CHAPTER I

INTRODUCTION

1.1 DEFINITION AND CLASSIFICATION OF FORGING PROCESSES

Forging in the conventional sense may be classified as (1) open-die (flat-tool) or smith forging, and (2) closed-die or impression-die forging, sometimes called drop forging. Open-die forging is the term applied to all forging operations, in which there is no lateral constraint except for friction and consequently no three-dimensional confinement. Closed-die forging is the term applied to all forging operations involving three-dimensional control. In swaging and edging operations, a considerable amount of lateral confinement may occur. In these cases, however, the nature of the forging operations and the equipment used will definitely place them in one category or the other.

Open-die or smith forging, is done with a hand hammer, a power hammer, or a power press by use of tools or dies that are flat or nearly flat (Fig. 1.1), in which the manipulation of the workpiece is done by hand or by a mechanical manipulator.
Fig. 1.1 Flat typical types of dies of simple shape commonly used in open-die forging. Ref. [1]
This process is used

(1) when the desired shape is simple,

(2) when the quantity of forgings required is too small to justify the time and cost of making of closed dies,

(3) as a preliminary operation to closed-die forging to produce a forging multiple or preform of the required shape and size,

(4) where the forging is too large to be forged in closed dies, and

(5) when, in some cases, the delivery date is too close, i.e., the lead time is too short to make the closed dies needed.

In some cases, the open-die forging is used in its final form as forged such as a crane hook or a clevis for farm equipment with perhaps only a scale removal and/or painting operation, or it may be rough machined, finished machined, heat treated, and finished ground to the final shape. Often, not only a considerable amount of machining is eliminated by open-die forging, but also much superior mechanical properties are imparted to the metal by breaking up the coarse, dendritic, cast microstructure; by welding voids; and by proper metal flow.
1.2 OPEN-DIE HOT-FORGING PROCESSES

1.2.1 OPEN-DIE (FLAT-TOOL) FORGING OPERATIONS

Some of the typical, principal open-die forging operations as shown in Fig.1.2 are as follows:

1. Cogging or drawing out, involving compression between narrow dies.
2. Upsetting, involving compression between flat, overhanging dies.
3. Heading, involving localized upsetting of the end of a workpiece between a confining or gripping die and a flat or contoured upsetting die.
4. Swaging, involving compression between longitudinal semi-circular or semi contoured dies.
5. Fullering, involving compression between rounded or convex dies to reduce a middle section of a bar.
6. Edging, involving compression with concave dies to form an enlarged middle section of a bar and to distribute the metal to the desired shape.

Some of the open-die forging ancillary operations as shown in Fig.1.3 are as follows:

1. Punching, involving indenting (as in center punching) or perforating with mating dies.
2. Piercing, involving impression an indentation into the workpiece.
FIG 1.2 Typical operations performed with open-die forging. Ref. [1]
FIG 1.3 Some typical ancillary operations associated with open-die forging. Ref.[1]

4. Extrusion forging or ring extrusion, involving the extrusion of a projection or spike into a die containing a hole or cavity.

5. Bending of a workpiece between mating dies.

6. Twisting, as of a flat bar or V-eight crankshaft.

Cogging is the systematic forging of an ingot to reduce it to a bloom as shown in Fig.1.4, whereas drawing out is the elongation of any shape by systematically reducing its cross section as shown in Fig.1.5. Upsetting is a compression operation usually parallel to the longitudinal or cylindrical axis of the workpiece. When an enlarged section is upset on the end of a smaller section, the operation is called heading. Swaging is radial compression operation by shaped dies for finishing, i.e., sizing and truing, a round or semiround workpiece after it has been drawn out or forged nearly to size. Fullering is the making of grooves or reduced sections in a bar yielding shoulders on both ends.

1.2.2 COGGING OR DRAWING OUT BY FLAT-TOOL FORGING

The object of cogging or drawing out is to reduce the cross section of the workpiece in a stepwise sequence by moving the ingot, billet, or bar from one end toward the other during forging in what is called a pass. To reduce
FIG 1.4 Forging sequence in open-die forging of an octagonal bloom from a fluted ingot. Ref.[1]
FIG 1.5 Sequence of operations in open-die forging of an octogonal bloom to a drawn-out forging. Ref: [1]
the workpiece in one pressing operation may require a very large force and/or also a very large press platen width, and consequently may be impracticable. Both the reduction in height $h$ and the bite $b$ shown in Fig.1.6, should be as large as possible without causing such defects as laps. Several passes alternating on each pair of faces are usually required to complete the operation.

Each compression or squeeze operation, resulting in a reduction in thickness, will cause the workpiece not only to elongate in length but also to spread in width as shown in Fig.1.6. These two dimensional changes may be expressed in terms of the coefficient of spread, $S$, and the coefficient of elongation, $1-S$, as follows:

$$S = \frac{\text{width elongation}}{\text{thickness reduction}} = \frac{\ln(w_1/w_0)}{\ln(h_0/h_1)} \quad \cdots (1.1)$$

$$1 - S = \frac{\text{length elongation}}{\text{thickness reduction}} = \frac{\ln(l_1/l_0)}{\ln(h_0/h_1)} \quad \cdots (1.2)$$

The above parameters may be obtained from the expression for the constancy of volume

$$\frac{h_1 w_1 l_1}{h_0 w_0 l_0} = 1 \quad \cdots (1.3)$$
Fig 1.6 Nomenclature for cogging and drawing out of a rectangular workpiece (a) end view, and (b) side view. Ref.[2]
If the natural logarithms are taken of both sides of the above expression (ln 1=0) and rearranged then

$$\frac{\ln(w_1/w_0)}{-\ln(h_1/h_0)} + \frac{\ln(l_1/l_0)}{-\ln(h_1/h_0)} = 1 \quad \ldots \ldots (1.4)$$

The Eqns. (1.2) and (1.3) may also be written as

$$\frac{w_1}{w_0} = \left[ \frac{h_0}{h_1} \right]^S \quad \text{and} \quad \frac{l_1}{l_0} = \left[ \frac{h_0}{h_1} \right]^{1-S} \quad \ldots \ldots (1.5)$$

If the first term in Eqn.(1.4) is set equal to S, then the second term is equal to 1-S (In sheet metal forming, S is analogous to the r ratio or r value).

Tomlinson and Stringer [3] found empirically that for hot, low-carbon steel, the bite ratio was the main factor influencing S as shown in Fig.1.7 although the height ratio $h_1/h_0$, also exerted a small but statistically significant effect. The spread coefficient S as a function of the bite ratio $b/w_0$, as shown in Fig.1.8, is given by

$$S = 0.14 + 0.36 \left[ \frac{b}{w_0} \right] - 0.054 \left[ \frac{b}{w_0} \right]^2 \quad \ldots \ldots (1.6)$$

Their analysis indicated that the coefficient of spread, S, derived for a bar forging depends mainly on the
FIG 1.7
Relation between the coefficient of spread and the bite ratio for open-die forging of rectangular blocks. Ref. [3]
\[ S = 0.14 + 0.36(b/w_0) - 0.054(b/w_0)^2 \]

**FIG 1.8**
Relation between the coefficient of spread and the bite ratio in cogging of rectangular blocks. Ref.[3]
shape of the tool contact area as defined by the bite ratio. Their analysis also showed no effects attributable to forging temperatures or cross-sectional shape and indicated that there are no other factors to consider. Their experimental data revealed that less spreading occurs during the forging of a bar than during the compression of a comparable rectangular block between overhanging platens, presumably due to the absence of the constraint of the bar material extending outside of the dies in drawing out. They showed that the spread coefficient for blocks can be predicted as shown in Fig.1.7 by the simple equation

$$S = \frac{b}{b + w_0} \quad \ldots \quad (1.7)$$

The longitudinal expansion per squeeze or stroke increases with both the bite and the height ratio as given by

$$x = \frac{b}{w_0} \left[ \left( \frac{h_0}{h_1} \right)^{1-S} - 1 \right] \quad \ldots \quad (1.8)$$

Schutt [4] carried out experimental work in this regard by making indendations in plasticine bars of square and rectangular sections and suggested that the Eqn. (1.9) given below involving the ratios $b/w_0$ and $h_0/w_0$ fitted the
experimental data better than any linear regression equation. If $\varepsilon_h$ and $\varepsilon_1$ are the true strains in the height and width direction, respectively, the equation proposed is

$$\frac{\varepsilon_h}{\varepsilon_1} = 1 + \frac{b}{w_0} \left[ 1.789 - 0.321 \frac{h_0}{w_0} \right] \ldots \ldots \ (1.9)$$

where $b$ in this case is half the width of the indentation.

The first successful theoretical attempt to obtain the sidewise spread and forging pressure in flat-bar forging is due to Hill [5], whose formula for the spread coefficient is given by

$$S = \frac{1}{2} \left[ 1 - \frac{1}{2\sqrt{3}(b/w_0)} + \tan h \left[ \frac{2\sqrt{3}}{b} \frac{b}{w_0} \right] \right] \ldots \ldots \ (1.10)$$

The effect of frictional constraint was neglected in the analysis, so that Eqn.(1.10) gives reasonable predictions for small bites only. Also, since the variations in stress and strain throughout the thickness were neglected in the analysis, Eqn.(1.10) is probably acceptable only when $(b/h_0) > 1$.

Baraya and Johnson [6] used an analytical velocity field and also the concept of rigid sliding blocks for
calculating the theoretical upper bounds to the loads in flat-tool forging. They also reported the specific forging pressure, coefficient of sidewise spread, bulge profile, elongation, and maximum amount of spread for various forging geometries from experimental work under the conditions of maximum constriction between the tool and workpiece. They concluded that the coefficient of spread, $S$, as evaluated by Hill [5] fits experimental results fairly well, especially for $0.5 \leq b/w_0 \leq 1.5$, even though his analysis neglected the effect of frictional restraint. Based on these experiments, they have also suggested an empirical formula for spread given as below:

$$S = a_0 + a_1 \frac{b}{w_0} + a_2 \left( \frac{b}{w_0} \right)^2 + a_3 \left( \frac{b}{w_0} \right)^3 \ldots (1.11)$$

where $a_0$, $a_1$, $a_2$ and $a_3$ are constants dependent on material properties and are determined by fitting a curve to experimental results by regression analysis [7].

By use of the upper-bound approach, Lahaoti and Kobayashi [7] obtained the following relationship by theoretical analysis for the average specific forging load:

$$\frac{P}{2Af} = 1 - \frac{1}{2b} \int_0^b a(x) \, dx - \frac{\mu}{4bh} \int_0^h a'(b) \, \Phi(z) \, dz \ldots \ldots (1.12)$$
where

\[ P \quad - \quad \text{the forging load, lb(KN)} \]
\[ A \quad - \quad \text{the area of the tool-workpiece interface} \]
\[ f \quad - \quad (2/3)\sigma_y \quad \text{for moderate to large bites} \]
\[ ((b/w_0) > (1/2)) \]
\[ f \quad - \quad 2/\sqrt{3} \sigma_y \quad \text{for small bites} \]
\[ (b/w_0 \leq 1/2) \]
\[ \sigma(x) \quad & \quad \phi(z) \quad - \quad \text{fairly involved functions describing the} \]
\[ \text{bulge in the x and z directions, respectively} \]
\[ \alpha'(b) \quad - \quad \text{the derivative of } \alpha(b) \quad ([7]) \quad \text{and} \]
\[ \mu \quad - \quad \text{a variable coefficient of friction at} \]
\[ \text{the tool-workpiece interface} \]

Experimental data was obtained for 1100-F aluminium [7]. The predictions for sidewise spread, elongation, and bulge in thickness compared reasonably well with experiment for small to medium bites. However, for large bites the correlation was not good, since a single class of velocity fields would not be expected to describe the deformation patterns for all geometrical ratios in a complex pattern such as flat-bar forging.

1.2.3 AXISYMMETRIC COMPRESSION OF A SHORT CYLINDER BETWEEN FLAT, OVERHANGING PLATENS

This problem has already been dealt with directly in conjunction with the compression test and indirectly with the analytical analysis of the friction in plane strain for rolling. It will be extended here to the estimation of the average or mean pressure by first estimating the
Coulomb coefficient of friction for a short cylinder or thin disc.

In the compression of a ductile cylindrical specimen with overhanging flat dies or platen, in addition to the extent of inhomogeneous deformation that may occur that was considered in the previous section for the case of compression of a long workpiece with narrow anvils or dies, the question of whether or not buckling will occur and the amount and type of friction that exists must also be considered. Let us first dispense briefly with the problem of buckling.

The maximum, initial height-to-diameter ratio that can be successfully used in upsetting is important in conjunction with the operation of the horizontal upset forging machine or upsetter. Suffice it to say at this point that this ratio should not exceed two or two and one-half at the most, when an unsupported cylindrical specimen or workpiece is compressed with flat dies, otherwise lateral buckling or skewing will occur as shown in Fig.1.9. The actual maximum limit that may be used may be found experimentally, and it depends on such factors as the accuracy with which the ends are cut, the parallelism of the die surfaces, the surface finish and lubricity of the faces, etc.
FIG 1.9 The effect of the maximum height-to-diameter ratio (aspect ratio) on the mode of upsetting of a right, circular cylinder in compression between flat, parallel, overhanging anvils. (a) If \( h_0/d_0 < 2 \) to 2.5, the cylinder upsetting successfully, and (b) if \( h_0/d_0 > 2 \) to 2.5, the cylinder skew or buckles as shown. Ref[1]
Since in an upsetter the stock is gripped firmly at one end and may be enclosed in a cavity which modifies buckling at the other, somewhat greater lengths can be upset than by flat, parallel die upsetting. The following three design rules illustrated in Fig.1.10 should be followed in designing parts that are to be upset forged [8].

1. The limiting length of unsupported metal that can be upset in one blow without buckling is three times the diameter of the bar.

2. Lengths of stock greater than three times the diameter may be upset successfully provided that the diameter of the die cavity is not more than 1.5 times the diameter of the bar.

3. In an upset requiring stock with a length greater than three times the diameter of the bar and where the diameter of the upset is less than 1.5 times the diameter of the bar, the length of unsupported metal beyond the face of the die must not exceed the diameter of the bar.

Even though the foregoing upsetting operations are constrained and would therefore be classified as closed-die forging, they are included here to complete the discussion of buckling.
FIG 1.10
Design rules governing upset forging. Ref. [1]
The amount and nature of the localized deformation or flow localization resulting from the inhomogeneous deformation may be analyzed by use of a number of different macroscopic methods to study the sectioned specimen such as by measuring the distortion of a grid pattern, obtaining the hardness gradient, etching of the cold-worked metal, etching of the recrystallized cold-worked metal, etc.

In the grid or visioplastic method, fine ductile wires may be threaded through small axial and/or diametral holes equally, or regularly spaced so as to form a grid on the diametral, axial plane of the specimen. Also, a higher melting point wire grid may be cast into a lower-melting-point metal such as, for example, a copper grid in an aluminium alloy.

After deformation the specimen is sectioned along a diametral plane and ground on a fine abrasive belt or wheel to expose the wires. A schematic representation of such a grid pattern before and after deformation is shown in Fig.1.11. As is illustrated in the figure, the material adjacent to the platens in region A remains virtually undeformed and behaves as a rigid metal "cone" or dead zone as it penetrates into the specimen. The cones approximately coincide with the surfaces of maximum shear, but their base angles are between 35 and 40° rather than
Figure 1.11
Illustration of inhomogeneous deformation and flow localization in compression of a right circular cylinder with overhanging anvils and with interface friction showing a cross section of a diametral plane of (a) the undeformed cylinder, (b) the distortion of the grid pattern and the region variable deformation (region A the least and C the most), and (c) the final cylinder showing barreling. Ref [1]
$45^\circ$, and decrease as the height of the specimen becomes less than the diameter. The bulk of the deformation or flow localization occurs in region C with the greatest deformation occurring at the center of the cylinder and a lesser amount in region B.

As the specimen is deformed, because of the interfacial friction between the metal and the platen, the material located in the central part of the specimen flows more readily than that in the immediate vicinity of the platen or die, causing the cylinder to become barrel-shaped. The degree of barreling developed for a given reduction of height increases with the frictional resistance at the material platen interface. For sticking friction, if the $h_0/d_0$ ratio and the reduction are high enough, the cylindrical surface folds over or is inverted so as to become a peripheral ring on the ends of the deformed specimen. If the cylindrical surface is tarnished or oxidized and the ends are polished prior to deformation, a dark peripheral ring can be seen on the ends of the specimen after deformation as shown in Fig.1.12.

The size of the slip zone goes through a maximum during the compression of a tall cylinder, i.e., one with a $h_0/d_0$ ratio of 1.5 to 2.2. During initial compression, the slip zone first grows by inversion as discussed above.
FIG 1.12
Schematic drawings showing the flow of metal by inversion during compression of a tall cylinder with sticking friction at the platen-workpiece interface. The tarnished, peripheral ring on the ends is maximum for sticking friction and decreases with the reduction in friction until it disappears for the frictionless case. Ref [9]
Then, as compression is continued the specimen begins to deform as a short rather than a tall cylinder. As the cylinder slides over the platen, the slip cone shrinks in size. The metal at the center flows outward and the center is in tension until the upper and lower dead-metal zones begin to interact, then they begin to deform and the stresses at the center become entirely compressive as shown graphically in Fig.1.13.

As the $h_0/d_0$ ratio is progressively decreased, the dead zones do not meet and interpenetrate as is sometimes thought, but they progressively flatten. In very short cylinders, they not only flatten but also begin to decrease in diameter when the $h/d$ ratio falls below a certain minimum value.

If the hardness, is taken of the cross-section in Fig.1.11 of a cold forged cylinder, the strain hardening will be nil in zone A, it will increase through the intermediate zone B, and it will be a maximum in zone C. When care is taken to reduce the friction to a minimum at the platen-metal interface, so that the deformation is practically homogeneous, the difference in strain hardening is virtually absent.

A good picture of the degree of deformation that takes place in different regions of a cylindrical specimen upon
FIG 1.13
Deformation in cylindrical billet upset forged between flat, parallel dies. Ref.[1]
axial compression may be obtained by drawing an isostrain contour map. Kobayashi [10] used the finite element method to obtain a solution for axisymmetric upsetting of a solid cylinder having a $h_0/d_0$ ratio of 0.8 under conditions of sticking friction such as of an aluminium alloy. The computed distribution of the effective plastic strain $\varepsilon$ and the bulge profile for a 20 percent reduction in height are shown in Fig.1.14(a). It should be noted that the effective strain is about 40 times greater in the vicinity of the corners of the specimen than at the center of its ends, and that the strain rises somewhat exponentially across the contact surface of the specimen from the center of the end to the similar point at the corner as shown in Fig.1.14(b). A Rockwell superficial 15T hardness traverse across the contact surface shows a similar distribution as in Fig.1.14(c).

The effect of tangential stresses on the average interface pressure in the compression of thin cylindrical specimens between overhanging platens has been investigated by Schroeder and Webster [11]. Their work was extended by Bishop [12].

In general, the average or mean pressure required for forging depends upon (1) the significant, inherent flow stress of the metallic material, (2) the strain pattern determined by the configuration or geometry of the part,
FIG 1.14
(a) Effective strain contour maps and bulge profile of the FEM computed effective strain distribution at 10% percent reduction in height;
(b) Computed strain distribution across the contact surface;
(c) HR15T superficial hardness distribution across the contact surface; \( r \) is the radial distance from the cylinder's center to any point along the radius. Ref [10].
and (3) the effect of friction at the die-material interface.

In analyzing the effect of friction of thin circular discs, Schroeder and Webster [11] considered three cases:

1. Where relative sliding motion or sliding occurs between the blank and the die surfaces at all points except at the geometric center of the blank.

2. When sticking friction occurs with no relative sliding motion at the interface and with the spreading action resulting from shearing of the metal below the surface of the blank parallel to the die surfaces.

3. The intermediate condition, where sliding takes place in an annular zone near the edge, and sticking results in the central core.

Schroeder and Webster categorized the above cases in terms of the k/μ ratio, where \( k = 1/\sqrt{3} = 0.577 \) for the Von Mises criterion and μ is the coefficient of friction, which follows from the fact that the tangential, frictional shear stress at the interface for sticking friction is limited to a value of the flow stress in shear, \( \tau_0 \). According to the Von Mises criterion, \( \tau_0 \) is related to the flow stress in uniaxial tension or compression by \( 2\tau_0 = 2\sigma/\sqrt{3} \).
Since

\[ \tau_0 = 0.577 \bar{\sigma} = K \bar{\sigma}, \]

\[ K = \frac{1}{\sqrt{3}} = 0.577 \] \hspace{1cm} (1.13)

If one follows the same procedure as was used in Ref.[1] for the friction hill for the axial compression of a cylinder by the elemental slab method for the plane-strain deformation of a strip or slab, the following axisymmetric equation for the pressure distribution at the platen-cylinder interface for which no sticking occurs, i.e., sliding friction occurs over the entire surface, is obtained:

\[ \frac{2\mu}{\sigma} \frac{p}{h[(d/2) - r]} = e \] \hspace{1cm} (1.14)

where

- \( p \) - normal interfacial pressure at a point
- \( d \) - the diameter of the cylinder or workpiece
- \( r \) - the radial distance from the center to any point on the face of the cylinder
- \( h \) - the height or thickness of the cylinder or disc
- \( \bar{\sigma} \) - flow stress of the workpiece
- \( \mu \) - coefficient of friction
The above nomenclature is also used in the discussion that follows.

The ratio of \( p/\bar{\sigma} \) is called the intensity or constriction factor \( Q_a \). The subscript in this case means that this factor is for the axisymmetric case.

The analytical expression for the critical radius \( r_c \) at which sticking ceases and sliding begins for the intermediate case can be found by equating the frictional drag \( \mu_p \) for sliding friction to that for sticking friction \( \bar{\sigma}/\sqrt{3} \) as follows:

\[
\mu_p = \frac{\bar{\sigma}}{\sqrt{3}}
\]

..... (1.15)

\[
p = \frac{\bar{\sigma}}{\sqrt{3} \mu}
\]

By substituting \( p \) into Eqn. (1.14), one obtains

\[
\frac{\bar{\sigma}}{\sqrt{3} \mu} = \frac{-2\mu/h(d/2-r_c)}{\bar{\sigma}e} \quad ..... (1.16)
\]

Taking the natural logs of both sides one obtain

\[
\ln \left[ \frac{1}{\sqrt{3} a} \right] = \frac{2\mu}{h} \left[ \frac{d}{2} - r_c \right]
\]

33
The average or mean pressure may then be obtained from

\[
\frac{d}{2} \int_0^{d/2} \rho \, dr = \frac{P_m}{A} \quad \text{and} \quad P_m = \frac{P_m}{A} \quad \text{.....(1.18)}
\]

The above cases may now be classified, and the expression for the pressure intensity, multiplying, or constraint factor given as follows:

Case 1 applies when both \( \mu \) and \( r/h \) are small, i.e., sliding friction applies, and

\[
\frac{P}{\sigma} < \frac{k}{\mu} < \frac{1}{\sqrt{3}\mu} \quad \text{or} \quad \frac{d}{2h} < \frac{1}{2\mu} \ln \frac{k}{\mu}
\]

\[\text{..... (1.19)}\]

The pressure intensity multiplying factor \( Q_a \), for this case, is equal to

\[
Q_a = \frac{P_m}{\sigma} = \frac{2(e^{\mu d/h} - \mu d/h - 1)}{(\mu d/h)^2} \quad \text{..... (1.20)}
\]
Case 2 applies when \( \mu \geq k \), that is, sticking friction occurs. The pressure intensity multiplying factor \( Q_a \), for this case, is equal to

\[
Q_a = \frac{P_m}{\sigma} = 1 + \frac{Kd}{3h} = \left[ 1 + \frac{d}{3\sqrt{3}} \right] \quad \text{..... (1.21)}
\]

Case 3 applies when \( \mu < K \) but \( p/\bar{\sigma} = K/\mu \), or

\[
\frac{h}{d} > \frac{1}{\mu} \ln \frac{K}{\mu} \quad \text{..... (1.22)}
\]

The pressure intensity multiplying factor \( Q_a \) is complex, and its function may be expressed as

\[
Q_a = \frac{P_m}{\sigma} = f(\mu, d, h, k \text{ and } r_c) \quad \text{..... (1.23)}
\]

where \( r_c \) is the critical value of \( r \) at which the average pressure \( p_c \) is equal to the critical pressure \( P_m \) at which the transition from sliding to sticking type of friction results.

The equation as formulated above are essentially functions of three non-dimensional ratios:

\[
\frac{P_m}{\sigma}, \quad \frac{h}{d} \quad \text{and} \quad \mu
\]
which relate the average pressure required to the flow stress of the material, the geometry of the workpiece, and the effects of friction. Therefore, the solution for one value of \( \frac{d}{h} \) and \( \mu \) provides a value of \( P_m/\sigma \) for all geometrically similar circular blanks with the same \( \frac{d}{h} \) ratio. The pressure intensity multiplying factor for axisymmetric upsetting \( Q_a \) may be plotted against the diameter-to-thickness ratio for a constant value of \( \mu \) for each of the above three cases in a non-dimensional graph showing the extreme importance of maintaining a low coefficient of friction for forging when the ratio \( \frac{d}{h} \) is relatively large. The frictional shear factor \( m \) may be substituted for \( \mu \) for the case of sticking friction.

1.3 UPSETTING PROCESS AND MATERIALS

As explained elsewhere [13] for the selection of an upsetting process, the following parameters are significant dimensions of the workpiece, strength, formability, required upset ratio, desired accuracy, surface quality as well as economic considerations.

For trouble free and economic production, the workpiece material must be of uniform quality (chemical composition, mechanical properties and surface finish).
Steels and non-ferrous metals with substantial formability (low-carbon steels, copper, aluminium) are suited for cold heating. Occasionally steels with higher carbon content, alloy steels and special alloys are formed as well. These are the same work materials as those normally used for extrusion. Wire, bar and billet sections that are produced by cropping or sawing are processed.

Customarily hot-rolled stock is used as the starting material. Due to the coarse tolerance, the first heading operation is often preceded by a sizing or preforming process during which the slug receives its exact intended shape. In some cases the use of drawn material is preferred, since variations in volume are reduced.

Smaller parts are cold-formed due to the small forming forces. Heating of such parts is not very advantageous, since rapid cooling results from the unfavourable surface to volume ratio. Production volume is high, and the increase in strength due to work hardening can be utilised constructively. On the other hand, formability is limited. This disadvantage can be dealt with by warm or hot forming.

1.4 FORGING APPLICATIONS

According to the Ref.[14], the applications are as follow: Electrical Engineering applications, aerospace
industry, pressure vessel industry, automobile industry, defence applications, ship building applications and rocket technology.

Gas turbine blades, impellers, bearing components, valves, valve seats, gears and worm wheels, housings for rocket engines, gun barrels, surgical instruments, conveyer parts, small gun wheels and shafts, connecting rods, steering shafts, cam shafts, bearings, levers, rollers, crankshafts, driving forks, front angles, ball pins, bolts, rivets, flywheels, stub curves, tie rods.

1.5 SCOPE OF THE PRESENT RESEARCH

In the present research, experiments were carried out to generate data on cold upset forging of annealed commercially pure Aluminium, copper and zinc solids of truncated cone billets under unlubricated and lubricated conditions at room temperature. No researcher has so far worked on forging behaviour of truncated cone billets. Height of specimen, top contact diameter and bottom contact diameter were measured. Upsetting tests were carried out with incremental loading. Height of the deformed specimen, bulge diameter, top contact diameter, bottom contact diameter and radius of curvature of barrel were measured.
The aim of the research work is

a) to identify the shape of the barrel of the truncated cone billets on upsetting

b) to reveal the effect of aspect ratio/taper on barrelling, geometrical shape factor, hydrostatic stress and stress ratio parameter.

c) to reveal the effect of strain or degree of deformation on stress namely effective stress, hoop stress, axial stress and hydrostatic stress.

d) to reveal the effect of geometrical shape factor based physical dimensions on barrel radius.

e) to reveal the effect of above said stresses on barrel radius.

f) to reveal the effect of above said stresses and geometrical shape factor with respect to barrel radius on different metals for comparative study.

g) to establish mathematical modelling on barrelling for different radii of curvatures namely circular and parabolic.

h) to study the barrelling effect behaviour of HCP metals zinc and
i) to establish mathematical modelling on barrelling of zinc.

1.6 OVERVIEW OF THE THESIS

This thesis is organised into six chapters. A very brief chapter-wise outline of the thesis is given below.

The present chapter is introductory in nature and presents a general description of open die hot forging processes, upsetting process and materials and applications of forging process.

Chapter II presents a review of related literature on barrelling study, finite element analysis of forging process, upper bound solution to forging, ductile fracture in forging, computer aided design in forging, forging of porous materials, forging process parameters and other aspects related to forging.

Chapter III deals with the experimental investigations of upset forming of Aluminium, Copper and Zinc at unlubricated and lubricated conditions.

The mathematical analysis of barrelling is presented in Chapter IV for circular arc, parabolic arc and elliptical arc.
Chapter V discusses the results of the experimental work and mathematical analysis of the present study.

Chapter VI is the concluding chapter in which the major contributions of the research study are highlighted. Guidelines for future work are also included in this thesis.

A bibliography of the literature relevant to the research study is listed at the end of this thesis.