In the name of God

Development of an Intelligent Knowledge–Based System (IKBS)

for

Forging Die Design

by

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SYNOPSIS

The work in this thesis is concerned with further development of an Intelligent Knowledge–Based System (IKBS) for forging die design. It follows on from initial work carried out at the School of Manufacturing and Mechanical Engineering.

The main parts of the original design for the system are a sequence design program (SDP) for two and three dimensional parts, an interface program which can be connected to a finite–element program for metal forming simulation and a Control Module which supervises these two parts and co-ordinates their activities. Of these three modules, only the SDP and the Control Module existed when the current work was started.

The purpose of the work reported here is to develop, improve and validate the original system. Among the five different families of components within the original IKBS, Stub Axles have been selected for the current research work.

An interface program has been written which can generate a datafile for the available finite–element program (EPFEP3). This interface program inputs one preform stage as the geometry for mesh generation and the corresponding product stage in order to determine the boundary conditions. It also inputs the data within the SDP database for completing the other parts of the datafile. This program is efficient, rapid and user friendly and can easily be extended for the other families of components in the SDP.

In the IKBS, when a new component is input to the system, each forming stage of the component should be compared with the same stage of the same family of all the components stored in the database. To do so, the significant processing and geometrical parameters and also their weighting effects should be input to the system. A new experimentally–based approach has been developed to obtain the weighting effects of the significant parameters. The weighting factors obtained are saved in the knowledge–base and have been shown to lead to the correct predictions when data for real forgings was used. The method for obtaining the weighting effects of the significant parameters can be extended to the other families of components within the IKBS.

Programs have been written to perform computer–aided reasoning in the IKBS. In particular, recognising and extracting the values of the significant parameters of the operational sequence of a component, creating the IKBS database based on real data and performing the comparison procedure for a new component stage with those stored in the IKBS database.

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CONTENTS

Chapter 1

Introduction

The work described in this thesis consists of the development of software and experimentation to enable the completion of an Intelligent Knowledge–Based System for the design of forging dies. This chapter gives a general overview of the work undertaken.

Among manufacturing processes, metal forming technology, and in particular forging, has a special position, since producing parts by forging leads to better mechanical and metallurgical properties compared to many other manufacturing processes. In this process, usually a billet of simple shape is plastically deformed between dies during one or more operations.

In industry, forging die design and its optimisation is accomplished using mostly empirical knowledge and a great deal of experience. In order to be able to set up the tools for a reliable process, considerable amounts of trial and error are necessary.

Thus, forging is a process in which tool cost is large compared with production costs, especially in low production quantities, and therefore has a great influence on the total cost of the process.

In recent years, the design of forging tools has been the topic of a large amount of research aimed at de–skilling this activity and reducing the associated cost and lead time to levels comparable with other manufacturing processes, especially by producing parts to net or near–net shapes.

During the last few years, a major advance in forging technology has been the application of computer techniques which are now considered to be an essential part of modern metal forming technology. Among these applications, Computer–

Aided Design (CAD) has had a significant impact. Several researchers have developed CAD programs for forging tools, some of which will be outlined in the next chapter.

To decrease the trial and error experimentation required for the application and validation of CAD software, another category of computer aids has been developed. This consists of techniques for process simulation, among which the application of the finite–element method (FEM) has been much under consideration and is still the subject of much research.These techniques allow most of the significant factors affecting the design process to be studied, reducing lead–time and cost. From the application of FE analysis, the greatest improvement in detail and accuracy has come in material deformation technology. The disadvantage of these techniques is that detailed studies require large amounts of computing time which make them inappropriate for routine use in industry, especially for small and medium–sized companies.

Recent work concerned with closed–die forging has shown a tendency to integrate the use of numerical simulation techniques and CAD programs based on empirical rules, because the complex shapes encountered in closed–die forging and other process variables make the operation too complicated to be described and analysed by stand–alone use of mathematical models. Also, these simulation techniques have some limitations when applied to real forming problems.

Thus, the most recent application of computers in forging has been the integration of experimental and numerical methods in Expert Systems or Intelligent Knowledge–Based Systems (IKBS), computer systems which reflect the decision–making process of human experts. In recent years, Expert Systems have been used widely in the forging industry, most of them concentrated on the design of preforming and final forming dies.The underlying philosophy of the IKBS is essentially to use rule–based procedures to design dies, and to resort to the more computationally expensive process simulation methods only when there is some uncertainty about the validity of design rules.

The author has talked to several people from industry about the current requirements of Expert Systems and IKBS from an industrial point of view and the following conclusions have been drawn:

1. In medium and small–sized companies they use experts and (in some cases) CAD programs in the design of dies. To verify the design results they normally do not use numerical simulation techniques. To do that, physical modelling, usually by the use of plasticine as a model material and plastic dies can be employed. The reason is that using the numerical simulation technique is currently costly, time consuming and expensive, and needs experts in modelling the process. Usually small and medium size companies have limited time to deliver the product to their customers. So, they do not care to obtain an optimum design.

2. In large companies the situation is different. They not only use Finite–Element simulation techniques to obtain the optimum design, but also usually have integrated systems that combine the numerical simulation tools with CAD programs [1–3]*. In particular representatives from Renault, Fiat and Ford Motors recommended and advised the use of Finite–Element techniques for validation of forging processes.

3. The idea of using the results of previous simulations in the design of a new component, which is discussed in the following chapters, has not been considered by any of the companies, but it is an interesting one, even for small companies.

The present work concerns an IKBS for forging die design. It follows on from preliminary work carried out at the School of Manufacturing and Mechanical Engineering of the University of Birmingham.

In particular, the current research concerns the process of decision–making based on the past examples stored in the IKBS database and also the integration of the CAD and the finite–element programs, together with related activities.

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* The numbers in the brackets indicate the reference numbers listed at the back of the thesis.

A brief description of the current research is as follows.

A general review of forging processes, different methods in the solution of forging problems, application of computer–aids and use of Expert Systems and IKBS in this process is given in chapter 2.

In chapter 3, the main parts of the existing IKBS and work already performed by other researchers are discussed and then the aims of the current programme of research are examined.

Integrating the IKBS with the available finite–element program, is discussed in chapter 4.

As part of the IKBS, decisions are made based on the comparison of a new component with previous ones stored in the database. The criteria for such a comparison are explained in chapter 5.

Chapter 6 is concerned with computer–aided reasoning in the IKBS, including recognising and extracting the required parameters stored in the CAD database, assessing a stage of a new component with those stored in the IKBS database and the method of creating the IKBS database.

In chapter 7, the finite–element simulation of a typical stage of deformation of a family of components which can be specified to the IKBS is examined and the results are compared with those obtained from experiments.

In chapter 8, the completed IKBS is used to examine some actual forging examples, and its recommendations are shown to be in agreement with experiment and finite–element simulation. Finally, in chapter 9, conclusions are drawn and suggestions made for the future work.

Chapter 2

Literature Survey

2.1 Introduction

To clarify the scope of the present research, it is necessary to describe previous work in this field. In the following sections, metal forming processes (especially forging), different methods of solving forging problems, their applications and limitations, use of Expert Systems and Intelligent Knowledge–Based Systems (IKBS) in forging are reviewed.

2.2 Review of Metal Forming and Forging

In metal forming processes, such as forging, rolling, bending and deep drawing, metal is formed by plastic deformation to transform a workpiece (usually with a simple geometry) into a product which usually has a complex shape. These processes include: (a) bulk forming, such as forging and (b) sheet forming, such as deep drawing. The processes may be cold, warm or hot [4].

Forging processes are capable of producing components with better mechanical properties compared to other manufacturing processes, such as casting, at moderate costs [4]. In Ref. [5] the different aspects of characteristics of forgings, such as higher mechanical properties, longer service life and optimum grain–flow orientation, compared with fabricated components in the other manufacturing processes are specified. However, it was stated that in reality a one–to–one cross–reference of a forging specification to a nonforging specification is not always possible.

Forging processes may be open–die, in which simple tools are used whose shape is not closely related to the desired shape of the workpiece, or closed–die, in which tools are used whose shape is closely related to the desired shape of the product [6].

Closed–die forging may be completely closed–die (without flash) in which an exact amount of the initial material should be prepared or closed–die with flash (conventional) [6]. Typical tool designs for these two types of forging processes are shown in Fig. 2.1 [6].

According to one estimate, on average 50% of the total cost of forgings is due to material cost, as shown in Fig. 2.2 [7]. Consequently, small improvements in material utilisation result in large savings. If these can be achieved together with greater component accuracy related to the finished product, the competitiveness of forging will be significantly increased compared with the other manufacturing processes [8].

During the last few years, the demand for more economical production processes, reduced machining and the need for technologically good properties of products have made metal forming processes such as net and near–net shape forging more important [9].

Often in forging, several forming operations (preforming) are required to produce the finished geometry from the initial simple geometry. One of the most important aspects of good forging practice is the proper design of preforms to establish adequate distribution of material. Thus, defect–free metal flow and complete filling of the die can be achieved in the final forging operation [10].

The operational sequences in manufacturing axisymmetric parts may include one or a combination of steps such as [11]:

1. Forward extrusion –Fig. 2.3.a
2. Backward extrusion –Fig. 2.3.b
3. Heading –Fig. 2.3.c

As an example, the operational sequences for a gear blank are shown in Fig. 2.4 [4].

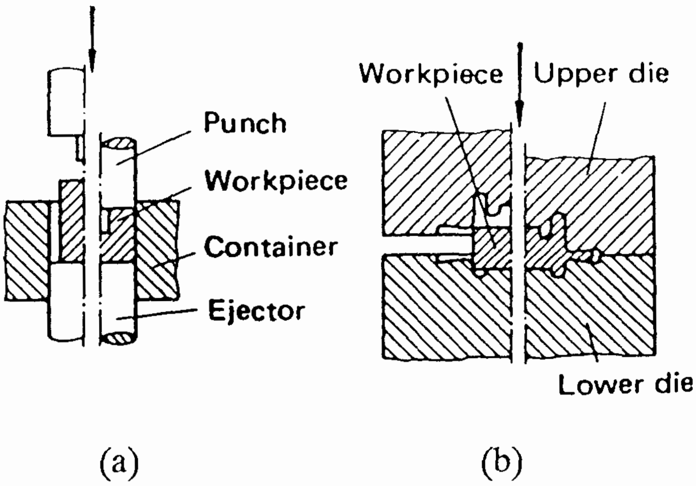


Fig. 2.1 Types of closed–die forging [6].
(a) Completely closed–die (without flash)
(b) Closed–die with flash (conventional)

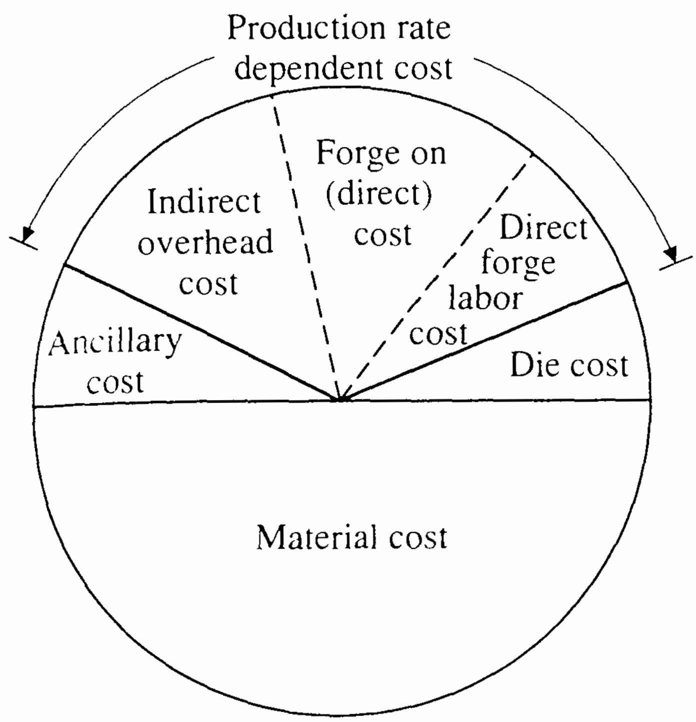


Fig. 2.2 The distribution of forging cost [7]

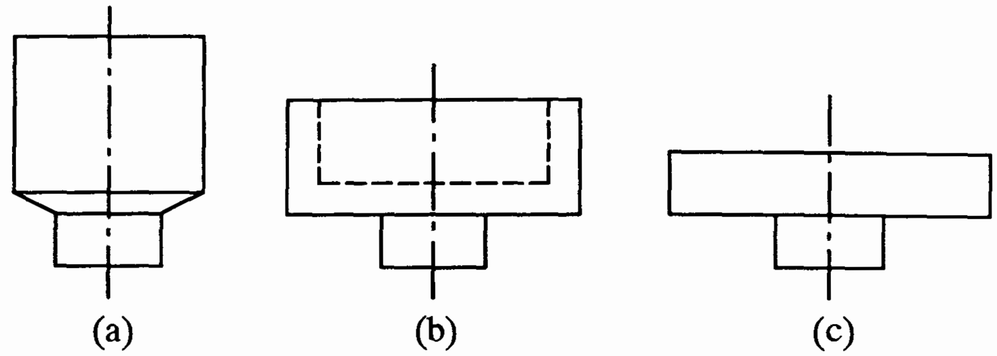


Fig. 2.3 Some operational sequences in forging [11].
(a) Forward extrusion
(b) Backward extrusion
(c) Heading

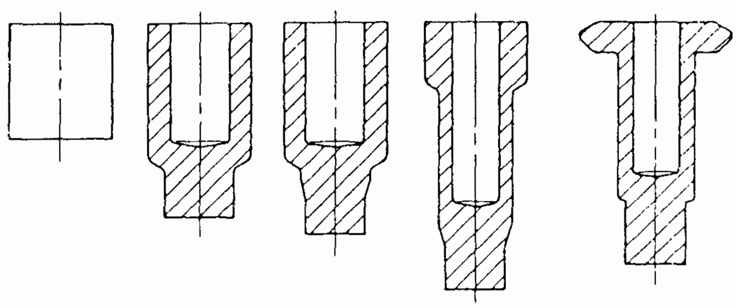


Fig. 2.4 Schematic illustration of operational sequences for a gear blank [4]. Left to right: billet, simultaneous forward and backward extrusion, forward extrusion, backward extrusion, simultaneous upsetting of flange and coining of shoulder.

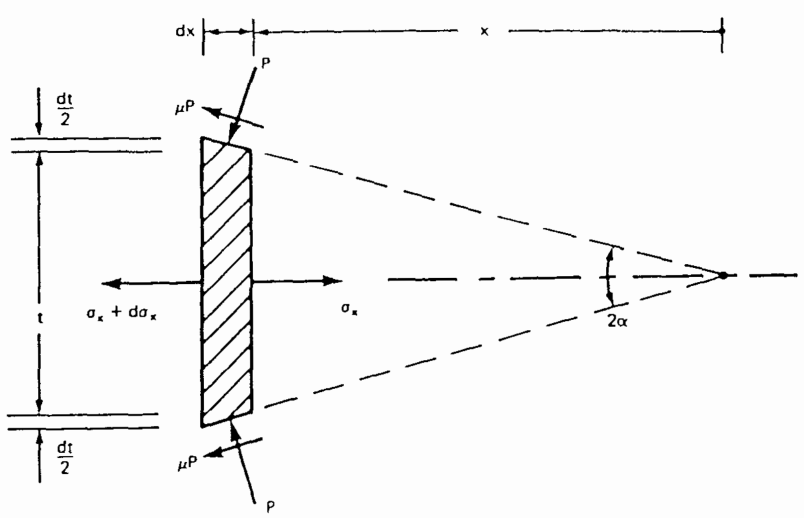


Fig. 2.5 State of stresses in the slab method for simple plane–strain [34].

2.3 Different Methods for the Solution of Forging Problems

Forging is a highly experience–oriented technology. An expert is required to design die and sequence stages to produce components without internal or surface defects, with adequate mechanical properties, with high yield from the raw material and with acceptable tool lives.

There are some major limitations in the traditional methods of designing dies, the most significant of which are as follows:

(i) A good level of expertise through many years' experience in the forging industry is required. The number of such experts is small and diminishes with time.

(ii) They are time–consuming, because sometimes an expert has to make trial and error designs to find acceptable results. So, many hours of valuable engineering time might be needed.

(iii) They are expensive, since even the most experienced designer may not produce a defect–free product the first time. Changes in the die geometries that require modification to existing dies or production of new ones will increase forging costs.

(iv) The designer does not have detailed information about material flow during the deformation, so the analysis of probable defects is not possible. In practice, to obtain some information, the cross–section of the deformed workpiece in any stage may be etched and therefore, the grain flow of the cross–section can be observed to see if the workpiece is defect–free or not. This is costly and time consuming.

(v) When a new component is to be made, the expert has to repeat the trial and error design stages.

Due to the limitations listed above in traditional forging industries, a large effort is expended on die design and development.

The most significant objective of any method of analysis of the forging process is to assist the die designer (finishing and/or preforming dies) in [4]:

(i) Predicting metal flow to ensure it is possible to make the desired shape.

(ii) Determining whether it is possible to produce the product without any surface or internal defects (folds or cracks).

(iii) Predicting loads and stresses to design tools or select forging equipment.

There are several methods, empirical, physical modelling and analytical, for solving forging deformation problems. In the following sections, some of these methods are reviewed.

2.3.1 Empirical Methods

From a mechanics of deformation point of view, closed–die forging is a complex process, because metal flow is not steady state and uniform, friction is an important factor and heat transfer (especially in warm and hot forming) between die and workpiece is significant and non–steady [12]. Also, the strain, strain rate and temperature are not constant during the operation and change from one deformation zone to another [13].

Due to these complexities, it is very difficult to obtain a general purpose method for solving forging problems which has the capability of simulating the process and optimising die design. In recent years many researchers, for example Akgerman *et al.* [10], have worked on the application of empirical methods to forging to eliminate the reliance on the memory of the experienced forging designer.

In empirical procedures, established formulae are used, which have usually been developed over years of experience. The main areas of application of these formulae are the design of operational sequences and dies [10], and estimating the maximum load and energy required to deform the material for equipment selection ([12] and [14]).

Since empirical formulae are not based on the fundamental phenomena of metal deformation and flow, they do not generally contribute very much to a better understanding of the forging process [13]. It is not possible to obtain detailed information and to predict stress and strain at different points inside the workpiece during the deformation by empirically–based rules. Also, by using empirical approaches it is very difficult to determine the variations of pressure across the interface between the die and workpiece which is an important factor in the selection of die material. With this approach the need for expertise is maintained and the only way to verify the formulae is by conducting experimental tests which are time consuming and costly.

2.3.1.1 CAD/CAM and Empirical Methods

The manual application of empirical approaches to forging processes is costly and time consuming and needs expert sequence and tool designers for successful results to be obtained.

Recent advances in Computer–Aided Design and Manufacture (CAD/CAM) have shown how the skill and experience of expert designers can be enhanced [13].

CAD/CAM has been widely used in different areas in metal forming processes, such as sheet metal forming in which work has been done by Tisza and Racz [15].

Many researchers have developed computer software to design operational sequences and dies and/or to predict load and energy based on empirical procedures in forging which have been proved to be successful, and some of them will be reviewed in this section.

The main objectives of CAD in forging are to [16]:

(i) Decrease the cost of the forging process.
(ii) Speed up and de–skill die/sequence design procedures.

Akgerman and Altan [17] developed a computer–aided technique for designing preforms for rib–web type structural forgings. Biswas and Knight ([18] and [19]) extended their work and developed computer software for designing axisymmetric and elongated forgings and dies based on empirical rules. This software was not interactive. Lui and Das [20] developed an interactive computer method for the design of axisymmetric forging dies using a desk–top computer.

Lengyel and Venkatasuramanian [21] proposed a computer–aided method of optimisation of alternative cold forging processes. Gokler, *et al.* [22] developed a computer–aided system for hot upset forging design in which the shape classification and geometric representation of the forged products was based on Group Technology and the process design was based on this method. Several other researchers extended the work on computer–aided process planning in forging, with the automatic recognition of the geometric characteristics of products, automatic design of the forming process and supporting the product design requirements such as interactive graphics and dimensioning, such as that done by Badawy, *et al.* [23], Sevenler, *et al.* [24] and Kim, *et al.* [25].

Another application of computers in forging is CAM, which can improve the accuracy and consistency of die–cavity manufacture by linking the design software to NC machines. Several researchers have developed integrated CAD/CAM packages for the design and manufacture of forging dies. Akgerman and Altan [26] developed a CAD/CAM technique for forging structural parts which could be used to predict forging load and determine the preforms. Both the preforming and finishing dies were manufactured via NC machining and EDM.

Yu and Dean [27] extended on the previous research work and developed a CAD/CAM package for axisymmetric forging dies by use of a microcomputer which could be used for the design of both hammer and press dies.

The advent of interactive computer graphics has enabled the die designer to observe the design results and using experience to modify them easily, if necessary.

Forging companies are now using CAD/CAM increasingly, taking the advantages of a computer's capabilities to modify traditional procedures for forging die design and manufacture ([16] and [28]).

2.3.2 Physical Modelling

The use of models has been accepted as a tool in the design and development of many branches of engineering science. The primary reason of using a model is that it can provide information which otherwise would be inaccessible or expensive [29].

Physical modelling in metal forming processes is based on the idea that metal flow can be simulated by the use of a soft model material, such as lead and plasticine, less expensive dies, such as hard plastic or mild steel, and simple tools. Therefore, it is easier, cheaper and faster to modify the geometries of the die and the corresponding preforms and optimise them, as well as to change the process variables than if the real materials were used [30].

The aims of the physical modelling are mainly studying and measuring [30];

(i) The filling of the die, strain and strain rate distribution during the deformation,
(ii) Load distribution on the tool surface,
(iii) Hardness and strength distribution of the deformed workpiece,

In Ref. [30] and [31] the laws of similarities of the model material and the real material are explained. It was shown that perfect similarity is not practically possible to achieve in complex metal forming processes. However, approximate similarity could be obtained. Based on the similarity laws, for friction it is required that an identical friction factor in the model and real material should be obtained, which represents a major difficulty. The conditions for the materials' laws (mainly flow stress) in hot forming are complex and it is practically impossible to achieve similarity over a range of deformation.

Physical modelling has been used in different aspects of metal forming processes; in predicting forming load, such as [31], in experimental verification of preform design in forging, such as [32], and to validate the results of finite–element simulation, such as [33].

For more detailed simulation, mathematical modelling discussed in the following section, is superior to physical modelling. The mathematical–numerical modelling techniques are most likely to be acceptable in order to facilitate integration with other aspects of computer integrated manufacturing and fit better into the modern concept of CAD/CAM where the designer can simulate the process, design the tools and send the raw data directly to the workshop for NC machining [30].

2.3.3 Analytical and Numerical Methods

Empirical rules do not avoid the need for extensive trial and error experiments when applied to non–standard components or materials. Also, the rules may not lead to an optimum die design. These limitations cannot be removed by the use of physical modelling. Thus, much work has been done in mathematically analysing forging problems. There are several analytical and numerical methods that have been developed, none of which is exact. This is because of the assumptions made in the mathematical models and the lack of knowledge concerning workpiece material characterisation and boundary conditions.

Some of the well known methods are: slab method, upper bound, uniform energy, slip–line field, visioplasticity, finite–difference and finite–element methods.

In this section a brief description of these methods is given.

The **slab method**, also called free body equilibrium method, is based on the force balance for stresses acting on a slab of material with a thickness dx (Fig. 2.5) [34]. This produces a differential equation in which stress variations are considered only in one direction. By using relevant boundary conditions, the integration of the equation produces a solution in the form of a pressure distribution over the surface of the workpiece [34]. In this method the friction effect at the die–workpiece interface is considered but the effect of friction stress upon the internal stress distribution is neglected and therefore an unknown magnitude of errors is introduced [13].

Based on the slab method, several researchers have analysed simple and complex forging shapes, especially by using modular analysis and computer techniques. Altan and Fiorentino [12] derived equations to predict stresses and forming loads for plane strain and axisymmetric upsetting under inclined surfaces by using the slab method. This is shown in Fig. 2.6 [12]. In order to determine the final force (or maximum load) in a forging, they used some previous rules to find the flow model at the final stage of deformation, which is a combination of plane strain and/or axisymmetric upsetting deformation zones shown in Fig. 2.6. By determining the load on each zone and adding them, the final force was calculated.

Akgerman and Altan [35], developed a computerised method for modular analysis of geometry, stresses, load and energy in closed–die forging of complex structural shapes based on the slab method. This method consists of dividing a forging into standard components, such as plane strain and axisymmetric 'H', 'U' and 'T' cross sections which could be assembled in a building block manner to analyse the given forging. This analysis was applied to an actual forging and the theoretical predictions were compared with experimental results.

Several other pieces of research have been done to simulate forging processes by the slab method, such as that done by Altan [36] and Biswas and Rooks [37] which were compatible with actual results but they needed much expertise in estimating flow models, large computing capacity and also the results were limited to the prediction of approximate stresses, load and energy.

In the **upper bound method**, the following steps should be performed [38]:

1. Describe a family of kinematically admissible velocity fields which must satisfy continuity in metal flow, incompressibility of material and the prescribed boundary velocity conditions or compatibility conditions.

2. Calculate the total energy rate according to the energy rates for deformation, internal shear and friction shear. These will all be upper bounds on the actual energy rate.

3. Minimise the total energy rate with respect to the defined parameters of the velocity field formulation, which leads to the lowest upper bound.

The forming load, thus calculated, is greater than the actual load required in the process, assuming the flow stress and boundary conditions are defined adequately, and represents an upper bound to the actual deformation load and the lower the upper bound load, the better the prediction would be.

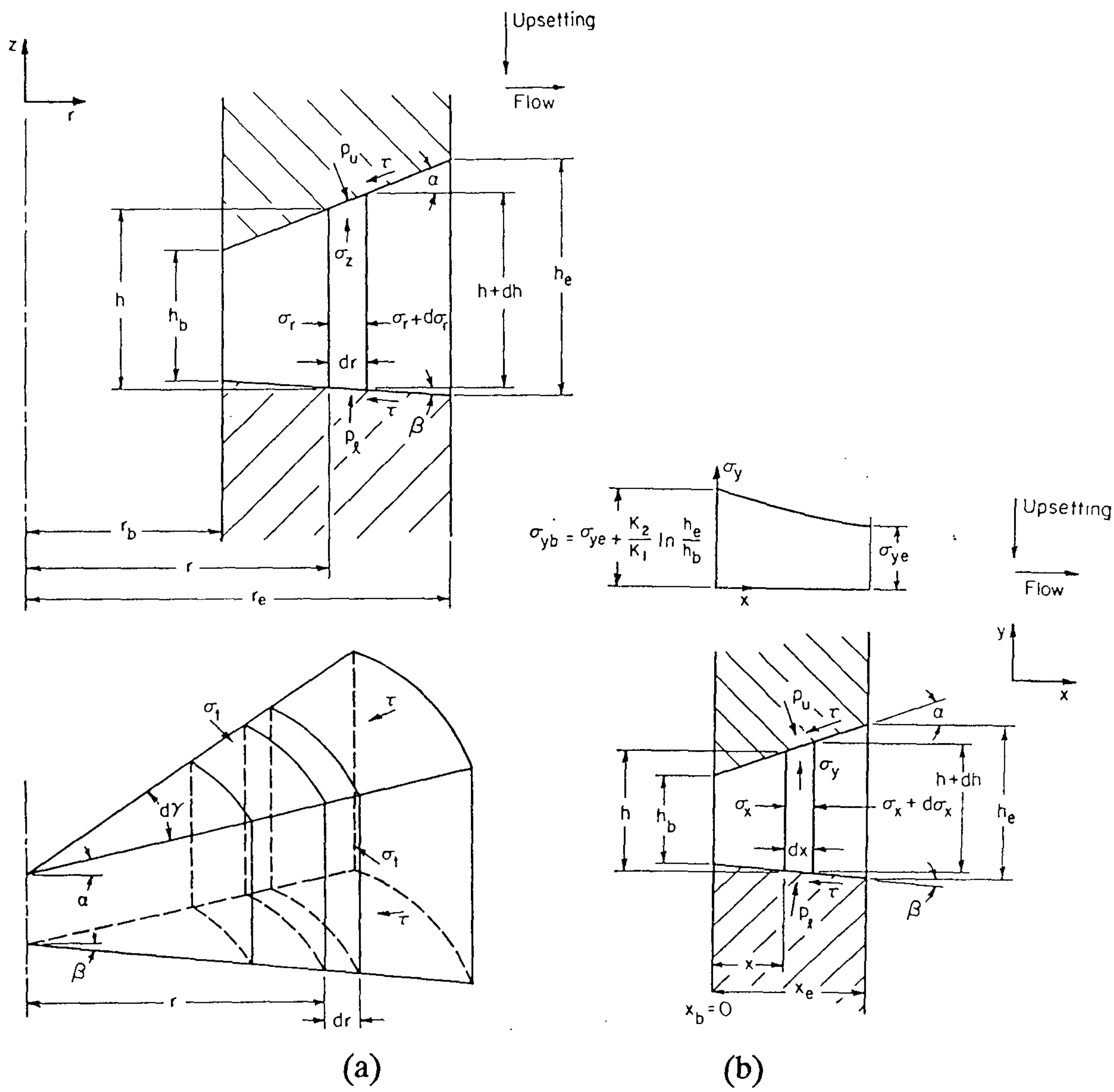


Fig. 2.6 Predicting stresses and load under inclined surfaces by using slab method [12]. (a) Axisymmetric (b) Plane strain

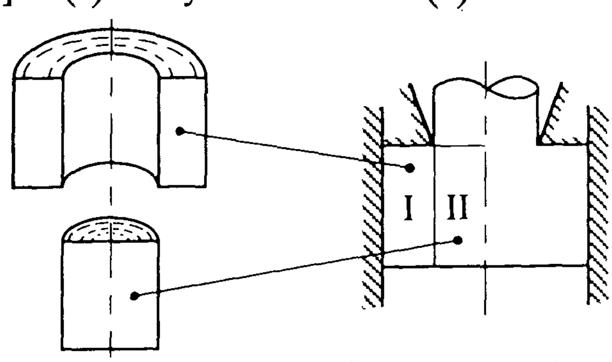


Fig. 2.7 Dividing an extrusion forging into a ring and a cylinder based on the UBET [39]

Using the upper bound method, many researchers have studied forging problems, such as Kudo [39].

Similar to the modular analysis based on the slab method stated in this section, the Upper Bound Elemental Technique (UBET), which is based on the upper bound method, has been applied to the analysis of forgings. In this technique, the forging is divided into basic elemental regions. Fig. 2.7 shows how an extrusion forging was divided into a rectangular ring and a cylinder by Kudo [39]. McDermott and Bramley [40] extended this concept and defined eight basic rings, as shown in Fig. 2.8, to analyse forgings.

In Fig. 2.9 [40] the process of dividing the half cross–section of a complex axisymmetric shape, Fig. 2.9.a, to simple elements, Fig. 2.9.b, based on the UBET is shown.

Some computer programs have been developed to simulate forging processes with the UBET to determine load and to predict metal flow in forging, such as that described by Osman and Bramley [41], and by Bramley [42].

The **uniform energy method** is a simple approximate method to predict forging load and average pressure in which the external work is equated to the consumed energy to deform the workpiece. This is an idealised method because it is assumed that the external work in the process is completely utilised in deformation, that there is no friction and that the deformation is homogeneous [34].

The **slip–line field** (or maximum shear plane field) **method** consists of setting up families of shear lines which are lines showing the directions of maximum shear within the plastically deforming body. They are orthogonal to each other and form a network called the slip–line field [43]. In order to determine the load and average pressure required to deform a workpiece in a particular operation, the slip–line pattern must be obtained. Several researchers have discussed the theory and developed extensive applications of the slip–line field, such as Rowe [43].

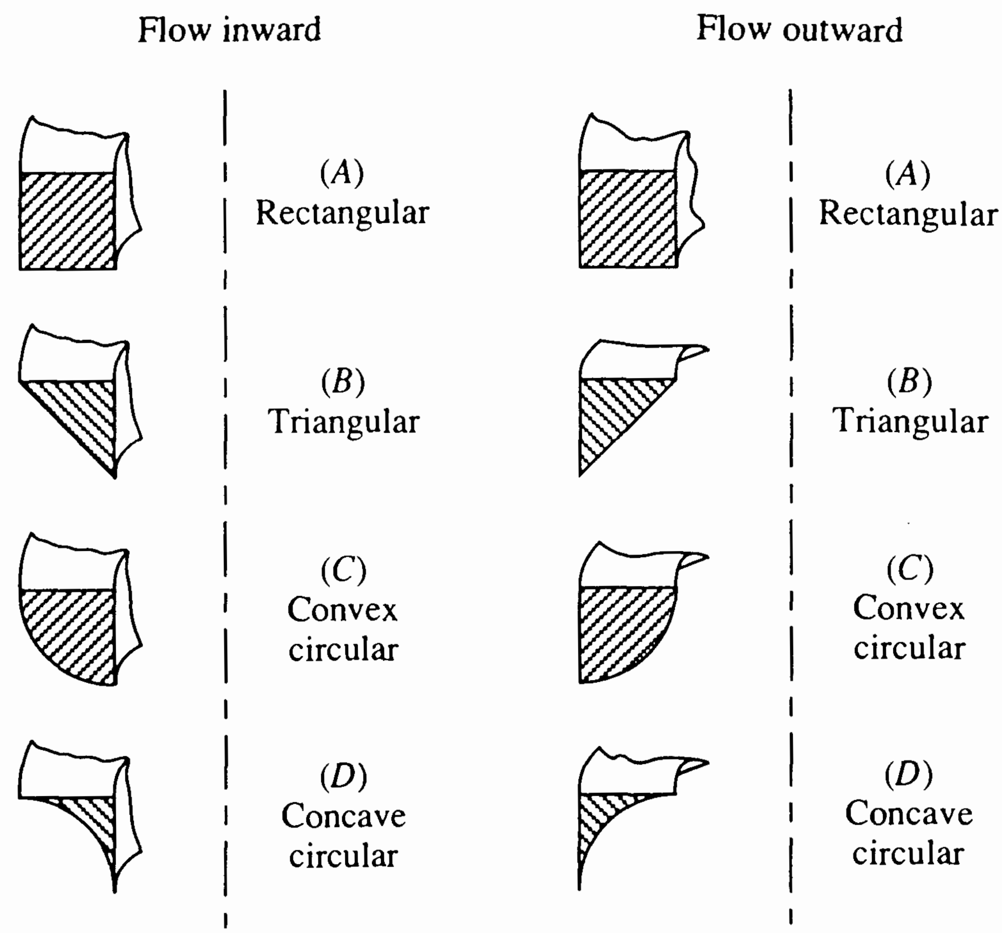


Fig. 2.8 Eight basic elemental rings in the analysis by UBET [40].

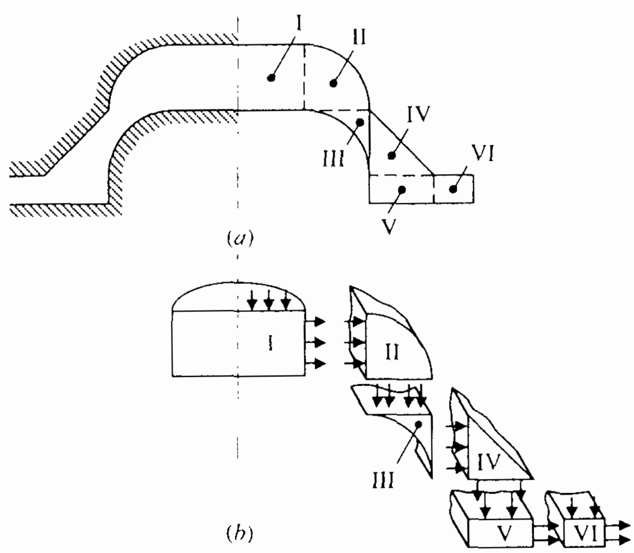


Fig 2.9 Schematic illustration of dividing half cross–section of an axi–symmetric complex shape into simple shapes in UBET [40].

(a) Cross–section

(b) Divided half cross–section

Often, the limitations made by the required assumptions in this method, such as homogeneous, isotropic and rigid–perfectly plastic material with no temperature, strain–rate or time effects [13] and its applicability to only plane strain, make it very difficult to apply to actual problems [44].

The methods mentioned so far have serious disadvantages, since in using them several assumptions should be made. They require knowledge of the metal flow pattern and velocity fields and they may be restricted to an idealised type of deformation [45]. Moreover, these methods can normally provide information only about certain aspects of the forming analysis, such as stresses, load and energy. Approximation of metal flow can also be obtained in the case of UBET [46]. With these methods, most of the work is restricted to axisymmetric or plane strain geometries which can be easily divided into deformation modules [47].

The **visioplasticity method** is an experimental technique for determining displacements, strains and strain–rates. In this method a grid pattern is placed on one face of longitudinally split billets which are reassembled and deformed between dies in several stages. After each stage, the distortion of the grid is measured, from which the strains and strain–rates are calculated by numerical differentiation. The stress distribution is obtained from plasticity equations [48].

The visioplasticity method can be utilised to validate the results of other analytical and/or numerical methods, though any errors in measuring grid distortions may lead to significant errors in the results [44].

In the visioplasticity method the chosen section must remain a plane during the deformation and the two halves of the billet must not separate.

In the **finite–difference method** an approximate differential equation is prepared to analyse the forming process. The basis of this method is to approximate a first derivative by a small finite step. The workpiece is divided into sub–sections by lines or curves, the intersections of which are called mesh points. The solution to the equation is expressed as a function involving the difference between the values of the parameters under consideration at the mesh points. The solution proceeds in small iterative steps until the difference between two successive values of the solution is small. In this method the starting values are obtained from a known initial condition [44].

Accurate determination of the effects of various process parameters on detailed metal flow became possible only recently, when the finite–element (FE) method was developed for the analysis of forming processes. Since then, the FE method has steadily increased in importance in the simulation of metal forming processes [47] and is the subject of the rest of this section.

The **finite–element method** is a fairly recent development in engineering applications and its early uses were limited to structural analysis.

The FE method is based on dividing a continuous body into elements which are interconnected at nodes. The desired parameters such as stress, strain and displacement are determined at the nodes. By interpolation, these parameters can be derived at other points in the elements. Therefore, FE analysis is an approximate method in which a series of points (nodes) are considered, i.e. the parameters are defined as the values at nodes [49].

In estimating stress and strain for static structural problems, the step–by–step procedure can be stated as follows [49]:

(i) Divide a continuum into discrete elements which are interconnected at nodes.

(ii) Define interpolation functions for elements to approximate the displacements of element points.

(iii) Determine nodal force–displacement equation for each element, i.e.:

$$[K^e]\ \{u^e\}=\{F^e\} \qquad (2.1)$$

in which $\{F^e\}$ is the element nodal force vector, $\{u^e\}$ is the element nodal displacement vector and $[K^e]$ is the stiffness matrix.

(iv) Assemble the above equations for elements to produce a stiffness equation for the global system, i.e.:

$$[K]\{U\}=\{F\} \qquad (2.2)$$

where $\{F\}$ is the nodal force vector, $\{U\}$is the nodal displacement vector and $[K]$ is the assembled stiffness matrix for the global system.

(v) Apply the boundary conditions to solve for the unknown nodal displacements.

(vi) Compute element strains and stresses from the nodal displacements, using the interpolation functions.

The finite–element method has been extremely useful in a wide range of engineering applications. In metal forming processes such as forging, the deformation is plastic. Moreover, during the process, the geometry of the part, material properties and boundary conditions are changing. Thus, the stiffness relationship (Eq. 2.2) is nonlinear and so the FE analysis must be performed incrementally [50].

In recent years one of the most significant advances in the analysis and simulation of metal forming processes has been the development and application of the finite–element method. Many researchers have simulated the large–strain material deformation in metal forming processes with different models used to define the constitutive relationships (such as rigid–plastic, rigid–viscoplastic and elastic–plastic) the details of which can be found elsewhere, such as references [51] and [52].

The main advantage of the finite–element method in metal forming processes is its ability to generalise, i.e., it can be applied to a wide range of boundary value problems with little restriction on the geometry of the workpiece and boundary conditions [53].

In comparison with the other mathematical methods, the FEM has the advantages of solving problems with complex shapes and non steady–state processes and obtaining information about material flow, stress and strain fields [13].

Using FE simulation software allows running forging experiments on the computer by simulating the process of deformation. Experiments can be repeated until satisfactory results are obtained. This eliminates trial and error using expensive dies and materials [28].

Among the researchers in the above area, the Solid Mechanics and Process Modelling Research Group in the School of Manufacturing and Mechanical Engineering of Birmingham University has been working on the development of finite–element programs and the simulation of different metal forming processes using an elastic–plastic approach with the associated large plastic deformations and rotations included. The main program used for this work is EPFEP3 (Elastic–Plastic Finite–Element Program for 3 dimensions) some aspects of which will be described in chapter 4. The predictions of this program have been shown to be in agreement with experiment ([45] and [52]) and it has been demonstrated that the large–strain finite–element technique provides a powerful tool for studying the deformation in metal forming operations [52].

In spite of the significant advantages of the finite–element method in studying metal forming processes, it does have some disadvantages, the most important of which may be stated as follows ([52] and [54]):

(i) It is not possible to design forging dies or determine the number of operational sequences or preforms which is required in practical forgings.

(ii) Detailed studies of metal forming processes by this method require large amounts of computing time and memory–space, which is a serious limitation in non–linear analysis and makes it inappropriate for routine use, because of cost and time taken.

(iii) A considerable amount of skill is required to set up a model (meshing, specifications of material characteristics and definition of boundary conditions) and an extensive background on metal forming is needed to interpret the results.

Large companies and those in high–technology fields are now using FE simulation packages to analyse their forging processes.

2.4 Integration of Different Methods

The available experimental or physical modelling techniques do not offer a solution for optimum preform design, except by repeated trial and error for guessed preform shapes.

Some efforts have been made to design optimum preforms by using analytical and numerical methods for reverse solution or backward tracing, in which the process is carried out in reverse, i.e. starting from the final forging shape and allowing the top and bottom dies to move apart in a direction opposite to that which occurs during the forming of the shape ([46], [55] and [56]).

Despite these attempts, no significant industrial usage of this procedure has been reported.

As discussed in the sections 2.3.1 and 2.3.3, CAD programs based on the empirical rules and the finite–element methods have some characteristics, which can be considered as being complementary.

Often, in practical forging, it would save time and cost to be able to use both of the methods in one single system. In other words, it would be beneficial to use CAD software to design operational sequences and to use the finite–element simulation to analyse each stage and thus to show whether or not the sequence predicted good results or to indicate how it could be improved, instead of performing experimental tests.

Using each system on a stand–alone basis will cause errors in transferring data and is also time consuming. There is an obvious need, therefore, for an integrated system.

In the next section, some advanced integrated systems in metal forming or forging such as expert systems or IKBS, are reviewed.

2.5 Expert Systems and IKBS in Forging Problems

More than thirty years ago, the attempts made to model problems such as machine translation and natural language led to a new field called ***Artificial Intelligence*** (AI) [57].

There are different definitions for AI, all of them are similar in their basic structure [58], such as: AI is a branch of computer science concerned with programs that exhibit intelligent behaviour, like human intelligence [59], or AI is the science that tries to replicate intelligent human behaviour on computers [58].

The need for symbol manipulation in AI to represent knowledge and knowledge handling, as something other than numbers, has led to the development of the AI programming languages such as LISP and PROLOG which are different from the conventional (procedural or algorithmic) programming languages like FORTRAN and PASCAL in several respects, the most important of which are as follows ([57], [58] and [59]):

1. They have better data structures for non–numerical computations, such as lists and strings which are type–free and extensible.

2. In contrast to algorithmic programming in which knowledge and control are integrated, AI programming does not represent the knowledge as part of the program procedure (separation of knowledge and control). This gives a great deal of flexibility and, therefore, the user is able to modify or update the knowledge easily and to solve different problems without considerable change to the program. While, in algorithmic programming changing the way a problem is handled requires a major rewriting of the program.

3. In conventional programming the computer is told in advance what must be done with the data subsequently entered. Thus, the procedures are the representation of how something is being done. In AI programming, on the other hand, declarative knowledge about a domain is represented, that is, what is known is represented without deciding in advance precisely how that knowledge will be used.

In Fig. 2.10 [59] the structures of traditional algorithmic and AI programming are shown.

Artificial Intelligence includes a range of more specific disciplines. The field concerned with the present work is ***Knowledge–Based Systems*** (KBS), which are more commonly described as ***Knowledge–Based Expert Systems*** (KBES) and ***Intelligent Knowledge–Based Systems*** (IKBS). This is also a broad field and includes several topics. The one which relates to the current research is concerned with ***Expert Systems*** (ES) [60].

Despite the above classification, the terms IKBS, KBES, KBS and ES, are used interchangeably during this work. When attention is to be focused on the knowledge the systems carry and the intelligent behaviour of the systems, the term IKBS is used.

There are different definitions of Expert Systems, which emphasise their different aspects. For example, some definitions focus on the tasks that these systems can perform, while others pay attention to the way the tasks are implemented. Generally, these systems are defined in the following way [61]:

> 'Expert Systems are a product of AI, the branch of computer science concerned with developing intelligent programs.'

An Expert System includes the following components [61]:

(i) A knowledge–base, containing the system's task–specific information such as data, facts and rules.

(ii) An inference engine (also called an inference mechanism, control structure or reasoning mechanism); a mechanism which selects and applies knowledge from the knowledge base to solve the specific problem and produces an explanation for the solution.

(iii) A user interface that allows the user to communicate and interact with the system in natural language.

(iv) A knowledge acquisition module which develops or modifies the knowledge–base.

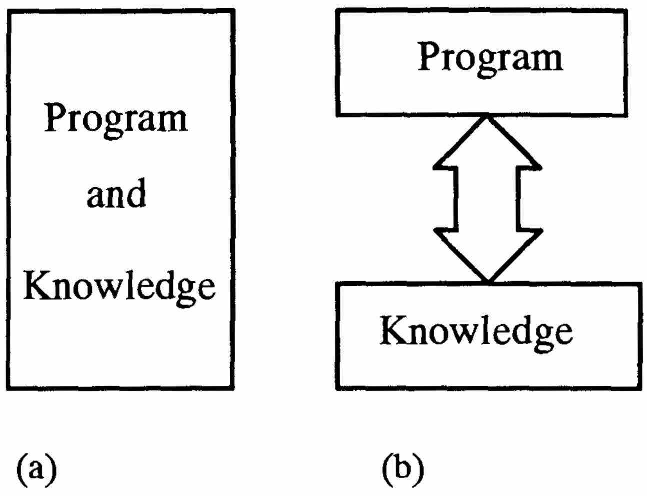


Fig. 2.10 The structures of traditional and AI based programming [59].
(a) traditional (b) AI based

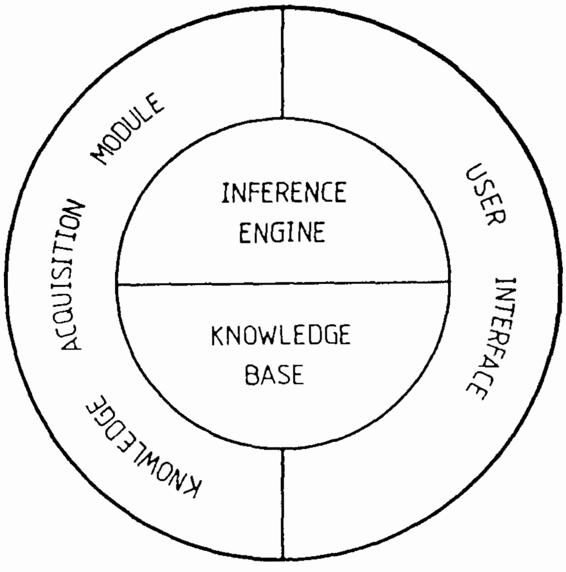


Fig. 2.11 A schematic illustration of different components of an Expert System [61].

Fig. 2.11 [61] illustrates the different components of an Expert System.

As is obvious from the figure, the central parts of an Expert System are the knowledge–base and the inference engine.

One of the characteristics of Expert Systems, as shown in Fig. 2.11, is the distinction, but interaction, between the two main parts which has two important consequences [62]:

(i) By substituting a new knowledge–base for the existing one, a new system can be produced. Thus, the same inference engine can be used in conjunction with the knowledge obtained from different domains to make different expert systems from the same basic building blocks.

(ii) It is possible to utilise the same knowledge–base in different ways, such as to provide explanations and to acquire new knowledge.

There are several ways to construct the knowledge–base, the three most popular ones are rules, frames and semantic nets [63].

In a rule–based system, knowledge of a problem area is represented as facts and rules for manipulation them [63].

Facts are asserted in statements which explicitly classify objects or specify the relationship between the objects [63], such as 'Forging is a metal forming process'.

Rules are statements of the form [64]:

'IF Situation THEN Action'

where the first part determines the condition(s) or situation(s) that must be satisfied for the rule to be applicable and the second part is the action(s) that must be taken once the rule is applied.

Despite the usefulness and importance of rule–based representation, it is unable to describe adequately the fundamental principles in a problem area. In contrast, representations that use frames or semantic nets allow a deeper insight into underlying concepts, provide a higher–level reasoning and representation, and makes possible the construction and manipulation of large knowledge bases ([58] and [61]), though frames and rules can be integrated, say by using the arbitrary LISP coded procedures [65].

Frames represent structured objects and are usually organised into a hierarchy, with those at the upper levels representing more general information and those at the lower levels are specific attributes of the upper ones [63]. This will be explained in chapter 6, where the structure and use of the IKBS database, which is a frame–based representation, will be discussed.

Knowledge representation schemes based on semantic nets are similar to those based on frames and are networks of nodes linked together by arcs. Further explanations on Knowledge representations can be found in ([58], [63] and [65]).

In recent years, significant successes have been recorded in packaging human expertise into Expert System software and Expert Systems, Knowledge–Based (Expert) Systems and Intelligent Knowledge–Based Systems have been used more widely in industrial applications in different areas, such as that by Motz and Haghighi [66] in which different modules interact through a design expert system for the design and selection of mechanical springs. In the rest of this section only some of the systems concerned with forging processes will be examined.

Among the possible uses of Expert Systems in forging processes is their applications to die design and process planning.

As stated in section 2.3.1.1, in forging processes much research work has been done on the development of CAD software to automate sequence and design tasks. In performing these tasks, decision–making is more important than computational considerations. Thus, Expert Systems or Knowledge–Based Systems are of great value in this area, by making the knowledge of human experts more easily accessible and widely available. These systems also can provide an explanation of how to select and apply design guidelines.

Several researchers have worked and developed such computer systems, some of which are reviewed below.

Kuhn and Ferguson [67] discussed the application of Expert Systems to preform design in powder forging. They developed software which included a geometry/ graphics module, a knowledge–base and an interface between these modules which performed the design decision. The design module could take the geometric data describing the workpiece and make decisions about dividing it into simple sub–segments. It then applied the rules from the knowledge–base to each of the segments and established a complete preform design.

Bariani and Knight [68] discussed some developments in the design of a Knowledge–Based System which is capable of generating operational sequences which are technologically feasible for multi–stage cold forging of solid and hollow rotationally symmetric parts. They focused on the classification and structure of the design rules in the knowledge–base into different groups and distinguished the sequence procedure from the design rules. The technological feasibility of this system is based on established design rules governing both the extent of possible deformation for individual cold forging operations and the sequencing and grouping operations in the different stations. They argued that since most of these rules translate the reasoning and the experience of experts, the technological feasibility guarantees that the workpieces will be formed at the different stages without any defects.

Bariani, *et al.* [69] extended the above work as a Generate, Test and Rectify (G, T & R) system. The basic structure of the generation procedure is similar to the above system. The testing procedure for suitability is based on load–peak and energy consumption distribution at the machine stations and effective strain accumulated in the workpiece.

Lengyel and Tay [70] described the development of a rule–based expert system to produce some operational sequences in the cold forging of steel. Among the sequences, the program selects those that satisfy the process rules and calculates parameters such as load and stresses for each operation. The rules have been classified into rules of design for production, process planning and selection, design and development of production equipment. They stated that several variations of operational sequences are feasible even for a component with a relatively simple shape. The method they used gives the user the opportunity to devise the sequences which are practicable and code them in the knowledge–base. The sequences then will be checked with the rules. The feasible one will be selected and the ones which are not practical will be rejected and the reason for rejection stated.

Danno, *et al.* [71] and Nakamishi, *et al.* [72] in TOYOTA Central Research and Development Laboratories developed a knowledge–Based System, called FOREST, for the automatic generation of forming sequences in multistage cold forging of axisymmetrical solid and hollow products. This system has a wider applicability to various kinds of cold forged products with a specific method for the generation of forming sequence called 'Transformation–Knowledge Unit'.

Osakada, *et al.* [73] used Artificial Intelligence techniques for process planning in cold forging of steel. They discussed the limitations of the conventional procedure for process planning and the applications and usefulness of AI techniques. They emphasized that pattern recognition of the product is an important function in designing a forming sequence. The method that they used for a product consists of simple primitive geometries and is similar to that used in the CAD program of the existing IKBS which will be explained in chapter 3. Once the sequence of preforms, which were assumed to be physically possible and industrially meaningful, was obtained, the possibility of the process could be tested by empirical and theoretical rules.

A Knowledge–Based System called BID [74] was developed by Vemuri *et al.* to automate blocker design which is a highly experience–based task. This system is flexible enough to generate different blocker designs by changing the procedures for modifying the design parameters. These procedures consider the effect of different variables such as finished part geometry, material properties and temperature.

Kim, *et al.* ([75], [76]) developed an expert system for multistage cold forging of axisymmetric geometries with or without a hole in one end. The system could determine the number and geometry of the intermediate steps. It could be run on an IBM 486 PC using PROLOG language. The system consisted of a user interface, a system shell including graphics, input, and output modules, an inference engine and working memory, and a material database and rule–base.

Several other researchers have developed design systems using Expert Systems or KBS. These include Wang and Chen [77] who proposed a structured method for knowledge extraction in building Expert Systems for designing dies for precision forging, Bettendorf and Davis [78] who designed and implemented a KBS for process planning in forging and Penchev [79] who developed an Expert System in the automatic design of hot die forging.

The systems that have been reviewed so far use Expert Systems in a way that, instead of using the designers' expertise or inflexible procedures in a CAD system, computerise the decision–making involved in the design of operational sequences, preform and finishing dies. Although these systems improve the efficiency of CAD programs based on empirical guidelines, they do not avoid the limitations of such programs which have been discussed in section 2.3.2. Thus, a large number of attempts have been made to integrate Expert Systems with simulation techniques to verify the designed sequences and dies. In the remainder of this chapter some of these integrated systems are discussed.

Yang and Osakada ([80] and [81]) extended their earlier work [73] and classified the process information into fundamental process information and sample process information. Fundamental process information concerned the type of forming process such as forward extrusion, backward extrusion, heading, etc. Sample process information referred to the actual changes in the state of the billet in each forming stage, which was acquired from forging practice. When a final shape of product was input to the user interface, the sample process database was searched to find whether there existed processes for the same kind of product. Otherwise, the system began to generate forming sequences using the fundamental process database.

Since several forming sequences could be obtained, a module was used in the system to evaluate the feasibility of the proposed processes by considering the order of evaluation of each sequence which could be identified in another module. The selected feasible sequence could be evaluated by FE simulation.

In the research work of Alberti *et al.* [82], an integrated system was developed in which a number of feasible operational sequences for cold forging may be selected by means of KBS and then a finite–element simulation technique can be used to perform a detailed comparison in order to determine the optimal sequence.

Sevenler [83] developed an integrated process planning system using KBS methodology for die design in cold forging with the aid of some commercial tools. This system consists of various major parts such as those for:

(i) Designing the cold forged product
(ii) Forging sequence design
(iii) Verifying the sequences using FE simulation
(iv) Die design and manufacture.

Lee and Hsu [11] proposed an integrated CAE system for cold forging in which a knowledge–based process planning system was developed as a central module for engineering design. This system which combines experience–based design rules and a finite–element simulation technique, is integrated with commercial software modules of:

(i) Plasticity analysis of the cold forging process
(ii) CAD/CAM
(iii) Production simulation and economics analysis.

The integrated systems discussed in this section, in general, contain the advantages of both expert systems and FE simulation techniques stated in the previous sections.

As stated before, the extensive use of FE simulation techniques appears still too expensive, especially in the work of Alberti in which they would be performed for each of the preliminary sequences. Therefore, the less these techniques are used, the more cost will be saved in the forging tool design process.

Recently, (Artificial) Neural Networks have been widely used in different areas of engineering applications as a kind of AI system.

The basic unit of a Neural Network is a neuron to which a set of inputs is applied. Each input is multiplied by a corresponding weight and all of the weighted inputs are summed and if this exceeds the activation level of the neuron it applies an input value to all the neurons connected to it [84].

The neurons are usually arranged in layers, a neuron receiving input from those in the preceding layer and transmitting output to those in the succeeding one.

To train a Neural Network, the output of the network is calculated and compared with the corresponding target (desired) output. The difference (error) is fed back through the network and weights are changed according to an algorithm that tends to minimise the error [84].

Fig. 2.12 [84] illustrates a simple two layer neuron Neural Network. It is shown in the literature that the two layer Neural Network with one or more neurons has little actual application and it is usually necessary to have at least one more hidden layer, as in Fig. 2.13 [84].

Osakada and Yang ([81] and [85]) used a Neural Network approach as part of an integrated expert system in process planning of cold forging. As an example, they introduced in the input layer the data of shape complexity of the workpiece, number of primitives of the workpiece, flow stress of the workpiece material and die strength, and as the output layer, the number of forging steps (deformation stages).

They used about 60 sample products and their actual number of forming steps to train the network and concluded that the application of Neural Network technique could greatly improve the performance of the expert system. These authors stated that to train a Neural Network does not need a knowledge base but the performance of the system depends on the amount of actual data that is introduced to the system. They stated that since the number of data used for the training of their system was too small, it was necessary to test under industrial conditions with a sufficiently large number of actual data.

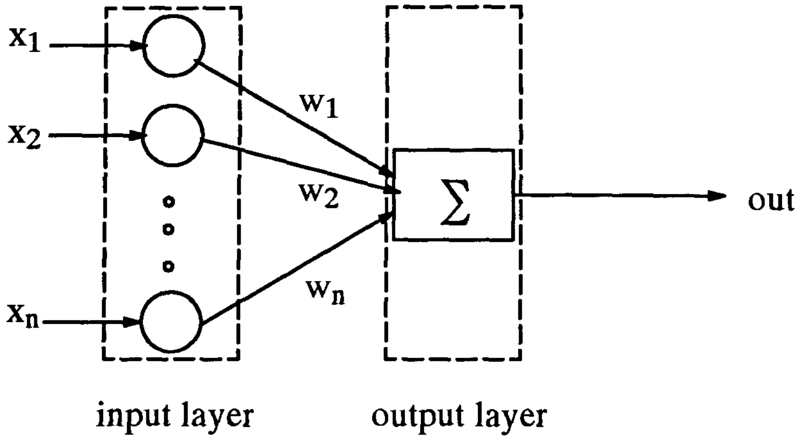


Fig. 2.12 A two layer single neuron Neural Network [84]

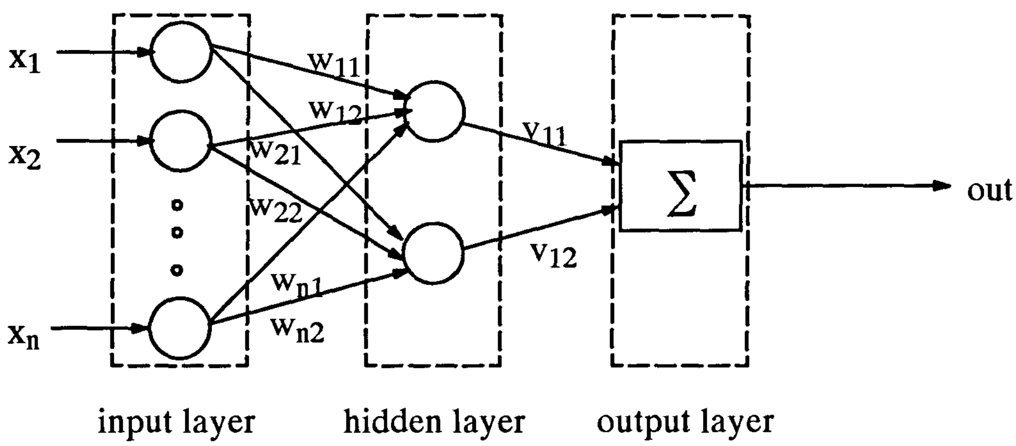


Fig. 2.13 A three layer Neural Network [84]

For many years research in the two areas of developing CAD and KBS based on empirical rules and predicting metal flow and properties with FE techniques has been in progress at the University of Birmingham, some of which has been discussed in the previous sections. An obvious next step was to extend the above fields to develop an integrated system which was more comprehensive and had more efficiency than either of the two areas in stand–alone use. This extension was the Intelligent Knowledge–Based System.

Hartley *et al.* [86], Eames [87] and Hartley *et al.* [88] discussed the basic idea and development of an IKBS for upset forging die design (the first system). In Fig. 2.14 ([86], [87] and [88]) a brief description of a possible integrated system is illustrated.

As shown in the figure, the two main parts of the system are:

(i) A CAD program, UPSETDIE [89],
(ii) EPFEP3, the finite–element simulation program.

Another part of the system is, obviously, an interface with the user together with a control program.

The main difference between this system and the integrated systems examined before, as can be seen from Fig 2.14, is a new module. In this system when a new component is being defined, the program will search for whether or not a sufficiently similar component to the current one, both geometrically and for operational conditions, has been made before. If a similar component is found, the FE package will not be invoked and the results of the CAD program will be accepted. If required, the process will proceed directly to the production of NC tapes for die manufacture. This will save time and cost.

The comparison module compares both geometries and operational parameters. The comparisons are quantified through the use of a closeness factor and the user will decide whether or not the similarity is strong enough.

Another part of the system is a program called 'LEARN' which provides the possibility for the system to assess the decision–making design rules.

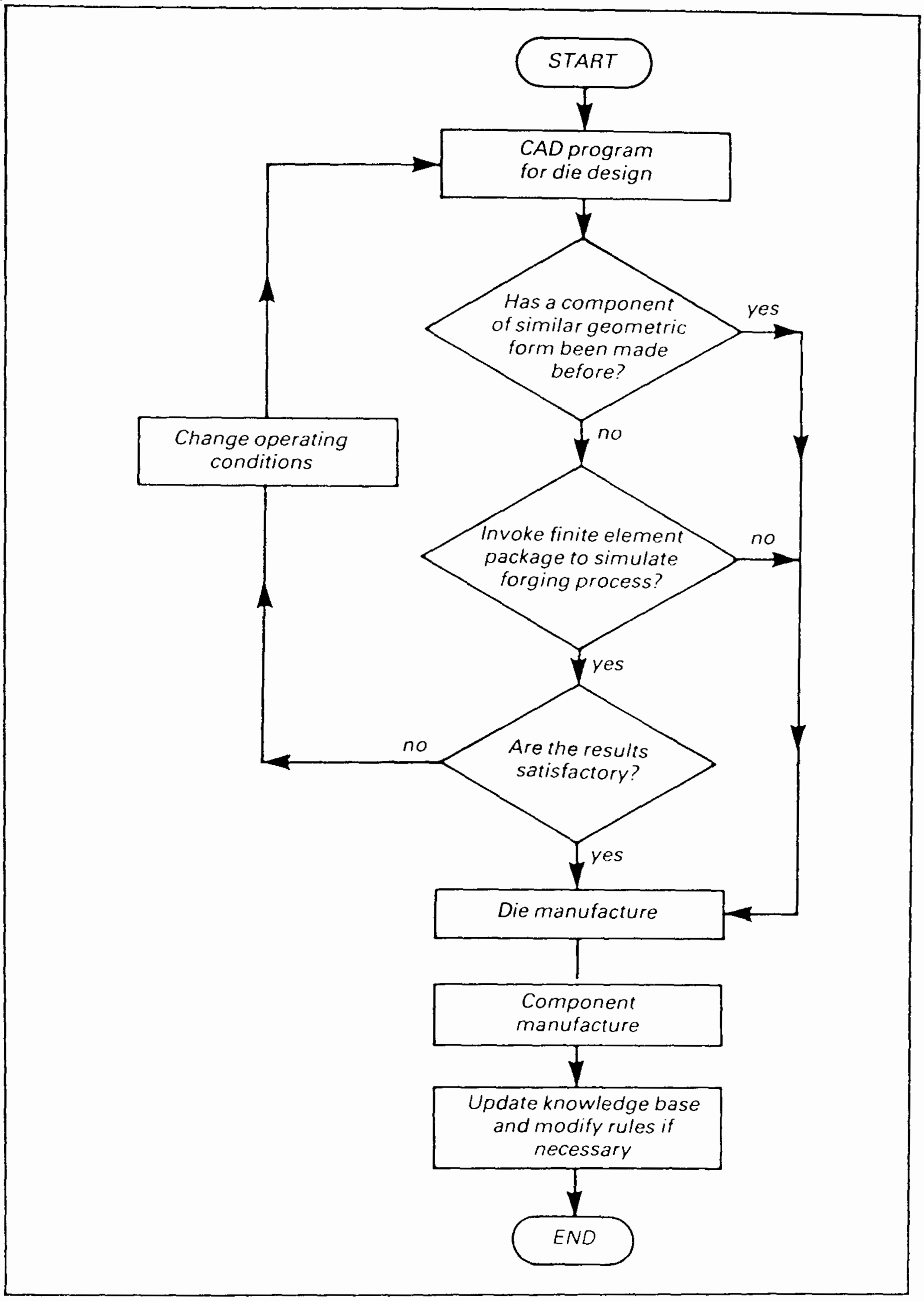


Fig. 2.14 A brief illustration of a forging Expert System [86], [87] and [88].

The system mentioned earlier was the start of research work which continued as a collaborative project between the Department of Mechanical Engineering of the University of Birmingham and the Austin Rover Group, sponsored by the UK Science and Engineering Research Council [90]. It was extended by Pillinger *et al.* [91], on the basis shown in Fig. 2.15 [91] (the second system). The main parts of this system are:

(i) Sequence Design Program (SDP) which is able to design the finished part, preforms, sequences and dies for axisymmetric and 3–D components.

(ii) Finite–element pre–processor which should create a datafile for EPFEP3.

(iii) Control Module (CM) to supervise the two parts and to provide other activities of the system.

Some parts of the system have been successfully and effectively completed. The SDP program with a specified pre and post–processor has been developed by Sims [92]. The finite–element program for simulation is EPFEP3 which has briefly been discussed before. The Control Module has been written and developed to a large extent by the first author of the system. In chapter 3, more details of these parts will be explained.

The existing system had been developed as a result of several years' work at the University of Birmingham but still needed more research to be completed. In the next section some of the work that was required, which is the scope of the present programme, will be discussed.

2.6 The Scope of the Present Work

The present programme of work, as explained in the previous sections, is the continuation of previous research which had been performed at the University of Birmingham for many years. The main topics of this work are:

(i) In the upset forging IKBS an 'INTERFACE' program had been written to prepare automatically the datafile of EPFEP3, but only for simple cylinders with a uniform mesh, which were the only preforms required for upset forgings.

For this work, in which the IKBS is for multi–stage forgings, an interface should be developed which is capable of dealing with the required complex axisymmetric shapes. This part of the work will be discussed in chapter 4.

(ii) What the previous researchers principally emphasised was how to reduce the time required to perform the analysis and design of a new product, which is a major objective of computer aids in forging. One major procedure, as discussed before, is comparing a new component with the previously encountered ones and thus performing FE simulation only when the component or process conditions are unfamiliar and new. To obtain a reasonable result, some reasonable criteria should be obtained.

In the IKBS for upset forging, the comparison criteria were estimation criteria which were not verified by experimental or simulation techniques.

Obtaining some reasonable criteria was one of the aims of the current programme of work which will be examined in chapter 5.

(iii) Working with the CM was easy and user friendly, but some parts of it needed to be completed. These include computer–aided reasoning in the IKBS, such as creating the IKBS database based on real data of components and explaining the results and making suggestions to the user. This is the third aim of the research which will be stated more fully in chapter 6.

(iv) Studying a typical stage of deformation of a family of components in the SDP with finite–element simulation and comparing its results with experimental results will be examined in chapter 7.

(v) Comparing the results of some examples by using the comparison algorithm, which will be discussed in the following chapters, with those of the experiments and FE simulation. This objective of the programme will be discussed in chapter 8.

More details of the present research work are explained in chapter 3, where the different parts of the existing system are discussed.

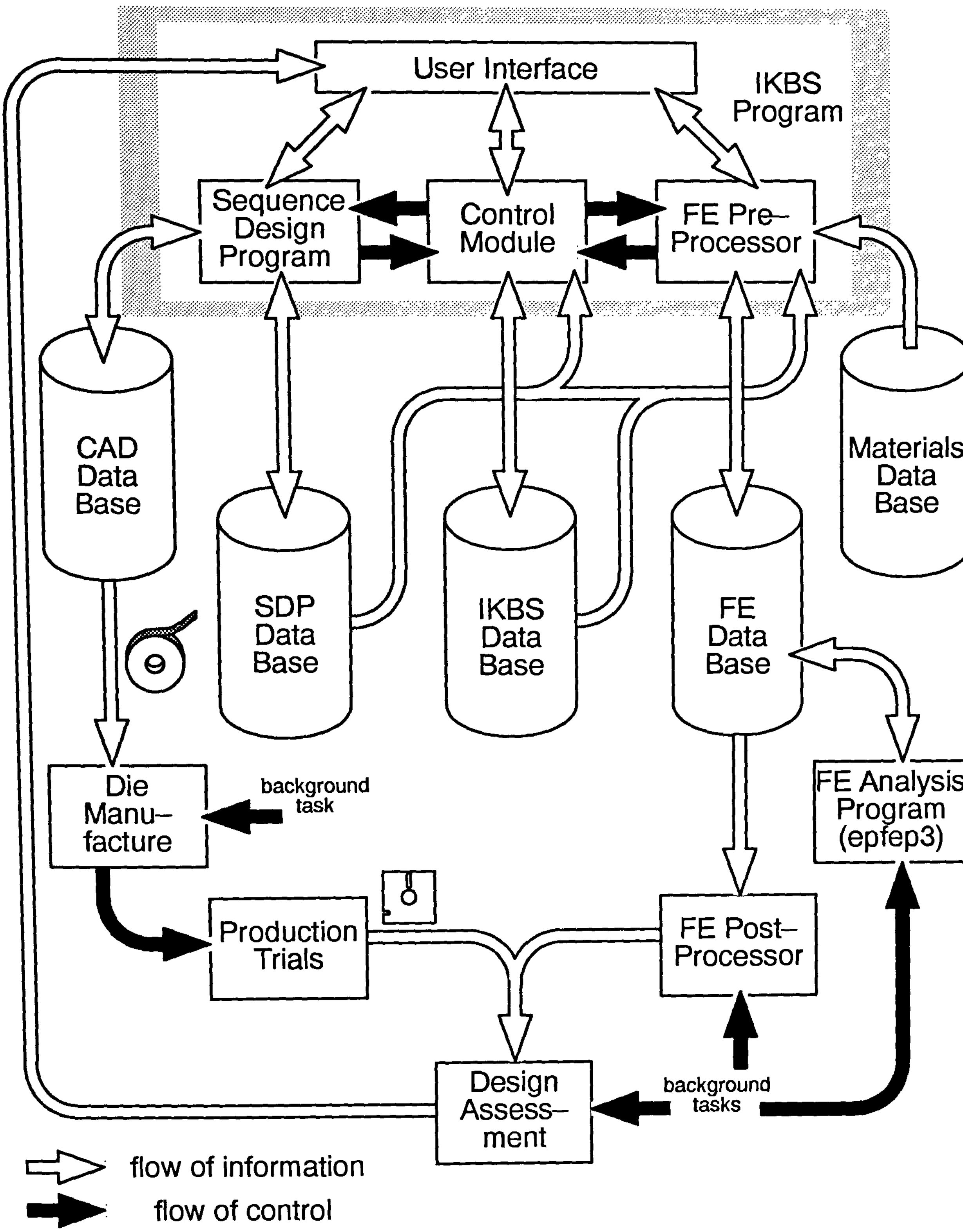


Fig. 2.15 The structure of an IKBS for the design of forging dies [91].

Chapter 3

Intelligent Knowledge–Based System (IKBS) for forging die design

3.1 Introduction

As stated in the previous chapter, earlier research in the areas of CAD based on empirical formulae, and the finite–element simulation of forging had already been integrated into an IKBS for forging die design before the present programme of work started. In this chapter the main modules of this system are examined and details of the present work are discussed.

3.2 The Graphical Interface (Interactive MODCON) for Input Data

MODCON, which is short for MODular CONstruction, is a computer system originated by Chan and Knight [93]. The purposes of this system are to generate input data for die/sequence CAD programs, generally in the form of selected cross–sections of the forging, and to facilitate the manufacture of dies by producing NC tapes.

A large range of forging products can be regarded as a combination of simple shape features such as truncated cones, cylinders, blocks, especially in the case of axisymmetric shapes. The idea of combinations of such primitives producing complex forging shapes is the philosophy underlying MODCON. This idea has been extensively used later in the CAD/CAM/CAE systems in forging industry, some of which have been reviewed in the previous chapter.

The manner in which forging die designers usually deal with certain aspects of complex forging shapes, such as volume determination, is consistent with this type of geometry description: since the volume of each primitive can be easily determined, the total volume can be readily estimated. The primitives that have been defined in MODCON are of the types that are commonly used in the forging industry.

Based on the original MODCON system, the geometry of a range of forging shapes were defined and their die electrode shapes were produced to show the utilisation of the system [93].

Despite the usefulness of the original system, it had a number of drawbacks and was therefore the subject of more research. The result of this work was named Interactive MODCON [92].

In developing Interactive MODCON the code was completely rewritten to deal with the limitations of the original system and to take advantage of modern approaches in computer programming [92].

The basic building blocks (primitives) which can be defined in Interactive MODCON are ARC–BLOCK, CONE, CURN, CURP, CYLINDER, PLUG and TOROID, among which CONE and PLUG are usually used for axisymmetric shapes.

In Figs. 3.1 and 3.2 [92], the general specifications and descriptions for the CONE primitive are given and Figs. 3.3 and 3.4 [92] show those of the PLUG primitive.

In addition to geometrical information, other data can be input to MODCON such as the percentage of shrinkage, the type of forging material, the temperature and a title for the shape. This can be used later by the SDP in conjunction with the design rules.

For more information about Interactive MODCON, reference can be made to its manual in Ref. [92].

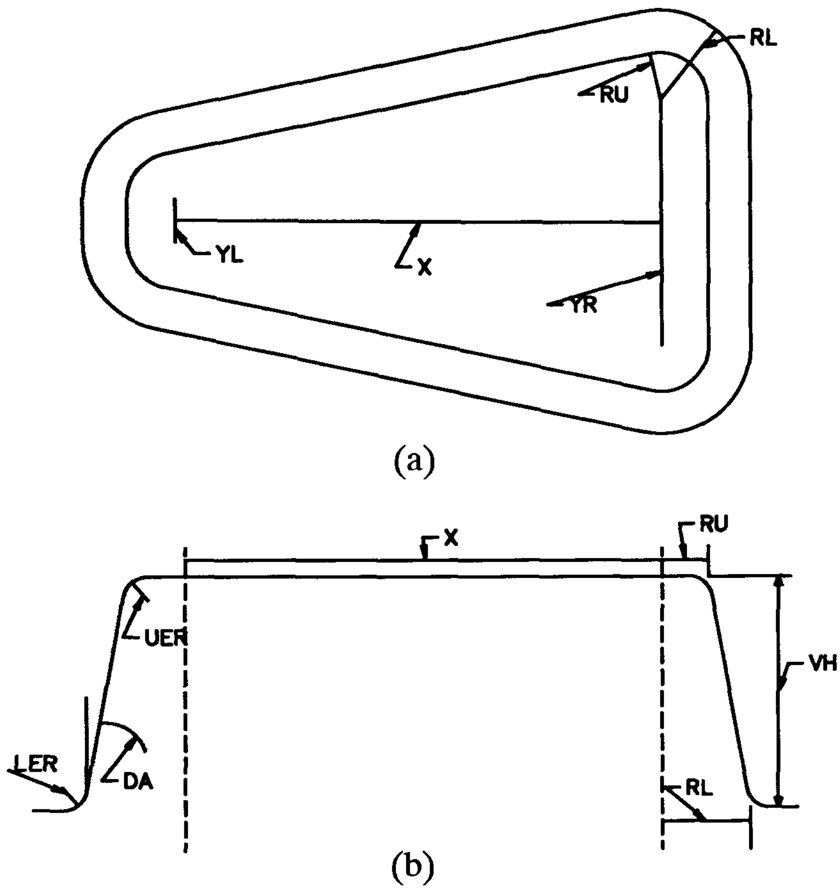


Fig. 3.1 The general definition of CONE (positive primitive) [92]
(a) plan view (b) elevation

RL : Lower Radius
YR : Y Right separation
UER: Upper Edge Radii
VH : Vertical Height
X : X separation
RU : Upper Radius
YL : Y Left separation
LER: Lower Edge Radii
DA : Draft Angle

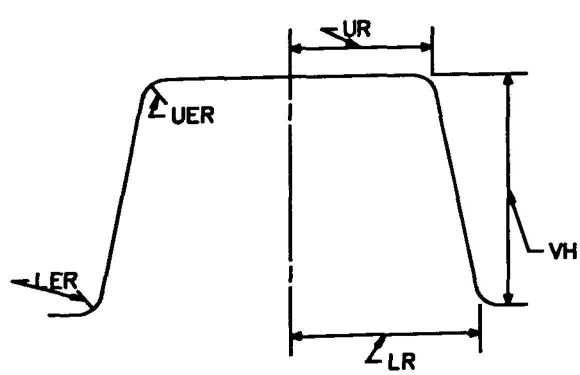
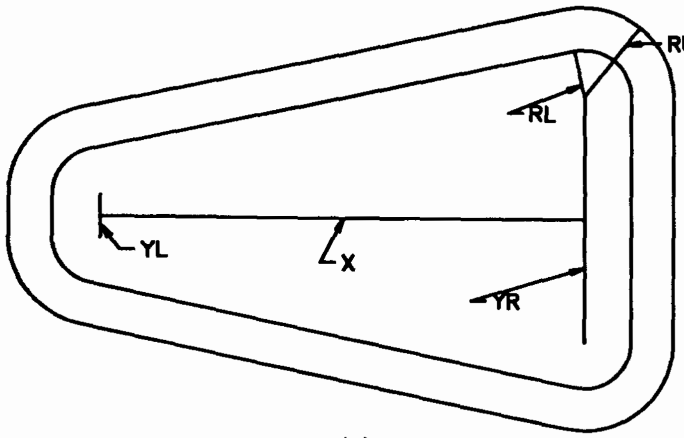
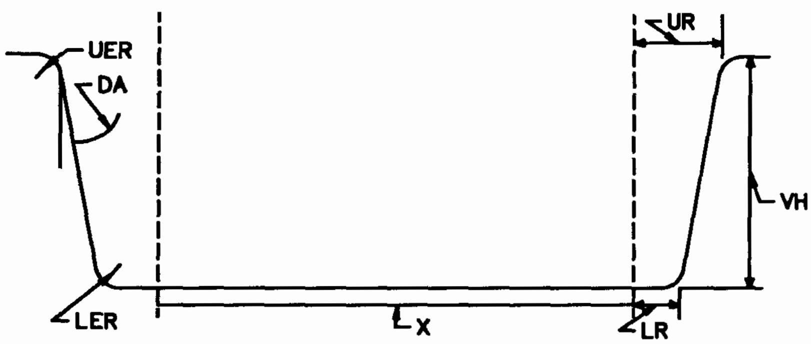


Fig. 3.2 The axisymmetric CONE [92]



(a)



(b)

Fig. 3.3 The general definition of PLUG (negative primitive) [92]
(a) plan view (b) elevation

RL :	Lower Radius	RU :	Upper Radius
YR :	Y Right separation	YL :	Y Left separation
UER:	Upper Edge Radii	LER:	Lower Edge Radii
VH :	Vertical Height	DA :	Draft Angle
X :	X separation		

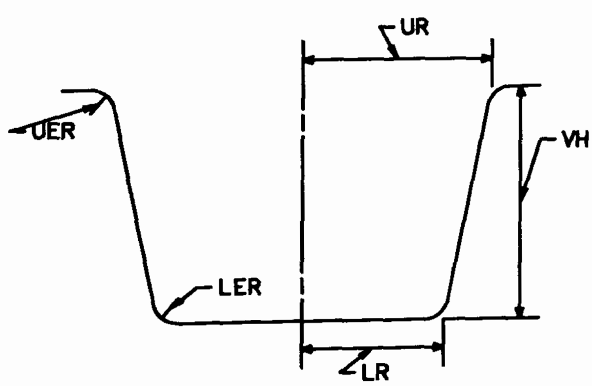


Fig. 3.4 The axisymmetric PLUG [92]

3.3 The Sequence Design Program (SDP) for Forging Die Design

This is a program developed by Sims [92] to design the operational sequences and dies for axisymmetric and three dimensional warm and hot forging.

In order to obtain a program which is able to design the proper sequences or preforms for all forged components, an appropriate set of design rules should be available. Producing such a set is not practical, because in the production of a specific component, a die sequence frequently reflects very specific attributes of the component. For example in some cases the components must be forged very accurately, while in others they need to be forged with less accuracy. Thus, the process of producing the products, and therefore the sequences, will be different.

For these reasons and due to the range of components which were used by the collaborating company, the components which can be specified to the SDP have been divided into five different families, namely Stub Axles, Drive Flanges, Gear Blanks, Bevel Pinions and Non–axisymmetric Components (specifically Engine Connecting Rods and Vehicle Suspension Lower Arms).

The Sequence Design Program inputs the description of the machined component (or any intermediate stage, such as the finished part) from the graphical interface and performs the process of sequence/preform design based on empirical design rules, calculates the load required for each stage of deformation, selects the required billet or bar dimensions and tool inserts.

The internal description of shapes in MODCON and the SDP are similar, i.e. they both use assemblies of primitives. However, it is possible to define using MODCON any component which can be created from the set of primitives, while only those shapes which belong to the permissible types of families can be input to the SDP.

In the rest of this chapter and the other following chapters, unless otherwise stated, attention will be given only to axisymmetric shapes, a particular family of which (Stub Axles) is chosen for the present work.

The operational sequence for a typical Stub Axle is shown in Fig. 3.5 [92].

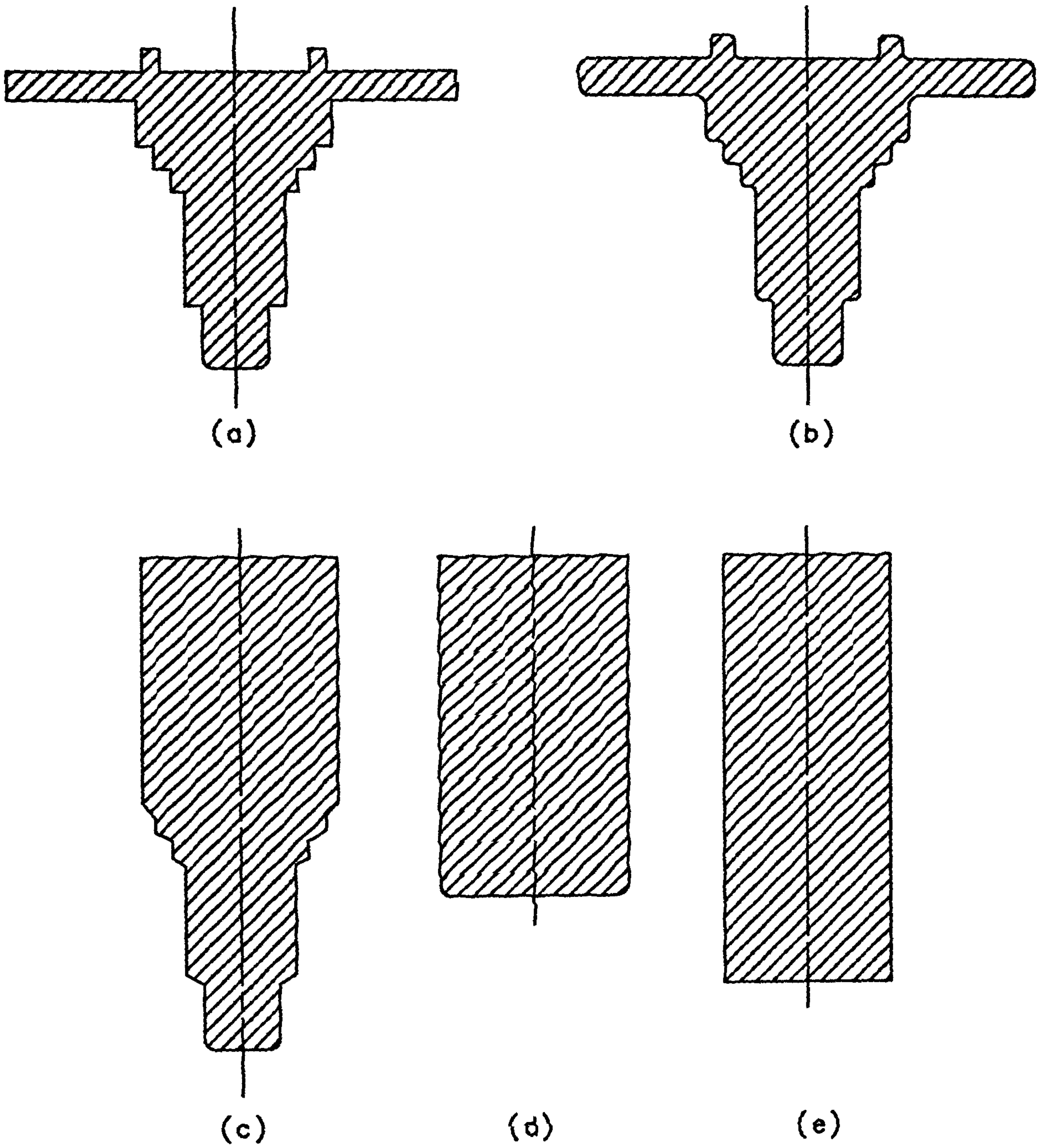


Fig. 3.5 The operational sequences for a Stub Axle [92]

(a) Machined part

(b) Finished part

(c) Preform

(d) Cheese

(e) Billet

The different stages of deformation from 'billet' to final 'finished' shape can be stated as follows:

(i) The upsetting of the 'billet' to produce the 'cheese'

(ii) The forward extrusion of the 'cheese' to produce the 'preform'

(iii) The simultaneous backward extrusion and heading to produce the 'finished' shape.

It should be pointed out that the 'machined' part is not considered a separate stage in the metal forming process.

These different stages are produced in a closed die and, except for the last forming stage, shaped in the cavity of the lower die (container). Therefore, the upper die is a flat ended cylindrical punch. Depending on detailed geometry the finished part may be formed either in the lower die or both in the lower and upper dies as shown in Fig. 3.6 [92].

As stated above, the input to the SDP is the 'machined' shape (or any other stage). Based on the design rules implemented in the SDP database, the program will design the sequence in reverse order, from the input stage back to the original 'billet'. When the maximum diameter of the designed 'preform' is close to any of the available billet diameters stored in the database, the 'cheese' will not be needed.

In the rest of this thesis, some words or symbols are used which have special meanings. When the words *preform* or *product* are used, they have general meanings and stand for two optional stages. For example in producing the 'cheese' from the 'billet' the word *preform* stands for the 'billet' and the word *product* stands for 'cheese'. Thus, the list of the *preform* stages in the Stub Axles are 'preform', 'cheese' and 'billet' and the list of the *product* stages are 'finished', 'preform' and 'cheese'.

3.4 The Graphical Interface (SDPLOT) for Output Data

This is an interface which transforms the data for all stages of a component die/sequence to graphical output and is used to produce the side views of the designed stages on the available computer system [92].

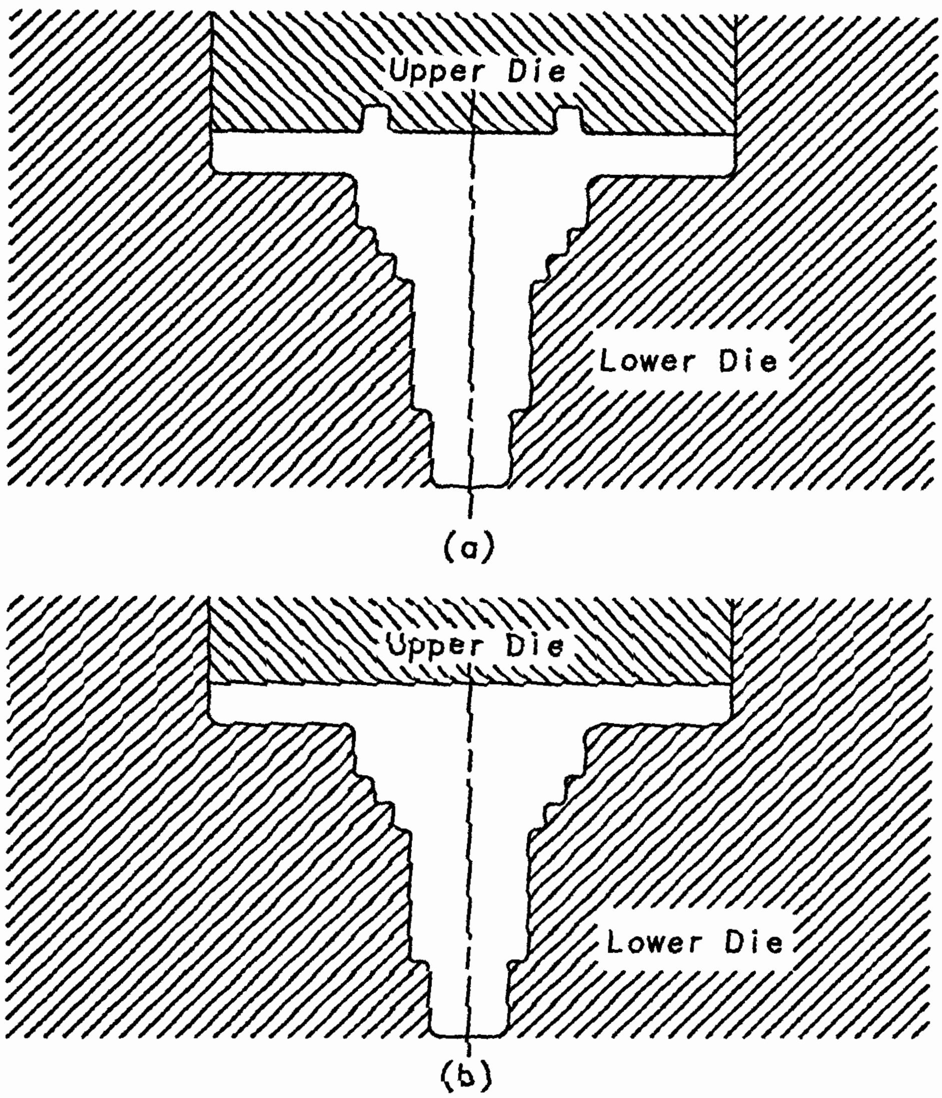


Fig. 3.6 Die types for finishing of two Stub Axle types [92]

(a) Punch shaped to suit Stub Axle features

(b) Flat ended punch enabled by component geometry.

3.5 The Control Module (CM) to Supervise the System

As described in the previous chapter, the 'inference engine' is considered as a central essential part of an IKBS. In this chapter and the following chapters, this engine is called the 'Control Module (CM)'.

The CM supervises the main activities of the IKBS, manipulates the knowledge stored in the different databases and is an interface that allows the user to communicate with the other modules.

The main actions of the IKBS for the design of forging sequences/dies are shown in Fig. 3.7 [91] and described as follows (the letters refer to the labels in the figure):

a) The assessment of a new component begins by invoking the graphical interface to describe the 'machined' or 'finished' shape specifications and also to define the family of the component together with the die type, material type and process conditions.

b) In the first instance, it is required to design the operational sequences/dies up to the 'finished' stage.

c) The assessment of the sequences/dies begins with the 'finished' stage.

d) The SDP is used to design the sequences/dies up to the target stage. As mentioned, in the beginning, the target stage is 'finished' but later it may be an earlier stage in the sequence, e.g. 'preform' or 'cheese' for the Stub Axles. The proposed designed stages will be assessed stage by stage, such as producing 'finished' stage from the 'preform' in the case of Stub Axles.

e) The current stage is compared with the same stage of the same family in the IKBS database. In comparing the stages, two numbers are evaluated.

(i) A Success indicator (*S*): This number indicates whether the designed stage is satisfactory or not. It varies between +1 (satisfactory) and −1 (unsatisfactory).

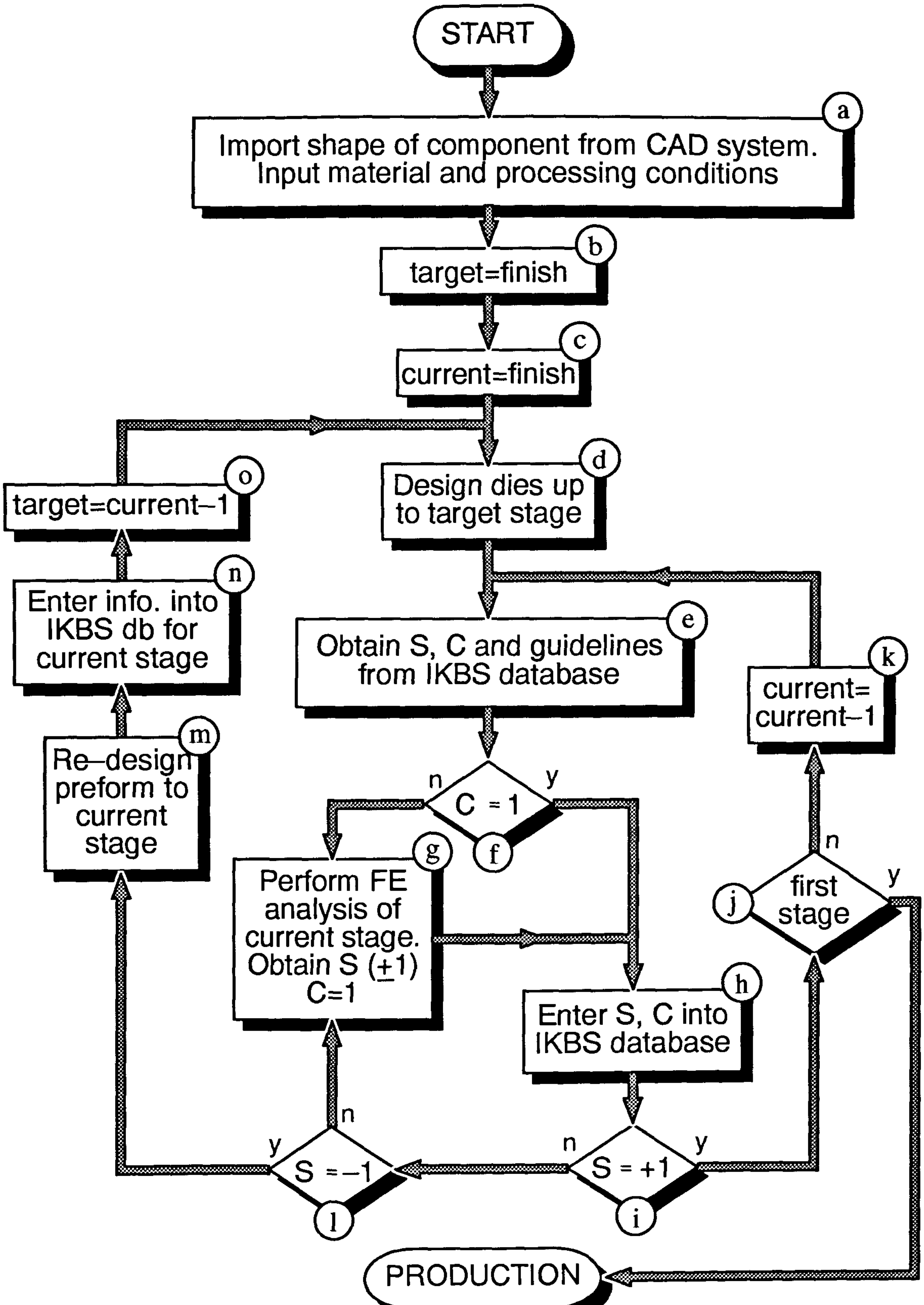


Fig. 3.7 The main actions of the CM [91]

(ii) A Confidence indicator (*C*): This number indicates how strongly the information stored in the IKBS database supports the success indicator. It varies between 1 (complete certainty in the value of *S*) and 0 (complete uncertainty in the value of *S*). When the current stage is completely similar to a previously encountered component stage in the IKBS database, the *S* indicator is +1 (the previous stage, and thus the current one, is successful) or –1 (the previous stage, and thus the current one, is unsuccessful).

When the result of comparison is unsatisfactory, a text string will give the recommendations about how to modify the preform of the current stage.

The details of the assessment process are explained in the next sub–section and those of the IKBS database are discussed in chapter 6.

f) If the confidence indicator is not close to 1, then there is not enough confidence about the results, so it is necessary to perform FE analysis of the current stage.

g) The geometry description of the corresponding preform of the current stage and that of the current stage in the SDP database will be used to produce an FE datafile. The examination of the FE results will indicate whether the product stage can be produced from the given preform successfully (S=+1) or not (S=–1). In both cases, the confidence indicator is 1.

h) The values of *S* and *C* which are known either from the FE results or by comparison to the previously experienced components should be stored in the IKBS database. In some instances, the results of experiments may be used instead of the FE results

i) If the success indicator is close to +1, then it is very likely that the current stage can be produced from the given preform stage successfully, so the previous product stage can be examined, if there is any, (step 'k' in the figure), otherwise proceed to production.

l) If the success indicator is close to –1, then it is very likely that the current stage cannot be produced from the given preform stage successfully, so the preform stage should be modified and the sequences/dies up to the preform of the current stage should be re–designed (steps ‘m’, ‘n’ and ‘o’ in the figure). If S is neither +1 nor –1, then more information is needed and therefore an FE analysis should be performed.

3.5.1 Calculation of the Design Assessment Numbers

The success indicator of a stage is calculated as the weighted average of the S values stored in the IKBS database for the same stage of the same family of components. The weighting factor associated with each stored S value indicates that how similar the current stage is to the stored stage.

The similarity between the two stages is based on both geometrical and process parameters, which are stored in the IKBS database for each designed stage. It is obvious that different parameters may have different effects on similarity and therefore on the assessment numbers.

To find the similarity between the two stages, a quantitative variable is defined as follows [91]:

$$d_i = \left[\sum_{j=1}^{n} w_j \left(P_{ij} - P_{mj}\right)^2 \right]^{\frac{1}{2}} \quad (3.1)$$

in which:

- d_i : the quantitative variable (see below)
- i : denotes the instance of the component stage in the database for which the success indicator is not null (between 1 and m–1)
- m : indicates the number of the current instance
- P : the value of the product or preform parameter of the current or previous component stage
- j : the geometrical or process parameter number
- w : the weighting effect of each parameter

Intuitively, d_i is the distance between the mapping of the current stage and the mapping of a previous one in a metric space of parameter values [91].

A suitable weighting factor for the calculation of the average stored values of S will be the ratio of the confidence indicator of the example and the distance in equation 3.1, with the condition that when the distance is zero, its inverse is very large, but not infinite. Thus [91]:

$$S_m = \frac{\sum_{i=1}^{m-1} \frac{C_i}{d_i} S_i}{\sum_{i=1}^{m-1} \frac{C_i}{d_i}} \tag{3.2}$$

Equation 3.2 will always produce a value of S_m between -1 and $+1$.

The value of confidence indicator is stated as [91]:

$$C_m = \frac{C_k}{1 + d_k} \tag{3.3}$$

In which, k denotes the previous instance of the current stage which is most similar to the current instance. Therefore, when the distance is zero, the confidence indicator of the current stage will be the same as that of the previous example k.

It should be pointed out that two different weighting factors have been defined in this sub–section. One of them relates to the determination of the success indicator and another one relates to the effect of individual parameters on the distance value d_i.

3.6 The Capability of the Previous System

In chapter 2, some of the capabilities of the previous IKBS have been stated in general. In this section, more details of these capabilities are discussed.

The IKBS was developed to run on a Unix–based engineering workstation. The SDP and the graphical input/output interfaces were written in FORTRAN, while Common LISP was chosen as the language of the CM. This module allows the other modules to be invoked as LISP functions and the interactions between the modules is easy.

Not all the activities illustrated in Fig. 3.7 are performed within the interactive program and the whole design process and related functions are not expected to be done all at the same time. In some cases these activities, such as examinations of the results of FE simulation, should be performed by the user. Thus, the different actions have been divided into separate tasks and a range of options have been provided in the main menu of the IKBS relating to the main tasks.

The different options of the main menu of the existing IKBS are:

1. Define a new component (by invoking MODCON)
2. Determine the die and preform sequence for a component (by using the SDP)
3. Modify a stage of the forging sequence for an existing component (by using the SDP)
4. View forging sequence for a component (by using SDPLOT)
5. Input the results of FE or experimental trials into the database

3.7 The Work Required to Complete the System

As stated in the previous chapter, the previous IKBS had been developed as a result of several years' research work, but still required more work for it to be completely applicable.

The different modules of the IKBS and their related activities needed to be completed. Although Interactive MODCON and the SDP were suitable for the present work, they still had some limitations.

In this section, attention is given to the completeness of the CM and its related functions, the module which is most concerned with this programme of research. Some of these areas which have been stated in chapter 2, are discussed in this section.

(i) When the results of the assessment for a stage of a new component indicate that there is not enough confidence (C is not close to 1) or when the success indicator is not close to +1 or –1, then more information is needed and, therefore, FE analysis should be performed. In this case, what was required was to add an option to the main menu of the IKBS to create the datafile.

In producing the datafile for a specified stage, the geometry of the corresponding preform would be used for mesh–generation and that of the product will be used to generate the boundary conditions.

The details of creating an EPFEP3 datafile for a stage of a Stub Axle will be discussed in chapter 4.

(ii) In section 3.5, a quantitative variable has been introduced. The calculation of this variable is based on the product, preform and process parameters of both the current and the corresponding stages stored in the IKBS database, and also on the weighting effect of each parameter. This variable directly influences the results of the design assessment numbers.

A criterion was needed to obtain the weighting effect of each parameter (w, in equation 3.1). Then these factors together with the important parameters could be used in the calculation of the design assessment numbers. This part of the programme is discussed in chapter 5.

(iii) As outlined in chapter 2, the knowledge–base is a major part of an IKBS, on which the manipulation of the data in the IKBS is based. The structure of the IKBS database is explained in reference [91]. This database needed to be created based on the actual experimental data obtained and those concerned with each stage of deformation, during the different activities of the system, as indicated in the last section.

In assessing a stage of a new component by comparison to the previously stored ones, an option needed to be added to the main menu of the IKBS. In this connection, the system should be able to extract the values of the significant parameters of the stage from the SDP database.

If the results of assessment indicate that the forging of the current stage will not be successful, then the system should be able to give explanations and make suggestions to the user, based on the results previously stored in the IKBS database.

These are typical intelligent behaviour of an IKBS, which is an important part of the system, discussed further in chapter 6.

(iv) Studying a typical stage of deformation in Stub Axles, i.e. closed–die upsetting, with finite–element simulation and comparing its results with experimental results obtained in chapter 5, is examined in chapter 7.

(v) Examining the results of some examples by using the comparison algorithm, stated in section 3.5, which will be explained in more detail in chapter 5, and also by experiments and FE simulation will be performed in chapter 8.

Chapter 4

Integrating with the EPFEP3 Program

4.1 Introduction

In the previous chapter, it was pointed out that in order to increase the likelihood of producing a defect–free component stage when unfamiliar components, materials or process conditions are encountered, it is necessary to examine the stage, either by FE analysis or by experimental tests.

As stated before, the FE program which has been used in the IKBS is EPFEP3. In the following sections some characteristics of this program are discussed first, and then the method of producing the input datafile and its integration with the program, is examined.

4.2 The EPFEP3 Program

This is a program specifically developed to predict material flow and properties in general three–dimensional metal forming processes, which takes into account both elastic and plastic components of strain [45]. The analysis process of the program is shown in Fig. 4.1 [52] which has four main parts, namely:

(i) Description of the forming operation
(ii) Pre–processing
(iii) FE calculation
(iv) Post–processing

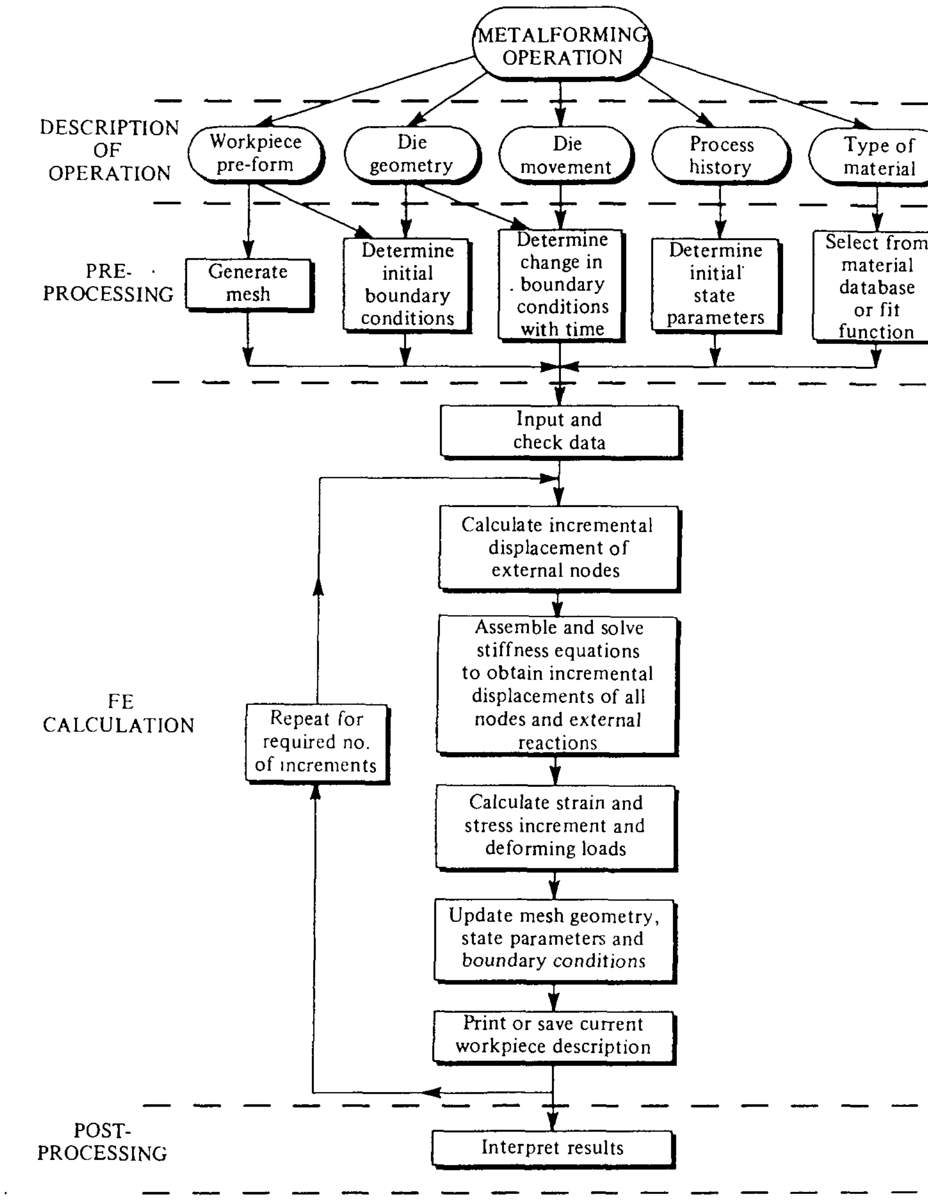


Fig. 4.1 Schematic illustration of the EPFEP3 analysis process [52]

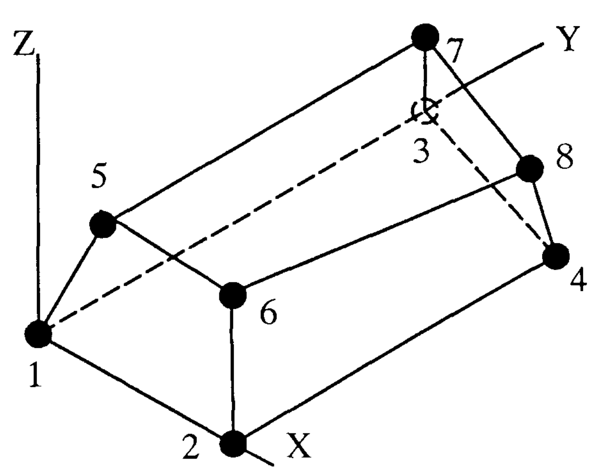


Fig. 4.2 The type of element used in EPFEP3 [45]

Among the above parts, only the FE calculation is in EPFEP3. The others are done separately and the first part may be a totally manual operation.

Only those parts relating to the current work in producing the input datafile are outlined in the following sections. The details of the analysis (FE calculation) can be found in [45] and [52].

4.2.1 Type of Element and Size of Mesh

A three–dimensional, eight–node, linear–isoparametric (brick–type) element is used in EPFEP3. This is shown in Fig. 4.2 [45].

In principle, the maximum size of mesh which can be examined in EPFEP3 is limited only by the hardware capabilities on which the program is installed, though in practice limits are defined in the program.

4.2.2 Boundary Conditions

In metal forming processes, the assumed stiffness equation takes the following incremental form:

$$\{\Delta F\} = [K]\,\{\Delta U\} \qquad (4.1)$$

In which $\{\Delta F\}$ and $\{\Delta U\}$ are the incremental nodal vectors of force and displacement, respectively and $[K]$ is the global stiffness matrix.

In metal forming processes, the incremental forces are not generally known at every node of the mesh, but the incremental displacement of the nodes on the boundary surfaces is determined by the geometry of the process. Thus, the solution of the above equation should be performed based on the specified boundary conditions, where the incremental nodal displacements have prescribed values [45].

4.2.2.1 Prescribed Displacements

This is the method of defining mechanical boundary conditions which describe the pre–determined values of nodal displacement increments and specify how a node is to move (or not to move) during the deformation. In this type of definition, a node can have a constant displacement vector or can be constrained to move in a particular line or a plane without having to assign a value to the movement within that line or plane. In other words, a nodal constraining condition will determine which components of displacement of a node are to have predefined (usually zero) values and which of them are undefined and thus to be obtained as solutions of the stiffness equations.

In practice, since nodes will not always be constrained on planes that are parallel with one of the global axis system planes, it is convenient to be able to specify the constraining conditions of a node with respect to locally rotated axes.

4.2.2.2 Prescribed Boundary Surfaces

The previous method of specifying boundary conditions requires that the constraint applied to a node is known beforehand and applies throughout the forming process. Therefore, it cannot model the constraining conditions for nodes which contact the die surface during the deformation, since the conditions before and after coming into contact are different. Thus, a second method of defining boundary conditions has been developed in the EPFEP3 program by means of a set of primitive geometric surfaces [45]. Fig. 4.3 [45] illustrates the primitives which are used in describing the complex tool surfaces.

4.2.3 Displacement of Surface Nodes

In EPFEP3, at the start of each increment the positions of external nodes are determined with respect to the specified primitive boundary surfaces. If it is found that a node has passed through a boundary surface, it must be moved back to the surface. This is shown in Fig. 4.4 [52].

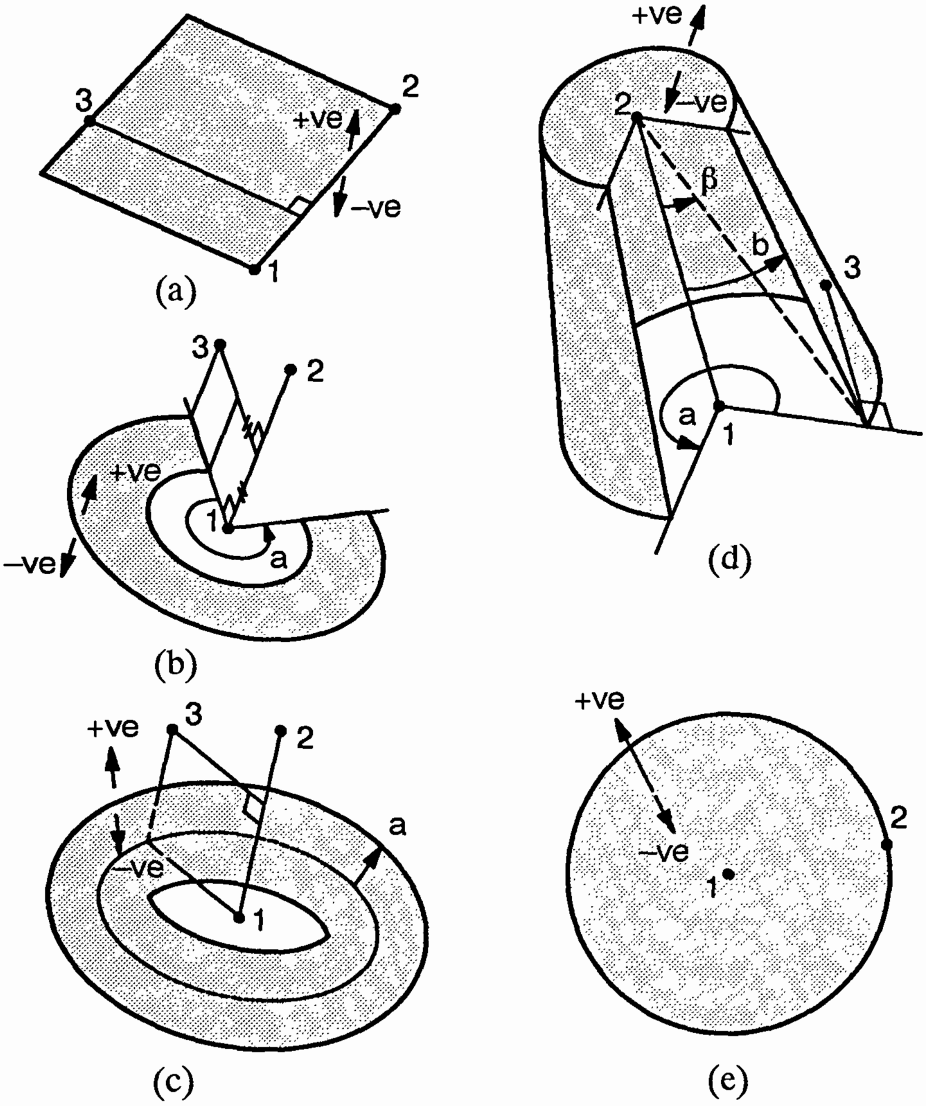


Fig. 4.3 Primitive geometric surfaces used in EPFEP3 [45]
(a) rectangle (b) annulus (c) torus (d) cone (e) sphere

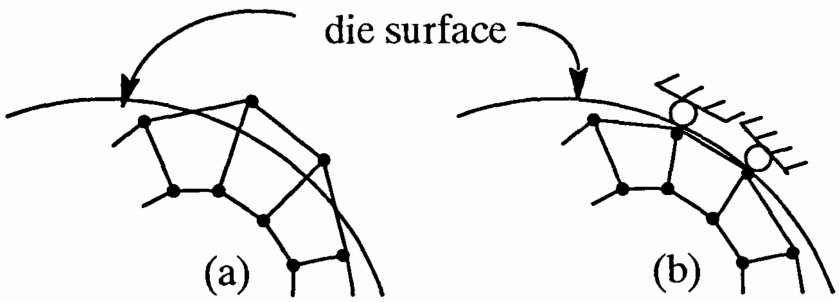


Fig. 4.4 Checking for contact between FE mesh and boundary surface
(a) at the end of increment, (b) after checking for contact with die [52]

If the boundary surface is stationary, then the node is constrained either to move tangentially to the surface or is fixed to it, depending on the frictional conditions. If the die surface has a translational movement, then the node is constrained either to move within a plane passing through the point P' (Fig. 4.5 [52]) that point P (the point of contact of the node with the surface at the start of the increment) will translate to at the end of the increment, or is fixed to this plane.

This situation will apply when a free–surface node contacts only one primitive surface. If the node has a previously defined constraining condition (e.g. on the plane of symmetry–Fig. 4.6 [52]), then the constraint will need to satisfy, if possible, all the required conditions. Thus, in Fig. 4.6, the marked node is constrained to move along the dashed–line after coming into contact with the boundary surface.

4.2.4 Modelling the Frictional Restraint

In metal forming processes, for a given die/workpiece interface and lubrication condition, the shear stress at the interface is a constant fraction of the yield stress of the workpiece. In practice this is an approximation, since the lubricant is affected by the interface pressure, but the assumption is good enough for most purposes [52]. This relation is:

$$\tau = \frac{m}{\sqrt{3}}\bar{\sigma} \qquad (4.2)$$

in which:

τ : shear stress at the interface
m : friction factor
$\bar{\sigma}$: flow stress of the workpiece

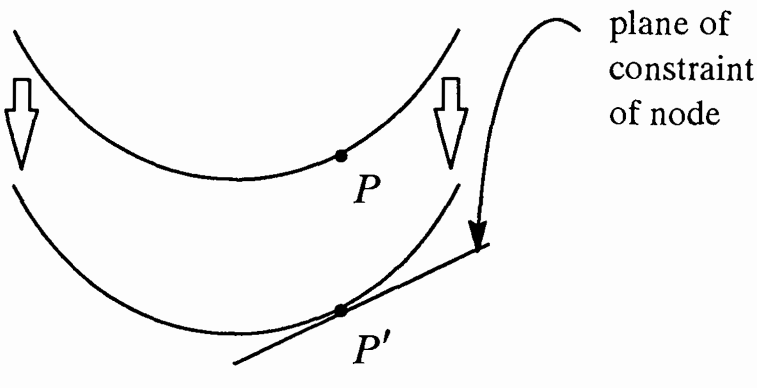


Fig. 4.5 Constraint of a node in contact with a translated die [52]

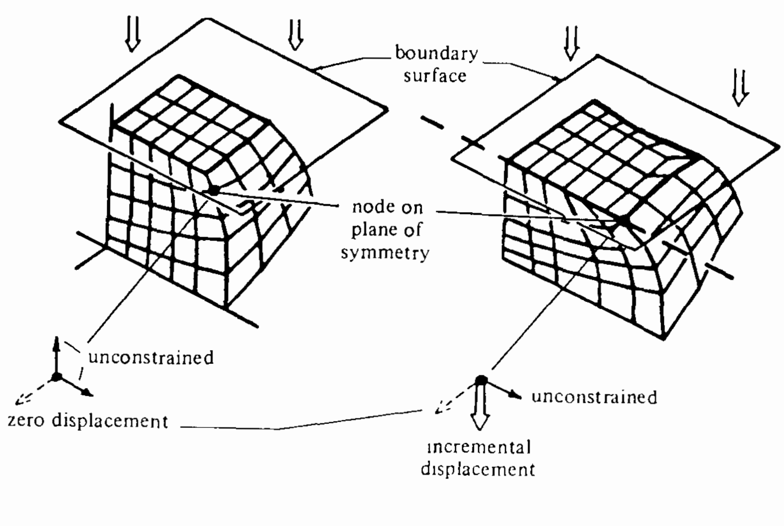


Fig. 4.6 Contact of a boundary surface with a node subject to previous constraining condition [52]

If m equals zero, then there is no shear force at the die/workpiece interface and if m equals one (sticking friction), then there is no relative movement between the workpiece and the die surface. In actual forming operations the value of m is between the two limits. The EPFEP3 program is capable of modelling the intermediate and the limit conditions of friction. The method that has been used in this modelling is called the Friction Layer Technique which requires an extra fictitious layer of finite elements to be placed on surfaces of the mesh on which friction acts [94]. EPFEP3 creates this fictitious layer automatically when required, but m must be specified for the interface condition.

4.2.5 Material Properties of the Workpiece

Material properties include the elastic coefficients (Young's Modulus and Poisson's Ratio), the thermal parameters (conductivity, emissivity, convection coefficient and specific heat) and the flow stress.

There are three ways of defining flow stress in EPFEP3. These are:

(i) flow stress as a function of strain (independent of strain rate and temperature)
(ii) stress–strain data points (independent of strain rate and temperature)
(iii) flow stress as a function of strain, strain rate and temperature. For this type of definition, the function is:

$$\overline{\sigma}(\epsilon_p, \dot{\epsilon}_p, T) = G(\epsilon_p) \left(1 + A(\epsilon_p) \ \dot{\epsilon}^{B(\epsilon_p)}\right) \ e^{f_0(\frac{1}{T} - \frac{1}{T_0})} \qquad (4.3)$$

where:

$$G(\epsilon_p) = \text{minimum}(H(\epsilon_p), y_f) \qquad (4.4)$$

and:

for $\epsilon_p < \epsilon_0$:

$$H(\epsilon_p) = h_1 + h_2\epsilon_p + h_3\epsilon_p^2 + h_4\epsilon_p^3 \quad (4.5)$$

for $\epsilon_p > \epsilon_0$:

$$H(\epsilon_p) = H(\epsilon_0) + h_5(\epsilon_p - \epsilon_0) + h_6(\epsilon_p - \epsilon_0)^2 + h_7(\epsilon_p - \epsilon_0)^3 \quad (4.6)$$

ϵ_p : plastic strain

$\dot{\epsilon}_p$: plastic strain rate

T : absolute temperature of workpiece (degrees Kelvin)

T_o : reference temperature of exponential function of absolute temperature (degrees Kelvin)

y_f : limiting value of cubic functions of plastic strain

ϵ_0 : plastic strain marking boundary between the two domains of the cubic functions of strain in flow stress expression

h_1–h_7 : coefficients of cubic functions of plastic strain in flow stress function (Nm^{-2})

4.2.6 Solution Technique

For reasons of saving CPU time, it is important to use large step sizes (normally a nominal deformation increment of 1 or 2%) in the FE analysis of metal forming operations. Since the stiffness equations are nonlinear, it is necessary to use some form of iterative solution procedure to determine the nodal displacement increments. The solution technique that has been used in EPFEP3 is the Secant–Modulus method [45].

4.2.7 Calculation of Stresses

The mean–normal technique is used in EPFEP3 to calculate the increments of deviatoric stress. The methods that are incorporated to calculate the hydrostatic stress are [45]:

(i) the direct method

(ii) the indirect method

The calculation of the hydrostatic stress by the indirect method is normally used and is carried out progressively through the mesh, starting from a number of free–surface faces, at which the hydrostatic stress is known to be the negative of the normal component of deviatoric stress.

4.3 Creating the EPFEP3 Datafile

In creating the EPFEP3 datafile, it is necessary to obtain the geometric data of a particular preform, use this to generate the mesh, define the boundary conditions using the corresponding product geometry and complete the datafile according to the other information stored in the SDP database.

In the following sections, the procedure of producing the datafile is illustrated.

4.3.1 The Process of Producing the Datafile

In producing the datafile, for each product stage, the geometry of the corresponding preform in the SDP database will be used for mesh generation and that of the product will be used to describe the boundary conditions. To have a general view of the procedure, the following explanations are necessary:

(i) Among the stages of the Stub Axles, as shown in Fig. 3.5, the machined part is not considered as a metal forming stage, for it is only a machining operation. So, the last product stage is the 'finished' part and consequently, the last preform stage is 'preform'. Other preform stages are 'cheese' and 'billet'. Thus, in producing the datafile, one of the 'preform', 'cheese' or 'billet' stages should be modelled for the initial mesh.

(ii) In the stages of producing a 'finished' part from a 'preform' and producing a 'preform' from a 'cheese' the product is axially symmetric. Therefore, only half the cross–section of each preform is needed for cross–sectional mesh generation. In the stage of producing a 'cheese' from a 'billet' there is an extra horizontal plane of symmetry in the product geometry. As will be explained in chapter 7, due to the effect of frictional forces between the workpiece and the die wall in the last stage of deformation, when the workpiece is being in contact with the die wall and also due to the effect of heat loss by conduction in the period while the billet is resting on the counter-punch before starting the deformation, it is still necessary to model half the cross–section of the billet for mesh generation. Therefore, in all the three stages of deformation in Stub Axles half the cross–section of each preform is used to generate the mesh.

(iii) Among the preform stages of Stub Axles, the 'cheese' and 'billet' have simple cylindrical geometries but the 'preform' has a complex shape. In mesh generation of the two former preforms, it is only necessary to define the number of elements in the radial and axial directions, so the algorithm of mesh generation is easy. In the case of 'preform', since it has a complex shape, the user should define the number of elements along each half cross–sectional curve.

Thus, the process of mesh generation needs to be interactive, during which the half cross–section of the preform should be on the screen to allow the user to define the number of elements for each specified curve.

(iv) According to the above comments, the I–DEAS commercial package (SDRC Software, version 4.1) [95] has been chosen as the graphical interface for EPFEP3 pre–processing (mesh generation). This software is adequate for generating the 2–D and 3–D meshes encountered in the present work.

Based on the above mentioned explanations, the process of producing the EPFEP3 datafile is illustrated in Fig. 4.7. This procedure has two distinct steps:

1. Transferring the data of the preform from the SDP to I–DEAS to generate the mesh.

2. After the mesh has been generated, the information in I–DEAS is converted into EPFEP3 format and the description of the product and the other information is added from the SDP database to produce the EPFEP3 datafile. These two stages are discussed in the following sections.

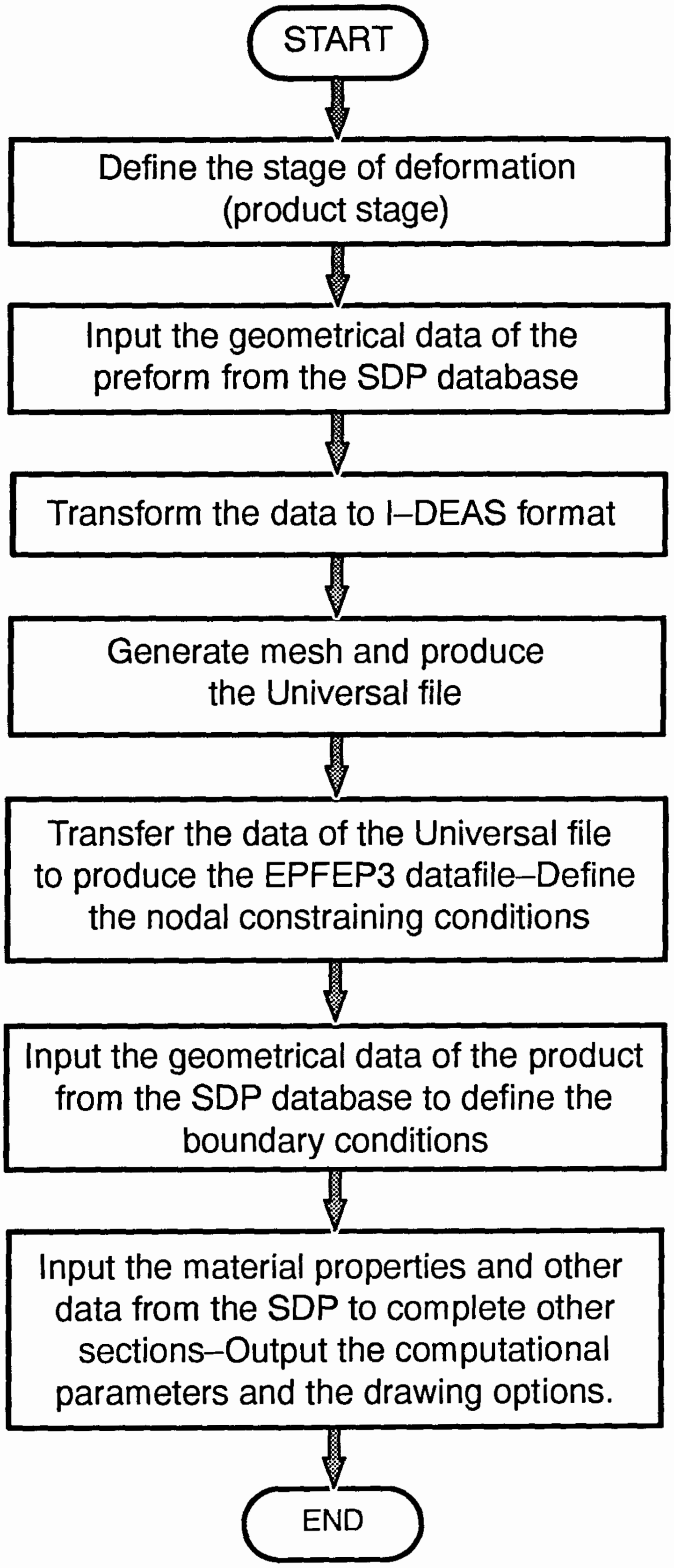


Fig. 4.7 The process of producing the EPFEP3 datafile

4.3.2 Mesh Generation

The main actions of this step are shown in Fig. 4.8 and are discussed below. First of all, it is necessary to explain the following points:

(i) As stated in section 4.2.1, only brick–type elements are available in EPFEP3. The workpiece must therefore be modelled as a three–dimensional segment. To produce 3–D elements for the Stub Axles, shell elements can be generated on the half cross–section, and then these can be rotated about the axis of symmetry. This is shown in Fig. 4.9.a.

Adopting this procedure, the shell elements which lie on the axis, when rotated, produce either nodes with the same coordinates or 6–node elements, neither of which is acceptable to EPFEP3.

One feasible way to overcome this problem is to rotate the shell elements which do not lie on the axis, twice about the axis . This is illustrated in Fig. 4.9.b.

(ii) There are different ways to transfer data from the SDP to I–DEAS. Because of the complexity of 'preform' preform shapes and therefore, the necessity of interactively generating the mesh (discussed in the last section), the I–DEAS programming Language (Ideal) has been selected as the mesh generation tool. This method is efficient, rapid, user–friendly and reduces the amount of code required to be written. Using this method, complex shapes can be defined using very few lines of input to the I–DEAS program.

(iii) In the process of mesh generation for 'preform' it is possible for the user to concentrate smaller elements in certain parts which may be subject to larger deformation or which may be considered more important by the user. In the case of cylindrical preforms ('billet' or 'cheese'), there is the possibility of generating two layers of small elements on the outer surfaces of the preforms, where the workpiece is in contact with the die surfaces.

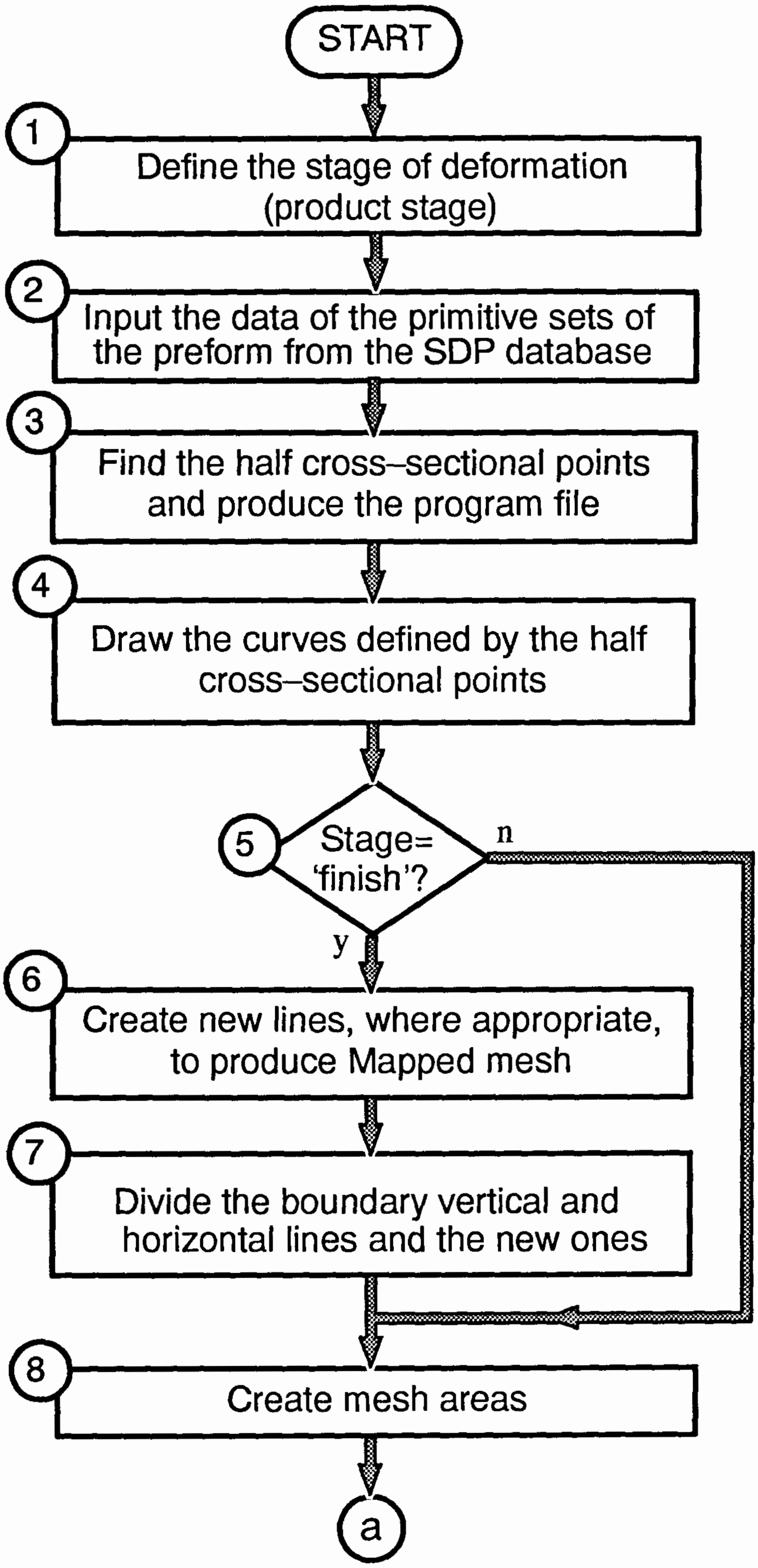


Fig. 4.8 The main actions of the mesh generation step

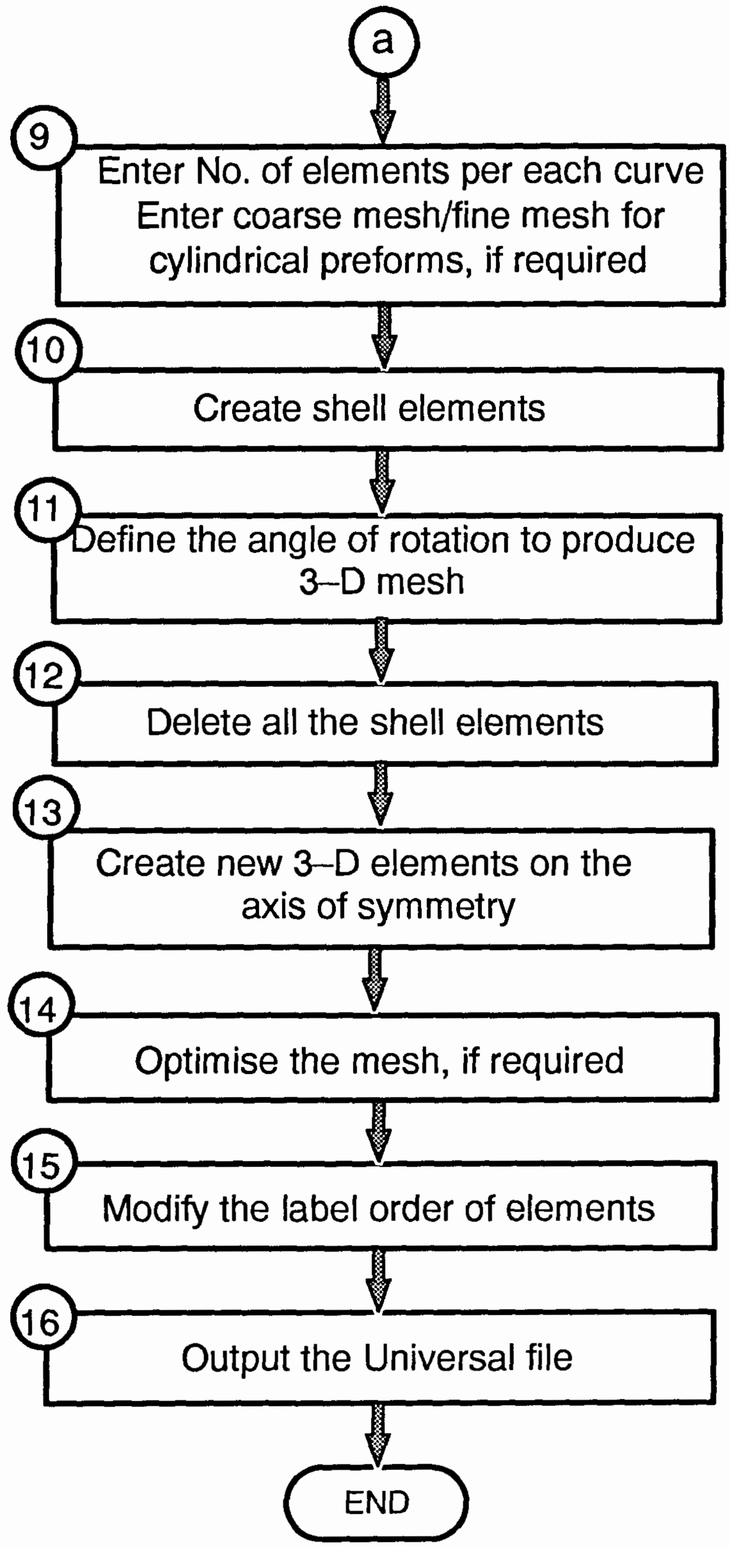
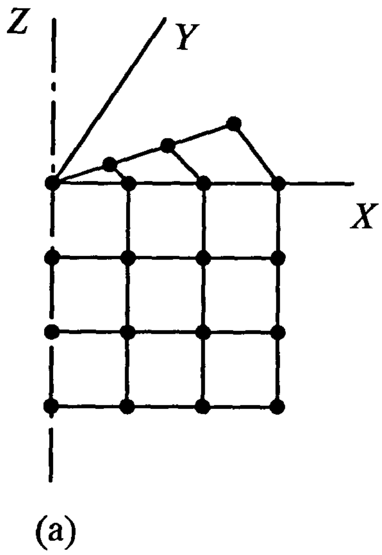


Fig. 4.8 The main actions of the mesh generation step (continued)



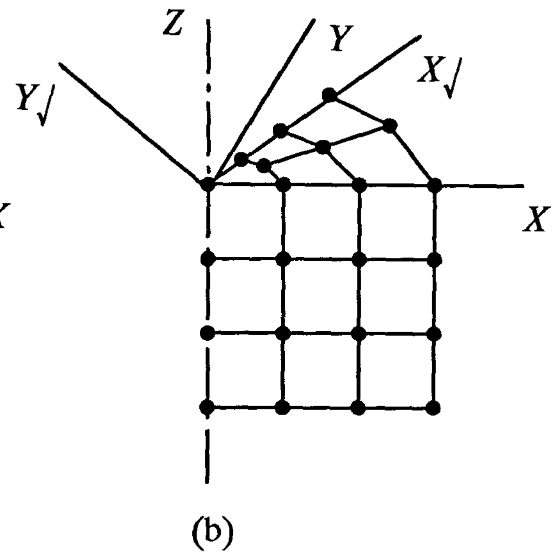


Fig. 4.9 Generating 3–D mesh for Stub Axles
(a) unacceptable (b) acceptable

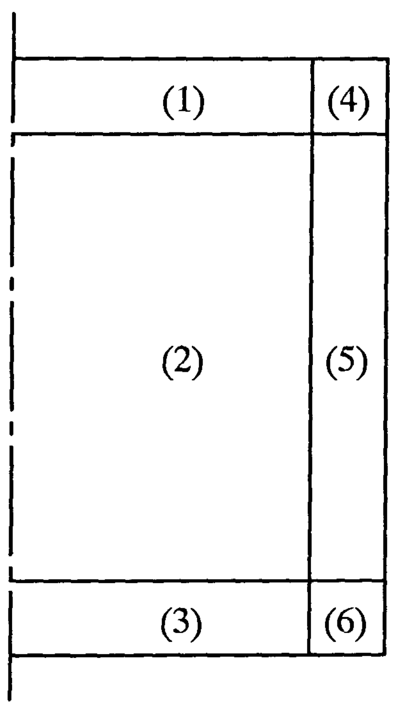


Fig. 4.10 Dividing the half cross–section of a cylindrical preform to 6 mesh areas when a fine mesh is required

(iv) For the method of mesh generation which is suitable for the current work, i.e. 'Mapped meshing', for the cylindrical preforms, when it is not required to generate the layers of smaller elements, only one mesh area is needed but when it is required to generate the layers of smaller elements, the half cross–section should be divided into 6 sub–areas. This is shown in Fig. 4.10. In this case the user inputs the value of coarse mesh/fine mesh in radial and axial directions, in addition to the number of elements in these directions. For mesh generation of 'preform' the half cross–section should be divided into sub–areas. This is shown in Fig. 4.11.a.

(iv) In this step of producing the datafile (mesh generation), the output of the program is a program file. Then the user invokes the I–DEAS and runs the program file. What he/she should do will be displayed on the screen during the execution of the program file. When the execution is finished, the mesh is optimised and an I–DEAS Universal file will automatically be produced and I–DEAS is exited by the program file. This Universal file will be used later in the second stage of producing the datafile.

In the following description, the numbers refer to the labels in Fig. 4.8.

1) The required stage of deformation is selected by the user.

2) As discussed in chapter 3, the description of shapes in the SDP is based on some three–dimensional primitives. At this step the interface program inputs the data of the primitive sets of the preform from the SDP database.

3) Based on the primitives defining the preform, the half cross–sectional points are determined and output is started to an I–DEAS program file describing the coordinates of the points which can be read in by I–DEAS. If a fine mesh is desired for the cylindrical preforms, some other points will be identified in order to be able to generate the mesh areas shown in Fig. 4.10.

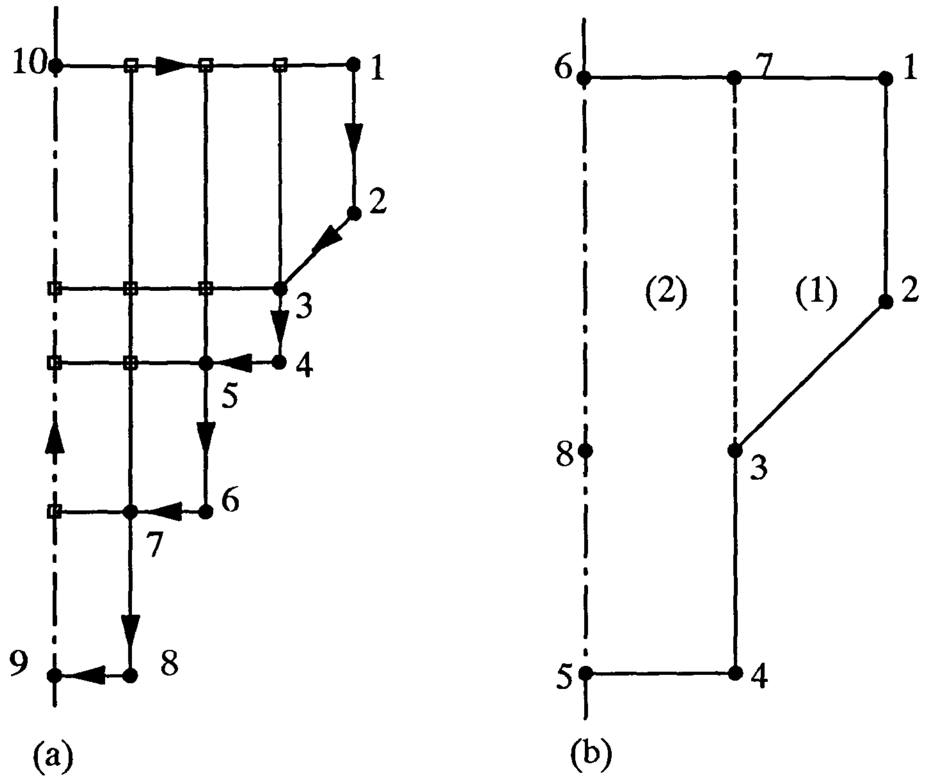


Fig. 4.11 Dividing the half cross–section of 'preform' to sub–areas to produce Mapped mesh
(a) actual half cross–section (b) points to create new lines

4) According to the coordinates of the points, the curves defining the boundary of the cross–section are drawn by I–DEAS commands written to the program file. If a fine mesh is desired for the cylindrical preforms, some other lines will be drawn to generate the 6 mesh areas shown in Fig. 4.10.

5) If 'finish' is the current stage, then some more work needs to be performed.

6) Some new lines need to be created on the half cross–section of the preform of the 'finish' stage. This is illustrated in Fig. 4.11.b. To produce an appropriate mesh, the half cross–section should be divided into sections 1 and 2. However, when using Mapped–meshes, these two areas are not acceptable, because line 7–3, which is a side of area 1, is part of line 7–4, a side of area 2. Therefore, line 3–8 should be created and the half cross–section should be divided into three areas. (If a line is generated from point 2, then an area will be produced with three sides which is not acceptable to I–DEAS.)

The program uses the following rule to produce these new lines:

> If the vector product of the two lines at the two sides of a point (the product performed clockwise) is positive, it is necessary to produce the lines, horizontally and vertically.

7) To produce a Mapped mesh, it is necessary to divide the lines, both the previous and the new ones, at the intersections.

In Fig. 4.11.a, the small dark circles show the points of the cross–section and the small squares illustrate the points at which the lines should be divided. This is done by commands contained in the program file.

8) The mesh area(s) are created according to the type of the preform (one area for the cylindrical preforms without fine mesh, 6 areas for the cylindrical preforms with fine mesh and with variable areas depending on the geometry of the preform for 'preform').

9) The number of elements along each curve is defined by the user when the program file is executed. When a fine mesh is required for a cylindrical

preform the ratio of coarse mesh/fine mesh is defined by the user in the radial and axial directions.

10) The half cross–sectional mesh (shell elements) is generated by the program file.

11) The angle of rotation about the vertical axis is introduced by the user to create 3–D brick–type elements from those elements that do not lie on the axis.

12) All the shell elements are deleted by the program file.

13) Based on the existing and the created nodes, additional 3–D elements are generated to lie on the axis of symmetry. In defining the number of elements along each curve by the user (in 9 above) for the 'preform' preform stage, the curves are displayed on the screen and the corresponding number for each curve is requested from the user. It is not possible in I–DEAS to save numbers in variables during the execution of a program file. Due to this limitation the generation of additional 3–D elements is done manually by the user for the 'preform' preform stage.

14) The mesh will be optimised in I–DEAS, if required.

15) The numbering of the elements is automatically modified, after deleting the shell elements and producing the new ones.

16) The nodal and elements data are automatically output into a Universal file to be used later in the second step of producing the datafile.

4.3.3 Producing the Datafile

When the mesh of the preform has been generated, this data together with the geometry of the product, in the form of boundary surfaces, and other data in the SDP database are processed and formatted to produce the EPFEP3 datafile. Fig. 4.12 illustrates the main activities of this step, some of which are discussed in the following sections.

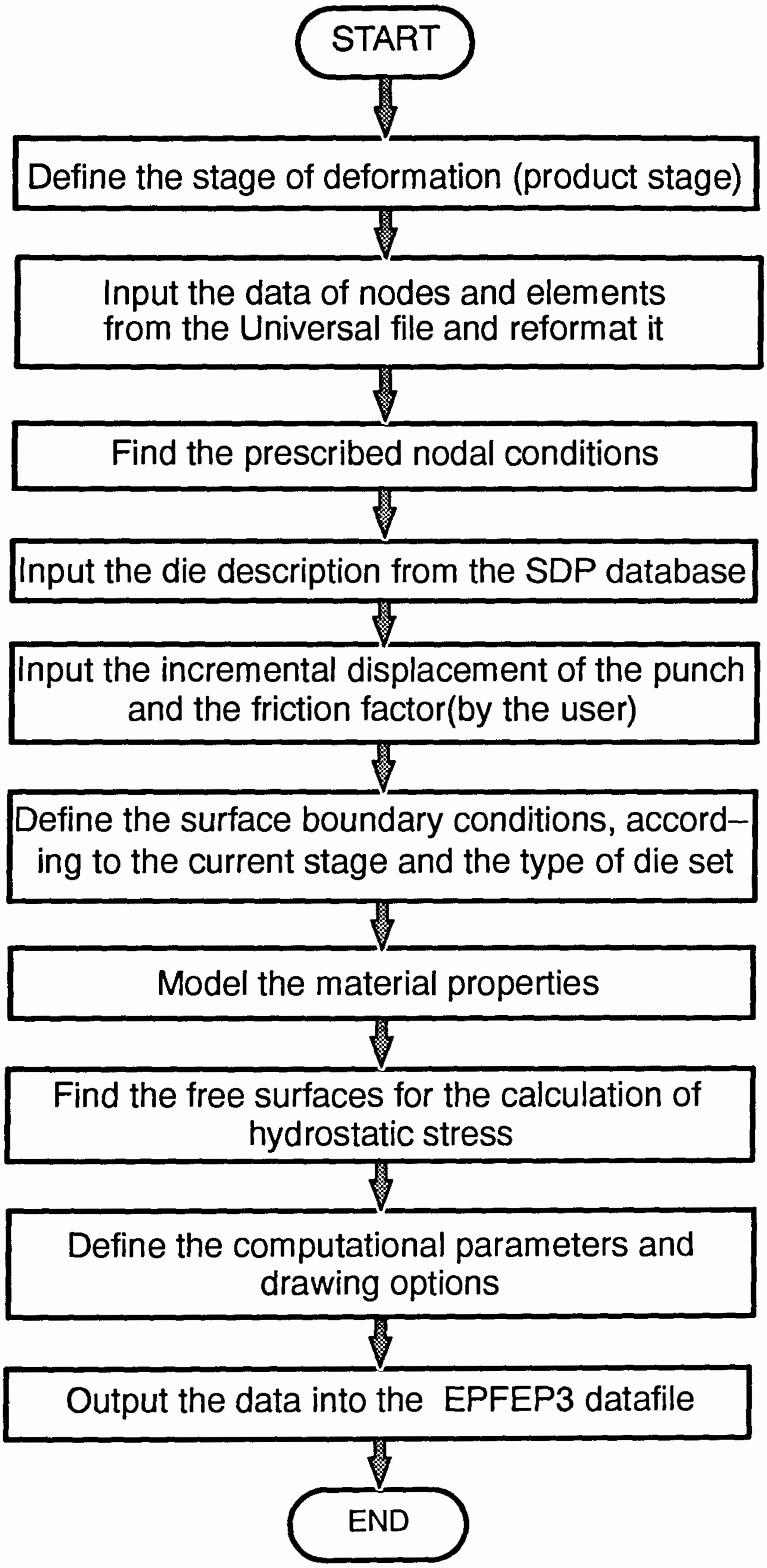


Fig. 4.12 The main actions of producing the datafile

4.3.3.1 Preparing the Data of Nodes and Elements

The coordinates of the nodes and the lists of nodes describing the elements are read from the Universal file. This data should be reformatted based on the format of the EPFEP3 datafile. The order of numbering nodes within an element in I-DEAS is not the same as that of the datafile. Thus, this order should be modified to satisfy the numbering in Fig. 4.2.

4.3.3.2 Defining the Prescribed Nodal Conditions

For the types of mesh generated for the Stub Axles, shown in Fig. 4.9.b, three different nodal constraining conditions can be defined:

(i) The nodes that lie on the axis of symmetry: these nodes are free to move only in the Z direction and are constrained to prevent movement in the other directions.

(ii) The nodes that lie on the X–Z plane: these nodes are free to move in the X and Z directions and are constrained to prevent movement in the Y direction.

(iii) The nodes that lie on the outer rotated plane about the Z axis ($X' - Z$ plane): these nodes are free to move on that plane and are constrained to prevent movement in the direction perpendicular to it (Y' axis). This is a locally rotated axis system, mentioned in section 4.2.2.1, which can be specified with two normal unit vectors (in the Z and X' directions) in the global axis system. Other nodes in the mesh are unconstrained.

4.3.3.3 Defining the Surface Boundary Conditions

Boundary surfaces are modelled in EPFEP3 by means of a set of primitive geometric surfaces shown in Fig. 4.3. This is the easiest way of making the shape and positions of the dies known to the FE program [52]. So, the complex die surfaces, especially in the case of axisymmetric shapes, can be described using a few primitive shapes.

Among the primitives shown in Fig. 4.3, the 'cone' and 'annulus' are generally used in the case of Stub Axles. The description of the die surfaces (the current stage) contained in the SDP is in terms of another set of primitives illustrated in Figs. 3.2 and 3.4.

As described in chapter 3, the different stages of deformation in Stub Axles are generally classified into three steps. These are producing the:

(i) 'cheese' from the 'billet'

(ii) 'preform' from the 'cheese'

(iii) 'finish' from the 'preform'

These stages are shown in Figs. 4.13 to 4.15 respectively, in which the die surfaces are also shown at the beginning of each forming process.

In defining the boundary surfaces, the primitives which are input from the SDP database for the current stage, are changed to EPFEP3 primitives and some modifications are performed. In this respect, the following explanations are required:

(i) It is possible to define some primitives in EPFEP3 as one die group. Thus, it would be a good practice to define the primitive(s) making the punch, container and counter–punch as separate die groups.

(ii) The data for the current stage stored in the SDP database gives the final position of the die set (the position at the end of deformation of the stage). Thus, it is necessary to determine the position of the dies at the beginning of the deformation by using the data of the current stage and that of the mesh.

The different die–groups of the first stage of deformation (producing the 'cheese' from the 'billet') are illustrated in Fig. 4.16. As shown in Figs. 4.14 and 4.15, the die–groups of the container in the two later stages of deformation and that of the punch in the last stage of deformation (when the punch is not a flat die) contain more primitives and are more difficult to model.

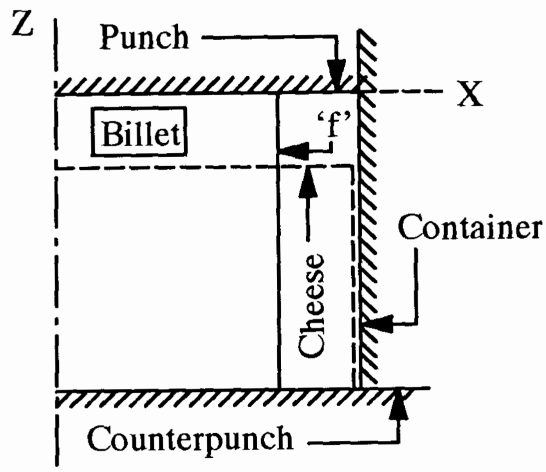


Fig. 4.13 Schematic illustration of producing 'cheese' from 'billet'

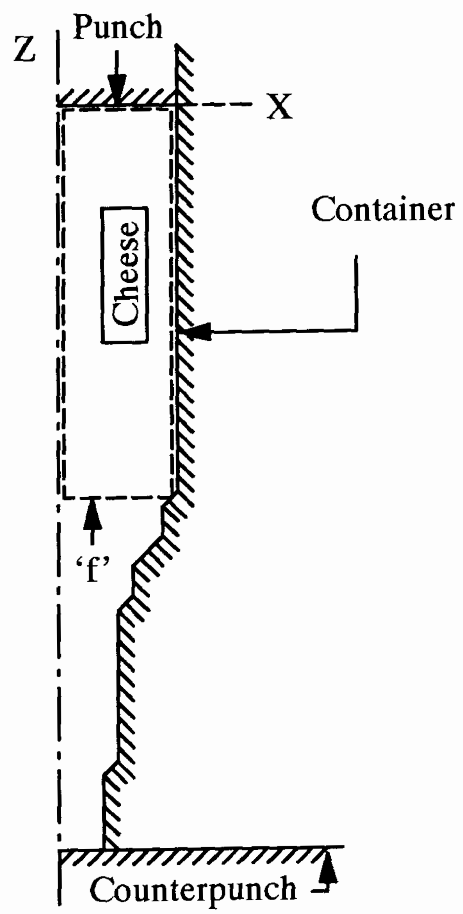


Fig. 4.14 Schematic illustration of producing 'preform' from 'cheese'

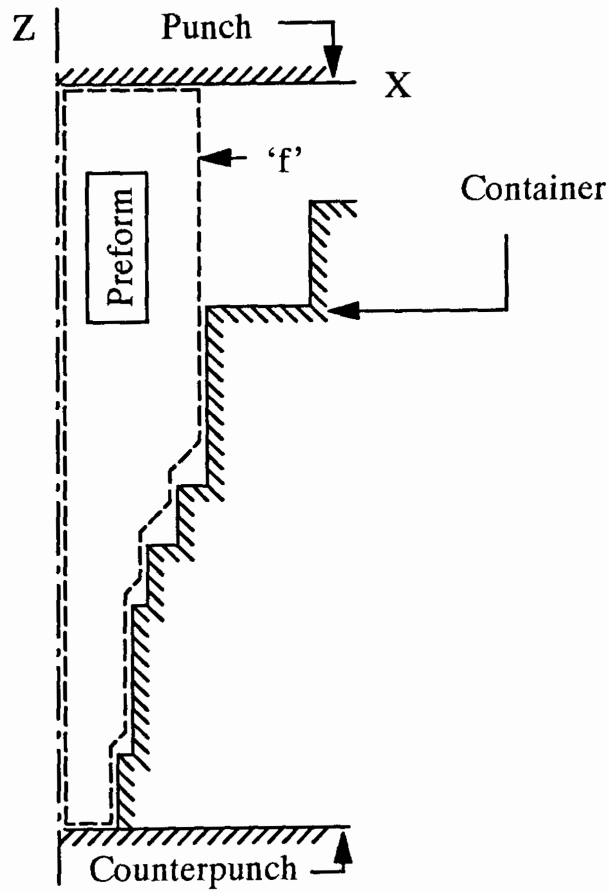


Fig. 4.15.a Schematic illustration of producing 'finish' from 'preform' (flat punch)

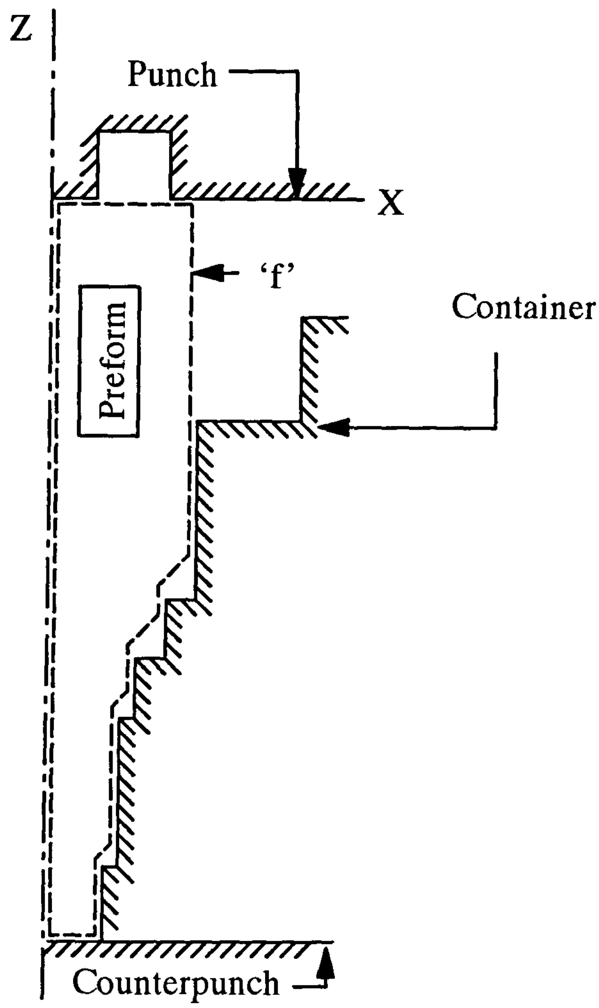


Fig. 4.15.b Schematic illustration of producing 'finish' from 'preform' (upper and lower dies)

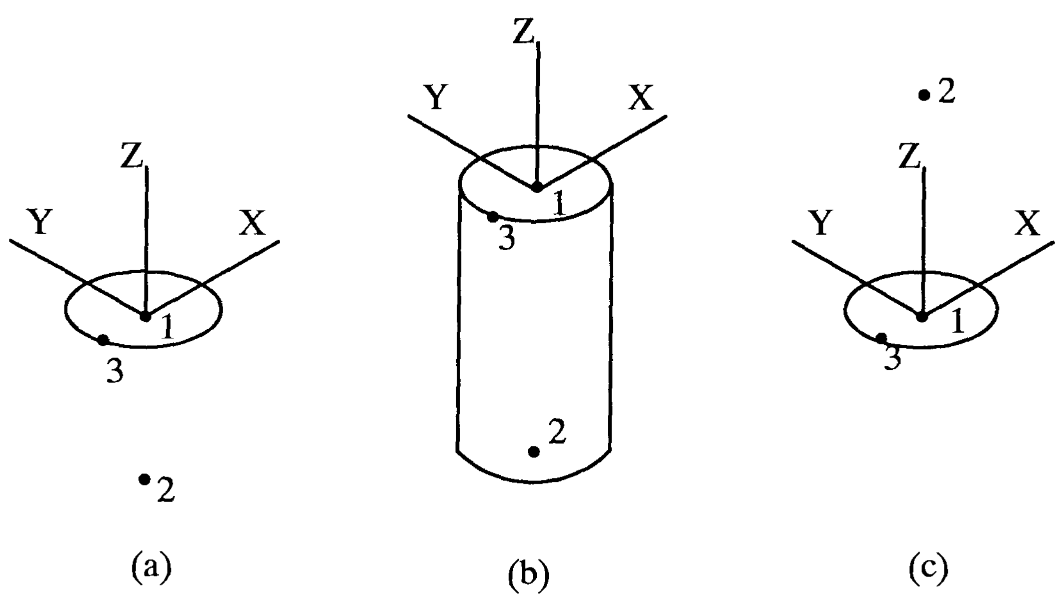


Fig. 4.16 The different primitives to model the 'cheese' die set
(a) The punch (die–group 1)
(b) The container (die–group 2)
(c) The counterpunch (die–group 3)

The description of the die surface will usually contain information about the frictional conditions resulting from the particular lubricant used (if any). The heat transfer coefficient of this layer, initial temperature of the die surface and its incremental movement may also be specified. These pieces of information can be input to the program by the user.

Another piece of data which is needed to describe the boundary surfaces is the thickness of the friction layer. In the program, half of the axial and radial dimensions of the element which lies on the origin of the global system are used to define the friction layer.

4.3.3.4 Defining the Material Properties

Since the design rules in the SDP considers different materials at elevated temperatures, it is necessary to input the mechanical properties of the materials based on the third type of modelling stated in section 4.2.5.

In this type of modelling, the following data are needed for input into the EPFEP3 datafile:

$ym,\ pr$

$h_1,\ h_2,\ h_3,\ h_4$

$h_5,\ h_6,\ h_7$

$\epsilon_o,\ y_f,\ f_0,\ T_0$

$C_v,\ k,\ e,\ h$

$[\epsilon_p,\ a,\ b]$

nh records

in which:

ym : Young's modulus

pr : Poisson's ratio

C_v : thermal capacity per unit volume of material

k : thermal conductivity of material

e : thermal emissivity of material

h : thermal convection coefficient of material

a : value of coefficient of power function of strain rate in yield express–ion, corresponding to a plastic strain of ϵ_p

b : value of exponent of power function of strain rate in yield express–ion, corresponding to a plastic strain of ϵ_p

Other parameters are defined in section 4.2.5.

It is tedious to manually fit equation (4.3) with experimental flow stress–strain data to find out all the specified coefficients, especially for the wide range of the materials and temperatures within the IKBS. Instead, a curve fitting program which had been previously developed in the Solid Mechanics and Process Modelling group [96] was used. This program is mainly based on the least squares method. In this respect, the following steps were carried out:

(i) The range of materials used in the SDP is between B.S 055 M15–B.S 543 A99 (EN2–EN31) and that of the temperatures is between 600–1250 °C. The flow stress–strain data of such ranges and at different strain rates are not available. Thus, the flow stress–strain data of B.S 605 M36 (EN16), one of the available material data curves [97], at the temperatures 900, 1000, 1100 and 1200 °C and at the strain rates 1.5, 8, 40 and 100 s^{-1} were digitised to produce the input data of the curve fitting program.

(ii) The data for B.S 605 M36 (EN16) at other temperatures were extrapolated by using the correction factors provided by Thomas and Bannister [14]. The factors for extrapolating are shown in table 4.1.

(iii) The flow stress–strain data of materials between the above mentioned range, which were among the materials in the above stated reference, were calculated for the B.S 605 M36 (EN16) values by using the correction factors introduced in Ref. [14] and also by extrapolating the correction factors for the range of 600–900 °C and 1200–1250 °C.

The factors for providing the data of the materials indicated above are shown in table (4.2).

(iv) For the materials between the range of B.S 055 M15–B.S 543 A99 (EN2–EN31) which were not considered in the above mentioned reference, the data of the previous material number in the reference was used as an approximation. This approximation was also made in the SDP in determining the forging load.

Thus, the constants h_1–h_7, *a, b* and f_o in section 4.2.5 can be determined by using the curve fitting program for any type of steel at any temperature within the range specified in the SDP. Other parameters may be found from standard handbooks and introduced into the program.

Temperature (°C)	600	700	800	1250
Correction factor (CF)	1.583 (based on the data of 900 °C)	1.333 (based on the data of 900 °C)	1.167 (based on the data of 900 °C)	0.75 (based on the data of 1200 °C)

Table 4.1 Correction factors to extrapolate stress–strain data of EN16 (B.S 605 M36)

4.3.3.5 Introducing the Free–Surfaces

To calculate the hydrostatic stress in EPFEP3, when the indirect method is chosen (which would normally be the case), there must be at all times at least one free–surface element face available to the program.

In Figs. 4.13 to 4.15, those surfaces labelled by the letter 'f', are the surfaces containing elements which have at least one free–surface during the deformation. The elements on these surfaces are found by the interface program and output to the datafile.

4.3.3.6 Defining the Computational Parameters and the Drawing Options

These parameters and options are selected by the interface program having been previously chosen to give acceptable results.

EN No.	B.S 970 No.	600	700	800	900	1000	1100	1200	1250
3	080 A27	0.973	0.970	0.966	0.960	0.952	0.941	0.923	1.000
8	080 M40	0.946	0.939	0.931	0.920	0.905	0.882	0.846	0.778
17	608 M38	0.973	0.970	0.966	0.960	0.952	0.941	0.923	1.000
18	530 M40	0.946	0.939	0.931	0.920	0.905	0.882	0.846	1.000
20		0.973	0.970	0.966	0.960	0.952	0.941	0.923	1.000
21		1.054	1.061	1.069	1.080	1.095	1.118	1.154	1.333
22		1.054	1.061	1.069	1.080	1.095	1.118	1.154	1.333
23	653 M31	1.054	1.061	1.069	1.080	1.095	1.118	1.154	1.333
24	817 M40	1.027	1.030	1.034	1.040	1.048	1.059	1.000	1.111
25	826 M31	1.027	1.030	1.034	1.040	1.048	1.059	1.077	1.222
26	826 M40	1.027	1.030	1.034	1.040	1.048	1.118	1.077	1.222
30	835 M30	1.054	1.061	1.069	1.080	1.095	1.118	1.154	1.222
31	543 A99	0.946	0.939	0.931	0.920	0.905	0.882	0.846	0.889

Table 4.2 Correction factors to determine the stress–strain data of some materials within the SDP by using the data of Ref. [14].

4.4 Discussion on the Interface with EPFEP3

In this chapter the structure and use of the program developed as part of this work has been explained. This program integrates the existing Sequence Design Program for the design of forging sequences and dies with the finite–element program, EPFEP3. The interface program is capable of transforming automatically the geometric data of an appropriate preform within the SDP from SDP format to I–DEAS format and of generating the mesh interactively. After mesh generation, the data relating to nodes and elements is saved in a Universal file. In the second stage, the interface program transfers the mesh data from the Universal file to the EPFEP3 datafile and by using the geometric data and the other data of the corresponding product stage, and by processing and formatting these data, the EPFEP3 datafile is produced. This interface program is efficient, fast and user–friendly, while performing these tasks manually is time consuming and prone to error.

The finite–element meshes that are generated in chapters 7 and 8 to analyse a typical stage of deformation in Stub Axles are based on this interface program and illustrate its efficiency.

An option has been added to the IKBS main menu that performs the tasks of mesh generation for a specified stage of deformation in Stub Axles.

Chapter 5

Development of Comparison Criteria

5.1 Introduction

In chapter 3, it was pointed out that when a new component is input to the IKBS, each forming stage of the component should be compared to the same stage of the same family of components previously stored in the IKBS database. This chapter gives, in detail, more explanation about the comparison procedure and the required tests undertaken in this respect.

5.2 The Comparison Procedure

This section gives the definition and general description of the procedure, the parameters considered and the method of obtaining the weighting factor of each parameter in the procedure.

5.2.1 The Aim of the Comparison

The aim of comparing instances of the forging stages can be stated as follows:

'To establish a level of confidence in the empirical rules used in the design of sequences and dies by using the knowledge stored in the knowledge–base without using directly, either experiments or FE simulation techniques.'

Thus, if the previous instances in the knowledge–base indicate that the current component stage can be produced successfully (or unsuccessfully) and the current stage is sufficiently similar to the previous ones, then it is very likely that the current stage can be produced successfully (or unsuccessfully).

5.2.2 Requirements of the Comparison Procedure

In comparing a stage of a new component with previously encountered stages, two assessment numbers have been defined in chapter 3. These variables, as described in that chapter, are affected by the product and preform parameters (both geometrical and process parameters) and the weighting effects of the parameters. These numbers are the indicators of the degree of similarity between the stages and the level of confidence in this estimate of similarity.

Thus, in comparing the stages, what is needed is to identify which parameters are significant and to quantify their significance in terms of the corresponding weighting factors.

5.2.3 Which Parameters Should be Considered?

As outlined before, both geometrical and processing parameters are important in the comparison procedure. The processing parameters are generally common among the different stages of sequences/dies but the geometrical parameters are specific to a specific stage of deformation. The geometrical parameters include both product and preform parameters.

Among the three stages of deformation in Stub Axles, described in chapter 3, the first one is a closed–die upsetting, the second one is a closed–die forward extrusion and the last one is a combination of closed–die upsetting and backward extrusion (or may be only a closed–die upsetting when the upper die is a flat punch). Due to the small dimensions of the rib in the 'finished part', the last stage can be assumed to be a closed–die upsetting. So, the three different stages of deformation in Stub Axles can be either a closed–die upsetting or a forward extrusion process.

As can be seen from Fig. 3.5, the stage of producing a 'preform' from a 'cheese' is a forward extrusion process with more than one shoulder. So, although a forward extrusion with only one shoulder is considered in the following investigations, it can be considered as an elementary module and its results can easily be applied to a forward extrusion process with more than one shoulder (that is, with several modules).

In the selection of the different parameters used to compare the stages, the following points have been considered:

(i) Some of the processing parameters, such as the accuracy of billet location in a die, cannot be controlled by the user or be assigned a value during the running of a sequence design program. Therefore these parameters can be assumed to be the same in specific stages of all production sequences and are not considered in the current investigation.

(ii) The geometric parameters associated with the deformation zones are more significant than the other geometric parameters. For example, in the stage of producing a 'finished part' from a 'preform', only those parameters in the deformation zone of closed–die upsetting are considered.

Due to the above mentioned points and also based on a survey in the literature, the author's experience and a long discussion with experts in forging, the parameters that are considered in the current investigation are as follows.

The geometric parameters which are important for closed–die upsetting are:

(i) upset ratio (initial height/diameter of the billet) as a preform parameter,
(ii) corner radius of the deformed workpiece as a product parameter,
(iii) final ratio (height/diameter of the deformed workpiece) as a product parameter.

The processing parameters which are important for closed–die upsetting are:

(i) frictional conditions,
(ii) pre–heat temperature,
(iii) type of material,
(iv) type of machine (strain rate).

The geometric parameters which are important for forward extrusion are:

(i) initial ratio of the workpiece (height/diameter) as a preform parameter,
(ii) extrusion ratio as a product parameter,
(iii) Ratio of the extrudate (height/diameter) as a product parameter.

Dean and Sturgess [98] have found that the relationship between forging–load and temperature for the forging of a component depends largely on the type of deformation taking place (extrusion or upsetting for example). So, the significance of pre–heat temperature as a processing parameter was investigated in forward extrusion as well as closed–die upsetting. Another process parameter that was studied in forward extrusion as well as closed–die upsetting was the frictional condition since the boundary conditions are obviously different in these two processes. It was assumed however that the effects of the two other process parameters were the same in forward extrusion as in closed–die upsetting and so experiments were only carried out for the latter process.

5.2.4 Obtaining the Weighting Effects of the Parameters

Once the significant parameters have been selected for the deformation of each stage, the next step is to obtain the weighting effect of each parameter. In this connection, the following explanations are necessary:

(i) In investigating the weighting effects of different parameters, two methods may be utilised:

1. If a database containing a large number of data on real forgings is available, the effects of different parameters can be examined by studying the examples.

2. An indicator can be used, on which the effects of different parameters can be investigated. This indicator should be a *quantitative variable*.

Obtaining a complete database of real forging examples is time consuming and expensive. In the existing IKBS, such a database is not available. Therefore, the second method of investigation has been utilised.

(ii) There are several quantitative variables which may be used in this relation, but it is much better to consider a variable which is fast, easy and accurate to measure.

Such a quantitative variable could be the *forging load* or *average pressure*.

Therefore, in obtaining a criterion to compare a forging stage with those stored in the IKBS database, the following steps should be carried out:

1. One of the significant parameters is selected.

2. The effect of a specified change in the parameter on the changes in forging load or average pressure is measured experimentally.

3. The above two stages are repeated for each of the parameters and thus, the relative significance of the effect of each parameter on forging load or average pressure can be determined and their corresponding weighting factors will be known.

Several empirical and/or analytical formulae are available which define the forging load or average pressure as a function of certain parameters. These are not suitable to be used within the IKBS assessment procedure, since:

(i) They are usually general formulae which are specifically developed to give an approximate forging load or average pressure required to deform the material for equipment selection. These formulae do not properly consider all the significant parameters, for example the effect of corner geometry, on the die filling in the last stage of deformation.

(ii) As discussed in chapter 3, in the case of SDP, in order to obtain a program which has the capability of designing the proper sequences for components which have different specifications (for example different accuracies for forged products), they should be divided into families, because it is not possible to produce a small set of design rules which can be applied to a large range of shapes. This reasoning can be extended to the case of forging load or average pressure. In the IKBS, it is necessary to have a more precise measure of the effects of different parameters in the comparison procedure compared to the general formulae of estimating the load or average pressure for a specific stage of deformation. If the *order of magnitude of error* in comparing the stages is greater than that of differences calculated by the design rules in the SDP, then the output of the comparison process can not be reliable.

Thus, it can be concluded that:

'In order to obtain a reliable set of comparison criteria, the effects of different parameters specific to a certain stage of deformation in the SDP should be examined and determined. The quantitative variables which can be utilised in this respect, are forging load or average pressure.'

5.3 Test Procedure

In performing the tests required to obtain the weighting effect of each parameter, the billets were prepared within the ranges specified in the SDP, as far as possible.

5.3.1 Die Design

Figure 5.1.a is a schematic of the general arrangement of the die–sets used for closed–die upsetting and Fig. 5.1.b shows the die–sets for forward extrusion. They consist essentially of a punch, container, counterpunch (die, in forward extrusion), bolster, ejector and also punch and container clamp rings and load–cell (not shown).

The difference between the type of forward extrusion considered here and that which is normally used is that the die in Fig. 5.1.b does not have a land. So, in this case all the length of the die wall will be in contact with the extrudate during the deformation.

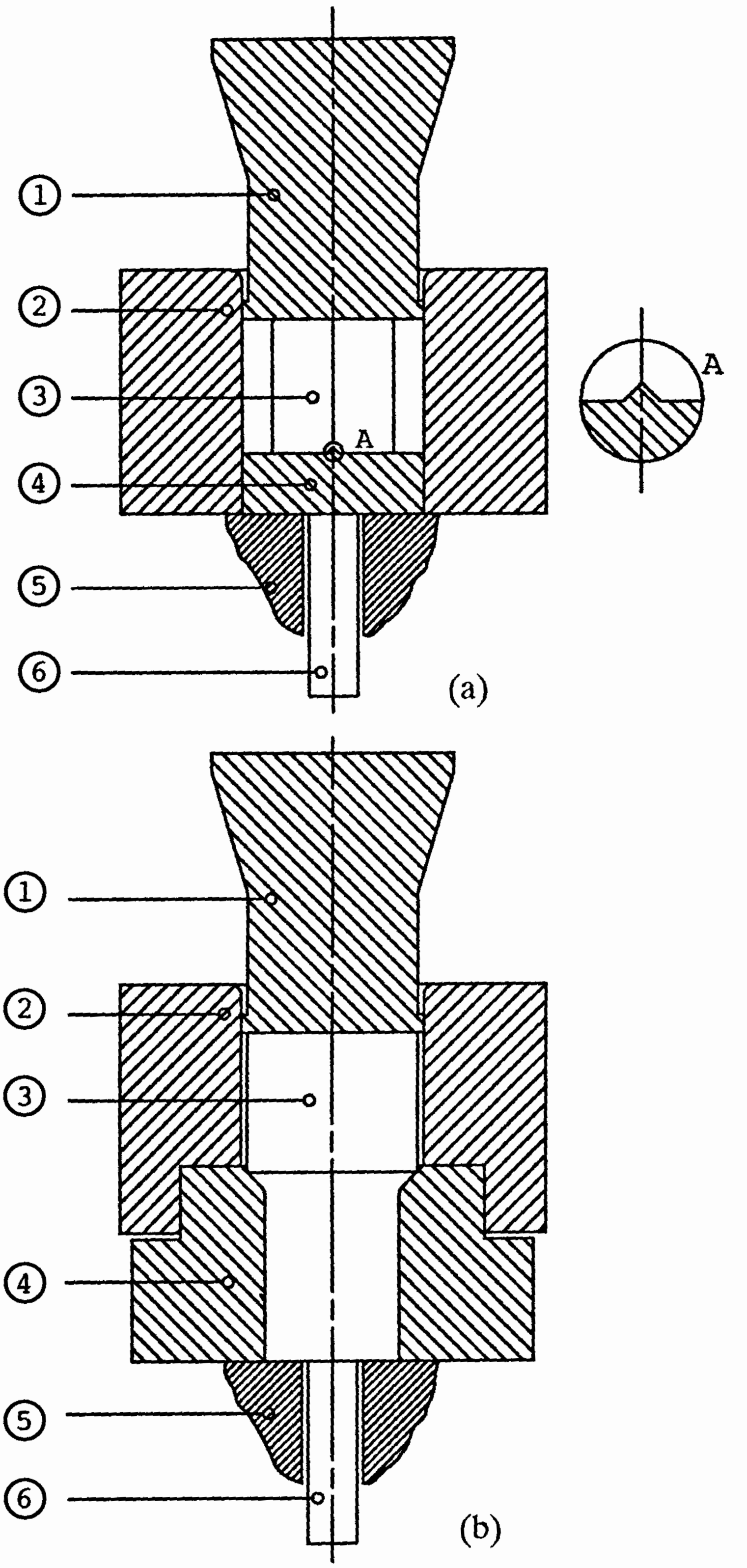


Fig. 5.1 Schematic illustration of the die–sets used,

(a) in closed–die upsetting (b) in forward extrusion

1–Punch 2–Container 3–Billet 4–Counterpunch (die, in forward extrusion)

5–Bolster 6–Ejector

As illustrated in Fig. 5.1.a, a small cone was machined on the counterpunch which mated with a conical indentation on the axes of the billets so that they could be centrally located in the dies. This ensured accurate and consistent positioning of billets. Since the small cone and the conical indentation were machined on the centreline of the counterpunch and the billets, their effects on the deformation load or average pressure are assumed to be negligible.

The punch, container and its liner, counterpunch and the load–cell were made from AISI H13, hardened and tempered to a hardness of 52–54 Rc. All other components were made from HB Impax (AISI P20).

5.3.2 Forging Machines

The machines used in the current investigations were:

(i) A 2000 KN mechanical press
(ii) A 1500 KN hydraulic press for the test No. 7.

5.3.3 Types of Test

Different types of test were carried out to investigate the weighting effects of various significant parameters. These tests are classified into two groups, i.e. closed–die upsetting and forward extrusion.

5.3.3.1 Closed–Die Upsetting

Test No. 1

Aim of the test: To investigate the weighting effect of product corner dimensions as a product parameter.

Two billets with the same dimensions, 32 mm diameter and 33.5 mm height, were deformed in the same 41 mm diameter die, but with different amounts of corner filling. Other data are:

(i) Type of material: B.S 080 M40 (EN8) (with a chemical composition of 0.442% C, 0.175% Si, 0.555% Mn, 0.011% P and 0.025% S).
(ii) Billet pre–heat temperature: 900 °C.
(iii) Lubricant: A water–based graphite lubricant was applied to the tools and all the surfaces of the billets. This is normal lubrication for warm and hot forging of steel.
(iv) Forging machine: A 2000 KN mechanical press with a strain rate of 13 s^{-1} (at the middle of deformation) was used.
(v) Die temperature (initial): 80 °C.

Test No. 2

Aim of the test: To investigate the weighting effect of upset ratio (initial height/ diameter of the billet) as a preform parameter.

Various billets with the same volume but with different upset ratios were used. The dimensions of the billets are shown in table 5.1 (the diameter of the final product in each case was 41 mm). The other data were as for test no. 1.

No.	Diameter of billet (mm)	Height of billet (mm)	Upset ratio
1	34	29.7	0.87
2	32	33.5	1.05
3	30	38.1	1.27
4	28	43.7	1.56
5	26	50.7	1.95

Table 5.1 The dimensions of billets of test No. 2

Test No. 3

Aim of the test: To investigate the weighting effect of the cheese ratio (height/diameter of product) as a product parameter.

Three billets with the same initial dimensions, 21 mm diameter and 42 mm height, were deformed in three different dies, with 26 mm, 32 mm and 41 mm diameter corresponding to different product ratios of 1.05, 0.57 and 0.27. The other data were as for test no. 1.

Test No. 4

Aim of the test: To investigate the weighting effect of lubrication condition as a process parameter.

Billets with the same dimensions, 30 mm diameter and 38.1 mm height, were deformed in the same 41 mm diameter die using three different lubrication conditions. One of the lubricants was the same as that used in tests 1, 2 and 3. The other lubricant in this test was glass–based and for the third lubrication condition the billets were not lubricated. In all three cases the dies and tools were lubricated with a water–based graphite lubricant. The other experimental details were as for test no. 1.

Test No. 5

Aim of the test: To investigate the weighting effect of different billet pre–heat temperatures as a process parameter.

The closed–die upsetting was carried out as for test piece no. 3 of test no. 2 but with the billets pre–heated to different temperatures between 700 and 1200 °C. This covered most of the temperature range acceptable to the Sequence Design Program (600 – 1250°C). All the other experimental details were as for test no. 1.

Test No. 6

Aim of the test: To investigate the weighting effect of material type as a process parameter.

Closed–die upsetting was carried out as for test piece no. 3 of test no. 2. Of the materials that can be specified with the Sequence Design Program, five different materials were tested. The types of materials used and their chemical composition are shown in table 5.2.

No.	Material	Chemical composition (%)				
		C	Si	Mn	P	S
1	B.S 080 M40 (EN 8)	0.442	0.175	0.555	0.011	0.025
2	B.S 080 A27 (EN 3)	0.172	0.221	0.816	0.027	0.031
3	B.S 605 M36 (EN 16)	0.400	0.211	0.659	0.027	0.026
4	B.S 709 M40 (EN 19)	0.437	0.273	0.763	0.020	0.024
5	B.S 817 M40 (EN 24)	0.425	0.260	0.540	0.020	0.029

Table 5.2 Steels used in test No. 6 and their chemical compositions

Test No. 7

Aim of the test: To investigate the weighting effect of the type of machine (i.e. the strain rate) as a process parameter.

Two different machines were used to deform identical billets at different rates. One of the machines (a mechanical press) was the same as that used for test no. 1 and the other was a 1500 KN hydraulic press which produced a nominal strain rate of 0.15 s^{-1}. The billets and other conditions were the same as for test piece no. 3 of test no. 2.

5.3.3.2 Forward Extrusion

Test No. 8

Aim of the test: To investigate the weighting effect of extrusion ratio as a product parameter.

Three billets with the same dimensions, 40 mm diameter and 40 mm height, were deformed in different dies with different extrusion ratios. The diameter of the container was 41 mm and the diameter of the dies was 33.4 mm, 29 mm and 26 mm. The other data were as for test no. 1.

Test No. 9

Aim of the test: To investigate the weighting effect of the initial height/diameter of the workpiece as a preform parameter.

Different billets with the same diameter (40 mm) were used. The heights of the billets were 30 mm, 40 mm, 50 mm and 60 mm. The diameter of the container was 41 mm and the diameter of the die was 29 mm. The other data were as for test no. 1.

Test No. 10

Aim of the test: To investigate the weighting effect of the height/diameter of the extrudate as a product parameter.

Different billets with the same dimensions, 40 mm diameter and 40 mm height, were used. The diameter of the container was 41 mm and the diameter of the die was 29 mm. The other data were as for test no.1.

Test No. 11

Aim of the test: To investigate the weighting effect of the workpiece pre–heat temperature as a process parameter.

Forward extrusion was carried out using the die–set specified in test no. 10 and different billets having the same dimensions as the billets in test no. 10 but which had been pre–heated to 6 different temperatures in the range 600–1100 °C. All the other experimental details were as for test no. 1.

Test No. 12

Aim of the test: To investigate the weighting effect of lubrication condition as a process parameter.

Forward extrusion was carried out as for test no. 10, but with the different lubrication conditions used in test no. 4. The other data were as for test no. 1.

5.3.4 Experimental Method

5.3.4.1 Lubrication

Lubrication of the billets was carried out before heating. In lubricating the billets with water–based graphite lubricant the following steps were performed. The billets were:

(i) Warmed in an oven at 150°C for about 3 hours
(ii) Removed from the oven
(iii) Dipped into the lubricant for 1–2 seconds
(iv) Lifted out for 1–2 seconds
(v) Subjected to steps (iii) and (iv) twice to achieve uniform lubrication
(vi) Dried in air.

The billets with glass–based lubricant were lubricated uniformly by a small paint brush and then dried by means of a hot air drier.

The dies were pre–heated to about 80 ^{o}C by electrical heating using electric cartridge heaters which heated the die bolster. The temperature controller was set on the required temperature which was fed back by a thermocouple in contact with the die surface. The punch was heated to about 80 ^{o}C by means of a gas torch. The working surfaces of the tools were lubricated after heating by means of a small paint brush. Care was taken to provide uniform and consistent lubrication on the die–sets from test to test.

5.3.4.2 Billet Heating

Billets were heated in an electric base type furnace with normal atmosphere and transferred from the furnace to the dies with tongs. In order to minimise the effect of heat conduction from the billets, the tongs were insulated with thermal wool.

Due to the large range of temperature, size and surface condition of the billets, it was important to estimate the heating time required to produce a uniform temperature when they were put in the dies. An experimental method was therefore used to calibrate the heating and cooling processes. This is described in appendix A.

By considering the time required to transfer each billet from the furnace to the die and using the calibration curve, the heating time and the initial temperature of the billet, and therefore the required working temperature of the furnace, could be estimated.

To speed the process of billet location in the die in the mechanical press, before starting each forging, the counterpunch was raised up to its upper position. Billets were rapidly located on its centre before it was returned to its lower position. The delay time in returning the counterpunch was about 2 seconds, which was allowed for by using the cooling calibration.

5.3.4.3 Recording Load–Displacement Data

The forging load was measured using a strain gauged cylindrical load cell positioned on the top of the punch. The load cell was calibrated before use, as described in appendix A.

The displacement of the punch after it had made contact with the billets was measured using a displacement transducer. The load cell and the transducer were connected to amplifiers and the output was fed into an oscilloscope. On the screen of the oscilloscope the load–displacement curve was displayed during each forging operation and photographed.

5.3.4.4 Measuring Corner Dimensions

A profile projector with a magnification of 20 was used to measure the corner dimensions of the deformed billets in closed–die upsetting. In section, these corners were more similar to a triangle than to a portion of a circle. In Fig. 5.2 the schematic illustration of a deformed billet is shown. Thus, the height and width of both upper and lower corners were measured at eight different points around the circumference of the billet and the average values of width and height in each case were used to find the upper, lower, and therefore the total, unfilled cavity volume.

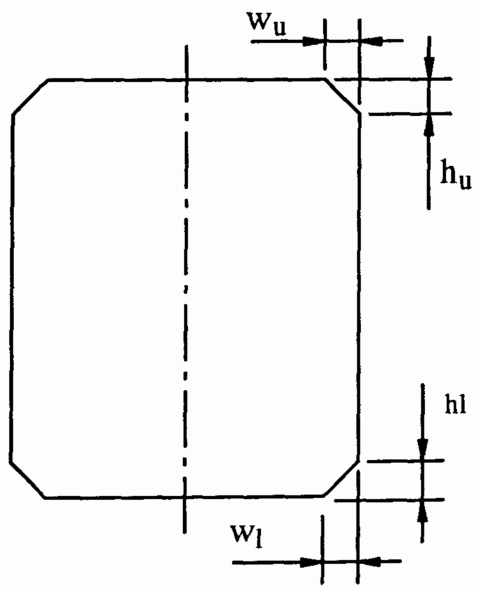


Fig. 5.2 Schematic illustration of a deformed billet in closed–die upsetting.

5.3.4.5 Number of Specimens in Each Experiment

In order to increase accuracy, three specimens were used for each experimental condition.

5.4 Experimental Results

Fig. 5.3.a shows a typical load–displacement curve in closed–die upsetting and Fig. 5.3.b illustrates a load–displacement curve in forward extrusion.

As can be seen from Fig. 5.3.a, in closed–die upsetting there are two main stages of deformation. The first stage relates to the deformation before contact with the die walls (free upsetting) and the second stage relates to when the corners are being filled.

In closed–die upsetting the final load was an ill–defined quantity because in practice it was very difficult to identify the stage at which a die cavity was just completely filled. To overcome this problem and to maintain consistency across the range of experiments the load for 2% unfilled die cavity volume was used in all tests except test no. 1, in which the variable being investigated was the percentage of unfilled corner volume. This was either measured directly, interpolated or extrapolated from the load–displacement trace. The load was divided by the plan area of the 'cheese' to produce the average pressure ($P_{0.02}$) that is used as the sensitivity indicator in the following sections.

The percentage of unfilled corner volume at any particular stage is defined as:

$$V_r = \frac{V_c - V_b}{V_b} \times 100 \qquad (5.1)$$

in which:

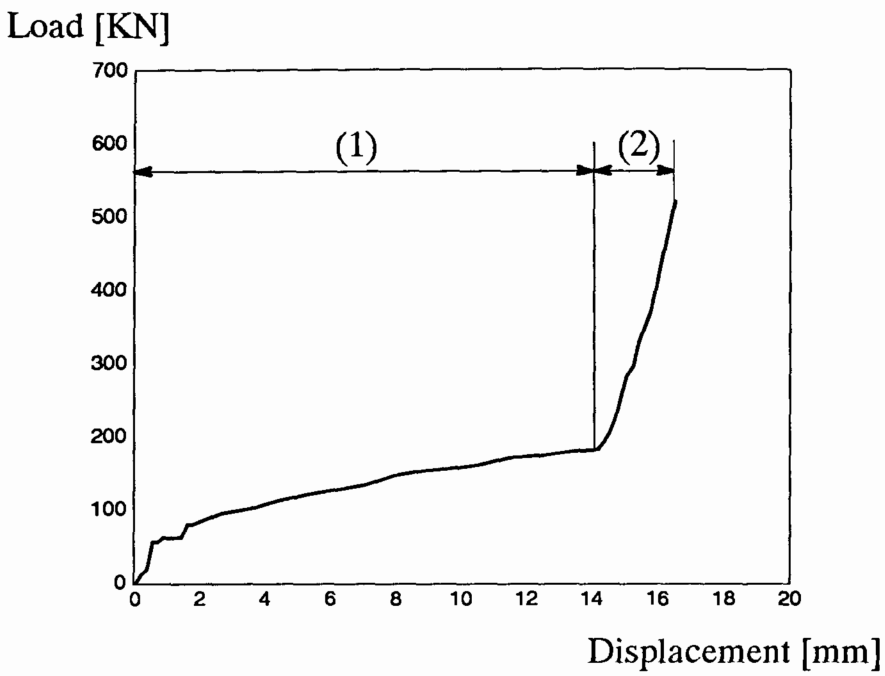
V_b billet volume

V_c volume of die cavity with imaginary sharp corners

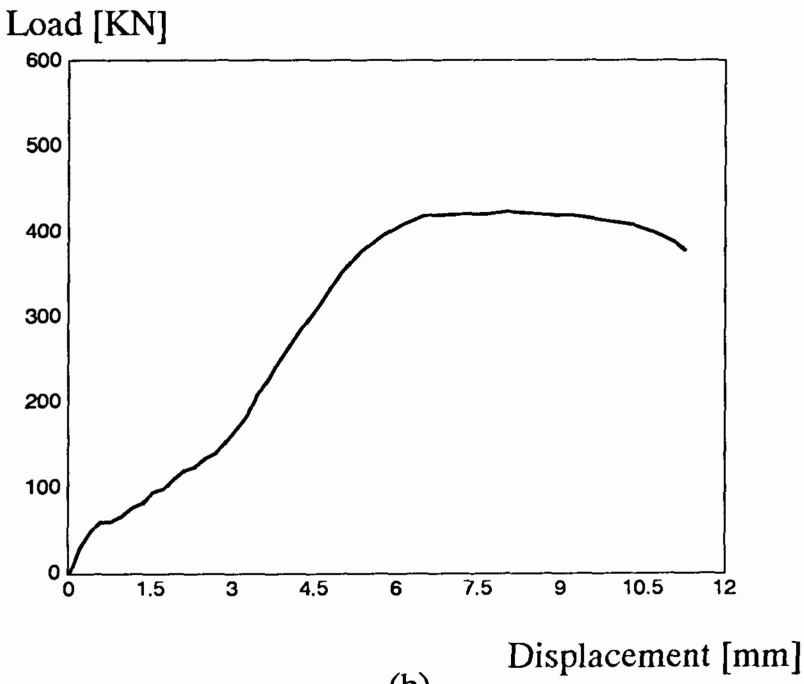
V_r percentage of unfilled corner volume

Thus by calculating the actual percentage of unfilled corner volume for the final measured load, it was possible to determine the load corresponding to the stage when 2% of the die cavity was unfilled.

In forward extrusion the maximum load is reached as soon as the die is filled with the workpiece material [99]. This load was measured and divided by the plan area of the workpiece to produce a maximum average pressure (P_{max}) which was selected as the sensitivity indicator in the following sections.



(a)



(b)

Fig. 5.3 A typical load–displacement curve,
(a) in closed–die upsetting
(1) the stage of free upsetting (2) the stage of corner filling
(b) in forward extrusion

5.4.1 Closed–Die Upsetting

Test No. 1

The values of the average pressure obtained for the two deformed workpieces with different corner dimensions resulting from 3.1% and 2.2% unfilled corner volume are shown in table 5.3.

Specimen No.	Corner unfilled (%)	Max. load (KN)	Upset ratio
1	3.1	490	1.05
2	2.2	555	1.05

Table 5.3 The data obtained for the test No. 1

It is not industrial practice to design dies with sharp corners but such corners may arise between the punch, die and counterpunch in completely closed–die forging. In the last stage of deformation, the workpiece may not have sharp corners due either to completely filling a radiused corner or to not completely filling a sharp corner. It can be seen that until actual contact at the corner takes place, the forging load increases as the radii of the corners of the workpiece decreases, irrespective of the radius of curvature of the corner of the die. For example, the situations in Fig. 5.4 (a) and (b) are essentially the same in so far as the effect on forging load is concerned, assuming gas entrapment is not significant.

Thus, what is important in determining the forging load is not so much the volume of actual gap between the workpiece and the dies as the volume of the gap between the workpiece and the shape the dies would have if the corner of the die was perfectly sharp, i.e. V_r in equation (5.1).

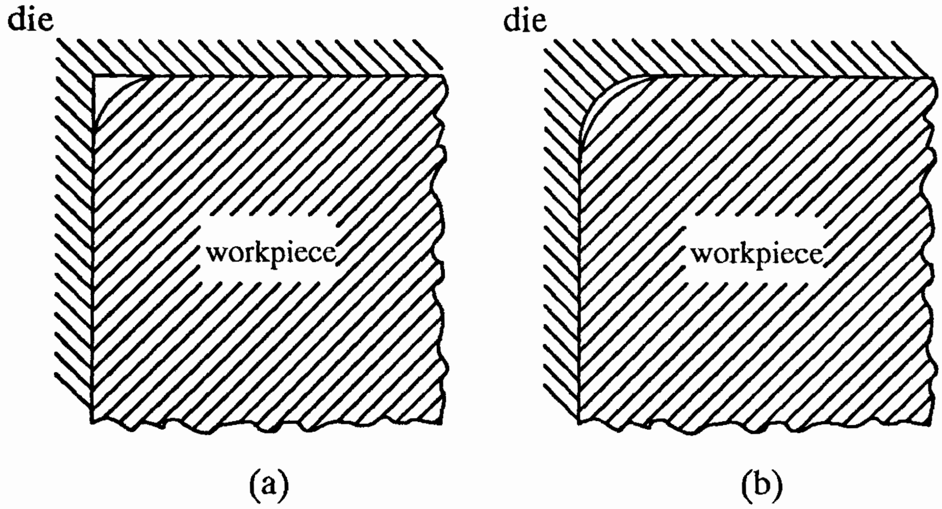


Fig. 5.4 Illustration of workpiece corner geometry in two different dies

(a) die with sharp corner–die cavity unfilled
(b) die with curve corner–die cavity (almost) filled

In practice it is not easy to predetermine the unfilled corner volume. What is usual is to define the specific product geometry and a fictitious die cavity with sharp corners. Since the percentage of unfilled corner volume is directly related to product geometry, it is considered as a product geometrical parameter which can be considered in the comparison procedure.

A method has been developed which relates the percentage of unfilled corner volume to an equivalent corner radius and vice versa for the stage of producing a 'cheese' from a 'billet'. The details of these calculations are described in Appendix B and the results are:

$$V_r = 270\frac{R}{V_b}\,r^2 \tag{5.2}$$

$$\therefore \quad r = \left[\frac{V_r\,V_b}{270\,R}\right]^{\frac{1}{2}} \tag{5.3}$$

Based on equation (5.3) and by using the results of this test and those obtained experimentally by Ibhadode [100] for load as a function of percentage of unfilled corner volume, the equivalent radius was determined for each percentage of unfilled corner volume at specified points and the results of load–corner radius was obtained from which the average pressure is determined. Fig. 5.5 shows the results of average pressure as a function of unfilled corner volume.

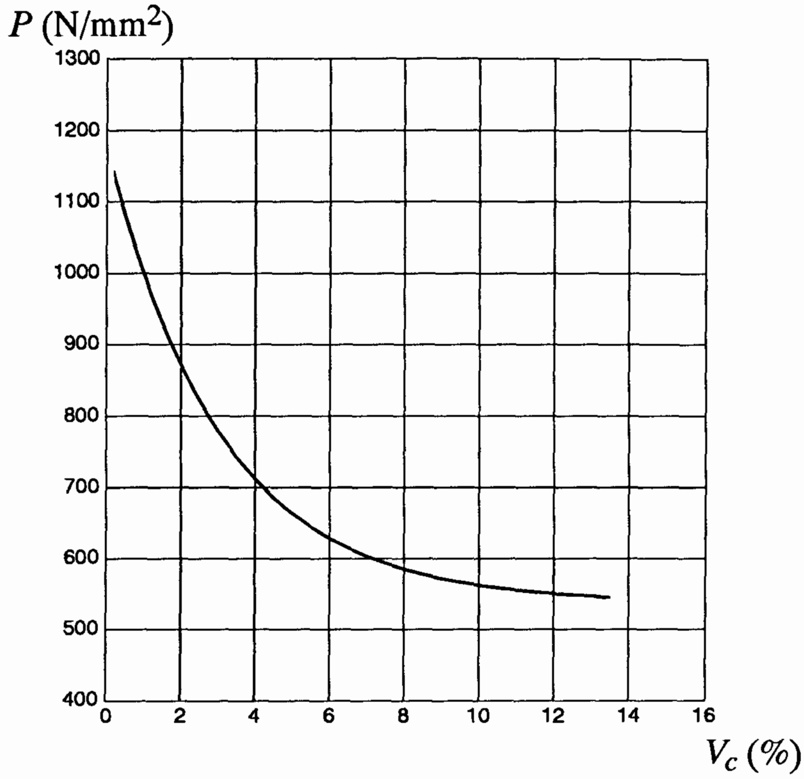


Fig. 5.5 Variation of average pressure P with unfilled corner volume V_c (test No. 1) –Fitted equation: $P(V_c)=539+645.5e^{-0.326V_c}$

Test No. 2

In table 5.4 the values of the average pressure $P_{0.02}$ obtained for each upset ratio r_u are shown and the corresponding graph is illustrated in Fig. 5.6.

Upset ratio (r_u)	0.87	1.05	1.27	1.56	1.95
$P_{0.02}$ (N/mm^2)	377	410	415.5	394	366

Table 5.4 The data obtained for the test No. 2

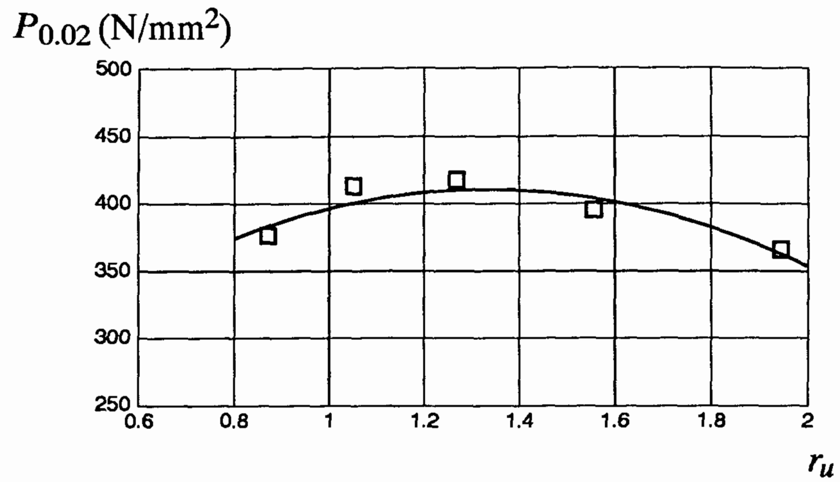


Fig. 5.6 Variation of average pressure at 2% unfilled die cavity ($P_{0.02}$) with upset ratio r_u for closed–die upsetting–test No. 2
Fitted equation: $P_{0.02}(r_u)=185.8+338.2\, r_u-126.9\, r_u^2$

In table 5.5 the final dimensions of the upper and lower corners for the two upset ratios are illustrated: (a) upset ratio 1.05 and (b) upset ratio 1.95.

Upset ratio	unfilled Corner volume (%)	h_u (mm)	w_u (mm)	h_l (mm)	w_l (mm)	h_u/w_u	h_l/w_l
1.05	3.1	2.41	1.18	2.99	1.29	2.04	2.32
1.95	3.0	1.83	1.29	2.4	1.74	1.42	1.38

Table 5.5 The corner dimensions of two deformed billets corresponding to the two upset ratios in closed–die upsetting (the variables are defined in Fig. 5.2).

Test No. 3

The values of the average pressure $P_{0.02}$ obtained for each cheese ratio r_c are shown in table 5.6 and the corresponding graph is illustrated in Fig. 5.7.

Cheese ratio (r_c)	1.05	0.57	0.27
$P_{0.02}$ (N/mm^2)	386	390.5	398

Table 5.6 The data obtained for the test No. 3

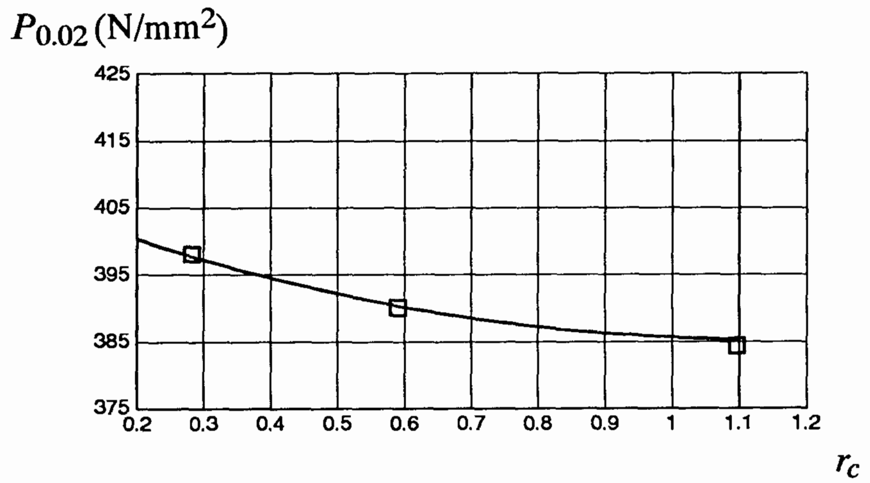


Fig. 5.7 Variation of average pressure at 2% unfilled die cavity ($P_{0.02}$) with cheese ratio (height/diameter of the product r_c) for closed–die upsetting– test No. 3

Fitted equation: $P_{0.02}(r_c)=407.7-39.5\,r_c+17.6\,r_c^2$

Test No. 4

The results of the average pressure obtained for the different lubrication conditions are shown in table 5.7.

The lubrication condition affects the forging load in both stages of deformation. This is illustrated in Fig. 5.8.

Lubrication condition of billet	graphite	glass–based	without lubrication
$P_{0.02}$ (N/mm^2)	415.5	386	439

Table 5.7 The data obtained for the effect of lubrication condition in closed–die upsetting– test No. 4.

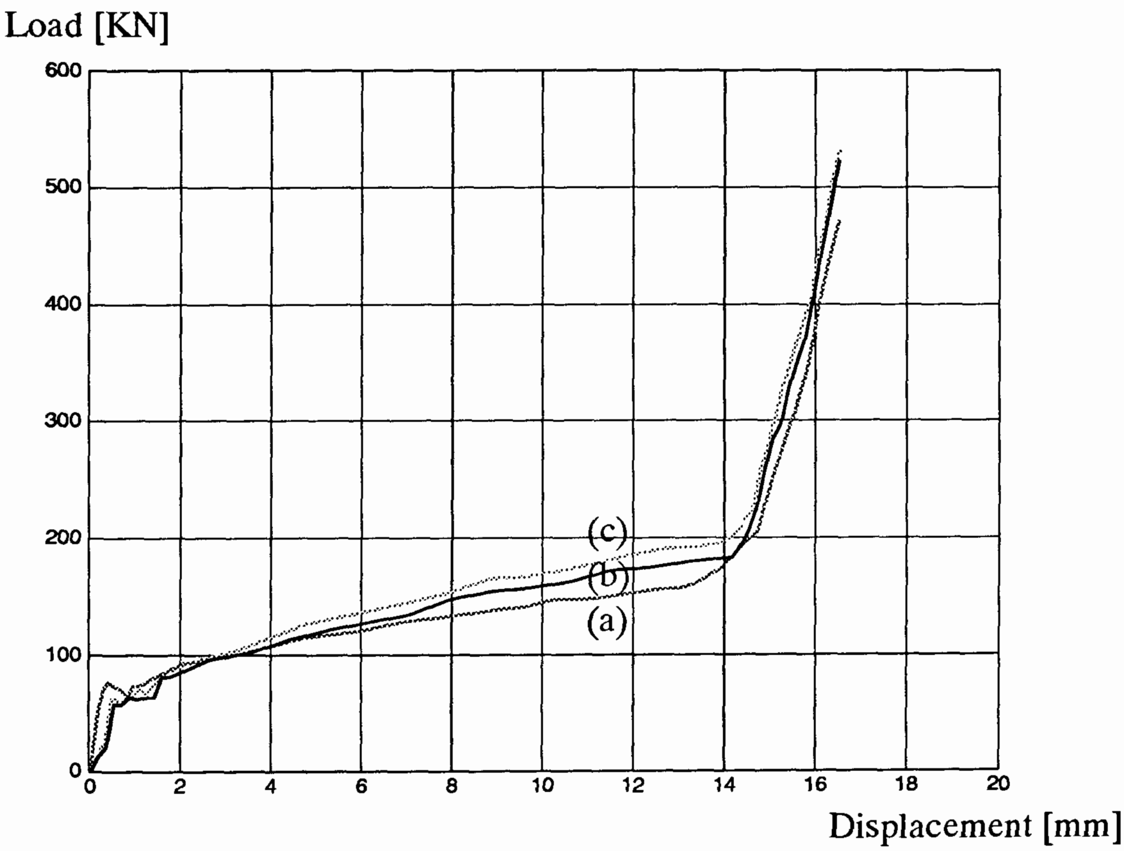


Fig. 5.8 The effect of lubrication condition on forging load in closed–die upsetting

(a) Glass–based lubricant (b) Graphite (c) No lubricant

Test No. 5

The results of the average pressure $P_{0.02}$ obtained for the different temperatures are illustrated in table 5.8, and in Fig. 5.9 the corresponding graph is shown. In Fig. 5.10 the digitised data for the load–displacement curves at various temperatures are shown.

Temperature (°C)	700	800	900	1000	1100	1200
$P_{0.02}$ (N/mm^2)	535.5	512	415.5	317	233	122

Table 5.8 The data obtained for the effect of billet pre–heat temperature in closed–die upsetting– test No. 5.

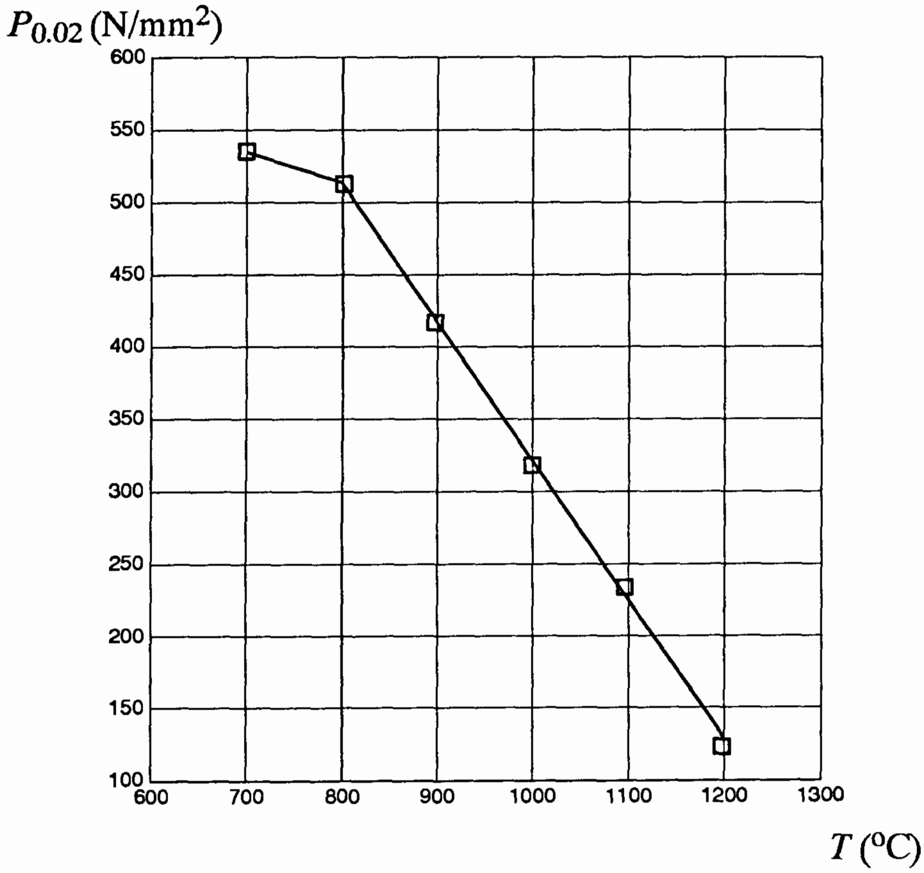


Fig. 5.9 Variation of average pressure at 2% unfilled die cavity ($P_{0.02}$) with billet pre–heat temperature T for closed–die upsetting– test No. 5.

Fitted line: $P_{0.02}(T)$=1282.4–0.96 T 800<T<1200 °C

Fitted line: $P_{0.02}(T)$=682.4–0.21 T 700<T<800 °C

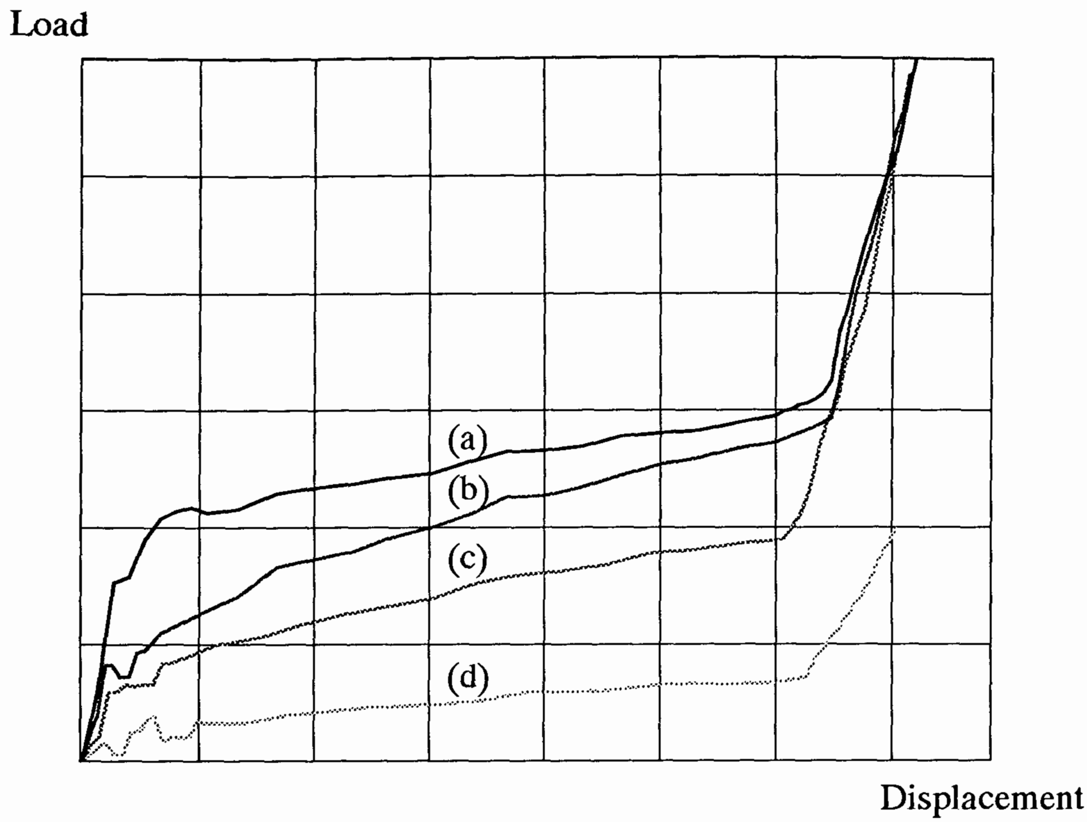


Fig. 5.10 The load–displacement curves at 700, 800, 900 and 1200°C.

(in closed–die upsetting)

Load (vertical) 100 KN/div.

Displacement (horizontal) 2.36 mm/div.

(a) 700 °C, 4.7% unfilled

(b) 800 °C, 4.3% unfilled

(c) 900 °C, 2.02% unfilled

(d) 1200 °C, filled

Test No. 6

In table 5.9 the values of the average pressure $P_{0.02}$ obtained for the different types of material used are given.

Material	B.S 070 M20 (EN 3)	B.S 080 M40 (EN 8)	B.S 605 M36 (EN 16)	B.S 709 M40 (EN 19)	B.S 817 M40 (EN 24)
$P_{0.02}$ (N/mm^2)	474.3	415.5	455.5	486.5	496.5

Table 5.9 The data obtained for the effect of material type in closed–die upsetting – test No. 6

Test No. 7

The values of the average pressure $P_{0.02}$ obtained for the two machines used are given in table 5.10, and in Fig. 5.11 the corresponding load–displacement curves are illustrated.

Machine type	strain rate (s^{-1})	$P_{0.02}$ (N/mm^2)
Mechanical press	13	415.5
Hydraulic press	0.15	895

Table 5.10 The data obtained for the effect of type of machine in closed–die upsetting– test No. 7.

In table 5.11 the corner dimensions of the two deformed billets used in the two machines are given.

Machine type	unfilled Corner volume (%)	h_u (mm)	w_u (mm)	h_l (mm)	w_l (mm)	h_u/w_u	h_l/w_l
Mechanical press	3.2	2.11	1.24	2.86	1.53	1.7	1.87
Hydraulic press	3.25	2	1.69	2	1.89	1.18	1.06

Table 5.11 The corner dimensions of two billets in the two machines in closed–die upsetting (the variables are defined in Fig. 5.2).

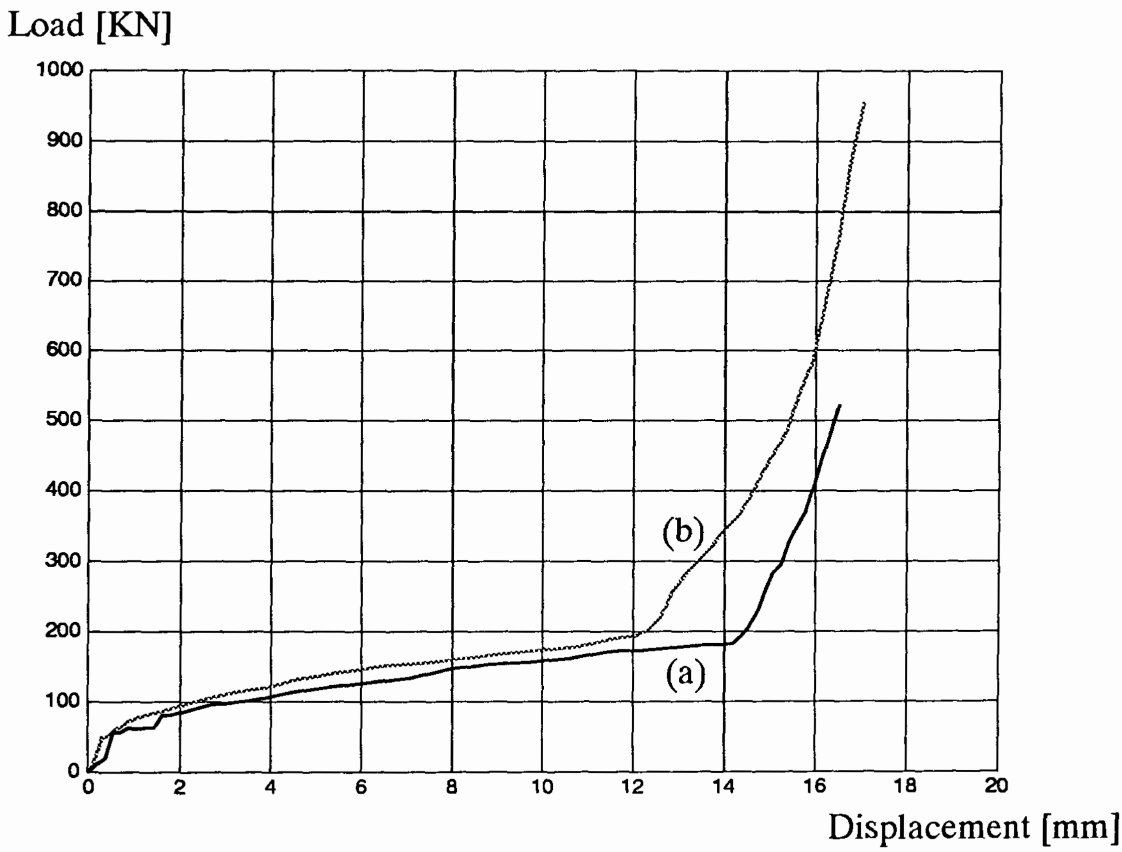


Fig. 5.11 The load–displacement curves in the two machines in closed–die upsetting.
(a) Mechanical press (strain rate 13 s^{-1}), 2.02% unfilled
(b) Hydraulic press (strain rate 0.15 s^{-1}), 3.5% unfilled

5.4.2 Forward Extrusion

Test No. 8

In table 5.12 the values of the maximum average pressure P_{max} obtained for each extrusion ratio r_e are shown and the corresponding graph is illustrated in Fig. 5.12.

Extrusion ratio ($\ln r_e$)	0.41	0.69	0.91
P_{max} (N/mm^2)	242	335.5	404

Table 5.12 The data obtained for the effect of extrusion ratio on the maximum average pressure in forward extrusion– test No. 8

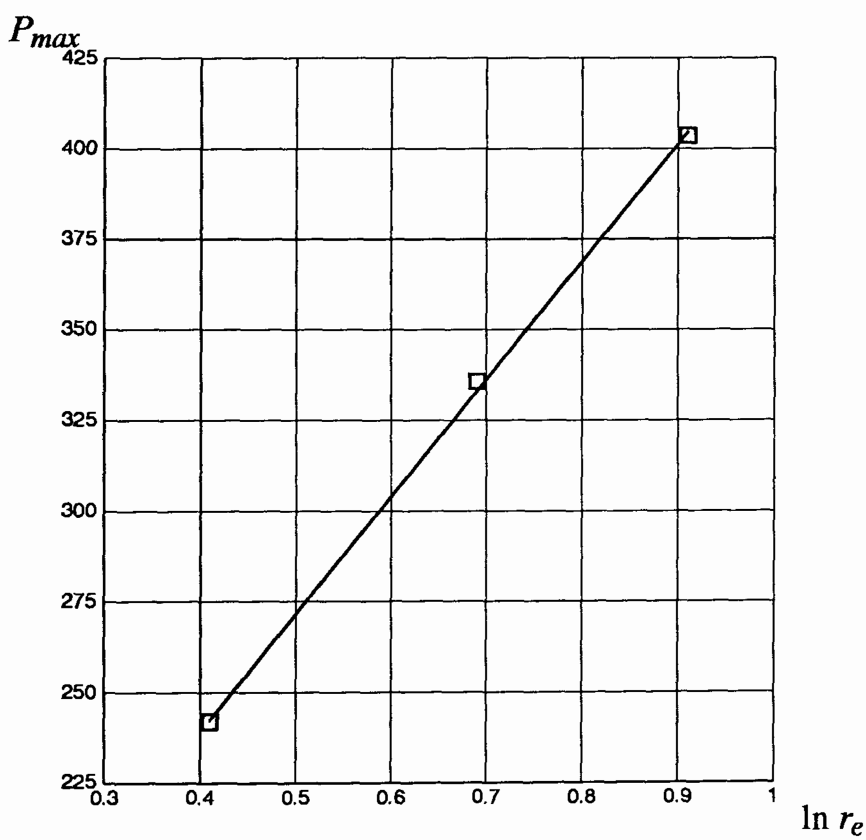


Fig. 5.12 Variation of maximum average pressure P_{max} with extrusion ratio r_e for forward extrusion– test No. 8.
Fitted line: $P_{max}(r_e)=110+324\ln r_e$

Test No. 9

In table 5.13 the values of the maximum average pressure P_{max} obtained for each initial height/diameter ratio r_i are shown and the corresponding graph is illustrated in Fig. 5.13.

Initial height/diameter (r_i)	0.75	1.0	1.25	1.5
P_{max} (N/mm^2)	280	335.5	361	380

Table 5.13 The data obtained for the test No. 9

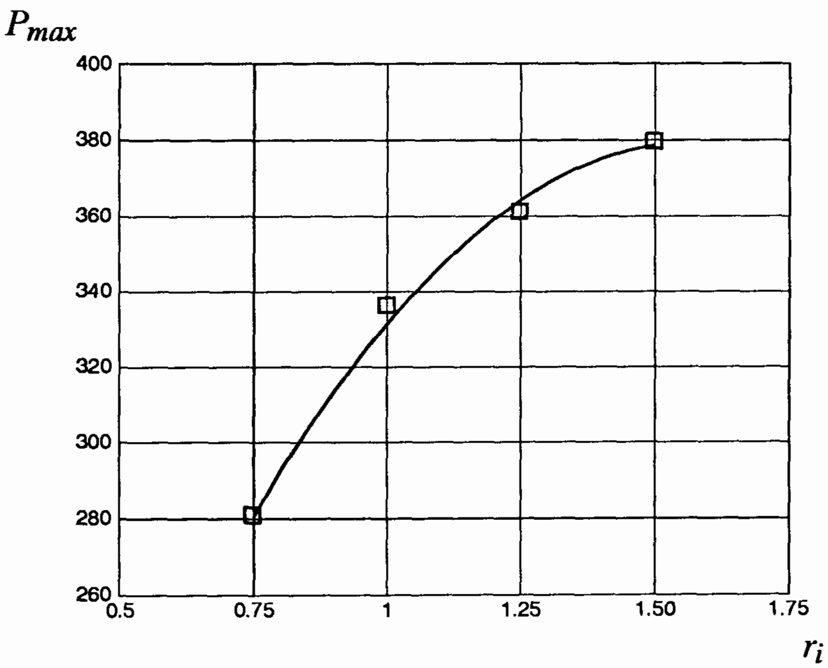


Fig. 5.13 Variation of maximum average pressure P_{max} with initial height/diameter ratio r_i for forward extrusion– test No. 9. Fitted curve: $P_{max}(r_i)=19+459\ r_i-146r_i^2$

Test No. 10

The results of this test (not shown) indicated that the height/diameter ratio of the extrudate does not affect the maximum average pressure.

Test No.11

The results of the maximum average pressure P_{max} obtained for the different temperatures are illustrated in table 5.14, and in Fig. 5.14 the corresponding graph is shown.

Temperature (°C)	600	700	800	900	1000	1100
P_{max} (N/mm^2)	684	664.5	373	335.5	285.5	240

Table 5.14 The data obtained for the test No. 11

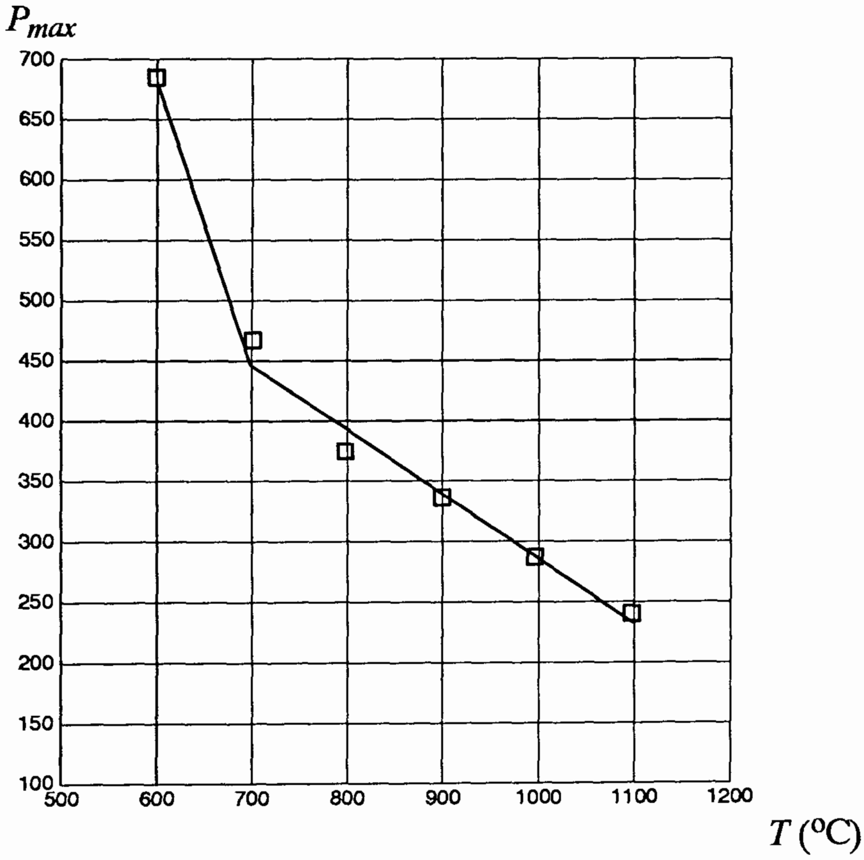


Fig. 5.14 Variation of maximum average pressure P_{max} with the workpiece pre–heat temperature T for forward extrusion– test No. 12.

Fitted line: $P_{max}(T)=823-0.536\ T$ $\qquad 700<T<1100$ °C

Fitted line: $P_{max}(T)=2106-2.37\ T$ $\qquad 600<T<700$ °C

Test No.12

The results of the maximum average pressure P_{max} obtained for the different lubrication conditions are shown in table 5.15.

Lubrication condition of the workpiece	graphite	glass–based	without lubrication
P_{max} (N/mm^2)	335.5	331	338

Table 5.15 The data obtained for the effect of lubrication condition in forward extrusion– test No. 12.

5.5 Discussion on the Experimental Results

The following discussion, centres around the aim of the experiments which is to identify the weighting effect of different parameters. In this respect the following explanations are necessary.

1. As mentioned in section 5.2.4, the quantitative variables which could be used to investigate the weighting effect of different parameters are forging load and average pressure required to deform a preform in a die to produce a product. Since the maximum load is proportional to the cheese area, it is not suitable as an index spanning different die–sets and therefore average pressure was used.

2. As is obvious from Fig. 5.3.a, there are two main stages of deformation in closed–die upsetting. The first stage relates to the deformation before contact with the die walls (free upsetting) and the second stage relates to when the corners are being filled. In the latter stage the change in load is much greater than in the first stage for a specified change in the value of deformation which leads to the likelihood of large errors in determining a load for a particular degree of filling.

5.5.1 Sources of Error in the Experiments

The major sources of error which existed in the experiments are as follows.

(i) The amount of oxidation (scale) affected the results due to its removal from the billets after forging. This produced an error in measuring the corner dimensions in closed–die upsetting and an overestimation of the unfilled volume which consequently led to a higher load being calculated for a specified value of corner filling. This error was more significant when the billet dimensions were smaller and the pre–heat temperature was higher.

(ii) There was some error in recording results and the subsequent calculations. This was more significant in the interpolation or extrapolation of the forging load in closed–die upsetting to determine the required load for 2% of the unfilled corner volume, due to the steep slope of the load–displacement curve in the last stage of deformation.

(iii) Variations in billet volume were another source of error. These variations did not affect the results significantly due to the differences in actual dimensions but they influenced the calculation of the percentage of unfilled corner volume and therefore could cause an error of the type described in (ii) above.

(iv) Other errors were present such as systematic errors of the machines and errors in the various measuring devices used.

5.5.2 Closed–Die Upsetting

Test No. 1

The percentage of unfilled corner volume has a significant effect on forging load or average pressure. By considering table 5.3, a 1% decrease in the value of unfilled corner volume will affect the maximum load as:

$$\text{Percentage of increase in load (average pressure)} = \frac{555-490}{490} * \frac{100}{3.1-2.2} = 14.7\%$$

The results obtained are in agreement with those obtained by Ibhadode [100] for a billet with the same upset ratio (1.0) and the same lubrication condition.

It should be pointed out that when a corner has a large radius, it does not have a significant effect on average forging pressure. This can be seen in Fig. 5.5. Therefore, only those corners should be considered which are deformed to a small radius in the last stage of deformation.

By considering Fig. 5.5, the difference between the average pressure corresponding to 0.2% and 10% unfilled corner volume is:

$$1144-564=580 \text{ N/mm}^2$$

Test No. 2

As can be seen from table 5.4 and Fig. 5.6, changes in upset ratio affect average forging pressure. There are two possible reasons. Firstly, due to the fact that in the stage of free upsetting, as the upset ratio increases the time required to deform the billet increases. This leads to more heat loss by conduction and a greater surface chilling of the workpiece near, and in contact with, the punch and counterpunch surfaces and therefore results in a higher flow stress of the material being deformed in the stage of corner filling. Secondly, in the stage of free upsetting, due to the differences in barrelling, the dimensions and geometry of the corners differ with upset ratio. This is shown in table 5.5. Thus, the fact that different shapes with different contact area and different frictional conditions are being forged in the stage of corner filling is expected to cause different punch loads.

The difference between maximum and minimum values of the average pressure within the range used is:

$$415.5–366 = 49.5 \text{ N/mm}^2$$

Test No. 3

According to table 5.6 and Fig. 5.7, increasing the cheese ratio decreases the average forging pressure. The difference between maximum and minimum values within the range of the experiments is:

$$398–385.5 = 12.5 \text{ N/mm}^2$$

Test No. 4

According to table 5.7, lubricating the billets with graphite lubricant will reduce the average pressure by 23.5 N/mm^2 compared with unlubricated billets and lubricating the billets with a glass–based one will reduce the average pressure by 53 N/mm^2 compared with unlubricated billets.

In Fig. A.10 of Appendix A, the heating curves for the two lubrication conditions are illustrated. As is obvious from the figure, the time required for a graphite coated billet to reach a temperature close to the furnace temperature is less than the corresponding time for a billet with a glass–based lubricant. The reasons is that the latter lubricant is white and therefore it has a smaller radiation emissivity factor compared with graphite which is black.

In Fig. A.11 of Appendix A, the cooling curves for the two lubrication conditions are illustrated. As can be concluded from the figure, the decrease in billet temperature for the two conditions is close together for a specified value of time interval.

Test No. 5

By considering table 5.8 and Fig. 5.9, the difference between the maximum and minimum values is seen to be:

$$535.5-122=413.5\ N/mm^2$$

As Fig. 5.9 shows, the effect of changes in temperature between 700 and 800 °C is less than for other intervals. This is probably due to the effect of a major phase change in the metal of the workpiece at about 700 °C. The effect of this behaviour can be seen in the calibration curves illustrated in Appendix A.

In Fig. 5.10 the load–displacement curve at 700 °C can be compared to that at 800 °C and also at 900 °C. For comparison, the load–displacement curve at 1200 °C is also shown in the figure.

Test No. 6

According to the data in table 5.9, the type of material will influence the average forging pressure. The difference between the maximum and minimum values is:

$$496.5-415.5=81\ N/mm^2$$

Test No. 7

As is obvious from table 5.10 and Fig. 5.11, the average pressure required to deform the billets in the hydraulic press is greater compared with those deformed in the mechanical press. This is more significant in the stage of corner filling.

It was expected that the hydraulic press would have reduced the average pressure due to its lower strain rate compared with the mechanical press. As Fig. 5.11 shows, when free upsetting is taking place, the load–displacement curves are similar. However, the average pressure for 2% unfilled corner volume in the hydraulic press is about 2.2 times greater than the value for the mechanical press. This is due to the fact that when the corner is being filled, the heat lost by conduction was greater, and the effect of surface chilling was more significant with the hydraulic press than with the mechanical press.

As can be seen from Fig. 5.11, for the hydraulic press the period of the stage of corner filling is longer than that for the mechanical press. This means that for the hydraulic press, barrelling is more significant and contact between the workpiece and the die wall takes place earlier. This is mainly due to the high surface chilling in the hydraulic press.

As can be seen from table 5.11, the ratio of corner height to width (for both the upper and lower corners) in the case of the hydraulic press is less than for the mechanical press. This means that in the hydraulic press, for a specified value of unfilled corner volume, the corner width was greater compared with that for the mechanical press. This caused a high surface chilling of the billet due to contact with the die surfaces. So, the average pressure in the hydraulic press in the last stage of deformation was much greater than with the mechanical press.

5.5.3 Forward Extrusion

Test No. 8

By considering table 5.12 and Fig. 5.12, the difference between the maximum and minimum values of the average pressure within the range used is :

$$404 - 242 = 162 \text{ N/mm}^2$$

The results conform to the well known phenomenon which shows that extrusion pressure is proportional to the area reduction.

Test No. 9

It is seen from Fig. 5.13 that increasing the height of the workpiece increases the average pressure. This is due to the increase in the frictional forces between the workpiece and the container.

According to table 5.13 and Fig. 5.13, the difference between the maximum and minimum values of the average pressure within the range of the experiments is:

$$380 - 280 = 100 \text{ N/mm}^2$$

Test No. 10

As stated in section 5.4.2, the results of this test indicated that the height/diameter ratio of the extrudate does not affect the maximum extrusion pressure. This can be seen from Fig. 5.3.b which shows that the maximum pressure occurs as soon as the die is filled with the workpiece material. As the deformation proceeds, the load decreases slowly. Although the contact area between the extrudate and the die wall is increased, the corresponding area between the workpiece and the container is decreased. Therefore, the contact area between the workpiece and the container is more important and the total load is decreased.

Test No. 11

As can be seen from table 5.14 and Fig. 5.14, the difference between the maximum and minimum values is seen to be:

$$684 - 240 = 444 \text{ N/mm}^2$$

Test No. 12

As can be seen from table 5.15, in forward extrusion when the die is lubricated properly, the lubrication condition on the workpiece surfaces does not considerably affect the average pressure.

5.5.4 Normalising the Weighting Effects of the Parameters

The parameters considered in the current investigations are of several different types. For example, the pre–heat temperature in closed–die upsetting changes from 600–1250 °C in the SDP, while the upset ratio changes from about 0.5–2.0. Therefore, the weighting effects of the parameters will not be of the same quantity in equation (3.1) and should be normalised for use in the IKBS.

The method that is used here is to divide the difference between the maximum and minimum value of pressure, obtained within the range of the tests performed, by the square of the difference between the maximum and minimum value of the parameters in the range of the experiments. Thus, the weighting factor for temperature in closed–die upsetting, *w(T)*, (test no. 5) would be:

$$w(T) = \frac{535.5 - 122}{(1200 - 700)^2} = 0.00165$$

Similarly, the weighting factor for extrusion ratio, $w(r_e)$ (test no. 8) would be:

$$w(r_e) = \frac{404 - 242}{(2.5 - 1.5)^2} = 162$$

It should be pointed out that some of the variable factors which are considered in this research work cannot be quantified and therefore, a value cannot be assigned to them and their weighting effects in equation (3.1). The results of the experiments carried out for these factors could not be illustrated as graphs and instead are shown as tables in this chapter.

In such cases, an index can be assigned to each different instance of the variable factor. A suitable index could be the value of the pressure obtained for a particular instance minus the lowest pressure obtained for the range of variables.

For example, Table 5.9 gives values of average pressure at 2% unfilled die cavity $P_{0.02}$ for 5 different types of materials. The lowest average pressure (415.5 N/mm^2) was obtained for the material B.S 080 M40 (En 8). Thus this material will have an index of 0. The material B. S 817 M40 (En 19) gave an average pressure $P_{0.02}$ of 486.5 N/mm^2. So, its index will be 486.5 – 415.5 or 71. A consequence of assigning index values in this way is that the weighting effect of the parameter, according to the definition given above, will be 0.0123.

The above procedure can be repeated for each material and the calculated weightings can be easily saved in the IKBS database for use in the comparison procedure.

The weighting factors of the different process and geometrical parameters are thus obtained. These values are saved in the knowledge base and can be specified to equation (3.1) to obtain the distance between a stage of a new component being considered by the IKBS and those of the previously encountered examples and also to obtain the corresponding success and confidence indicators by using equations (3.2) and (3.3). These indicators indicate that whether a stage of a new component will be produced successfully, unsuccessfully or there is not enough confidence about the results and therefore it is necessary to perform finite–element analysis of the current stage.

5.5.5 Summary of the Experimental Results

Tables 5.16 and 5.17 give a summary of the results obtained for the parameters considered in the current investigation and their weighting factors in closed–die upsetting and forward extrusion.

Type of parameter	Difference between maximum and minimum value of the average pressure(N/mm^2)	Weighting factor (w_j in Eq. 3.1)
upset ratio r_u	50	42.87
cheese ratio r_c	12	19.72
corner unfilled volume V_r (0.2% – 10%)	580	6.04
lubrication condition	53	0.0189
pre–heat temperature T	413.5	0.00165
type of material	81	0.0123
type of machine	497.5	0.00208

Table 5.16 Summary of the results obtained for closed–die upsetting and the weighting effects of the parameters

Type of parameter	Difference between maximum and minimum value of the average pressure(N/mm^2)	Weighting factor (w_j in Eq. 3.1)
extrusion ratio r_e	162	162
initial height/diameter of the workpiece r_i	100	177.8
pre–heat temperature T	444	0.00178
lubrication condition	7	0.143

Table 5.17 Summary of the results obtained for forward extrusion and the weighting effects of the parameters

Chapter 6

Computer–Aided Reasoning in the IKBS

6.1 Introduction

In this chapter, computer–aided reasoning in the IKBS is examined. In particular, consideration is given to recognising and extracting the data of significant parameters of the operational sequence of a component, creating the IKBS database based on real data and performing the assessment of a new component stage with those stored in the IKBS database.

6.2 The Structure of the IKBS Directory

Fig. 6.1 illustrates the structure of the IKBS directory which is based on the hierarchical file store system.

As can be seen from the figure, the CM directory includes all the LISP programs for the different activities of the IKBS and a sub–directory called 'DB'. The 'DB' directory includes sub–directories for the users of the IKBS, each having the corresponding IKBS database and the sub–directories for the components designed by the system, each includes sub–directories for the different stages of deformation for a component.

The SDP directory contains all the FORTRAN programs corresponding to the graphical interface for input data (MODCON), the Sequence Design Program and the graphical interface for output data (SDPLOT) for forging components. Also, this directory includes the FORTRAN programs for computer aided reasoning in the IKBS which are discussed later in this chapter.

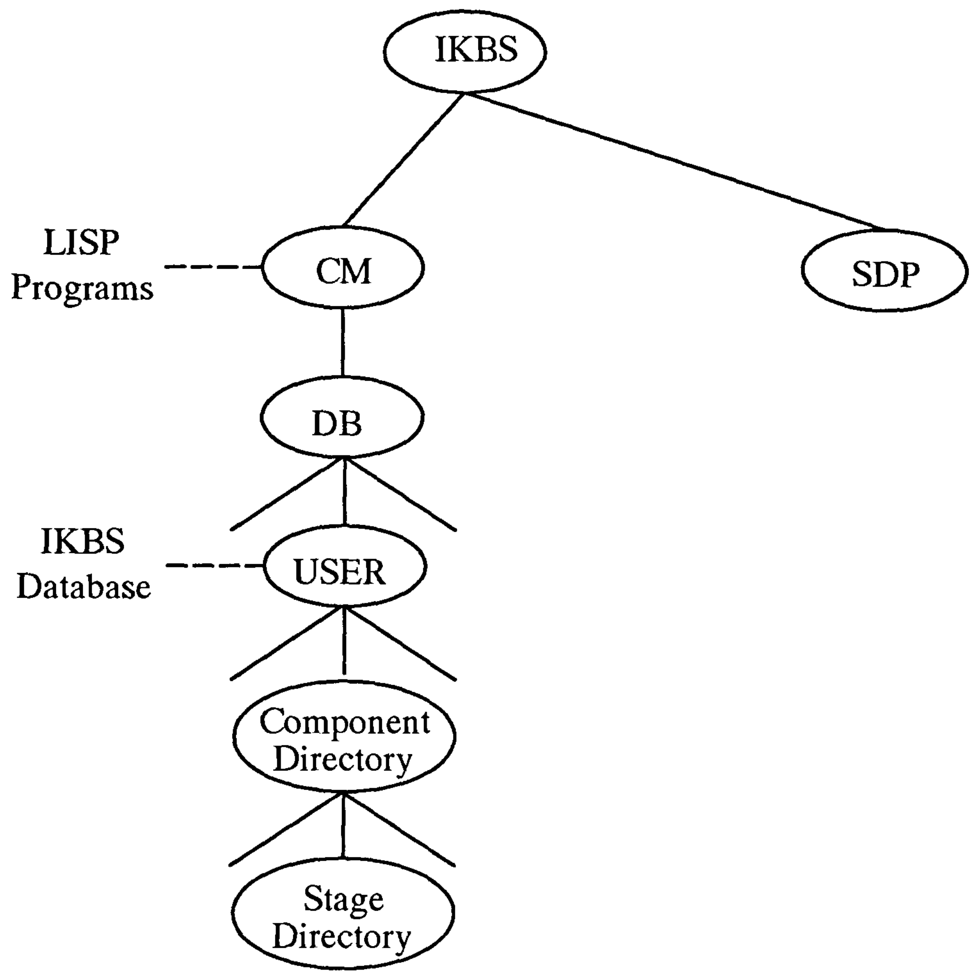


Fig. 6.1 The structure of the IKBS directory

6.3 Recognising and Extracting the Required Data

In creating the IKBS database and performing some other activities of the system which are explained in the following sections, it is necessary to recognise and to extract the values of the significant process and geometric parameters of the designed sequence from the input stage up to the 'billet'.

By referring to Fig. 3.5, as explained in chapter 3, the forming sequence of Stub Axles may be from the 'finished' part or from an earlier stage up to the 'billet'. Therefore, it is necessary to recognise and to extract the values of significant process and geometric parameters from any stage up to the 'billet'.

As explained in chapter 5, the process parameters for each stage in the forging sequence are lubrication condition, temperature, type of material and type of machine. The geometric parameters that are considered for each stage in the sequence are:

(a) For the 'finished' part:

   (i) Product ratio of the heading section in the lower die,
   (ii) Percentage of unfilled corner volume.

(b) For the 'preform':

   (i) Initial height/diameter of each shoulder,
   (ii) Extrusion ratio of each shoulder,
   (iii) Percentage of unfilled corner volume.

(c) For the 'cheese':

   (i) Cheese ratio (height/diameter of the cheese)
   (iii) Percentage of unfilled corner volume.

(d) For the 'billet':

   (i) Upset ratio (height/diameter of the billet)

A Fortran program ('dbase') has been written to recognise and to extract the required parameter values of any input stage up to the 'billet' from the SDP database. This program automatically performs this task after the Sequence Design Program has finished examining a component. Since it is not possible to input the data for lubrication condition and type of machine to the CAD software while the initial geometry of the 'machined' part and the other data are being input, the user inputs the appropriate data among the available options for the lubrication condition and type of machine specified in chapter 5 when running the 'dbase' program. Also, the program searches to see if the type of the workpiece material and the forging temperature were specified to the CAD database. If not, the program asks the user about these values within the range available in the SDP.

As discussed in chapter 5, some of the process parameter values (including lubrication condition, type of material and type of machine) cannot be quantified and it is needed to assign an index to them to be used in equation (3.1). This is done by the program based on the procedure discussed in chapter 5.

When the program has finished running, the results are saved in a file in the appropriate input stage directory. This file will be used later in the other activities of the IKBS.

6.4 Creating the IKBS Database

Generally, this structure is based on the capabilities of the Common LISP programming language which was selected as the principal language of the Control Module and for data manipulation within the IKBS modules.

6.4.1 LISP Data Structure

The only data structure which is available to LISP is the list structure. This structure is not as limited as it might seem. For example, it is possible to represent a tree–type data structure as the following list:

(root subtree1 subtree2 ... subtreeN)

The first member of the list is the 'root'. Each subtree is itself a list. The first member of each subtree is a root of that subtree and a branch of the higher level root. This is illustrated in Fig. 6.2 [59].

This data structure is the method used to construct the knowledge–base of an Expert System and is usually called frame–based representation (frames). This was briefly reviewed in chapter 2.

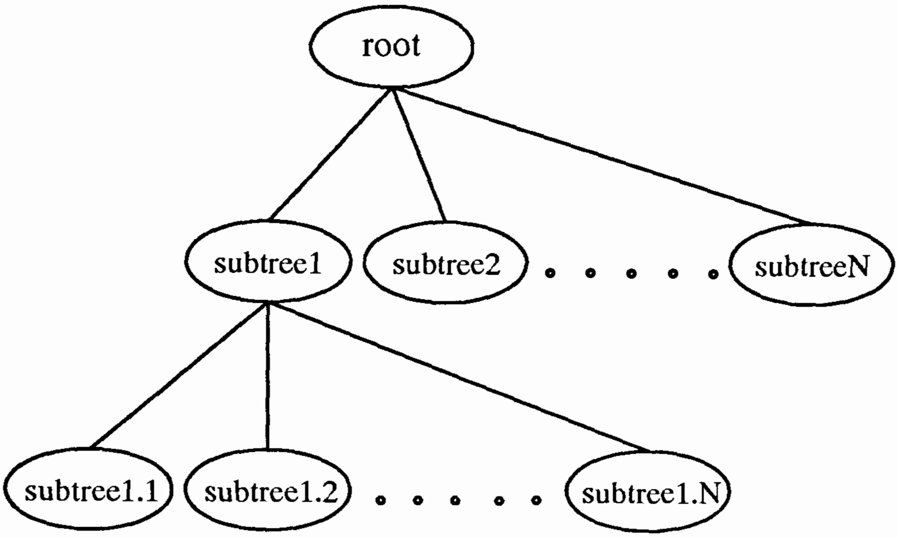


Fig. 6.2 The general representation of a tree–type data structure (frame–based representation) [59].

6.4.2 The Structure of the IKBS Database

This structure is based on the general LISP data structure stated in the last section. In Ref. [91] the structure and use of the IKBS database is suggested and was generally used in the current research.

Since the components which can be applied in the SDP have been divided into five different families (categories) with different design rules, a separate partition of the database for each of the families is maintained. So, each partition is in the form of a LISP list. At the highest level this is a list of the data of the components which have been examined by the system for the specific family. At a deeper level, the structure is more complicated because each stage of the forging sequence for the specified family may have more than one instance, each having a different preform and/or different processing condition. This is due to the fact that, by considering step 'm' in Fig. 3.7, when the current stage cannot be produced from the given preform stage successfully, the preform stage should be modified and therefore the sequences/dies up to the preform of the current stage should be re–designed. Therefore, the list structure must accommodate the potential of repeated branching.

A semi–formal description of the IKBS database for a particular family of component is given in Ref. [91] as:

db–for category (family)	:	({component–entry}*)
component–entry	:	((component number [component–information] [component–name]) preform–sub–entry)
preform–sub–entry	:	(preform–name ({instance–of–preform}+))
instance–of–preform	:	(({description–parameters}+) [(success–indicator confidence–indicator guidelines)] [preform–sub–entry])

In the above description, {}* represents any number (including zero) occurrences of the enclosed item, {}+ represents one or more occurrences of the enclosed item and [] represents zero or one occurrence of the enclosed item. (In practice, an absent item is normally represented by the LISP nil construct, or a null string as appropriate.)

In Fig. 6.3 an example of the proposed database is shown.

```
((“sa”  ((100 “Stub Axle No. 1” “w3001.sa”)
        (“fin” (((0.5  0.8  4.0  1050)
               (0  0  “”)
               (“prf”  (((0.4  1.0  4.5  1100)
                       (1  1  “Successful”)
                       (“chs”  (((0.4  1.5  5.0  1150)
                               (1  1  “Successful”)
                               (“bil”  (((0.5  2.0  1200)
                                       (–1  1  “Unsuccessful”)))))))))))))))
(“df”  nil)
(“gb”  nil)
(“bp”  nil)
(“na”  nil))
```

Fig. 6.3 A simple example of the IKBS database (“sa”: Stub Axle, “df”: Drive Flange, “gb”: Gear Blank, “bp”: Bevel Pinion and “na”: Non–axisymmetric)

A LISP program has been written which creates the database. If the system is running for the first time and therefore the database was not previously created, it makes the database in the form of a LISP list in which, by considering Fig. 6.2, the root is the IKBS database and each subtree is a family of components which can be specified to the SDP. To this end, the database will be of the form:

((“sa”) (“df”) (“gb”) (“bp”) (“na”))

When the SDP has finished examining a component, the LISP program automatically obtains the value of the significant parameters previously stored in the appropriate file, as stated in the last section, and also some other data if the component is a new one. If the component did not exist in the database, it inputs the data at the highest level of the partition for the corresponding family. Otherwise, it inputs the data as one instance of the appropriate stage, if similar data was not previously stored.

In addition to the values of the significant parameters for a new component that were previously stored in the appropriate stage directory, some other data may also need to be obtained. These are, the component number, which is the last stored component number incremented by 10, component information, which is some information about the component that has been input by the user when defining a new component, and the name of the new component.

Fig 6.4 illustrates the IKBS database thus generated based on the data of four 'machined' parts from Rover Group. These components are examined in the next chapter.

6.5 Inputting the Results of Trials into the IKBS Database

As stated in chapter 3, one option in the main menu of the IKBS is to input the results of the experimental or finite–element trials for a specific stage of deformation of a previously defined component. The results will be automatically saved in a file in the appropriate stage directory including any relevant details of the trials.

When the results of a stage have been input, a LISP program automatically checks through the corresponding stored file to see whether there is any experimental or any finite–element simulation results and relevant details. If these exist, then if the results of the trials were satisfactory, the success and confidence indicators will both be +1. If the results were unsatisfactory, then the success and confidence indicators will be –1 and +1, respectively. In either case, the list of the success indicator, confidence indicator and the relevant details will be saved in the IKBS database in the preform–sub–entry of the preform in Fig. 6.3.

6.6 Performing the Assessment of a Component in the IKBS

As explained in the previous chapters, when a new component is input to the IKBS and its operational sequence has been designed by the SDP, each forming stage of the component should be compared with the same stage of the same family of components previously stored in the IKBS database. An option has been added to the IKBS main menu that performs the assessment procedure for a specified stage of a component. In the following sections the process of performing this task is explained.

6.6.1 Extracting the Data for Preform and Product

As explained in chapter 5, in assessing a stage of a new component it is necessary to obtain the values of the significant process parameters and also the values of the preform and product geometric parameters.

A Fortran program has been written that extracts the required data from the SDP database and outputs the results in the form of two lists; a list of preform and process parameters and a list of product parameters. The results will be saved in a file in the appropriate stage directory which will be used in the next stage of the assessment procedure.

6.6.2 Modifying the List of Weighting Factors

As explained in chapter 5, in assessing a stage of a new component it is also necessary to have the weighting effect of each parameter. Based on the criterion stated in chapter 5, the weighting effects of the significant parameters have been normalised and stored as a LISP list in a file in the IKBS directory.

In some cases it is necessary to modify the list of the weighting factors. For example, in the stage of producing a 'preform' from a 'cheese', the 'preform' might include multiple–shoulders and require a varying number of parameters.

In such cases, the modifications required will be made during the running of the assessment part of the LISP program.

```
( ("sa"
 ((130 "XX Stub Axle (WFM 3001)" "w3001.sa")
  ("mac" (((0.068 0.211)
           (0 0 "")
   ("fin" (((0.08 0.175)
           (0 0 "")
    ("prf" (((1.286 0.09 0.128 1.015 1.323 1.59 1.546 2.19 0.611 30 1120 40 0)
            (1 1 "Successful, based on WFM 3001")
     ("chs" (((1.809 0.043 4 1160 40 0)
             (1 1 "Successful, based on WFM 3001")
      ("bil" (((2.586 30 1200 40 0)
              (1 1 "Successful, based on WFM 3001"))))))))))))))))
 ((120 "Stub Axle (WFM 2059)" "w2059.sa")
  ("mac" (((0.216 0.0)
           (0 0 "")
   ("fin" (((0.233 0.182)
           (0 0 "")
    ("prf" (((1.217 0.53 1.144 2.025 3.645 2.469 1.535 30 1070 0 0)
            (1 1 "Successful, based on WFM 2059")
     ("chs" (((1.807 0.054 4 1110 0 0)
             (1 1 "Successful, based on WFM 2059")
      ("bil" (((1.845 30 1150 0 0)
              (1 1 "Successful, based on WFM 2059"))))))))))))))))
 ((110 "Masetro Stub Axle (WFM 2029)" "w2029.sa")
  ("mac" (((0.133 0.0)
           (0 0 "")
   ("fin" (((0.151 0.247)
           (0 0 "")
    ("prf" (((0.744 0.363 0.61 1.016 2.019 3.274 0.361 30 1060 0 0)
            (1 1 "Successful, based on WFM 2029")
     ("bil" (((1.757 4 1100 0 0)
             (1 1 "Successful, based on WFM 2029")))))))))))))
 ((100 "Stub Shaft Forging (WFM 2023)" "w2023.sa")
  ("mac" (((0.157 0.135)
           (0 0 "")
   ("fin" (((0.176 0.21)
           (0 0 "")
    ("prf" (((0.888 0.292 0.462 1.141 2.446 2.318 0.383 30 1120 0 0)
            (1 1 "Successful, based on WFM 2023")
     ("bil" (((1.677 4 1160 0 0)
             (1 1 "Successful, based on WFM 2023")))))))))))))
)
("dg" nil) ("gb" nil) ("bp" nil) ("na" nil) )
```

Fig. 6.4 The IKBS database generated based on four real parts from Rover Group.

6.6.3 Output of the Results of the Assessment

Once the values of the significant process and geometric parameters have been obtained and, if required, their weighting factors have been modified, the program will compare the stage of deformation of the component with the same stage of the same family of components previously stored in the IKBS database for which the success and confidence indicators are not null. The output from the assessment procedure will be a success indicator, a confidence indicator and an explanation stored in the database for the nearest component stage to the one under consideration.

The results of using the assessment algorithm for some examples are given in chapter 8.

6.7 Discussion on the Computer Aided Reasoning

As discussed in chapter 2, the central parts of an Expert System are the knowledge–base and the inference engine (Control Module), the parts on which the present research has concentrated.

In connection with the knowledge base, the significant geometric and process parameters in the different stages of deformation of Stub Axles have been identified and their weighting factors have been obtained by experiments. These factors have been normalised and stored in the knowledge base that can be modified later, if required.

A program has been written in Fortran and LISP that obtains the values of significant process and geometric parameters for the sequence of a component from an input stage up to the 'billet', assigns an index to those process parameters that cannot be quantified and stores them in the IKBS database in which the results of experimental or finite–element simulation trials can be specified too. This database is based on the general frame–based representation in Common LISP language and is efficient for the aims of the current work.

Each stage of deformation of a component can be assessed by the system by comparing the state of its parameters with those previously stored in the database and which were assessed before. The results of such assessment are a success indicator, a confidence indicator and an explanation message.

Some real examples of Stub Axles have been assessed by the assessment algorithm in chapter 8.

Chapter 7

Simulation of Closed–Die Upsetting

7.1 Introduction

In this chapter, a typical stage in the deformation of Stub Axles, i.e. closed–die upsetting, is studied by the finite–element program, EPFEP3. The aim of this study was to ensure that the interface program with EPFEP3, discussed in chapter 4, was working properly, and to provide a basis for chapter 8, where the results of some real examples are assessed.

It should be pointed out that, of the two types of forging processes that are considered in chapter 5, since in the simulation of forward extrusion a re–meshing package suitable for axisymmetric shapes was not available, therefore attention is made on closed–die upsetting.

7.2 Finite–Element Modelling

The accuracy of the results of the finite–element simulation depends strongly on the accurate reproduction of the process variables, such as material properties and frictional conditions. The following sections explain how these are modelled.

7.2.1 Billet and Die Geometry

From the range of billets and dies used in chapter 5 for closed–die upsetting, one specific geometry was selected for the finite–element analysis. The dimensions of the billets were as for test no. 2, test piece no. 1 (34 mm in diameter and 29.7

mm in height) and the diameter of the container was as for test no. 2 (41 mm in diameter). The other data were as for test no. 1.

The dimensions of the billets and container were measured when these were cold and in a clean state. During the experiments the dimensions changed due to,

(i) the presence of lubricant on the billet and container,
(ii) formation of oxide on the billet surface,
(iii) the thermal expansion of the billets .

The approximate thickness of the lubricant applied to the billet was about 0.15 mm. The amount of scale formed on the billet surface by heating in a furnace for 12 minutes to a temperature of about 900 °C was not significant. This is in agreement with the observations of Keung [101], who reported that the total thickness of oxide layer for a billet lubricated with a water–based graphite lubricant, heated to about 800 °C for 15 minutes in a muffle electric furnace was approximately 0.025 mm. Since in the present work the lubricant was water–based, the approximate thickness of the lubricant and scale after heating and evaporation of the water was 0.1 mm. The thickness of lubricant on the die surface would also be about 0.1 mm.

A 0.1% increase in linear dimensions per 100 °C was assumed, based on the values published by Touloukiau *et al.* [102] for the temperature and material used.

Taking into account the above factors, the finite–element simulation was carried out assuming the billets were 34.5 mm in diameter and 30.1 mm in height, and the diameter of the container was 40.8 mm.

7.2.2 Mesh Generation and Tool Modelling

The finite–element meshes were generated based on the procedure specified in chapter 4. Figure 7.1 shows the mesh used to analyse the deformation in closed–die upsetting and figure 7.2 illustrates the corresponding 3–D view of the mesh with a segmental angle of 15°, and with two layers of small elements on the outer surfaces of the billets.

As stated in chapter 4, only the punch, the container and the counterpunch were modelled in the analysis which were assumed to be rigid.

One variable that should be specified in modelling the tools is the friction factor. A value of 0.3 was selected based on the data of Ref. [103] for a mild steel with a similar lubricant forged in the same press at 900 ^{o}C.

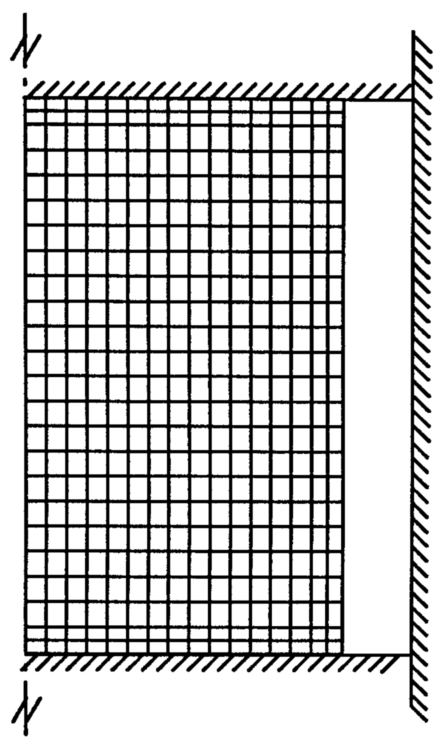


Fig. 7.1 FE mesh used to analyse the deformation (a half of the axial cross–section of billet, scale=2.5:1)

7.2.3 Simulation of the Mechanical Press

Fig. 7.3 shows the trace of punch movement with time in the mechanical press used for the experiments. As can be seen from the figure, the variation of displacement with time is sinusoidal and as deformation proceeds, for a specified amount of time interval, the deformation decreases sinusoidally.

As stated in the previous chapters, in closed–die upsetting the last stage of deformation is critical and it was therefore necessary to model the displacement history of the punch as a function of time.

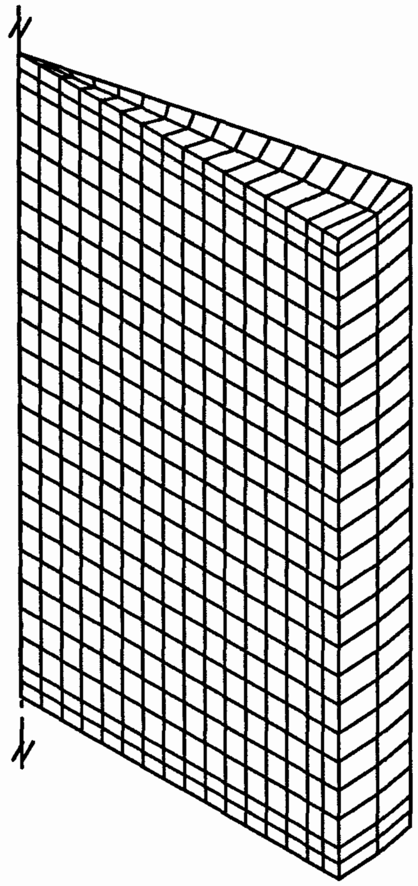


Fig. 7.2 Three dimensional view of the mesh used to analyse the deformation

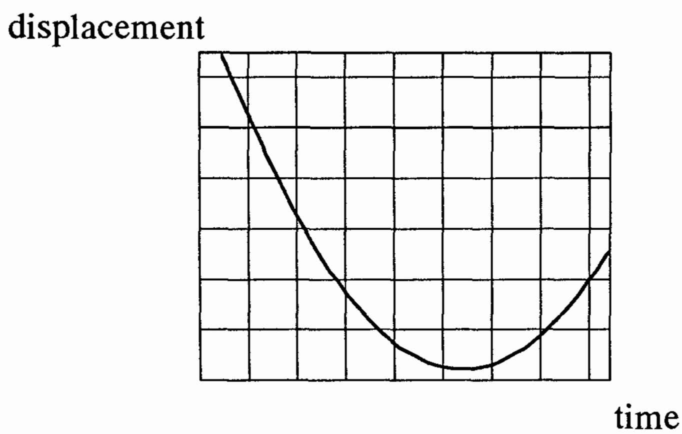


Fig. 7.3 Displacement–time curve of the mechanical press used
time: 20 ms/div., displacement: 2.44 mm/div.

7.2.4 Modelling the Flow Stress Data of the Material

This is based on the procedure stated in section 4.3.3.4.

7.2.5 Thermal Properties of the Material

In the current warm/hot forging operation the following phases can be distinguished:

1. Transfer period: transferring the billet, which has been heated to the required temperature, from the furnace into the die (about 5–6 seconds) – heat is lost from the billet to the surroundings by radiation and convection.

2. Free resting period: resting of the billet on the counterpunch before starting the deformation (about 2 seconds) – heat is lost from the billet to the surroundings by convection, radiation and conduction.

3. Deformation period: in this phase, the heat transfer is mainly due to conduction between billet and counterpunch, punch and container (once the workpiece is in contact with the container). The deformation time in the mechanical press is about 0.1 seconds.

The thermal properties of the workpiece required are:

C_v : thermal capacity per unit volume ($J\ m^{-3}\ K^{-1}$)
k : thermal conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)
e : thermal emissivity
h : thermal convection coefficient ($J\ s^{-1}\ m^{-2}\ K^{-1}$)

These data were obtained from [104] and [105] and are given in Table 7.1. In order to make sure that the data were specified properly, phase 1 of the forging operation which involves no material deformation, was simulated using the FE program and the resulting cooling curves were compared with those measured experimentally.

Figure A.1 shows the geometry of the billet used to obtain the experimental cooling curves and figure 7.4 shows the FE mesh used to model the cooling (due to symmetry about a horizontal centre–line plane in phase 1, a quarter of the billet cross–section was modelled).

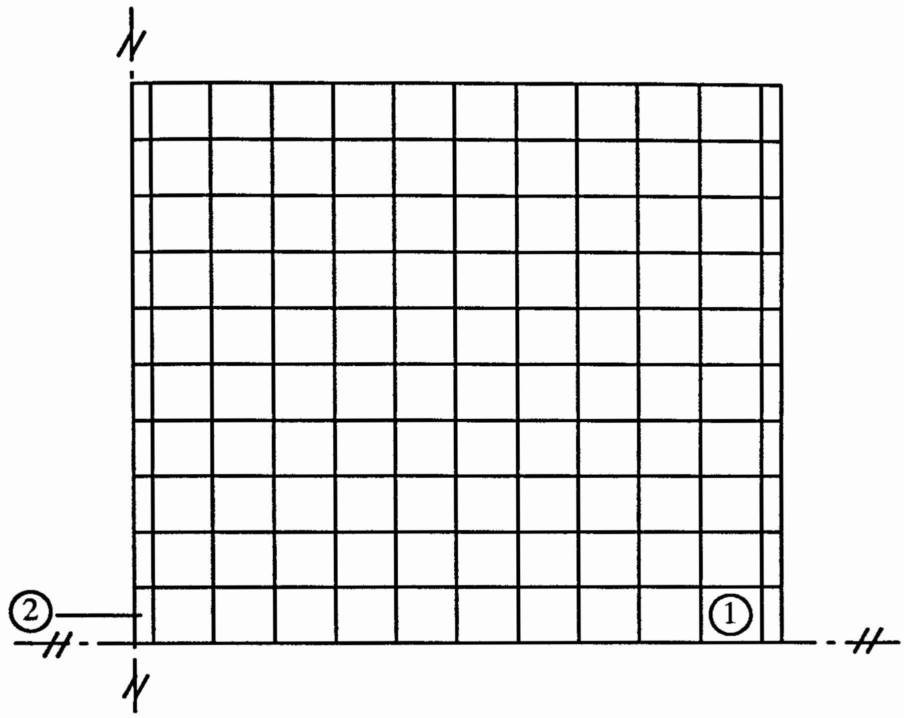


Fig. 7.4 FE mesh used to obtain cooling curves by the simulation corresponding to Fig. A.1
(a quarter of the axial cross–section of billet, scale=5:1)
(1): near the surface (2): at the centre

Figure 7.5.a shows the results obtained near the surface of the billet and figure 7.5.b shows those at the centre of the billet. As can be seen from the figures, the FE predictions agree very well with the experimental measurements, thus validating the thermal part of the closed–die upsetting.

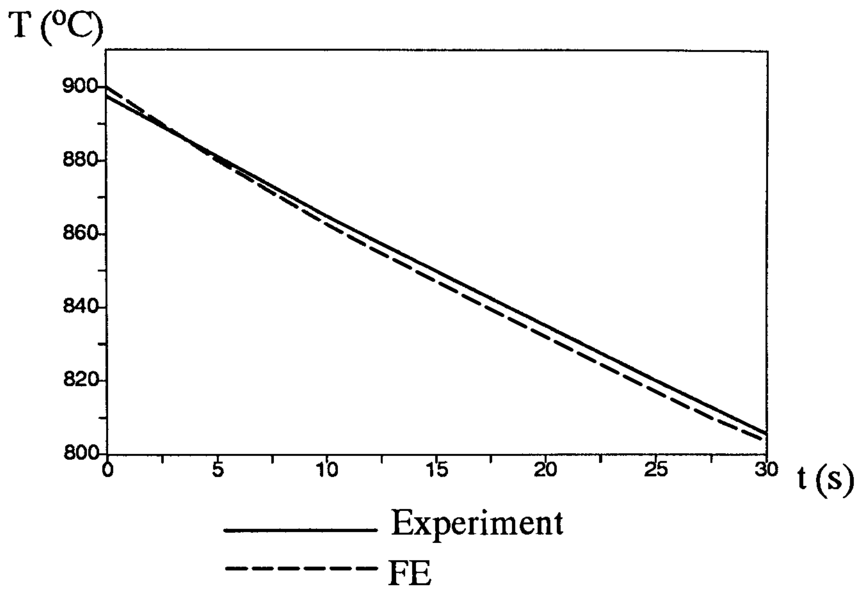
7.2.6 Heat Transfer Coefficient

One of the parameters that must be specified is the value of the heat transfer coefficient between the workpiece and the die. An accurate value of this variable is critical for modelling of a metal forming process [106].

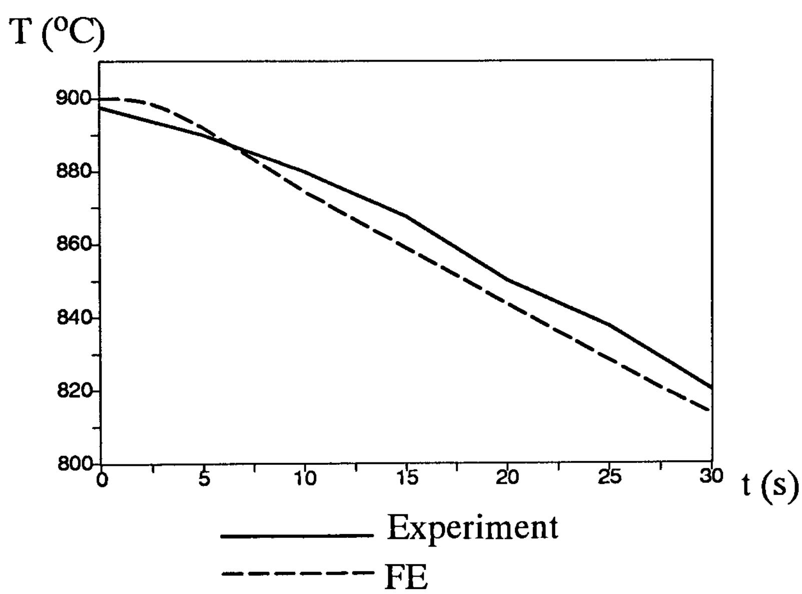
It has been suggested [107] that the heat flux by conduction at the billet/die interface during deformation in hot forging is high whereas the heat transfer due to radiation and convection is not significant.

In closed–die upsetting, especially in the last stage of deformation, the workpiece material in contact with the dies is 'chilled', leading to an increased flow stress.

The amount and extent of chilling are a function of the interface heat transfer co-efficient, the deformation rate and the initial temperature difference. Chilling has a great influence on the pattern of metal flow and the forging load [108].



(a)



(b)

Fig. 7.5 Variation of billet temperature with time (transfer period)
(a) near the surface (b) at the centre

The most important result of the experiments carried out by Semiatin, *et al.* [108], was that the heat transfer coefficient under nominally zero load was an order of magnitude less than that under high pressures. In addition, above a certain threshold pressure, its value was relatively constant. The value of this threshold was not greater than 85 N/mm^2.

The forging pressure during the closed–die upsetting performed in the current analysis was greater than the above mentioned threshold pressure. Therefore, the second phase in section 7.2.5 can be assumed to take place at zero pressure and the third phase at high pressure.

In the analysis of Im [109], the magnitude of the heat transfer coefficient for the free resting period was assumed to be one tenth of the heat transfer coefficient for the deformation period. This assumption was generally verified later in [110].

There are several references concerned with measuring the heat transfer coefficient in warm/hot bulk metal forming processes (some of which are referred to here). The results of these differ from each other over a broad range and none is similar to the current analysis in terms of process variables and boundary conditions.

The method that has been used in the current investigation was to obtain experimentally the cooling curve at a point on the centre–line of the billet near the lower surface of the billet (1 mm from the surface), as shown in Fig. 7.6, while the billet was resting freely on the counterpunch before starting the deformation. The value of the heat transfer coefficient was specified to the simulation process by trial and error, until the predicted cooling curve agreed closely with that obtained from experiment. Figure 7.7 illustrates the FE mesh (half of the billet) used in this case. Figure 7.8 shows the results obtained which indicates a very close correlation between the FE predictions and experiment and verifies that the combination of the thermal variables, such as heat transfer coefficient, were selected properly.

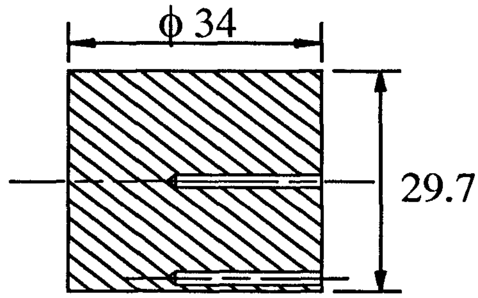


Fig. 7.6 Illustration of the billet used to obtain cooling curves
(free resting period)

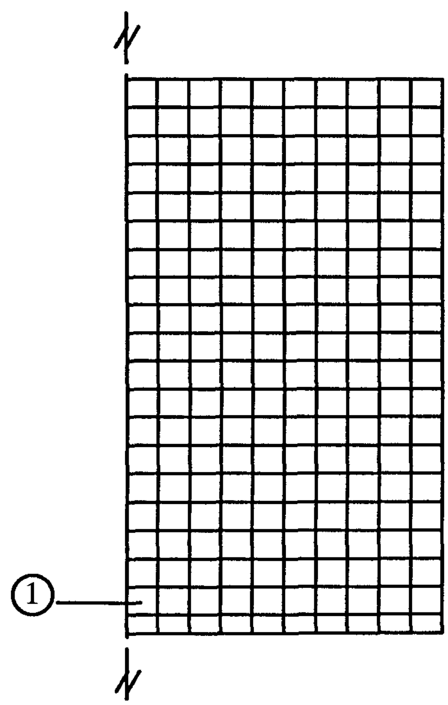


Fig. 7.7 FE mesh used to obtain cooling curves by the simulation
corresponding to Fig. 7.6
(a half of the axial cross–section of billet, scale=2.5:1)
(1): near the surface

Once the value of the heat transfer coefficient had been obtained for the free resting stage, a value 10 times greater was assumed and used for the deformation stage.

Table 7.1 shows the values of the thermal parameters that have been used in the simulation.

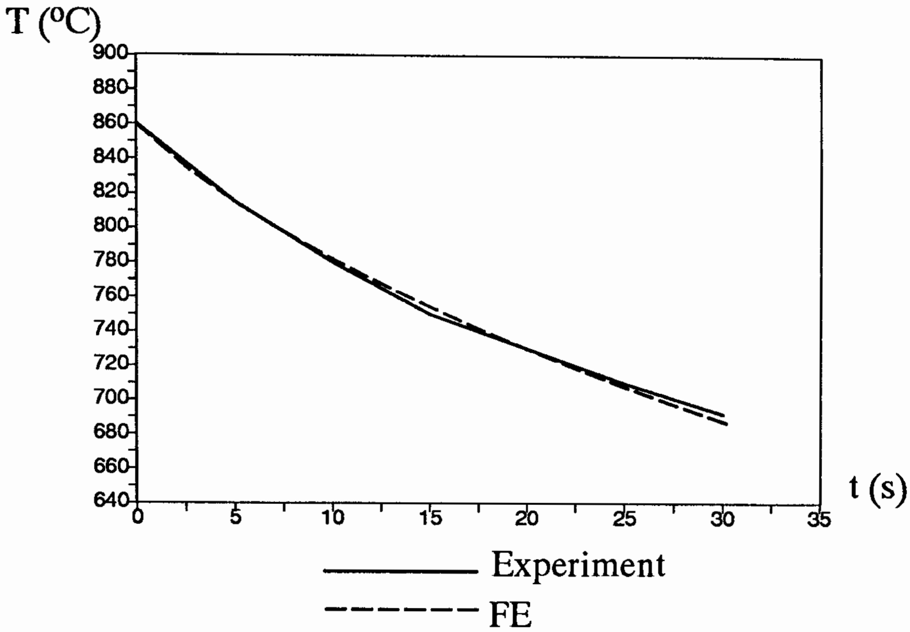


Fig. 7.8 Variation of billet temperature with time near the surface corresponding to Figs. 7.6 and 7.7

7.3 Simulation Results

Figure 7.1 shows the mesh used to analyse the deformation in closed–die upsetting. The geometry of the deformed and cooled workpiece after the barrelled outer surface has first made contact with the die wall and that of the simulation at a similar stage (when the maximum diameter corresponding to a node is equal to that of the cooled deformed workpiece) are illustrated in Fig. 7.9. The geometry of the deformed mesh corresponding to this stage is shown in Fig. 7.10.

Figure 7.11 illustrates the geometry of the workpiece and mesh at the stage of corner filling. The geometry of the deformed mesh corresponding to this stage of deformation is shown in Fig. 7.12.

Figure 7.13 shows the load–displacement curves obtained from experiment and simulation.

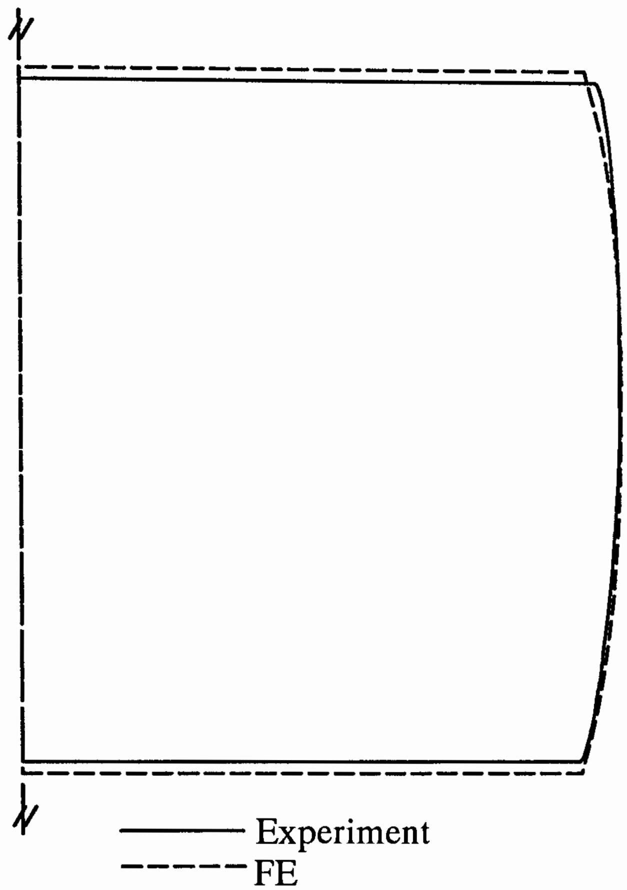


Fig. 7.9 Comparison between the geometry of the workpiece and that of the mesh, just when contact with the die is being made (scale=4:1)

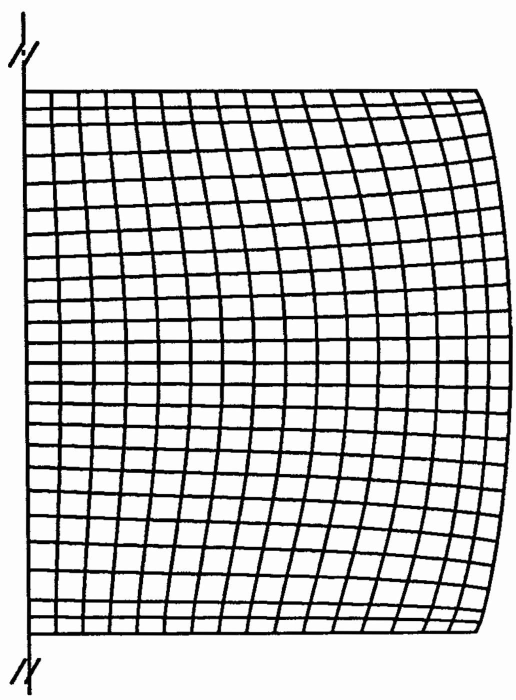


Fig. 7.10 The geometry of the deformed mesh corresponding to the stage in Fig. 7.9

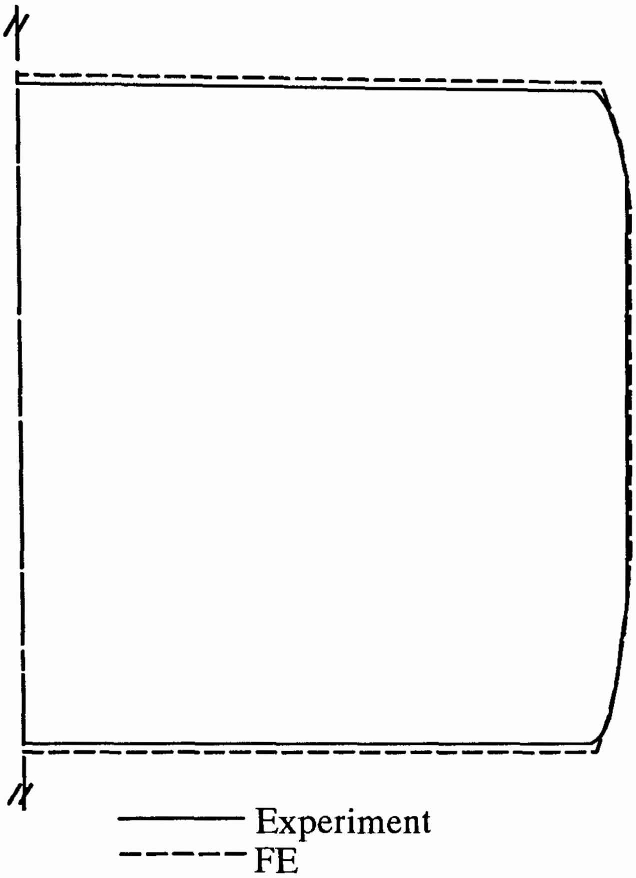


Fig. 7.11 Comparison between the geometry of the workpiece and that of the mesh, in the stage of corner filling (scale=4:1)

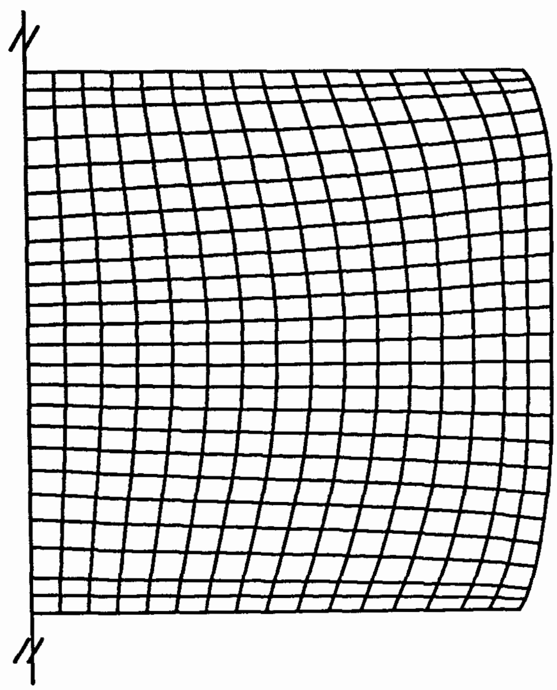


Fig. 7.12 The geometry of the deformed mesh corresponding to the stage in Fig. 7.11

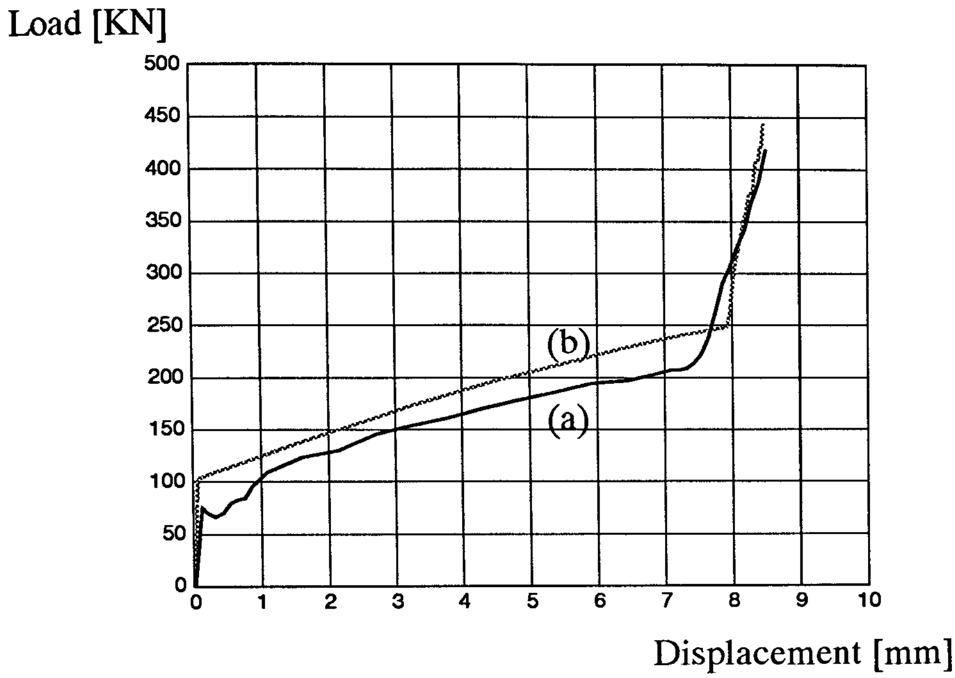


Fig. 7.13 Load–displacement curve obtained from experiment and simulation
(a) Experiment (b) FE

C_v $(\frac{J}{m^3\,K})$	k $(\frac{J}{s\,m\,K})$	e	h $(\frac{J}{s\,m^2\,K})$	K_{bf} $(\frac{J}{s\,m^2\,K})$	K_{bd} $(\frac{J}{s\,m^2\,K})$
4.8×10^6	27.1	0.8	16.3	600	6000

Table 7.1 The values of parameters used in the thermal simulation

C_v : thermal capacity per unit volume
k : thermal conductivity
e : thermal emissivity
h : thermal convection coefficient
K_{bf} : heat transfer coefficient for free resting period
K_{bd} : heat transfer coefficient for deformation period

7.4 Discussion on the Simulation Results

As can be seen from Fig. 7.9, there is in general close agreement between the external profiles of the geometry of the deformed and cooled workpiece after the barrelled outer surface has first made contact with the die wall and the profiles predicted by the simulation at a similar stage of deformation.

As stated in section 7.2.1 the measured geometry of the billet was modified for the simulation to take into account several factors that affected the billet dimensions, one of which was thermal expansion. The measurement of the geometry of the deformed workpiece was performed when it had cooled. This is one of the main reasons why the volume of the FE mesh was more than that of the cooled workpiece and therefore, in Fig. 7.9 the height of the deformed workpiece is slightly less than that of the simulation. Another reason is that after deformation, some of the scale and lubricant on the top and bottom surfaces of the billet was removed, resulting a small decrease in the height of the deformed workpiece.

By considering Fig. 7.11, the geometry of the workpiece and mesh at the stage of corner filling are in close agreement, taking into account the fact that these are obtained at different temperatures, as discussed above.

According to Fig. 7.13, the results of the load–displacement curves obtained from experiment and simulation are generally in agreement but the following points need to be mentioned.

(i) At the start of deformation the loads from the simulation are higher than those from experiment. This is mainly due to the fact that in the mechanical press the tools are not completely rigid and there is some clearance between the members at the joints, while in the simulation the tools are assumed to be rigid.

(ii) In the stage of free upsetting the trend of the curves is similar but the results from the simulation are greater compared with those of the experiments. This is probably due to the difference between modelling the material properties used in simulation, stated in section 4.3.3.4, and the actual behaviour of the workpiece material.

(iii) The start of the second stage of deformation (when the workpiece comes into contact with the container) in the simulation curve is slightly later (about 0.3 mm) than in the experiment.

In section 5.3.1 it was mentioned that a small cone was machined on the counterpunch which mated with a hollow cone on the axes of the billets to ensure that they could be centrally located in the dies. In spite of this, there was a small clearance between the cones, when the billet was at room temperature, to make sure that the mating could be done. This clearance was more when the billet was heated to a higher temperature and could have permitted some movement of the billet.

As can be seen from figure 7.9, there is a close agreement between the lateral geometry of the deformed workpiece and that obtained from experiment just as the workpiece makes contact with the die wall. Therefore, it can be concluded that the clearance between the small cones is the main reason that the contact in the experiments began slightly earlier. This is confirmed by inspection of a deformed workpiece which showed that most of the vertical surfaces of the workpiece were only just in contact with the container wall while some others clearly had made greater contact. As can be seen from the curves, the inflection point in the simulation curve is very distinct while in the experimental results such a point is not as clear. This means that in the actual experiment complete contact with the die wall by the whole periphery of the workpiece occurred incrementally.

(iv) As is obvious from figure 7.13, the simulation curve in the stage of corner filling is steeper than that in the experiment. This is due to the fact that the tools in the simulation are rigid while those in the experiment have some elastic deformation.

Chapter 8

Assessment of Typical Stages of Stub Axles

8.1 Introduction

In this chapter, some real forgings are examined using the comparison algorithm. Two sets of components have been selected to assess the use of the algorithm. In the following sections the method of obtaining the limiting values of success and confidence indicators are stated first and then these two sets of components are examined.

8.2 Obtaining the Limiting Values of Success and Confidence Indicators

As will be obvious later in this chapter, the components that have been specified to the IKBS are all satisfactory and therefore the values of success indicators obtained from the comparison algorithm for all the new components that are examined in this chapter are +1, although the algorithm works properly for the case when hypothetical unsuccessful data were specified to the IKBS. Therefore, in the current version of the IKBS a limiting value of +1 (or –1) was selected for the success indicator to indicate when the deformation of a stage is satisfactory (or unsatisfactory).

To obtain the limiting value of confidence indicator, the average value of forging pressure in the experiments described in chapter 5, which is about 450 N/mm^2, has been used as a basis. To do this, approximately 5% of this pressure, 20 N/mm^2, was selected and specified to the algorithm and a value of about 0.6 was obtained for C.

Thus, in performing the main actions of the Control Module in Fig. 3.7, the limiting values of success indicator will be $\pm$ 1 and that of the confidence indicator will be 0.6.

8.3 Assessment of Stages of Components from Rover Group

Figs. 8.1 to 8.4 show the geometry of four machined parts from Rover Group. They have been defined as new components to the IKBS. The operational sequences of these components have been designed by the system and the results of experimental trials have been input to the IKBS as satisfactory.

Figs. 8.5(a) to (d) show the operational sequences designed by the system, corresponding to Fig. 8.1.

As stated in the chapter 6, the value of the significant process and geometric parameters of different stages of deformation are extracted from the SDP database and are stored in the IKBS database. The IKBS database thus generated is shown in Fig 6.4.

Several instances of new components have been assessed by the comparison algorithm and are discussed briefly as follows:

(i) For the stage of producing a 'finished' part from a 'preform', by referring to Fig. 8.5:

(a) In order to verify the performance of the comparison algorithm and the upper limit value of C in equation (3.3), the parameters relating to the stages in Figs. 8.5(a) and (b) were introduced to the assessment algorithm and the results were:

S=1,

C=1,

Nearest guide: Successful, based on WFM 3001.

As an identical instance already existed in the database, these values were to be expected.

(b) For this set of data, the only parameter that was changed compared with those of the previous set was the value of cheese ratio for the product in Fig. 8.5(a) which was altered from 0.08 to 0.074, and the results were:

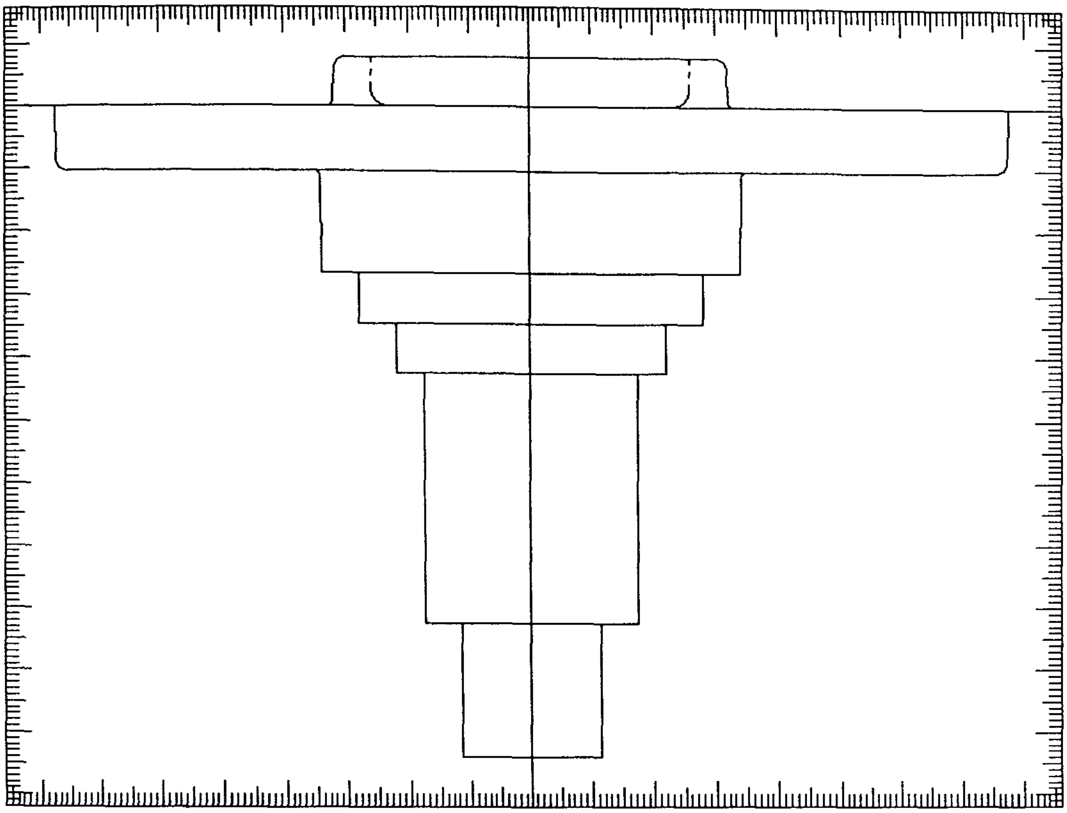


Fig. 8.1 Stub Axle, WFM 3001 (machined part)

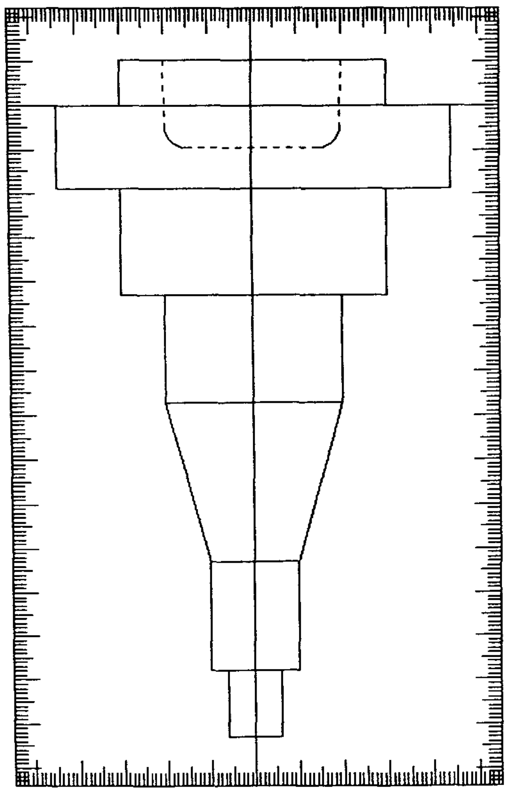


Fig. 8.2 Stub Axle, WFM 2059 (machined part)

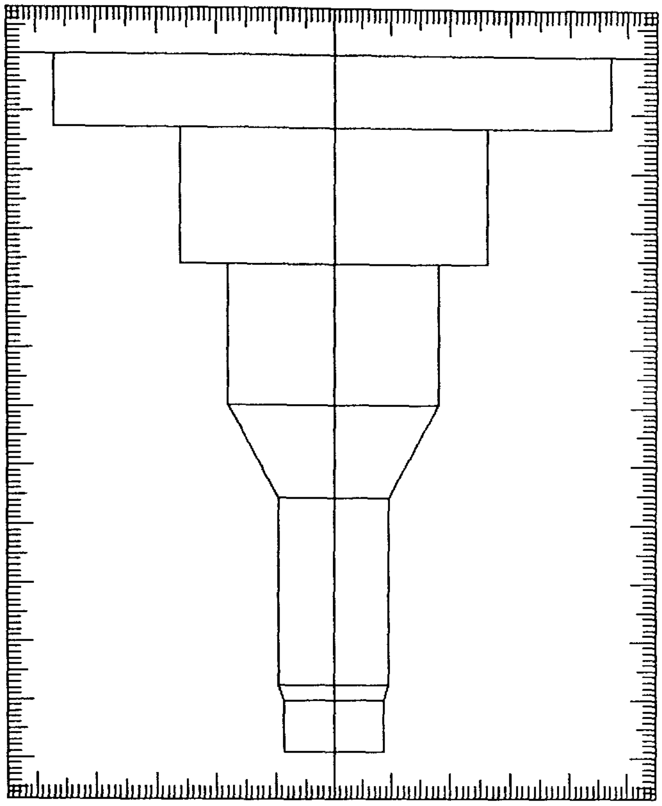


Fig. 8.3 Maestro Stub Axle, WFM 2029 (machined part)

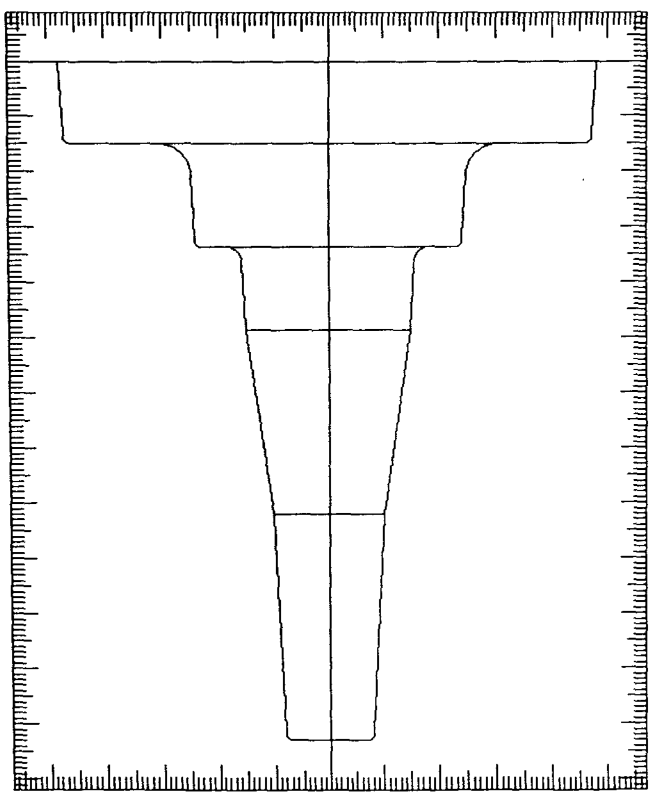
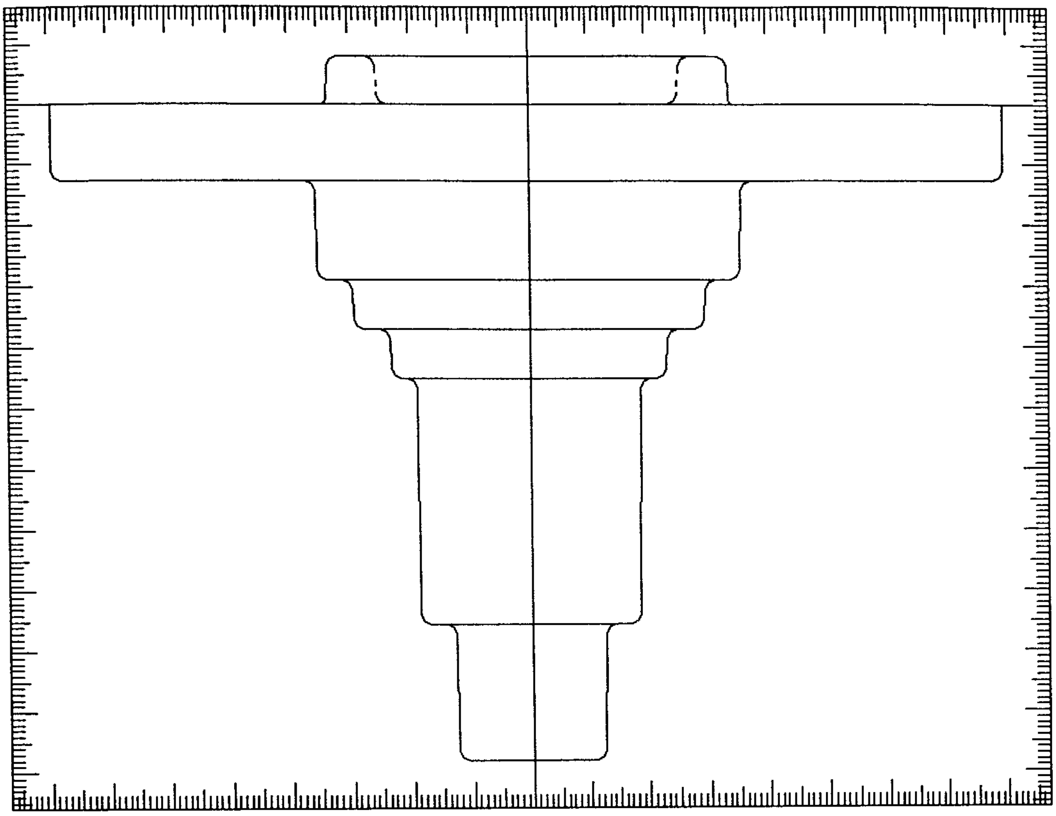
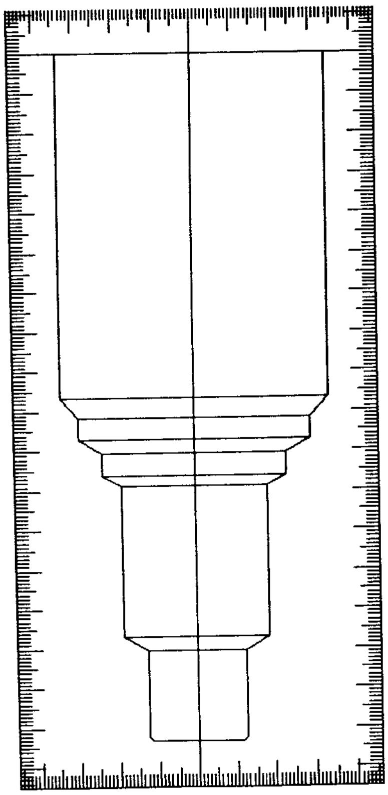


Fig. 8.4 Stub Shaft Forging, WFM 2023 (machined part)

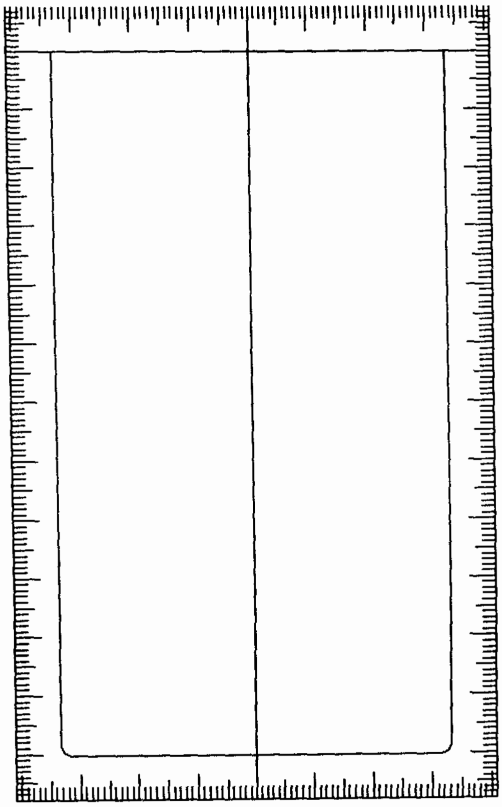


(a)

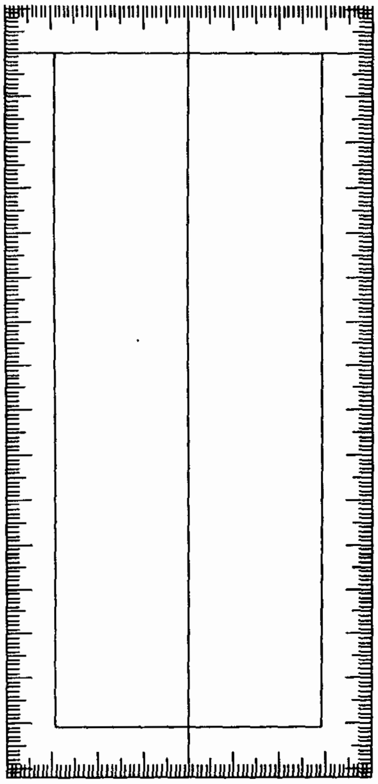


(b)

Fig. 8.5 The operational sequences corresponding to Fig. 8.1
(a) Finished part (b) Preform (c) Cheese (d) Billet



(c)



(d)

Fig. 8.5 The operational sequences corresponding to Fig. 8.1 (continued)
(a) Finished part (b) Preform (c) Cheese (d) Billet

S=1,

C=0.97,

Nearest guide: Successful, based on WFM 3001.

(c) For this set of data, the parameters that were changed compared to set (b) above were the data for the lubrication condition which was altered from graphite to glass–based and the forging temperature which was changed from 1120 °C to 920 °C and the results were:

S=1,

C=0.1,

Nearest guide: Successful, based on WFM 3001.

(ii) For the stage of producing a 'preform' from a 'cheese', by referring to Fig. 8.5, the only parameter that was changed compared with those of Figs. 8.5(b) and (c) was the value of extrusion ratio of the first shoulder in Fig. 8.5(b) which was altered from 1.32 to 1.52, and the results were:

S=1,

C=0.28,

Nearest guide: Successful, based on WFM 3001.

(iii) For the stage of producing a 'cheese' from a 'billet', by referring to Fig. 8.5:

(a) For this set of data, the only parameter that was changed compared to those of Figs. 8.5(c) and (d) was the value of upset ratio in Fig. 8.5(d) which was altered from 2.586 to 2.5, and the results were:

S=1,

C=0.64,

Nearest guide: Successful, based on WFM 3001.

(b) For this set of data, the only parameter that was changed compared to those of Figs. 8.5(c) and (d) was the value of upset ratio in Fig. 8.5(d) which was altered from 2.586 to 2.406, and the results were:

S=1,

C=0.46,

Nearest guide: Successful, based on WFM 3001.

(c) For this set of data, the parameters that were changed compared to the above sets were the values of upset ratio in Fig. 8.5(d) which were altered from 2.586 to 2.186 and the forging temperature which was changed from 1200 °C to 1000 °C, and the results were:

S=1,

C=0.11,

Nearest guide: Successful, based on WFM 3001.

8.4 Assessment of the Stage of Producing a 'cheese' from a 'billet' carried out in the Experiments

Fig. 8.6 shows the geometry of the billet used in test no. 1, test piece no. 1 performed in chapter 5. The data for this test were stored in the IKBS database and the results of experimental trials were stored in the database as satisfactory. The load–displacement curve obtained from experiment and FE simulation for this test was previously shown in Fig. 7.13.

(a) For this set of data, the only parameter that was changed was the value of upset ratio in Fig. 8.6 which was altered from 0.87 to 1.05, corresponding to test piece no. 2 in test no. 1 of chapter 5. Fig. 8.7 illustrates the geometry of the billet and the results were:

S=1,

C=0.46,

Nearest guide: Successful, based on test no. 1, test piece no. 1.

The load–displacement curve obtained from experiment and FE simulation for this test is shown in Fig. 8.8.

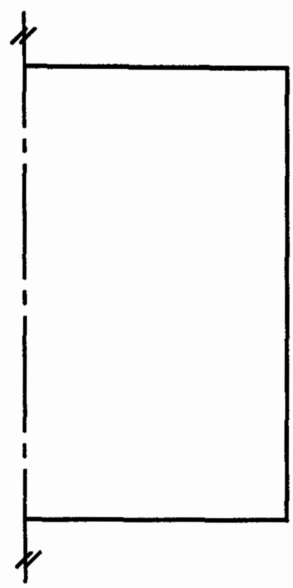


Fig. 8.6 Test no. 1, test piece no. 1, height=30 mm, diameter=34.3 mm

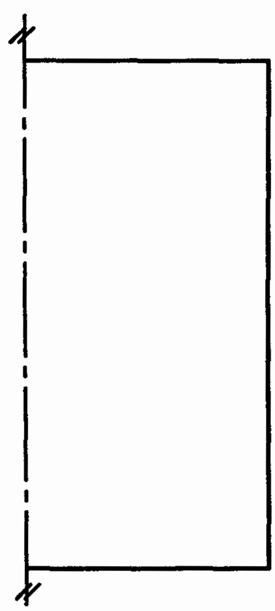


Fig. 8.7 Test no. 1, test piece no. 2, height=33.8 mm, diameter=32.4 mm

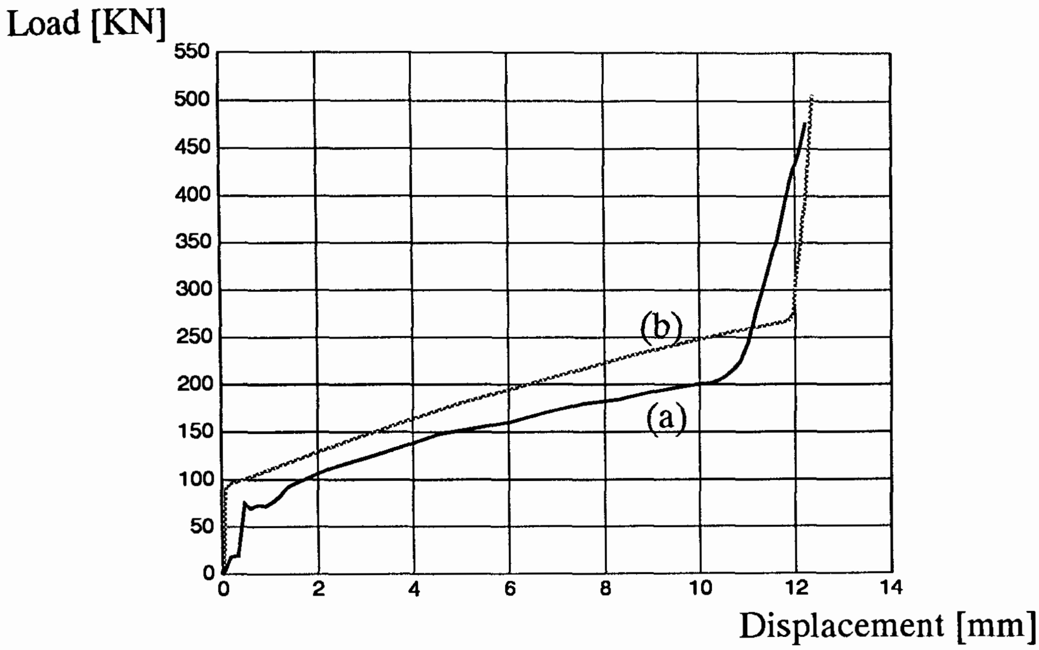


Fig. 8.8 Load–displacement curves obtained from experiment and simulation corresponding to Fig. 8.7.
(a) Experiment (b) FE

(b) For this set of data, the parameters that were changed compared to set (a) above were the values of upset ratio in Fig. 8.6 which were altered from 0.87 to 1.27 and the forging temperature which was changed from 900 °C to 1100 °C. Fig. 8.9 shows the geometry of the billet and the results were:

S=1,

C=0.11,

Nearest guide: Successful, based on WFM 3001.

The load–displacement curve obtained from experiment and FE simulation for this test is shown in Fig. 8.10.

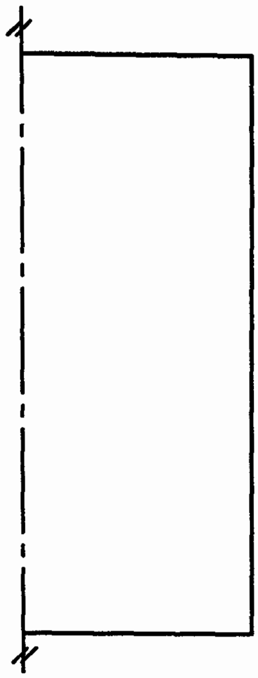


Fig. 8.9 Test no. 1, test piece no. 3, height=38.1 mm, diameter=30 mm

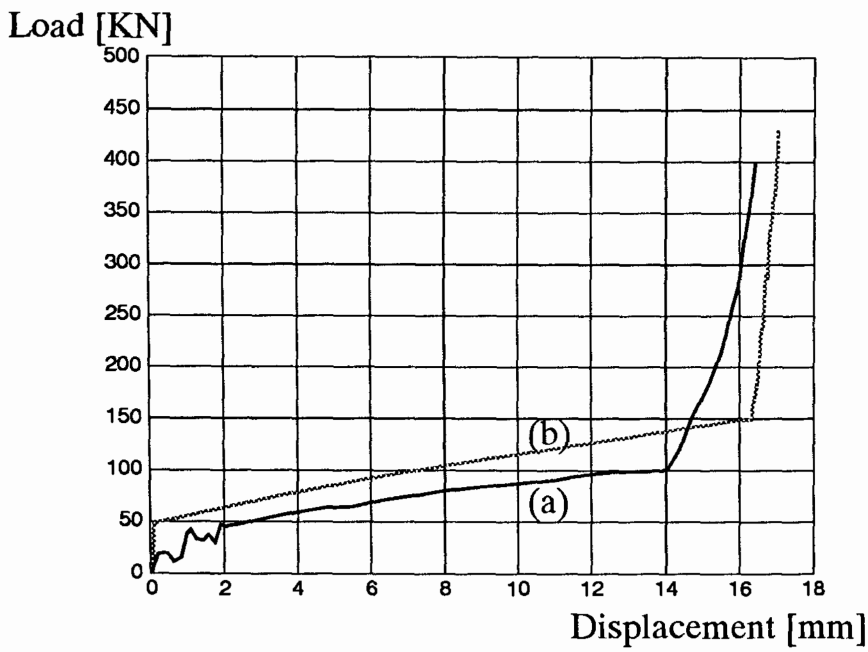


Fig. 8.10 Load–displacement curves obtained from experiment and simulation corresponding to Fig. 8.9.
(a) Experiment (b) FE

8.5 Discussion on the Results of Assessment of Some Real Forgings

Some instances of real forgings have been selected to examine the use of the comparison algorithm in this chapter. Since the results of experimental trials that were specified to the IKBS were obviously satisfactory, the stored values of success indicators were +1 and thus the value of success indicators obtained for the different instances examined were +1.

As can be seen from the results of instance (b) of part (i) in section 8.3, when the state of the parameters of a new component stage is close to that of a stored one, then $S_m \rightarrow S_k$ and $C_m \rightarrow C_k$, in which S_k and C_k are the success and confidence indicators of the stage stored in the IKBS database which has the nearest distance to the one under consideration and S_m and C_m are those of the current one.

Although the value of confidence indicator in equation (3.3) changes from 0 to 1, it is not a linear indication of the confidence about the results of an instance. For example, by considering the results of instance (b) of part (iii) of section 8.3, a value of confidence indicator near to 0.5 does not indicate a 50% confidence on the results. Therefore, a method has been used to obtain a limiting value for confidence indicator which is about 0.6. This is valid for the different parameters due to the way that the weighting factors have been normalised in section 5.5.4.

By this method of defining a limiting value for success indicator, even though C_m might not be close to C_k, as in the case of instance (a) of part (iii) of section (8.3), the results of an instance can be considered successful with reasonable confidence.

As is obvious from the results of some instances, when the values of the parameters of a new component stage are far from those of the stored ones (when $C<0.6$), then there is little confidence about the results of the current instance, especially when C_m tends to 0.

Chapter 9

Conclusions and Suggestions for Future Work

9.1 Introduction

The present research programme was concerned with the development of an IKBS for forging die design which followed on from previous research work carried out at the School. Some parts of this system had already been developed but much research was still required. During this current research work those parts that related directly to the IKBS, illustrated in Fig. 3.7 were completed. There are some other pieces of work that relate to the other families of components in the IKBS or relate indirectly to the IKBS activities and improve the efficiency of the system. In the following sections, the conclusions arising from the work undertaken by the author will be presented first, and finally the work required to complete the system will be outlined.

9.2 Conclusions

1. A new experimental–based approach has been developed to obtain the weighting effect of the significant process and geometric parameters for different stages of deformation in Stub Axle manufacture which could be either a closed–die upsetting or a forward extrusion. The results have been used in the IKBS to carry out computer–aided reasoning through the use of the comparison criterion algorithm.

2. Among the geometrical parameters considered in closed–die upsetting, the unfilled corner volume (or the corner dimensions) had the most significant effect on the average pressure within the range of the experiments performed.

3. Among the processing parameters in closed–die upsetting, the forging temperature and the type of machine were the most significant parameters.

4. In forward extrusion, among the geometrical parameters, the extrusion ratio is the most significant parameter, followed by the initial ratio (height/diameter) of the workpiece.

5. Among the process parameters in forward extrusion, the forging temperature is the most significant parameter.

6. In closed–die upsetting, the cheese ratio considered as a geometrical parameter has the least significant effect within the range of the tests performed.

7. In forward extrusion, the workpiece lubrication condition considered as a process parameter, when the die is properly lubricated, is the least significant parameter. The height/diameter of the extrudate does not have any effect on the average pressure.

8. The method that has been used in developing comparison criteria is quite general and can easily be applied to the other families of components in the SDP in particular, or to other metal forming processes.

9. Some aspects of computer aided reasoning have been performed to complete the activities of the IKBS, in particular those related to the knowledge–base and Control Module (inference engine).

10. As stated before, the weighting effect of the significant geometric and process parameters have been obtained by experiments. These factors have been normalised and stored in the knowledge–base and have been used in the comparison algorithm.

11. According to the frame–based representation in the Common LISP programming language and the idea suggested in Ref. [91], a sample part of the IKBS database was created based on the data of real forgings. This data structure is efficient in the different activities of the IKBS.

12. Based on the actual experimental data obtained for the weighting effect of process and geometric parameters and the different aspects of computer aided reasoning in the IKBS, stated in chapter 6, several instances of real forging have been selected to examine the use of the comparison algorithm. The results obtained indicate that the algorithm works properly and efficiently.

13. The three dimensional elastic–plastic finite–element program, EPFEP3, has been used to simulate a typical stage of deformation in Stub Axle manufacture, i.e. closed–die upsetting. Some experiments were carried out to ensure the thermal properties of the workpiece and the heat transfer coefficient at the die/workpiece interface were modelled properly. The results indicate a good agreement between the FE predictions and the experimental measurements.

The geometry of the deformed workpiece when it was just in contact with the die wall, the geometry of the workpiece at the stage of corner filling, and also the load–displacement curve obtained from experiments were compared with those of the simulation and were generally in agreement, taking into account the effect of temperature and the removal of the scale and lubricant from the surfaces of the billet.

14. The correlation between the results obtained from experiments and FE simulation in this thesis indicate that, in addition to the direct use of the finite–element simulation in metal forming process modelling, it can be used indirectly to obtain the weighting effects of geometric and process variables, by using the average forging pressure in the last stage of deformation in closed–die upsetting, or other processes in the SDP part of the IKBS, as a sensitivity indicator.

15. An interface program has been developed to create the EPFEP3 datafile necessary for the modelling of each stage of deformation for the forging of Stub Axles. This program and the tools used make it possible to create the datafile rapidly and efficiently.

16. The interface program makes it possible to concentrate smaller elements in certain parts of the mesh which may be subject to large deformation or which may be considered more important by the user, such as the outer surfaces of the mesh where the workpiece is in contact with the die surfaces (see for example Figs. 4.10 and 4.11).

17. The technique used in creating the datafile is general and can easily be applied and extended to the other families of components in the SDP.

9.3 Suggestions for Future Work

1. The current research work has been confined to a family of components in the SDP, i.e. Stub Axles. The method of investigation which has been used in the different parts of the research work is general and therefore can be extended to the other component families within the IKBS.

2. In the current investigation the effect of backward extrusion in the stage of producing a 'finished' part from a 'preform' in Stub Axles, when the upper die is not a flat ended one, was assumed to be negligible. The effect of significant parameters in backward extrusion which may be important for the other families of components in the IKBS can be investigated.

3. The formulae which have been used in the initial version of the SDP to estimate the forging load of the different stages of Stub Axles are generally simple. As stated in [92], these estimates would be modified in the light of further information.

Based on the experimental results obtained, a general formula for load estimation in closed–die upsetting and forward extrusion needs to be obtained.

4. When a stage of a component in the SDP is being modified, some rules need to be implemented by the system to ensure that volume constancy is not violated. Also, the existing design rules in the SDP are not parametric and are constant. Work should be done to investigate how the design rules can be modified and improved.

5. As stated in section 3.4, there are some limitations in the existing graphical interfaces and the sequence design program. The efficiency of the IKBS can be increased by using better graphical interfaces and solid modelling packages.

6. In the comparison algorithm, as can be seen from equation (3.1), the distance between the state of the parameters of a stage of deformation of a new component with those stored in the IKBS database is a function of the absolute difference between the parameters.

Work can be done to compare the results obtained in the current work with the case when, instead of the absolute difference, the vector difference is considered.

7. The IKBS has been validated to some extent. As stated in chapter 8, the instances of real forgings that have been specified to the IKBS were satisfactory. The efficiency of the system can be increased by specifying the data of more successful and unsuccessful components to obtain the limiting values for success indicator.

8. As stated in chapter 7, since in the simulation of forward extrusion a re–meshing package suitable for axisymmetric shapes was not available, the simulation of this process was not considered in the current research. Work needs to be done to complete an available re–meshing package for plane–strain shapes that can be applied to axisymmetric shapes.

9. As stated in chapter 2, (Artificial Neural Networks) have recently been used in different areas of engineering applications. This approach can be used to examine the process of comparing a stage of a new component with those stored in the IKBS database. The input to the net should be the values of the significant parameters for each stage and the output from the net are success and confidence indicators. To train the net, it is necessary to have the data of enough components which were previously examined.

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Appendix A

Experimentatal Calibration Curves

A.1 Heating and Cooling Calibration

The purpose of this work was to establish the minimum heating times to obtain prescribed temperatures for different billets and to determine the temperature changes arising during billet transport.

Thermocouple was located in the billet of example No. 1 in table 5.1, as shown in Fig. A.1. The billet was put into the furnace which was at 900 °C. Temperature versus time at the centre of the billet was recorded at 10 second intervals by using a thermocouple connected to an amplifier until the temperature was constant, i.e. close to the furnace temperature. Then, the billet was removed from the furnace and the values of cooling temperature versus time were recorded. This procedure was repeated for the example at the hole near the surface.

In table A.1 and Fig. A.2 the data obtained for heating at the centre of the billet are shown. The data for cooling near the surface of the billet are illustrated in table A.2 and Fig. A.4.

By using the results of Fig. A.2, the time required to heat the sample to a temperature close to 900 °C is found to be 12 minutes.

To apply the obtained experimental results to other billets, the following equation was considered [111]:

$$\frac{T - T_f}{T_i - T_f} = e^{-\frac{hA}{\varrho C_p V} t} \qquad (A.1)$$

in which:

T : Current temperature of billet (^oC)
T_f : Ambient temperature (^oC)
T_i : Initial temperature of billet (^oC)
h : Convection coefficient between billet and ambient
ϱ : Density of billet
Cp : Specific heat of billet
A : Billet surface (m^2)
V : Billet volume (m^3)
t : Time (s)

Equation A.1 is applicable if the internal thermal resistance of the billet material is negligible which is a reasonable assumption for the billets under consideration and was verified by the heating and cooling curves obtained at the centre and near the surface of the example. This equation can be rewritten as follows:

$$\frac{T-T_f}{T_i-T_f} = e^{C\frac{A}{V}t} \qquad (A.2)$$

In which:

$$C = -\frac{h}{\varrho C_p} \qquad (A.3)$$

To find the value of C in equation A.3, the results of the experiments were used. This has two consequences:

1. The value obtained gives more accurate results for the specific conditions (such as lubricated billets, geometries, furnace used, etc.) of the problem under consideration.

2. Although in equation A.1 radiation is neglected, it can be assumed that C is a generalised variable in which the effects of convection and radiation are considered, an assumption which is verified by the experiments.

At t=20 s and using table A.2, equation A.2 will give:

$$\frac{835-22.5}{895-22.5}=e^{C(1.85\times10^{-4})20}$$

Which will give: C=–19.3 m s^{-1}

By using the obtained value for C and tables A.2, the following results can be achieved:

t (s)	Temperature (°C) equation A.2	Temperature (°C) experiment
10	864.4	865

The difference between the predicted and experimental values is less than the error of experiment (which is about 2.5 °C).

Thus, equation A.2 can be applied to determine the working temperature of the furnace for each billet at about 900 °C. The time required to transfer a billet from the furnace to the machine was about 6 seconds and the time required to return the counterpunch from its upper position to lower position (discussed in section 5.3.4.2) was about 2 seconds. Therefore, the total delay time between removing a billet from the furnace and starting the deformation was about 8 seconds. By considering t=–8 s and equation A.2, the furnace working temperature for the example at about 900 °C will be 920 °C.

To estimate the heating time of different billets at 900 °C, by using table A.1 (at T=895 °C and t=720 s), equation A.2 gives:

$$\frac{895-900}{22.5-900}=e^{C(1.85\times10^{-4})720}$$

Which will give: C=–38.8 m s^{-1}

Thus, the time required to heat other billets at 900 °C was obtained and used in experiments.

The experiments in test Nos. 5 and 11 discussed in section 5.3.3 are for temperatures other than 900 °C, and it is obvious that the previous results at 900 °C could not be applied for the temperatures specified for this test. To find the value of C at these temperatures two other heating and cooling curves were obtained at 720 and 1100 °C. In tables A.3 to A.6 and Figs. A.4 to A.7 the results are shown and the following data were obtained:

Temperature (°C)	Furnace working temperature (°C)	Heating time (minutes)	C (for cooling)
700	705	26	–9.82
1100	1130	8.5	–21

The working temperature and heating time at temperatures other than 700, 900 and 1100 °C (i.e. 800, 1000 and 1200 °C) were found by linear interpolation or extrapolation and applied to the experiments.

During the experimentation it has been realised that the type of lubricant may be an important factor in heating/cooling procedures. Figs. A.8 and A.9 show the heating and cooling curves of example No. 3 in table 5.1 for two lubrication conditions.

A.2 Load–Displacement Calibration

Before setting up the tools it was necessary to calibrate the load cell. A hydraulic press was used in this respect in which for a specified input load the value of the output volts could be measured. The results of calibration is shown in Fig. A.10.

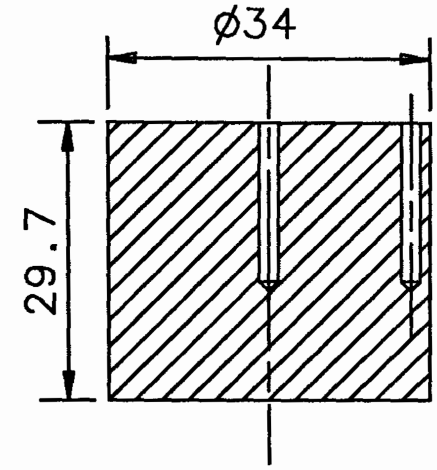

Fig. A.1 Billet used for experimental calibration curves
(Example No. 1 in table 5.1)

Time (s)	Temp (^oC)	Time (s)	Temp (^oC)	Time (s)	Temp (^oC)
0	22.5	270	705	540	855
10	77.5	280	715	550	860
20	117.5	290	723.9	560	862.5
30	157.5	300	728.7	570	865
40	194.3	310	731.1	580	870
50	240	320	731.1	590	872.5
60	267.5	330	733.5	600	875
70	300	340	735.8	610	877.5
80	330	350	740.8	620	880
90	360.6	360	745.6	630	882.5
100	391.8	370	750.4	640	885
110	417.5	380	755	650	885
120	446.1	390	760	660	887.5
130	472.5	400	767.5	670	887.5
140	495.7	410	772.5	680	890
150	519.1	420	778.9	690	890
160	540	430	788.7	700	892.5
170	561.3	440	795.8	710	892.5
180	580	450	802.5	720	895
190	599	460	810		
200	612.5	470	817.5		
210	629.3	480	825		
220	643.4	490	830		
230	657.5	500	837.5		
240	672.5	510	842.5		
250	683.7	520	847.5		
260	692.5	530	850		

Table A.1 Heating data for the centre of the billet

Temperature of furnace: 900 ^oC

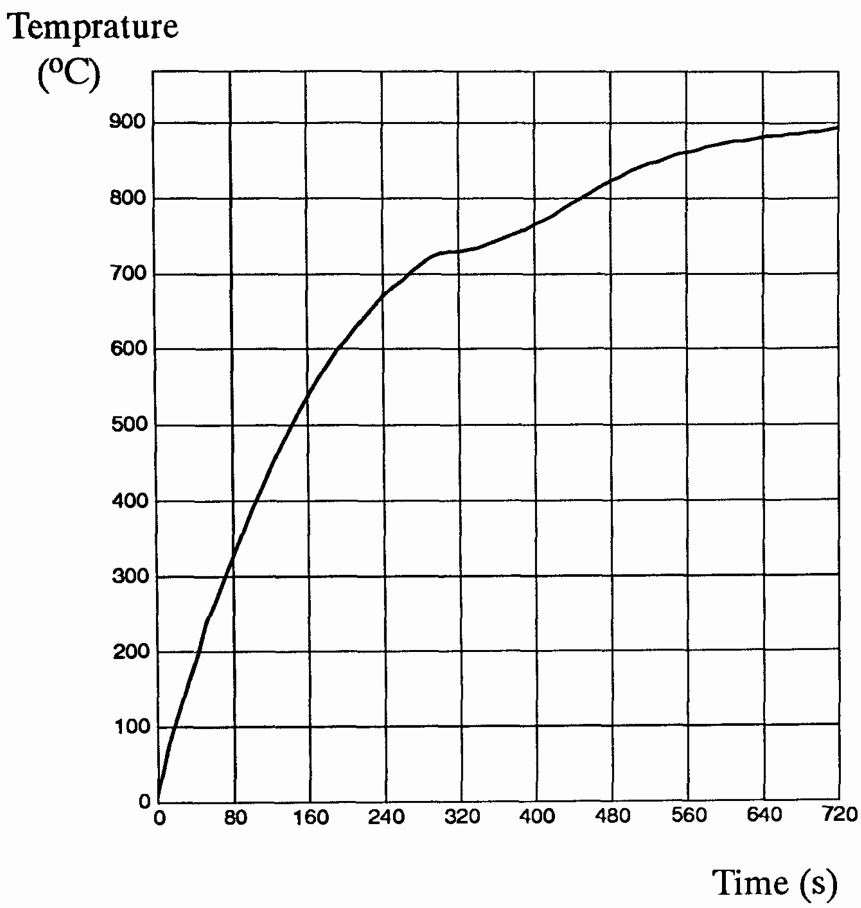

Fig. A.2 Heating curve for the centre of the billet

Temperature of furnace: 900 °C

Time (s)	Temp (^{o}C)
0	895
5	877
10	865
15	850
20	835
25	820
30	805.5
35	793.5
40	781.3
45	769.4
50	757.5
55	747.5
60	735.8
65	726.3
70	717.5
75	709.8
80	705.1
85	702.5
90	700.4

Table A.2 Cooling data for near the surface of the billet

Temperature of furnace: 900 ^{o}C

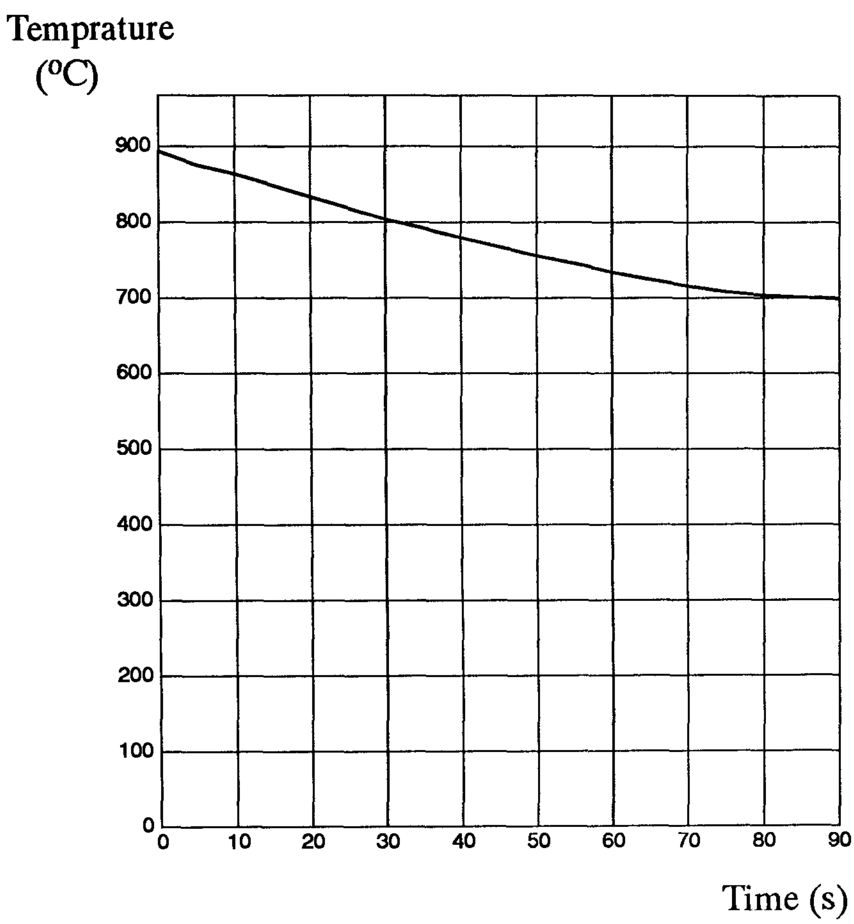

Fig. A. 3 Cooling curve for near the surface of the billet

Temperature of furnace: 900 °C

Time (s)	Temp (°C)	Time (s)	Temp (°C)	Time (s)	Temp (°C)	Time (s)	Temp (°C)
0	22.5	270	487.5	540	647.5	1040	708.5
10	45	280	499	550	650	1120	711
20	71	290	513	560	651.5	1230	713
30	97.5	300	517.5	570	656.5	1560	715
40	122.5	310	525	580	659		
50	145	320	533	590	661		
60	167.5	330	542.5	600	663.5		
70	190	340	548	610	663.5		
80	209	350	555	620	666		
90	231.5	360	562.5	630	668		
100	248.5	370	570	640	670		
110	267.5	380	576.5	650	673		
120	285	390	581	660	675		
130	302.5	400	587.5	670	675		
140	319	410	592.5	680	677.5		
150	335	420	600	690	680		
160	350	430	604.5	700	682.5		
170	367.5	440	609	720	685		
180	381	450	614	740	687.5		
190	395	460	618.5	760	690		
200	407.5	470	621	780	692.5		
210	421.5	480	625	810	695		
220	432.5	490	630	830	697		
230	445	500	632.5	860	699		
240	457.5	510	637.5	890	701.5		
250	468.5	520	640	940	704		
260	477.5	530	645	980	706		

Table A.3 Heating data for the centre of the billet

Temperature of furnace: 720 °C

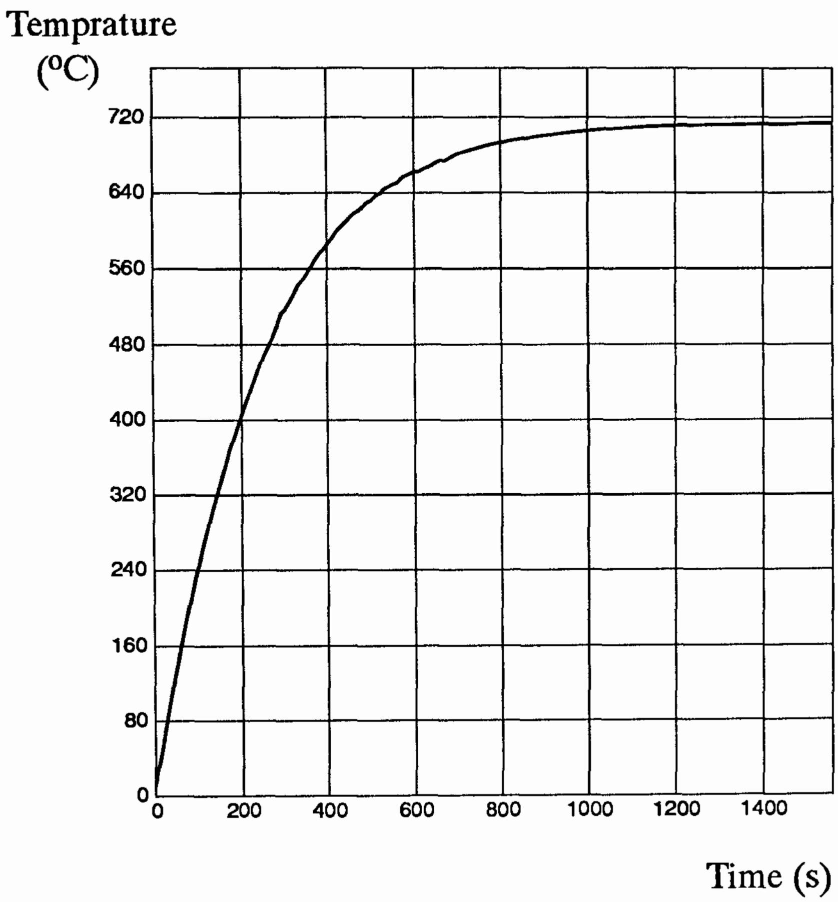

Fig. A.4 Heating curve for the centre of the first example

Temperature of furnace: 720 °C

Time (s)	Temp (^oC)	Time (s)	Temp (^oC)	Time (s)	Temp (^oC)
0	22.5	270	856.5	540	1095
10	90	280	881	550	1095
20	157.5	290	906	560	1098
30	219	300	931	570	
40	270	310	951	580	
50	319	320	971	590	
60	370	330	987	600	
70	412.5	340	1002.5	610	
80	450	350	1015	620	
90	480	360	1025	630	
100	508	370	1035	640	
110	536.5	380	1047	650	
120	562.5	390	1056	660	
130	585	400	1062	670	
140	611.5	410	1067	680	
150	635	420	1072.5	690	
160	661	430	1075	700	
170	685	440	1080	710	
180	711.5	450	1082.5	720	
190	728	460	1085		
200	737.5	470	1088		
210	737.5	480	1088		
220	740	490	1090		
230	754	500	1093		
240	780	510	1093		
250	805	520	1095		
260	830	530	1095		

Table A.4 Heating data for the centre of the billet
Temperature of furnace: 1100 ^oC

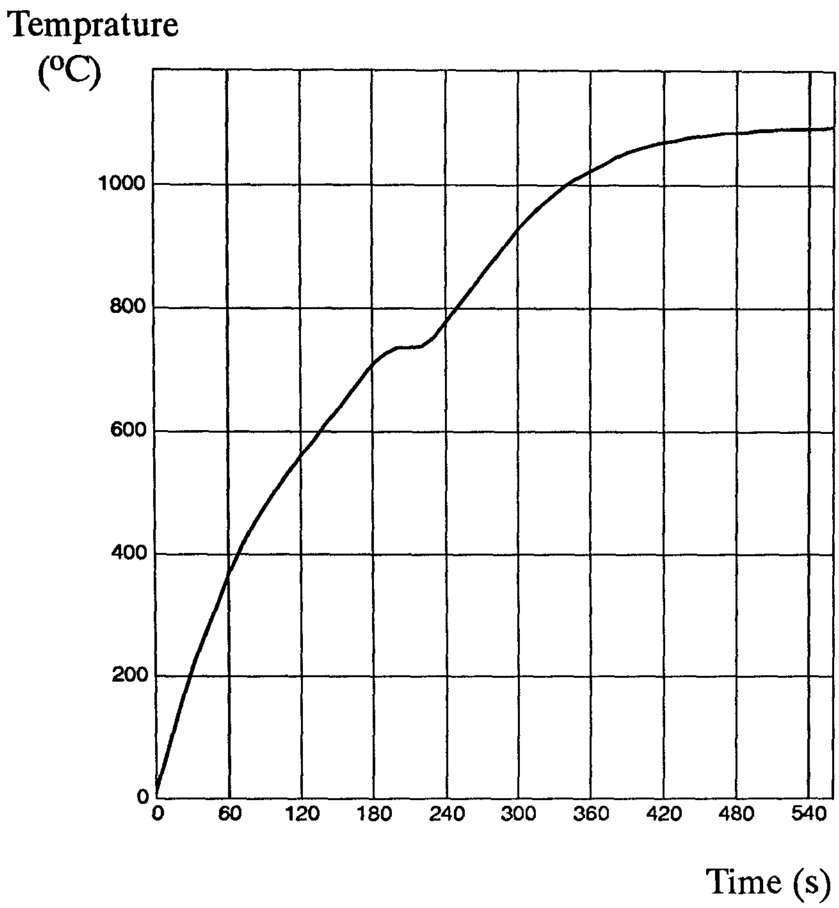

Fig. A.5 Heating curve for the centre of the billet

Temperature of furnace: 1100 °C

Time (s)	Temp (^oC)
0	715
5	711
10	708.5
15	704
20	697
25	692.5
30	685
35	680
40	673
45	668
50	661
55	656.5
60	650
65	645
70	640
75	632.5
80	627.5
85	622
90	618.5

Table A.5 Cooling data for near the surface of the billet
Temperature of furnace 720 ^oC

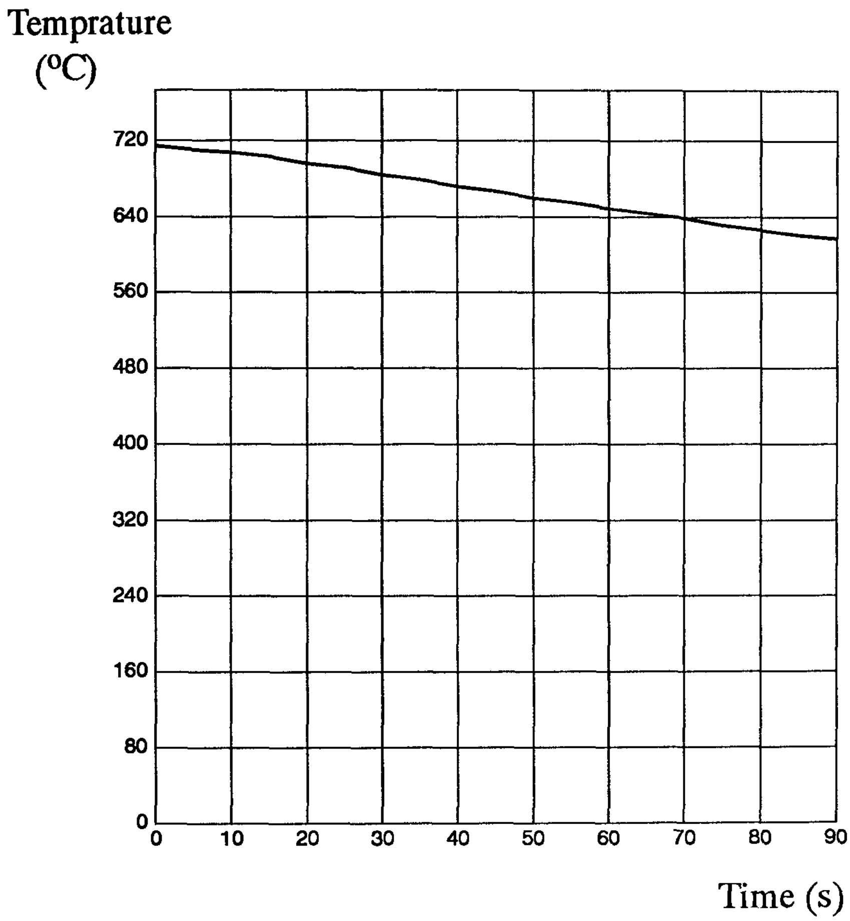

Fig. A.6 Cooling curve for near the surface of the billet

Temperature of furnace: 720 °C

Time (s)	Temp (^oC)
0	1098
5	1072.5
10	1056
15	1035
20	1015
25	995
30	974
35	956
40	938.5
45	921
50	903.5
55	891.5
60	873.5
65	859
70	844
75	832
80	820
85	807.5
90	795

Table A.6 Cooling data for near the surface of the billet
Temperature of furnace: 1100 ^oC

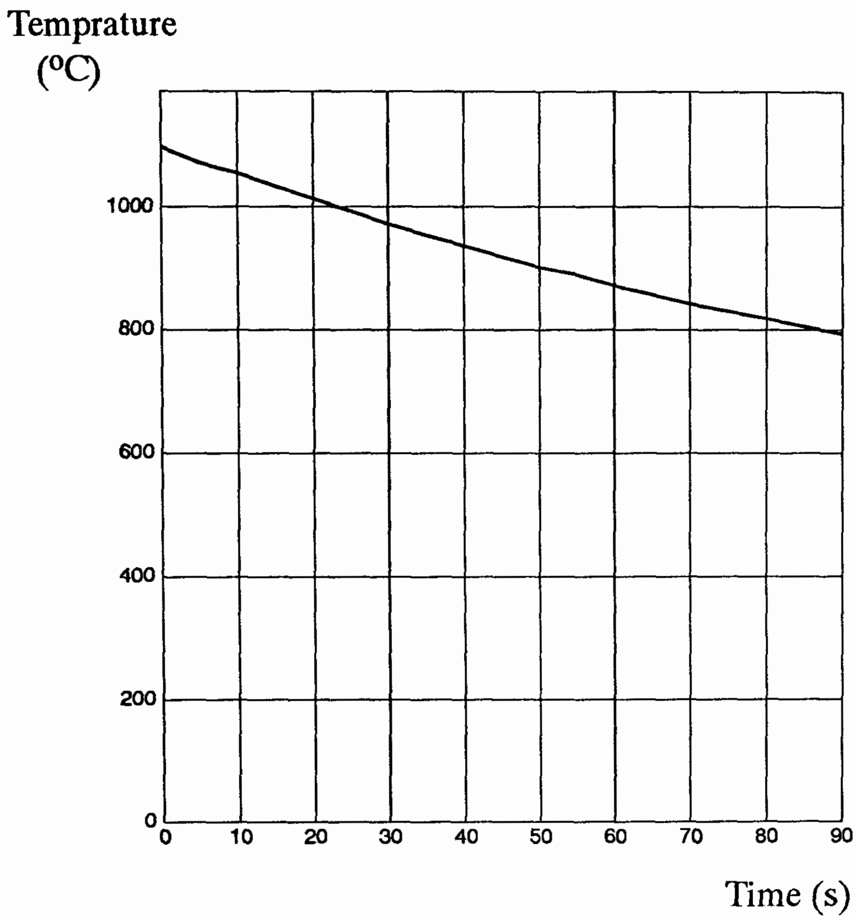

Fig. A.7 Cooling curve for near the surface of the billet

Temperature of furnace 1100 °C

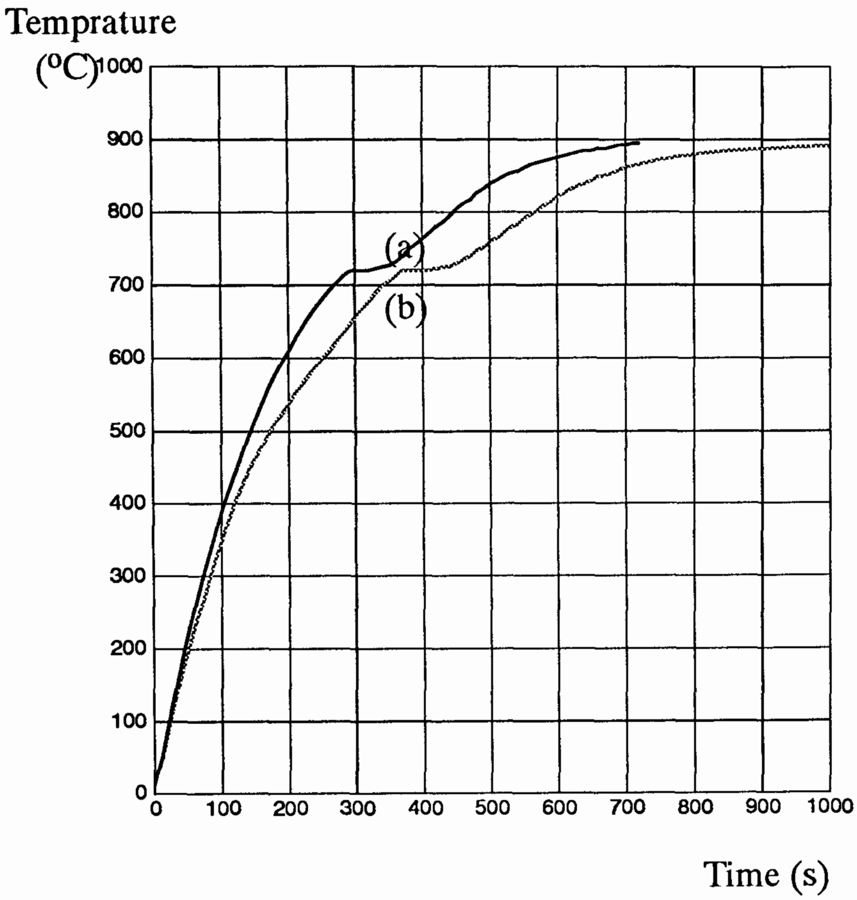

Fig. A.8 Heating curves for the centre of two examples with two different lubricants

(example No. 3 in table 5.1)

(a) Graphite–based lubricant

(b) Glass–based lubricant

Temperature of furnace: 900 °C

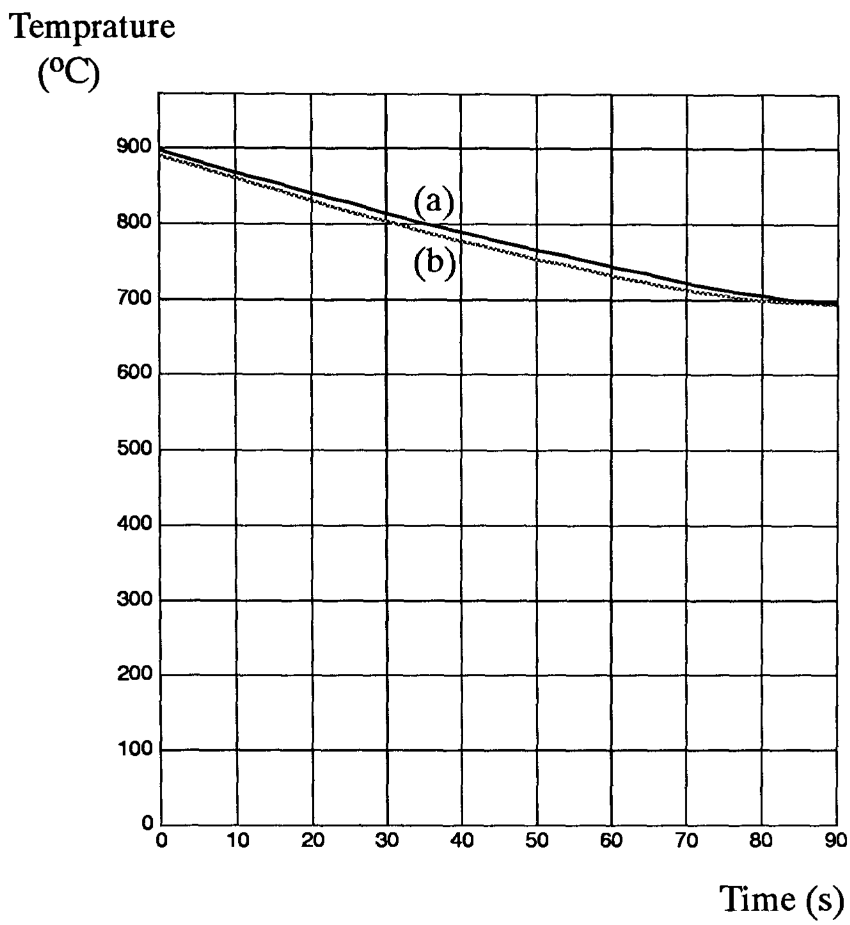

Fig. A.9 Cooling curves near the surfaces of two examples with two different lubricants
(example No. 3 in table 5.1)
(a) Graphite–based lubricant
(b) Glass–based lubricant

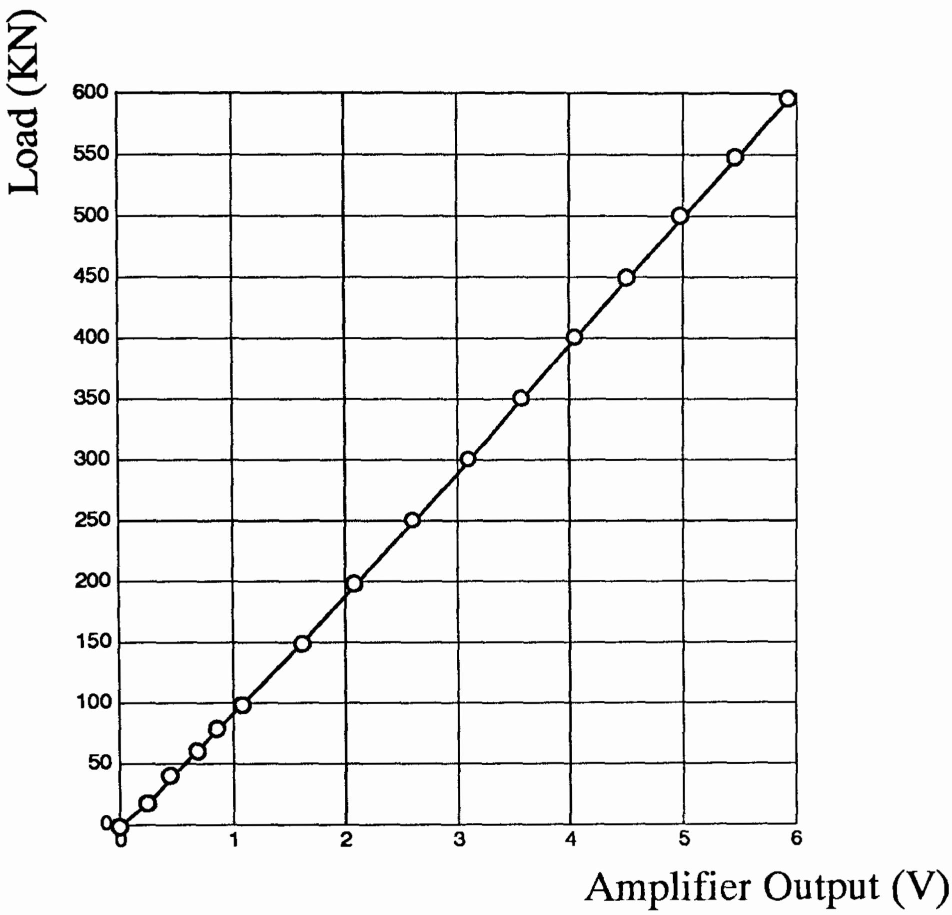

Fig. A.10 Load–cell calibration curve

Appendix B

Relation Between Corner Radius and Unfilled Corner Volume

As outlined in section 5.3.4.5, in actual forging practice it is not easy to describe the value of unfilled corner volume at the end of deformation. What is usual is to define the corner geometry (corner radius) in a certain product. Therefore, it might be necessary to obtain the value of unfilled corner volume for a specific corner geometry or vice versa.

In Fig. B.1.a, the schematic illustration of a cheese–die geometry is shown in which it is assumed that the product has two similar corners with radius r. By considering Figs. B.1.b and c, the following calculations are applicable:

$$\bar{X} = \frac{4}{3\pi} r \tag{B.1}$$

$$\bar{r} = R - r + \frac{4}{3\pi} r \tag{B.2}$$

in which:

$\bar{X}$: Distance from the centre of area of the corner to Y_2 axis

$\bar{r}$: Distance from the centre of area of the corner to Y_1 axis

The volume produced by the hatched section in Fig. B.1.c, V_1, is:

$$\begin{aligned} V_1 &= \pi R^2 r - \pi (R-r)^2 r - 2\pi \left(\frac{\pi r^2}{4} \right) (R - r + \frac{4}{3\pi} r) \\ &= \pi r^2 (2R - r) - 2\pi (\frac{\pi r^2}{4})(R - r + \frac{4}{3\pi} r) \\ &= \pi[-0.096r + 0.43R]\ r^2 \end{aligned}$$

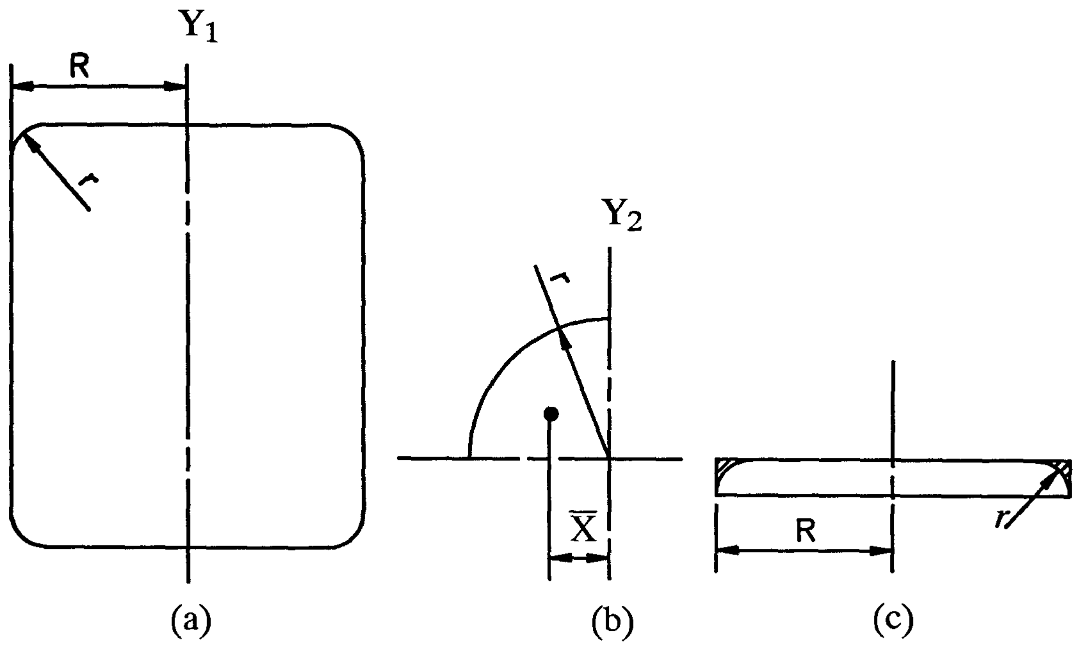

Fig. B.1 Schematic illustration of cheese–die geometry
(a) axial cross section
(b) corner geometry
(c) unfilled corner section (hatched)

The first term in the brackets can be neglected compared with the second one. Therefore:

$$V_1 = 0.43\pi \; R \; r^2 \qquad \text{(B.2)}$$

The percentage of unfilled corner volume, V_r, according to Fig. B.1 is:

$$V_r = \frac{2V_1}{V_{bil}} \times 100 = 270\frac{R}{V_{bil}}r^2 \qquad \text{(B.3)}$$

For a specific value of unfilled corner volume (in percents), the corner equivalent radius, r, is:

$$r = \left[\frac{V_r \, .V_{bil}}{270R}\right]^{\frac{1}{2}} \qquad \text{(B.4)}$$

Appendix C

Photographs of Selected Specimens and Equipment Used in the Experiments

C.1 Introduction

In this appendix the photographs of some selected specimens and equipment used in the experiments, stated in chapter 5, are illustrated.

C.2 Closed–Die Upsetting

Fig. C.1 illustrates (from left to right) the geometry of a billet (test piece no. 3 of test no. 2), the geometry of the deformed workpiece after the barrelled outer surface has first made contact with the die wall, and the geometry of the deformed workpiece at the stage of corner filling.

C.3 Forward Extrusion

Fig. C.2 shows (from right to left) the geometry of the billet (test no. 8) and the geometry of the deformed workpieces with different ratios of the height/diameter of the extrudate.

C.4 Forging Equipment

Fig. C.3 illustrates the tool sets used in the experiments. The photographs of the mechanical press and the hydraulic press are shown in Figs. C. 4 and C.5, respectively.

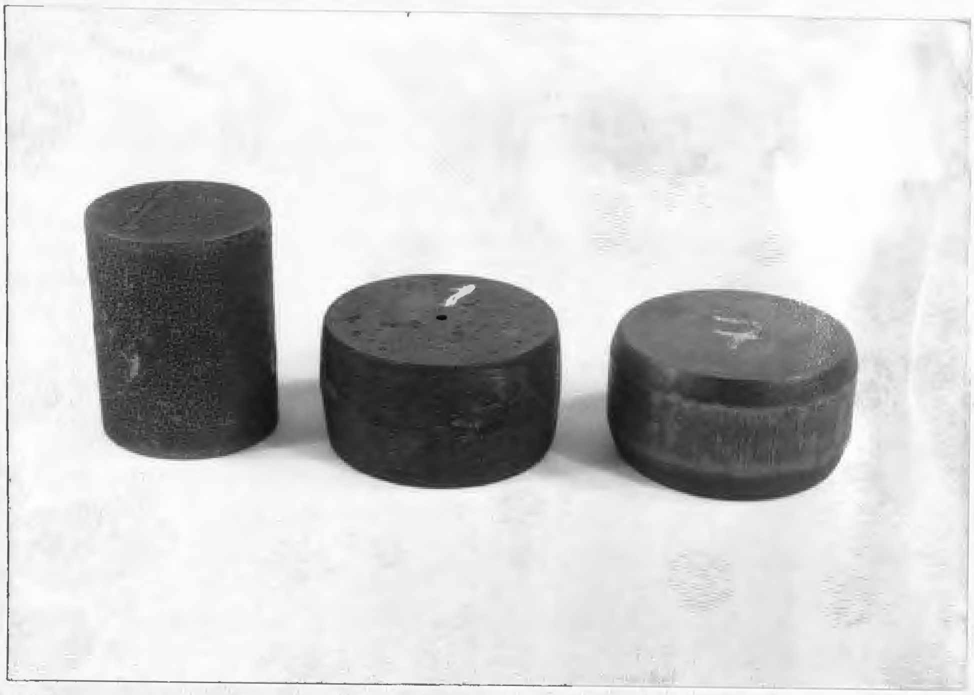

Fig. C.1 The geometry of the specimens in closed–die upsetting
Left to right: billet (test piece no. 3 of test no. 2), the deformed workpiece just after making contact with the die wall, and the deformed workpiece at the stage of corner filling.

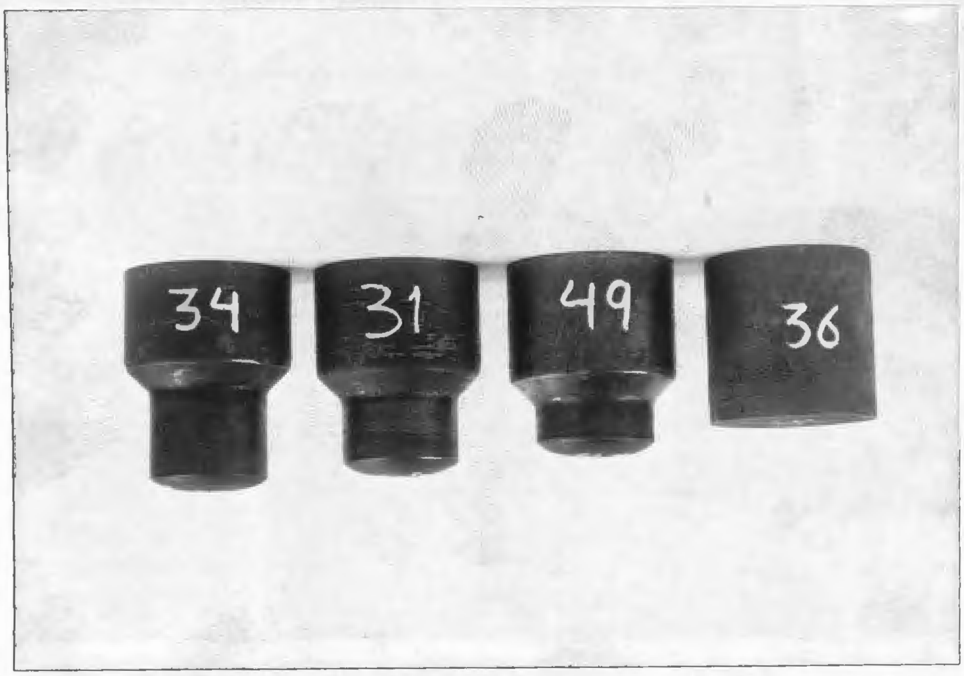

Fig. C.2 The geometry of the specimens in forward extrusion
Right to Left: billet (test no. 8), and the deformed workpieces with different ratios of height/diameter of the extrudate.

Fig. C.3 The tool sets used in the experiments.

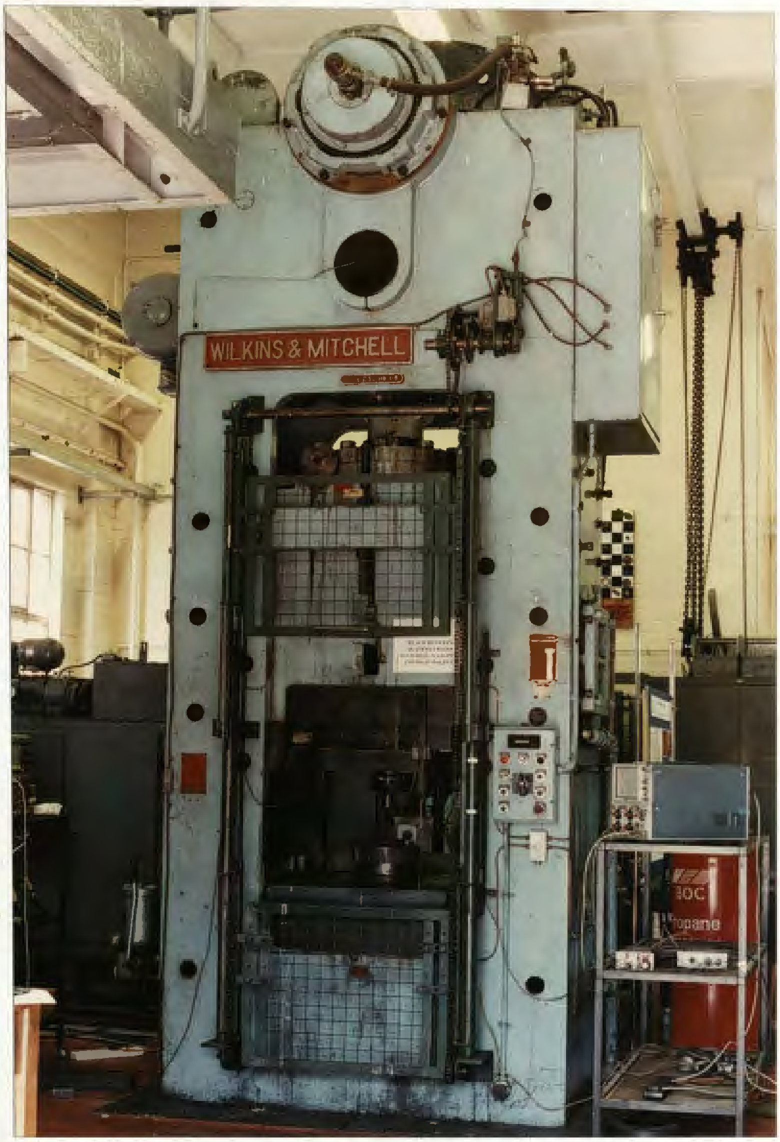

Fig. C.4 The 2000 KN mechanical press used in the experiments.

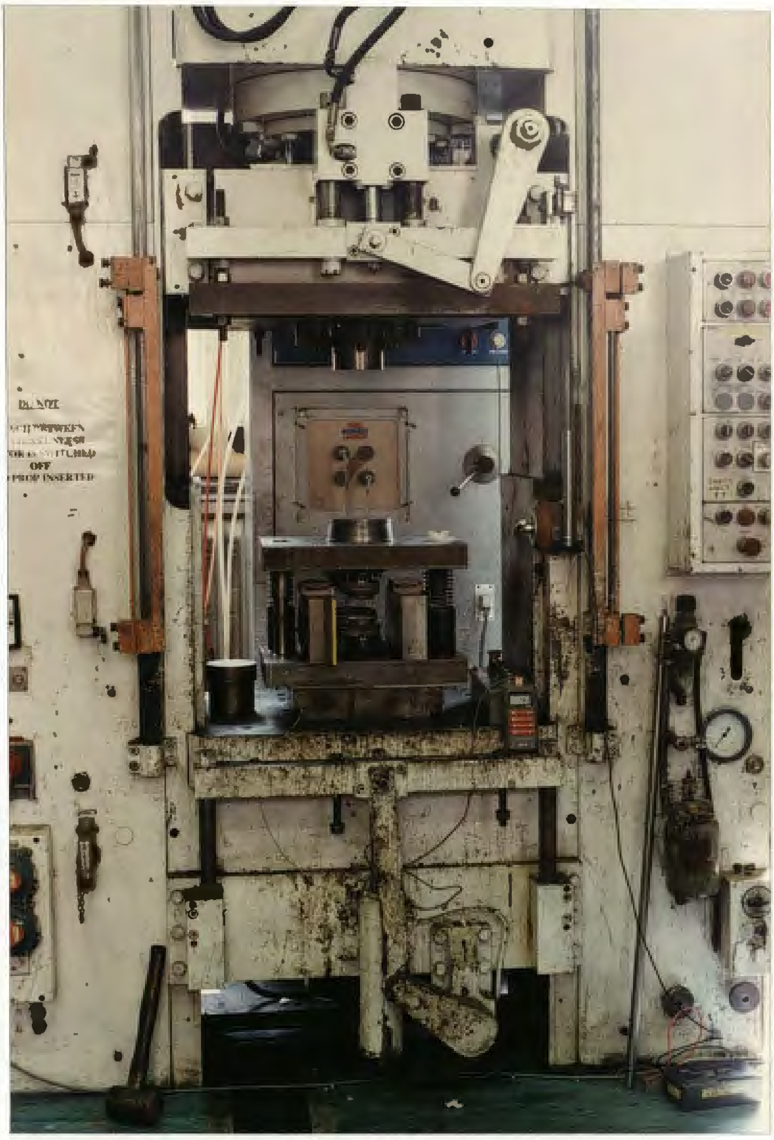

Fig. C.5 The 1500 KN hydraulic press used in the experiments.

Appendix D

Further Results of Finite–Element Simulation of Closed–Die Upsetting

The finite–element simulation of closed–die upsetting was examined in chapter 7 where those results that were directly related to the current research were presented and compared with those from the experiments.

In this appendix some further results of the finite–element simulation of this process are presented.

Figs. D.1 to D.3 illustrate the displacement vectors, generalised plastic strain and absolute temperature contours corresponding to Fig. 7.10. Figs. D.4 to D.6 show the results corresponding to Fig. 7.12.

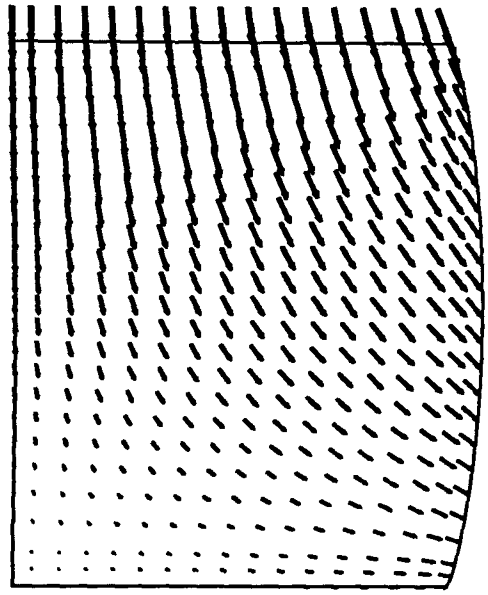

Fig. D.1 Displacement vectors corresponding to Fig. 7.10.

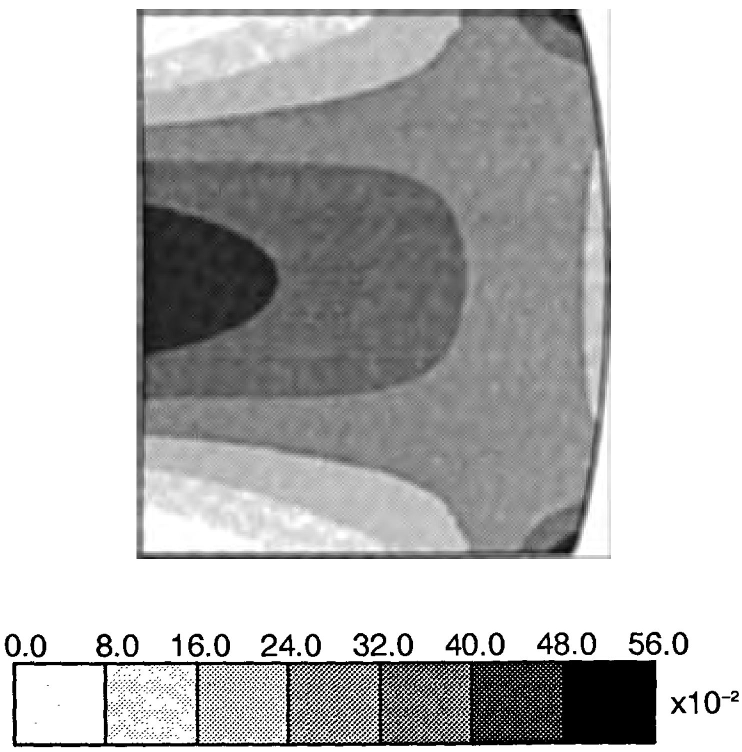

Fig. D.2 Generalised plastic strain corresponding to Fig. 7.10.

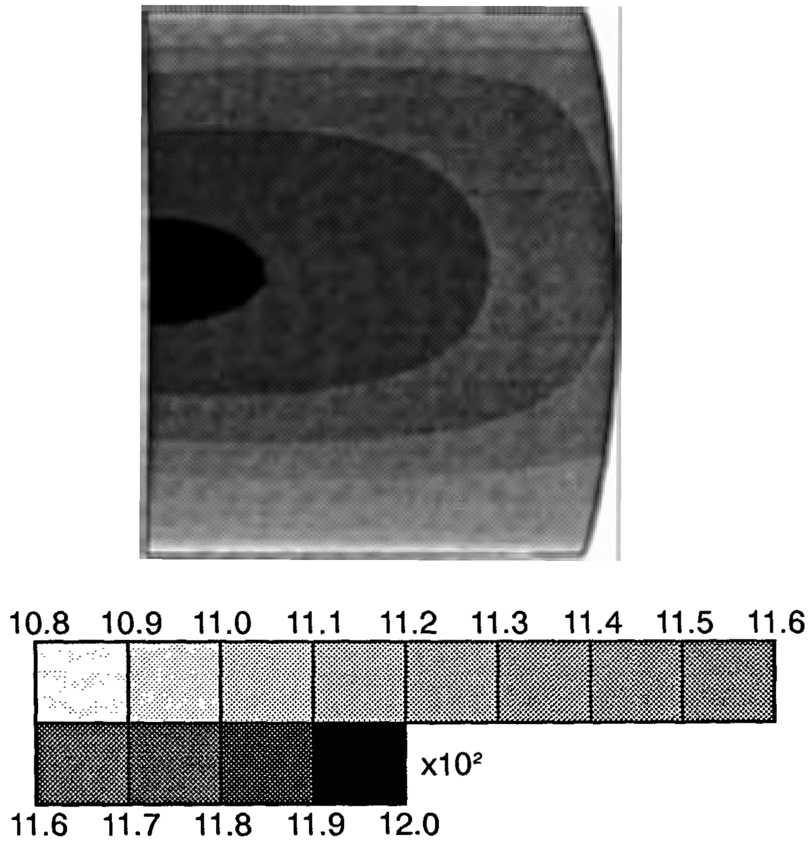

Fig. D.3 Absolute temperature (K) contours corresponding to Fig. 7.10.

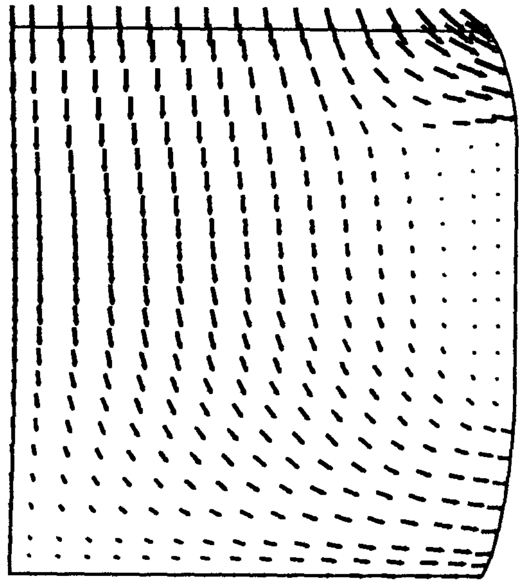

Fig. D.4 Displacement vectors corresponding to Fig. 7.12.

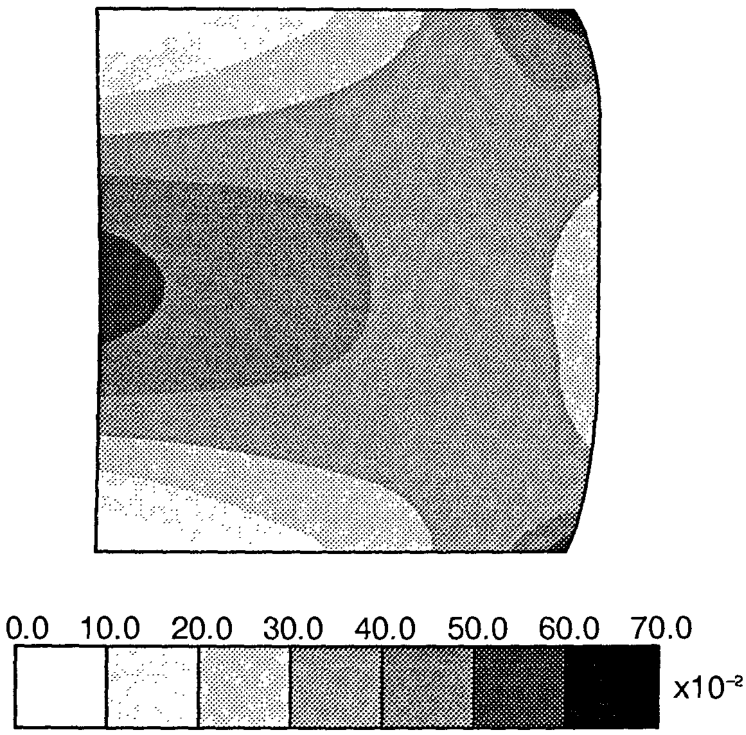

Fig. D.5 Generalised plastic strain corresponding to Fig. 7.12.

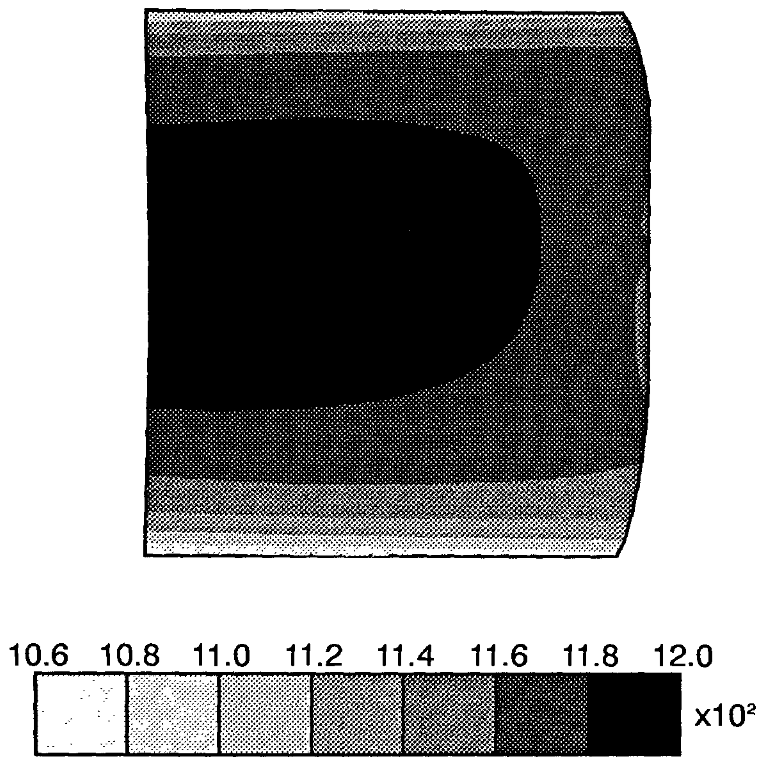

Fig. D.6 Absolute temperature (K) contours corresponding to Fig. 7.12.

Appendix E

Publications

(1) M. Bakhshi–Jooybari, I. Pillinger and T. A. Dean

'Development of an Intelligent Knowledge–Based System (IKBS) for Forging Die Design'

Proc. 5th Int. Conference on Metal Forming, the University of Birmingham, UK, Eds. P. Hartley, *et al.*, pp. 689–694 (1994).

(2) M. Bakhshi–Jooybari, I. Pillinger, T. A. Dean and P. Hartley

'Development of Product and Process Comparison Criteria in an Intelligent Knowledge–Based System for Forging Die Design'

Submitted to the Institution of Mechanical Engineers.

ELSEVIER J. Mater. Process. Technol. 45 (1994) 689–694

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Development of an Intelligent Knowledge–Based System (IKBS) for Forging Die Design

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This paper describes some of the research being carried out to complete an IKBS for Forging Die Design which is under development at the University of Birmingham. It deals with integration of the IKBS with an FE simulation program, the experimental work performed to establish comparison criteria and the creation of the IKBS database.

1. INTRODUCTION

The design of forging tools has been the topic of a large amount of research in recent years. A major advance in this area has been the application of computer techniques, among which Computer–Aided Design (CAD) has had a significant impact, such as [1] and [2]. To decrease the amount of experimentation required for the application and validation of CAD software, another category of computer aids has been developed. This consists of techniques for process simulation, among which the finite–element method (FEM) has been the most important ([3], [4]). The disadvantage of these techniques is that detailed studies require large amount of computing time which makes them inappropriate for routine use in industry, especially for small and medium–sized companies.

Recent work concerned with closed–die forging has shown a tendency to integrate the use of numerical simulation techniques and CAD programs based on empirical rules in the form of Expert Systems or Intelligent Knowledge–Based Systems (IKBS), such as [5] and [6].

The underlying philosophy of this approach is essentially to use rule–based procedures to design dies, and to resort to computationally–expensive process simulation methods only when there is some uncertainty about the validity of the design rules.

This approach was adopted at the University of Birmingham in developing an Expert System for Upset Forging Die Design [7] which combined the results of many years' research into die design based on empirical guidelines [8] and FE metal forming simulation [9].

This research was carried a stage further by Pillinger *et al* in their initial work on an IKBS for Forging Die Design [10]. The important innovation in this proposal was the recording of all components designed by the system in a computer database which could be subsequently used by the IKBS to determine whether FEM should be employed to analyse the forging sequences for new components.

This paper presents part of the on–going research being carried out by the authors to complete the IKBS for Forging Die Design. Specifically, it describes how the IKBS is integrated with the FE metal forming program, the experimental work that has been performed to identify appropriate criteria for comparison of components and how the IKBS database is constructed.

2. IKBS FOR FORGING DIE DESIGN

The main parts of the IKBS are shown in Fig. 1. These are:

(i) Sequence Design Program (SDP) to design the operational sequences and dies for axisymmetric and 3–D warm and hot forging [11].

Producing a set of design rules which is able to design the proper sequences or preforms for all forging components is not practical, because in the production of a specific component, a die sequence frequently reflects very specific attributes of the components. So, the components which can be specified to the SDP have been divided into five different families, namely Stub Axles, Drive Flanges, Gear Blanks, Bevel Pinions and Non–axisymmetric Components (especially Connecting Rods and Lower Arms) [11].

(ii) Finite–element pre–processor to initiate FE simulation. The finite–element program for simulation is EPFEP3* (Elastic–Plastic Finite–Element Program for 3 dimensions) [9]. This part of the IKBS should create a datafile for EPFEP3 and perform any necessary job–control tasks.

(iii) Control Module (CM) to supervise the two other parts and to provide other activities of the system such as access to the IKBS database.

Some other parts of the system which are not shown in the figure are the graphical interfaces for input of data (Interactive MODCON) and output of data (SDPLOT) associates with the SDP [11] and a set of databases including the IKBS database, SDP database and CAD database.

3. INTEGRATING WITH THE EPFEP3 PROGRAM

In creating the EPFEP3 datafile, it is necessary to obtain the geometric data of a particular preform, use

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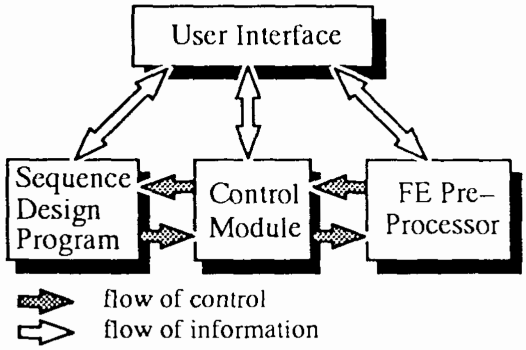

Fig. 1 The main parts of the IKBS for Forging Die Design [10].

this to generate the mesh, define the boundary conditions using the corresponding product geometry and complete the datafile according to the other information stored in the SDP database, such as the nature of the workpiece material and the preform temperature.

Of the five families of components in the SDP, the present work is confined to Stub Axles, although the general principles resulting from this research will be applicable to all five families of components. The operational sequences for a typical Stub Axle are shown in Fig. 2.

Among the stages of the Stub Axles, the 'machined' part is not considered as a metal forming stage. So, the different forming stages are producing the:
(i) 'cheese' from the 'billet'
(ii) 'preform' from the 'cheese'
(iii) 'finished' from the 'preform'

In mesh generation of the 'preform' for stage (iii), since it has a complex shape, the user must define the number of elements along each half cross-sectional curve. This means the process of mesh generation needs to be interactive, with the half cross-section of the preform displayed on the screen, to allow the user to define the number of elements for each specified curve. To this end, the I-DEAS commercial package (SDRC software, version 4.1) [12] which has the necessary interactive capability and mesh generation facilities was chosen as the means of producing the FE meshes for EPFEP3.

Fig. 3 shows the process of producing the EPFEP3 datafile. This procedure has two distinct steps:

1. Transferring the data of the preform from the SDP database to I-DEAS to generate the mesh. In order that the user may interact with the mesh generation facilities, this is done by creating a program file of I-DEAS commands using the built-in scripting language (Ideal). The user then invokes I-DEAS and runs the program file. What he/she should do will be displayed on the screen during the execution of the program file. When the execution has finished, an I-DEAS universal

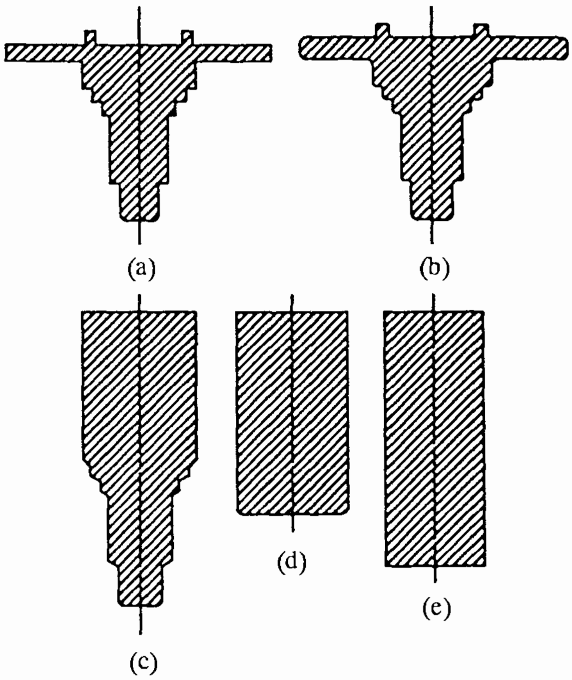

Fig. 2 The operational sequences for a Stub Axle
(a) Machined part (b) Finished part
(c) Preform (d) Cheese (e) Billet.

file will be automatically produced containing the definitions of the nodes and elements in the mesh and I-DEAS will be exited by the program file.

2. After the mesh has been generated, the information in the universal file is converted into EPFEP3 format and the description of the product and the other information is added from the SDP database to produce the FE datafile.

An example of the modelling of the 'preform' to 'finished' stage of a Stub Axle is shown in Fig. 4. The outline of the 'preform' is shown before the generation of the mesh. The various tools are the ones the SDP has proposed after this particular stage of the sequence. The initial position of the tools is determined by reference to the shape of the 'preform'. The motion of the punch is calculated using the initial position, and the height of the 'finished' product. Other information required to perform the FE simulation, such as material properties and tool frictional conditions, is obtained from values stored in the SDP database.

4. DEVELOPING CRITERIA FOR COMPARISON

4.1. Comparison procedure

In the IKBS, when a new component is considered by the system, each forming stage of the component

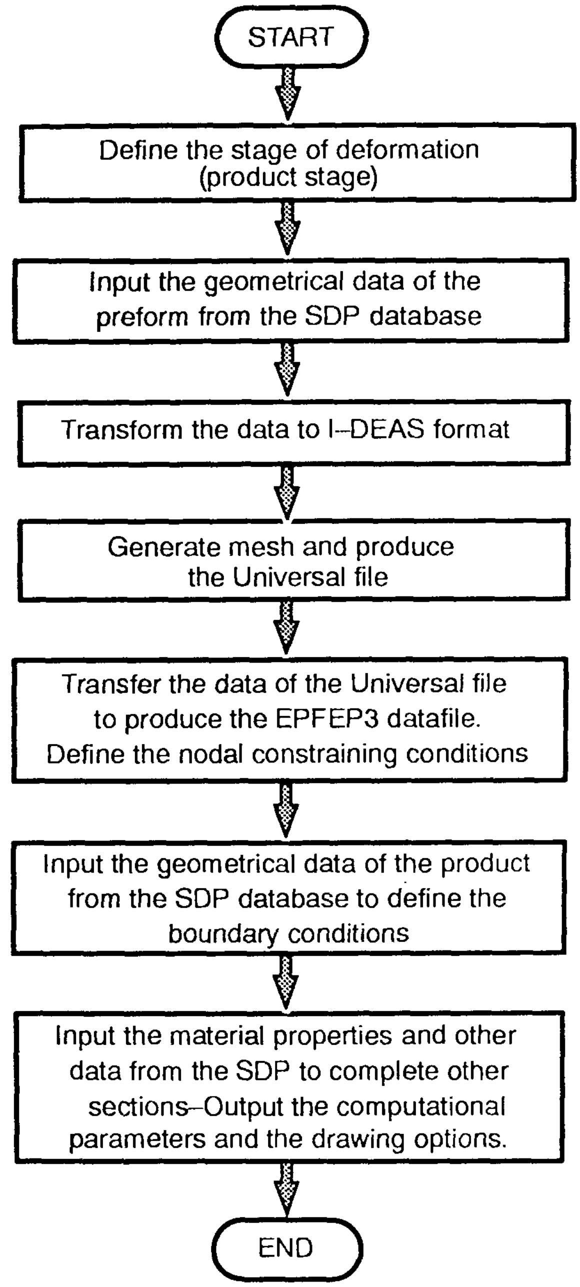

Fig. 3 The process of producing the EPFEP3 datafile.

should be compared to previously encountered examples of the same stage of the same family of components. The aim of comparing the forging stages can be stated as follows:

'To verify the results of empirical rules in the design of sequences/dies by using the knowledge stored in the knowledge–base without using directly, either experiments or FE simulation techniques.'

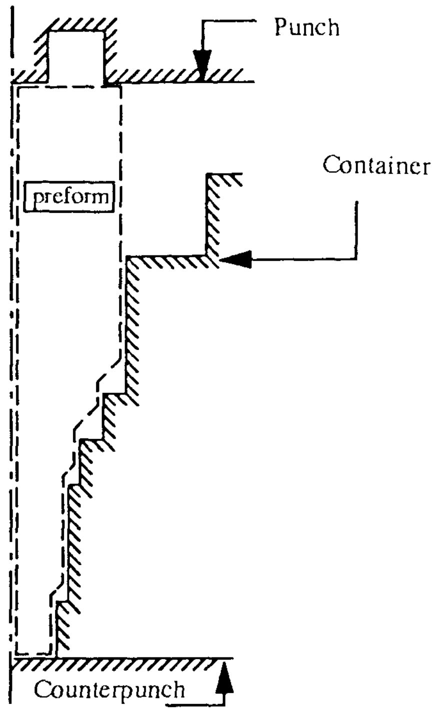

Fig. 4 Schematic illustration of producing the 'finished' part from the 'preform'.

Thus, if the previous instances in the knowledge–base indicate that the example component stage can be produced successfully (or unsuccessfully) and the current stage is sufficiently similar to the previous ones, then it is very likely that the current stage can be produced successfully (or unsuccessfully).

In comparing a stage of a new component with previously encountered ones, two indicators are defined [10]:

(i) A Success Indicator (S): This number indicates whether the designed stage is satisfactory or not. It varies between +1 (satisfactory) and –1 (unsatisfactory).

(ii) A Confidence Indicator (C): This number indicates how strongly the information stored in the IKBS database supports the Success Indicator. It varies between 1 (complete certainty in the value of S) and 0 (complete uncertainty in the value of S). When the current stage is completely similar to a previously encountered component stage in the IKBS database, the S indicator is +1 (the previous stage, and thus the current one, is successful) or –1 (the previous stage, and thus the current one, is unsuccessful).

In the IKBS the process of comparing the stages is based on the following equations:

$$d_i = \left(\sum_{j=1}^{n} w_j \left(P_{ij} - P_{mj}\right)^2 \right)^{\frac{1}{2}} \qquad (1)$$

$$S_m = \frac{\sum_{i=1}^{m-1} \frac{C_i}{d_i} S_i}{\sum_{i=1}^{m-1} \frac{C_i}{d_i}} \qquad (2)$$

$$C_m = \frac{C_k}{1 + d_k} \qquad (3)$$

In which:

- i : denotes the instance of the component stage in the database for which the Success Indicator is not null (between 1 and m–1)
- d_i : the distance in the metric space between the mapping of the current stage and the mapping of the stored instance i
- m : indicates the number of the current instance
- j : the geometrical or process parameter number
- P_{ij} : the value of the jth geometrical or process parameter of the stored instance i
- w_j : the weighting effect of each parameter j (a constant number)
- S : Success Indicator
- C : Confidence Indicator
- k : denotes the previous instance of the current stage which is most similar to the current one (i.e. has smallest value of d_i)

Thus, in comparing the stages, what is needed is to identify which parameters are significant and to quantify their significance in terms of the corresponding weighting factors.

4.2. Obtaining the weighting effects of significant parameters

For simplicity, the following discussion relates to the stage in which the 'cheese' is formed from the 'billet'. This is a closed–die upsetting operation. The experimental procedure for other stages will be analogous.

The significant processing parameters which are common in the different stages of deformation and are considered in the present research are: frictional conditions, preheat temperature, type of material and strain rate (type of machine). The geometrical parameters which are important for the stage under consideration are: upset ratio as a preform parameter, corner radius and final ratio (height/diameter) of the 'cheese' as product parameters and the actual dimensions of the preform and the product. It should be pointed out that some of the processing parameters, such as the accuracy of billet location in a die, cannot be controlled by the user or be assigned a value during the running of a sequence design program. Therefore, these parameters can be assumed the same in specific stages of all production sequences and are not considered in the current investigation.

In order to assess the significance of the selected parameters an indicator must be found on which the effects of different parameters can be investigated. This indicator should be a quantitative variable. There are several quantitative variables which may be used in this relation, but it is much better to consider a variable which is fast, easy and accurate to measure. Such a quantitative variable could be the maximum forging load or average pressure. Since the maximum load is proportional to the cheese area, it is not suitable as an index spanning different die–sets and therefore the average pressure was used.

4.3. Experimentation

Different types of tests have been carried out to investigate the weighting effects of the significant parameters in the closed–die upsetting of 'billet' to produce a 'cheese' [13]. Fig. 5 is a schematic of the general arrangement of the die–sets used for the tests performed. It consists essentially of a punch, container, anvil (counterpunch), bolster, ejector and also punch and container clamp rings and load–cell (not shown).

As an example, different billets with the same volume have been used to investigate the weighting effect of upset ratio as a geometrical preform parameter. The dimensions of the billets are shown in table 1 and the cheese diameter was 41 mm. The other data are:

(i) Type of material: BS 080 M40 (EN 8) (with chemical composition of 0.442% C, 0.175% Si, 0.555% Mn, 0.011% P and 0.025% S)

(ii) Billet preheat temperature: 900 °C

(iii) Lubricant: graphite–based diluted in water was applied to the tools and all the surfaces of the billets. This is normal lubrication for warm and hot forging.

(iv) Strain rate (forging machine): A 2000 KN mechanical press with a strain rate of 13 s^{-1} (at the middle of deformation) was used.

(v) Die preheat temperature: 80 °C

4.4. Results and discussion

As the experiments investigated a closed–die process, the final load was an indeterminate quantity because it was very difficult to identify the stage at which a die cavity was just completely filled. Instead, the load for 2% unfilled die cavity was measured, interpolated or extrapolated from the load–displacement trace and

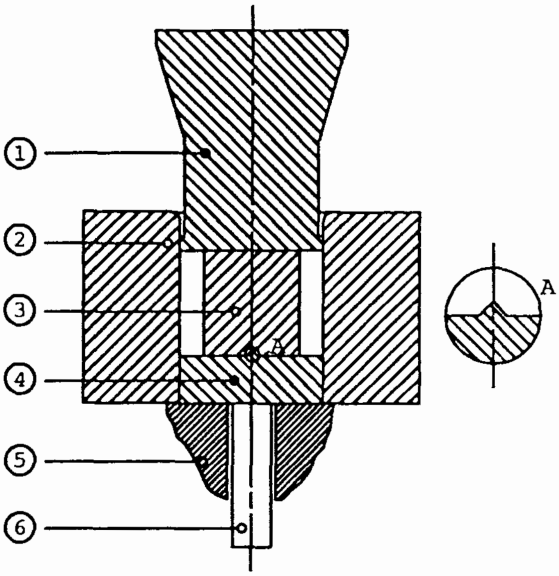

Fig. 5 Schematic illustration of the die–sets of closed–die upsetting (producing the 'cheese' from the 'billet'

1–Punch 2–Die insert (Container) 3–Billet 4–Anvil (Counterpunch) 5–Bolster 6–Ejector.

Table 1
The dimensions of the billets used.

No.	Diameter (mm)	Height (mm)	Upset–ratio
1	34	29.7	0.87
2	32	33.5	1.05
3	30	38.1	1.27
4	28	43.7	1.56
5	26	50.7	1.95

divided by the plan area of the 'cheese' to produce an average pressure. The variation of this average pressure with upset ratio is plotted in Fig. 6 [13].

In completely closed–die forging there are two main stages of deformation. The first stage relates to the deformation before contact with the die walls (free upsetting) and the second stage relates to when the corners are being filled.

As can be seen from figure 6, changes in upset ratio affect average forging pressure. This might be due to two reasons. In the stage of free upsetting as the upset ratio is increased the load required to deform the billets decreases. Secondly, in the stage of corner filling the different shapes of corners which could produce the same unfilled corner volume, influenced the forging load [13].

The fitted curve and the corresponding equation are also shown in the figure. This equation can be used to find the weighting effect of upset ratio by considering the values of the upset ratio of the current and the stored instances.

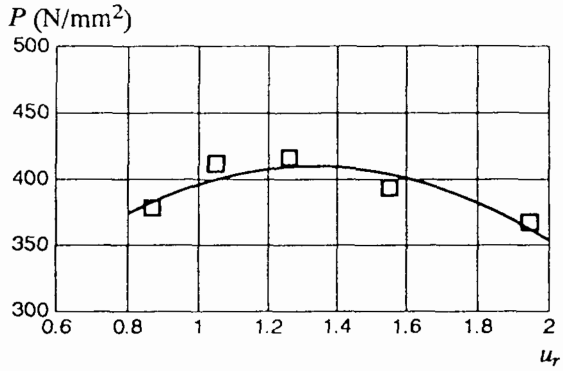

Fig. 6 Variation of average pressure with upset ratio for 2% unfilled die cavity (cheese diameter=41 mm)

Fitted equation:

$$P(u_r) = 186 + 338\ u_r - 127\ u_r^2$$

In which:

P : Average pressure (N/mm^2)

u_r : Upset ratio.

Among the geometrical parameters considered, the corner radius and among the process parameters, the billet preheat temperature have more relative importance, the details of which can be found elsewhere [13].

5. CREATING THE IKBS DATABASE

The IKBS Control Module was written in Common LISP, as this simplified the manipulation of complex data structures. The IKBS database itself is therefore in the form of a LISP list [10].

Since the components which can be considered by the SDP are divided into five different families with different design rules, a separate list is maintained for each family. At the highest level each of these is a list of the data of the components which have been examined by the system for the specific family. At a deeper level, the structure is more complicated because each stage of the forging sequence for the specified family may have more than one instance, each having a different preform and/or different processing condition.

Therefore, the list structure must accomodate the potential of repeated branching.

Thus, in the IKBS when the forging stages are being designed or modified, the required data will be extracted from the SDP database and be stored as LISP lists in the IKBS database. Fig. 7 shows an example of such a database.

```
((sa  ((123 "Stub Axle No. 1")
        (fin (((0.5  0.8  4.0  1200)
              (0 0 "")
              (prf  (((0.4  1.0  4.5  1300)
                    (1  1  "")
                    (chs  (((0.4  1.5  5.0  1300)
                           (1  1  "")
                           (bil  (((0.5  2.0  1350)
                                  (1  1  ""))))))))))))))
(df  nil)
(gb  nil)
(bp  nil)
(na  nil))
```

Fig. 7 A simple example of the IKBS database
(sa: Stub Axle, df: Drive Flange, gb: Gear Blank, bp: Bevel Pinion, na: Non-axisymmetric, fin: 'finished part', prf: 'preform', chs: 'cheese' and bil: 'billet').

The list of numbers in the line of a stage describes the values of the significant parameters and the list in the next line describes the values of Success Indicator and Confidence Indicator and any existing comment when the result is unsuccessful.

6. FUTURE PROSPECTS

Although some parts of the IKBS for Forging Die Design have been developed, there is a lot of work that needs to be accomplished in the future, particularly:

(i) Interpretation of the experimental results obtained for the weighting effects of the different parameters and putting them into the comparison algorithm.

(ii) Extending the experimental method to the two other stages of deformation of Stub Axles.

(iii) Self-learning of knowledge and giving recommendations to modify the corresponding preform when the results of comparison is unsuccessful.

7. CONCLUSIONS

This paper has reported on work that has been carried out to develop an IKBS for Forging Die Design. It has shown how FE simulation datafiles may be produced semi-automatically by extracting the stored description of the preform geometry and using a commercial mesh generation software.

A new experimental approach has been described for assessing the significance of various geometric and process parameters in the comparison of different instances of a forming stage. This paper has also discussed how the IKBS creates and manages its database of previously encountered examples.

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