CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Two broad categories of forging processes are open-die forging and closed die forging. Open die forging is carried out between flat dies or dies of very simple shape. The simplest open-die forging operation is the upsetting of a cylindrical billet between the flat dies. The compression test is a small prototype of this process. In the simplest view, the cylinder deforms homogeneously into a shorter cylinder during upsetting, in reality, the presence of friction at the tool cylinder interface not only increases forging pressures and forces, but also leads to non homogeneity of deformation. Frictional restraint retards the growth of the end face and part of the new end face is actually formed by folding the sides of the original cylinder into the platen surface. Frictional restraint causes internal inhomogeneity too, with slightly deforming or non-deforming zones developing adjacent to the platens and severe deformation concentrated in zones that occupy a roughly diagonal position between opposite edges of the workpiece. This results in much strain hardening in the heavily deformed...
zone during cold working and in a highly variable grain size on subsequent annealing.

2.2 BARRELLING IN SOLID CYLINDERS

A series of investigations on cold upset forging of solid cylinders had been carried out by many investigations due to its relevance in metal forming applications. A comprehensive review of literature has been published by Johnson and Mellor [15]. Another significant aspect of axisymmetric compression from the standpoint of testing the mechanical manufacturing properties of metals was the estimation of their forming limits up to plastic instability and fracture [16]. In upsetting, the existence of frictional constraints between the dies and the workpiece directly affect the plastic deformation of the latter. When a solid cylinder is compressed axially between the punch and bottom platen, the workpiece material in contact with the surfaces undergoes heterogeneous deformation that results in 'Barrelling' of the cylinder. Friction at the faces of contact retards plastic flow of metal on the surface and its vicinity. A conical wedge of a relatively undeformed metal is formed immediately below it while the rest of the cylinder suffers high strains and bulges out in the form of a barrel. This demonstrates that the metal flows most easily towards the nearest free surface which is the point
of least resistance, a well-known principle in plastic deformation. However, the use of lubricants reduces the degree of bulging and under the conditions of ideal lubrication, bulging can be brought down to zero. However friction could not be eliminated during upset forging and it is necessary to go for a correction factor for the bulging during the die design.

Kulkarni and Kalpakjian [17] examined the arc of barrel assuming it to be circular or parabolic, whereas Schey et al. [18] presented a comprehensive report on the geometrical factors that affect the shape of the barrel. Banerjee [19] and Narayanasamy et al. [20] showed theoretically that the barrel radius could be expressed as a function of axial strain and confirmed the same through experimental verification. Yang et al. [21] developed an upper bound solution for the determination of forging load and deformed bulged profile during upset forging of cylindrical billets considering the dissimilar frictional conditions at flat die surfaces. Chen and Chen [22], developed a theoretical solution for the prediction of flow stresses during an upsetting operation considering the barrelling effect. Gokler et al. [23] studied taper upset forging using elastic-plastic finite element analysis.

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Malayappan and Narayanasamy [24] conducted experiments on cold upset forging of solid cylinders of annealed Aluminium using a die with constraints and observed two barrels. Radius of curvatures of both barrels measured was found to conform with calculated values, on the assumption that the curvature was in the form of a circular arc. Measured radius of curvature exhibited a straight line relationship against new geometrical shape factor, irrespective of the aspect ratio of cylinders. Empirical relationship was established between the measured radius of curvature and stress ratio parameter and the hydrostatic stress.

2.3 FINITE ELEMENT ANALYSIS OF FORGING PROCESS

The conventional rigid-plastic finite element methods (FEMs) posses a common demerit in that they are almost a solution in closed form, which need repetitious calculations in every computing step. Therefore the CPU times of these methods are long or the computation costs of these methods are large, and there are some possibilities of divergence with the repetitious calculations for these methods. A solution in open form, which does not need repetitious calculations in any computational set up, is an ideal solution for rigid-plastic analyses. Guo and Nakanishi formulated a rigid-plastic finite boundary element method (FBEM) [25], which
was a solution in open form, and have done some simulations for plane-strain problems by this method [26].

Equations in the axisymmetric form of the rigid-plastic finite boundary element method were formulated by the same authors in [27]. As examples of analyses, forging processes for frictional cases 0-20% reduction in the vertical height were analyzed.

Upset forging is carried out with a sequence of operations through which the workpiece is brought to its final form. Design of the preforms directly affects the number of operations required, the quality of the product and the cost. The cylindrical and tapered preforms are two alternative methods for intermediate stages of multistage upsetting process. In practice, the tapered preforms are widely used and result in well-filled and uniform upsets, allowing greater upset ratios when compared with cylindrical upsetting [28]. The related parameters of tapered preforms are given in Fig. 2.1.

Naujoks and Fabel [29] summarized the three basic rules governing die design for upsetting as illustrate in Fig. 2.2. These three rules can be explained as follows:

Rule 1: The limit of length of unsupported stock that can be gathered or upset in one blow without injurious buckling is not more than three times the diameter of the bar.
Fig. 2.1 Important parameters for tapered upsetting. Ref.[28]
Fig. 2.2 Three basic rules for upset forging. Ref. [29]
Rule 2: Length of stock more than 3 times the diameter of bar can be successfully upset in one blow, provided that the diameter of the upset made is not more than 1.5 times the diameter of the bar. The midpoint, M, of the unsupported length must be inside the impression of the die, since the stock, which has a length of more than three times its diameter, is likely to start buckling at this point, M, in upsetting.

Rule 3: For an upset requiring more than three diameters of stock length and for which the diameter of the upset is 1.5 times the diameter of bar, the amount of unsupported stock length beyond the face of the die must not exceed one stock diameter. If, however, the diameter of the die cavity is reduced below 1.5 diameters, then length of the unsupported stock beyond the face of the die can be correspondingly increased. If the die cavity diameter is not greater than 1.25 times the diameter of the stock, then the amount of stock beyond the face of the die can be increased to a maximum of 1.5 times the diameter of the bar.

The several suggestions about upset limit and sequence design rules have been reviewed in [28,30]. Meyer [31]
conducted a number of experiments for taper upsetting. The relationship between the maximum allowable upset ratio and the diameter ratio based on his experimental studies is shown in Fig. 2.3. Gokker [28,30,32] has rationalized the established design rules for hot upset forging. His interpretation of Rule 3 is graphically represented in Fig. 2.4. He also stated that the equivalent mean diameter should be determined by considering the second moment of inertia of area, which buckling is dependent on, in the calculation of the upset ratio.

The deformation of a billet is also affected by the method of billet preparation since this determines the initial shape of the billet. Cropping is one of the most commonly used billet preparation processes. The fundamental problem of measuring and describing the quality of the cropped billet has been discussed and seventeen different billet defects have been described by I.C.F.G. [33]. Importance of the type of defect varies for each cold forming process.

It is known that besides the upset ratio and the initial shape of the billet, the final geometry also influences the intermediate shapes. In design of tapered preform dies, the height of the stock is gradually reduced to a length below the limit, which allows applications of the final blow giving the required shape of the part. In
Fig. 2.3  Suggested relationship between shut-height distance beyond cavity (l'0), and maximum taper diameter (dg). Ref. [32]
Fig. 2.4 End-face inclination of the billet geometry. Ref.[33]
other words, sufficient number of preforms are designed to reduce the length of unsupported stock beyond the upsetting limits defined. Therefore, investigating the relation between upset ratio \( s \) versus the ratio of maximum cavity diameter to billet diameter \( (d_g/d_0) \) for the tapered preforms would make clear many points including the design limits of the process.

Design of preforming shapes requires experienced designers, time and a considerable number of trial and error approaches. However, the recent developments in finite element analysis (FEA) technique supported by powerful computers, permit significant reduction in time and cost of the design and analysis of metal forming processes. FEA allows a designer to carry out large numbers of iterative simulations of metal flow, which are compatible with the experimental procedures [34-39].

The preforms should be free from flash formation and buckling injuries and the results that depend on elastic-plastic finite element analysis of taper upset forging were also given in [40]. The buckling analysis was realized by using the modified Riks method. For a given upset ratio which is the ratio of unsupported length to diameter of the initial billet, reduction in the height of the billet and the diameter ratio are the important design parameters in taper upsetting. For several values of the
design parameters, the analysis were carried out and the results were compared with the results of the well-known Meyer's experimental and Gokler's suggestions. In the analysis, the perfectly square end (ideal billet case) and the end with face inclination angle were considered as two different end conditions of the billet. The results for the ideal billet case were in good-agreement with Meyer's results. The end-face inclination angle, which is a significant imperfection on the billet, reduces the limits of allowable upset ratio. It was observed that although the tapered header dies designed at the limits suggested by Meyer [31] produce flashless preforms, in some of the cases, injuries due to buckling are not eliminated. However, Gokler's [28,30,32] suggested limits provide elimination of both flash formation and injuries due to buckling.

In the cold forming process, the material in a die flows continuously into the complex geometrical shape of the die under the progressive forming procedures. When the die design and the preform design of material are not optimized, internal damages of material like as void and micro-crack occur. According to the accuracy of initial volume of material shape, difference between the designed and the final shapes exists [41]. A poorly estimated initial volume of material may cause the geometrical forming defects such as the underfilling or the
overlapping in the forging process. Therefore, the optimization of the forming process is required to obtain the proper product without any damage.

The numerical simulation techniques using the rigid-plastic finite element method (FEM) have been successfully applied to investigate the forming characteristics of various forming processes such as the stress-strain state of the material and clarify the effects of various forging parameters on formability [42-46].

The forming process of torque converter impeller hub used in an automobile's transmission consists of the sequential cold forming processes: forward extrusion, upsetting, piercing and finishing operations. The final finishing operation governing the final shape of impeller hub is a closed-die forging process. In this forming operation, the forging load increase abruptly to flash formation and geometrical forming defects of the underfilling occasionally occurs due to the limit of the forging machine's load capacity. Moreover, excessive initial volume of material may cause the failure of forming die and forming machine.

Rigid-plastic finite element simulation was applied by Kim et al. [47] to analyze the deformation characteristic of the whole impeller hub forming processes and to
optimize the process. Two kinds of improvement for the impeller hub forming process satisfying the limit of the machine's load capacity and the geometrical quality are suggested and the results are verified by experiment.

The precipitation hardenable aluminium alloy 7075 was one of the first of the 7xxx series of aluminium alloys to be produced in large quantities. It was invariably heat treated into its highest strength temper to exploit its outstanding tensile properties. For thin products this did not present a problem, but when thicker sections were manufactured, the low resistance to stress corrosion cracking (SCC) in the maximum strength condition resulted in numerous failures of 7xxx series alloys in the late 1960s after the material had become popular in the construction of civil aircraft [48]. This problem was surmounted by the introduction of T7 type overaging treatments.

Another limitation of 7075 is its relatively high quench sensitivity. In Europe the alloy 7010 [49] was developed during the mid 1970s under the sponsorship of the British Ministry of Defence by Alcan and HDA Forgings Ltd. to exploit the strength of the 7xxx series alloys over a greater range of thickness by reducing their quench sensitivity [50]. The alloy chemistry of 7010 places precise control limits on the levels of iron and silicon
impurities thereby improving the material's toughness [50]. These improvements and the use of zirconium as a wrought grain refiner combined to make 7010 more favourable over traditional alloys such as 7075 when used for large forgings and thick plate.

7010 attains its high strength through a high temperature (475°C) solution heat treatment followed by a rapid quench into water/organic quenchant/spray quenching system and a subsequent artificial ageing treatment. The quenching part of this process sets up severe thermal gradients acting as a source of inelastic strains leading to compressive residual stresses near the surface and tensile stresses in the core. These internal stresses can affect the final forging at three different stages; firstly, they can cause distortion during quenching in thin sections. Secondly, they can cause distortion during machining operations and lead to dimensional instability; and finally, in certain situations, enough material can be removed to expose material in a state of tension which can reduce fatigue resistance and provide the driving force for stress corrosion cracks (SCC) in die forgings [51].

Applying a less severe quench using quenchants such as boiling water or organic quenchants is a common method of reducing quench-induced stresses in forgings. However, reducing the cooling rate generally reduces the final
mechanical properties, as alloying elements will precipitate out of the aluminium matrix at the slower cooling rates leading to the development of coarse equilibrium precipitates. Cooling curves were idealized whereby cooling is slow initially and fast at lower temperatures. These quenchants have been found to reduce quench-induced stresses while still maintaining the required properties [52].

Residual stress relief can be achieved after solution heat treatment by plastically deforming parts in a controlled manner through either further heat treatment (e.g. uphill quenching [53] or through mechanical deformation. Uphil quenching processes, where the material is cooled in liquid nitrogen and then rapidly heated using jets of steam, is generally considered too laborious and unpredictable as each part has to be individually analyzed after the process to ensure that the quench-induced stress has been relieved. Apart from this, large baths of liquid nitrogen may be considered too dangerous in large forging plants. Mechanical deformation, on the other hand, can take place at room temperature through tensile deformation (designated Txx51), compressive (Txx52) or a combination of the two (Txx54-involving a re-strike of the die forging in the finish-forging die after quenching that both compresses and stretches the part). While application of tensile deformation has been found to result in a

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substantial reduction in quench-induced stresses [54-56] the technique is limited to parts that have a substantially uniform cross-section in the stretching direction [57] (e.g. sheet and plate products). Similarly, application of a combined compression-tension loading is limited by configuration, shape and size [58].

Residual stress development during quenching was modelled using the finite element technique and the effect on the final residual stress magnitude of varying the process parameters was evaluated in [59]. The effect of stretching to relieve residual stresses and the effect on residual stress magnitudes of sectioning samples of the material was also analyzed using the finite element technique. The models of each of the stress relieving techniques were compared both by observing stress magnitudes and by using the FE model to predict the results from a layer removal technique.

For a Finite element analysis (FEA) of metal forging, values for a large number of mechanical and thermal parameters need to be supplied. These parameters define the bulk material properties of the workpiece, its initial conditions, conditions at its free surface and die surface constraints.

While it is indisputable that the accuracy of an FEA of forging depends on the quality of the values ascribed
to the input parameters, two factors restrict the scope for improving an analysis of industrial forging by refining parameter values: (i) inherent approximations in the FE method will limit how closely the analysis can match the industrial process being modelled; and (ii) the industrial process itself will vary.

A practical problem faced when analysing industrial forgings is that of knowing which parameters are important to the analysis and which produce second order effects. Changes to some parameter values will affect the results of a FEA critically, whereas the effect of similar adjustments to other parameter values might be insignificant compared to the resolution or accuracy required of the model. The analyst should obviously scrutinize the accuracy of critical parameters more than non-critical parameters. Similarly, more experimental time and money should be invested in measuring the key parameters.

Attaining high quality input data for the finite element analysis (FEA) of forging can be difficult and expensive. Snape et al. [60] examined the sensitivity of the results of an FEA of forging to key input parameters. The case examined was a closed-die forging operation. Six input parameters, four used to define the plastic flow stress of the workpiece and two to define the conditions at the die-workpiece boundary, were varied. Results of
full-factorial experiments, with each of the variable parameters assigned nine different values, were collated and analyzed. Each response was then subjected to a regression analysis to establish linearity. In this way it was possible to assess the accuracy required of input data relative to the output requirements of the analysis. In the constitutive equation used for flow stress, the constant coefficient and temperature sensitivity term had a greater influence on the FEA results than that the strain-rate sensitivity and strain-hardening terms. At the die-workpiece interface, friction was more important than the cooling effect of the die. None of the parameters examined affected shape and strain predictions significantly. Results may well differ for the analysis of other shapes, metals and types of forging process. To gain a general picture of how accurately the input parameters for the FEA of forging need to be specified, the same investigation should be applied to other shapes and processes.

The occurrence of material failure due to cracking means a process limit in cold and also partially in warm forging operation. Its non-observance might lead to severe consequence for the final product, especially when, during a multiple stage forging operation cracks or fissures occur, which are closed again during later stages. The
identification of such material defects is possible with sumptuous material testing only. Another problem arises from internal cracks (such as chevrons in extrusion) as they can be detected only by full ultrasonic testing or sectioning of the specimen. Nowadays finite element (FE) simulations during the design stage of the product can be regarded as a standard in modern forging industry. Thus it seems convenient to integrate suitable models for the description of material failure into the FE simulations of the forging processes. The awareness of critical areas in the workpiece allows for process modifications in order to minimise material failure additional to the standard evaluation of the simulation (material flow forces, stresses, strains etc.). First of all geometrical modifications of the forming parts (punches, dies) should be examined, but also annealing operations or the use of alternative materials can be considered to extend the forming limits in the critical areas.

Behrens and Just [64] carried out the tensile test and the collar compression test with simultaneous FE simulations.

The prediction of ductile material failure was based on strain-dependent macromechanical damage criteria (also known as integral damage criteria) or the MES by Lemaitre [61]. As other damage models (like the Gurson model) often
need an elaborate determination of material parameters, they were not considered.

Integral damage criteria can simply be integrated into the FE simulations, as they are mostly combinations of stresses, strains and some material-dependent parameters. It should already be mentioned here that the universal applicability of these criteria is limited as they lack reference values that clearly indicate a first appearance of cracking in a special load case. Their significance is bounded to the identification of a potentially critical area in a workpiece during the forging operation on the basis that the calculated criteria values reach a maximum. This value is nevertheless dependent on the material and the forming geometry of the tools. Studies performed by Landgrebe [62] also showed, that the integral damage criteria are the only ones, able to predict correctly a potential critical area in the experiments.

Apart from these criteria, it was possible to determine accurately, the first appearance (e.g. the resulting punch position) of a macroscopic visible material failure with the MES by referring the actual calculated damage value $D$ to a reference value, the critical damage $D_c$. Important mathematical relations concerning the MES are explained in detail [61,63].
In order to predict ductile material failure during bulk metal forming processes, several different damage models were modified and integrated into the FE software MSC-SuperForm 2002. The so-called macromechanical strain-dependent damage criteria failed to predict ductile damage as they were not able to give a critical reference value for an occurring crack that could be transferred from experiments to complex simulations. The model of effective stresses (MES) by Kachanov and Lemaitre showed good performance for this task in the FE evaluation of experiments with tensile and collar compression specimen. The damage location and the fracture propagation could be simulated with high coincidence. The appearance of a first crack in the experiments was measured by passive ultrasonic testing with subsequent filtering. From the visible necking and the drop of the stress-strain curve in the tensile test the damage related signals were extracted and taken as a reference for the collar compression test. At elevated temperatures a high-speed CCD-camera allowed for the identification of cracks.

In forging, the material is deformed plastically between two or more dies so as to give it the desired shape and size. Although the forging problem appears similar to that of the simple compression problem, there are significant differences between the states of deformation and stress in the two cases. In the case of
forging, the friction at the die-workpiece interface makes the deformation as well as the stress distribution non-uniform. This inhomogeneity of the deformation gets manifested in the bulging of the workpiece. Another significant consequence of the inhomogeneity is the generation of residual stresses on unloading.

Residual stresses are self-equilibrating internal stresses that exist in the workpiece after the removal of the external forces. It is generally believed that the poor shape or bad surface finish are caused by the residual stresses. Further, a tensile residual stress near the surface can cause rapid propagation of a micro-crack. Experimental methods for the determination of residual stress have been developed [65]. However, when a process is to be optimised for the improvement of the product quality, experimental methods do not provide an economical solution. Therefore, it is necessary to determine them by analytical or numerical methods.

The slab method [66], the slip-line method [67,68] and the upper bound method [69,70] have been used for solving forging problems, especially for determining the forging load. However, these methods cannot be employed for the determination of residual stresses because of obvious limitations of these methods. Since, the finite element method (FEM) is capable of determining the detailed
deformation and stress fields; it seems to provide the only choice as far as the analysis of the residual stresses is concerned.

There is a large body of literature on the application of FEM to forging problems. The early applications of the FEM to forging problems were based on the incremental method proposed by Lee and Kobayashi [71]. The method uses the elasto-plastic stress-strain matrix based on the Prandle-Reuss equations. Even though the stress-strain matrix and geometry are updated after every increment, only linearised incremental equations are used. The interfacial friction is modelled by friction factor where the change in the direction of the shear stress is incorporated by introducing a velocity-dependent coefficient. This method was applied to solid cylinder upsetting [72], to ring compression [73] and for predicting defects [74]. Whereas Lee and Kobayashi [71] used the velocity as the primary unknown, Hartley et al. [75-76] proposed an incremental method with the displacement as the primary unknown. They also used linearised incremental equations and updated the stress-strain matrix and geometry after every increment. However, in their methods, the friction factors is incorporated by the beta stiffness method [75]. Shima et al. [77] used the rigid-plastic constitutive equation and the Coulomb
friction model to study the upsetting of a circular cylinder and validated their results by conducting experiments. Finite element formulations involving non-linear strain measures and objective stress measures (i.e. the stress measures remaining invariant under the rigid body rotation) have been discussed in the books by Kobayashi et al. [78]. Rowe et al. [79] and Hartley et al. [80].

Linearised incremental equations give only an approximate solution. If the incremental size is not sufficiently small, the error between the exact and the approximate solutions grow rapidly with the applied load, as the error of the current increment propagates into the next increment while updating the stress-strain matrix and the geometry. To avoid this, non-linear incremental equations must be employed which need an iterative scheme like the Newton-Raphson method for its solution. Such a formulation was first proposed by Bathe et al. [81]. This formulation (with or without elastic effects) has been applied to the axisymmetric forging problems by quite a few researchers. The typical studies in this category are by Dadras and Thomas [82] and Carter and Lee [83].

Some of the typical latest applications of FEM (rigid/elasto-plastic/viscoplastic) to cold axisymmetric forging process employ the non-linear incremental
equations. Further, in most of the references, the interfacial friction has been modelled by friction factor rather than by Coulomb's law. Michel and Boyer [84] have carried out elasto-visioplastic finite element analysis of cold upsetting process. They have calculated and measured the residual stress variations on the flat end of a cylinder. They have used the friction factor model to represent the interfacial friction. Zhao et al. [85] have used forward and inverse finite element simulations to design the preform shapes in forging processes. Even though the example considered was that of plane strain forging, the method is equally applicable to axisymmetric forging. Liou and Jang [86] have used FEM (ANSYS code) along with robust design methodology to identify the process parameters that control the residual stresses in radial forging. The parameters identified were the inlet angle, corner fillet, die land, reduction and friction coefficient. Yang and Yoo [87] have modelled the multi-blow hammer forging process as a high-velocity impact phenomenon. The explicit time integration FEM was used to analyse the process.

Joun et al. [88] have proposed a finite element simulation technique for forging process which uses a spring attached die. The strategy of spring attached die controls the metal flow lines in such a fashion that it results in prevention of defects and improvement of
product quality. Kim et al. [89] have applied rigid-visioplastic FEM to cold axisymmetric forging of aluminum alloy to study its ductile fracture. The Cockcroft and Latham [123] criterion has been used for predicting the fracture. Yang et al. [90] have developed an intelligent system for complete design methodology of forging process by integrating the FEM with expert systems and computer-aided design (CAD) interface modules.

Mungi et al. [91] analysed residual stresses in axisymmetric cold forging process. The updated Lagrangian formulation, which is convenient for handling the geometric and material non-linearities were used. A new incremental objective stress measure and the logarithmic strain measure were employed as they allow the use of a larger increment size. The Newton-Raphson iterative technique was used to solve the non-linear incremental equations. The material was assumed to be elasto-plastic yielding according to the Von Mises yield criterion and hardening according to a power law. A Coulomb friction law was used to model the interfacial friction.

An axisymmetric large-deformation elasto-plastic finite element code, which incorporates unloading, has been developed for the analysis of the residual stresses. The code was validated by comparing the predicted finite element results with available experimental results. A
detailed parametric study of the residual stresses was carried out to study the effects of four process parameters, namely the reduction, height-to-diameter ratio, friction coefficient and material properties. It is observed that the maximum value of the residual stress decrease with the height-to-diameter ratio. Further, as the friction coefficient is increased, the deformation becomes more inhomogeneous, because of which the residual stress levels go up. It is also observed that reduction and material properties do not have much effect on the pattern of residual stress distribution.

The friction phenomenon and the shape of the dies play a fundamental role in determining the plastic flow of material in the dies. Maccarni et al. [92] vary the fillet radius of the die, and tested in a process of extrusion forging. The rake angle of the extrusion hole provides a solution similar to the devices actually in use. The well-known matrix method (first introduced by Professor Kobayashi) was used by the authors to study theoretically the problem of filling the die cavity during cold forging of copper.

Mitani and Mendoza [93] showed that the analysis of 134 ton steel ingots for low pressure rotor shaft manufacturing based on the rigid-plastic finite elements was helpful for designing the die geometry which produced
the suitable metal flow and stress distribution. The accuracy of prediction in final diameter was achieved by a limited number of isoparametric elements on a microcomputer. On the other hand the load prediction required some adjustment with regard to ram velocity; which was slowed down during upsetting.

Düdra and Yong [94] conducted void closure studies numerically and experimentally for open-die forging processes. The plane-strain FEM analysis was compared with bite forging experiments in order to determine how well the plane-strain approximation predicted the material flow in open-die forging. In addition physical modeling with plasticine was used to compare the measured and calculated deformation of the internal defect. The FEM analysis was in good agreement with the experimental results. Correlations for the computed effective strain and hydrostatic stress to the void closure were then calculated. Simulations of a solid cylinder side pressed with flat dies, V-shaped dies, etc. were done to determine the effectiveness of these dies at consolidating internal porosity based on the calculated strain and hydrostatic stress at the center of the billet. The V-shaped dies were found to be the most effective among those investigated. However, the press load for the V-shaped dies was also the highest.
Yang Qingchun et al. [95] introduced a FE simulation method for a forging system considering both the workpiece and die in detail and adopting a multisubstructure technique. This reasonably described the coupling of the workpiece and the die during the forging procedure. It has not only simplified the calculation but also provided a convenient service for process CAD by means of FE simulation. This was used in a general FE program MAFAP (Mass forming Analysis Program) for forging.

2.4 UPPER BOUND SOLUTION TO FORGING

The closed-die forging of a general non-axisymmetric shape by the forging of a cylindrical billet has found many practical applications in the production of automobile and aircraft components. Nevertheless, the forging load must be predicted to avoid die damage and to choose a forging machine with sufficient loading capacity to meet the die design.

The problems associated with the evaluation of the forces required to achieve the maximum die fill-out during forging have been investigated by a number of authors by the upper-bound elemental technique. Ihbhandode and co-workers [96,97] investigated the influence of the process variables on the load and accuracy when forging in a completely closed cavity die. Monaghan Torrance [98]
analyzed the problems of the closed-die forging of hexagonal and square workpieces from circular shaped billets. Monaghan and Peard [99] studied the closed-die forging of a cylindrical die cavity from an initially square-sectioned preform. Cho et al. [100] and EI-Domiaty et al. [101] did research in the closed-die forging of spur gears and gear-like elements.

Chin Tarn Kwan [102] proposed a kinematically admissible velocity field suitable for the closed-die forging of a general non-axisymmetric shape such as the forging of a cylindrical billet. By using the proposed velocity field, the upper-bound forging load and the velocity field for the closed-die forging of elliptic and trochoidal shapes by the forging of cylindrical billets were determined with respect to a chosen parameter. Experiments were carried out with commercially pure aluminium billets at room temperature. The forging loads between theory and experiments were shown to agree well, thus validating the proposed velocity field.

Kudo [103] obtained results from several forging and extrusion tests at room temperature and low speed, compared with theoretical results, and concluded the following:

1. The working pressures for the compression of soft aluminium cylinders between rough flat dies, for the
compression of soft aluminium annuli in a container between lubricated or rough dies and for the steady-state lubricated extrusion and piercing of hard aluminium and copper cylindrical billets, were 10-20 per cent below the calculated upper bound.

2. Calculated upper bounds agreed qualitatively with the working pressures obtained during some non-steady extrusions and piercings of soft aluminium, hard aluminium, copper and soft brass.

3. The steady pressure divided by the mean yield stress in combined bar and tube extrusions from cylindrical billets and in tube extrusions from hollow billets, together with those in ordinary extrusion and piercing, were found to be almost entirely a function of the total reduction in area, when the tools were lubricated.

4. The working pressure in opposed extrusion-piercing forging was considerably lower than that for a one-way extrusion forging. The working pressures in opposed extrusion forging with two dies and in opposed piercing forging with two punches were lower than that in corresponding one-way working, using a die or punch of the larger orifice when the length of billet was moderate. In symmetrically opposed working, the
pressure exceeded that in one-way working when the billet length became very small. When the material flow through one orifice was interrupted midway in an opposed forging, the working pressure hence followed that of the corresponding one-way working.

5. The deformation of hard aluminium and copper annuli compressed between lubricated flat dies was as predicted from the most suitable velocity field. The speed of efflux of material through two separate orifices was affected by the frictional resistances acting on the material rather than by the difference in the areas of the orifices when the billet length was moderate. But, as the length was reduced, the speed from the wider orifice tended to increase. These results were in qualitative accordance with those derived from plane-strain analysis.

6. The internal flow pattern observed on the meridian section of a lead billet as photographed through a glass plate was in qualitative agreement with the corresponding most suitable velocity field and was very similar to that of the comparable plane-strain working.

7. The main types of defect found in the various extruded and extrusion-forged products were skin inclusion, cavity formation and internal cracking. They were
predicted quantitatively and qualitatively from the velocity field of the least upper bound. The inclusion was prevented by using a rough die in contact with the material surface from which the skin was unfolded. Cavity formation and internal cracking was thought to be prevented by restraining the material flow through the orifices. The onset of the latter defects was retarded by intermediate annealing.

8. The internal pressure acting on the container during extrusion forging and coining was found to be lower than the mean working pressure within the range of conditions tested. The pressure acting on the projection of the coining die was in excess of the mean working pressure, the difference being larger for higher projections and for thinner slug thickness. The residual pressure between the material and the container after extrusion or closed-die coining was found to be nearly equal to the uniaxial yield stress of the material.

Forging spur gear forms in completely closed cavity dies was investigated by means of an upper bound analysis by Abdul and Dean [104]. A velocity field comprising three unit deformation region was proposed. The tooth regions were approximated by prismatic rectangular sections. The effects of root diameter, number of teeth and workpiece
die interface friction, on flow and forging pressures, were determined.

They concluded that the forging pressure without friction is independent of root diameter but increases with the number of teeth. In the presence of friction forging pressure increases with reducing root diameter.

Sagar and Juneja [105] presented an analysis of open die forging of any irregular four sided disc. Experiments indicated a similar trend. Upper bound technique was used in this analysis with the assumption of constant frictional stress on top and bottom faces. The solution took into account the bulging of sides during compression as it was experienced in practical forging.

An upper bound solution was constructed for determining the average die pressure and velocity field developed during forging of a rhombus shaped disc between two flat dies by Juneja [106]. In the forging operation, due to non-uniformity of material flow, both barrelling along the thickness and bulging of lateral sides of the disc take place. Only the bulging of lateral sides was taken into account. A uniform frictional stress was assumed over the entire interface between the dies and the disc. The shapes of compressed discs as predicted by this solution were similar to those obtained experimentally. The solution can
be extended to open-die forging of any irregular polygonal disc in which the bisectors of facial angles meet at a point.

A model for the closed die flashless forging of a work-hardening polymer material (polycarbonate) was developed using an upper bound approach by Fox and Lee [107]. Deformed geometry, effective strains and stresses were computed at various stages in the upsetting process. The influence of ram and die wall friction was considered through the formation of dead zones within the workpiece after it made contact with the die surface. Both axisymmetric and plane strain cases were investigated in the analysis, and results of plane strain compression experiments were compared with analytical predictions. Strain measurements showed good agreement for initial billet dimensions of height to width ratios greater than one.

In general, forging is an unsteady state process and as a consequence, empirical techniques, frequently based on past experience, have dominated the method used to evaluate forging loads and tool stresses. Brayden and Monaghan [108] presented an analytical approach to investigate the deformation arising during an extrusion forging operation. The method of analysis was based on the upper bound technique for which the necessary velocity
fields were obtained from a series of experimental tests. The resulting upper-bound expressions provided a systematic approach to load and stress evaluation during an extrusion forging process.

Monaghan and Peard [109] did a theoretical and experimental analysis of a cold forging closed-die process in which an initially square sectioned preform was deformed within a cylindrical die cavity. The energy dissipated internally due to plastic deformation and that dissipated in overcoming friction and internal shearing was summed to produce an upper-bound expression for the forging pressure ratio. A comparison was made between the theoretical predictions and the experimental results. The results indicate that the derived upper-bound expression could be used to predict the forging pressure ratio with some degree of confidence.

Hexagonal nuts have been shaped by forging circular blanks in a number of ways. One of them is pressing the circular disc in a hexagonal shaped die, with a punch of similar profile. Sagar and Juneja [110] obtained an Upper Bound Solution for finding the mean die pressures for the given geometries of disc, for the above method of forging. It was found that for certain dimensional ratios of the nut the die pressure is minimum. Uniform frictional stresses were assumed on top and bottom interfaces and
along the interfaces on sides. The solution could be extended to closed die forging of any polygonal shape.

The closed-die hot forging of components for the automobile industry involves heavy forces, high energies and severe wear conditions in the die. After a relatively short period of time in service - corresponding to the production of about 5000 components - the dies must be re-engraved. A conventional die is usually re-engraved twice and consequently the tool can only be used for the production of about 15000 components. The cost of the tools amounts to about 10% of the total expense for closed-die forged products. The material yield in closed die forging is low: the material losses are about 30%, the main part of which constitutes the flash. Considering the total expenses for a product, the cost of the material makes up about 50 per cent. From the above, it is clear that the material yield and the tool life are two factors of utmost importance in considering the economy of a closed-die forging process.

Keife and Stahlberg [111] presented plane-strain numerically-optimized upper-bound solutions for various flash designs for the closed-die forging of a spindle. Metal flow just before and just after filling of the die cavity was analysed. The theoretical results were compared with experimental results obtained by the use of
plasticine. It was concluded that from the material yield point of view it is favourable to use a flash land with a V-notch. When the material flows through this kind of flash gap the notches are filled with material and intense shear takes place within the material itself. This kind of braking or restraining device was found to improve the material yield by restricting the material flow out into the flash gap. After die filling, however, the mean die pressures were much heavier than those for dies with conventionally lubricated flat flash-lands. V-notched flash-lands were recommended provided that it is possible to stop the deformation process just before die filling. This statement presupposes, however, that the initial shape and weight of the workpiece can be accurately controlled and reproduced.

The formation of hexagonal and square shapes by forging circular workpieces within closed-dies is a common practice particularly in the manufacture of "headed" fasteners. Monaghan and Torrance [112] proposed an upper-bound method of solution which can be used on any polygonal shape. The solution was based on observed velocity fields, and die geometry and took into account the effect of friction on all surfaces of contact between the die and workpiece. Very close agreement was found between the predicted values of mean forging pressure and
those obtained from experimental test performed on hexagonal and square shapes.

A new upper-bound elemental technique (UBET) was proposed to improve the ineffectiveness of UBET for solving forging problems that were geometrically complex or need a forming simulation for predicting the profile of free boundary by Lin and Wang [113]. This method combined the advantages of the stream function and the finite element method (FEM), specifically, the curve fitting property of FEM and the fluid incompressibility of the stream function. The formulated optimal design problems with constrained conditions were solved by the flexible tolerance method. Three forming problems (ring upsetting, closed die, and backward-extrusion forging were used to illustrate this method; the results of ring upsetting showed a good ability of simulating for predicting the forming profile of a free boundary; the closed-die forging produced a lower upper-bound solution than UBET; and backward-extrusion forging demonstrated the flexible curve fitting property for a complex geometric boundary.

To calculate the load required to perform certain kinds of plastic working operations and to account approximately for the modes of flow encountered, a description of a new upper bound approach was first presented in [114]. To facilitate the calculation of good
upper bounds, the concept of a unit region was introduced. After finding that the type of velocity field which consisted of several rigid triangular parts was the most suitable, the lowest rate of energy dissipation and the related form of rigid-triangle velocity field were determined for each of the unit rectangular deforming regions having various height-width ratios and frictional boundary conditions. On analysing a particular working problem, the work-piece is supposed to be composed of several unit regions and the lowest upper bound for the working pressure, as well as the most suitable velocity field inside the material, is obtainable directly from those determined for unit regions.

(a) Results on the compression of a plate between two flat parallel dies and on the indentation of a flat punch into a semi-infinite or a finite body were in close agreement with slip-line solutions by other investigators.

(b) The working pressures and the modes of deformation in open-die extrusion - forging were obtained.

(c) the working pressure and the mode of deformation in heading were estimated. Some of these results were compared with slip-line solutions and found to be in good agreement. (d) the indentation of a flat punch into a work-piece held in a container was analysed
and the upper bound for punch pressure, mode of deformation and distortion of material were related to the dimensions of the working tool and the work-piece, as well as to the conditions of lubrication. The upper bound approach offered a fairly accurate and simple means in analysing plane-strain forging problems.

The upper-bound approach method was applied to various types of plane-strain extrusion and forging of rigid-perfectly plastic material with closed dies and the results were seen to be of sufficient accuracy despite the little labour required for calculation. Kudo [115] has applied the UBA to the steady-state extrusion and found out that the piercing pressures agreed with those derived from slip-line theory by the other investigators within an error of 10 per cent, for a range of reductions 0.2 to 0.95. The most suitable velocity fields which gave the minimum upper bounds resembled essentially the corresponding slip-line fields.

Extrusion pressures for a three-orifice extrusion and a sideways extrusion were found exactly or nearly equal to those for the usual extrusion having the same total reduction.
In a stepped extrusion, the working pressure was found to be a little higher than that of the usual extrusion having an identical reduction.

In the extrusion forging and piercing forging of short slugs, the working pressures vary with the thickness of the slug and in a manner depending on the condition of lubrication. These pressures and the most suitable velocity fields showed good agreement with slip-line solutions. The most suitable velocity fields also gave a good explanation of the formation of extrusion defects. Some opposed extrusion forgings, with both top and bottom dies having orifices, were analysed and their working pressures were found to be lower than those of the usual one-way extrusion forging.

A method of estimating the coining pressure with perfectly closed dies was proposed, using the velocity fields for extrusion and piercing.

2.5 DUCTILE FRACTURE IN FORGING

The upsetting of a cylindrical billet is commonly used to determine bulk workability of metallic alloys. The test method involves the measurement of axial and hoop strains at the equatorial free surface as the height of the billet is reduced by compression between two platens. The development of barreling continues until one or more
visible cracks are observed, thus signalizing ductile fracture. The surface strains measured at 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 [116].

Several experimental investigations were conducted to determine the strain and stress distributions during upsetting [117-120]. Theoretical and semi-empirical solutions to the problem were also devised, viscoplasticity by Thomason [117], analytical plasticity analysis by Kobayashi [118], upper bound by Avitzur [121], and finite element by Needleman [122]. Some of these solutions attempted to predict the fracture limit line through a suggested instability or failure criteria. Thomason [117] derived a load instability criterion and applied Cockcroft and Latham ductile fracture criterion [123]. He found unsatisfactory agreement with his experimental results. No support to local necking proceeding ductile fracture on the equatorial free surface was reported. Nevertheless Kuhn and Lee [124] expanded and modified the model devised by Marciniak and Kuczynski [125] for localized thinning in sheet metal stretching to provide information on fracture in bulk deformation processes.
Ragab [126] predicted the fracture limit curve in upsetting cylindrical billets. The analysis uses a semi-empirical solution for the stresses and strains together with a formulation based on plasticity theory for voided solids [127,128] similar to that applied to necked tensile specimens [129] based on a semi-empirical solution presented by Dadras [130]. Two fracture criteria were suggested. The first monitored the growth of the initial void volume fraction to the point where the load-carrying capacity of the material vanished. The equatorial axial and hoop strains attained at this incident represented fracture strains. Being in disagreement with experiments a second modified fracture criterion was proposed in which the equatorial free surface axial and hoop strains being related through a void growth law were calculated to the point at which deformation became localized. The predictions of this second criterion was in favourable agreement with experiments on several conventional and powder compact materials for a variety of upsetting conditions.

Correct design of the forging devices in closed-die forging is fundamental in reducing both the number of intermediate steps and the total compression force. Furthermore, the die geometries greatly influence the plastic flow of the material under deformation, so that the final shape of the deformed body may be
unsatisfactory, e.g. ductile fractures or incomplete die filling. In order to avoid these problems, the material must flow correctly from the first stages of the compression procedure.

First phases of the process were studied, presenting some theoretical and experimental results concerning the material flow in extrusion-forging operations [131-134].

According to Giardini et al. [135] the correct design of forging devices in industrial practice is extremely important. In particular, the die geometries, which greatly influence the plastic material flow, can give rise to unsatisfactory final shapes, e.g. ductile fractures or incomplete die filling and showed some results obtained when studying the influence of die geometries and lubrication conditions in extrusion-forging operations, simulating the initial phases of closed-die forging. In particular, attention was focussed on ductile fracture phenomenon and material flow, taking these two features as formability indexes. The study was carried out coupling the plastic strain with the stress fields as indicated in the McClintock fracture criterion [136]. This criterion was implemented in the FEM program developed by the authors to furnish a useful tool in die design.
The production of cold forged components is constrained by the occurrence of defects in the form of ductile fractures. A means of identifying the conditions under which they occur would therefore be a useful aid in reducing such defects and optimising the cost effectiveness of the process. Experimental studies are valuable in providing greater insight into the process conditions and modes of deformation associated with these defects, while the use of theoretical models can reduce pre-production experimental trails. The ability to predict these defects using damage models incorporated into finite-element (FE) simulation offers an attractive solution to optimising the process. The principal methods adopted for this are the macroscopic approach, which predicts fracture based on values of stress or strain (or a combination of these in various fracture criteria) reaching a critical value [137,138], and the continuum damage mechanics approach, which involves the inclusion of a damage model that evaluates the evolution of damage, and its effect on material strength, until failure is reached [139,140].

Sljapic et al. [141] described the appearance of fractures in cold forming of brass during axi-symmetric collar upsetting tests and also in the upsetting of hexagonal shaped bars. The latter was introduced to examine fracture under non-axi-symmetric conditions. The
collar tests produced typical ductile fractures, but the hexagonal bars displayed fractures similar to brittle fractures even though they were preceded by large plastic strain. Each experimental test was also modelled using the finite-element method to examine local stress/strain conditions at fracture. The simulations of the collar tests showed that fractures appeared in the presence of a circumferential tensile stress together with either a tensile or compressive axial stress. The compressive axial stress was present when fracture occurred at a much lower level of deformation than when the axial stress became tensile. The simulations of the hexagon bar upsetting revealed a maximum plastic strain coincided with the most likely site of fracture initiation. This mixture of differing stress and strain states at fracture led to the conclusion that a single fracture criterion is unlikely to satisfy all the conditions that lead to fracture.

In the last few decades, the mass production of components by cold forging has increased drastically. Cold forging has various advantages compared to other forming processes, such as machining. It involves little loss of material, improved strength, geometrical precision of components, and high production rates. However, considerable difficulties can be encountered due to the high stresses induced within the workpiece and tooling
because of the very large forming loads [142]. Obviously, the prediction and reduction of these high stresses within the tooling is paramount. A significant economic advantage can also be achieved through an increase in the service life of the tooling [143]. With recent advancements in software development and the availability of more powerful computers, a finite element analysis (FEA) package called DEFORM has enabled an entire cold forging process to be simulated, while simultaneously predicting all the necessary stress/strain states in both die and workpiece. The prediction of ductile fracture is far more difficult than flow induced defects such as folding, under filling and piping [144].

Ductile Fracture Criteria can be generally represented by a function having the form:

\[
F \text{(deformation history)} \, d\tilde{\varepsilon} = C \quad \ldots \ldots (2.5.1)
\]

where \( \tilde{\varepsilon} \) is the effective strain and \( C \) the 'damage value. The common hypothesis of ductile fracture as represented by Eqn. (2.5.1), is that the ductile fracture occurs when the maximum damage value in a workpiece exceeds a critical value or 'critical damage value' [144]. For a homogeneous material, this critical damage value can be considered as a material constant, similar to yield stress or tensile strength. Since different ductile fracture criteria lead
to different damage values, the critical damage values corresponding to different ductile fracture criteria are different for a given material. Many experimental studies have been conducted to establish testing methods to determine formability and/or fracture limit diagrams [145] and several ductile fracture criteria have been suggested [146-149]. Mathematically derived ductile fracture criteria, have been proposed based on experimental observations [150-154]. Extensive research has been focused on testing seven ductile fracture criteria by using the FEA package DEFORM and experimental testing. It was concluded that the Cockroft and Latham's criterion [123] may be the best for practical applications [144]. The Cockroft and Latham's criterion is as follows:

Latham's criterion is as follows:

\[
\frac{\bar{\varepsilon}_f^{*}}{\sigma} \sigma_{d} = C \quad \ldots \quad (2.5.2)
\]

where \(\bar{\varepsilon}_f^{*}\) is the effective fracture strain, \(\sigma^{*}\) the Max principle stress and \(\bar{\sigma}\) the effective stress.

The trimming process consists of two phases. Phase 1 encompasses the time when the trim die first makes contact with the workpiece and reaches its final stopping distance. Phase 2 deals with the shearing off of the
excess material to produce the trimmed hexagonal fastener head. Extensive research has been carried out in the area of phase 1, to determine the stresses within a trim die during a forging process, has been completed [155-157]. One of the conclusions from phase 1 was that the stresses within the trim die rise very sharply at the end of the stroke. This is due to the material becoming trapped between the die and the holder for the workpiece.

Conor and John [158] analysed the method used to 'trim' a hexagonal shape on the head of a fastener. The fastener head geometry was achieved by forcing the die, known as a trim die because of its function, onto the workpiece, whereupon a combined forging and cutting action produced the desired well-known hexagonal shape for the head. The size of the trim die modelled was that for an M16 fastener. The trim die material was taken as M2 high-speed steel.

When the trim die reached the end of its stroke, a knockout pin sheared of the excess trimmed material. A finite element analysis package called DEFORM was implemented to simulate the trim die forging process. DEFORM utilises Cockroft and Latham's fracture criteria [123] to calculate the damage induced within the workpiece material during the process. Elements were deleted from the model when they exceeded a specified damage value. The
trim die geometry, if incorrect, could cause premature shearing of the waste material during forging. This premature shearing has a detrimental effect on tool life and the forging machinery. The relationship between the trim die geometry and its final stopping distance, the consequent induced stresses and the energy required to shear off this excess material was investigated. The effect of altering the damage value C was analysed. Optimum trim die shape and final stopping distance which would facilitate increased die life, were obtained.

Workability can be defined as the degree of deformation that can be achieved in a particular metal working process without the occurrence of a defect, the latter being when the properties of a component do not conform to the design specifications.

In most metal forming processes, workability is determined by the occurrence of ductile fracture and therefore limitations are set by the appearance of surface or internal cracks within region that are highly strained due to extensive material flow. Still, the occurrence of ductile fracture can be inherent part of the process, for metalworking operations such as blanking and machining that concern the separation of parts by the initiation and propagation of cracks.
The advent of numerical methods such as the general purpose finite element method to handle large deformation plasticity has made it possible to analyse the relative success of a metalworking process during the development stage. However, these techniques still have limitations in predicting the occurrence of fracture, a crucial issue in the process design stage. 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 processes such as forging and extrusion [159-163]. Very recently, efforts were focussed on the prediction of the propagation paths of initiated cracks in metalworking processes such as blanking and metal cutting [164-166].

Kobayashi [159] was the first to investigate ductile fracture in finite element analysis, by implementing the Cockcroft-Latham fracture criterion [123] in a rigid-plastic finite element formulation to study the formability of solid cylindrical specimens and ring-test specimen. Oh et al. [160] applied the rigid-plastic finite element formulation in conjunction with the Cockcroft-Latham criterion and a modified version of the McClintock criterion [150] to determine workability in bar extrusion and drawing. The study was not conclusive in predicting workability, but reasonably good agreement was found.
between theoretically and experimentally observed fracture strains. Clift et al. [161] utilised an elastic-plastic finite element formulation to solve formability problems of simple upsetting, extrusion and strip compression and tension. Several ductile fracture criteria were investigated, conclusions seeming to indicate that only Freudenthal's [167] generalised plastic work per unit of volume is capable of estimating fracture initiation sites for all of the processes. However, considerable discrepancies were found between the tensile test value of plastic work per unit of volume at fracture and the corresponding finite element predictions. Toda and Miki [162], applied a rigid-plastic finite element formulation together with the ductile fracture criterion due to Oyane [152] to predict and prevent failure during indentation forging of steel components. The critical value at fracture of the workability criteria was not determined by conventional upset formability tests, but through the utilisation of regression equation dependent on the carbon content of the steel. Numerical predictions when compared with experiments revealed difficulties in establishing the amount of deformation necessary for crack initiation. Ko et al. [163] studied the prediction of surface-fracture initiation in the axisymmetric extrusion and simple upsetting of an aluminium alloy using the Cockcroft-Latham fracture criterion [123] and reported a successful
prediction of the initiation site and of the level of deformation at which fracture occur.

Altan et al. [164] simulated the different phases of the blanking process using a rigid-plastic finite element formulation. The prediction of fracture initiation was modelled using the McClintock criterion [150], and its propagation was simulated by an element removal and remeshing algorithm. The blanking process was also analysed by Brokken et al. [165] who combined Rice and Tracey's [168] void growth criterion with a discrete fracture model based on a global mesh modification algorithm for estimating the fracture propagation path. Despite the good correlation between numerical and experimental results claimed in both [164] and [165] it was clear that numerical modelling of the propagation path of the initiated cracks it was still an open field for research. The same conclusion followed when analysing on finite element modelling of metal cutting processes, e.g. [166].

Typical criteria for room temperature ductile fracture are usually based on combinations of stress with strain or strain rate rather than on either of these quantities separately. It was shown by Atkins and Mai [169] that nearly all the integrated stress-strain criteria are
versions of Freudenthal's critical plastic work per unit of volume [167]

\[ \int_0^{\varepsilon_f} \sigma d \varepsilon = C_1 \]  \quad ..... (2.5.3)

In view of the importance of the largest tensile stress, Cockcroft and Latham [123] and have suggested an alternative fracture criterion based on a critical value of the tensile energy per unit of volume

\[ \int_0^{\varepsilon_f} \sigma_1 d \varepsilon = C_2 \]  \quad ..... (2.5.4)

Explicit dependence of the level of both the largest principal stress, \( \sigma_1 \) and the hydrostatic stress, \( \sigma_m \), was proposed by Brozzo et al. [170] by means of an empirical modification of the above mentioned criterion.

\[ \int_0^{\varepsilon_f} \frac{2\sigma_1}{3(\sigma_1-\sigma_m)} d \varepsilon = C_3 \]  \quad ..... (2.5.5)

Recent experimental results showed conclusively that ductile fracture in metal working processes follows a void growth model [171]. According to this model, voids initiate at inclusions or hard second-phase particles in
regions of the micro-structure that are highly deformed, grow under plastic deformation caused by normal or shear stress systems and finally link up between each other to form macroscopic cracks. Based on this hypothesis, several different criteria were suggested by McClintock [150], Rice and Tracey [168] and Oyane [152], the latter, derived under the fundamental laws of the theory of plasticity for porous materials [172] being expressed as

\[ \bar{\varepsilon}_f \int_0^{\bar{\varepsilon}} \left[ 1 + A \frac{\sigma_m}{\sigma} \right] d\varepsilon = C_4 \] 

(2.5.6)

where \( A \) is a material constant to be determined experimentally.

Gouveia et al. [173] contributed for the discussion on ductile fracture criteria and their implementation in finite element computer programs in order to predict the conditions within the deforming workpiece that may lead to the initiation of cracks. The relevant issues addressed were: (1) characterisation of the states of stress in the regions where surface or inner cracking occurs; (2) definition of the experimental procedures to be utilised for obtaining the experimental value of the critical damage at fracture; and (3) assessment of two currently utilised ductile fracture criteria and presentation of the basic guidelines for their implementation in a finite
element computer program. The first issue is significant because it is related directly with the domain of validity of a ductile fracture criterion. The relevance of the second topic is self evident in view of most of the researchers / finite element users considering the value of the critical damage as a material constant that can be obtained by means of a single tensile or compression test. The last issue is representative of the importance that the finite element method has, in terms of simulation of complex metalworking processes.

An important concern in metalworking is whether the desired deformation can be accomplished without failure of the material and they described the utilisation of ductile fracture criteria in conjunction with the finite element method for predicting surface and internal failures in cold metalworking processes. Four previously published ductile fracture criteria were selected, and their relative accuracy for predicting and quantifying fracture initiation sites was investigated.

Ring, cylindrical, tapered and flange upset test samples were utilised for providing the experimental values of the critical damage at fracture under several different loading conditions.

Two of the ductile fracture criteria were then utilised to predict the initiation site and the level of
deformation at which surface or internal cracking will occur during finite element simulation of three types of metalworking processes, namely, radial extrusion, open-die forging and blanking. The analysis was made in conjunction with metal experiments, good agreement being found to occur.

The occurrence of ductile fracture is a major limitation governing the limits of producibility in cold forging processes. The prediction of ductile fracture in metalworking operations has therefore attracted the attention of many researchers for more than five decades. Workability refers to the relative ease with which a material can be shaped through plastic deformation and it is a function of the material as well as the process. Several approaches have been proposed, to understand the constitutive response of the materials to mechanical working processes [174-176], in order to predict the optimal temperature and strain-rate for processing. However, understanding the influence of the process related parameters such as friction and die geometry on the limits of deformation in metalworking has been a difficult problem all along. Several attempts were made to explain the limits of workability based on the stress and strain-states, and an overview of this is presented in the following paragraphs.
The initiation of ductile fracture was a major factor influencing the limit to workability in many metalworking operations. Although, the macro-defects set a visible limit to workability, a limit defined based on plastic deformation was considered better [177]. In the past, various theoretical failure criteria on the initiation of ductile fracture were proposed by research workers. The criteria can be broadly classified as empirical and semi-empirical. The empirical criteria can either be strain-based [178-180] that define a fracture locus, or stress-based [181-184] defined in terms of the stress formability index. The semi-empirical criteria are in general of two types, i.e., cumulative plastic energy models and void coalescence models. Several models were proposed based on the integration of plastic energy of deformation along the strain path [167,123,185-188] at potential fracture sites in the work-piece. Fractures in metalworking have also been modeled as void initiation and growth [189,151], followed by coalescence to form a crack. A completely different approach to the formulation of a fracture criterion, based on the upper bound concept, was suggested by Avitzur [190]. There have been several publications [177,191-193] explaining the philosophy behind various criteria and the scope of their application. To successfully predict the occurrence of ductile fracture, the theoretical failure criteria are important tools to be
used in conjunction with workability experiments. The evaluation of these criteria in turn depends on accurate determination of the distribution of the various stresses and strains throughout the critical deformation zone. The advent of powerful numerical methods such as general purpose FEM to handle large deformation plasticity has made it possible to analyze accurately the metalworking processes during the development stage. Thus, an integrated approach involving the theoretical failure criteria, FEM, and workability experiments emerged as a promising technique for accurate workability analysis [194-199].

Kobayashi and Lee [194] were one of the earliest to analyze ductile fracture in metalworking by the application of McClintock and Cockroft criteria using FEM. Since then, several research workers [195-202] studied various aspects of the application of the computer-based numerical techniques to predict ductile fracture in a wide range of metalworking processes. These include attempts to correlate experimental and theoretical results pertaining to fracture predictions in compression specimens of different geometry. A review of the published literature referred above reveals the need for a systematic comparative evaluation of the theoretical failure criteria.
for their effectiveness and reliability. Earlier efforts [195,201] to study the relative merit of different theoretical failure criteria seemed to concentrate only on classifying the criteria as successful or unsuccessful where the type of material or geometry was restricted. There is a need for examining the reliability of the criteria using wider database.

The commonly used theoretical failure criteria were examined by Venugopal Rao et al. [205] using the statistical mean deviation of the threshold values of different failure criteria (at the instant and location of fracture), for cylindrical specimens of different aspect ratios. In addition, the spatial dispersion of the respective criteria was also noted so that their sensitivity in the prediction of fracture was simultaneously examined. To start with, the commonly used theoretical failure criteria for metalworking were chosen from the published literature as shown in Table 2.5.1. In preparing this information, the criteria with relatively arbitrary material constants were ignored and where appropriate, the material constants were assumed suitably. The workability parameters studied included the deformation path-dependent integrals as well as the commonly known variables such as effective stress and hoop stress. Upsetting of cylinder being the simplest and most widely used workability test, was used in this study to
<table>
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<tr>
<th>S No</th>
<th>Criterion</th>
<th>Equation</th>
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<th>Remarks</th>
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<tr>
<td>1</td>
<td>Frudenthal</td>
<td>( \frac{1}{\sigma} \int_{0}^{\varepsilon} \sigma \ d \varepsilon = C )</td>
<td>FRUD</td>
<td>167</td>
<td>Normalized with ( \sigma )</td>
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<td>2</td>
<td>Cockroft &amp; Latham</td>
<td>( \frac{1}{\sigma} \int_{0}^{\varepsilon} \sigma \ d \varepsilon = C )</td>
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<td>Oh &amp; Kobayashi</td>
<td>( \int_{0}^{\varepsilon} \left( \frac{\sigma - \sigma_{0}}{\sigma} \right) d \varepsilon = C )</td>
<td>OHKO</td>
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<td>Brozzo et al</td>
<td>( \int_{0}^{\varepsilon} \frac{2 \sigma_{0}}{3(\sigma - \sigma_{0})} d \varepsilon = C )</td>
<td>BROZ</td>
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<td>5</td>
<td>Norris et al</td>
<td>( \int_{0}^{\varepsilon} \left( \frac{1}{1 - c \sigma_{0}} \right) d \varepsilon = C )</td>
<td>NORR</td>
<td>187</td>
<td>C is assumed to be ((1/(2</td>
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<td>6</td>
<td>Oyane et al</td>
<td>( \int_{0}^{\varepsilon} \left( 1 + \frac{\sigma - \sigma_{0}}{A \sigma} \right) d \varepsilon = C )</td>
<td>OYAN</td>
<td>189</td>
<td>A=2/3 : mean of 1/3 &amp; 1 (i.e between uniaxial &amp; triaxial stress states)</td>
</tr>
<tr>
<td>7</td>
<td>Mc Clintock</td>
<td>( \int_{0}^{\varepsilon} \frac{\sqrt{3}}{2(1-n)} \sinh \left( \frac{\sqrt{3}(1-n)}{2} \right) \left( \frac{3}{4} \frac{\sigma_{i} + \sigma_{j}}{\sigma} \right) d \varepsilon = C )</td>
<td>MCNK</td>
<td>151</td>
<td>i=1,2,3; and j=2,3,1</td>
</tr>
<tr>
<td>8</td>
<td>Shabaic &amp; Vujovic</td>
<td>( \frac{3 \sigma_{0}}{\sigma} = C )</td>
<td>SHAB</td>
<td>181-184</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Im &amp; Argan</td>
<td>( \int_{0}^{\varepsilon} \left( \sigma - \sigma \right) d \varepsilon = C )</td>
<td>IMAR</td>
<td>188</td>
<td>Normalized with ( \sigma )</td>
</tr>
<tr>
<td>10</td>
<td>Tresca energy</td>
<td>( \int_{0}^{\varepsilon} \frac{1}{\sigma} \left( \sigma_{i} + \sigma_{2} + \sigma_{3} \right) d \varepsilon = C )</td>
<td>TRES</td>
<td></td>
<td>Introduced in the present study, normalized with ( \sigma )</td>
</tr>
</tbody>
</table>

*\( \sigma \) is the yield strength of the material; \( \sigma \) the effective stress; \( \sigma_{0} \) the hydrostatic stress; \( \sigma_{1}, \sigma_{2}, \sigma_{3} \) the principal stresses where \( \sigma_{1} > \sigma_{2} > \sigma_{3} \); \( d \varepsilon \) the incremental effective strain; \( C \) the threshold value of the criterion at the instant of fracture initiation.*
examine the comparative effectiveness of the criteria. Published literature [179,195,197,198,203] on the physical workability experiments, pertaining to upset cylindrical specimens of different aspect ratios, was collected as in Table 2.5.2. The data contains the deformation to fracture at the equator, on the bulged free surface of the upset specimens of different aspect ratio, for each of the materials considered.

The theoretical failure criteria listed in Table were incorporated into VIDHAN (an in-house developed elasto-plastic large deformation FEM based software package). VIDHAN employs an algorithm based on total-elastic incremental-plastic (TEIP) strain for large deformation plasticity and the constitutive formulation of the software was presented elsewhere [204].

Various theoretical failure criteria was evaluated pertaining to workability in cold forging reported in the published literature for their reliability and sensitivity in predicting the occurrence of ductile fracture in metalworking. Finite element (FE) simulation of the published upsetting experiments on cylindrical test specimens was performed to determine the threshold values attained by various criteria at the fractured locations, for a wide variety of materials. A comparison of the experimental threshold values of different criteria, with
Table 2.5.2 Summary of published experimental data on critical fracture in cylinder upsetting

<table>
<thead>
<tr>
<th>S.No</th>
<th>Ref.</th>
<th>Material tested</th>
<th>Constitutive details</th>
<th>Interface details</th>
<th>Experimental details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\bar{\sigma} = 950.821 (\bar{\varepsilon})^{0.14}$ MPa (source [33]); $\sigma_y = 396.462$ MPa, $\phi 12.7$ mm rod</td>
<td>Rough dies (dry); $m = 0.70$ (source [33]);</td>
<td>0.75, 1.00, 1.25, 1.50</td>
</tr>
<tr>
<td>1</td>
<td>178, 179</td>
<td>1045 steel; cold drawn and annealed rod</td>
<td>$\bar{\sigma} = 950.821 (\bar{\varepsilon})^{0.14}$ MPa (source [33]); $\sigma_y = 396.462$ MPa, $\phi 12.7$ mm rod</td>
<td>Lubricated dies (Ca based graphite); $m = 0.10$ (source [33])</td>
<td>Hoop str. b; 0.430, 0.460, 0.482, 0.530</td>
</tr>
<tr>
<td>2</td>
<td>178, 179</td>
<td>1045 steel; cold drawn and annealed rod</td>
<td>$\bar{\sigma} = 950.821 (\bar{\varepsilon})^{0.14}$ MPa (source [33]); $\sigma_y = 396.462$ MPa, $\phi 12.7$ mm rod</td>
<td>Degreased and descaled dies (dry); $m = 0.25$ (source [25])</td>
<td>0.75, 1.00, 1.25, 1.50</td>
</tr>
<tr>
<td>3</td>
<td>195</td>
<td>Lead free 60-40 brass; $\phi 20$ mm rod</td>
<td>$\bar{\sigma} = 68.670 [1 + 9.440 (\bar{\varepsilon} - 0.000654)^{0.33}]$ MPa (source [33]);</td>
<td>Lubricated dies (grease-graphite); $m = 0.15$ (source [33])</td>
<td>0.50, 1.00, 1.50, 2.00</td>
</tr>
<tr>
<td>4</td>
<td>197</td>
<td>Commercial Al-alloy (Al-Cu1.6-Mn0.77-Mg0.70-Fe0.55-Si0.21)rod</td>
<td>$\bar{\sigma} = 346.490 (\bar{\varepsilon})^{0.173}$ MPa $\sigma_y = 113.564$ MPa, $\phi 30.7$ mm rod</td>
<td>Compression</td>
<td>0.75, 1.00, 1.25</td>
</tr>
<tr>
<td>5</td>
<td>198</td>
<td>Lead alloy (ASTM-SAE: UNS L52905)</td>
<td>$\bar{\sigma} = 66.700 (\bar{\varepsilon})^{0.102}$ MPa $\sigma_y = 35.792$ MPa, $\phi 25.0$ mm rod</td>
<td>No lubricant (dry); $m = 0.35$ (source [28])</td>
<td>1.00, 1.50</td>
</tr>
</tbody>
</table>

*a Aspect ratio of cylindrical specimen.

*b *Hoop strain* denotes the circumferential strain at the equator.

c *Compression* refers to the overall compression at the instant of fracture.
those obtained through FEA of complex metalworking processes at fracture was also made. A statistical analysis of the results revealed that none of the criteria were truly friction and geometry-independent for universal application. Nevertheless, within a family of processes such as upsetting, the criteria depending on cumulative specific plastic energy adjusted suitably with the maximum tensile stress, were the most reliable ones in the estimation of workability limits.

Workability diagrams are important aids in determining the maximum strain values that can be achieved in bulk-forming processes. In upsetting, the strain-path configuration was apparently affected by the $H_0/D_0$ ratio, the friction condition, and pre-straining. Different strain-path slopes at fracture were obtained by Shabaik et al. [206] using different geometrical pre-straining conditions of upset specimens.

2.6 COMPUTER AIDED DESIGN IN FORGING

In manufacturing operations, many parts are formed into various shapes by applying external forces to the workpiece by means of tools and dies. Typical operations are forging, extrusion and rolling. Because the deformation in these processes is carried out by mechanical means, an understanding of the behaviour of the materials in response to applied forces is important. In
addition, the behaviour of a manufactured part during its expected service life is an important consideration [207].

Die design, material behaviour during deformation, as well as friction, and material flow characteristics in a die cavity, are important in design a consideration. Also important is the proper selection of die materials, temperature, speed, lubricant and equipment.

Recently, computer-aided design (CAD) and computer aided manufacturing (CAM) are being implemented increasingly in all aspects of forging design and manufacturing. Techniques being used include modelling of the deformation of the workpiece and finite element analysis during forging in the dies, die design, calculations of forces, and prediction of die failure [208-210].

The ultimate goal of manufacturing engineer is to produce a component of selected material with a required geometrical shape and a structure optimised for the proposed service environment. In general, forging processes tend to be a complex system of independent variables, dependent variables and independent-dependent interrelations. Independent variables are those aspects of the process over which the engineer has a direct control and are generally selected or setup when setting up the process, such as; starting material, starting workpiece
geometry, tool or die geometry, and the amount of deformation.

The goal in manufacturing research and developments is to determine the optimum means to produce high quality products at lowest cost and least time. The optimisation criteria may vary, depending on product requirements, but establishing an appropriate criterion requires a thorough understanding of manufacturing processes.

A strategy of producing a forged part instead of a machined one is adopted since the machining process is no longer economical to produce this part because of the material wasted in machining and due to the valuable saving normally accompanied with forging process, especially in mass production.

One of the primary tasks of the forging design procedure is the conversion of the available machined part data into forged part data. In the process of conversion, the necessary forging cavity, corners and fillet radii and appropriate draft angles are added to the machined part cross-section. The cross-section of the machined part needs to be modified to conform to the process limitations. This process involves the selection of the parting lines, the addition of machining allowance, and fillet and corner radii [211]. The selection of these
parameters is critical for obtaining a defect-less forging [212].

The application of computer-aided engineering (CAE), computer-aided design (CAD), and computer-aided manufacturing (CAM), is essential in modern metal forming technology. Thus, the process of modelling for the investigation and understanding of deformation mechanics has become a major concern in recent and advanced research, and the finite element method (FEM) has assumed increased importance, particularly in the modelling of deformation processes. Jolgaf et al. [213] contributed to the development of a CAD/CAM system for the closed-die forging process. The system development consisted of three stages; namely, metal flow simulations, die failure analysis and design optimisation, and the development and implementation of a machining code. In the first stage, the FEM was used to simulate the axisymmetric closed die forging process of copper material. The method was used to study the metal flow; die filling, retaining the non-linearity involved in the large change in the geometry; the continuous change in the contact surface condition; and the isotropic material work-hardening characteristics. In the second stage, a finite element analysis and optimisation algorithm was developed to examine the die fatigue life and to optimise the die design. The finite element analysis in the first and second stage was carried
out using commercially available finite element software called LUSAS. In the third stage, a machining code for the optimised die was developed and implemented using CAD/CAM software called Unigraphics and CNC machine.

For the mass production of small or medium-sized mechanical parts, cold-former machines, sometimes called multi-station automatic cold-forging machines, are being used in a wide range of mechanical parts manufacturing industries. In cold-former forging, initial materials, cut from simple bars, are formed progressively to final shapes by automatic and synchronized operations, including shearing, upsetting, forward and/or backward extrusion, piercing and the like. Usually, the number of forging sequences in cold-former forging is larger than that in conventional forging because of the mass-production purpose of this machine. Simultaneous operation and production automation are also important characteristics of cold-former forging processes.

It is very difficult to carry out the process sequence design in cold-former forging because many aspects should be considered, including production economy as well as the proper distribution of plastic deformation, machine limitation, production automation and the like. In addition, the reliability of process design in automatic multi-station forging is of great importance since a
design failure or an intermittent stop of the manufacturing and design cost and loss of opportunities. In order to reduce possible failures in process sequence design, several works [214-229] have been reported for developing design assisting environments such as expert systems and CAD/CAM techniques. However, in addition to the intrinsic nature of forging sequence design, which is very creative and empirical, complexity in plastic deformation and high correlation between design parameters in different stages have made it difficult to realize process design automation in cold-former forging.

The automatic design system is usually composed of a process design module and simulation or verification module. Most conventional research has focused on process sequence generation in the former. Ehrismann and Reissner [228] emphasized the importance of the integration of a simulation system with a design or manufacturing assisting system in order to promote mutual understanding between simulation experts and design experts and reduce the engineering time and cost. A practical viewpoint of process designers that an automatic design system has to possess can be found in the work of Kim and Altan [219]. According to their work, firstly a process design module should minimize routine work, including sequence design generation, satisfying volume consistency, modifying
designs, checking basic design rules, making detailed drawings and generating die manufacturing information. However, they underestimated the importance of the simulation module, since computers in those days were not powerful enough for the forging simulator to play a main role in the design information and knowledge system.

Based on the above considerations, a fully integrated design system was developed by Im et al. [230], in which a forging simulator plays the core role in assisting forging sequence design. Cold-former forging of ball studs used as ball joint components is selected as an application example, since there are many different sizes of ball studs manufactured in a company and the related technical materials can be obtained.

Several researchers [214-229] have studied the process design automation of cold-former forging. Most research has been focused on automatic process sequence generation in the process design module based on knowledge-based expert system or AI technique. However, there are limited applications for the whole sequence design of a new process, since the sequence design itself is very creative and human experts have only narrow information. Of course, conventional research works can be used for the sequence design of the special process if the design databases have many similar processes and the related design information
can be accessed easily and modified with accompanying automatic detailed verification.

It should be noted that the most important activity in an automatic design system or in a design assisting systems lies in the verification of the design candidate, and such verification capability should be the core of the design system from the standpoint of the process designer. Constraints on process parameters from either machine specification or rule-based design specification can be checked with relative ease. The most difficult problem arises in metal forming mechanics. The plastic deformation in cold-former forging is very delicate and dimensional tolerance is inherently very tight. Therefore, conventional approximate analysis approaches cannot avoid many limitations and obstacles.

Recent enhancement in computer hardware technology makes it possible to use a finite-element-based forging simulator as the core verification tool. The simulator can be used to investigate the detailed effect of a process parameter on the process conditions and the product quality if it is integrated with a design assisting system. In this case, a forging simulation technique is the major part of the design assisting system. Even though some approaches [222-229] employed a finite-element-based forging simulator as a verification tool, the functions
were not fully integrated and the computer simulation required quite a large amount of time due to the user interface as well as to the computational time. As a result, the simulator could not be an active design tool in the related systems.

According to Im et al. [230], a computer aided process design technique, based on a forging simulator and commercial CAD software, was presented together with its related design system for the cold-former forging of ball joints. The forging sequence design and its detail designs were generated through user-computer interaction using templates, design database, knowledge-based rules and some basic laws. The forging simulation technique was used to verify the process design. The detail designs, including die set drawings and die manufacturing information, were generated automatically. It was shown that engineering and design productivity was much improved by the presented approach from the practical standpoint of process design engineers.

Titanium alloy turbine dies for aero-engines were normally produced by hot forging to near net shape followed by precision machining because of the stringent quality requirements, pertaining to dimensional tolerances and mechanical properties, imposed on the final component. The near net shape forging of titanium alloy discs demands
meticulous design of the die profile as well as the process. A computer-aided engineering (CAE) procedure comprising two steps was used in [244] for modelling the deformation mechanisms as well as the mechanics of flow that occur during the forging. The first step involved process modelling to select the suitable parameters such as temperature and strain rate (related to ram speed) in order to improve the workability during forging as well as to achieve desirable microstructure in the final component. The second step involved a large deformation finite element analysis (FEA) for suitably designing the die cavity profile that renders streamlined flow of the material during forging. While the former guarantees metallurgically sound disc, the latter ensures defect-free flow of the material during forging. Computer-aided design (CAD) of the actual dies then followed, and the advancement in CAD allowed automatic integration with computer-aided manufacturing (CAM) of the dies. The entire procedure fell under CAE-CAD-CAM approach [231-232] and CAM refers to precision machining.

Material modelling becomes important since titanium alloys are susceptible to unstable flow [233] during forming and the process parameters significantly influence [234] the microstructural development in the component. Some of the microstructural mechanisms [235] such as shear banding, inter-crystalling cracking, dynamic strain
aging result in unstable metal flow during deformation. Whereas, dynamic restoration mechanisms like dynamic recrystallization, dynamic recovery and super plasticity, result in good workability [235] and desired microstructure in the final product. The 'processing map' techniques [236,237], developed on the basis of material models, provide optimum combination of process parameters and one such approach is dynamic materials model (DMM) [237].

In DMM, a set of uniaxial compression tests was performed on cylindrical samples at different combinations of temperature and strain rate and the maps were constructed using the corresponding microstructural responses of the material.

Flow modelling is necessary since improperly designed die profile leads to incomplete die filling, excessive load requirement, die breakage, folding, etc. For modelling material flow in metal forming, FEA [238-241] is being increasingly employed because of its cost and time effective solutions. This involves process optimization, tool shape design, preform design, etc. The material flow involves large strain and material rotation that necessitate finite deformation-based framework for the FEA. In this investigation, the finite element modelling (FEM) simulation of the disc forging was performed using a
large deformation-based finite element code VIDHAN [242] developed in-house. The constitutive relation used in the code was based on a total-elastic and incremental-plastic (TEIP) strain. The constitutive framework as well as the validity of the code were described elsewhere [243]. The Ti alloy used study exhibited flow softening and the above algorithm is specially suited for this type of cases where the tangent modules of the stress-strain variation becomes negative.

The FEA can be used, also to understand the microstructural development in the actual component during forging. The computer distribution of the process parameters in the deforming billet, integrated with the results of the processing maps, aided in designing the forging scheme to achieve uniform and desirable microstructure in the final component. Using this procedure, the advantage of upsetting prior to forging for obtaining uniform microstructure was also analyzed.

Once the die profile was finalized using CAE, the actual die design was carried out in a CAD environment and subsequently integrated to CAM of the dies.

Titanium alloy aero-engine turbine discs are subjected to stringent quality requirements pertaining to dimensional tolerances and mechanical properties.
Therefore, the forging process of the disc was meticulously designed. Srinivasan et al. [244] dealt with computer-aided engineering (CAE) of the die profile as well as the process design for the forging and in addition briefly addresses the integration of CAE with computer-aided design—computer-aided manufacturing (CAD-CAM) for the fabrication of the dies. The CAE involved study of (i) mechanics of the material flow using large deformation FEA for streamlined flow and (ii) the mechanisms of deformation using dynamic materials modelling (DMM) technique for the process optimization. In addition, concurrent modelling using DMM as well as finite element modelling (FEM) facilitates understanding the development of microstructure at different locations in the forged component. The predicted flow pattern and the load-stroke values were found to be in good agreement with the experimental results. The results of the CAE were fed to a CAD environment and finally linked to CAM for the fabrication (precision machining) of the dies. The integrated approach was cost effective and time saving.

Recent trends of manufacturing industry can be characterized by the flexibility and complexity of products due to rapid development of manufacturing technology and various preferences of customers. The trends and increasing competition require fast and cost effective development of high quality products, and rapid
changes in design and functionality to meet market demand. Especially, design and manufacturing of real products and dies, which require a long lead-time due to so many trial-and error during the development, holds the key to the reduction of lead-time and investment cost [245]. Metal forming was deeply related to the general framework of design and manufacturing, so that a new manufacturing technology with a concept of concurrent engineering was necessary.

A new manufacturing technology includes styling, design, analysis, prototyping, testing and manufacturing. The basic concept of concurrent engineering was that all activities related to product development procedures were to proceed simultaneously and they should be addressed from the beginning as an integrated set. Concurrent engineering makes it possible to reduce development time and investment cost, as well as to improve quality of the product. Moreover, it can be effectively connected with virtual prototyping and manufacturing (VP&M) technology including CAD/CAM/CAE and physical prototyping and manufacturing (PP&M) technology including rapid prototyping / tooling / manufacturing.

VP&M technology has advantageous features; easy understanding of products to be manufactured and a systematic investigation of the effects of the effects of
the process parameters and part configuration from the design stage [246].

PP&M technology has advantageous characteristics; evaluation of the geometrical conformity and styling, ergonomic studies, manufacturability check, and other functional testing [247]. The technical connection between VP&M and PP&M is thus keenly required in metal forming.

Schreiber and Clyens [248] fabricated laminated blanking tools using the laser cut sheet. Walczyk and Hardt [249] developed a new rapid tooling (RT) method for sheet metal forming die using a closed loop sheet metal forming system with finite element analysis (FEA), rapid fabrication machine, laser CMM, etc. Park et al. [245] investigated a concurrent engineering approach to the die design for metal forming process using rapid prototyping and FEA. Park et al. [250] was investigated the development of prototyping and die / mold manufacturing technology using rapid prototyping (SLA). Chua et al. [246] made a comparative study for VP and RP with respect to their relevance in product design and manufacturing. Kuzman et al. [251] developed the rapid sheet metal process development chain supported by laser sintered active tool parts. Kuzman et al. [252] investigated the integrated technology with RP and CAE in mould manufacturing. Ahn et al. [253] investigated net shape
manufacturing of three-dimensional parts using a new RP and its applied technology.

The technology integration of CAD/CAM/CAE as practical VP&M methods, and rapid prototyping and manufacturing (RP&M), as practical PP&M methods, in metal forming was investigated by Yang et al. [255] in order to improve the efficiency of development for trial products and dies for metal forming processes. The technology integration was applied to both bulk and sheet metal forming. By comparing the results of CAD/CAM/CAE with those of RP&M, the number of trial-and error had been reduced effectively. The results had been successfully reflected in the process modification procedure.

CAD/CAM/CAE technology, including simulation, in metal forming was effectively used to design the process and die, to investigate the effects of process parameters, to acquire high quality products, and to reduce manufacturing cost utilizing a virtual model [254].

The design of the process and die, and effects on process parameters are examined by:

1. checking the mechanical form, fit, interference, and assimilability [246],
2. investigating strains/stress distributions, flow patterns and dimensions of final shape,
3. investigating flow induced defects and temperature distributions in the final shape.

The improvement of product quality is examined by investigating microstructure and grains in products. It is possible for the reduction of manufacturing cost to decrease tryouts, rejects and lead-time [254].

Rapid prototyping and manufacturing technology, including RT, has advantageous characteristics that can directly fabricate a three-dimensional part from the CAD data in a CAD/CAM environment, and also the technology can rapidly manufacture plastic and metal parts indirectly or directly using RT and RM [247].

Hence, RP&M technology in metal forming is used to rapidly examine and verify the CAD/CAM/CAE results and to prove the process concept and die design utilizing a physical model. In addition, RP&M was used to fabricate rapidly the prototype tools based on the CAD/CAM/CAE results in order to perform the functional testing successfully.

The verification of CAD/CAM/CAE results and proof of the concepts are examined by:

1. Visualizing the die shape and deformed shape,
2. Checking manufacturability, including verification of tooling design, assemblability, and reliability, and styling using a physical model.

3. Comparing the experimental results with the results of simulation.

RP&M technology was influenced by the complexity of shapes due to its fabrication principle, so that lead-time and cost are drastically reduced.

CAD/CAM/CAE and RP&M technology have highly advantageous characteristics described so the integration of two technologies can supply a good solution to reduction of time and cost in the stage of development.

The key technologies are the generation of input data for a CAM system using CAD/CAE data and the fabrication of products and tools. In general, the standard input of CAM system for RP&M apparatus was .stl format with a group of triangular facets on the surface of objects. Commercial CAD software, for example, CATIA, I-DEAS, Pro-Engineer, Solidworks and so on, have their own module for data translation, so that the translation of CAD data into format can be easily implemented.

The conversion of CAE results to .st2 format requires special technique. Because the intermediate shapes of a workpiece in the format of a finite element mesh data are
obtained from CAE results, the conversion utilizes the mesh data in each analysis step. Firstly, the surface boundary was extracted from the solid mesh such as hexahedral or tetrahedral mesh, in order to obtain a shell mesh. Then, the facets of the rectangular shell mesh were divided into triangular facets were stored in .stl format.

The die data are generally generated from CAD data except for a special purpose such as investigation of surface defects and die deformation during forming. The workpiece data are generated from CAE results except for the initial data.

Typically, the die and the workpiece are metallic, so that the experimental tools and initial billet should be also metallic so as to realistically undergo functional testing and experiments. The tools and products can be manufactured directly in the RP&M apparatus, for example SLS, and indirectly using RT technology such as lost wax casting, spray metal tooling, etc. The indirect tooling technology includes multiple steps of reversals to produce metallic parts.

In general, it is preferable to select the indirect RT due to dimensional accuracy, surface roughness and strength of parts comparing with the direct RT.
In order to reduce lead-time and investment cost for the development of metal forming processes, the technological fusion of VP&M (Virtual prototyping and manufacturing) and PP&M (physical prototyping and manufacturing) with the concept of concurrent engineering is needed. The technology integration of CAD/CAM/CAE, as a part of the practical VP&M methods, and rapid prototyping and manufacturing (RP&M), as part of the practical PP&M methods, in metal forming was investigated by Yang et al. [255] in order to improve the efficiency of development of trial products and dies for metal forming processes. The technology integration did not necessarily require fabrication of conventional trial dies and parts including drawing, machining and final treatments. The technology integration can also consider the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of workpiece, deformation induced defects, etc. so that it could reduce the trail-and-error in the design stage. Hence, the technology integration enables a remarkable shortening of the lead-time for development of metal forming processes and investment cost for the period. The integrated technology was examined by case studies such as a spider forging, preform design of a rib-web part, extrusion of a triple-connected rectangular tubular section and underframe part for a railroad vehicle, and deep drawing of a clove punch. As a result of
the studies, it was verified that the technology integration could be effectively applied to various metal forming processes and reduce remarkably the lead-time and cost of the process.

Several methods for computer-aided cold forging process planning and die design have been proposed. However, most of their applications are restricted to simple shapes which are represented by combinations of primitive shapes or their sections drawn with lines and circles. This is primarily due to two reasons. First, cold forging products tend to have simple shapes. Second, the systems often restrict product shape to facilitate building a knowledge-base and understanding the process. Furthermore, development of forging technology enables the manufacture of increasingly more complex shaped cold forging products in actual shops. These products often have free curved sections, so it has been difficult to treat them using conventional systems.

Ohashi et al. [256] considered forging to be a procedure for adding features to a raw material, and process planning to be the inverse procedure. Each step of the forging process is thought of as a combination of feature eliminating processes. Depending on the above, they developed a CAD system to design forging sequence and die profiles. The system designs the forging sequences and
die profiles from the product to its raw material by eliminating feature's which is the inverse of forging processes. First, the system detects features from a product's shape. A shape is represented by its cross-section including the axis with free curves. Its outline is described as successive finite vectors. The system extracts features by using the change of the vector direction. Second, the system searches a database of "manufacturing cases" using features such as search keys to find a candidate case in which the manufacturing process can be applied to the product. A manufacturing case is a data set having three kinds of data; search key, validity checking procedure of itself, and eliminating the procedure to get a partial preform after the elimination of the feature. Search key is the name of the feature to which a case can be applied. If the system finds a matched case by using the search key, it applies a validity checking procedure described in the matched case data. By only eliminating features it is not possible to obtained a process plan. Each case must represent an actual forging method by which the feature can be manufactured. The validity checking procedure ensures that the eliminating process is actually to be realized as the inverse of forging. The system checks if the case can be applied on the feature or not by the validity checking procedure. If it passes, it eliminates the feature by the
eliminating procedure described in the case. The procedures in each case are independent but they exchange information about the cases and dimensions by using a working memory like a blackboard. Using the working memory, the system combines eliminating procedures automatically to get an actual manufacturing process. Thus, the system designs one forging process and preform, and after then, it also does the internal profiles of dies and exports them as point line into general purpose CAD systems. Repeating the above procedure, the system generates process plans and die profile design from the product's shape to its raw materials. Multiple plans and profiles are designed by repeating the procedure recursively.

Open die hot forging involves the shaping of heated metal parts between a top die attached to a ram and a bottom die attached to a hammer anvil or press bed. Metal parts were worked above their recrystalization temperature and gradually shaped into the desired configuration through the skillful hammering or pressing of the workpiece.

While impression or closed die forging confines the metal in dies, open die forging is distinguished by the fact that the metal is never completely confined or restrained in the dies. Open die forgings are made with
repeated blows in an open die, where the operator manipulates the workpiece in the die. During the forming process, as the height of the workpiece is decreased, both the length and width are increased by the rule of material volume conservation.

Rational choice of forging pass schedule significantly increases the productivity of metal forming processes and ensures high quality of the product. However, until quite recently, forging pass schedule has been developed by experiment, on the basis of empirical experience, and has not involved mathematical methods. Also there is not a standard to evaluate the existing forging processes. To form a pass schedule of the forging process reducing large ingots or billets into square or wide, accurate prediction of width spread is essential. Tomlinson and Stringer [257] defined a quantity called the 'spread coefficient', which can be used to generate forming schedules. Also there have been several attempts to analyze the block-forming processes using new techniques such as the FEM [258,259] and the upper bound analysis [260,261].

Although numerous studies on width spread have been done, it is difficult to find applicable method to industrial environment. The problem lay on the variety of forging products and lack of information for the mechanical properties.
Because the metal forming is very complicated and the parameter optimization is still in developing, there were various optimization methods used for metal forming including mathematical optimization [262], backward tracing method [263], expert system [264], neural network [265] and genetic algorithm [266].

According to Kim et al. [267] forging pass schedule algorithm on billet to square bare and billet to wide bar developed by neural network with systematic procedures; data acquisition, mechanical parameter search and forging schedule. To analyze mechanical properties, forging pressure, ram position, manipulator position, tong angle and temperature of thermometer signals are processed with data acquisition system. Mechanical properties including deformation resistance, width spread, forging load, forming velocity and temperature are found by functional neural network through the parameter search and optimization. Developed forging pass schedule algorithms are mainly composed of calculation of optimum number of passes and reduction in each pass to economize power and minimize forging cycle time. The algorithm based on the void closure in forged products provided reasonable reliability in the application of industrial environments.
2.7 FORGING OF POROUS MATERIALS

In an open die forging of porous materials, one can actually follow the average value of the porosity. This, in general, may not be enough for design purposes. A spatial distribution of the porosity is much more informative, since a 'weak spot' is the volume (i.e. an occasional domain with large porosity) may trigger a failure.

For the foregoing analysis, Gurson's yield function [268] was employed. This function has successfully served some numerical-oriented studies of metal forming processes, e.g. Aravas [269], Becker and Needleman [270], Tirosh and Iddan [271], and others. Somewhat different yield functions were suggested by Berg [272], Green [273], Shima and Oyane [274] (summarized comprehensively by Doraivelu et al. [275], focussing on the mean stress effect on the yield locus without a direct link to the porosity state. As pointed out by Berg [272] and Gurson [268], the theorems in plasticity that enable the construction of the yield function of porous material, (the 'normality rule' and 'maximum work principle'), were implied from early work of Bishop and Hill [276]. Consequently, it enabled the use of the limit-analysis theorems as they were used with incompressible materials. The difficulties in extending the limit-analysis to
materials whose yielding depends upon the mean normal stress was discussed by Drucker et al. [277].

Between the various yielding models cited above, Gurson's model seems relatively convenient. It is perhaps due to the ease by which one can attribute physical meaning to the internal variables in the yielding equation (the porosity state, \( f \), and the mean stress, \( \sigma_m \)). In recent years, several 'correction factors' have been introduced in order to include the material strain hardening and the strain rate hardening (Spitzing et al. [278]), and / or to better accommodate certain experimental measurements (Tvergaard [279]).

Shirizly et al. [280] suggested and applied a formulation for the evolution of the material density in an open die forging of porous axisymmetric solid with Gurson's yielding model. An admissible porous-dependent velocity field was obtained and applied to form the constitutive behaviour of the compressible material. Concurrently, an admissible stress field of the yielded material was used to estimate the effect of the hydrostatic stress on the bulk flow. Such a combination of the dual bounds enable one to assess the non-steady loading path in terms of the current porous state and the geometry of the workpiece, regardless of the mechanism by which the densification process was achieved. Emphasis was
given to the use of the newly porous-dependent shear boundary condition along with some classical interfacial friction models. The suggested procedure to simulate the evolution of the densification during the forging process is compared with FEM solution and self-generated data.

In recent years powder metallurgy (P/M) techniques combined with conventional deformation processes had been used as a competitive method of manufacturing particular engineering products of high-performance, such as machine-tool components, parts for automotive and aerospace industries, etc., providing simultaneously economical and technical benefits over processes using wrought materials, the advantage being the reduction of manufacturing cost, improved properties, design flexibility and the production of unique materials.

Powder forging involves the fabrication of a preform by conventional pressing and sintering techniques followed by forging of the preform with substantial densification [281]. This processing of P/M preforms has wide industrial applications because of the good dimensional accuracy and surface finish of powder components together with the enhancement of the load-bearing capacity achieved.

In order to advance P/M technology, it is necessary to obtain a better understanding of the behaviour of P/M
products under plastic deformation. Although a considerable amount of work has been reported on the various technological aspects of the industrial processing of P/M techniques, few systematic theoretical attempts have been made to study and predict the processing load and the deformation characteristics during the bulk forming of P/M preforms [282-286].

The open-die forging (upsetting) of sintered porous materials was used widely as one of the key metal processing operations for fabricating various engineering products, and in some cases, for predicting the mechanical properties of such materials. An analysis of the upsetting of axisymmetric cylindrical billets of porous materials was made on the basis of plasticity theory by Mamalis [287]. A newly established yield function for porous materials—proposed by the authors—was applied to simulate the consolidation of porous billets, taking into account the current state of porosity at each stage of deformation. The proposed theoretical model, combined with the concepts of the 'slab method' and assuming suitable friction conditions at the workpiece / tool interface, provides with a valuable design too, allowing for a more precise evaluation of the process loading and the shape changes of the porous billets obtained during upsetting.
2.8 FORGING PROCESS

The quality, accuracy and cost of forged components are determined, in the main, by the design of the process: tool design is, perhaps, the most important component of this economic balance, which has resulted in a substantial effort to optimise the design of metal forming processes, in particular, die-design.

Jinn and Rong [288] and Lee et al. [289] attempted to optimise the die surface design of extrusions by using an integrated CAD/CAM/CAE system. In this approach, the die surface was represented by a surface model with a tension parameter which allowed the design of shapes - clover, polygonal, T-and L-sections and gear splines - using a single surface model. An upper-bound optimisation procedure was used to minimise the extrusion pressure. Reddy et al. [290] combined the upper-bound and slab methods to predict the die pressure distribution and the total extrusion power of eight geometrically dissimilar dies, to conclude that third-and fourth-order polynomial dies and the cosine die required the minimum amount of energy. Lo [291] also used the slab method to present a streamlined extrusion die in which the strain-rate in the work-material was retained at a nominal value. This approach would prove useful in the processing of materials that are sensitive to strain-rate distribution. The
optimisation technique proposed by Giffort [292] considered the work-material to have the flow behaviour of a fluid: solutions were derived using three-dimensional computational fluid dynamics. This approach appears to be suitable for the optimisation of three-dimensional components.

Morita and Hattori [293] used FE simulation to define the optimum position of the billet in the die with reference to the precision of a forged titanium-alloy turbine blade. Lapovok [294] optimised the design of the preform with reference to die-life and damage accumulation. Sheng and Guo [295] proposed a reverse simulation technique for process design based on the UBET: reverse simulation is initiated from the final perfect state of a forging and evaluates a set of intermediate states of deformation, in reverse order until achieving the original billet form: this enables the development of the "component and process" simultaneously. Srinivasan and Reddy [296] conducted similar research but selected an optimum path based on constraint placed on the deformation of the work-material. Minimisation of the variation of effective strains within the work-material was an objective to be sought. During the analysis, the sequence of the separation of nodes on the material-surface from the tool was determined with reference to the achievement of this objective.
Apart from the expectation of optimising the forging force, power, cost, tool-life, billet and die surface, an important consideration was the attainment of greater accuracy in the geometrical form. Functional surfaces are often specified to within a few microns. Specifications of this level are difficult to achieve by material-removal operations from both the fixturing and materiel-removal points of view. It is known that the errors of netting-forming components are generated by different error-generators such as die-elasticity \[297,298\], secondary yielding \[299\], temperature-changes and springback \[300\]. The compensation of the errors resulting from different generators requires different die design approaches. Zhao et al. \[301\] developed sensitivity analysis methods for the design of preforming dies using the rigid viscoplastic finite element method. In this approach, the preforming dies were represented by sets of cubic B-spline curves which enabled the use of the coefficients of the B-splines as design variables. The reference for the optimisation was the acceptability of the match between the designed and actual final forging. Badrinarayanan and Zabaras \[302\] also researched a similar method for extrusion, the method enable optimisation of the preforming die from which complete filling of the final die can be achieved. However, rigid finite element analysis excludes
consideration of the influence of die-elasticity and springback on component-form errors.

Wanheim et al. [303] proposed the design of an extrusion die which auto-compensated for elasticity-dependent errors. Finite element simulation supported the development of design specifications which were verified by simulation. Ibhadode [304] developed an analytical equation for shrink-fitting to compensate for the elastic expansion of the die; the approach assuming that the pressure profile in the die was uniform, a consequence of using thick-walled cylinder theory.

Nett-shape manufacturing of engineering components is a major objective of modern material-conversion industries; relevant technologies depend on tools in which error-compensation can be effected. A novel die-design approach, known as the least squares approach, to minimise the component errors was presented by Chen et al. [305]. Shrink-fitting compensating die structure was employed. The errors caused by die-elasticity, secondary yielding, springback and temperature were considered in the process of Minimisation. The main factors that may influence the accuracy of the optimisation procedure were analysed. The final component errors were controlled to within a few micrometers. The approach was illustrated using axisymmetric closed-die forging.
The casting-forging compound technique is a kind of metal working method, which adopts a casting for the performance of finish forging instead of rolled stock. Because the shape of the casting can be close to that of the forging, the technique cannot only decrease forming operations, but also increase the material utilization ratio. Thus, it can decrease production cost substantially, and it can be applied to produce complex forgings especially. The study of the casting-forging technique has been carried for three decades. The foundation theory and the applied development about it have been investigated comprehensively and thoroughly by many international researchers. Some basic and applied research accomplishments have been obtained [306-309]. At the same time, even the forging industry has tried especially to improve hot forging processes with regard to higher accuracy of the forged parts and reduction of final machining operations by near-net-shape forging. Closed die forging without burrs [310,311] is a newly developed technique for the manufacturing of near-net-shape or net-shape parts by precision forging, which has been applied successful to forge gears, connecting rods etc.

Because of the defects existing in current manufacturing processes of alternator poles, such as more material demand, higher forming force and lower accuracy,
a casting-forging precision forming process of alternator poles was developed by Chen et al. [312] and investigated. In the process the pole was produced by casting and closed die flashless forging. It could not only shorten process, decrease material and power demand, but also increase the accuracy of the forgings. The forming process was investigated by testing and numerical simulation. The result provided a basis for applying the process in practice.

Cold forging is a production process often used when forming tubular components in high strength aluminium alloys where high concentricity and close tolerances are required [313]. Very often, the forming is carried out by a combination of forward and backward cold forging. If the geometry is complex, several severe forming operations follow one another that also involves intermediate soft annealing and lubrication. This often requires an interruption of the production line that is both time-consuming and expensive.

A new alternative production process was therefore developed [314,315]. The forging was accomplished at moderate temperatures where it is possible to form rather complicated geometrical shapes in less forming operations without leaving the production line to soft-anneal and re-lubricate the workpiece.
Studies were conducted on cold forging, warm forging and a combination of the two methods in steel [316-318] in the past 10 years.

Cold forging is a process suitable for manufacturing low-cost and high quality automotive components in high strength aluminium alloys. This method is particularly suitable for parts with narrow geometrical tolerances, good concentricity, smooth surface finish and for near net shape products. However, an increasing request for producing components at a lower cost requires even more economical production processes. Forming in the warm condition is an alternative process that has the advantages of producing rather complicated geometrical shapes in less operation steps compared to cold forming. In addition, warm forming at moderate temperatures has all the benefits of cold forming including good control of the microstructure and thereby improved strength and ductility. Ola Jensrud et al. [319] compared the process parameters of warm forging with cold forging process parameters.

The forging process is one of the most representative metal forming processes and can be classified into hot and cold forging according to the forming temperature. As the hot forging process is performed at hot working temperature, i.e., above the recrystallization
temperature, the work-piece undergoes large plastic deformation and hot forging is usually used for producing the blocker. On the other hand, cold forging is a special type of forging process wherein cold metal is forced to flow plastically under compressive force into a variety of shapes, with several forming steps being used to produce a final part of relatively complex geometry, starting with a slug or billet of simple shape. Some of the advantages provided by this process are: (a) high production rate; (b) excellent dimensional tolerances and surface finish of the forged parts; (c) significant savings in material and machining; (d) higher tensile strength in the forged part than in the original material, because of strain hardening; (e) favourable grain flow to improve strength. By far the largest area of application of cold forging is the automobile industry [320].

Until now, the steering yoke which is object has been manufactured by hot forging or welding of forged head and shaft parts because of technical difficulties. Thus the hot forged steering yoke cannot satisfy the required accuracy, and also involves economical loss and increase of the process number due to secondary machining being unavoidable [321].

The steering column in a steering system, one of the main devices of an automobile, is a very important part to
attain stability and steady movement of the vehicle. The steering yoke, the core part of steering column is manufactured through various processes, such as hot forging, machining and assembly by welding.

Dong-Kyun Min [322] proposed a new method for manufacturing an united steering yoke of high manufacturing productivity, improved mechanical properties and low cost through precision cold forging. The rigid-plastic finite-element method for precision cold forging was used in order to reduce development time and die cost. Practical considerations in the manufacturing stage such as hardness in heat treatment and coating condition in lubrication were also investigated and the results were applied in mass production.

Corti et al. [323] studied the flow behaviour during isothermal forging of high temperature materials. Kobayashi et al. [324] found that average forging pressures predicted by approximate theories based on simplified states of stress were in substantial agreement with the experimental observations.

Slip line field analysis and force-plane diagrams drawn from force equilibrium considerations were used by Mamalis et al. [325] to predict forging loads during intermediate i.e., post incipient, deformation stages in
the plane strain closed die forging of rectangular billets with diamond-shaped dies. The theoretically calculated loads were in agreement with experimentally determined values.

Kruth [326] found rules or procedures for calculating the flash gap dimensions. Nediani and Dean [327] worked on forging on rectangular sections in a completely closed die cavity and proposed theoretical analysis. Monaghan and O'Reilly [328] presented an upper bound solution based on observed velocity fields resulting from the deformation of initially cylindrical work pieces within hexagonal and square dies.

Erman et al. [329] conducted physical modelling experiments in press forging to develop basic understanding regarding the influence of several upsetting parameters on the distribution of deformation in the upset forged ingots.

2.9 OTHER ASPECTS RELATED TO FORGING PROCESS

Cold forging is a metal forming process which shapes a workpiece between dies at room temperature. It has advantages over machining such as little material waste, higher productivity, good dimensional and form error tolerance, and improved properties of the workpiece. Usually, cold forging needs several "preforming"
operations to make the required formable part from an initial round slug without product and die-defects. Determining the feasible or optimum serial preforming operations for making a part has been called process planning. This task is usually considered as an "art" to be undertaken by highly experienced die designers who use both empirical judgement and established (but mostly not well documented) design or technology rules which were obtained through many years of experimentation.

By process planning, usually people mean machining process planning since much research has been conducted in this area. However, according to recent developments in cold forging technology and computer technology, the application of computers in cold forging process planning (CFPP) has been growing rapidly, the initial development being led by Badway et al. [330]. After the expert system approach was introduced to engineering applications, several knowledge-based system [331-335] were developed for CFPP. Since the nature of the heuristic knowledge and experience is fragile, and not well structured, it is not acquired easily and represented well in an expert system. In addition, to build an expert system, a knowledge engineer has to interview molding personnel and try to elicit appropriate knowledge in the form of rules. This knowledge is difficult to uncover and the knowledge acquisition becomes a bottleneck in the construction of
the expert system. A new approach, case-based reasoning (CBR), was adopted to solve the problem, CBR can mean old solutions to meet new demands using old cases to explain new situations and using old cases to critique new solutions. There are several benefits of applying CBR technology in computer-aided CFPP. It allows the reason to propose solutions quickly, hence reducing the time needed to work them out. In addition, remembering previous experience helps to avoid the repetition of past mistakes. The learning process available with a CBR system enables it to become more efficiency by increasing its memory of old solutions and adapting them.

The concept of Case Based Reasoning was first described as Dynamic Memory [335]. Since the CBR technology has been applied in a wide range of application areas, including catering, recipe making, dispute mediation, criminal sentencing, mechanical design etc. [336,337]. At the highest level of generality, a CBR cycle may be described by the following processes.

1. Determine feature: Find features which can describe new problems completely and correctly.

2. Retrieval: Retrieve one or several similar cases from the case-base.
3. Adaptation: Recognize the difference between the selected design case (cases) and the new design problem, and adapt the selected design case (cases) to solve the new design problem.

4. Evaluation: Evaluate the proposed solution to decide whether it is acceptable in new problem solving. If failure occurs explain the reason and try to repair it with repair rules. If this is successful, store the new solution case in the case-base in order for it to be used afterwards.

It can be concluded that CBR is different to rule-based reasoning and model-based reasoning, being analogous to the way humans naturally solve problems, so it is appropriate to be used in computer-aided CFPP.

On the basis of the practical situation of cold forging process planning, the disadvantages of a rule-based solution were discussed, and a case-based reasoning-based cold forging process planning (CFPP) system model was proposed by Yonggang Lei et al. [338]. Several key problems involved were analyzed, among which a feature-based part representation scheme and a two-level retrieval mechanism were introduced to solve the problems of case representation and case retrieval. It was established in that case-based reasoning-based CFPP is a promising
technology for both long-term research and the promotion of efficiency for current cold process planning systems.

In most cases, the analytical calculation of the press load in closed-die forging with flash is done by upset slab method of analysis [339]. On the other hand, Akata et al. [340] used successfully an empirical backward extrusion formulation for the calculation of a press load of the round shaped forgings. However, the use of this formula has some limitations since the backward can extrusion is different than the forging process which has a flash area and die-wall angles. Hence, Capan and Baren [341] have separated the forged piece fictiously into extruded and upset areas. A round shaped forging with flash was chosen to keep similarity with the work of Akata et al. [340].

Capan and Baran [341] have calculated the required press force by separating the forged piece fictiously into upset and extruded areas. Conventional upset slab method of analysis is applied to the material under the punch and the flash area, while the analytical formulation given for the extrusion is adopted for the rising material along the annular ring area between the punch and the die-walls. Die-wall angles are also included in the calculation. The results fit remarkably well with the values measured in the experiments carried out with lead and AISI 1020 steel.
samples. The size of the punches used in the experiments were changed to give three different shape difficulty factors.

Modern production companies are faced today with problems of assuring high quality of their products on one hand, while at the same time they are forced to be as cheap as possible on the other. The two goals are very much in contrast because it is known that increasing product quality goes usually hand in hand with increasing production costs. In mass production, where every small savings of money at the workpiece means millions saved at the end of the year, this is the aspect to be emphasized.

In order to comply with these two wishes, it is necessary to bring the production to such a stage that no quality control will be necessary. Saying otherwise, the available machinery should produce only "good" pieces.

Such an approach to production means of course the total control over the process, and a precondition which we have to bear in mind is a detailed knowledge of the producing process and parameters affecting. According to Zlatko and Karl [342,343], changing the input parameters of the process causes an appropriate varying of the desired output process parameters. The parameters building the input in the process could be different, regarding the
type of the process. In the case of wire forming, the most important process parameters are material properties, machinery stiffness, lubrication and tool surface quality.

Nastran and Kuzman [344] dealt with accuracy problem in different forming processes. In cold forging, the outcoming part is exactly defined with tolerance and mechanical properties. On the incoming side, where the material is defined, the definition of geometry and mechanical properties fluctuations is not so clear, because they depend also of the chosen technology, available machinery, etc. In the contribution, they presented some industry examples and underline the problems connected with the stability of these processes. It is very important nowadays to balance between production in very single detail. There is the need to have a clear picture of main influencing parameters that affect the end-product geometry. The connection between the fluctuating tensile strength on the geometrical accuracy in the cold flat forging of wire as well as its influence on the curvature after roller straightening was studied. The results obtained are very useful to a production engineer in making quick decision about the raw material tolerance needed for appropriate quality.

Up to now, works on the process planning of cold forging have been mainly concentrated on the rotationally
symmetric parts. Process planning for non-axisymmetric parts has difficulties of shape cognition and expression, calculations of the process variables such as forming load, effective strain, effective stress. As for the study about this fields, Cho et al. [345] have studied about the computer-aided design system for the stepped asymmetric parts and Kim et al. [346] proposed a simple kinematically admissible velocity field to determine the final-stage extrusion load and the average extruded length in the square-die forward extrusion of non-axisymmetric bars from circular billets. Kim et al. [347] have developed UBET program to predict forging load, die-cavity filling, and the preform in non-axisymmetric forging. Lee et al. [348] have analysed forward and backward extrusion of hexagonal and trochoidal-shape wrench bolts using UBET.

It has been reported that SuperForge provides results very close to those obtained from a validated 3D finite element analysis package - Deform 3D [349].

Lee et al. [350] developed a process planning system for cold forging of non-axisymmetry parts of comparatively simple shape.

Since dies used in the cold-forging processes have to undergo severe impact and loading conditions, they are more prone to sudden fracture than most of the other
machine components. To obtain an acceptable die life against fatigue failure, the ductility and hardness of the die material are the important factors in the production of the die. Usually, die materials must be hardened sufficiently to withstand severe service conditions, but also need to have enough ductility to prevent their cracking and brittle fracture, i.e. dies are designed for higher degrees of both hardness and ductility. However, a die with a higher degree of hardness could be associated with insufficient ductility due to a poor heat-treatment process. In general, sufficient ductility of dies can be obtained by a proper heat-treatment process, but the hardness may vary over a wide range. Therefore, a heat-treatment process that produces a higher degree of hardness for the die material without loss of ductility is to be developed for actual practice, so that the die design engineer can measure only the hardness of the die material to estimate the die quality, assuming that the ductility of the die material is good to the specification. Following this concept, a simple guideline that associates the die fatigue life with the die hardness will be useful to engineers for die design.

Yi-Che Lee and Chen [351] selected different die materials commonly used in the cold-forging process were examined in the present study to obtain the relationship between the hardness and the die fatigue life. The die
materials were first heat-treated by a developed process to obtain different values of hardness, while the ductility was retained at a favourable level. The material properties of these die materials were then obtained from tension and impact tests. By investigating the experimental data, the relationship between the mechanical properties and the hardness was established. A theoretical model was also proposed in the present study to predict the die fatigue life, considering the mechanical properties of the die material obtained in the experiments and the fatigue total strain as parameters. Since the material properties can be expressed in terms of hardness, it is convenient for a die design engineer to establish a simple guideline for the prediction of the fatigue life of cold-forging dies using the proposed theoretical model.
2.10 LIMITATIONS OF THE EXISTING LITERATURE

Some of the major limitations of the existing literature on barrelling during upset forming are observed as follows:

1. Most of the technical papers referred have not dealt with the barrelling of truncated cone billets and the effect of aspect ratio and taper on barrelling, geometrical shape factors and stress ratio parameter.

2. 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 during cold upsetting of truncated cone billets.

3. The effect of geometrical shape factor, stress ratio parameter and stresses on the radius of curvature of barrel has not been reported for truncated cone billets.

4. The effect of barrelling in metals like Zinc, Aluminium, and Copper has not been reported in the literature for truncated cone billets.

5. Mathematical modelling on barrelling for the different radii of curvature of barrel namely, circular,
parabolic and elliptical has not been developed for truncated cone billets.

No attempt has been made on open die forging of truncated cone shaped billets. Earlier research works on open die forging have been made only on solid cylinders to establish relationship between measured radius of curvature and geometrical shape factor developed based on contact diameters, barrel diameters, initial height and height after deformation.