billet, between two flat parallel dies, the top die having
a hole, and the bottom die being a plain die.

Study is conducted to optimize the die and billet geometry in order to obtain the most sensitive response of metal flow for a small variation in deformation.

Analytical solution of this process is based on the theory developed by Saida et al [ref 2] and modified by Jain et al, [ref 3]. Numerical solution is carried out using Nike2D, an FEM based software developed by Lawrence Livermore National Laboratories, California, [ref 4]. The physical modelling is carried out using various lubricants and aluminum and lead as workpiece materials and tool steel as the die. As discussed in the later part of the thesis, it is clearly visible that the Extrusion Forging process, is a more reliable and easier test, when compared to the ring compression test.
ANALYTICAL MODELING OF EXTRUSION FORGING TEST
AND RING COMPRESSION TEST:

Theory based on technical papers ref(2) and ref(3,4)
<table>
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<tr>
<th>Symbols</th>
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<tr>
<td>$\sigma$</td>
<td>Avg flow stress</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Flow stress</td>
</tr>
<tr>
<td>n</td>
<td>Strain rate sensitivity parameter</td>
</tr>
<tr>
<td>$\dot{\varepsilon}$</td>
<td>Strain rate</td>
</tr>
<tr>
<td>h</td>
<td>Flange height</td>
</tr>
<tr>
<td>$V_o$</td>
<td>Velocity of the extrusion</td>
</tr>
<tr>
<td>u</td>
<td>Radial velocity component</td>
</tr>
<tr>
<td>v</td>
<td>Axial velocity component</td>
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<tr>
<td>$\alpha$</td>
<td>Parameter chosen for velocity field</td>
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<td>$\beta$</td>
<td>Parameter chosen for velocity field</td>
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<td>Initial height</td>
</tr>
<tr>
<td>$H$</td>
<td>Total height</td>
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<td>Interface shear friction factor</td>
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<td>Coulomb friction coefficient</td>
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<tr>
<td>$\varepsilon_r \varepsilon_\theta \varepsilon_z$</td>
<td>Strain rate components in radial, axial and tangential direction</td>
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<td>$R_n$</td>
<td>Radius of neutral surface</td>
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<tr>
<td>$P_{avg}$</td>
<td>Average upsetting pressure</td>
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<tr>
<td>$E$</td>
<td>Energy dissipation rate</td>
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<tr>
<td>$\tau$</td>
<td>Friction shear stress $\tau = (m \cdot \sigma) / 3$</td>
</tr>
<tr>
<td>$\kappa$</td>
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EXTRUSION FORGING UPPER BOUND SOLUTION:

The upper bound solution presented in this thesis is based on the modification of the original Upper Bound Solution developed by Saida et al [ref 2], and further modified by S. Jain et al [ref 3]. The solution takes into consideration of the influence of process variables such as strain, temperature, and lubrication which affect the yield stress.

The theoretical analysis developed here utilizes an assumed velocity field, which satisfies the incompressibility condition and preserves material continuity, across, velocity discontinuity surfaces. The two types of assumed velocities, combined to give two modes of deformations. The two modes of deformation are as given in fig. 1. There are three different zones of material, at any given instant. Zone 1 represents the material which flows in the lateral direction. Zone 3 moves as a rigid body in the vertical direction while, Zone 2 is the intermediate zone between the above two, in which the material is possible to move in either lateral or vertical direction depending on the sign of velocity of extrusion. Ve, which is shown in fig. 2. From the upper bound solution originally developed by Saida et al and further modified by Jain et al which assumes three stages of deformations, the first stage of deformation deals with Ve <= 0

This mode of deformation is met during the first stage of the
Fig. 1a. (Top) shows the mode of deformation and position of neutral radius \( r_n \) when \( V_e \geq 0 \) indicating an upward velocity of extrusion.

Fig. 1b. (Bot) shows the mode of deformation and position of neutral radius \( r_n \) when \( V_e \leq 0 \) indicating a downward velocity of extrusion.

Fig. 2. Description of assumed velocity and the three zones of deformations.
Fig. 3 (top) Shows the initial stage of deformation when $V_e$ is negative and is downward causing reduction of the total height. (center) Shows the intermediate stage of deformation when $V_e = 0$, causing the total height to remain constant as the top die moves downward. (bottom) Shows the final stage of deformation when $V_e$ is positive causing increase in total height as deformation proceeds.

Fig. 4 Shows the geometrical definition used in the upper bound solution.
extrusion forging process, since the velocity of extrusion is less than zero the total height of the specimen decreases as the test progresses. The second stage of deformation is when, 

\[ V_e = 0 \]

This mode of deformation is met at the second and third stage of the experiment, that is when the total height stabilizes as the reduction in height increases. The third mode of deformation is met when, 

\[ V_e > 0 \]

that is when the extrusion velocity increases with the reduction in height, which makes the metal flow in the vertical direction, causing the total height to increase as the deformation proceeds. These three stages are illustrated in fig. 3, and the geometrical definitions follow fig. 4.

The radial and axial velocity component in Zone 1 are:

\[
\begin{align*}
u_1 &= 1 / 2h \left[ r - (1 + V_e) \frac{r^2}{2h} \right] = u_{11} \\
v_1 &= -1 / h z = v_{11}
\end{align*}
\]

(1a)

(1b)

for a unit downward velocity of the upper die.

In Zone 2 the velocity components for type I are:

\[
\begin{align*}
u_1 &= -\frac{re}{2h} V_e , \quad \text{and} \quad v_1 = -\frac{re}{2h} V_e \left( \frac{z}{r} \right)
\end{align*}
\]

(2a)
EFFECT OF SPEED ON LOAD AND ENERGY REQUIREMENTS

At low speeds the locus of the load/displacement trace is independent of the final reduction over the range of the reductions investigated. The highest loads are obtained under dry conditions or when the interface friction factor is at its maximum, from the previous studies carried by S. C. Jain [ref 7] the curve for Copaslip lying above that for colloidal graphite. This trend is in agreement with the results reported in this thesis and discussed in this section, this phenomenon is also seen in experimental and finite element simulation discussed in the later sections of this thesis. The ratio of maximum load with lubricant to the ratio of maximum load without lubricant does not appear to have any significant effect until the height reduction of 35 per cent.

At high speed the locus of the load / displacement trace is dependent upon the final reduction. This is presumably a result of the fact that as final percentage reduction is increased, the impact speed and therefore the instantaneous strain rate is increased; the effect of the increase in strain rate being to increase the yield stress of the material and hence the load required for its deformation. This is taken into consideration in calculating the extrusion velocity in the upper bound solution of extrusion forging test.
for type II are:

\[ u_{11} = -\frac{V_e}{h} r , \quad \text{and} \quad v_{11} = \frac{V_e}{h} z \]  \hspace{1cm} (2b)

Zone 3 moves as a rigid body with the axial component Ve. The boundaries between the zones, namely AB and A1 for velocity field I, and A'B' and A'C' for type II field, shown in fig. 2. are the surfaces across which the tangential velocity components are discontinuous. For the deformation mode given by fig.3 for Ve ≤ 0, the neutral surface, where the radial velocity component is zero, appears in Zone 1, the neutral radius in this case is shown to be

\[ r_n = \sqrt{1 + V_e} r_e \]  \hspace{1cm} (3)

**ENERGY DISSIPATION RATE**

The total Energy Dissipation Rate, can be found by summing the deformation energy rate in

Energy Dissipation Rate = Energy due to plastic work in Zone 1 and 2 + Frictional Energy at the tool and workpiece interface and the energy rate due to velocity discontinuities.
\[ \dot{E}_1 = 2\pi \int_0^h \int_{R_0}^R \sigma \dot{\varepsilon}_r \, dr \, dz \]  

where the effective strain rate is defined by

\[ \dot{\varepsilon} = \sqrt{\frac{2}{3} (\dot{\varepsilon}_r^2 + \dot{\varepsilon}_\theta^2 + \dot{\varepsilon}_z^2) } \]  

the strain rate components can be found from the velocity components of eqn as

\[ \varepsilon_r = \frac{1}{2h} \left[ \frac{1 + (1 + V_0)}{r^2} \right] \]  

\[ \varepsilon_\theta = \frac{1}{2h} \left[ \frac{1 - (1 + V_0)}{r^2} \right] \]  

\[ \varepsilon_z = \frac{-1}{h} \]
substitution of eqn 5 and eqn 6 into eqn 4 results in

\[
\dot{E}_1 = 2\pi \sigma \int_{r_e}^{R} \sqrt{r^4 + \frac{1}{3} (1 + V_e)^2 r_0^4} \, dr
\]

\[
= \pi \sigma \alpha^2 \left[ \sqrt{1 + 3 (R^4)} - \sqrt{1 + 3 (r_0^4)} + \right.
\]

\[
\left. \sqrt{3} \alpha \right] \left\{ \sqrt{1 + 3 (r_0 / \alpha)^4} + 1 \right. \ R^2 \left. \right\} \] 

Energy dissipation rate \( E \) due to friction at the tool and workpiece interface range \( r_e \leq r \leq R \) can be expressed by

\[
\dot{E}_{fo} = 2 m \int_{r_e}^{R} |\Delta u| \ 2\pi r \ dr
\]

where \( m \) is the interface shear friction factor, and is assumed to be the same for the top and the bottom die interfaces, \( k \) is the shear strength \( (\sigma / \sqrt{3}) \) and \( \Delta u \) the relative radial velocity at the interface, is given by

\[
|\Delta u| = \frac{1}{2h} \left| r - (1 + V_e) r_0^2 \right| \quad \text{when} \ V_e < 0
\]

and

\[
\dot{E}_{fo} = 2m \pi k \left\{ \frac{R^3 - r_0^3}{\alpha^2} \left( R - r_0 \right) \right\}
\]
when $Ve > 0$ the radial velocity components vanishes at

$$r = \sqrt{(1 + Ve) \cdot re}$$

which gives the neutral radius, and

$$\dot{E}_{fo} = \frac{2m\pi k}{h} \left[ \int_{re}^{\alpha} (\alpha^2 - r^2) \, dr + \int_{\alpha}^{R} (r^2 - \alpha^2) \, dr \right]$$

$$= \frac{2m\pi k}{h} \left[ \frac{4a^3 - \alpha^2 (R + re) + 1 (R^3 + re^3)}{3} \right] \quad (10)$$

It can be readily shown that the energy dissipation rate due to friction at the bottom die workpiece interface over the region $0 \leq r \leq r$ is given by

$$\dot{E}_{fo} = \frac{m\pi k}{h^2} |Ve \cdot re^3|$$

for the type 1 velocity field.

The deformation energy rate in zone 2 is calculated according to

$$\dot{\varepsilon} = \int \int \sigma \dot{\varepsilon} 2\pi r \, dr \, dz$$

where the effective strain rate is expressed by

$$\dot{\varepsilon} = \sqrt{2(\dot{\varepsilon}_r^2 + \dot{\varepsilon}_\theta^2 + \dot{\varepsilon}_z^2 + \dot{\gamma}_{rz}^2)}$$

in which for the type 1 velocity field,

$$\dot{\varepsilon}_r = 0, \quad \dot{\varepsilon}_\theta = -\frac{re \cdot Ve}{2hr}, \quad \dot{\varepsilon}_z = \frac{re \cdot Ve^2}{2hr}, \quad \text{and} \quad \gamma_{rz} = \frac{re \cdot Ve \cdot z}{2hr \cdot r^2} \quad (11)$$
The strain rate components given by eqn (11) come from velocity components expressed by eqn (2a). Then

\[ \dot{E}_s = \frac{\pi \sigma}{\sqrt{3}} |V_e| r_e^2 \left\{ \frac{1}{\sqrt{3}} \left( 1 + \frac{h^2}{4r_e^2} \right) \right\} \]

\[ = \frac{r_e}{h} \ln \left[ \frac{h}{2r_e} + \sqrt{1 + \frac{h^2}{4r_e^2}} \right] \tag{12} \]

Energy dissipation rate along the discontinuity AB is written as

\[ \dot{E}_{sa} = \int k |\Delta v| 2\pi r_e dz = \frac{\pi \sigma}{\sqrt{3}} \frac{r_e}{h} (1 + V_e) h \tag{13} \]

since

\[ |\Delta v| = |v_2 - v_1| \quad \text{at } r = r_e \]

\[ = \frac{1}{h} \left( 1 + \frac{r_e}{2} \right) z \]

Similarly, the energy dissipation rate \( E_{sb} \) along AO is given by

\[ \dot{E}_{sb} = \int k |\Delta s| 2\pi r dr = \frac{\pi \sigma}{\sqrt{3}} \frac{1}{3} \frac{|V_e| r_e}{h} \tag{14} \]

where

\[ |\Delta s| = |V_e \sin \theta - u_2 \cos \theta - v_2 \sin \theta| \]

\[ = \frac{1}{2} |V_e| \sqrt{\left[ 1 + \frac{r_e^2}{b} \right]} \]
and $\phi$ is the angle of slope of line AO and given by

$$\phi = \tan^{-1} \left( \frac{h}{r_e} \right)$$

The integration of eqn (14) becomes

$$\dot{E}_{sb} = \frac{\pi \phi}{\sqrt{3}} \left| V_e \right| \frac{r_e h^2}{2} \left( 1 + \frac{r_e^2}{h^2} \right)$$ (15)

The total energy dissipation rate, which becomes equal to the forging load, for a unit downward velocity, is the sum of the energy dissipation rates given by eqns (7), (8) on (9),(10),(12),(13) and (15).

$$\dot{E}_{fc} = \frac{m \pi k}{h^3} \left| V_e \right|^3$$ (16)

and

$$\dot{E}_{\phi} = \pi \phi \left| V_e \right| r_e^2$$ (17)
respectively, using the velocity components of eqn (2b). The energy
dissipation rates along the discontinuities A'B' and A'C' are shown to be

\[ \dot{E}_{sa} = \int k |\Delta V| 2\pi r_e \, dz = \pi \tilde{\sigma} r_e \left( 1 + V_e \right) h \quad (18) \]

and

\[ \sqrt{3} \]

\[ \dot{E}_{sb} = \int k |\Delta V| 2\pi r \, dr = \frac{\pi \tilde{\sigma}}{3} \sqrt{3} \frac{1}{|V_e|} r_e \quad (19) \]

Therefore the total energy dissipation rate for type II velocity field
is obtained by adding the energy rates expressed by eqns (7),(8) or
(9),(16),(17),(18)and (19). It must be noted that when extrusion
forging is made with a solid cylindrical specimen, The energy
dissipation rate along the discontinuity A'C' does not appear in total
energy rate until the central projection is formed.

Thus the total forging load becomes as follows
\[
\frac{(p)}{\pi \sigma /\sqrt{s}} = a^2 [\sqrt{1 + 3 (R)^4} - \sqrt{1 + 3 (re)^4}] + a a
\]

\[
\ln \left\{ \sqrt{1 + 3 (re/a)^4} + 1 \right\} + \sqrt{1 + 3 (R/a)^4} + 1 \quad \text{re}^2
\]

\[
|a^2 - re^2| \left\{ 1 \left( r_e + \sqrt{1 + h^2} \right) + \frac{h}{2} \frac{4r_e^2}{4r_e^2} \right\}
\]

\[
\frac{r \ln \left\{ h + \sqrt{1 + h^2} \right\} + m r e 2}{h} \quad 2r e \quad 4r e^2 \quad 2h
\]

\[
+ a^2 (h) + 2m \left[ 4a^3 - a^2 (R + re) + 1 (R^3 + r^3) \right] \quad \text{for } a \geq re
\]

\[
+ r^2 (h) + 2m \left[ 1 (R^3 - r^3) - a^2 (R - re) \right] \quad \text{for } a \leq re
\]

for the type I velocity field
\[
|\alpha^2 - r_{e}^2| \left[ \sqrt{3} + \frac{1}{3} \left( r_{e} \left( 1 + m \right) \right) \right] + \alpha^2 \left( \frac{h}{r_{e}} \right) \\
+ 2m \left[ \frac{4\alpha^3}{3} - \alpha^2 \left( R + r_{e} \right) + \frac{1}{3} \left( R^3 + r^3 \right) \right] \quad \text{for } \alpha \geq r_{e} \tag{20b} \\
+ 2m \left[ \frac{1}{3} \left( R^3 - r^3 \right) - \alpha^2 \left( R - r_{e} \right) \right] \quad \text{for } \alpha \leq r_{e} \\
\]

for the type II velocity field
DETERMINATION OF THE PARAMETER, $\alpha$

The parameter in eqns (20a) and (20b) is given by

$$\alpha = \sqrt{1 + V_e} r_e$$

(21)

and is equal to the neutral radius $r_n$, as given by eqn (3), when $r_n$ is equal to or larger than $r_e$. Note the two types of velocity fields become identical when $V_e = 0$. Parameter $\alpha$ in eqns (20a) and (20b) can be determined from the conditions that $\frac{\partial P}{\partial \alpha} = 0$. This results in satisfying the functional relationship given by

$$\ln \left\{ \frac{\sqrt{1 + 3 \left( \frac{r_e}{\alpha_0} \right)^4} + 1}{\sqrt{1 + 3 \left( \frac{R}{\alpha_0} \right)^4} + 1} \right\}$$

$$= 2m \left[ \left( \frac{R + r_e}{h} - 2 \alpha_0 \right) - \frac{m r_e}{2h} - \frac{1}{2} \left( \frac{r_e}{h} + \sqrt{1 + h^2} \right) \right] + \frac{4r_e^2}{4} \right\}$$

(22a)

$$- \frac{r_e}{h} \ln \left[ \frac{h + \sqrt{1 + h^2}}{h} \right]$$

for $\alpha_0 \geq r_e$

$$= 2m \left( \frac{R - r_e}{h} \right) + \frac{m r_e}{2h} + \frac{1}{2} \left( \frac{r_e}{h} + \sqrt{1 + h^2} \right)$$

(22b)

$$+ \frac{r_e}{h} \ln \left[ \frac{h + \sqrt{1 + h^2}}{h} \right]$$

for $\alpha_0 \leq r_e$

for the type I velocity field.
\[ \ln \left\{ \sqrt{\frac{1}{1+3\left(\frac{r_e}{a_o}\right)^4}} + \frac{1}{R^2} \right\} \quad \text{for } a_o > r_e \quad (23a) \]

\[ = \frac{2m}{h} \left( (R + r_e) - 2a_o \right) - \sqrt{3} - \frac{1}{3} \left( \frac{2a_o}{r_e} \right) (1 + m) + \left( \frac{h}{r_e} \right) \]

\[ = \frac{2m}{h} (R - r_e) + \sqrt{3} + \frac{1}{3} \left( \frac{2a_o}{r_e} \right) (1 + m) - \left( \frac{h}{r_e} \right) \quad (23b) \]

or \( a_o = 0 \), for \( a_o \leq r_e \)

for the type II velocity field.

It must be noted that in eqns. (22) and (23) the value of friction factor \( m \) which gives \( a_o = r_e \) is not the same as that in eqns (22a) and (22b) or (23a) and (23b). Further examination of the forging load as a function of given by eqn (20), reveals that for (22a) or (23a), and for \( m \leq m_2 \), is equal to or less than \( r \) and the value of should be determined by eqns (22b) or (23b), while \( a_o = r_e \) for the range \( m \) given by \( m_1 \leq m \leq m_2 \). The limiting factors \( m_1 \) and \( m_2 \) for type I velocity fields are

\[ m_1 = \frac{h}{2R - (5r_e/2)} \left[ \frac{\ln\left\{ \frac{3}{\sqrt{\left[ 1 + 3\left(\frac{r_e}{R\cdot a_o}\right)^4 \right]} + 1} \frac{r_e^2}{R^2} \right\}}{2h} + \frac{1}{2h} \left[ r_e + \frac{1}{2} \left( 1 + \frac{h^2}{4r_e^2} \right) \right] + \frac{2r_e}{2} \left[ \frac{h}{4r_e^2} + \frac{1}{2} \left( 1 + \frac{h^2}{4r_e^2} \right) \right] \]

and
\[
m_{12} = \frac{h}{2R - (3\, \text{re} / 2)} \left\{ \ln \left[ \frac{3}{\sqrt{\left[ 1 + 3 \left( \frac{R}{\text{re}} \right)^4 \right] + 1}} \right] \right\}_{\text{re}^2}
\]

\[
- \frac{1}{2} \left[ \text{re} + \sqrt{(1 + h^2)} \right] - \ln \left[ h + \sqrt{(1 + h^2)} \right]
\]

\[
\frac{4\text{re}^2}{h} 2\text{re} 4\text{re}^2
\]

for the type II field, the limiting factors, from eqns. (23a) and (23b), become

\[
m_{11} = \frac{h}{2R - (7\, \text{re} / 3)} \left\{ \ln \left[ \frac{3}{\sqrt{\left[ 1 + 3 \left( \frac{R}{\text{re}} \right)^4 \right] + 1}} \right] \right\}_{\text{re}^2}
\]

\[+ \sqrt{3} + \frac{1}{3} \left( \text{re} \right) + \left( h \right) \]

and

\[
m_{12} = \frac{h}{2R - (5\, \text{re} / 3)} \left\{ \ln \left[ \frac{3}{\sqrt{\left[ 1 + 3 \left( \frac{R}{\text{re}} \right)^4 \right] + 1}} \right] \right\}_{\text{re}^2}
\]

\[+ \sqrt{3} - \frac{1}{3} \left( \text{re} \right) + \left( h \right) \]

\[
(25)
\]

The problem still remains regarding the type of velocity field that should be selected at various stages during forging operation. A selection must be made for each stage for the velocity field which yield a smaller total energy dissipation rate under identical conditions of geometry and friction factor. It can be shown, by comparing the limiting values for the two types of velocity fields, that for \( m_2'' \geq m \geq 0 \), type II is operative, and is equal to or less
than $r$ as can be found from eqn (23b)

for $m > m'_1$ type I is appropriate, and becomes larger than $r$ as shown by the solution of eqn (22a)

for the range of $m$ given by $m'_1 > m > m''_2, \ r_e$.

Once the value of the parameter is determined, the forging load can be calculated from eqns (20a) or (20b), depending on the operating velocity fields. Also, the dimensionless changes are obtained according to

\[
\begin{align*}
\frac{dR}{2h} &= \frac{1}{2h} \left( R - a_0^2 \right) |dh| \\
\frac{dH}{re^2} &= Ve |dH| = \left( \frac{a_0^2}{re^2} - 1 \right) |dh|
\end{align*}
\]

(26)

These values are coded in FORTRAN 77 and the graphical results are plotted by using Plot 10 subroutines available on all Vax systems. The following figures 5, 6, and 7 illustrate the sensitivity of the aspect ratio and extrusion hole diameter to the extrusion height.
Fig. 5. Shows plots of total height($h_5$) vs. reduction(%) for various values of $m$
(top left) $d/D = 0.5$ and $Ho/D = 0.75$, (top right) $d/D = 0.5$ and $Ho/D = 1.0$
(bottom left) $d/D = 0.5$ and $Ho/D = 1.5$, (bottom right) $d/D = 0.5$
and $Ho/D = 2.0$

The values choosen for $m$ are 0.0, 0.2, 0.4, 0.6, 0.8, 1.0
Fig. 6. Shows plots of total height(%) vs. reduction(%) for various values of m
(top left) \(d / D = 0.25\) and \(H_0 / D = 0.75\), (top right) \(d / D = 0.25\) and \(H_0 / D = 1.0\)
(bottom left) \(d / D = 0.25\) and \(H_0 / D = 1.5\), (bottom right) \(d / D = 0.25\)
and \(H_0 / D = 2.0\)
The values chosen for m are 0.0, 0.2, 0.4, 0.6, 0.8, 1.0
Fig. 7. Shows the plot of total height(%) vs. reduction(%) for the most sensitive response of metal flow and the $d/D = 0.50$, $H_0/D = 0.75$, this dimensional ratio is used for the finite element simulation, and experimental modeling.
NUMERICAL SOLUTION OF RINGS UNDER COMPRESSION

Ring compression test was first utilized for friction studies by Kunogi [ref 5], and later improved by Male and Cockroft [ref 6]. A numerical solution for this method which provided more accurate analysis was done by T. Altan [ref 7,8], whose analysis takes into consideration the effects of bulging during deformation.

To determine the velocity, strain rate, and strain distribution, across the ring under compression, an existing upper bound solution has been improved. In the upper bound solution a kinematically admissible velocity field which satisfies the following conditions such as incompressibility, continuity, and velocity boundary conditions is selected. Based on limit theorems the total forging load, calculated using the assumed velocity field is higher than the actual load. Thus to obtain a good approximation a general kinematically admissible velocity field, with some arbitrary parameters is chosen. The upper bound solution is then minimized with respect to these parameters, this technique gives good approximations, to the behavior of metal flow and the associated velocities, strain rates, and strain distributions.

The basic assumption made to derive the upper bound solution
are. The deforming material is isotropic and incompressible, elastic deformations are negligible, the internal forces are small and hence can be neglected, the friction shear stress, is constant at the die workpiece interface, and is given by the factor \( m \).

\[
T = f \sigma = \frac{m \sigma}{\sqrt{3}}
\]

and the material flows according to Von Mises criteria, the flow stress is given by

\[
\sigma_{\text{avg}} = \int_{V} dV/V
\]

\( V = \text{total volume of deforming material} \)

The velocity field for ring compression:
The two modes of deformation of ring compression are illustrated in fig. 8a and 8b.

Due to symmetry in flow, and the two dies move at a velocity of \( V_0/2 \), only one quadrant is considered. The axial velocity component \( v \) which incorporates bulging is assumed to be

\[
v = -2Az \left( 1 - \beta \frac{z^2}{3} \right)
\]
Fig. 8a Illustrates the mode of deformation causing bulging

Fig. 8b Illustrates second mode of deformation causing caving.
where $\beta$ is a parameter representing the amount of bulge, and the constant $A$ is determined from the velocity boundary conditions for $z = H / 2$ and at $v = V_0 / 2$

$$A = \frac{V_0}{2H \left(1 - \beta \frac{H^2}{12}\right)}$$

The incompressibility condition is given by

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial v}{\partial z} = 0$$

from eqn (1) and (3) after integration, the radial velocity component $u$ is given by

$$u = A \left(1 - \beta z^2\right) r + \frac{C(z)}{r}$$

where $C(2)$ is determined from the following boundary conditions, the neutral surface at $r = R_n$ is defined as the surface that has no radial displacement at a given deformation time $r = R_n$ and $u = 0$

using these conditions in (4) we get

$$C(2) = -A \left(1 - \beta z^2\right) R_n^2$$
The strain rate components are obtained from the velocity components of equation (1) and (4)

\[
\dot{\epsilon}_r = \frac{\delta u}{\delta r} = A (1 - \beta z^2) \left[ 1 + \left( \frac{R_n^2}{r} \right) \right] \\
\dot{\epsilon}_t = \frac{\delta u}{\delta r} = A (1 - \beta z^2) \left[ 1 - \left( \frac{R_n^2}{r} \right) \right] \\
\dot{\epsilon}_z = \frac{\delta u}{\delta z} = -2 (1 - \beta z^2) \\
\gamma_{rz} = \frac{\delta u}{\delta z} + \frac{\delta v}{\delta r} = -2A\beta zr \left[ 1 - \left( \frac{R_n^2}{r} \right) \right] \\
\gamma_{tz} = \gamma_{rt} = 0
\]

It is seen that the velocity field symmetry requirements for

\[ r = 0, \quad z = 0, \quad \gamma_{rz} = 0 \]

The effective strain rate is given by

\[
\ddot{\epsilon} = \sqrt{\frac{2}{3} (\dot{\epsilon}_r^2 + \dot{\epsilon}_t^2 + \dot{\epsilon}_z^2 + \frac{1}{2} \gamma_{rz}^2)} \]

or

\[
\dot{\epsilon} = \frac{2A}{\sqrt{3}} \left\{ (1 - \beta z^2) \left[ 3 + \left( \frac{R_n}{r} \right)^4 + (\beta rz)^2 \left[ 1 - \left( \frac{R_n}{r} \right)^2 \right] \right] \right\}^{1/2}
\]
The unknowns of these equations can be evaluated by minimizing the energy equation with respect to that unknown,

\[ \frac{\partial \dot{E}}{\partial \beta} = 0 \quad \text{and} \quad \frac{\partial \dot{E}}{\partial R_n} = 0 \]

In the upsetting of the ring the total energy dissipation rate \( E \) which includes the plastic deformation energy and the frictional energy is given by

\[
\dot{E} = 2\pi \int_{R_i}^{R_o} \overline{\sigma} \dot{\varepsilon} r \, dr \, dz + \frac{4\pi m}{\sqrt{3}} \int_{R_i}^{R_o} u_s \overline{\sigma} r \, dr
\]

\[
u_s = A \left( 1 - \beta \frac{H^2}{r^2} \right) \left( 1 - \frac{R_n^2}{r^2} \right)
\]

The total load applied can be computed from the minimum energy required by the initial velocity

\[ L = E_{\text{min}} / V_0 \]

\[ u = \text{velocity of the material die interface for } z = \frac{H}{2} \]

The average deformation pressure \( P_{av} \) is got from,

\[ P_{av} = \frac{L}{\pi} \left( R_{o}^2 - R_{1}^2 \right) \]

The method used to minimise the energy equation is the Simplex minimization technique, which is available in the IMSL library of subroutines, or an average flow stress value can be used in each deformation step using a constitutive equation.
The deformation of the internal diameter is plotted against the total reduction and the interface shear factor is characterized by the different curves for different values of m, any point lying between two curves can be interpolated to get the value of m. The graphics is done by using TcsPlot 10 subroutines. The theoretical curves for ring compression test for various values of m is plotted, as a function of decrease in diameter of the ring versus reduction in height.

Fig 9. Theoretical calibration curves for a ring of 6:3:2 size calculated with upper - bound theory that includes bulging.
Fig. 9. Theoretical calibration curves for a ring of 6:3:2 size calculated with the upper bound solution ref (3,4). X axis Reduction in Height(%), Y axis Decrease in Internal Diameter.
FINITE ELEMENT MODELING OF EXTRUSION FORGING TEST AND RING COMPRESSION TEST

Software used for finite element simulation is NIKE2D developed at Lawrence Livermore National Laboratories, Lawrence, California
Finite element modelling.

Finite element modelling of extrusion forging process is carried out using a software NIKE2D developed by LLNL, and is generally used to simulate various two dimensional metal forming processes. Nike2D is a vectorized implicit, finite deformation, finite element code for analyzing the Static and Dynamic response of 2D solids with interactive rezoning and graphics capabilities. This software can be used to simulate, plane strain, plane stress and axis symmetric modes of deformations.

The problem is treated as Isothermal, Nonlinear, Isotropic elastic plastic, deformation. Since the deformation is axis symmetric only one half of the billet is used for simulation purposes. The material properties required are Youngs modulus, poissons ratio, yield stress, Hardening modulus, hardening parameter. It is also possible to use an effective strain effective stress plot, for the specimen, this is found experimentally by conducting a plane strain compression test.

Automatic step size control allows the program to reach convergence, by being able to adjust the step size such that when the convergence is not attained for the current step size, then the step size is reduced and interactions are carried out.

If convergence fails, Nike2D automatically goes to the last
converged state and restarts with a new step size, this procedure is

carried out till convergence is reached.

The interactive rezoning eliminates the cumbersome work, of
creating another input data file, when eliminates get distorted
beyond a reasonable amount. Nike2D automatically enters the
interactive rezoning phase, at the users command, and after rezoning
Nike2D interpolates the new nodal values such as stress, strains,
velocities, etc.. from the last converged step, this feature also
allows the user to interrupt the program and view the grid
deformations as check the stress, strain behaviors and to see
whether the solution is behaving as expected. Any global variable
to be remapped is approximated by a continuous field, which is
defined over each element in terms of nodal variables as where are
shape functions of the same order. Nike2D prints in the output file,
the values of total volume, mass, velocity, etc., before and after
rezoning. Generally boundary shapes may alter slightly, while
smoothening a grid system. The total number of nodes and elements
are preserved.

The die material is assumed to be totally elastic of a very high
Youngs modulus, to avoid calculations for the die material in order
to reduce calculations.

Since the deformation velocity is high the effects due to strain
rate variations are ignored, a corner radius of 0.125 is introduced to assure a smooth deformation of elements when the material flows through the extrusion hole. This corner radius is also provided for the experimental modelling, which helps in increasing the duration of the die life. The plastic range of the material is sufficient for calculations since the amount of deformation is high the elastic deformation of the billet is ignored.

A slideline is defined, to achieve relative movement between different material surfaces. An interface shear friction factor is provided for the purpose of calculating the frictional stress and the relative movement of nodes. One side of the contact surface is referred to as master nodes and the other is slave node. The slave surface must lie to the left of the master surface as one moves along the master nodes in an incrementing manner. In the region of contact, interface springs are inserted to appose penetration. Any node that violates the boundary surface, causes a linear interface spring to be inserted into the stiffness matrix that couples the penetrating node to two adjacent nodes on the contact surface. A very high spring stiffness factor such as 10000, assumes that the nodes of different material stay with the material boundaries.

In put file generation is done by using a 2D mesh generating software.

Maze was also developed at LLNL [ref 9]. Maze is an interactive program, which creates the input data file for Nike2D at the format which is compatible for using Nike2D. Maze has three phases.
Phase I, involves in defining the geometries of the system. Nodes and different types of material regions are created in this phase. Phase II, defines boundary conditions, slidelines, load, pressure and velocity, time histories for the nodes. Phase III, creates the material constants, constitutive equations, iteration techniques, output file generations, time step sizes, automatic rezoning option, etc. Since the Maze generator is the 1983 version, certain changes have to be made for the output file, in order to be used as the input data file for Nike2D.

Post processing of Nike2D output is done using ORION 2D [ref 10], an interactive color post processor for two dimensional finite element codes, which also has been developed at L.L.N.L. and revised in August 1985. Contour and color fringe plots of a large number of variables and constants are displayed on grids consisting of triangular and quadrilateral elements. ORION also can plot strain measures, interface pressures along slidelines and time history plots of various, material behaviors. A plot file created by Nike2D, is the input data file. ORION generates a text data file, which can further be used with other graphic packages. The above mentioned softwares can be run on all Vax systems and Cray computers.
EXTRUSION FORGING DATAFILE

Billet: dimension refer fig.10a.

The symmetric right half of the billet is generated with two regions where the mesh densities are differed. The top 1/3 of the billet consists of 10x20 elements and the bottom 2/3 consists of 10x20 elements. The elements chosen are rectangular (quadrilateral) for node linear elements. The top region is provided with a finer mesh because, the degree of deformation is higher in this region. The nodes on the vertical axis of the billet are constrained in direction in order to prevent separation or material discontinuity at this axis. Slideline of type 4 which is frictional sliding with voids is used for the boundary surface. The chosen materials are Al2011 and fine lead, the stress, strain relationship is obtained by conducting plane strain compression test on these specimen.

Dies: dimension refer fig.10b.

The elements used are quadrilateral 4 node elements, the bottom die is generated with 2x20 nodes, while the top die is generated with 4x40 nodes. The material used is tool steel and follows an elastic formulation. A high Youngs modulus and low poissons ratio is used in order to prevent any plastic deformation of the die. Slideline definitions are the same as for the billet. The top die is kept in a fixed place while the lower die is moved at a constant velocity of 4in/min in the upward direction. The interface
Fig. 10a. Billet dimension for extrusion forging model

Fig. 10b. Die dimensions for extrusion forging model

Fig. 10c. Ring dimensions for ring test model

Fig. 10d. Die Dimension for Ring test model
shear friction factor is varied from 0.05-0.8. For factors higher than 0.8 m, convergence becomes difficult to attain, similarly instead of m=0.0. the type of slideline is changed to frictionless sliding with voids, though this case is impossible in reality.

The output plot file is used as an input file for ORION. Time histories are obtained for flange reduction and total height are generated. This data is used by plot 10 for the comparison of finite element predictions.

FINITE ELEMENT MODELLING OF RING TEST

Ring test dimensions 6:3:2 (ref fig.10c.)

As in this case of Extrusion forging, the ring is assumed to be axis symmetric in deforming. The right half of the ring is considered for simulation purposes. Slideline definitions are similar as the previous simulation. The materials used are the same as extrusion forging.
Die dimension 4":1" (ref. fig. 10d)

The material properties, die boundary conditions are similar to the previous simulation. The die velocity is 4in/min, which means that the deformation is up to 60% height reduction. The interface shear factor also varied from 0.1 to 0.9, although 60% deformation wasn't possible in the case of \( m=0.9 \).

Time history plots are obtained from ORION, for reduction in height and for reduction of internal diameter. Plots are obtained for maximum load as reduction and compared with the experimental and analytical solution.

Sample data files for \( m=0.5 \) for extrusion or forging and the ring tests are provided from Maze output, and the Maze command file. Deformation plots of grid distortions, and stress, strain contours and hoop stress, etc. are provided from the ORION processing.
Fig. 11. Initial grid plot of die and billet for extrusion test. Mesh generated using MAZE pre processor.
Fig. 12a. Grid distortion plot at 30 % height reduction for m = 0.1

Fig. 12b. Grid distortion plot at 80 % height reduction for m = 0.1
Fig. 13a. Grid distortion plot at 30 % height reduction for $m = 0.3$
Fig. 13b. Grid distortion plot at 80 % height reduction for $m = 0.3$
Fig. 14a. Grid distortion plot at 30% height reduction for m = 0.5
Fig. 14b. Grid distortion plot at 80% height reduction for m = 0.5
Fig. 15a. Grid distortion plot at 30% height reduction for $m = 0.7$

Fig. 15b. Grid distortion plot at 80% height reduction for $m = 0.7$
Fig. 16a. Contours of maximum shear stress for $m = 0.1$

Fig. 16b. Contours of maximum shear stress for $m = 0.7$
Fig. 17a. Contours of deviatoric hoop stress for \( m = 0.1 \)

Fig. 17b. Contours of deviatoric hoop stress for \( m = 0.3 \)
Fig. 18. Plot of total height(%) vs. reduction(%) obtained from finite element simulation results.
Fig. 19. Initial grid plot of die and billet for ring compression test. Mesh generated using MAZE pre processor.
Fig. 20a. Grid distortion of ring compression test for m = 0.1 at 30% height reduction

Fig. 20b. Grid distortion of ring compression test for m = 0.1 at 80% height reduction
Fig. 21a. Grid distortion of ring compression test for $m = 0.3$ at 30% height reduction

Fig. 21b. Grid distortion of ring compression test for $m = 0.3$ at 80% height reduction
Fig. 22a. Grid distortion of ring compression test for \( m = 1.0 \) at 30% height reduction

Fig. 22b. Grid distortion of ring compression test for \( m = 1.0 \) at 80% height reduction
Fig. 23a. Contours of maximum shear stress for m = 0.3

Fig. 23b. Contours of effective stress for m = 0.3
Fig. 24a. Contours of effective stress for m = 1.0

Fig. 24b. Contours of effective stress for m = 0.1
Fig. 25a. Contours of effective plastic strain for $m = 0.3$

Fig. 25b. Contours of effective plastic strain for $m = 0.1$
CASTING OF LEAD BILLET

Pure lead is obtained in 5 lbs. ingot form. It has to be melted cast into bars, before it can be made into billets of 1 x .75 in dimension. The casting was done in the foundry of the Industrial technology department of Ohio University. A casting flask of 18'x12'x12' dimension of two split halves of 6 inches is used for casting. The casting sand is first graded to remove foreign material, and large chunks of sand is broken down, by using a mechanical grades. The sand is then put in a mixer, to ensure uniform mixing of the graded sand. The mixer is operated at 30 rpm, for about 10 minutes.

The sand is then compacted into the flask in layers of approximately 3 inches height at a time. This results in fine compaction of the sand, after the first layer, two bars of aluminum are held vertical of 1.1 in diameter, and sand is filled around the bars, and compacted. These bars were removed once, the flask is completely filled with compacted sand, leaving a vertical hole. The lead is melted in a melting skillet, has to be taken to provide maximum exhaust facilities. This is because, lead produced oxides, and nitrites in gaseous state, which can cause nausea, fainting, etc. if inhaled. When the lead has completely melted it is poured into the hole from one side, such that the air in the hole is displaced by the lead. The hole has to be over filled to compensate for shrinking
of the metal, when it comes into contact with the cold sand. The lead bars can be removed after an approximately 4-5 hours of cooling time. The surface of the bars are found to be very rough due to the texture of the sand. This can be rectified by filling, the bar is then reduced to 1.0 diameter by turning, and billets of .75 in height are cut and machine ground to an approximate roughness of 80 micro inches.

FABRICATION OF AL2011, BILLETS AND DIES

Aluminum 2011, T3 is commercially available in the form of extruded bars of 12' ft. length. This has been used for our experimental material. The 1" diameter bars are cut into billets and reduced to .75" height by machine grinding. The rings are fabricated from 1.5". diameter extruded bars. These bars are cut into 6" long segments, and a center hole is drilled to 7" diameter. A boring tool is then inserted into this hole and a .75" diameter hole is bored, by using the boring tool a better surface finish is possible.
FABRICATION OF DIES

The dies are fabricated using tool steel AISI-S7, UNST41907 CHROME MOLY. Which is available as round bar stock 4" diameter bar is cut to the approximate height. The top die being 2" high and 4" diameter, while the bottom die is 1" high and 4" diameter, a hole of 0.5 inches is drilled and bored to a fine finish. A billet radius of 0.125 inch is cut and is extruded towards the top while, a taper of as shown in the figure. The top die and the bottom die are given a step shape in order to align the two dies perfectly. This notch is also useful for the proper centering of the billet. The dies are heat treated and air cooled, then machine ground to approximately 60 micro inches 4 nos of bolt holes are drilled at the top and bottom surfaces in order to fix then, to the independent die platens. Another plane top die is fabricated in the similar manner to perform the ring compression test. Two semi circular disks of aluminum are also fabricated, these were known as the centering disks. These aluminum disk also have the same dimensioned step cut. When these disks are placed on the bottom die, they form a circular hole in the center aligned with the center line of the hole of the top die.
EXPERIMENTAL APPARATUS

A PHI is used for the experiments, (donated by Ford Motor Co.). This press is electro hydraulic (125 ton max. load capacity), and is operated using an Osbornne II, personnel computer. The load gauge, is calibrated using a load cell, and the load gauge of the press was found to be accurate. Two numbers of Dial gauges, with magnetic stands, and a set of vernier calipers, a stop watch to calculate the ram velocity. (ref fig. 26.)

EXPERIMENTAL PROCEDURE

The dies are secured firmly to the independent moving die set. This die set is fixed to the press using 4 nos. of angle irons. The upper die is clamped to the frame, while the bottom die is clamped to the ram. The extrusion forging dies are mounted on these two independent die plattens. This arrangement is useful to keep the dies secured in position when load is applied, and also is very easy to change the top die to a flat one for the ring compression test.
Fig. 26. Photograph of extrusion forging experimental setup, showing specimen (lead), top and bottom die, two dial gages, independent die platen set, etc.

Fig. 27. Photograph of computer hook up of the hydraulic press
Fig. 28. Photograph of fabricated dies used for extrusion forging test and ring compression test.

Fig. 29. Photograph of various stages of deformation of AL2011 specimen, deformed during extrusion forging test.
Fig. 30. Photograph of final deformations for various frictional conditions of lead specimen. (left to right: Dry condition, Silicon spray, graphite powder, Oil additive (STP), Lithium grease, Teflon spray)

Fig. 31. Photograph of final deformations for various frictional conditions of Al2011 specimen during the ring compression test.
A cylindrical pipe of 0.5 in wall thickness and 4" is used to transfer the load to the dies from the press. A circular hole is cut on the wall of the pipe in order to view the dial gauge movement and to keep track of readings, and a rectangular slot is made in order to fix the dial gauge to the magnetic stand. A second dial gauge is set on the lower die platter, and measures the displacement of the ram.

The press controls are operated using an Osborne II personnel computer. The press to the computer interfacing is done using a Peripheral Interface Adapter. fig 27. The PIA consists of two bi-directional 8 bit peripheral data bus, and four control lines, two programmable registers, two programmable data direction registers, handshake control logic for input and output peripheral operations. High 3 state and direct transistor drive peripheral lines.

PHI is a electro hydraulic press with a maximum loading capacity of 125 tons. The upper platen is fixed to the press frame, and the lower platen is fixed to the ram. The maximum ram displacement is 12 inches. The ram slides with the help of 4 sliding rolls on each side of the press frame. Care has to be taken that the hydraulic oil level should always be slightly above half full, when the ram displacement is zero.

The lubricant is applied by means of spraying or by using a brush. The top and the bottom die are applied with a thin film of lubricant. The top and bottom surfaces of the billet were also
provided with a thin film of lubricant. The dies are lifted up and the billet is placed on the bottom die, and kept, aligned using the semicircular rings. The bottom die is raised till the billet slightly touches the upper die. This is done by setting the dial gauge, in such a way that the distance between the dial gauge tip and the top of the billet is known, when the dial indicator corresponds to that reading, the power is shut off. The dial gauge used to measure the spike height is inserted into the hole, and the circular pipe section is placed, on the upper platter, and the magnetic stand is inserted through the rectangular slot. The dies are wiped clean using acetone, and then blow dried, using a hot air blow drier. This process is done when the lubricant is changed each time. But before each new specimen billet is kept, the die surface is wipe clean to make sure there are no metal fragments of the old specimen.

The initial readings of the two dial indicators and the load gauges are noted down. Readings are taken for approximately every 0.05 in displacement of the ram. This is possible by using the disengage upward travel command, of the menu, and the experiment can be continued by using the upward travel command.

The experiment is carried out on about 7-10 specimens for each lubricant system that is tested.
The lubricants that are tested are as follows. Dry condition, graphite, teflon, silicon spray, lithium grease, and SPT oil additive. These lubricants are also used for the ring compression test.
Fig. 32a. Graph of experimental data of total height (%) vs. reduction for dry condition

Fig. 32b. Graph of experimental data of total height (%) vs. reduction for graphite powder
Fig. 33a. Graph of experimental data of total height (%) vs. reduction for silicon spray
Fig. 33b. Graph of experimental data of total height (%) vs. reduction for Lithium grease.
Fig. 34. Graph of experimental data of total height (%) vs. reduction for oil additive (STP).
PHYSICAL MODELING OF RING COMPRESSION TEST

Most of the preliminary work and set up remain the same. The top die is replaced using a plane flat die of 1 in thickness and 4" in diameter. It is not essential to align the ring to the center axis of the dies. Lubricants are applied in a similar manner. Only one dial gauge is used to measure the height reduction, each ring specimen is used only for one reading. The internal diameter is measured of the ring specimen.

The readings of the tests are then plotted using GRAPHER subroutines using the intergraph systems, and the results are compared.
COMPARISON OF RESULTS

From the upper bound solutions, the various reduction vs. height plots are drawn from different values of interface friction factor m. It is seen that stage I of deformation where the velocity of extrusion is found from 0-50% in reduction. This stage is delayed for lower values of m. This is due to the quality of lubricant, and the consistency of its properties. For lubricant systems with lower interface friction factors, the axial velocity component remains less than the velocity of the die.

Stage II begins early for the higher interface friction factors, but the duration of Stage II remains almost constant for all friction factors, which implies that the Ve=0 for about an additional 50% reduction.

Stage III is met at lower reduction percentage for higher friction factors and the ratio of total height vs. reduction is higher for higher friction factors.

When the corner radius of 0.125 is introduced for experimental modelling and finite element modelling, the behavior of the family of these curves were more or less as expected. The whole set of curves moved upwards on the total height scale by about 20%, which indicates that the introduction of the billet radius, increases material flow in the axial direction, and the predicted loads were
also reduced by 20%.

This is in fact true as compared to extrusion through square dies and extrusion conical or streamlined dies.

Stage I of deformation was encountered from 0 - 40% of reduction and here too the duration of stage I is lesser for higher friction factors.

Stage II of deformation, where the extrusion velocity \( V_e = 0 \) lasts for almost 40% of height reduction. Here too the simulation agrees with the Upper Bound solution, where for higher values of \( m \) stage II ends earlier, than for lower values of \( m \).

Stage III of deformation occurs from reductions 60% onwards. The higher ratio of height to reduction ratio is found in the curves for higher values of \( m \), while as the value of \( m \) decreases the gradient of the curve decreases.

Though the curves tend to be rough when stage III is met, while during stage I & II the curves tend to be more smooth. This may be due to the fact that during stage III the degree of element distortion is very high and rapid, and the direction of flow changes from horizontal to vertical.

From the experimental data collected for 5 kinds of lubricants
and for 6 kinds of conditions including dry condition the following conclusions are made, while comparing with the finite element modelling. The lubricants used were Teflon, Silicon Spray, Lithium Grease, Oil Additive (STP), and Graphite.

The following results which were obtained during finite element simulations, are also found in the experimental data.

Stage I was found to occur in all lubricants from 0-40 % of height reduction. From the deformation behavior for lubricants with higher interface friction the stage I ends earlier.

Stage II lasted for a height reduction of 20 % in height reduction. For lubricants with higher friction factors stage II ends earlier than for lubricants with lower friction factors.

Stage III was found to occur from 60 - 80 % height reductions. The gradients of higher friction factors were found for lubricants with higher friction factors.
### LUBRICANT SYSTEM

<table>
<thead>
<tr>
<th>LUBRICANT SYSTEM</th>
<th>FRICTION FACTOR</th>
</tr>
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<tbody>
<tr>
<td>Dry condition</td>
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<tr>
<td>Silicon spray</td>
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</tr>
<tr>
<td>Graphite</td>
<td>0.3</td>
</tr>
<tr>
<td>Oil additive (STP)</td>
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</tr>
<tr>
<td>Teflon</td>
<td>0.2</td>
</tr>
<tr>
<td>Lithium grease</td>
<td>0.1 - 0.3</td>
</tr>
</tbody>
</table>

It is interesting to note that the behavior of grease was very inconsistent. This indicates that the material deformation was in spurts, which means that the effect of lubricant wasn't always the same, the lubricant trapped within the die workpiece interface kept on escaping with increasing pressures. (fig 33b)

A number of ring compression tests were also conducted with rings of dimension 6:3:2. As explained earlier due to the implications of measuring internal radius the interpretation of the results may not be very accurate. Each deformed ring represents only a point on the plots. The ring test gave rather high values for dry condition and low values for tests conducted with lubricants.
Fig. 35a. Graph comparing experimental data for dry condition with finite element solution results.

Fig. 35b. Graph comparing experimental data for Teflon spray with finite element solution results.
Fig. 36a. Graph comparing experimental data for Silicon spray with finite element solution results.

Fig. 36b. Graph comparing experimental data for graphite powder with finite element solution results.
<table>
<thead>
<tr>
<th>LUBRICANT SYSTEM</th>
<th>FRICTION FACTOR</th>
</tr>
</thead>
<tbody>
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<td>Dry condition</td>
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<tr>
<td>Lithium grease</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The grid deformations of extrusion forging and ring test are given for various degrees of deformation and friction factors from Finite Element Simulations and plots for Reduction vs Total Height for the upper-bound solution, finite element simulation and physical modeling are given in the preceding pages.

The phenomenon of piping occurred during extrusion forging experiments, which indicate the material flow in the vertical direction, this phenomenon is generally found in extrusion process. The phenomenon of lip forming during ring tests was also observed
[ref 12], as mentioned by Gunasekera in his paper this is due to the lubricant getting trapped within the die work piece interface.
CONCLUSIONS

Till recent times the modelling of metal forming process such as extrusion, forging, etc. it was customary to use an approximate value for shear friction factor. In most of this cases, due to this error in estimating \( m \) the final prediction tend to deviate from the real forming process. It is also possible that the lubricant looses some of its lubricating properties due to breaking of intermolecular structures mainly due to high pressures developed between die and material surfaces. This would mean that the value of \( m \) would also change with applied pressure, load. The advantage of using extrusion forging as an alternative to the ring test is evident from the following conclusions. The specimen could be obtained without much trouble because of its cylindrical geometry, while for the ring test the specimen have to be specially fabricated with the concentric hole of precise dimension. The experimental setup does not have to be disturbed once the experiment has begun and the measurements are simply measured using a couple of dial gauges. Whereas, the ring test has to be stopped for each deformation and the specimen removed to measure the internal dimension, or a complicated arrangement has to be made to measure the internal dimension. If the specimen is disturbed, then the change in lubricating properties are destroyed, and if new specimen are used then obviously more specimens have to be fabricated for evaluating the shear friction factor of each lubricant. Further, a data base has been proposed to generate the friction factor for a various
combination of dies and work pieces and lubricants most commonly used in the metal forming industry.
REFERENCES


