2.1 INTRODUCTION

In conventional upset forging, the upsetting of a cylindrical billet is commonly used to determine bulk workability of metal alloys. In the simplest view, the upsetting is deforming a cylindrical specimen to a thinner cylinder of larger diameter. The increasing of forming load occurs by friction between the die and material surface. Friction between the ends of the test specimen and platens constrains lateral flow at the contact surfaces, which leads to barrelling or bulging of the cylindrical surface. This deformation behaviour clearly means that the stress state is not uniform axial compression. In addition to the axial compressive stress, a circumferential tensile stress develops as the specimen barrels [18]. Tarnovski [19] investigated the strain rate and forces at upsetting of an ingot, forging of a strip, etc. on the basis of the minimum total power principle. Hartley et al. [20] predicted the platen forces, the pressure distribution and the strain and hardness distributions within the billet for various levels of interface shear stress. Shyam Kinkar Samanta [21] conducted simple upsetting model tests on cylindrical specimens of steel at higher temperature to study the relationship of deformation energy per unit volume and the percentage of reduction. Erman et al. [22] carried out experiments with plasticine as an easy-to-deform model material to develop basic understanding regarding the influence of several upsetting parameters on the distribution of deformation in the upset forged ingots.
The information on the intensity and distribution of the contact stresses in bulk metal forming operations is essential both for the die design and the die process analysis. Plancak et al. [23] experimentally investigated the contact stress measurement by pin load cell in bulk metal forming. The pin load cell technique produces a dynamic output, which simulates the non-steady state conditions that are predominant in metal forming processes. This method was applied in different metal forming operations such as upsetting and forging [24] and extrusion [25].

2.2 STUDY ON BARRELLING

In practice, upsetting is used either as a separate forming process or as the primary stage of more complex forming operations. In upsetting, the existence of frictional constraints between the dies and the work piece directly affect the plastic deformation. The Friction and cooling at the tool-workpiece interface cause barrelling. Sachs [26] suggested that barrelling could be avoided by using conical platens. Gärtner [27] investigated the effect of conical dies on barrelling using aluminium specimens up to a height-to-diameter ratio of 2 between platens of inclination angle of three degrees. From investigation, it is observed that barrelling is nearly eliminated when the inclination angle equals the friction angle. When the inclination angle is larger than the friction angle there is reverse barrelling and Hsu [28] also found a similar effect through his investigations. In many industrial metal-forming processes, bulging of free work piece surfaces occurs. At the same time these surfaces may fold over and come into contact with the dies. These kinds of phenomenon are often neglected in metal forming analyses. Jin Hou et al. [29] studied the problem of bulging and folding over in plane-strain in upset forging and a computer program was developed to study the influence of work piece geometry and friction. Majerus et al. [30] presented a quantitative analysis of axial-force, internal radial displacement and work piece contour for upset tests and a
quantitative comparison between the experimental results and a computer-code simulation of forging force and internal radial displacements.

Johnson and Meller [31] published a comprehensive review of the literature on upsetting of solid cylinders. Another significant aspect of axisymmetric compression form the standpoint of testing the mechanical manufacturing properties of metals is the estimation of their forming limits up to the plastic instability and fracture as explained by Shaw and Avery [32].

Schey et al. [33] studied the significance of the geometrical factors that affect the shape of the barrel, such as aspect ratio, reduction ratio as defined by initial height/instantaneous height and the diameter ratios of the specimen. Banerjee [34] and Narayanasamy et al. [35] showed theoretically that the barrel radius could be expressed as a function of height strain and confirmed the same by means of experimentation. Narayanasamy and Pandey [36] established a relationship between the measured radius of curvature of the barrel and a new geometrical shape factor, based on the contact diameters, the barrel diameter and the initial height. Malayappan and Narayanasamy [37-41] studied the effect of barrelling in aluminium solid cylinders under different experimental conditions. Sathiyanarayanan et al. [42] studied the effect of barrelling in zinc solid cylinders during cold upsetting. Sathiyanarayanan and Narayanasamy [43-44] also studied the effect of barrelling in solid cylinders of copper and a comparative study on non-ferrous metals under unlubricated conditions. Thomson and Myoe Aung [45] studied the profiles of billets of circular, square and rectangular cross-section of intermediate aspect ratio, upset under conditions of high and low friction. The adequacy of approximating the barrel profile to a circular arc was confirmed and the same non-dimensionalized curvature was found to describe the barrel profile of square and rectangular billets at the same reduction in height. Kim and Yang
[46] proposed a simple kinematically admissible velocity field for three-dimensional deformation in upset forging of square blocks, which considers not only the sidewise spread but also bulging along thickness.

Yang and Kim [47] proposed an upper bound method to determine the forging load and the deformed configurations during upset forging of elliptical disks. Syed Abu Thaheer et al. [48-49] studied the some aspects of barrelling of copper and aluminium truncated cone billets during cold upset forging under unlubricated conditions. Cook and Larke [50] studied the resistance of Copper and its alloys to homogeneous deformation in compression. Hsu and Young [51] also studied the effect of lubrication on barrelling in pure Copper in upsetting. Chen and Chen [52] developed a theoretical solution for the prediction of flow stresses during an upsetting operation considering the barrelling effect.

Mustafa İthan Gökler et al. [53] analysed tapered preforms in cold upsetting and for analysis the perfectly square end and the end with face inclination angle were considered as two different end conditions of the billet.

2.3 STUDY ON FRICTIONAL FORCES

The friction forces developed between the work piece and the forming tools are important considerations in metalworking. Frequently, the interfacial conditions at the top and bottom of die surfaces are dissimilar during the upsetting process in an industrial forging workshop. This unequal interface frictional constraint at the end faces of the billet may cause an uneven shape of the product and unequal wear of the die surfaces. Kulkarni and Kalpakjian [54] conducted tests in which some specimens were upset in the dry condition whilst others were lubricated. A suitable parameter was chosen to characterize the extent of barrelling, the influence of the various variables on this
parameter being studied. Schey et al. [55] also performed upsetting experiments with both lubricated and un lubricated grooved anvils, upsetting of relatively slender cylinders aiming at evaluating the effects of interfacial friction on the pressure and the deformation mode. The upsetting of cylindrical billets of elastic-linearly strain hardening material between a free-falling tup and stationary anvil with unequal interface frictional properties has been simulated [56], the effects of the unequal interface frictional force on the radial displacement and on the billet of the profile, together with the variations in the tup and anvil loads and in the consumption of kinetic energy being predicted.

Thore and Felder [57] constructed a simple model using the upper bound method, giving the relationship between asymmetrical friction conditions and plastic flow in the hot forging of cylinders. The validity of the model had been verified by a set of experiments, which allowed the study and prediction of the abrasive wear of hot forging dies. An upper bound method was applied to the determination of the forging load and the deformed bulge profile during the upset forging of cylindrical billets, which takes into account dissimilar frictional conditions as well as identical frictional conditions at the top and bottom of the die surfaces [58]. Lin [59] presented a method of assessing die-work piece interface friction that is related to the amount of work piece deformation in the upsetting process, two continuously varying functions being properly proposed to approach the continuously varying behaviour of interfacial friction during the upsetting process.

Lin [60-61] investigated the effects of various combinations of unequal interfacial frictions at the top and bottom die surfaces on the deformation characteristics of the billet during the upsetting process. Abhijit Chandra and Rajesh Srivastava [62] analysed the axisymmetric problems involving both material and geometric nonlinearities to investigate the effects of interfacial conditions on the stress and
deformation histories. Abdul [63] also studied the determination of friction during plastic deformation of metals.

2.4 COMPARISONS OF FRICTION MODELS IN BULK FORMING

The importance of tribological considerations in bulk metal forming has been generally recognized as affecting: tool and tool life, metal flow during forming, work piece integrity and surface finish, the relationship of lubricant to machine elements, cost considerations and energy conservation [64-68]. Friction models normally applied in finite element analyses for bulk metal forming are

a) Coulomb friction model $\tau = \mu p$

b) The constant Friction model $\tau = m \kappa$

c) The general friction model $\tau = f \alpha \kappa$

where $\tau$ is the friction stress, $\mu$ is the co-efficient of friction, $p$ is the normal pressure, $\kappa$ is the shear flow stress, $f$ is the friction factor expressing friction in the real contact, and $\alpha$ is the ratio of the real to the apparent contact area. Xincai Tan [69] investigated the comparison of friction models in bulk metal forming and the various forms of friction models are reported in Table 2.1. Bay [70] analytically expressed the plastic deformation of surface asperities, the influence on friction stress of normal pressure, friction factor and surface roughness using slip-line analysis. Bay and Wanheim [71] developed a general model for expressing friction at the tool-workpiece interface. In practical terms the model assumes friction to be proportional to the normal stress at low normal pressure, but going towards a constant value at high normal pressure, the two ranges being combined via an intermediate transition region. The validity of the Wanheim-Bay model has been experimentally demonstrated [72-74]. Petersen et al. [75] shown that the application of the general friction model, developed by Wanheim and Bay, involves major improvements in the ability to simulate processes where tool-workpiece interface
Table 2.1 Various friction models used in bulk metal forming. Ref. [69]

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Friction Model</th>
<th>Friction stress distribution</th>
<th>Main assumptions and applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\tau = \mu p$</td>
<td><img src="image1" alt="Friction stress diagram 1" /></td>
<td>Dry slipping occurs over the whole tool/workpiece interface. Friction stress $\tau$ is directly proportional to local normal pressure $p$. It is mainly used for cold metal forming due to its simplicity.</td>
</tr>
<tr>
<td>2</td>
<td>$\tau = mk$</td>
<td><img src="image2" alt="Friction stress diagram 2" /></td>
<td>Dry slipping occurs over the whole tool/workpiece interface. $K = \sigma_v \sqrt{3}$ is the shear flow stress, and $\sigma_v$ is the yield stress. It is the most popular model since its simplicity and seemingly indicating the material feature of plastic deformation.</td>
</tr>
<tr>
<td>3</td>
<td>$\tau = k/2$</td>
<td><img src="image3" alt="Friction stress diagram 3" /></td>
<td>Sticking occurs over the whole interface between tools and workpiece. $K = 1.15\sigma_v$ It is used for hot metal forming or unlubricated cold forming of soft materials.</td>
</tr>
<tr>
<td>4</td>
<td>$\tau = \eta (dv_x/dy)$</td>
<td><img src="image4" alt="Friction stress diagram 4" /></td>
<td>Viscous slipping friction proportional to relative velocity of slip occurs over the whole interface between tools and workpiece. Due to its relative complexity, its applications are very limited.</td>
</tr>
</tbody>
</table>
| 5     | Area I: $\tau = k/2$  
Area II: $\tau = \mu p$ | ![Friction stress diagram 5](image5) | The interface is divided into two zones(I) sticking occurs at the central zone whose centre is the neutral point;(II) dry slipping occurs at the edge zone when friction stress is less than yield stress in shear. It is used for rolling and forging |
| 6     | Area I: $\tau = \tau_0 (r/OA)$  
Area II: $\tau = k/2$  
Area III: $\tau = \mu p$ | ![Friction stress diagram 6](image6) | A zone of restricted plastic deformation exists in the middle of the sticking zone: the tool/workpiece interface is divided in to three zones: (I) the stick zone, $0 \leq r < OA$; (II) the drag zone, $OA \leq r \leq OB$; and (III) the slip zone, $OB \leq r \leq R$, in which R is the contact radius. It is used for general metal forming. |
| 7     | Area I: $\tau = \tau_A (r/OA)$  
Area II: $\tau = f_{sk}$  
Area III: $\tau = \mu p$ | ![Friction stress diagram 7](image7) | Three zones are similar to the model of Tscklov and Unskov: (I) the central sticking zone; (II) the sliding zone, $OA < r < OB$, $p/\sigma_v \geq 1.5$; and (III) the homogeneous deformation zone, $r > OB$, $p/\sigma_v < 1.5$. It is used for general metal forming. |
stresses may prevail. This was confirmed by experimental and numerical investigations in to the upsetting of a semi-tapered specimen between parallel dies. Pawelski et al. [76] investigated the analysis of the symmetrical upsetting test with extremely high strain rate as a tool for friction measurement. Stancu-Niederkorn et al. [77] developed friction and lubrication test to examine the quantitative relation between real contact and the coefficient of friction in metal forming processes.

2.5 STUDY ON THE EFFECT OF LUBRICATION IN METAL FORMING

In most liquid lubricated metal working operations some asperity contact is unavoidable. The metal-to-metal contact carries a significant portion of the load and pockets of liquid in the valleys of asperities carry the rest. This mixed film lubrication is common in metalworking. In selecting a suitable lubricant, the work piece, the die and the lubricant should be considered a total system [78].

Lazzarotto et al. [79] investigated the performance of lubricating oils containing extreme pressure agents using the upsetting sliding test. The investigators proposed three selection criteria: (a) the friction coefficients: (b) the occurrence of defects and (c) the resulting roughness. It was shown that these criteria indicate the ability of the lubricant to reduce friction stress, delay the forming limits, maintain boundary or mixed lubrication regimes and improves the surface finish [80-81]. Rasp and Wichern [82] studied the effects of surface-topography directionality and lubrication condition on frictional behaviour during plastic deformation. Doraivelu and Gopinathan [83] studied the behaviour of lubricants under different temperature using a hot upsetting device. Wallace and Schey [84] investigated the effect of forging speed on the efficiency of selected solid lubricants. Thiébaut et al. [85] determined the friction factor of a molybdenum workpiece during upsetting tests at different temperatures using F.E. code and presented a comparison between experimental and numerical data for (i) the forging load, (ii) the
sliding at the top and bottom faces, which provides the value of the best co-efficient for the friction laws.

2.6 FRACTURE

Workability is concerned with the extent to which a material can be deformed in a specific metalworking process without the formation of cracks. In some processes the limit of workability is determined by the formation of local necking (plastic instability) rather than by the occurrence of fracture [86]. It is not surprising that a generally acceptable laboratory test for workability has not been developed [87]. The upsetting of a cylinder under controlled strain rate conditions comes closest to a standard test. Abdel-Rahman [88] studied the workability of less ductile materials in upset forging.

To predict workability, a fracture criterion for ductile-fracture criterion is established. The most generally applicable ductile-fracture criterion is that proposed by Cockcroft and Latham [89]. They reasoned that a criterion of ductile fracture would be based on some combination of stress (σ) and strain (ε) and that only the highest local tensile stress σ* will be important. They proposed that ductile fracture would occur when

\[ \int_{\varepsilon_r}^{\varepsilon} \sigma^* \, d\varepsilon = \text{Constant} \quad (2.1) \]

for a given temperature and strain rate. More extensive studies [90] of free surface fracture in room temperature deformation have shown consistent fracture criteria in the form of a unique correlation for each material between the tensile and the compressive strains at fracture.

The upsetting test method involves the measurement of the axial and the hoop strains at the equatorial free surface as the height of the billet is reduced by compression between two platens. The development of barrelling continues until one or more visible
cracks are observed, thus signalizing ductile fracture. The surface strain measured at the fracture for a wide range of test conditions, e.g. friction between the platen and the billet and the aspect ratio (height to diameter) of the billet, lead to the construction of a fracture limit line for the material [87]. The fracture limit curve in upsetting cylindrical billets was predicted by Ragab [91].

In recent years researchers have tried to implement fracture criteria in available finite element computer programs so that crack nucleation can be prevented in cold metal forming process such as forging and extrusion [92-96]. Lin and Lin [97] used the strain energy failure theory and a coupled thermo-elastic-plastic model to analyse ductile fracture. Very recently, efforts were focused on the prediction of the propagation paths of initial cracks in metal working processes such as blanking and metal cutting [98]. Ko et al. [99] studied the prediction of surface-fracture initiation in the axisymmetric extrusion and simple upsetting of an aluminum alloy using the Cockcroft-Latham fracture criterion. Free surface cracking and internal cracking under a triaxial tension or tension-compression state of stress can be estimated successively using both the Cockcroft- Latham and Oyane ductile fracture criteria [100]. Zheng et al. [101] proposed a new damage model to the dissipation of ductility of metal based on the principles of irreversible thermodynamics.

Bradley Dodd and Philip Boddington [102] examined the parameters that influence the edge cracking in rolling. Kopp et al. [103] described a practicable method for developing a crack-free forming strategy in the case of the hammer forging process. Reiss and Pöhlandt [104] investigated the material properties of the wrought alloy AlCuMg2 (AA-2024-T3511) after homogeneous compression to high strains. Hitoshi Moritoki and Eiki Okuyama [105] presented the general criteria for the ductility based on plastic instability and demonstrated the application of the criteria to the prediction of
cracking in several metal forming: the formality under linear strain paths in sheet metal forming, the free surface ductility and cracking mode in upsetting and the central bursting in drawing and extrusion. Landre et al. [106] described the utilization of ductile fracture criteria in conjunction with the finite element method to predict when and where material is likely to fracture during cold forging. Nikolina Bontcheva and Rumen Iankov [107] investigated the damage process during metal forming by considering the coupling of the deformation, thermal and damage process.

2.7 POWDER METALLURGY FORGING

Powder forging is currently arousing in many parts of the world as an economic method of producing high strength, high ductility parts from metal powders [108]. Powder forging [109] involves the fabrication of preform by conventional press-and-sinter processing, followed by forging of porous preform into a final shape through substantial densification. Working with a sintered powdered metal preform introduces new aspects to the mechanics and metallurgy of plastic deformation. Because it contains a dispersion of interconnected voids, the deformation of a P/M preform is much different from a conventional fully dense workpiece. The presence of voids causes a significant decrease in local ductility, which increases the chance of fracture during forging. However the forming limit concept can be applied [110] to design of P/M preforms to prevent fracture in forging. Han et al. [111] presented a finite element formulation of elastic-plastic deformation and analysed the punch indentation and closed die compaction of a sintered copper billet. Mori and Osakada [112] used the rigid-plastic finite element in analysing powder forging.

For the analysis of the deformation of porous metals, the previous studies started from the assumption of a homogeneous density distribution of initial preform. Even after the hydrostatic compaction process, which allows the most uniform density distribution
[113], because of friction between the powders and the metal. Aly EI-Domiaty and Mostafa Shaker [114] determined the workability of different compacts having different densities; from which it is shown that the density is the parameter controlling the workability of porous performs. Kuhn and Downey [115-116] analysed the more practical problems of compression of a disk between dies with friction using the basic plasticity mechanics of a porous powder metallurgy preform.

Doraivelu et al. [117] proposed several yield functions for compressible P/M materials. A major objective in metal forming is the determination of the initial shape of the work piece (Preform) and of the process parameters that lead to a final product with desired geometry and material properties. The solution to these problems is usually obtained by trial and error methods using the results of direct analysis for a set of preforms and process parameters. The analysis of cold forging of sintered powder metal preforms using finite element method for elastic plastic analysis was done by many researchers [118-120]. Oh and Mun [121] studied the analysis of ring compression on the basis of plasticity theory for porous metal employing the upper bound approach.

A plane-strain solution for analyzing the open-die forging of a plastically compressible sandwich panel is developed by Elzey and Wadley [122]. Zhang et al. [123] established a finite element procedure to analytically determine the strain path similar to those determined by the experimental studies by taking the effect of lubrication, height to diameter ratio, initial relative density, die shaping and preform shape on the limit of P/M products. Many authors claim that forging of powder preforms without sintering gives mechanical properties comparable with those attained by the usual sinter forging method [124].

Analysis of forging of P/M parts is also not well understood as wrought metals. With the development of more and more sophisticated parts for missiles, aerospace and
automobile applications and the increase in trend to produce parts at more competitive price, application of P/M forging has advanced rapidly and developments are taking place in all aspects throughout the world [125-126].

Artificial neural network (ANN) models have been studied in recent years, with an objective of achieving human like performance in many fields of knowledge engineering. Many researchers have attempted to use neural networks for various applications in manufacturing, such as, tool wear prediction, TTT diagrams prediction, green sand control, grinding process control, powder packing density optimization. Ohdar and Pasha [127] predicted the process parameters of metal powder preform forging using artificial neural network.

2.8 UPPER-BOUND ANALYSIS

Upper-and lower bound techniques [128-129] have been developed that have general applicability. An upper-bound solution provides an over estimation of the required deformation force while a lower-bound solution provides an underestimate of the force. No attempt is made to satisfy the stress equilibrium conditions at any point in the field. Baraya and Johnson [130] analysed bar forging using upper-bound technique. Three solutions were suggested through triangular velocity fields, for each of which the power dissipation and load were determined for three different metals. Park et al. [131] proposed a new method of constructing a velocity field to solve metal forming problems by the upper-bound elemental technique (UBET). The velocity fields can be composed of nodal points using a shape function. The forging load and deformed profile are obtained by minimizing the total energy-consumption rate, which is the function of unknown velocities at each nodal point. Kudo [132] presented a procedure to facilitate the analysis of complicated problems for plain strain forming operations by introducing the concept of a “unit rectangular deforming region”. In Kudo’s work there were some
restrictions, where it was assumed that the overall forging must be capable of being split into elements of rectangular cross-section only. Aksakal et al. [133] analysed the open die forging process as a part of a computer-controlled robotics flexible forging system for the economic production of small-batch quantities.

Sagar and Juneja [134] introduced work on the problem of determining load requirements by taking bulging in to account. Oudin and Ravalard [135] developed a method that can be used in the industry for predicting the optimum geometry of the work piece and metal flow developed from the basis approach defined by Kudo. Wang and Lin [136] developed the upper bound stream-function elemental technique (UBST) for the load analysis of the plain strain forging processes. This improves the ineffectiveness of UBET for solving forging problems that are geometrically complex or need a forming simulation for predicting the profile of the free boundary. Lin and Wang [137] also proposed a new upper-bound elemental technique (UBET) to improve the ineffectiveness of UBET for solving forging problems that are geometrically complex or need a forming simulation for predicting the profile of free boundary. This method combines the advantages of the stream function and the finite element method. Maity et al. [138] proposed an upper-bound analysis for the extrusion of square sections from square billets through curved dies having prescribed profile. Guo and Nakanishi [139] analysed the plain strain upsetting processes under two friction conditions by rigid-plastic domain-boundary element method.

2.9 FINITE ELEMENT METHOD

The finite element method has a major impact on the analysis of complex problems concerned with elastic stress analysis, is beginning to be applied to problems in metal working plasticity. Early applications of FEM to plasticity problems concentrated on elastic-plastic solutions. Lee and Kobayashi [140] achieved a practical adaptation of
the FEM to metal working analysis by a technique called matrix method. This method
neglects elastic strains compared with the larger plastic strains and assumes rigid plastic
behaviour. Dudra and Yong [141] performed axisymmetric upsetting and plane-strain
analyses with finite element method to predict the press loads and material flow when
forging with different die and billet (or ingot) geometries. Xua Kemin et al. [142]
analysed the process of twist-compression forming by using 3D-FEM. Pei Chi Chou
and Longwu Wu [143] used a modified dynamic finite element program to solve static
metal forming problems. Oh et al. [144] studied the analysis of the practical plastic flow
problems, using the rigid-plastic finite-element method and it appears to be the most
promising technique. Mori and Yoshimura [145] proposed a rigid-plastic finite element
method using a diagonal matrix for simulating large-scale three-dimensional deformation
in metal forming processes. Xiong Shangwu et al. [146] presented a comprehensive
analysis of the theoretical foundations of the rigid-plastic boundary element method for
the numerical simulation of bulk metal forming processes. Toyoshima et al. [147]
proposed a rigid-plastic finite element method (FEM), in order to recover the volume
loss and thus to maintain the volume constancy within an allowable amount even for a
relatively large increment at one calculation step, a simple computational scheme.
Michel and Boyer [148] developed an elasto-visco-plastic formulation based on the
displacement approach to study the importance of the stress field prediction in upsetting
test. Kim and Im [149] adopted a parallel computational technique to study the rigid-
visco plastic approach in order to increase the computational efficiency. Jin Hee Kim et
al. [150] investigated the damage propagation during metal forming process with the
concept of continuum damage mechanics. An elasto-viscoplastic isotropic damage
model [151] based on the theory of material type N [152] is adopted to analyse the
damage propagation during forming process. Kang and Yoon [153] investigated the
variation of the distribution of the solid fraction and the material behaviour under the upsetting process for the various values of friction and die speed.

Matsumoto et al. [154] developed an elastic plastic finite element method for compressible materials allowing large deformation. Lee [155] adopted a finite elastoplastic deformation with a complete formulation for sliding friction to precise treatment of the deformation occurring in metal forming processes and the analysis results indicate that the frictional response at the die-work piece interface is a bulk phenomenon. Meng et al. [156] presented a plasto-hydro lubrication model to metal forming processes. A computer simulation of the processes of lubricant film formation and transportation in the upsetting of metal cylindrical billets illustrates the validity of the proposed model. Vander Lugt and Huetink [157] presented a combined Eulerian-Lagrangian finite element formulation for the analysis of metal forming, coupled with thermal effects. This procedure can be applied to the upsetting and the wire–drawing process. Liu and Baker [158] investigated the deformation characteristics of titanium alloy in unlubricated–die upset forging under isothermal conditions. Antúnez [159] presented linear elements for the analysis of metal forming processes in the context of explicit time integration. Simulation of transient and stationary metal-forming processes is presented in the context of a mixed velocity-pressure formulation with a rigid-viscoplastic material model. The method shows to efficiently simulate different metal-forming operations. Wang et al. [160] developed the flow-function elemental technique combined with viscoplasticity to analyse dynamic metal forming processes. The finite element method for the determination of material flow stress is analysed by few researchers [161-162]. Marin and Dawson [163] presented a pressure-velocity element formulation using an elasto–viscoplastic polycrystal model for small elastic strains. Dadras and Thomas [164] also presented a flow-based model for upset forging of
cylindrical billets. Ken-Ichiro Mori et al. [165] developed a method for simulating plastic deformation in forming of solid metals with a liquid phase on the basis of the rigid-plastic finite element method. Mitani et al.[166] analysed the rotor shaft forging by rigid plastic finite element method to examine practical design for upset forging. This method is helpful for designing the die geometry which produces the suitable metal flow and stress distribution.

2.10 LIMITATIONS OF THE EXISTING LITERATURE

The some of major limitations of the existing literature on barrelling during upsetting are observed as under:

(i) Most of the technical papers have dealt with the analysis of cylindrical solid billets.

(ii) The analysis for the forging of square and rectangular billets have mostly been carried out using analytical solutions.

(iii) Most of the technical papers referred have not dealt with the effect of aspect ratio on barrelling, geometrical shape factors, stress ratio parameters and hydrostatic stress.

(iv) Many studies have not dealt with the effect of strain or degree of deformation on stresses namely the effective stress, the hoop stress, the axial stress and the hydrostatic stress.

(v) The effect of geometrical shape factors and stress ratio parameters and stresses on barrel radius of barrelling of square and rectangular billets have not been reported.