AN EXPERT SYSTEM FOR NEAR NET SHAPE AXISYMMETRIC FORGING DIE DESIGN

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By

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ABSTRACT

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In this thesis, the application of rule base expert system to the near net shape axisymmetric forging die design, and development of a knowledge base for it, is carried out.

The developed system is aimed to cover the design of forging dies for axisymmetric parts and meet them with the power of expert system. This package has a modular structure and has been undertaken in the four main chapters. Firstly, the drawing file of a final product, taken from AutoCAD, is converted into DXF format and it is integrated with the system by means of feature recognition module. After the recognition of input geometry of the product, checking that whether it is forgeable in closed die or not forms the second step. In the third stage, the required forging load is calculated so as to fill the die cavity completely. The power and energy requirements for making the finished forging are also determined at this stage. Die stress calculation and die shape determination come after this process as a fourth chapter. In this chapter, amount of thermal shrinkage due to temperature difference and elastic expansion between workpiece and die is taken into account.

The main contribution of this thesis is the realisation of forging die design for not only specific industrial parts but also all axisymmetric components. For this purpose, an expert system application is developed for the recognition of product geometry, forging load calculation and the determination of die dimensions.

This study has knowledge base structure in general and rule base in particular. In the program special inference engine has been developed. The developed expert system is written in Borland C++ language by using lots of database and SQL (Structured Query Language) facilities.

Key Words: Expert System, Axisymmetric Forging, Die Design, Near Net Shape Forging

ÖZ

NETE YAKIN ŞEKİLLİ EKSENEL SİMETRİK DÖVME KALIPLARININ TASARIMI İÇİN BİR UZMAN SİSTEM

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Bu tezde, nete yakın şekilli eksenel simetrik dövme kalıplarının tasarımı ve bunun için bir bilgi tabanının oluşturulması amacıyla kural tabanlı bir uzman sistem uygulaması gerçekleştirilmiştir.

Geliştirilen sistem, eksenel simetrik parçaların dövme kalıplarının tasarımını ve bunların bir uzman sistemin gücü ile tanıştırılmasını amaçlamaktadır. Bu paket modüler bir yapıya sahip olup dört ana bölümden oluşmaktadır. İlk olarak, AutoCAD'ten alınan ürünün son haline ait çizim dosyası, DXF formatına dönüştürülmekte ve unsur algılama modülü ile sisteme entegre edilmektedir. Ürün geometrisinin algılanmasından sonra bunun kapalı kalıpta dövülebilirliğinin kontrolü ikinci adımı oluşturmaktadır. Üçüncü adımda, kalıp boşluğunun tamamen doldurulabilmesi için gerekli dövme yükü hesaplanmaktadır. Dövme işleminin tamamlanması için güç ve enerji gereksinimi yine bu bölümde hesaplanmaktadır. Kalıptaki mukavemet hesabı ve kalıp şeklinin belirlenmesi ise dördüncü bölümü oluşturmaktadır. Bu bölümde, iş parçası ile kalıp arasındaki sıcaklık ve elastisite farkından dolayı meydana gelen değişimler ele alınmaktadır.

Bu çalışma ile sadece belirli endüstriyel parçaların değil eksenel simetrik tüm parçaların dövme kalıplarının tasarımı gerçekleştirilmektedir. Bu amaçla ürün geometrisinin algılanması, dövme yükünün hesabı ve kalıp ölçülerinin belirlenmesi gibi parametreler için bir uzman sistem uygulaması geliştirilmiştir.

Bu çalışma genelde bilgi tabanlı, özelde ise kural tabanlı bir yapıya sahiptir. Programda özel bir çıkarım mekanizması hazırlanmıştır. Geliştirilen uzman sistem, Borland C++ dilinde pek çok veritabanı ve SQL imkanlarından yararlanılarak yazılmıştır.

Anahtar Kelimeler: Uzman Sistem, Eksenel Dövme, Kalıp Tasarımı, Nete Yakın Şekilli Dövmecilik.

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This work is dedicated to the memory of;

My wife **Sema,**

My sons **Furkan** and **Hakan,**

My mother **Gülten,**

My father **Muhsin,**

My brothers **İbrahim** and **Ali İrfan,**

My sisters **Nilüfer** and **Ayşe**

And all others in my family.

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

In this chapter, the place of forging in metal forming processes and reason to use expert system is explained. Purpose and domain of the thesis and the organisation of the chapters are outlined.

1.2. GENERAL FORGING PRACTICE in METAL FORMING

Many manufacturing enterprises are continually improving their strategic competitive advantages with flexibility and cost effectiveness to remain competitive in a changing world economy. They must have the flexibility to produce a variety of high quality products, which are cost effective to meet the changing needs of the consumers in many market-oriented societies. To do so, companies are adopting new strategies to meet the challenges of changing technologies; shorter product life cycles and globalisation of manufacturing operations [1]. The economical benefits of a final product depend very much on a successful choice of the basic production method. Earlier it was very common to see that an assembled product was produced by casting, welding, machining, etc.

The development in metal forming area brings new technologies together and forces the existing methods to become more efficient. In this manner forging, although the oldest metal forming process, has recently become one of the competitive technologies in manufacturing. Material costs are an important fraction of the total cost of forging and any reduction in material waste during operation has a direct effect on the price of the finished product. In order to improve the productivity of forging at low production cost, an integrated system approach is necessary in handling the material preparation and the optimum process design considering the forming machines, tooling and operation [3].

The forging process is fundamentally the deformation of metal under pressure or impact to produce a desired shape. This controlled deformation assures the elimination of internal gas pockets or voids and results in greater metallurgical behaviours and improvement of mechanical properties.

Forging is better suited for many applications than cast materials, due to their greater strength and ductility in a given material, as well as greater soundness, uniformity in chemistry and finer grain size. Forging products are not subject to change in state or volume as are casting during solidification. Forged components are more reliable than parts machined from bar stock or plate; because properly developed grain flow in forgings closely follows the outline of components [13].

Today's trend toward higher speeds and greater loads in many types of mechanical equipment is leading to the recognition by designers and mechanical engineers of the increasing importance to impact and fatigue, as a portion of total component reliability. Forged products meet those requirements and they are specified where strength, reliability, economy, and resistance to shock and fatigue are vital considerations. The optimisation criteria may vary, depending on product requirements, but establishing an appropriate criterion requires through understanding of manufacturing processes. In metal forming technology, proper design and control requires the determination of deformation mechanics involved in the processes.

In view of the increasing globalisation of raw materials and sales markets, productivity and production costs represent ever more important criteria for a company's competitiveness. Today and in the near feature the investment in equipment for the different basic production methods is and will be so high that the numbers of basic technologies must be reduced as much as possible [2]. For this purpose, an advanced production system called IMS (Intelligent Manufacturing System) is oriented towards the needs of the 21st Century and designed to maintain and improve the validity of manufacturing sector.

In net shape forging, a given material of a simple geometry is transformed under controlled application of energy into useful component. The net shape forged components may only need little or no finishing, thus reducing the manufacturing cost. Forging operation comprises all the process input variables such as billet material, dies, the conditions at the die-workpiece interface, the mechanics of shape change in the workzone, and the characteristics of the processing equipment, as illustrated in Figure 1.1.

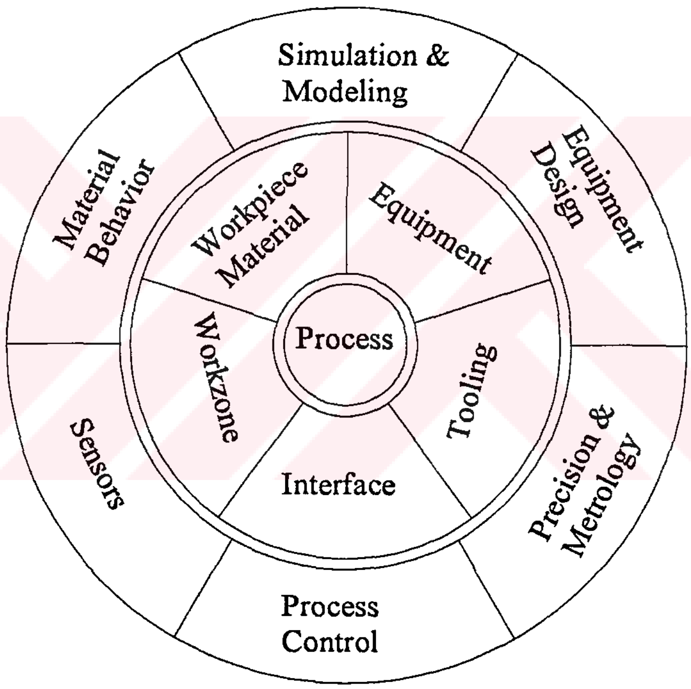


Figure 1.1 Variables of Forming Processes [14]

In closed die forging, dies are moved toward each other to form a metal billet, at a suitable temperature, in a shape determined by the die impressions. The main objective of forging process is to ensure adequate flow of the metal in the dies so that the desired finished part geometry can be obtained without defects and with prescribed properties [15]

Recent years the introduction of techniques that result in minimal material wastage have seen. These are usually referred to as flashless, or in other name it is net shape forging. Since the die cavity is filled completely, material is not allowed to form flash by keeping the billet volume and the die cavity volume equal. On the other hand, the power of artificial intelligence technique is almost necessary for forging operations, since forging is a field in which expert systems can be effectively applied. It depends on rules derived from the past experience of forging die design engineers and production engineers. Therefore, there is an advantage in using expert systems for forging applications.

1.3. THE REASON FOR USING EXPERT SYSTEM TO FORGING

There are many programming and system design languages being used or that are still under development. Artificial Intelligence tools such as expert system, neural network, fuzzy logic and etc. play an important role in this area. During the past decade there has been great interest in the field known as expert systems or, alternatively known, knowledge based systems.

Expert systems generally mean systems that can make use of expert-like knowledge by searching as necessary for technological knowledge accumulated in the past. The employment of these systems has now begun in the field of forging as well. Additionally, it can be said that, forging is a field in which expert systems can be effectively applied, particularly because a large part of this field depends on rules derived from the past experience of forging die design engineers and production engineers [5].

Traditionally, since there isn't enough analytical method available for the design of forging dies, which currently relies mainly on experience forging is done by the experienced forging designers using empirical forging guidelines [17]. Throughout the years, a great deal of knowhow and experience has been accumulated in the form of design guidelines for designing forgings.

The power of Artificial Intelligence (AI) tools (like Expert Systems, Neural Networks, Genetic Algorithms, Fuzzy Logic) on the planning of manufacturing processes has been proven by recent research projects and actual implementations. There are numerous packages being developed for almost any manufacturing activity. At this present time, however, it is not known how many of these systems are practical and are being used. For example, most of the software for operations planning has led to the development of large and complex application packages, which are too rigid when manufacturing variables, are included.

The methods for acquiring knowledge from experts to develop expert systems are not very well understood. They usually contain several thousand rules and are huge software systems which are difficult to use on conventional computer systems. There are only a few qualified expert people available who really know how to apply AI tools. These problems can be solved by using or developing right tools, methods and environments [16]. Based on the recent developments in computer technology, the application of computers has been growing rapidly in the area of CAD/CAM (Computer Aided Design/ Computer Aided Manufacturing), CAPP (Computer Aided Process Planning), and numerical simulations of manufacturing processes using numerical techniques. The latest trend of research into automated process planning involves the use of expert system [1, 4].

The forging process can greatly reduce material waste, ensure good surface finish and tolerances in the manufacture of engineering components. For its full potential to be realised, the assistance of experienced process planning engineers is essential in the product design stage in design for forging, and in the pre-production stage when they are needed to establish the sequence of operations and be responsible for tooling and other equipment. Expert systems could be of great value in this application, by making the knowledge of the human expert more easily accessible and widely available [17].

Additionally, due to the development of knowledge treatment techniques, knowledge based manufacturing systems have become popular, based on qualitative and ambiguous human experiences. In these systems expert system [6], neural network or fuzzy theory [7] are used with the help of the operator's skill. It is widely known that the expert system has emerged as one of the most active and powerful area for research in the application of human knowledge for problems which do not lend themselves to solution by conventional methods. Expert system can therefore provide a flexible, intelligent solution to the kind of problem involving complex logic which occurs in engineering; automatic generation of sequence of design for forging being a good example.

1.4. PURPOSE AND DOMAIN OF THE THESIS

The main objective of this thesis is the application of an expert system to the near net shape axisymmetric forging die design, and development of a knowledge base for it.

Some researchers have investigated different approximate methods to improve the forging of axisymmetric and axisymmetric like parts [8, 9,10]. But, very little effort has been focused on the development of methods to improve and generalise the near net shape axisymmetric forging die design and application of it to one of the artificial intelligent technique. In this case, the use of numerical simulation and physical modelling techniques are necessary to be able to predict the accuracy of the forged part, when the final dimensions of the die components are specified. Hence, the designer has to transfer that information to the CAD program and use experience to produce the best design in his/her own judgement. The ideal procedure for axisymmetric forging die design is shown in Figure 1.2.

The biggest drawback in the manufacture of precision forging in the early years of development was the high cost of forge tooling, mainly related to die cavity production and the short die life expectancy. Recent developments in materials, surface treatments, lubrication, workpiece heating, as well as the application of CAD/CAM, have significantly affected forging design technology, die life and cost [11]. Nowadays, since artificial intelligent techniques are playing an important role in metal deformation [3, 12], it is necessary to meet metal deformation techniques with one of the intelligent system. Therefore, in this thesis an expert system, which is the most suitable artificial intelligence tool for near net shape axisymmetric forging die design [5, 17, 18, 19, 20], will be developed.

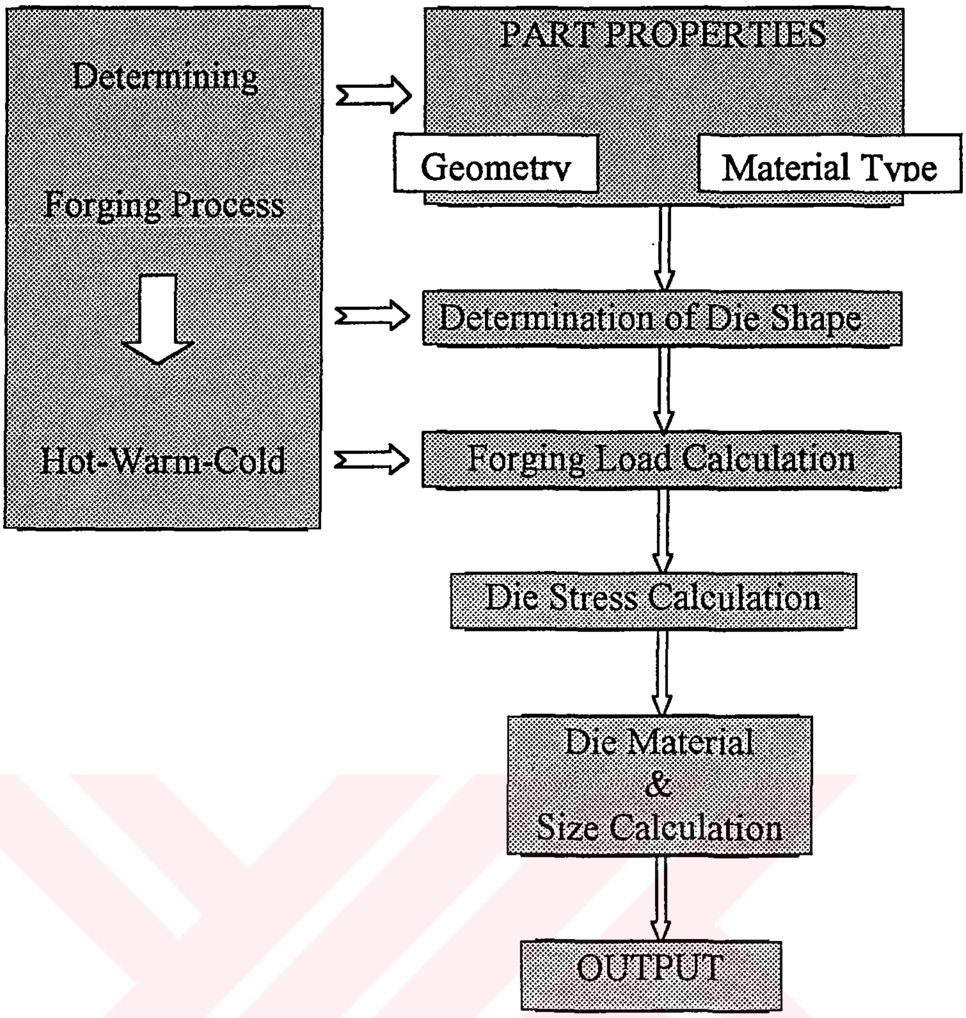


Figure 1.2. Die Design Process

The first procedure for die design is the geometry recognition. The input product geometry is converted into the forgeable geometry to facilitate the forging process and then the die cavity dimensions are determined. In the determination of die shape, the amount of thermal shrinkage due to temperature difference between the workpiece and die, elastic die expansion and elastic recovery of the workpiece should be evaluated. Forging load and die stress calculations come after this procedures.

Significant differences from the previous studies are the use of CAD database from AutoCAD and the application of an expert system in developing a knowledge based program incorporating manufacturing logic to generate process plans.

Based on the discussion above, it is concluded that the development of an expert system is necessary to improve the die design for forging of axisymmetric components. The design procedure will be formed by the rule based structure. Therefore, the main objectives of the present study can be expressed by the followings:

1. Development of a geometry definition and feature recognition system
2. Determination of forgeable geometry for axisymmetric components.
3. Determination of die cavity for final product.
4. Selection of an appropriate of tool and die materials.
5. Calculation of forging load and stress in die.
6. Determination of die size.
7. Preparation of an expert system, which can satisfy the above stated objectives.

The developed system has knowledge base structure in general and rule base structure in particular. This expert system has it's own inference engine and written in Borland C++ language, which is designed to run on IBM compatible PC computers.

1.5. ORGANISATION OF THE THESIS

In this thesis, the near net shape forging die design is criticised in respect of product geometry, forging process and die design considerations. Furthermore, a rule based expert system is developed for the fulfilment of the determination of process parameters. The developed system consists of a knowledge base for:

- Feature recognition module based on DXF standards by interfacing between CAD and CAPP.
- Determination and elimination of undercuts in product.
- Material data base
- Material flow properties under forging conditions and lubrication
- Essentials for upper bound elemental technique (UBET)

- Stress calculation in die
- Parting line
- Punch and die design.

The expert system, which is developed, has a modular structure. For each of the module, rule based knowledge is structured. By this way, optimum die cavity size, forging load and stress calculations are going to be possible for axisymmetric forging operations.

The following chapter, Chapter 2, denotes the most related works on axisymmetric forging, expert system applications on forging, Upper Bound approach for load calculation and stress calculation.

Chapter 3 presents the general knowledge on Artificial Intelligence tools. But, Expert System methodology is mentioned in detail. Knowledge acquisition and framework of the system are expressed.

Chapter 4 explains the fundamentals of forging processes and forging parameters such as, workpiece, tooling and etc.

After Chapter 4, chapters are organised in modular structure and undertaken in four chapters.

Chapter 5 gives an outline of DXF standard and integration with the system by means of feature recognition.

Chapter 6 expresses the geometry considerations. In this chapter, geometry is checked whether it is forgeable in closed die or not by new generated coding system.

Chapter 7 involves the forging load and energy estimation methods. Particularly Upper Bound Elemental Technique, which is the most suitable one for axisymmetric components, is put into perspective. All mathematical formulae and expressions are also presented in this chapter.

Chapter 8 expresses the die stress and geometry correction calculations. This chapter also covers the final die shape criteria.

Chapter 9 is devoted for execution of the prepared computer program. Capabilities and facilities of the program for users are presented in detail.

Chapter 10 discusses the present work and concludes the achieved results.

CHAPTER 2

LITERATURE SURVEY

2.1. INTRODUCTION

In this chapter the most relevant studies, which are presented in different papers and books, are outlined. Since forging and expert systems have wide range of application, there are many studies such as geometry definition, billet material, forgeable geometry, forging load and stresses in die. CAD/CAM integration works are also outlined briefly.

2.2. LITERATURE ON "FORGING PROCESSES"

The increasing worldwide interest in the production of forging products lead to researchers to study on forging technology.

Net shape forming processes have special place in forging and it is one of the most important goals for metal forming technology to achieve due to its economical benefits.

Kudo [50] put into perspective the net shape forging in 1990's. He analysed examples of how imprecision in the quality of the formed parts are effected by what elements or sources, such as the geometrical, mechanical or chemical properties of the material, billet or blank, the lubricant, the tool machine, the design of the as-formed product, the plan and practice of the operational sequence. The net shape product are then described for each element mentioned above, by showing practical examples.

Cold forging in small quantity production is described and compared with high quantity production by Maegaard [51]. The demands on integrated product development and process tool design for cold forging of near net shape, NNS, and net shape, NS, components were analysed in the light of an inductive tool design philosophy the finite element.

Chu and Lee presented thinning algorithm for design analysis of near net shape products. The geometry was digitised and skeleton line of the geometry was extracted [52]. The skeleton model and its application to casting and forging design analysis were constructed.

Sensitivity analysis based preform die shape design for near net shape forging is developed by Zhao et al [53] using the viscoplastic finite element method (FEM). The method developed in this study was used to design the preform die shape design of H-shaped forging processes including both plane strain and axisymmetric deformations.

The demands for automobile industries have spearheaded the development of complex precision cold forging of steel. The trend is still continuing toward sophisticated near net shapes thus required. Onodera and Sawai studied on precision cold forging of complex automobile parts and presented some features of manufacturing sequences of near net shape products [43, 44]

Kim and Altan [45] studied to reduce the design cycle time in product and sequences design for cold forgings. They generated FORMEX for forming sequences and DEFORM were conducted in order to evaluate one of the sequences designed by FORMEX to utilise and demonstrate the capabilities of finite element simulations for forged parts.

Nakano, described complex forming and multi-action forming, both being useful means for achieving net-shape forming [47]. Rodiger et al. [54] used near net shaping in hardmetal industry. They focused on the powder shaping methods used mostly commonly in the hardmetal industry.

In some cases researchers preferred to use precision forging as a term, instead of net or near net shape forging. Doege et. al [55] presented a tool system to improve the exactness of the machine tool system substantially by compensating the system dimensions which are dependent on the temperature by means of computer aided adjustment of the guidance. By using methods of quality control which are inevitable for the quality of the process as well as of the product in precision forging.

Lange [56] described the complex structure of the cold forging process with a variety of interfaces between material, tool, machine tool and automation, etc., under the aspect of the requirements for precision cold forging.

On the basis of the practical situation of cold forging process planning, the disadvantages of a rule based solution were discussed and a case based reasoning based cold forging process planning system model were proposed by Lei et. al., [119].

An experimental study of the internal deformations generated during a precision closed die, isothermal forging was carried out by Majerus et. al [57]. On the other hand, Osakada et. al. [58, 59] proposed a method in two different paper employing an axially driven container to reduce the forming pressure of precision forging to a feasible level. In this method, a movable container, which is axially driven by an actuator while the billet is squeezed by the punch, was employed.

Cold and warm forging applications were discussed by many researchers. Pale et. al [60] investigated cold forming tooling, machines and processing. Hirschvogel and Dommelen [61] made some comparison between various manufacturing methods and discussed some economical aspects regarding the process costs. Development of warm forging technology and some practical examples were given by Sheljaskov [62] .

Siegert et. al. demonstrated the different procedures applied to the precision forming of parts dependent on the specific critical aspects of the process. They gave an examples for the geometrical and thermal layout of the forging process, the influence of material behaviour on the forged part and a procedure for the compensation of the die deflection [46].

2.3. LITERATURE ON "CAD/CAM on FORGING APPLICATIONS"

The last thirty years have seen the development of a wide range of computer programs for computer aided design (CAD) and computer aided manufacture (CAM) in order to improve the effectiveness and economics of each function. The introduction of CAM techniques resulted in the productivity depending on the type of CAM technique introduced. The most effective systems however are those that combine CAD and CAM to form centres for computer integrated manufacture (CIM) and so take advantage of the natural links between the design and the manufacture [35].

A large number of process planning systems have been found in the CAD/CAM literature. They are primarily developed to integrate CAD and CAM using the CAPP and its interfaces as key technologies. Each CAPP system has its own method to generate process plans. Reviews of the systems reported in the literature can be found in one of the numerous survey articles [19, 115].

Process planning systems employed artificial intelligence techniques like expert systems to enhance their capabilities and to improve the level of automation (integration) between CAD and CAM. The use of "features" was first taken into consideration in the design stage. After the features were extensively used in the design stage, the "feature based systems" on the CAD/CAM integration have appeared in the literature. The need for the "feature recognition" was also conceived [16, 21, 22, 23, 24, 25].

Computer-aided technologies are currently being used in metal forming industry. Flaszka et. al. used computer aided forging design for material simulation. They stated that tooling costs, in forging operations, are reduced and lead limes shortened by applying an interactive CAD-system, automating the design process and verifying cavity filling by model materials as a low cost simulation method [26].

Hirai et al. [27] developed an intelligent CAD system for specifying the operation sequence in cold forging. They applied fuzzy theory for an intelligent CAD system which has uncertain factors in human knowledge. Various actual design data about forming method and about selection of the number of operation stages were collected and organised, and these data were applied to the system as the case base.

Kim and Altan, [28] developed computer aided design system for designing parts for cold forging and established the associated process sequence. For metal simulation in cold forging they used finite element method, called FORMEX.

One of the successful study titled by "computer-aided" was carried out by Gokler et. al. [29] They described initial developments on an interactive computer-aided procedure for the design of processing sequence for upset forgings, with the overall aim of reducing the time and effort involved in die design and manufacture.

Eyercioglu and Dean, [30] studied another CAD/CAM application to gear forging dies. They gave possible configurations of precision forging dies for spur and helical gears. Detailed features of the die design and the factors influencing the accuracy of the forged gears are described.

In order to reduce possible failures in process sequence design, a series of works [29, 34, 111, 112, 113, 114] have been reported for developing design assisting environments such as expert systems and CAD/CAM techniques. However, in addition to the intrinsic nature of forging sequence design, complexity in plastic deformation and high correlation between design parameters in different stages have made it difficult to realize process design automation in cold former forging. In this perspective, Im et. al., presented computer aided process design technique, based on a forging simulator and commercial CAD software together with its related design system for the cold former forging. The forging sequence design and its detail design were generated through user computer interaction using templates, design databases, knowledge based rules and some basic laws. The forging simulation technique was used to verify the process design. The detail design, including die set drawings and die manufacturing information were generated [115].

Chul et. al. [120] described research work in developing an automated computer aided process planning system for a hot forging or blanking product by press working. Their integrated computer aided process planning system was composed of two main modules: hot forging and blanking modules. An approach to the computer aided process planing system was based on knowledge based rules and process knowledge base consisting of design rules was built.

2.4. LITERATURE ON "EXPERT SYSTEMS for FORGING PROCESSES"

More recently artificial intelligence (AI) techniques have begun to find applications in engineering. These techniques provide the greatest potential for future developments in CAD, CAM and CIM systems. Within the general AI field the specific areas of relevance here concern knowledge based system and expert systems or use one of them.

The one of early studies was carried out by Balakrishnan and Dwivedi [48]. In the study, various aspect of forging die design was addressed using OPS5, which is a powerful tool in developing knowledge based expert systems. The requirements of a good data base and heuristic rules which help in reaching an optimal design goal for this particular design problems were discussed.

Tisza [116] stated that there are a small number of expert systems applied in metal forming, when compared with other manufacturing fields. The numerous variables involved in metal forming processes make difficult the automation of decision making and planning of these processes, but some examples can be found particularly for multistage processes like cold and hot forging [117, 118].

Kuhn et. al., [49] developed an expert system for net shape forging of axisymmetric shapes. Knowledge bases were developed for design stages, along with control structure that implements an efficient iterative design logic. Finite element method was used in conjunction with a workability analysis.

Wang and Chen [37] presented a structured method (SMKEM) for extracting knowledge in building expert systems for designing precision forging dies. They used Turbo- PROLOG as an expert system shell. Lengyel and Tay [17] also studied expert system in the cold forging of steel. Development of a rule based system for establishing a number of different cold forging sequence of operations for a component carried out by using PROLOG as an expert system shell.

Ferguson et. al., [38] investigated the feasibility of an expert system approach to design of P/M preforms for precision forging. They illustrated the details of implementing an expert design system in a step by step example.

Osakada and Yang [39] applied neural networks to an expert system for cold forging in order to increase the consultation speed and to provide more reliable results. One of another artificial intelligence tool fuzzy logic was used by Biglari et.al [3]. In their study they presented optimisation method for the design of preform die shapes in multistage forging processes using a combination of the backward deformation method and a fuzzy decision making algorithm.

Mori et. al., [40] were studied an expert system for inferring the forging processes in breakdown rolling of H-beams. In this study, knowledge stored in the database for the deformation behaviour was acquired from the finite element simulation of breakdown simulation.

Kim and Im [34], developed an expert system for multi-stage cold forging process design for axisymmetric geometries with or without a hole in one end by using PROLOG language. According to the prescribed geometry they generated the forgeable geometry and the basic process design, depending on the initial billet size and material.

Fujikawa et. al. [42] presented cold and warm forging applications in the automotive industry such as automotive joint parts and gears. Developing technology directed them to artificial intelligence tools. Fujikawa and Ishihara [5] developed an another study by using expert system for use in the forging department of Nissan Motor. They studied automatic design system for forging dies, which can reduce the design costs and shorten the development time of new parts, called "YOURS". The second part of study, which is called "FORDIA", was developed for diagnosing the causes of forging defects.

2.5. LITERATURE ON "UPPER BOUND TECHNIQUE AND GEOMETRY"

Forging design is similar to many mechanical design activities that involve the design of part geometries. Computer Aided Design (CAD) of forging geometry is carried out using interactive graphics [41].

In the field of forging, the product geometry can be defined, in general, by combination of simple patterns. The design rules for the patterns are well established, thus having allowed several expert systems to be developed successfully and used in practice [31, 32]. However, in the field of hot forging, the product geometry is complicated since it is consisted of many curves. Kim and Park [33] developed an expert system to automate the process design of axisymmetric hot steel forging. They designed the geometry of the finisher, blocker, buster, billet and corresponding dies from the geometry of the machined part. They used rule based system written in Fortran and Autolisp and operated in the Autocad environment.

Many researchers have studied on part geometry and forging process conditions. Tang et al., generated AFD (Automated Forging Design) system for which designs the forging section geometry automatically. To simplify the development efforts on the required geometric manipulations, AFD concentrates on the computerisation of the 2D section geometry design for the rib-web type of forgings, forged in closed dies with flash. [36].

One of the earliest study for analytical and experimental studies of axisymmetric forging using upper bound solution was carried out by Kudo [64, 65]. He simplified the analysis of complicated problems and to reduce the labours of calculation, the concept of the unit cylindrical deforming region analogues to the unit rectangular deforming region was used. Similar approach was also studied by many searchers in many years.

As compared to most of the other methods used in the calculation of the forging load for the analysis of axisymmetric forging, upper bound technique is the most appropriate method [63]. In the following, some studies are outlined.

Osman, Bramley and Chobrial used upper bound technique to simulate the bulk flow chracteristics and preform design in closed die axisymmetric forging processes [66]. The technique was performed in an incremental manner. Internal flow inside the cavity was predicted using a velocity field that minimises the rate of energy consumption.

Cser and Ziaja [67] used upper bound technique with easy formalisation of the boundary condition. In their studies the parameters, such as tool's geometry, the preliminary shape of the workpiece and the material properties, which were varied for the direct minimisation of functional describing the increment of total potential energy, were chosen by the system automatically.

Almost in the same dates Kiuchi and Karato [68] applied upper bound technique to non-axisymmetric forging. They declared that, although UBET had been mainly applied in the axisymmetric field, in the non-axisymmetric forging field few analytical studies had been done. In their studies, they made possible to calculate the ultimate filling rate of the die cavity and to anticipate the ultimate shape and dimensions of product.

Walker [69] applied upper bound procedures for plane strain metal forming analysis. He proposed and evaluated a methodology for the discretisation and subsequent optimisation of two-dimensional steady state flow type problems in metal forming.

Oyekanmi et al. [70] presented a comparison between the strain distribution predicted by UBET with those obtained by an experimental metallographic technique. They described an experimental evaluation of strain distributions within a moderately complex axisymmetric forged component, using an established micro-structural evaluation technique. The resultant analysis was then applied to validate the simulated forging and strain distribution obtained by UBET.

Lin and Wang [71] proposed a new upper bound elemental technique approach to axisymmetric metal forming processes to improve the ineffectiveness of UBET for solving forging problems that are geometrically complex or need a forming simulation for predicting the profile of free boundary. By this method, the advantages of the stream function and the finite element method (FEM) were combined. The formulated optimal design problems with constrained conditions were solved by the flexible tolerance method.

Lee et. al. [72] developed an upper bound elemental technique program to analyse the forging load, die cavity filling and effective strain distribution for forgings with and without flash. The simulation program was applied to axisymmetric, plane strain and non-axisymmetric closed die forging with a rib web type cavity. To analyse the process easily, they suggested to divide non-axisymmetric forgings into two parts, these being on the axisymmetric part in corners and a plane-strain part in lateral areas. They made an experimental study to determine the forging load in both axisymmetric and non axisymmetric parts.

Another forging load calculation study was made by Shuqin and Yuan [73]. Both upsetting and complex forming were simulated using plasticine as a model material, evolution process of the holes in the cylinders being observed, principle and the expected results of reducing the forming load of the process being analysed by the theory of plasticity, and the strain distribution of new process being predicted using FEM.

In order to get better metal flow and to achieve complete cavity fill. Osakada [58] has proposed a concept of forging with an axially driven container. The container oscillates after the part has reached the final stroke, although this type of tooling has given good results, its implementation in production might not be economical feasible due to the added costs in tooling and additional time required to fill the corners of the product.

One of final study was carried out by Bramley [74]. He described the evolution of research led by the author into rapid approximate numerical techniques for analysing and extrusion type processes. He described how the original work of Kudo [64, 65] with his unit deforming regions had been adapted to develop the simulation tool known as the upper bound elemental technique. Its use for load, flow, strain and tool pressure prediction together with preform design was described.

2.6. PLACE OF THIS THESIS IN THE LITERATURE

From the literature survey it is realised that all studies are concentrated on one specific subject. Forging process, geometry recognition, forging load calculation methods, die design considerations or expert system applications were investigated separately. The most of the emphasis is given to the feature recognition and forging process on specific industrial products such as H-beam, gear, connecting rod and etc. However, there are little work on the die design which covers all axisymmetric components considering the forging process conditions. Additionally, there are small number of expert system application in the forging process. Therefore, this thesis attempts to fill the gaps in the generalisation of axisymmetric components and designs the forging die by developed expert system.

CHAPTER 3

EXPERT SYSTEM FRAMEWORK of NEAR NET SHAPE AXISYMMETRIC FORGING DIE DESIGN (EX-AFORD)

3.1. INTRODUCTION

In this chapter, the meaning of AI and ESs are presented. The expert system tools and knowledge inference approaches are outlined. Knowledge Acquisition, sources of knowledge and framework of the developed system are explained.

3.2. ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is a part of computer science concerned with systems that exhibit the characteristics usually associated with *intelligence in human behaviour*, such as learning, reasoning, problem solving, understanding language, and so on. The main goal of AI is to simulate human behaviour on the computer. The knowledge and the use of knowledge are the key characteristics. The art of bringing relevant principles and tools of AI together for solving difficult application problems is therefore sometimes referred to knowledge engineering [16].

Manufacturing systems in industrialised countries have dramatically changed as a result of advanced manufacturing technologies employed in today's factory. Factories are now striving to attend and maintain a world-class status through automation that is made possible by sophisticated computer programs. The development of

CAD/CAM systems is evolving towards the phase of *Intelligent Manufacturing Systems (IMS)*. The systems belonging to this phase may be characterised by their ability to solve problems without either a detailed, explicit algorithm available for each solution procedure, or all the facts, mathematical relationships and models available in perfect arrangement and complete form for a deterministic and unique answer to be found. A tremendous amount of manufacturing knowledge is needed in an intelligent manufacturing system.

AI based techniques are designed for capturing, representing, organising, and utilising knowledge by computers, and hence play an important role in intelligent manufacturing. AI has provided several techniques with applications in manufacturing like; *Expert Systems (ESs), Artificial Neural Networks (ANNs), Genetic Algorithms (GAs)* and *Fuzzy Logic (FL)*. Among the all, the expert systems are emphasized in this chapter.

There have been numerous applications of AI for CAD/CAM for almost all design and manufacturing activities; from feature recognition to optimisation. ES is widely used in design, process planning, scheduling, material handling, quality control, machine diagnosis, machine layout and other operations. ANNs can be used for; quality control, pattern recognition, resource allocation, optimisation, scheduling, maintenance and repairing, process control and planning, database management, simulation, and robotics control. FL has been preferred for those problems in which there are conflicting process parameters, while GAs have been generally used for the optimisation issues such as optimisation of cutting parameters and operation sequences.

The impact of Artificial Intelligence (AI) tools (like Expert Systems, Neural Networks, Genetic Algorithms, Fuzzy Logic) on the planning of manufacturing processes has been proven by recent research projects and actual implementations. There are numerous packages being developed for almost any manufacturing activity. At the present time, however, it is not known how many of these systems are practicable and are being used. For example, most of the software for operations planning has led to the development of large and complex application packages which are too rigid when manufacturing variables are included. A conservative estimate is that only 5% of all research endeavours have found their place in the factory. This may be a very discouraging reality; but there are numerous reasons for this problem. The tools for building intelligent systems are not sufficiently developed and are difficult to apply. The methods for acquiring knowledge from experts to develop **expert systems** are not very well understood [110]. Good knowledge based systems usually contain several thousand rules and are huge software systems that are difficult to use on conventional computer systems [92].

There are too few qualified people available who really know how to apply AI tools. Problems can be solved by using or developing right tools, methods and environments. However, the potential and power of AI is very great and it is believed that with the exploitation of AI methods it will only be possible to build well conceived and intelligent CIM systems in which many routine jobs (which may become very repetitive and boring, after the skill has been acquired) are taken out of the responsibility of the experienced manager so that his creativity can be devoted to solving more complex problems in factory [94].

The development of powerful, intelligent, optimised and flexible CAD/CAM systems would only be possible with the extensive and true use of Artificial Intelligence (AI). AI tools like ESs, ANNs, GAs, FL, SA offer promising solutions in the areas of product definition, layout design, process planning, optimisation and so on. The next generation of intelligent manufacturing systems will hopefully integrate the computational paradigms of expert or knowledge based systems and artificial neural networks, as well as other promising methodologies like fuzzy logic and genetic algorithms [97]. To design intelligent systems, one or several AI technique(s) have been utilised. It should be noticed that each AI implementation paradigm has its own advantages or disadvantages. None of them may completely solve "intelligence" problem alone. Therefore, different techniques or approaches related to AI must be used in amalgamation to eliminate and to take the disadvantages and advantages of individual methodologies, respectively. Thus, it will be possible to realise the goals of intelligent manufacturing systems. In this work, an attempt has been made to include the power of expert systems for forging-related issues.

3.3. EXPERT SYSTEMS

An Expert System (ES) also called *a knowledge-based system* is an intelligent computer program that uses knowledge and reasoning techniques to solve problems that are difficult enough requiring significant human expertise for their solution [93]. An expert system may emulate the external behaviour of an expert, or it may attempt to closely model the internal mental processes of an expert as well. ESs have the ability to justify or explain the rationale behind a specific problem solution [94]. ESs are particularly useful for problems based on a limited knowledge domain. Like conventional programs, ESs usually perform relatively well-defined tasks. Unlike conventional programs, expert systems can explain their actions, justify their conclusions, and provide end users with details of the knowledge they contain [94]. One of the main difference between the conventional programs and ESs is that the knowledge is separated from the algorithms and is readily accessible at a run time in the ESs, while data and algorithm are executed together in conventional programming. An expert system generally consists of the components as shown in Figure 3.1. They are; a user interface, a knowledge base, an inference engine, a working memory and a knowledge acquisition mechanism.

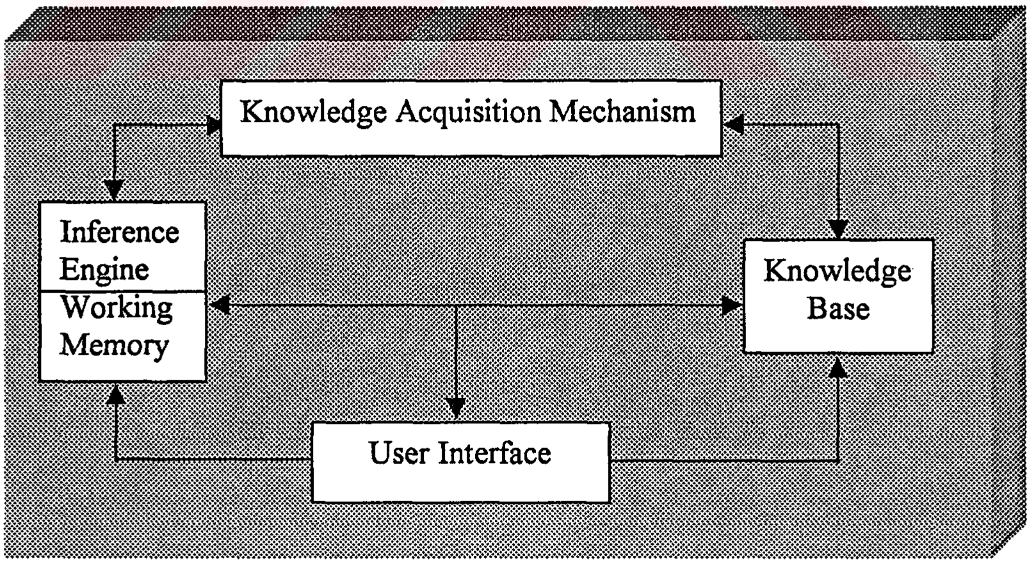


Figure 3.1 General Structure of an Expert System [95]

3.3.1. User Interface

The *user interface* is designed to provide a convenient means of two-way communication between the user and the inference engine. It enables a tutor to set up and maintain the expert system, and prepare the knowledge to be entered into the knowledge database. An end user who tries to find a solution to a problem can describe the context of his problem to the system by means of the user interface.

The developed expert system, called EX-AFORD, provides an interface for development. The ***menu interface*** provides menu support for defining EX-AFORD objects and building applications. The **Rule Base** menu provides structured menu support for entering rules without programming syntax. Rule Base editor for geometry definition is shown in Figure 3.2.

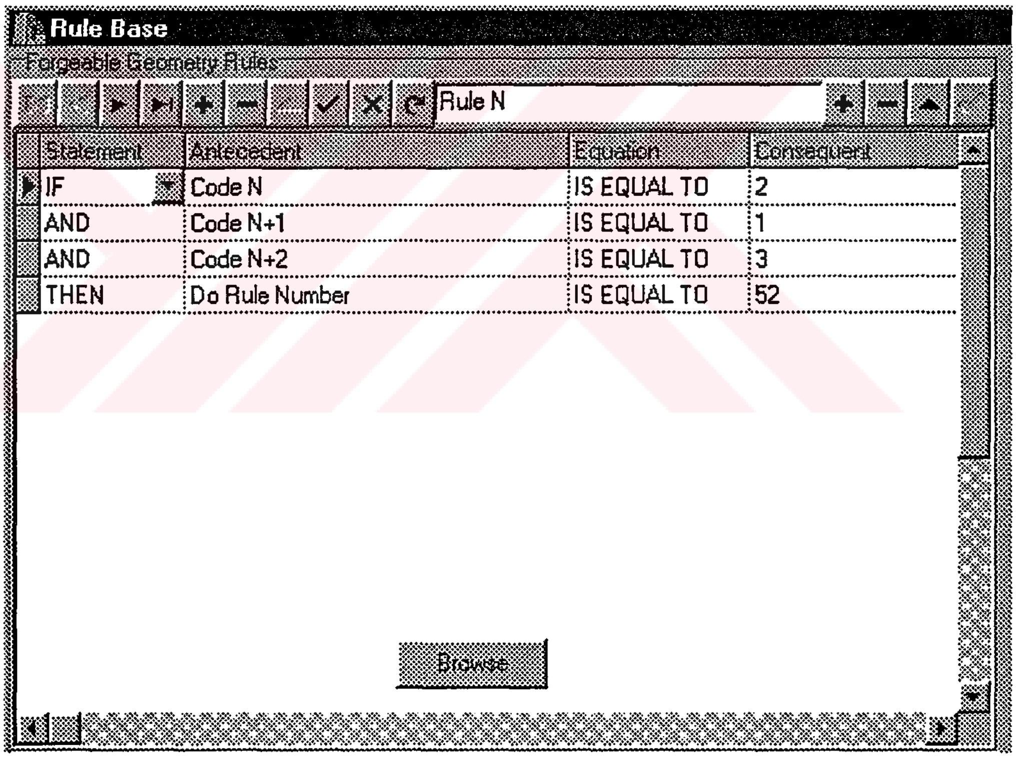


Figure 3.2 Rule Base Editor

The relationships between the objects can be viewed from "*Browse*" button. The algorithm and program generation.

3.3.2. External Interface

EX-AFORD provides an additional facility. Since it uses the graphical interface, it is important to import end export the data. The generated entities can be exported to the conventional programs such as Basic, C++, Delphi, AutoLISP and etc. "Write TXT" button, in the "Geometry Formation" main menu, enables the user to use this facility (Figure 3.3).

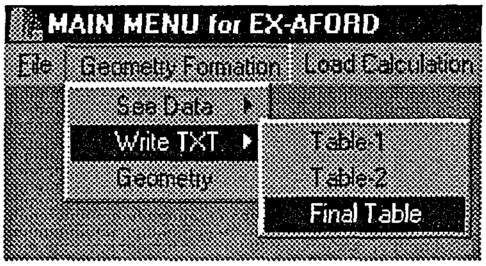


Figure 3.3. External Interface Facility: "Write TXT"

3.3.3. Inference Engine

An important subset of the general area of ESs concentrates on explicitly representing an expert's knowledge about a class of problems and providing a separate reasoning mechanism called *inference engine* that operates on this knowledge to produce a solution. These kinds of systems are called *knowledge-based expert systems*.

The *inference engine* is the knowledge processor that looks at the problem description and tries to find a solution with the help of factual and meta-knowledge. It can be considered as a program that applies domain knowledge to known facts to draw conclusions. Inference engines are domain independent such that they apply domain knowledge to case-specific application.

An inference engine is necessary to support intelligent agent behaviour. In this process, the agent uses a knowledge acquisition mechanism to gather facts, then these facts and associated sets of rules are supplied as input to the inference engine. Then, the new facts that are produced by the engine are fed to actuators, mechanisms that implement agent reactions. Consequently, an agent framework should be flexible enough to allow integration of one or more inference engines. Integrating an engine into an existing system is a nontrivial task because inference algorithms are time consuming, and the engine should fit into the scheduling model of the agent and interface the knowledge acquisition model and the actions model of the agents.

3.3.4. Knowledge Base

The *knowledge base* is a file that contains the facts and heuristic that makes up an expert's knowledge. A knowledge base is different from a typical data file or database. In a database, knowledge about the problem domain may be implicitly represented by the structure of the database. The actual contents of a database are the facts, data or information rather than knowledge. On the other hand, in the ESs, knowledge about the problem is explicitly represented in the knowledge base. The knowledge base is expressed in computer codes, usually in the form of *"if-then"* rules (in backward or forward chaining) or frames, with a series of questions. The problems are solved by using these rules through inference engine.

In expert systems knowledge is separated from control mechanism. By this, the rules forming a knowledge base or expert knowledge is separated from the methods for applying the knowledge to the current problem.

In the EX-AFORD, especially, material database has a big amount of knowledge on material type and their properties. There are 29 different material group (Figure 3.4), with 5 different designation (Figure 3.5), and 27 different material property (Figure 3.5), for each material.

In the following one of the material property rule is presented.

```
RULE MTPROP-S
IF             Material Type is Carbon Steel
AND            Designation is 1006
THEN           Tensile Strength is 300 Mpa
```

Data Registration

GROUP	MATERIAL
1	Carbon Steels
2	Low Alloy Steels
3	HSLA Steels
4	Gray Cast Irons
5	Ductile Cast Irons
6	Malleable Cast Irons
7	Corrosion-resistant Cast Irons
8	Aluminum Alloys
9	Copper Alloys
10	Pure and Low Alloy Nickels
11	Ni-Cr and Ni-Cr-Fe Alloys
12	Fe-Ni-Cr Alloys
13	Controlled Expension Alloys
14	Magnesium Alloys
15	Tin base solders

Figure 3.4. Material Group

MATERIAL	GROUP	AISI	ASTM	DIN	BS	MPIF
1	1	1006		1.0288, D5-2	970 030A04	
2	1	1006		1.0288, D5-2	970 030A04	
3	1	1008		1.0010,D9	1449 3CR	
4	1	1008		1.0010,D9	1449 3CR	
5	1	1010		1.0204,UQSt36	1449 40F30	
6	1	1010		1.0204,UQSt36	1449 40F30	
7	1	1012		1.0439,RSD13	1449 12HS,12CS	
8	1	1012		1.0439,RSD13	1.0439,RSD13	
9	1	1015		1.0401,C15	970 040A15	
10	1	1015		1.0401,C15	970 040A15	
11	1	1016		1.0419,RSt44.2	3059 440	
12	1	1016		1.0419,RSt44.2	3059 440	
13	1	1017			1449 17HS,17CS	
14	1	1017			1449 17HS,17CS	

Figure 3.5. Material Designation

PROPERTY	PRONAME
1	Type,Class or Grade
2	Alloy Name
3	Alloy Number
4	Product Forms
5	Condition
6	Type of Processing
7	Tensile Strength (Mpa)
8	Ultimate Tensile Strength (Mpa)
9	Ultimate Strength (Mpa)
10	0.2% ofsett Yield Strength(Mpa)
11	Tensile Yield Strength (Mpa)
12	Elongation in 200mm%
13	Elongation in 50mm %
14	Elongation in 25mm %
15	Reduction Area %
16	Hardness
17	Shear Strength (Mpa)
18	Impact Energy (J)
19	Compressive Strength (Mpa)
20	Torsional Shear Strength (Mpa)

Figure 3.6. Material Properties

3.3.5. Knowledge Acquisition Mechanism

A *knowledge acquisition mechanism* is used to acquire human expertise and transform into the knowledge base. This module processes the data entered by the expert and transforms it into a data presentation understood by the system. A knowledge base can involve all of the methods that the expert uses to perform a task. These methods may include computer programs, rules of thumb, theories, logic, etc. When the explicitly represented knowledge is combined with the fact of a specific problem, the ES is able to compute a solution to the problem [16].

3.4. KNOWLEDGE INFERENCE in EXPERT SYSTEMS

One of the major functions of the inference engine is the implement a procedure for reasoning with the rules and data found in the knowledge base. There different approaches are commonly employed in the programming of expert systems to find the solution: forward chaining (FC), backward chaining (BC) and goal-directed forward chaining (GD-FC) [140, 141].

3.4.1. Forward Chaining (FC)

This method starts with a series of facts and looks to see if any conclusions can be made. In forward chaining, when one rule fires and asserts values and assertions that matches the antecedents ("IF" part of a rule) of other forward or bi-directional rules, the system can then fire these rules, asserting more values and creating more assertions, initiating further forward chaining. The system forward chains until there are no more forward or bi-directional rules whose antecedents match in the knowledge base.

The first step in the forward chaining process is the matching of rule antecedents and objects in the system. When the system successfully matches the antecedent patterns of the rule, it creates a forward agenda item out of that rule, the objects that match the rule and the bindings created during the match.

3.4.2. Backward Chaining (BC)

Backward chaining starts with the goal of selecting a conclusion and then looks for support for conclusion. It is supposed that the application is large and only particular amount of the problem will be considered. If forward chaining is used for the solution, resources will be used searching for solutions which might not be needed. Instead, it is more efficient to consider only that particular amount of the problem as a goal and using backward chaining to solve for that one goal. In other words, backwards for a sequence of rules, which can be asserted the goal into the system, will be searched. When the system backward chains, it first searches the knowledge base for objects that match the pattern of the goal posted. If it cannot find any matching objects in the knowledge base, the system searches for backward or bi-directional rules. The system then begins a match fire cycle by matching the consequent pattern of one of the matching rules.

In EX-AFORD, both forward and backward chaining methods are used. For forging die design process forward chaining method is used while backward chaining method is used for verification. In the following sample example, die insert radius and shrink ring radius are calculated in forward chaining method (Table 3.1).

Table 3.1. Sample for rule Forward Chaining

Forward Chaining			
RULE AB1			
Statement	Antecedent	Equation	Consequent
IF	Die Insert Radius	=	A
AND	Shrink Ring Radius	=	B
IF	B	>	A
THEN	Design	=	Wrong

But, as it is seen from the result, since shrink ring radius is greater than die insert radius, system fires the related rule, and alerts the user to change the values. Verification of this calculation is done by backward chaining (Table 3.2).

Table 3.2. Sample for rule Backward Chaining

Backward Chaining			
RULE AB1-2			
Statement	Antecedent	Equation	Consequent
IF	Design	=	Wrong
THEN	B	>	A
IF	B	>	A
THEN	odulus of Elasticity of Die Insert	<	Modulus of Elasticity of Shrink Ring

Since Modulus of Elasticity of die insert is selected less than Modulus of Elasticity of shrink ring, EX-AFORD warns the user to select stronger material for die insert than shrink ring material.

3.4.3. Goal-Directed Forward Chaining (GD-FC)

This method uses both backward and forward chaining methods. In this method, forward rules can be fired during backward chaining. For this purpose, an enabling pattern is associated with a collection of forward rules in a rule package consisting of particular forward rules for a particular goal. Enabling pattern includes the information about a particular case of problem. During the query or searching phase of program, enabling pattern matches an attempt, which contains the information of query. Then, the system activates the rule set, so that the rules in the rules set are added to the list of active rules. Backward chaining is then suspended while the system performs all forward chaining possible with those rules. These forward rules can possibly assert the goal pattern which is searched for, thus minimising the need to continue the backward chaining.

3.5. ADVANTAGES and DISADVANTAGES of EXPERT SYSTEMS

ESs represent a revolutionary transition from the traditional data processing to knowledge processing. They offer an environment for incorporating the capabilities of humans and the power of computers. Some of the advantages of ESs are summarised as follows [16];

- ESs can accommodate new expertise whenever new knowledge is identified
- ESs are able to explain their recommendations
- ESs can apply heuristics to reduce the complexity of search
- ESs reduce the company's reliance on human experts by capturing expert knowledge and store the knowledge in computers

There are significant implementation challenges with the ESs, known as the knowledge acquisition bottleneck. Some of their disadvantages are listed below [16];

- Debugging and maintenance of a large (or complex) ES is very difficult
- The human expert must be available in order to build an ES

- The human expert must be able to articulate the rules that define the solution and not lapse into vagueness or incoherence
- The development of an ES can be a lengthy-process depending on the size of the problem domain
- An ES's performance drops off sharply if the problem deviates even slightly from the expected problem domain
- In a large and complex ES, the execution time of the system can also be a problem

3.6. APPLICATIONS of EXPERT SYSTEMS

There are numerous ESs being developed for almost any manufacturing activity [96]. Many major applications of ESs can be found in the design and manufacturing. ES is widely used in design, process planning, scheduling, material handling, quality control, machine diagnosis, machine layout and other operations. Joshi and Gülesin's works are two good examples to the expert process planning systems for prismatic parts in which sequence of operations are determined by establishing a precedence among the set of features comprising the part [98, 99]. Vosniakos and Davis [100] developed a knowledge-based system in which hole-making operations are selected and sequenced producing a single plan with minimum tool changes. Arezeoo and Ridgway [101] have used a knowledge-based approach in the development of a system for selection of cutting tools and determination of cutting conditions. They used Prolog and a hybrid knowledge representation scheme in the development of the system (logical and rule based).

A general structure for building up an inference and control engine for the decision-support expert system as well as an algorithm for finding a compromise solution for the metal-cutting parameter selection problem is discussed in Reference [102]. Lee, et al. [1], have developed an intelligent knowledge-based object-oriented process planning system called IKOOPP for manufacture of progressive die plates. The system uses part definition data extracted from a plate model based on a computer aided die design system. A generic Intelligent Tool Selection (ITS) system developed in collaboration with two different manufacturing companies is described in Reference [103]. Kusiak has classified process-planning activities into various phases and assigned a dominant solution approach for each individual phase [104, 105]. It is stated that most process planning functions are solved using either a knowledge-based approach or a combination of optimisation and knowledge based approaches. Those phases and their solution approaches were discussed in detail in the literature [105, 139]. In a recently published paper of Mayer, et al, [106] a methodology that represents, reasons and plans with multiple knowledge types and multiple planning strategies existing in the domain of process planning have been discussed. The plan generation strategies for a master planner component, which is a part of a knowledge-based automated, process planning system (KAPPS). Their methodology is an approach termed as architecture of cognition. They mainly focused on the planning mechanism of the process planning system. Yilmaz et.al., have recently developed an expert system for the determination of forgeable geometry in near-net shape manufacturing [107]. An inclusive survey on the use of ESs in manufacturing and process planning can also be found in Reference [108].

Good knowledge-based systems usually contain several thousand rules and are huge software systems, which are difficult to use on conventional computer systems. The tools for building knowledge-based systems are not sufficiently developed and are difficult to apply. The methods for acquiring knowledge from experts are not very well understood. There are too few qualified people available who really know how to apply AI tools [92].

Expert systems work on a real-time basis, and their short reaction times provide rapid responses to problems. The most common programming languages are C++, LISP, and PROLOG; other languages can also be used. A more recent development is expert-system software shells *or environments,* also called *framework* systems. Some of the well-known shells are; Leonardo, VP-Expert, KES-PS, and GoldWorks, etc. These software packages are essentially expert-system outlines that allow a person to write specific applications to suit special needs. Writing these programs requires considerable experience and time [109].

3.7. KNOWLEDGE ACQUISITION for EX-AFORD

It is widely known that literature is the most common form of knowledge. The principal sources of knowledge are human experts in the development of expert systems. The process of studying the expert's behaviour and selecting and employing a tool to build a knowledge based system is called knowledge acquisition [138]. The types of information, which a human expert may provide, include personal experience of past problems solved, personal expertise or methods for solving the problems and personal knowledge about the reasons for choosing the methods used.

The process of acquiring knowledge from a human expert is an iterative process that requires close interaction between the expert and the knowledge engineer. In an another way, knowledge acquisition is getting information from human expert and codifying it within an expert system. But, unavailability of a standard methodology used by experts to solve a domain problem is an important issue. If there was an only one standard method for a problem there would be no need to develop an expert system to solve the problem. Knowledge acquisition can be expressed in three steps:

- Objective: Construction a model to perform defined task.
- Participants: Collaboration between problem expert(s) and modelling expert(s).
- Process: Iteration until it is done.

There are some difficulties in transferring knowledge. These are:

- Hard to get experts to express how they solve problems
- Representation on machine requires detailed expression i.e. at a very low level. Must be represented in a structured way.
- Bringing together the ideas of all those involved in the knowledge transfer process.

The use of natural language interfaces by the experts can communicate directly and overcomes these difficulties

3.8. KNOWLEDGE ACQUISITION METHODS

There is no single methodology for the process of knowledge elicitation from experts that has been proven universally effective. Knowledge acquisition methods can be divided into two main groups and two subgroup for each one as shown in Figure 3.7

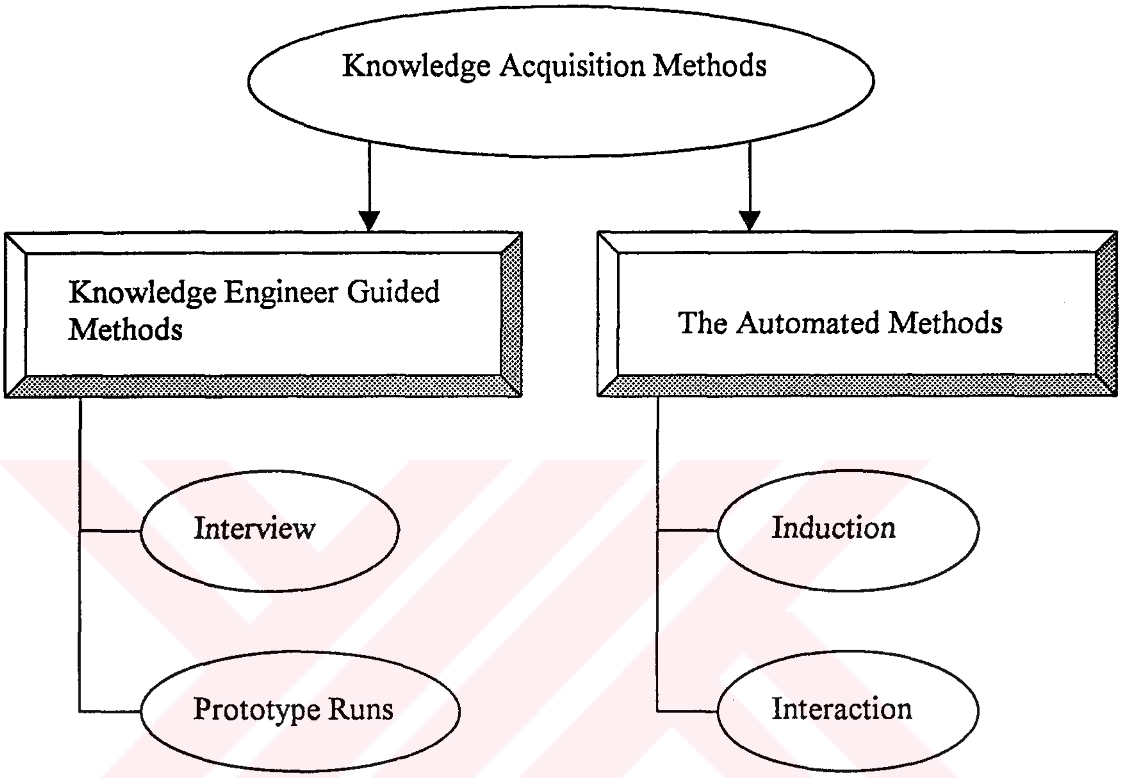


Figure 3.7. Knowledge Acquisition Methods

"The knowledge engineer guided" methods are designed to structure and guide the process of knowledge elicitation, usually from experts, by knowledge engineers. The method consists of interviews and experimental runs on partially completed prototype systems. "The automated" methods elicit knowledge from experts automatically, using computer programs instead of the knowledge engineer [142]. One approach in automated tools is learning by interaction, which relies on computer aided knowledge acquisition. The expert directly interacts with a computer program which helps capture the knowledge. Another approach is learning by induction In this approach, a computer program derives knowledge by examining data and examples. This approach focuses on algorithms that analyse data and examples and generalise them to obtain knowledge.

3.9. SOURCES of EXPERT KNOWLEDGE IN EX-AFORD

To perform the knowledge acquisition task, potential knowledge sources relevant to forging die design have been identified. These potential sources include the followings:

- Published material including papers, books, theses, standards and handbooks.
- Researchers in the field of forging die design.
- Technicians, working in forging industry.
- Rules, created by the outer of this thesis.

3.9.1. Published Material

The first source in acquiring knowledge during the development of an expert system for forging die design was to consult published material. The purpose consulting the published materials was the identification of typical problems and how these problems are handled by researchers. This initial phase of knowledge acquisition for the system made it clear that structuring and representation of the knowledge would be a major problem.

In the search of literature, it was realized that, special industrial parts were considered and also expert system was applied to these parts. Knowledge on the determination of forgeable geometry criteria, entity recognition, upper bound application for forging load calculation, geometry decomposition, lubrication, friction factor, material property and die design considerations are collected from papers and books. All these knowledge are utilized and it was seen that there was almost no generalisation of axisymmetric forging parts and application of expert system was also rare. Additionally, there wasn't any available standard procedure which could be used to encounter the problem.

3.9.2. Researchers in the Field of Forging

Another source of knowledge were the researchers in the Mechanical Engineering Department of University of Gaziantep. The researchers for informal discussions were selected through personal contacts by the author. During the selection of these researchers, their availability, willingness and experience were considered. The purpose of these discussions was to gain other opinions from experienced people. Informal discussions with researchers in the problem domain resulted in the acquisition of valuable information.

The researchers were specialised in one part of the subject of this thesis. Some of them gave knowledge on expert system and the others gave knowledge on forging processes.

3.9.3. Technicians

The third source of knowledge acquisition on the elicitation of knowledge that is used by technicians in the practice. For the knowledge elicitation in forging and die design processes, four industrial foundation were visited and interviewed informally by the most relevant person, who is expert in forging and die design processes. During the selection of experts, forging experience in general and design problems in particular were considered. Since each of them were concentrated on special part of the design process, they don't know the whole process from raw material to finished product. Therefore, knowledge is collected form the experts partially and combined by the author of this thesis. For this reason, standard questionnaire was not prepared.

In the duration of each visit, informal discussions were made. Their previous experience, encountered problems, how they solve these problems, continuing problems and special cases that they have stated were noted in paper. These notes assisted in eliciting the expert's decision making steps for the problems.

3.9.4. Created Rules

Before combining any knowledge, collected from the experts and literature, some time was spent to become familiarised with the domain. The purpose was to determine the existence of any existing manuals, reports, or other written material which described the problem domain and the terminology employed. In the process of knowledge acquisition, collected information were classified according to their subject. Because, there are several stages in die design process. By using the literature review and the discussions, made by the experts, the author created his own new rules in the determination of forgeable geometry. Product geometry was recognised by its entities. Each entity was coded by a number and entities, which was causing undercuts were eliminated. After these processes, the forgeable geometry was proposed using new rules, created by the author.

There was contradictory knowledge collected from the experts and the literature in the determination forging load. Each expert stated that there is no exact value for forging load and they are applying the load according to the voice coming from the punch and die at a contact time to each other. In some cases, they also stated that, due to the excessive load die failure occurs and they manufacture new die. After a several experience they are adjusting the punch stroke and find the required forging load.

One of the other expert stated that, they are producing the same products all the time and they have no such a problem. Actually, they don't know the reason why they are applying a certain amount of load.

In the literature, there are some approaches for forging load calculation. It is found that, there is no exact solution for load calculation but, there are approximate methods to predict the forging load. These approximate methods will be discussed in the proceeding chapters.

By considering all these knowledge, the author acquired his own knowledge. In order to determine the forging load, Upper Bound Elemental approach was used. A new method and the series of rules were developed combining the acquired knowledge from the experts and literature. Product was considered by decomposing its geometry into elemental basic regions. Load was calculated for each region by taking the effects of material property and lubrication conditions. Summation of load for each region gave the total amount of forging load.

3.10. A FRAMEWORK for EX-AFORD

Knowledge representation in EX-AFORD is structured in the network representation. Parent frames (geometry, forging load, die geometry, die assembly, material), are connected to the top frame. Each parent frame has also child frames. In the following Figure 3.8. general frame structure is shown.

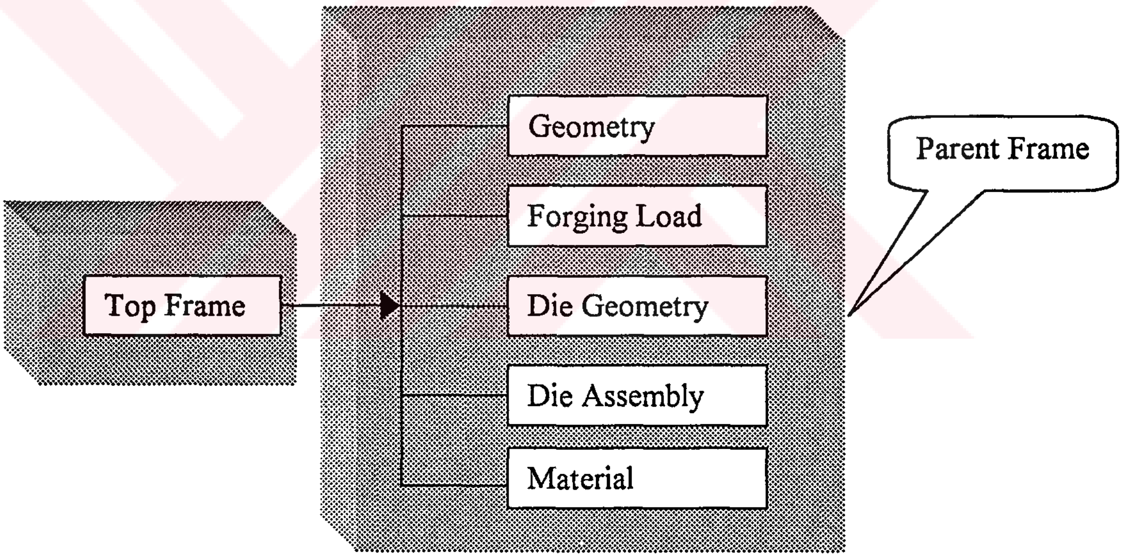


Figure 3.8. General Frame Structure

Parent frames are used to describe the general class of objects. In database, the data definition of a record specifies how the data is stored so that the database can search and sort through the data. To actually enter the values into the system, child frame and instances are formed to represent the specific objects.

3.10.1. Geometry Frame

The geometry frame is defined as a parent frame. All geometric processes, feature recognition and forgeable geometry determination are held in this parent frame. Framework for geometry frame is shown in the following Figure 3.9

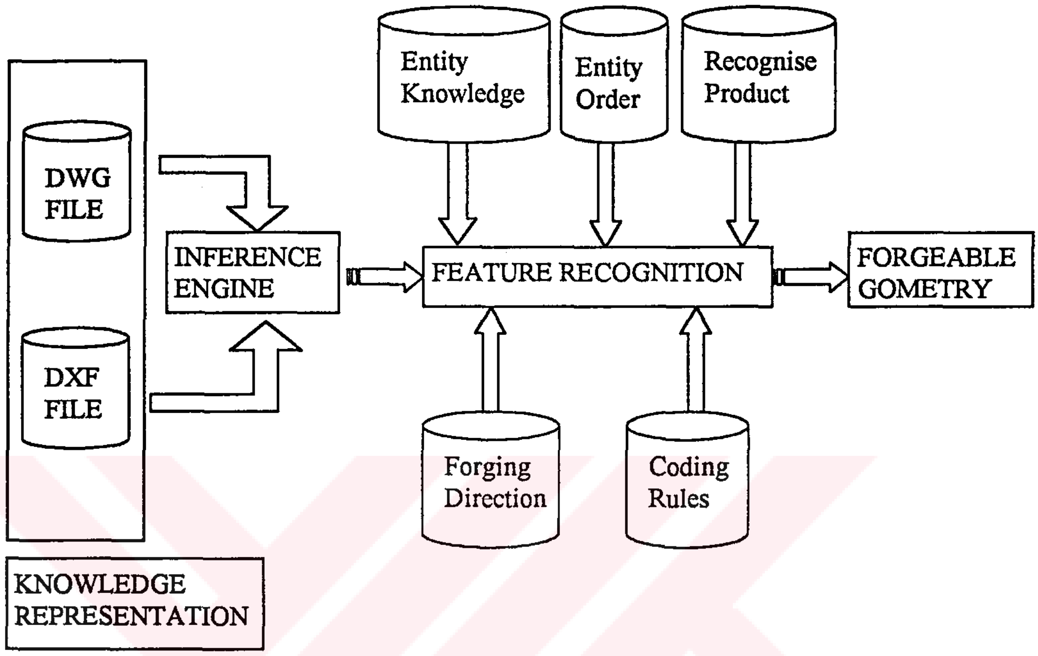


Figure 3.9 Framework for Geometry Frame

Knowledge Representation: The first input to the system is DWG file of the product. This file is converted into DXF file and imported to the system. This file covers the all entity parameters to be used by inference engine. The aim of geometry frame is feature recognition and then achieve the forgeable geometry.

In order to avoid the repetition knowledge about DWG and DXF files are not presented here. All explanations and knowledge are presented in detail in Chapter 5. Entity knowledge, entity order, recognise product, forging direction and coding rules form the child frame of geometry parent frame. and shown in Figure 3.10

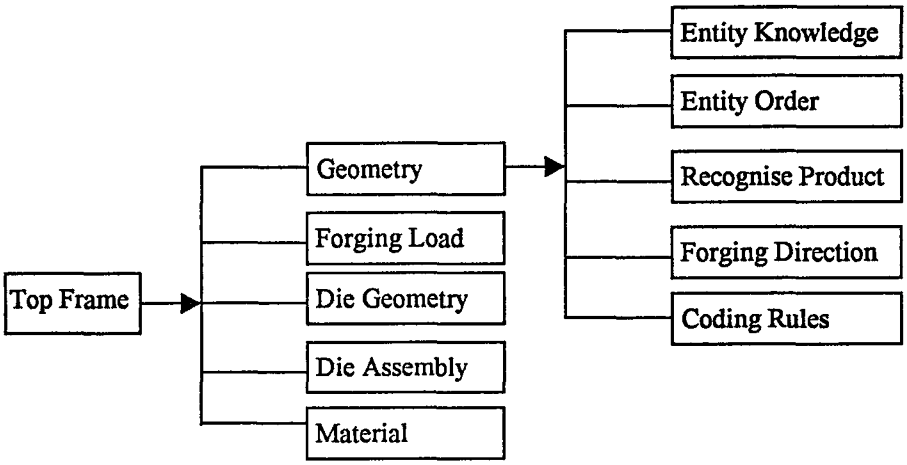


Figure 3.10. Child Frames of Geometry Parent Frame

3.10.2. Forging Load Frame

This frame has six child frame and it is defined as a parent frame of EX-AFORD to predict the forging load.

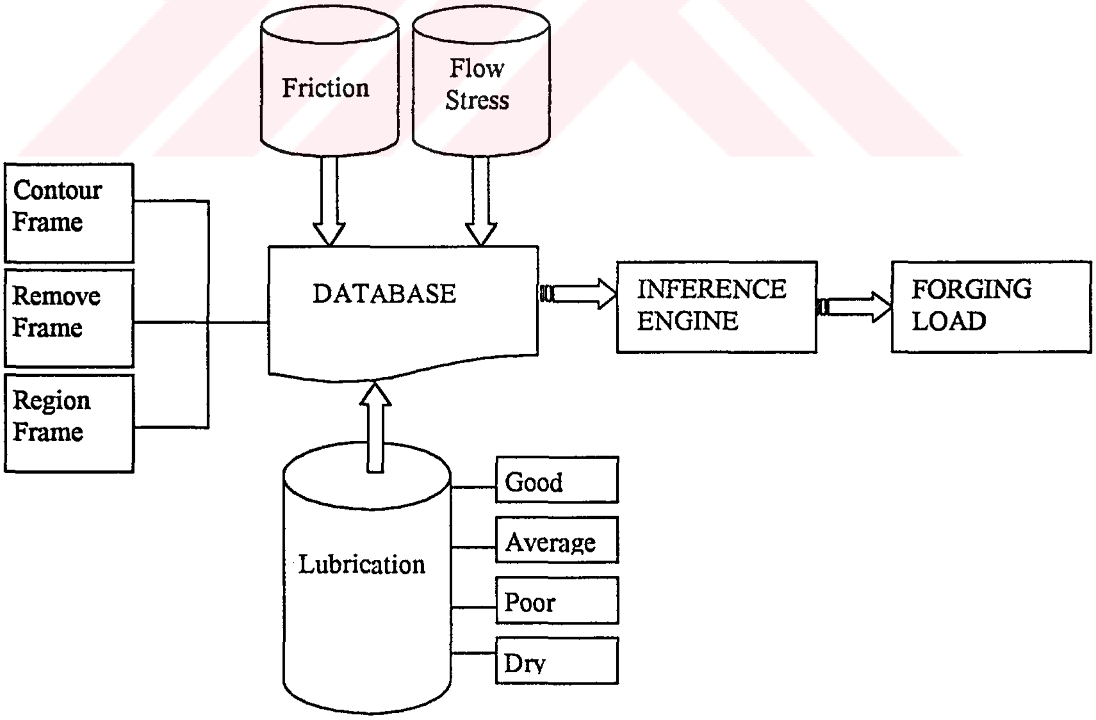
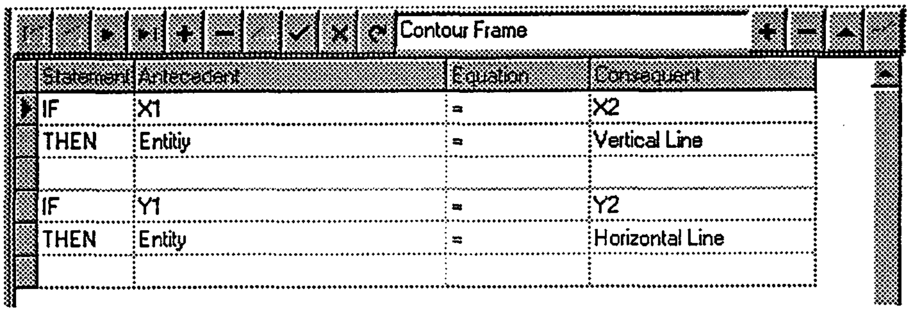


Figure 3.11. Framework for Forging Load Frame

Contour Frame: This is the child frame of forging load parent frame. This frame takes its knowledge from the geometry parent frame. In order to determine the forging load, contour frame is the first frame that is to be fired. The entities are searched to find the inclined lines and arcs. During this process, related rules are fired so that the found entities are inclined line or arc. In the following Figure 3.12 two of the rules are presented.



Statement	Antecedent	Equation	Consequent
IF	X1	=	X2
THEN	Entitiy	=	Vertical Line
IF	Y1	=	Y2
THEN	Entity	=	Horizontal Line

Figure 3.12. Example Rule for Contour Frame

Remove Frame: This is the child frame of forging load parent frame. In this frame, removed entities are stored in the database. There are two instances. One of them contains the knowledge about inclined lines and the other contains arc.

Region Frame: This frame is the child frame of forging load parent frame. The geometry decomposition is made by the knowledge taken from this frame. Vertical and horizontal lines are drawn from the corners to the corresponding line. By this way, rectangular regions are obtained. The knowledge about the regions are stored in the database.

Friction Frame: The one side of region contacts to one of the material, die or punch. Therefore, each side must be checked and friction factor must be determined. This frame is used for the determination of sides weather it is contacting to material or die and punch.

Lubrication Frame: This frame takes its knowledge from friction frame and adds its own knowledge. This frame has four slots; good lubrication, average lubrication, poor lubrication and no (dry) lubrication. These slots are required from the user. The entered values are used for the determination of friction factor for each side of the region and therefore, for all forging product.

Flow Stress Frame: Deformation characteristic of each material is different from the other materials. Flow stress value changes for all deformation conditions. Therefore this property of the material must be in hand.

3.11. CONCLUSION

In this chapter, the application of information technology to the forging die design was detailed. The meaning of artificial intelligence and some application areas were given. Expert system components were explained and a sample from EX-AFORD was given for each component.

There are a number of expert system shells. Each one offers almost the same facilities with slightly different attributes. They have one common feature in that they all process data and produce output reports, but almost non of them has no capability to handle the graphical interface, complex mathematical formulae and combining them in the expert system shell, together.

From the review of a number of applications, it was seen that the forging process and die design is suitable subject for expert system application. As it was stated in this chapter, there are several way to develop an expert system. In this thesis, any of the existing expert system tool was not used, due to the unavailability of the all requirements. Therefore, a new expert system is developed using forward chaining mechanism. In die design considerations, backward chaining was used for verification.

The system was described in terms of frame objects to represent the known facts. The rules are set for a particular purpose and the procedures controlled the system interaction and determined of same variables. The knowledge acquisition methods, capturing and representing the knowledge were explained. The framework of the system was expressed, but detail of the subjects were not given since they have huge knowledge. These frames will be explained in detail in the proceeding chapters.

CHAPTER 4

PRECISION FORGING PROCESSES

4.1. INTRODUCTION

In this chapter, forging processes types; cold forging, warm forging, hot forging, and some related parameters such as workpiece, tooling, machine tool and etc., will be outlined. Definitions of Near Net Shape (NNS) and precision forgings are clarified.

4.2. NEAR NET SHAPE AND PRECISION FORGING

The term "Near Net Shape Forging" does not specify a distinct forging process but rather describes a philosophical approach to forging and also can be called "Precision Forging". The goal of this approach is to produce a near net shape in the as-forged condition. The net indicates that no subsequent machining or finishing of a forged surface is required. Thus, a net shape forging requires no further work on any of the forged surfaces, although secondary operations may be required to produce minor holes, threads and other such details. A near net shape forging requires only minimal machining.

There are basically two types of applications for computers in near net shape forging technology [30]:

i) Preparation of parts, die and fixture drawings and generation of NC cutter paths for controlling a CNC machine to produce a model, an electrode (for EDM) or die cavity directly from the die block.

ii) The analysis of forging process, ie. Prediction of stresses, metal flow, temperatures, forming load and energy.

The aim of precision forging is to achieve parts to net shape. Precision forged parts are characterised by shape and dimensional tolerances, which correspond to those of machining methods. Conventional forging takes place in an impression die that allows the formation of flash. However, in most precision forgings the dies are completely closed and do not allow the formation of flash. This difference makes it possible to produce parts with high shape and dimensional accuracy with only a few forming steps and significant savings in material [75]. On the other hand the motivation for precision forging is the elimination, or at least the reduction, of the costs associated with this machining allowance. These costs include not only the labour and indirect costs of the machining and finishing operations but also the cost of the excess raw material that is lost during machining.

Precision forging is only economically feasible if the following conditions are met:

1. The production volume is high
2. The material savings are considerable
3. Precision forging eliminates expensive and time consuming machining operations like broaching and shaving
4. Tool life is long enough so that considerable savings in tooling are achieved

After the decision is made that, the part will be manufactured by forging, either a traditional or a precision forging process is selected. Precision forging can not be used for all part shapes, forms and materials. The precision of a forging is defined in terms of its conformity to finished part requirements concerning overall geometry, dimensional accuracy and surface finish. The impact of the requirements should be derived from the performance of the part that is desired in service.

Another motivation for precision forging is that the mechanical properties of a precision forging are better than, those of, forging that has undergone extensive machining. This occurs because the forged microstructure is preserved intact in the precision forging.

Due to process limitations in the forging at elevated temperatures, the achievable tolerances by cold forging process are generally tighter than those obtainable by warm and hot forging. Table 4.1 compares the achievable tolerances of steel for forging methods at different temperatures.

Table 4.1. Dimensional Accuracy in Cold, Warm and Hot Forging of Steel [76, 77]

		COLD	**WARM**		**HOT**	**HOT PRECISION**
Forging Temperature (^{0}C)		20	200-500	600-750	1100-1250	1100-1250
Surface Roughness (µm)		<6	<7	<10	<20	8-15
Depth of Decarburisation (mm)		None	None	0.1-0.4	0.3-0.4	0.2-0.4
Dimensional Accuracy	**Shape (mm)**	±0.025-±0.16	±0.05-±0.15	±0.1-±0.2	±0.5-±1.0	0.12-0.2
	Thickness (mm)	±0.1-±0.25	±0.1-±0.25	±0.2-±0.4	±1.0-±2.0	±0.3-±0.5

The tolerances achievable by hot precision forging are comparable to those of warm forging. In order to make a better use of the technology several authors have suggested the combination of cold and warm forging processes to manufacture assembly ready components like, alternator poles, bevel gears and tripods [78, 79]. Some other authors have suggested the manufacturing of preforms by hot forging and finishing by cold forging or cold coining [80].

4.3. PARAMETERS AFFECTING FORGING ACCURACY

The interaction of factors that affect the accuracy of forging is very complex. Material, tool, equipment and the process layout affect the dimensions, form, surface and strength of forging [76]. Process parameters are outlined in the following.

4.3.1. Workpiece

All process parameters have an effect on the accuracy of the final forged product. However, one of the most important parameters to control is the workpiece. First of all, the dimensional errors in the workpiece may lead to significant variations in the volume of the billet or preform. The form or shape of the initial billet or preform affects the accuracy of the subsequent forging operations. The common form errors in billets are:

- Parallelism
- Flatness
- Cylindricity
- Roundness

Different material properties like, composition, or hardness may affect the metal flow in the forging operation. These variations affect the final dimensions of the part due to differences in shrinkage (hot and warm forging) or springback (cold forging). Also a material composition with higher resistance to deformation will require more energy to achieve the desired shape. In certain cases the die may fail due to overloading and that will result in higher production costs due to repair and production time.

4.3.2. Tooling

Variations in the tooling dimensions result in systematic errors in the parts and dimensional accuracy of the forged product is affected by the tool accuracy. In forging tooling costs can account for 5 to 30 percent of the manufacturing costs [81].

Due to high initial tooling costs forging is only practical for high volume of production.

The dimensional accuracy of the tools change during the forging process mainly due to variation in the deflection, wear and plastic deformation. The changes in elastic deformation are due both to changes in the volume of the workpiece and variations in the temperature of the billet and dies (in hot forging).

- Plastic deformation occurs mainly at the beginning of the forging process but it may also occur due to softening of the die material after exposure to high temperatures for a long time.
- Wear occurs during the whole process and depends mainly on the amount of workpiece material sliding over the surface of the die and the pressure at which this material slides. The effects of wear can be minimised by using hard tools, coatings and effective lubrication practices.

The forging tools have to be removed from the equipment before the dimensions of the forged product fall out of tolerance. Figure 4.1 shows dimensional change in forging dies subject to high forming pressures. The dies have to be removed from the operation before they enter the failure region.

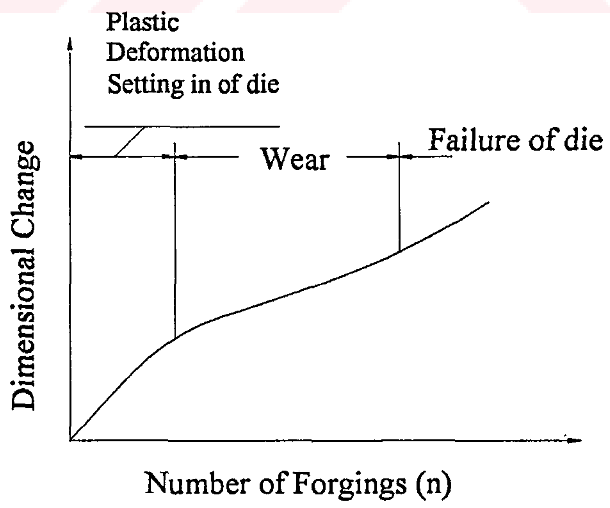


Figure 4.1. Schematic Representation of Dimensional Change in Dies With High Inner Pressure [76]

The die materials used in precision forging affect significantly the accuracy of the process. In cold forging high speed steels are used for most punches and in some dies where ductility of the tool material is an issue. Carbide inserts are used when wear resistance and dimensional control are issues in the production of the part. In hot and warm forging the most common tool materials used are hot work tool steels which have a good strength at high temperatures, are resistant to thermal shock and thermal softening.

4.3.3. Machine Tool

The accuracy of the forged part also depends on the accuracy of the machine tool. In precision forging mechanical and screw presses are commonly used due to their accuracy and production rate. Hydraulic presses are generally used when it is necessary to perform severe forging operations [77]. The important factors in selecting a press for a specific forging operation are:

- Available energy
- Time dependent characteristics: Strokes per minute under load, contact time under pressure, and velocity under pressure
- Characteristic data for accuracy:
  a) Unloaded machine conditions: Clearance of gibs, parallelism of upper and lower beds, perpendicularity of slide motion with respect to lower bed, and concentricity of tool holders
  b) Loaded machine conditions: Tilting angle of the ram under off center loading and stiffness of the press

From the parameters above the most important factors for the working accuracy of the press are the tilting angle of the ram under off center loading and stiffness of the press [82]. The tilting of the ram produces skewed surfaces and an offset on the forging. The stiffness influences the thickness tolerance. Figure 4.2 shows the stiffness measured by Douglas and Altan [137] for a mechanical press of 500 tons.

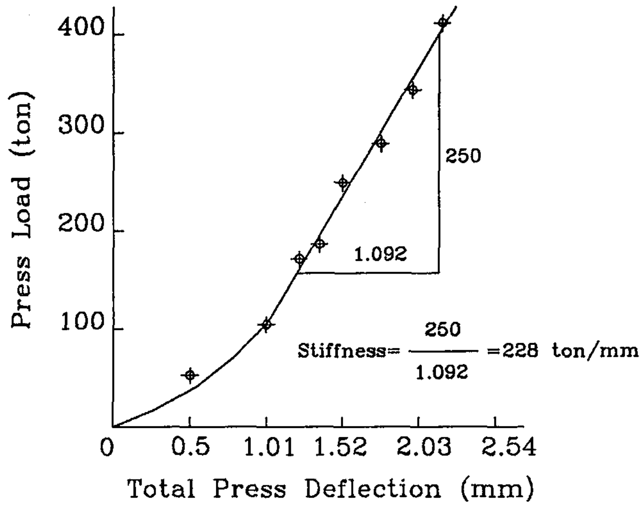


Figure 4.2. Total Press Deflection Versus Press Loading Obtained Under Dynamic Forging Conditions

The deflection of the press at 80 % of the capacity (400 ton) is approximately 2.28 mm. Hence, depending on the equipment available the designer should compensate for the stiffness of the press, since this may influence significantly the tolerances of the forged product. In the case of the screw press the touches after each blow, the stiffness of the press does not influence the thickness tolerance of the part, but the contact time determines the amount of energy lost in press deflection.

4.3.4. Die Design and Part Complexity

In order to prevent the premature die failure and maintain the accuracy of the product in cold and warm forging shrink rings or stress rings are used. These are less common in hot forging although they are used in hot forging of gears [8]. The advantage of using shrink rings is that it is possible to use hard but brittle materials like carbides (cold forging) or ceramics (warm and hot forging) to construct inserts with the cavity required to make the forging. This allows to take advantage of the durability of these materials while preventing the premature failure of the insert.

In the case that the part is too complex to be forged in one blow, it is necessary to divide the process into several forming operations to control the metal flow and achieve the tolerances required. Figure 4.3 shows one example of cold forged part with decreasing diameter in one end [34].

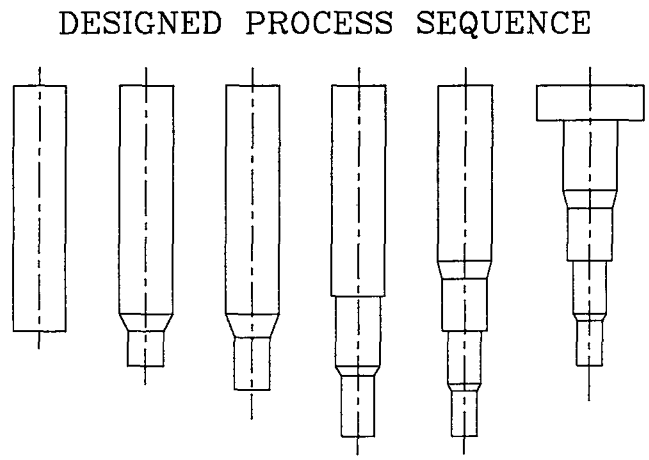


Figure 4.3. Sequence Design for a Solid Part With Decreasing Diameter at One End

4.3.5. Process Conditions

In order to obtain accuracy and good quality in forged product it is necessary to control very closely the following process variables [77]:

- Billet temperature
- Die temperature
- Handling between forging operations
- Lubrication

It is obvious that first three variables are important for hot and warm forging but, lubrication is important for all forging operations.

Significant variations in the *billet temperature* may result in either excessive formation of scale on the surface of the billet or higher load requirements to form the part due to high flow stress values at the coldest portions of the workpiece. The temperature of billet in hot forging of steel must be controlled within ±10 ^{0}C [80].

The lack of consistency and control of the *die temperature* may cause significant variations in the thermal expansion of the die, thus the tolerance of the forged part will be affected by this process variable. Therefore, the dies are preheated with two objectives in mind:

1) Reduce the possibility of thermal shock
2) Maintain a temperature as close as possible to the workpiece temperature and minimise the effects of thermal expansion.

The handling of the workpiece in precision hot and warm forging is a very important issue. In warm and hot forging the temperature of the billet changes as soon as it is removed from the furnace, hence slight variations in the times to transfer the workpiece from one station to the next may affect significantly the dimensions of the part. Therefore, in most precision forging operations automated handling equipment is used to obtain better consistency in the temperature changes of the workpiece during forging process.

The performance of the *lubricant* may be the most difficult to quantify for all forging operations. However, lubrication is also recognised as one of the factors that is most critical to the success of any forging process. Too little lubricant may increase the forging loads due to higher friction. Too much lubricant could become entrapped in the die and affect the dimensional accuracy of the part. In hot forging, the lubrication is applied to dies mainly by spraying the lubricant on the surface of the tooling. In some other cases the billets are coated with the lubricant. In the case of cold forging of steel, if the billet is coated, more uniform application of the lubricant is obtained and excessive wear is avoided on the dies while allowing an efficient metal flow. In some hot forging operations the billets are coated mainly to reduce the thickness of the scale layer during heating, but also provide a more uniform layer of lubricant. The requirements made of lubricants for warm forging are good cooling and lubricating properties, good wetting of tools, sufficient adhesion to the tool surface and good wear protection [130].

4.4. COLD FORGING

As cold forging becomes more competitive even for small lot sizes, there is an increasing need for quick product and process design. Computer aided systems may satisfy this need by assisting the design of cold forged products, the generation of forming sequences, and design and manufacturing of dies [83].

In the cold forging process the billet is formed at room temperature. Therefore, high forming forces are required to fill the cavity, especially the corners [84]. Although the billets are heated during the operation due to the plastic work, it is necessary to compensate for the thermal expansion of the part. On the other hand in most cases, it is necessary to compensate for the elastic deflection of the die.

Pale, et al. [60] described additional advantages and disadvantages for cold forging. Grain flow and strain hardening provide improved part strength so that in many cases heat treatment requirements are kept to a minimum. A disadvantage aside from the high pressure on the tooling is that for complex parts several preforming steps are required. As cold formed materials strain harden and lose formability special annealing steps are required during the forming process. Finally special coatings must be applied to reduce friction and to maintain a lubricant film throughout the entire forming sequence.

For most cold forging processes a grinding operation may be needed to finish the part. Rarely, it is possible to produce net shape parts, where grinding operation is not necessary, and the parts are ready for assembly right after forming. In the near net forged components, die consists of a closed die and an upper and lower punches that move simultaneously towards the billet and form the complex features of the product. Figure 4.4 shows an example for cold forging of automobile and railway industries for applications which demand good strength, fracture, toughness and fatigue properties [85].

(a)

(b)

(c)

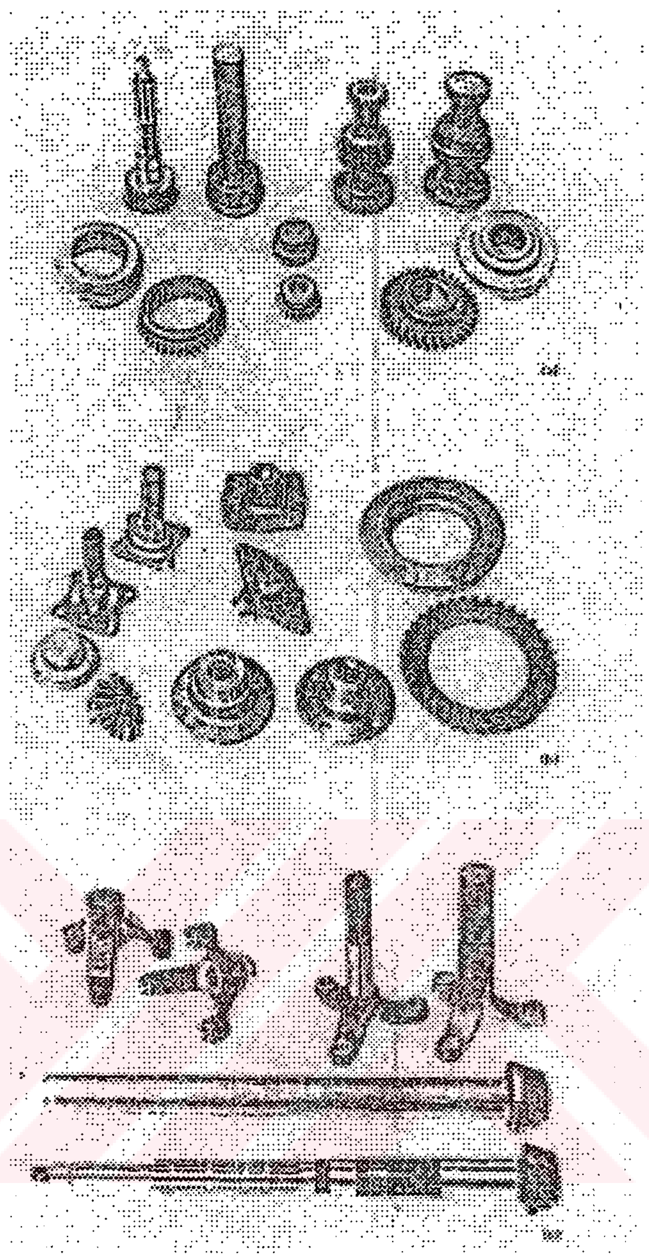


Figure 4.4. Forgings for Automobile Industry:
(a) Gearbox items, (b) Rear-axle items, (c)Transmission items [85]

In the production of near net or net shape parts that may have undercuts, it is difficult to meet the tolerance requirements. These dimensional requirements for the parts and the tooling lead to some problems:

- Insufficient die filling in the corners
- Extremely high tool pressures at the moment of maximum die filling
- Too low die life resulting from premature fatigue fracture

- Negative effect of elastic tool deflection on the precision of the dimensions of the parts.

In order to get a better metal flow and to achieve complete cavity fill, Osakada [58] has proposed a concept of forging with axially driven container. The container oscillates after the part has reached the final stroke, although this type of tooling has given good results, its implementation in production might not be economically feasible due to the added costs in tooling and additional time required to fill the corners of the product.

4.5. WARM FORGING

In warm forging, steel billets are preheated to a temperature between 500 ^{0}C and 850 ^{0}C. As in cold forging, mainly processes are employed forward, backward and lateral extrusion with no flash. Warm forging combines the advantages of hot and cold forging. These are good formability of the billet with low pressures, close tolerances and good surface quality. However, the costs for the tooling are higher than those for hot and cold forging. The tooling has to withstand both the pressures resulting from the forming process and exposure to high temperatures. Warm forging is used to produce high volume precision parts made of steel grades that can not be cold formed [86]. While in cold forging the process is limited to a certain deformation ratio per step, higher deformation ratios can be achieved in warm forging. This is due to the fact that recrystallisation occurs parallel to the forming process and no annealing is necessary.

Warm forging is mainly applied to reduce the flow stress of the material, the forging loads and to be able to produce more complex parts [46]. The tool materials used in warm forging are low alloy cementation steels, heat treatable steels, steels for superficial hardening, ball bearing steels and stainless steels. In contrast to cold forging processes the shape of the parts could be more complex because of better formability of the material. Table 4.2. gives a comparison of hot, cold and warm forging [86].

Table 4.2. Comparison of Hot, Cold and Warm forging [86]

	HOT FORGING	COLD FORGING	WARM FORGING
Tolerances	IT 12 – IT 16	IT 7 – IT 11	IT 9 – IT 12
Weight of the part	5 g – 1500 kg	1 g – 50 kg	100 g – 50 kg
Economical batch (weight 1kg)	Min. 500 pieces	Min. 3000 pieces	Minimum 10.000 pieces
Steel Grade	Any	Low alloyed steels (C<0.45%; other elements <3%)	C desirable, other alloying elements <10%
Shape	Any, without undercut	Mainly axisymmetric without undercut	Rotational axisymmetric
Formability	Normally no limit	Deformation ratio φ<1.6	Deformation ratio φ>1.6 (Upper limit depends on steel grade and temperature)
Surface quality	>100 μm	≈10μm	<50μm
Possibilities of automation	Limited	Appropriate	Advantageous
Surface treatment	Not necessary	Annealing	Normally no surface treatment
Intermediate treatment	Not necessary	Annealing (If φ>1.6)	Normally not necessary
Die life	2.000-5.000 workpieces	20.000-50.000 pieces	10.000-20.000 pieces
Cost for developing and building tools	Generally <10.000 DM	10.000-20.000 DM	Generally >20.000 DM

The flow stress of the billet material determines the mechanical tool stresses depending on the forming temperature, the forming degree and the strain rate. Figure 4.5 shows the trend of the flow stress curve for several materials as a function of the forming temperature [62]. The flow stress for various materials differs in the temperature range of cold forging but there is no significant difference in the warm forging range.

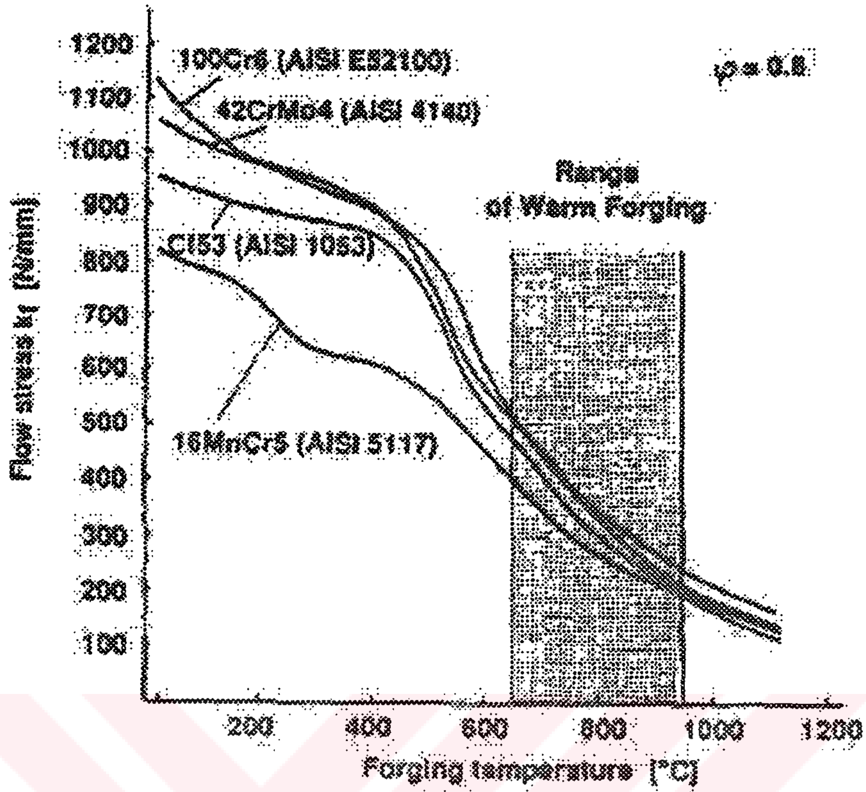


Figure 4.5. Flow Stress Curve of Several Materials Depending on Temperature [62]

As in the case of other forging processes lubrication plays an important role in warm forging. Lubrication techniques can be described as follows [79]:

a) Tooling lubricated with oil graphite emulsion
b) Slug coated with graphite, die lubricated with oil graphite emulsion
c) Slug coated with graphite and tool lubricated with water graphite suspension or graphite free lubricant
d) Slug coated without graphite, tool lubricated with oil graphite free lubricant.

For a warm forging press, the requirements can be outlined as follows [87]:

1) The press should work in such a way that it will have short contact times during deformation and provide enough time for cooling of the die to avoid heat and for inspection to provide good maintenance.

2) Since the billet temperature in warm forging is considerably lower than in hot forging the cooling of the billet in contact with the die occurs rather rapidly, therefore the press should have enough space to perform at least two forging operations, this is, to maximise the achievable deformation.
3) Since the amounts of lubricant required for warm forging are very large, the application of the lubricants lead to the deterioration of the surrounding environment. Therefore, the press must be enclosed to prevent leakage of the lubricant or its vapours. Also the press must be protected against corrosion by the warm forging lubricants.

4.6. HOT FORGING

Hot forging has performed for a long time in the production of aerospace and ordinance components, like turbine blades, turbine wheels, landing gear wheels, missile components, airframes, and bevel gears [82]. Recently the trend is to apply this technology for the production of commodity forgings like bevel, helical and spur gears [8,9], and flashless wrought steel connecting rods [88].

Due to the low flow stress of the material, hot forged parts have higher complexity than parts produced by cold and warm forging. However, their accuracy can only be as good as that of warm forgings. One of the main disadvantage of hot forging is the formation of scale on the surface of the billet during heating. In order to avoid this problem the use of precoated billets or heating of the billets in induction furnaces with inert atmosphere helps to minimise the problem. Another alternative is to use rapid induction heating to avoid the formation of scale in prior to forging of helical gears [75].

The accuracy of hot forgings can be improved by applying the following guidelines:

1) Correct the impression die by the exact calculation of the shrinkage of the forging and the thermo elastic deformation of the die during the forging process.
2) Exact manufacturing of the impression die by EDM after heat treatment.

3) Increase wear resistance by surface treatment, nitriding, nickel alloy deposition or welding.
4) Tight process control to reduce variations of the process. The control should be specially in the temperature of billet and dies, lubrication and automatic transfer of workpiece from one forging station to the next, and volume control of the billet.

Hot precision forging has been very successful in the production of axisymmetric parts, such as bearing races, for both ball and taper antifriction bearings [10], and for the production of spur helical and bevel gears [9], The main reason is that there are available approximate design methods to compensate for the shrinkage, elastic and thermal expansion of the dies [8]. In order to obtain near net products by precision forging it is necessary to control the volume of the billet to tight tolerances. Also the metal flow has to be controlled carefully from one station to the other so that the maximum allowable deformation is obtained without the formation of defects.

CHAPTER 5

PART GEOMETRY and FEATURE RECOGNITION

5.1 INTRODUCTION

Rotational axisymmetric parts are basically forged from cylindrical bars. The aim of this part of the study is the determination of part geometry. For this purpose DXF (Data Exchange File) format is used. Subsections and properties of DXF is expressed. Although rotational axisymmetric components are 3-D objects, their definitions are based on a 2-D profile interpretation.

5.2. GEOMETRIC MODELLING

Geometric modelling is the process in which a geometric model is created to represent the size and shape of a component in computer memory. It is the starting point of the product design and manufacturing process. Another crucial reason for its importance is that the accuracy of the model and the way in which the model is structured and stored in computer memory will have far-reaching effects on other CAD/CAM functions such as finite element analysis and drafting. Geometric modelling is often performed with the assistance of software programs, like AutoCAD, since interactive graphics enables users to enter, manipulate and modify the data easily for the construction of geometric models. A geometric model representing a component in computer memory may be a 2D or 3D depending on the capabilities of the CAD/CAM system and the requirements of the users.

Some CAD systems describes a component by low level information such as points, curves, surfaces and primitive solids. However, in downstream applications like CAPP and CAM, form features and technological information, namely tolerance, surface roughness, hardness, material, etc. are required. In these circumstances, interface between CAD and CAM, feature recognition system which analyses a CAD model can effectively be used. In this case, only geometric and topological information about a form feature can be extracted [16].

5.3. DATA EXCHANGE

The data exchange standards are mainly defined as the structures that make the transfer of the part information or product models possible between CAD and between CAD/CAM systems [90].

Automatic feature recognisers conceives features after the part is modelled on a solid modelling system. Recognition of features is performed using the geometric and topological information of the CAD data [89].

There are two important reasons for CAD data exchange. The first one is the need for enabling parts of companies with different CAD systems to transfer data to each other. The second one is due to the facilitation of concurrent engineering within a company or between companies. If CAD data is not exchanged, it has to be recreated or modified on a different CAD system. Some works have been undertaken to develop standard formats that would provide available means of communication between CAD systems. At present, several formats such as IGES, SET, STEP, DXF and etc., have been developed.

5.3.1. IGES (Initial Graphics Exchange Specification) Standard

IGES addresses the problem of exchanging CAD data between one CAD system and another. It is not concerned with communications between CAD systems and other computerised functions in a factory. IGES does not support complete product definition including features, tolerances, surface roughness, material, etc., which is essential for data transferring between CAD and CAPP/CAM systems. It assumes that a person is available at the receiving end to interpret the meaning of product model data [91].

5.3.2. SET (Standard d'echange Et de Transfert) Standard

SET is French national standard. SET allows the data exchange between dissimilar CAD/CAM systems. It was developed to exchange data in a more compact structure than that of IGES. It has a more general data structure than IGES and the data is compressed. Hence, the neutral data file size is smaller than that of IGES. Wire-frame models, surface models, B-Rep models, FEM models and technical drawings can all be transferred via SET standard.

5.3.3. STEP (Standard for the Exchange of Product Data) Standard

STEP is the international standard for geometric and non-geometric data transfer between CAD, CAE and CAM systems. The STEP which is also referred as ISO 10303 can be defined as a series of standards providing a platform or a mechanism that is designed for the standardisation and definition of all the processes and their parameters required to convert a CAD model to a product, independent of any of the design, application or manufacturing hardware and software or system [92].

Another data exchange file, DXF, is expressed in detail in the following section, after part geometry definition.

5.4. DRAWING PART GEOMETRY

In this system, an arbitrary two dimensional cross section which is composed of the entities including lines and arcs are dealt with. This section is decomposed and modified so that the system can appreciate the geometrical features. Creation of part geometry files has four main steps:

- Drawing of final part geometry using by AutoCAD
- Generation of DXF file (AutoCAD interface module)
- Feature recognition module
- Definition of forgeable geometry (will be expressed in Chapter 6)

AutoCAD is used as a complete drawing editor. Hence, the part geometry, which is fundamental input to the system, is drawn by using AutoCAD.

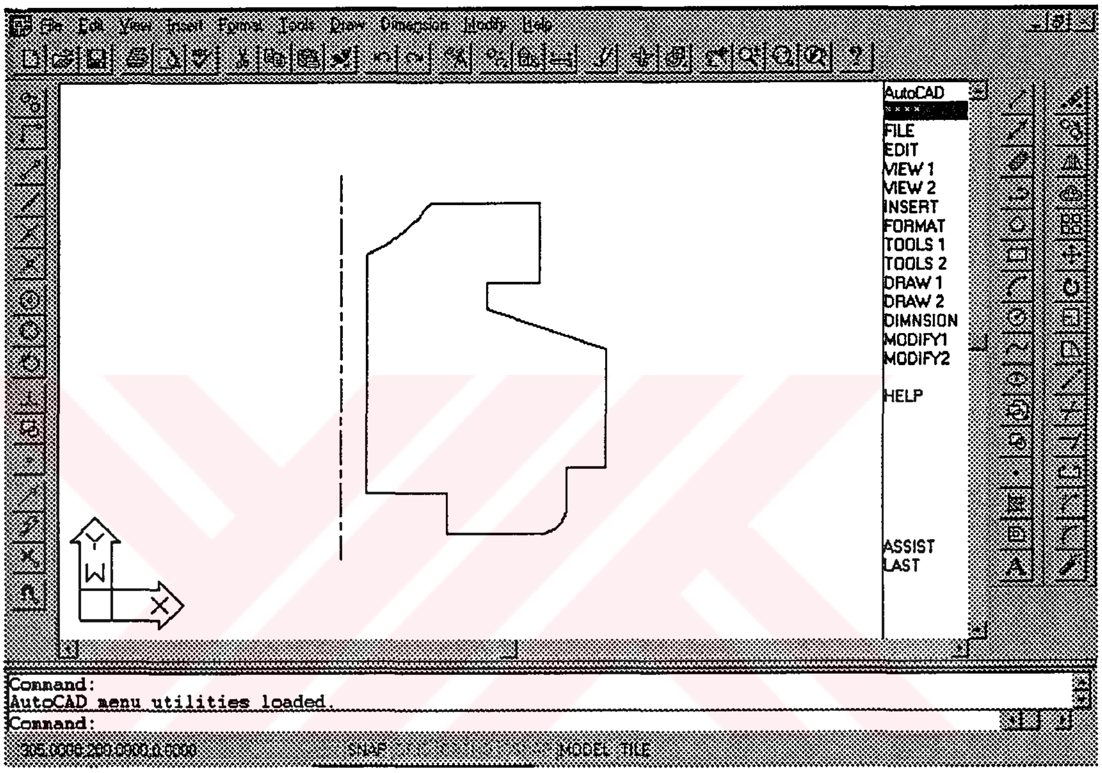


Figure 5.1. An Example for Right Portion of Axisymmetric Part

Since the part is rotational axisymmetric, it is enough to draw only one portion of the part. Thus, right hand portion of the product is considered throughout the work. When the part is drawn, as shown Figure 5.1, AutoCAD forms the file by "*.DWG " extension automatically. However, for some applications, other programs must examine AutoCAD drawings and use these drawings for modification. Data Exchange Files (DXF) enable the interchange of drawings between AutoCAD and other programs.

5.5. GENERATION OF DXF FILE

Before generation of DXF, the first step is the determination of the part geometry. Since the input data includes the final product geometry and material type, geometry definition plays an important role in CAD/CAM area.

DXF is a text file containing drawing information that can be read by other CAD systems or programs. If one works with consultants who use a CAD program that accepts DXF files, it is possible to share a drawing by saving it in DXF format. Once the drawing file is saved, the user must generate the DXF file of the related part by "DXFOUT" command. The computer program reads the DXF file and extracts all the entities from the file. The overall organisation of a DXF file contains six main groups:

- HEADER Section: General information about the drawing is found in this section. It consists of an AutoCAD database version number and a number of system variables. Each parameter contains a variable name and its associated value.
- CLASSES section: Holds the information for application-defined classes, whose instances appear in the BLOCKS, ENTITIES, and OBJECTS sections of the database. A class definition is permanently fixed in class hierarchy.
- TABLES section: This section contains definitions for the following symbol tables:
  APPID (Application identification table)
  BLOCK_RECORD (Block reference table)
  DIMSTYLE (Dimension style table)
  LAYER (Layer table)
  LTYPE (Linetype table)
  STYLE (Text style table)
  UCS (User Coordinate System Table)
  VIEW (View table)
  VPORT (Viewport configuration table)
- BLOCKS section: Contains block definition and drawing entities that make up each block reference in the drawing.

- ENTITIES section: This section contains the graphical objects (entities) in the drawing. If one use the ENTITIES option of the DXFOUT command, the resulting DXF file contains only the ENTITIES section and the EOF (End Of File) marker. The ENTITIES section contains only the objects you select for output. If you select an insert entity, the corresponding block definition is not included in the output file.
- OBJECTS section: Contains the nongraphical objects in the drawing. All objects that are not entities or symbol table records or symbol tables are stored in this section. Examples of entries in the OBJECTS section are dictionaries that contain MLINE style and groups.

The DXF format is a tagged data representation of all the information contained in an AutoCAD drawing file. Tagged data means that each data element in the file is preceded by an integer number that is called a group code. A group code's value indicates what type of data element follows. This value also indicates the meaning of a data element for a given object (or record) type. Virtually all user-specified information in a drawing file can be represented in DXF format. Group code ranges are presented in Appendix A1.

Essentially a DXF file is composed of pairs of codes and associated values. The codes, known as group codes, indicate the type of value that follows. Using these group code and value pairs, a DXF file is organised into sections, composed of records, which are composed of a group code and a data item. Each group code and value is on its own line in the DXF file.

Each section starts with a group code 0 followed by the string, SECTION. This is followed by a group code 2 and a string indicating the name of the section (for example, HEADER). Each section is composed of group codes and values that define its elements. A section ends with a 0 followed by the string ENDSEC.

Group codes and the associated values define a specific aspect of an object or entity. The line immediately following the group code is the associated value. This value can be a string, an integer, or a floating-point value, such as the X coordinate of a point. The lines following the second line of the group, if any, are determined by the group definition and the data associated with the group. Special group codes are used as file separators, such as markers for the beginning and end of sections, tables, and the end of the file itself.

Entities, objects, classes, tables and table entries, and file separators are introduced with a 0 group code that is followed by a name describing the group.

5.5.1. HEADER Section

The HEADER section of a DXF file contains the settings of variables associated with the drawing. Each variable is specified by a 9 group code giving the variable's name, followed by groups that supply the variable's value.

The following is an example of the HEADER section of a DXF file:

Variable	Description
0	Beginning of HEADER section
SECTION	
2	
HEADER	
9	Repeats for each HEADER variable
$<Variable>	
<Group Code>	
<Value>	
0	End of Header section
ENDSEC	

5.5.2. CLASSES Section

The CLASSES section holds the information for application-defined classes whose instances appear in the BLOCKS, ENTITIES, and OBJECTS sections of the database. It is assumed that a class definition is permanently fixed in the class hierarchy. All fields are required.

The following is an example of the CLASSES section of a DXF file:

Variable	Description
0	Beginning of CLASSES section
SECTION	
2	
CLASSES	
9	Repeats for each entry
<Class DXF Record>	
1	
<Class Name>	
2	
<App name>	
90	
<Variable number>	
280	
<Flag>	
281	
<Flag>	
0	End of CLASSES section
ENDSEC	

5.5.3. TABLES Section

The TABLES section contains several tables, each of which can contain a variable number of entries. These codes are also used by AutoLISP and ObjectARX applications in entity definition lists.

The order of the tables may change, but the LTYPE table always precedes the LAYER table. Each table is introduced with a 0 group code with the label TABLE. This is followed by a 2 group code identifying the particular table (APPID, DIMSTYLE, LTYPE, STYLE, VIEW, VPORT, or BLOCK_RECORD), LAYER, UCS, 5 group code (a handle), a 100 group code and a 70 group code that specifies the maximum number of table entries that may follow. Table names are output in uppercase characters. The DIMSTYLE handle is a 105 group code not a 5 group code. Following this header for each table are the table entries. Each table entry consists of a 0 group identifying the item type (same as table name, such as LTYPE or LAYER), a 2 group giving the name of the table entry, a 70 group specifying flags relevant to the table entry (defined for each following table), and additional groups that give the value of the table entry. The end of each table is indicated by a 0 group with the value ENDTAB.

5.5.4. BLOCKS Section

The group codes described in this chapter are found in DXF files and used by applications. The BLOCKS section contains an entry for each block reference in the drawing.

The BLOCKS section of the DXF file contains all the block definitions, including anonymous blocks generated by the HATCH command and by associative dimensioning. Each block definition contains the entities that make up that block as it is used in the drawing. The format of the entities in this section is identical to those in the ENTITIES section. All entities in the BLOCKS section appear between block and ENDBLK entities. Block and ENDBLK entities appear only in the BLOCKS section. Block definitions are never nested, although a block definition can contain an insert entity.

The block table handle, along with any XDATA and persistent reactors, appears in each block definition immediately following the BLOCK record, which contains all of the specific information that a block table record stores.

5.5.5. OBJECTS Section

This OBJECTS section presents the group codes that apply to nongraphical objects and these codes are used by AutoLISP and ObjectARX applications in entity definition lists.

The root owner of most objects appearing in the OBJECTS section is the named object dictionary, which is, therefore, always the first object that appears in this section. Objects that are not owned by the named object dictionary are owned by other entities, objects, or symbol table entries. Objects in this section may be defined by AutoCAD or by applications with access to ObjectARX API. The DXF names of application-defined object types should always be associated with a class name in the CLASS section of the DXF file, or else the object record cannot be bound to the application that will interpret it.

5.5.6. ENTITIES Section

The most important section, which defines the graphical objects is ENTITIES section. This section presents the group codes that apply to graphical objects.

The following Table 5.1 shows group codes that apply to virtually all graphical objects. Some of the group codes shown here are included with an entity definition only if the entity has nondefault values for the property. When group codes are referred by entity type the lists of codes associated with specific entities, the codes shown here are also present.

Table 5.1. General Group Codes Descriptions for Graphical Objects

Group code	Description
–1	APP: entity name (changes each time a drawing is opened)
0	Entity type
5	Handle
102	Start of application defined group "{application_name"
102	End of group, "}"
330	Soft pointer ID/handle to owner dictionary
102	End of group, "}"
360	Hard owner ID/handle to owner dictionary
102	End of group, "}"
330	Soft-pointer ID/handle to owner BLOCK_RECORD object
100	Subclass marker (AcDbEntity)
67	Absent or zero indicates entity is in model space. 1 indicates entity is in paper space
410	APP: layout tab name
8	Layer name
6	Linetype name (present if not BYLAYER). The special name BYBLOCK indicates a floating linetype
62	Color number (present if not BYLAYER); zero indicates the BYBLOCK (floating) color; 256 indicates BYLAYER; a negative value indicates that the layer is turned off.
48	Linetype scale
60	Object visibility
92	The number of bytes in the image
310	Preview image data

As it was stated at the beginning of the section drawing file is formed by lines and arcs. The following Table 5.2 and Table 5.3, taken from ENTITIES section of DXF file, show the group codes for a single *line entity* and *arc entity.*

Table 5.2. DXF Group Codes Descriptions for Line Entity

Group Codes	Description
0	Text String indicating the entity type
LINE	Entity
5	Entity handle
4D	
100	Subclass data marker
AcDbEntity	
8	Layer name group code
0	Name of layer
100	Subclass data marker
AcDbLine	
10	Group code of starting point of a line (X)
138.733972	X value of starting point
20	Group code of starting point of a line (Y)
165.0	Y value of starting point
30	Group code of starting point of a line (Z)
0.0	Z value of starting point
11	Group code of ending point of a line (X)
180.0	X value of ending point
21	Group code of ending point of a line (Y)
165.0	Y value of ending point
31	Group code of ending point of a line (Z)
0.0	Z value of ending point

Table 5.3. DXF Group Codes Descriptions for Arc Entity

Group Codes	Description
0	Text String indicating the entity type
ARC	Entity
5	Entity handle
5F	
100	Subclass data marker
AcDbEntity	
8	Layer name group code
0	Name of layer
100	Subclass data marker
AcDbCircle	
10	Group code of center point of an arc (X)
90.0	X value of starting point
20	Group code of center point of an arc (Y)
200.0	Y value of starting point
30	Group code of center point of an arc (Z)
0.0	Z value of starting point
40	Group code for radius
60.0	Radius value
100	Subclass data marker
AcDbArc	
50	Group code for start angle of an arc
294.624318	Start angle (in CCW direction)
51	Group code for end angle of an arc
324.314665	End angle (in CCW direction)

5.6. FEATURE RECOGNITION MODULE

Feature Recognition Module (FRM) is designed to interpret the part geometry from DXF file of the drawing.

Once the DXF file is obtained, it is seen that, *Entities section* presents all the graphical information in *drawing order*. Drawing entities can be either LINE or ARC and these entities can be drawn in 14 different ways (Figure 5.2.a). As it is shown in Table 5.2, while group codes 10, 20 and 30 representing the starting point of X, Y and Z coordinates of LINE and 11, 21 and 31 group codes represent the end point of X, Y and Z coordinates of LINE respectively, it is important to define the drawing sequence (Figure 5.2.b). For 2D drawing objects, group codes of 30 and 31 have no importance.

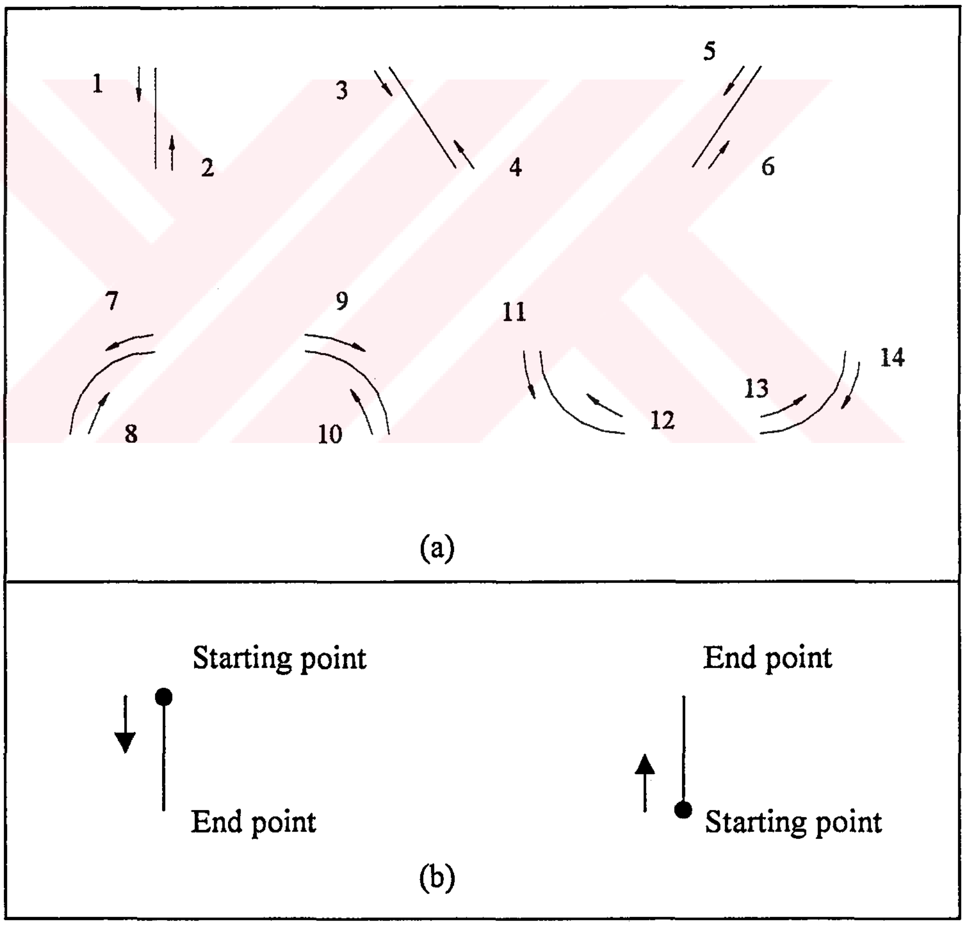


Figure 5.2. Drawing Way
a) Different Way of Drawings
b) Drawing Sequence for Single Line Entity

In the following sample drawing, co-ordinates of vertices, drawing sequence and drawing directions are shown in Figure 5.3 and Figure 5.4.a respectively.

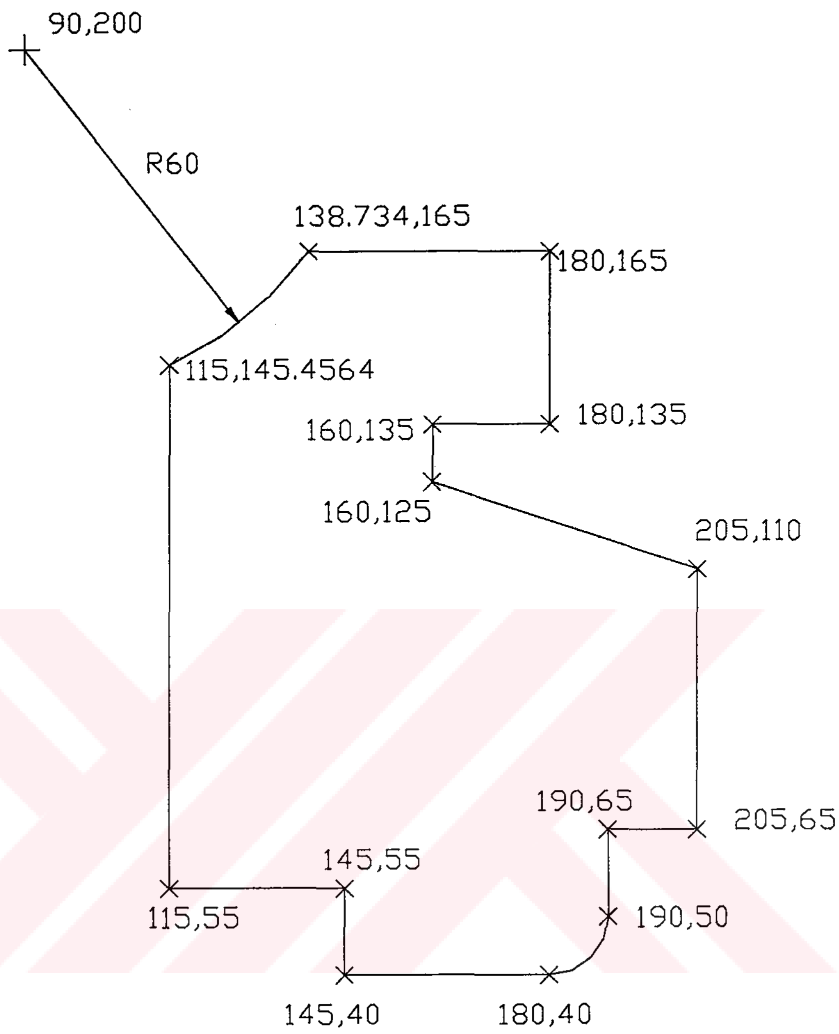


Figure 5.3. Co-ordinates of Sample Drawing

After drawing of part geometry, DXF file is generated. The DXF format is quite wordy and it uses a single line for each data item. The DXF file of Figure 5.3 has about 2000 lines. Therefore, understanding of a DXF file is important in order to make some changes and regenerate the file. In order to understand the co-ordinates of LINES and ARCS, only *Entities section* of DXF file is shown in Table 5.4. Whole DXF file can be found in Appendix A2.

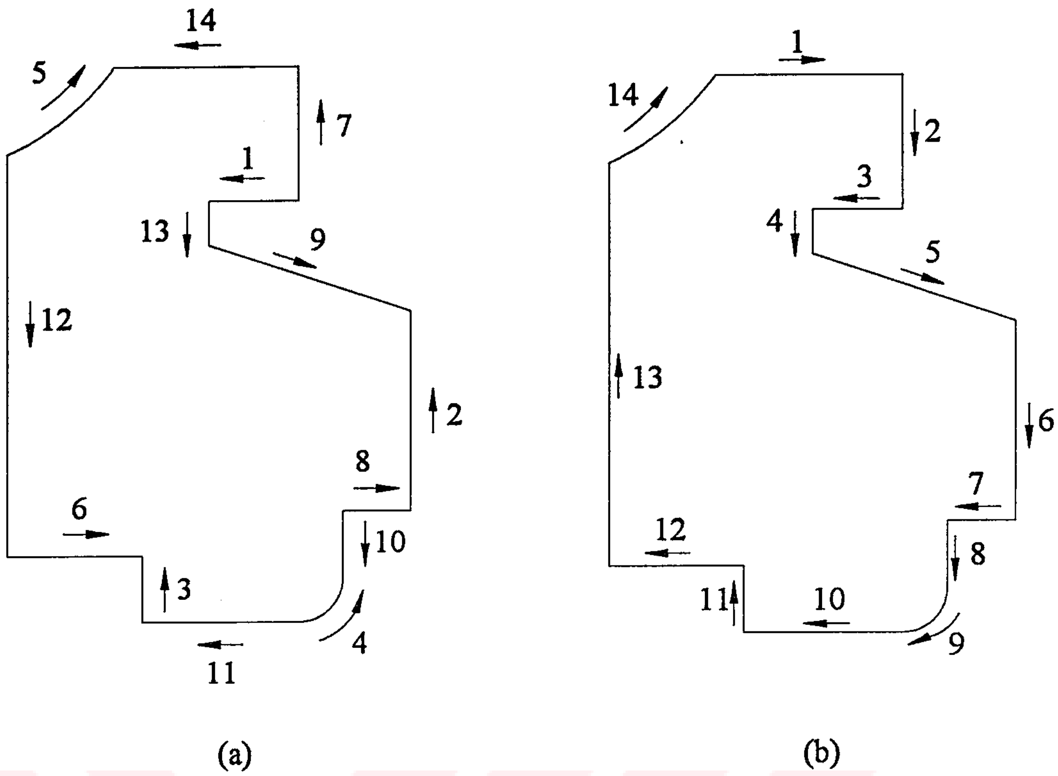


Figure 5.4. Drawing Way for Product
(a) Arbitrary Drawing Sequence and Direction of Entities
(b) Reorganisation of Entities

As it is seen from the Figure 5.4.a, entities may not be drawn in sequence. This situation must be taken into account. Because, as it will be stated in the following chapter, forgeable geometry and all geometric calculations are based on certain rules. While creation of the rules, drawn entities must be put into order (Figure 5.4.b).

A computer program, which is going to be written, reads a DXF file and extracts all the line entities from the drawing. It displays the values of 10, 20, 11, 21, 40, 50 and 51 group codes which is related to the entities and put them into table (Table 5.5).

When the table is obtained, LINE and ARC values are put into order from top to bottom. This is very important to define the forgeable geometry due to the formation of RULES. In order to determine the forgeable geometry small steps and under cuts should be eliminated. This elimination is based on certain RULES.

Table 5.4. Entities Section of DXF File for Figure 5.3.

```
0
SECTION
 2
ENTITIES
 0
LINE
 5
4F
100
AcDbEntity
 8
0
100
AcDbLine
 10
180.0
 20
135.0
 30
0.0
 11
160.0
 21
135.0
 31
0.0
 0
LINE
 5
53
100
AcDbEntity
 8
0
100
AcDbLine
 10
205.0
 20
65.0
 30
0.0
 11
190.0
 21
65.0
 31
0.0
 0
LINE
 5
57
100
AcDbEntity
 8
0
100
AcDbLine
 10
145.0
 20
40.0
 30
0.0
 11
145.0
 21
55.0
 31
0.0
 0
LINE
 5
5C
100
AcDbEntity
 8
0
 6
CENTER
100
AcDbLine
 10
105.0
 20
175.0
 30
0.0
 11
105.0
 21
30.0
 31
0.0
 0
LINE
 5
7E
100
AcDbEntity
 8
0
100
AcDbLine
 10
115.0
 20
145.45643
9
 30
0.0
 11
115.0
 21
55.0
 31
0.0
 0
LINE
 5
7F
100
AcDbEntity
 8
0
100
AcDbLine
 10
205.0
 20
65.0
 30
0.0
 11
205.0
 21
110.0
 31
0.0
 0
LINE
 5
80
100
AcDbEntity
 8
0
100
AcDbLine
 10
180.0
 20
135.0
 30
0.0
 11
180.0
 21
165.0
 31
0.0
 0
LINE
 5
81
100
AcDbEntity
 8
0
100
AcDbLine
 10
190.0
 20
50.0
 30
0.0
 11
190.0
 21
65.0
 31
0.0
 0
LINE
 5
82
100
AcDbEntity
 8
0
100
AcDbLine
 10
205.0
 20
110.0
 30
0.0
 11
160.0
 21
125.0
 31
0.0
 0
LINE
 5
83
100
AcDbEntity
 8
0
100
AcDbLine
 10
115.0
 20
55.0
 30
0.0
 11
145.0
 21
55.0
 31
0.0
 0
LINE
 5
84
100
AcDbEntity
 8
0
100
AcDbLine
 10
145.0
 20
40.0
 30
0.0
 11
180.0
 21
40.0
 31
0.0
 0
ARC
 5
85
100
AcDbEntity
 8
0
100
AcDbCircle
 10
180.0
 20
50.0
 30
0.0
 40
10.0
100
AcDbArc
 50
270.0
 51
0.0
 0
LINE
 5
86
100
AcDbEntity
 8
0
100
AcDbLine
 10
160.0
 20
125.0
 30
0.0
 11
160.0
 21
135.0
 31
0.0
 0
LINE
 5
87
100
AcDbEntity
 8
0
100
AcDbLine
 10
180.0
 20
165.0
 30
0.0
 11
138.73397
2
 21
165.0
 31
0.0
 0
ARC
 5
88
100
AcDbEntity
 8
0
100
AcDbCircle
 10
90.0
 20
200.0
 30
0.0
 40
60.0
100
AcDbArc
 50
294.62431
8
 51
324.31466
5
 0
ENDSEC
```

Once the values are obtained form the DXF file, they are placed into the table. Table 5.5 shows DXF file group codes of 10, 20, 11, 21, 40, 50 and 51 for Figure 5.3. from the *Entities section.*

Table 5.5. Group Codes for Sample Figure 5.3

10	20	11	21	40	50	51
180	135	160	135			
205	65	190	65			
145	40	145	55			
115	145.4564	115	55			
205	65	205	110			
180	135	180	165			
190	50	190	65			
205	110	160	125			
115	55	145	55			
145	40	180	40			
180	50			10	270	0
160	125	160	135			
180	165	138.7339	165			
90	200			60	294.6243	324.3146

This table should be put into order according to the entity continuation. As it is seen from Table 5.5, co-ordinates of lines and arc are not following each other. Therefore, co-ordinates of the end point of a line should also be the starting point of continuing line. This is the key point of lines for putting them into order. However, this procedure is interrupted when the arc comes after line. Because, in DXF file, the co-ordinates of starting and end points of an arc can not be seen. For arc entity, group codes are:

10	X co-ordinate of center point
20	Y co-ordinate of center point
40	Radius of an arc
50	Start angle of an arc
51	End angle of an arc

Therefore by using these values, co-ordinates of starting and end point of arcs must be determined. Figure 5.5 and following mathematical expression calculates these needed values for the arcs drawn in counter clockwise direction.

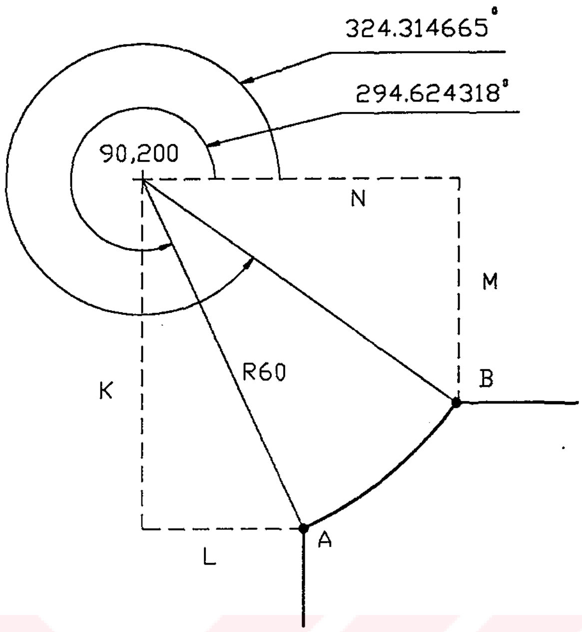


Figure 5.5. Presentation of an Arc Drawing Parameters

$Ax = 90 + L = 90 + 60.\cos 294.624318 = 115$

$Ay = 200 + K = 200 + 60.\sin 294.624318 = 145.4564$

$Bx = 90 + N = 90 + 60.\cos 324.314665 = 138.7339$

$By = 200 + M = 200 + 60.\sin 324.314665 = 165$

These expressions can be formulated according to the group codes. Following Figure 5.6 shows the formulae for an arc drawn in counter clockwise direction. In the following formulation; boxed numbers show the group codes.

$Ax = \boxed{10} + \boxed{40}.\ \cos \boxed{50}$

$Ay = \boxed{20} + \boxed{40}.\ \sin \boxed{50}$

$Bx = \boxed{10} + \boxed{40}.\ \cos \boxed{51}$

$By = \boxed{20} + \boxed{40}.\ \sin \boxed{51}$

Figure 5.6. Co-ordinate Formulae for an Arc Drawn in CCW

Following Figure 5.7 shows the formulae for an arc drawn in clockwise direction.

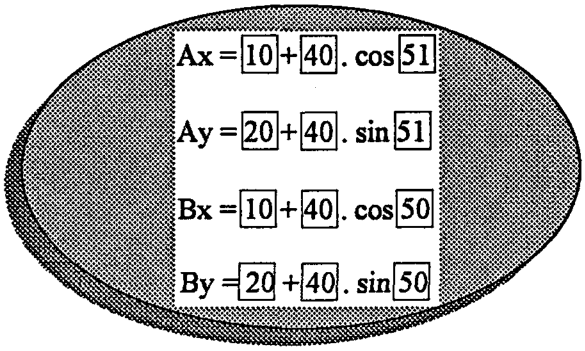


Figure 5.7. Co-ordinate Formulae for an Arc Drawn in CW

The algorithm for putting into sequence of lines and arcs is shown in Figure 5.8

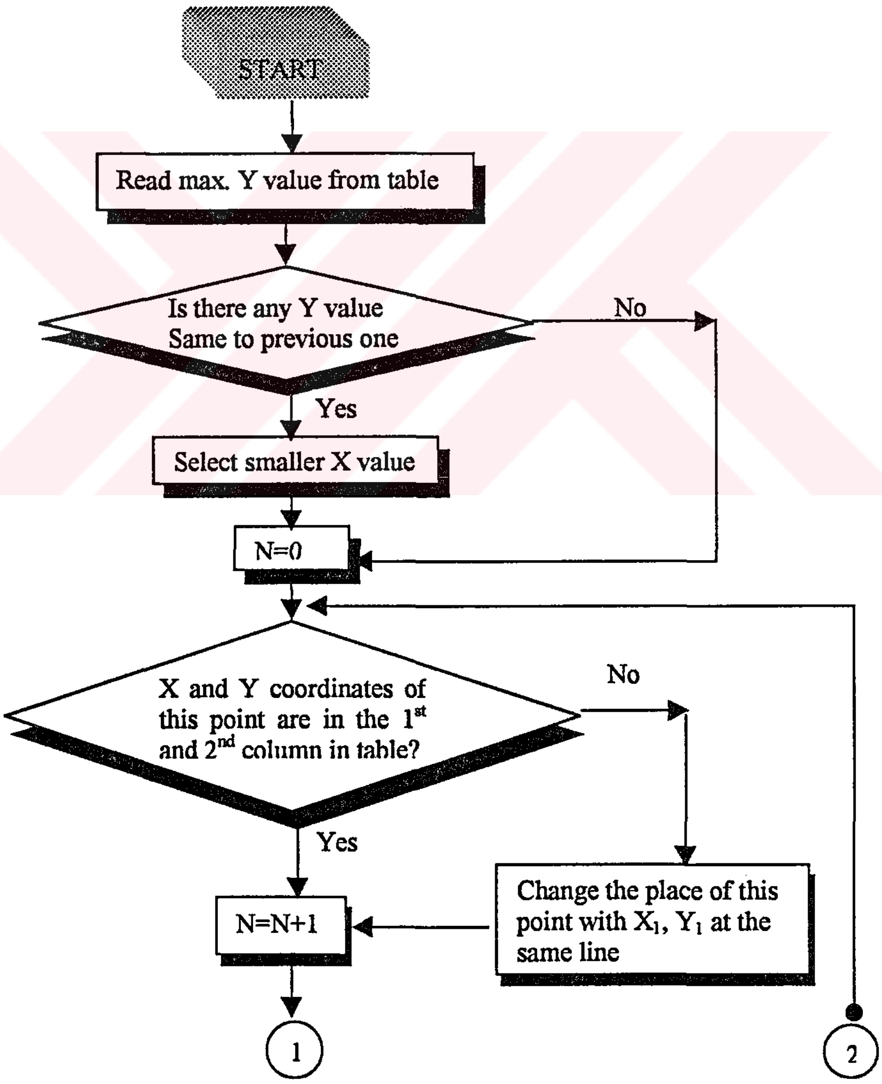


Figure 5.8. Algorithm for Putting into Sequence of Lines and Arcs

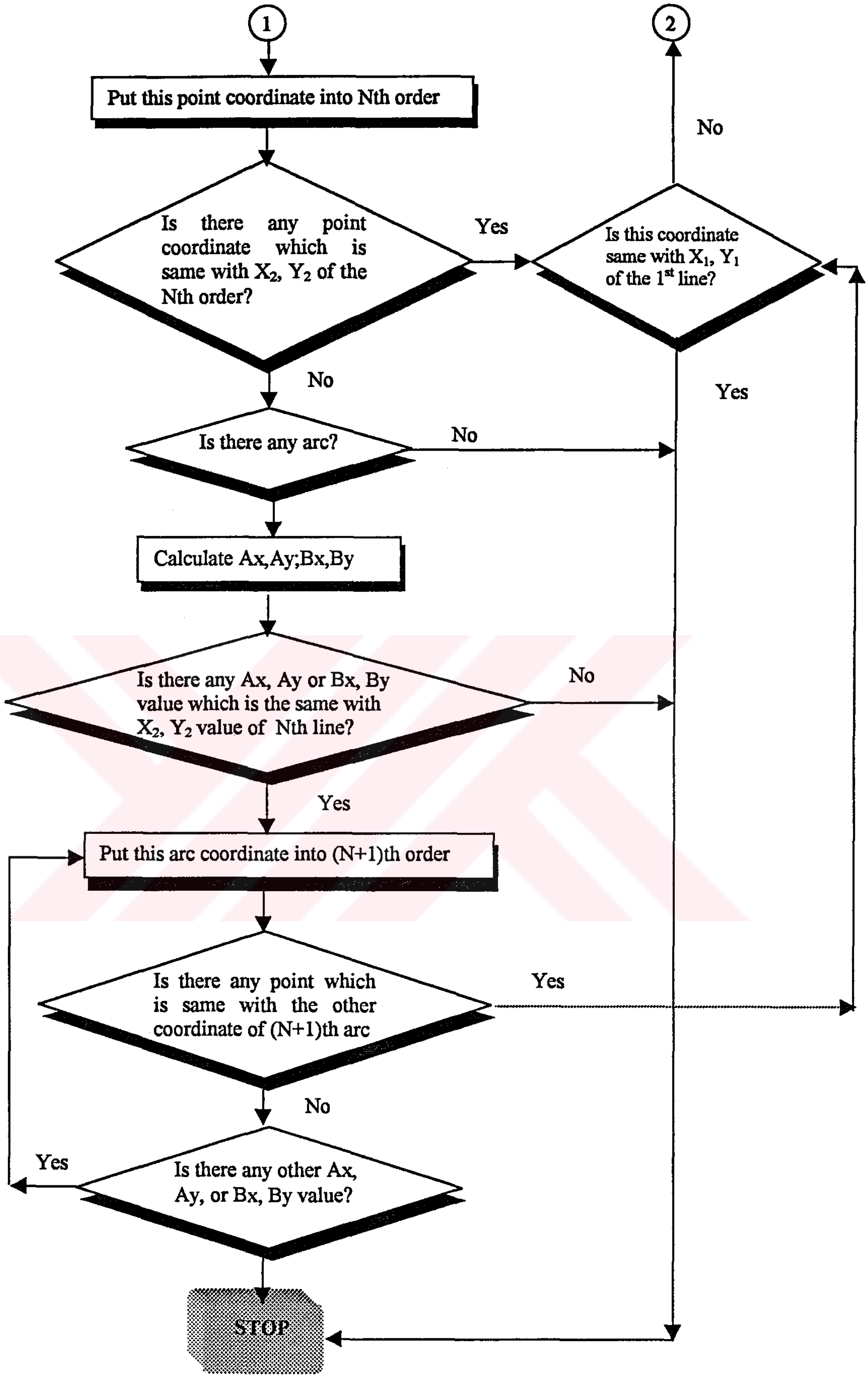


Figure 5.8 Algorithm for Putting into Sequence of Lines and Arcs (Continued)

After this algorithm is applied to the Table 5.5, which is obtained from DXF file, all the line and arc entities can be put into order from top to bottom. This is shown in Table 5.6. Since the center line is not from the actual geometry, it is placed at the end of table.

Table 5.6. Ordered Group Code Data for Figure 5.3

10	20	11	21	40	50	51
138.7339	165	180	165			
180	165	180	135			
180	135	160	135			
160	135	160	125			
160	125	205	110			
205	110	205	65			
205	65	190	65			
190	65	190	50			
180	50			10	270	0
180	40	145	40			
145	40	145	55			
145	55	115	55			
115	55	115	145.4564			
115	145.4564			60	294.6243	324.3146

At this point, co-ordinates of all graphical entities are then transferred into Table 5.6. After this, the part drawing data is processed in order to prepare the entity definition data table, which is to be used in proceeding processes. The next step is the determination of forgeable geometry. In the next chapter, the data in this table will be used for forgeable geometry.

CHAPTER 6

FORGEABLE GEOMETRY

6.1. INTRODUCTION

Generation of DXF file is very important to determine the forgeable geometry. In this chapter, after presenting some different approaches, forgeable criteria will be discussed and new generated coding system will be explained by giving practical examples.

6.2. STRUCTURE of the GENERATED WORK

General outline of the developed program is shown in the Figure 6.1. It has four main parts. Once the final product geometry is provided as input, the system gets the DXF file, extracts entities formed by arcs and lines and puts them into order from top to bottom of the shape.

The current program can handle rotational axisymmetric geometries. Moreover, since the program structure has individual rules for each entity and geometry, it is possible to enlarge the system by adding new rules to get forgeable geometry for different geometric shapes without modifying the system shell. This program also recommends the most appropriate forging direction by considering the required forging load and forging criteria.

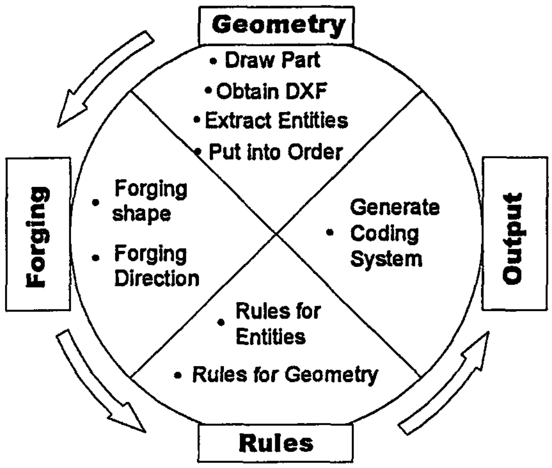


Figure 6.1. A General Outline of the Generated Work for Forgeable Geometry

Geometry section of the Figure 6.1 was discussed and explained in the previous chapter in detail. Forging, rules and output sections are explained in the following sections.

6.3. AXISYMMETRIC FORGING SHAPES

Rotational axisymmetric parts are basically forged from cylindrical bars. If both sides of the centre line of part is exactly alike, it is called axisymmetric part.

The most critical information necessary for forging die design and equipment specification for a given material is the geometry shape of forging to be produced. The initially given input geometry of the final product should be checked whether it is forgeable in closed die or not. The forgeable geometry is obtained by removing under-cuts, small steps or unforgeable fillets.

There is no completely satisfactory system as yet for classifying the shapes of forgings that is both practical and lends itself conveniently to mathematical and computer manipulation [63]. In order to achieve the input of the forged section geometry and make some rules for forgeable geometry, forging shapes should be classified.

The forging group represents a family of geometry types that can be produced by similar forging sequences. Currently, the developed system is concentrated on two broad groups as shown in Figure 6.2. These are:

- Unilateral shapes
- Bilateral shapes

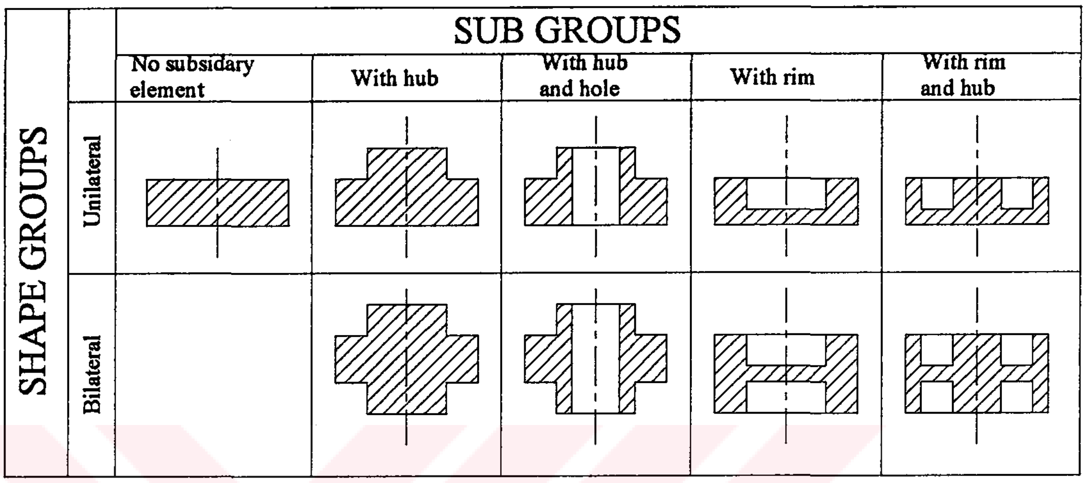


Figure 6.2. Classification of Axisymmetric Forging Shapes [63]

If the shape is forged from only its one side, it is called "unilateral shape". If the shape is forged from its both sides and therefore forming occurs in die and punch cavity, it is called "bilateral shape".

6.4. FORGING DIRECTION

Each forging geometry group is determined by examining the final forging geometry, the only relevant rule-base will be accessed to a working memory. In the graphical representation, if Y coordinate of the maximum X coordinate of a point is the maximum or minimum Y value of the shape, it is said to be unilateral shape (Figure 6.3). In near-net shape forging (closed die forging), exact volume of the finished part should be placed into die. The input geometry may not be given in correct forging direction. Therefore, in order to define the forging side of the part, it is checked first whether it is unilateral or bilateral, and then program proposes the appropriate forging side of the shape.

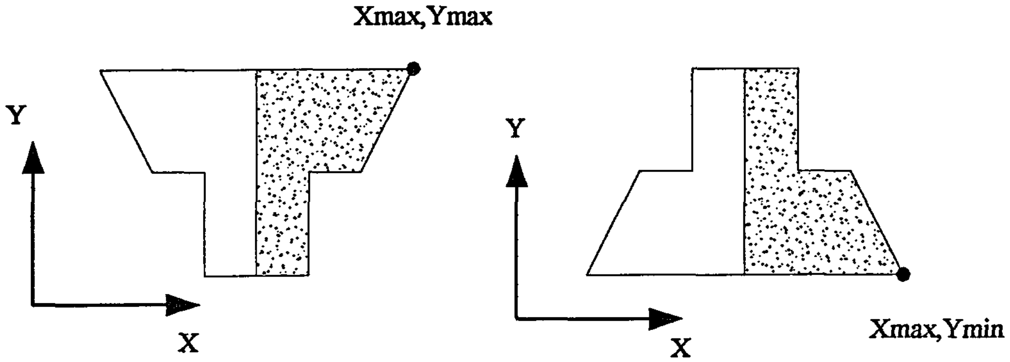


Figure 6.3. Sample for Unilateral Shapes

Unilateral forging shapes use solid punches. That means no cavity in punch. Therefore, maximum diameter of the shape should be placed on top. If the input geometry has maximum diameter at the bottom, it needs to be converted (Figure 6.4).

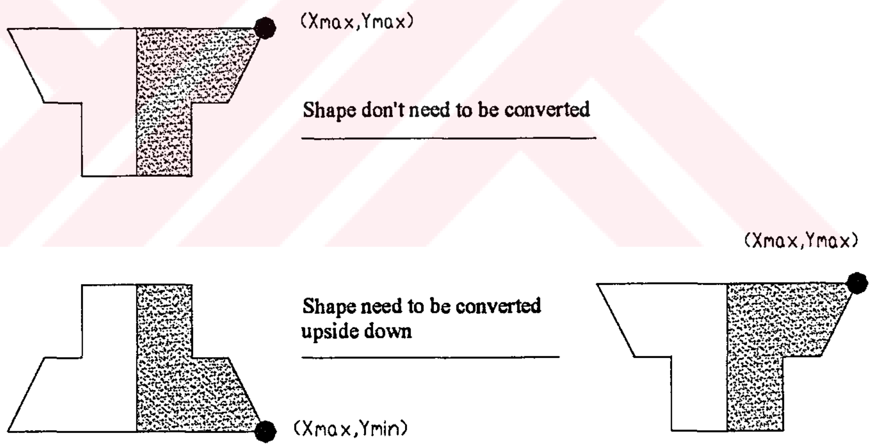


Figure 6.4. Forging Direction for Unilateral Shape

If Y coordinate of the maximum X coordinate is not maximum and minimum Y value of the shape, it is said to be bilateral shape. For bilateral shapes, forging side is determined according to required forging load. Therefore, forging load must be calculated for both sides of forging direction and the smaller one should be selected. Figure 6.5. shows the algorithm for unilateral and bilateral shapes.

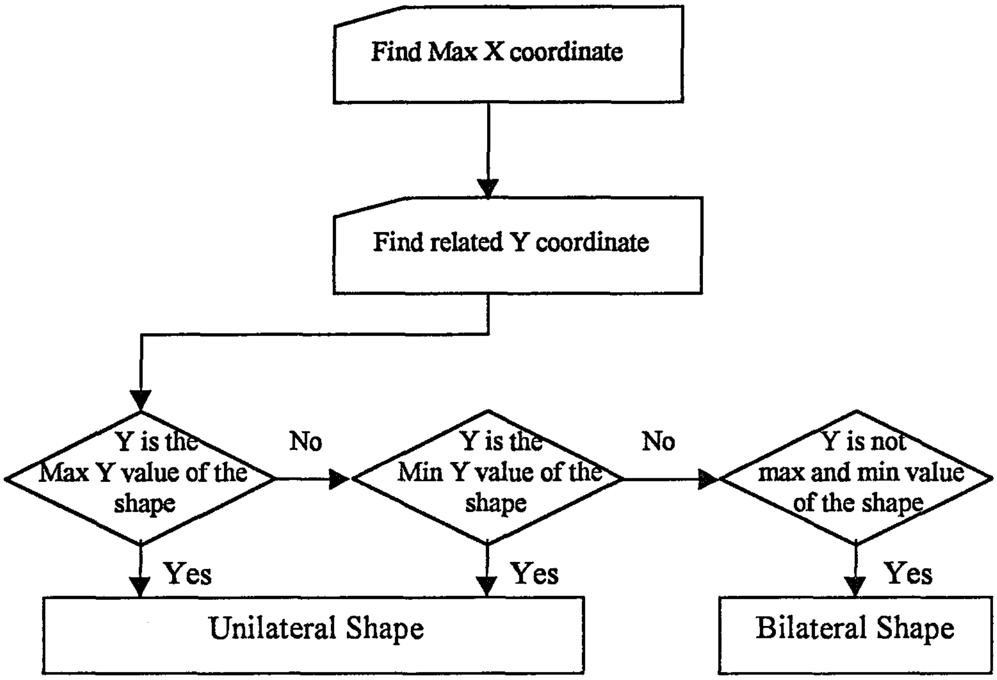


Figure 6.5. Algorithm for Unilateral and Bilateral Shapes

In closed die forging, maximum volume of the forged part should be placed into die. But, Initially given input geometry may not be given in required position. For forging direction it is checked first, whether unilateral or bilateral. And then, decision is given in order to convert direction of the shape or not. For unilateral shapes computer flowchart is shown in Figure 6.6. According to this flowchart, forging direction is determined.

For unilateral shapes, shape is converted or not according to the outer side. Figure 6.4 shows forging direction and Figure 6.6 shows the process. For outer side, if there is only one X value, inner side is controlled.

Forging side rule for outer side of unilateral shapes:

```
RULE OUT_CON_A
FIND        maximum X coordinate of a point on figure.
IF          Y coordinate of this point has also maximum Y coordinate
THEN        Shape does not need to be converted upside down
ELSE        Shape needs to be converted upside down
```

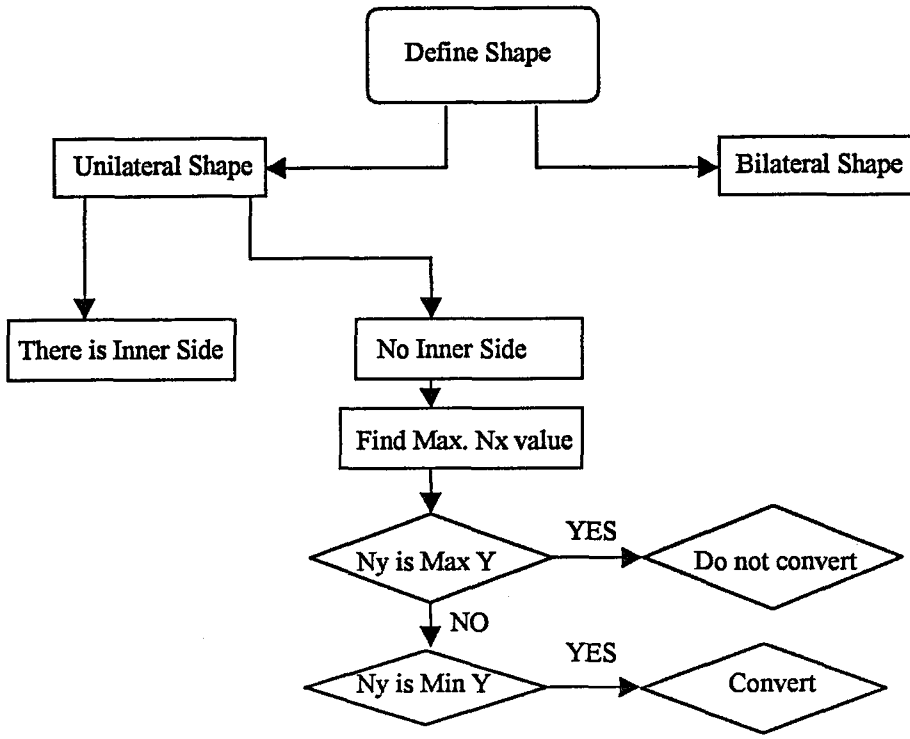


Figure 6.6. Unilateral Shapes Computer Flowchart

The nomenclature for Figure 6.7 is:

Nx: X coordinate of a point on shape.

Ny: Y coordinate of a point N.

For the inner side, firstly the smallest X value is determined. Then its Y value is checked. If Y distance to the *top point (TP)* is bigger than Y distance to the *bottom point (BP)*, then do not need to convert otherwise it is need to be converted. On the inner side if there are two points which have the smallest X value, Y values of these points are compared with top and bottom points of the shape. If the distance between the TP and the greater Y value is bigger than the distance between the BP and the smaller Y value, then it is converted otherwise it is not. Definitions of TP and BP are given below.

<u>Top Point (TP):</u> Top point is the intersection of inner and outer sides which have the biggest Y coordinate. If there are two biggest Y coordinate, then smaller X value of them is *top point*.

<u>Bottom Point (BP):</u> Bottom point is the intersection of inner and outer sides which have the smallest Y coordinate. If there are two smallest Y coordinate, then smaller X value of them is *bottom point*.

Figure 6.7 shows a sample for unilateral shape. For this figure according to the outer side, it doesn't matter weather it is converted or not. This figure shows the inner side positions for both only one point which has smallest X value (Figure 6.7.a) and two points which have the same smallest X values (Figure 6.7.b).

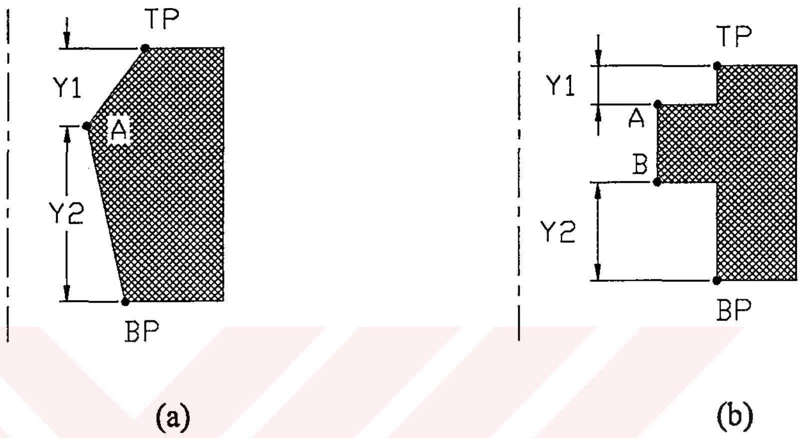


Figure 6.7. Inner Side Positions for Unilateral Shapes

a) There is only one point which has the smallest X coordinate

b) There are two points which have the smallest X coordinate

Forging side rule for inner side of unilateral shapes:

```
RULE IN_CON_A
IF          there is only one point which has a minimum X coordinate
     AND IF      the distance from this point to TP is greater than
                 or equal to the distance from this point to BP
THEN        Shape does not need to be converted upside down
ELSE        Shape needs to be converted upside down
```

From Figure 6.7. a mathematical expression can be given as:

$Y1 < Y2$ ⇒ This is the appropriate forging direction for Figure 6.7

$Y1 > Y2$ ⇒ This is not the appropriate forging direction for Figure 6.7

6.5. FEATURE BASED DESIGN (FBD)

The main deficiency with feature-based modelling is associated with the difficulty in representing composite features with complex curves and surfaces. A methodology for overcoming this deficiency is to have a user interactively identify complex features from basic geometrical features and entities [121]. These geometric features for each entity is structured in a knowledge base.

The knowledge base contains the required data to execute the program and it is available for new geometric shapes to generate the knowledge base without modifying the system shell. Knowledge within the system is not stored in specific memory locations. Knowledge is distributed throughout the system and it is dynamic response to the inputs. Since knowledge is distributed, the system uses many connections to retrieve solutions to particular problems.

6.6. CODING SYSTEM for FORGEABLE GEOMETRY

In the present work, all entities are manipulated by numerical operations by the coding system. From the input geometry of the final product, each line and arc is coded according to its property by the developed computer program, called FORGAX. In order to determine the forgeable geometry each line and arc is named and a digit number (code) is given individually according to its property. Each code represents different entity and these codes, are used for the determination of part feature. Thus, knowledge base for forgeable geometry is formed by using several IF-THEN rules.

Entities section of the DXF file which is converted into table, should be put into order from top to bottom for outer section and bottom to top for inner section (this part is discussed in previous chapter). Each entity is then coded individually. Figure 6.8 shows the codes of entities and Figure 6.9 shows the entity definition rules.

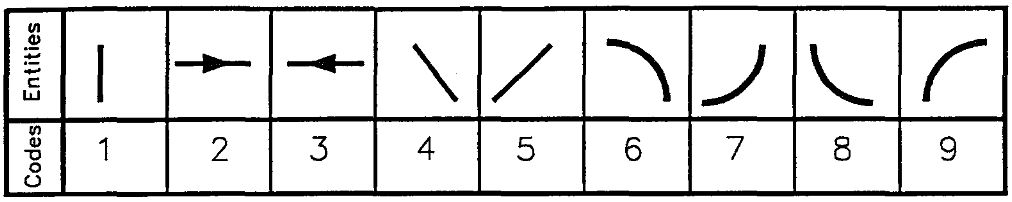


Figure 6.8. Entitiy Codes

All forgeable geometry rules are generated from the coordinates of entities and the codes. In the following Figure 6.9 entity rules and codes are presented.

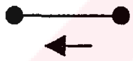
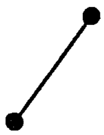
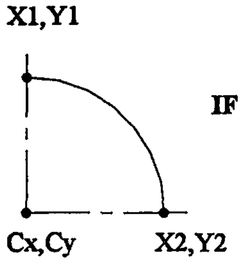
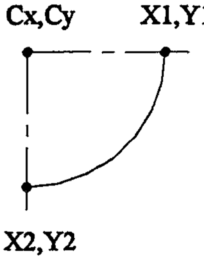
X1,Y1  X2,Y2	IF	X1=X2 and Y1>Y2 or Y1<Y2 and Entity=LINE	THEN	"Vertical Line"	Code:1
X1,Y1 X2,Y2 	IF	X1<X2 and Y1=Y2 and Entity=LINE	THEN	"Right Hand Horizontal Line"	Code:2
X2,Y2 X1,Y1 	IF	X1>X2 and Y1=Y2 and Entity=LINE	THEN	"Left Hand Horizontal Line"	Code:3
X1,Y1  X2,Y2	IF	X1<X2 and Y1>Y2 or X1>X2 and Y1<Y2 and Entity=LINE	THEN	"Left Hand Inclined Line"	Code:4
X1,Y1  X2,Y2	IF	X1>X2 and Y1>Y2 or X1<X2 and Y1<Y2 and Entity=LINE	THEN	"Right Hand Inclined Line"	Code:5

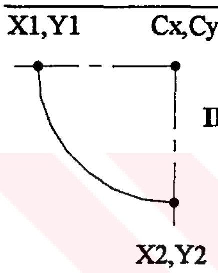
Figure 6.9. Entity Definition Rules



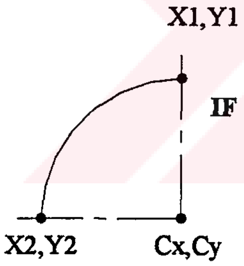
IF	X1<X2 and Y1>Y2 and Entity=ARC Cy < Y1 and Cx < X2	OR	X1>X2 and Y1<Y2 and Entity=ARC Cy < Y2 and Cx < X1	THEN "1st Quarter Arc"	Code:6



IF	X1>X2 and Y1>Y2 and Entity=ARC Cy > Y2 and Cx < X1	OR	X1<X2 and Y1<Y2 and Entity=ARC Cy > Y1 and Cx < X2	THEN "4th Quarter Arc"	Code:7



IF	X1<X2 and Y1>Y2 and Entity=ARC Cx >X1 and Cy>Y2	OR	X1>X2 Y1<Y2 Entity=ARC Cx >X2 and Cy >Y1	THEN "3rd Quarter Arc"	Code:8



IF	X1>X2 and Y1>Y2 and Entity=ARC Cx >X2 and Cy <Y1	OR	X1<X2 Y1<Y2 Entity=ARC Cx >X1and Cy <Y2	THEN "2nd Quarter Arc"	Code:9

Figure 6.9. Entity Definition Rules (Continued)

The entities section from DXF file is transferred into table in drawing order. But this table should be revised from TP to BP and introduced with coding system. The developed program, FORGAX, part features are denoted by simple abbreviations as shown in Table 6.1. The group codes of entities and coding numbers of Figure 6.10 is shown in Table 6.2. Group code definitions for line and arc were explained in Chapter 5. But for very short repetition;

- Group codes of 10 and 20 are starting point of LINE,
- Group codes 11 and 21 are end point of LINE.
- Group codes of 10 and 20 are center coordinates of ARC,
- Group code of 40 is radius,
- Group codes of 50 and 51 are start and end angle of ARC.

Table 6.1. Features and Their Acronyms

NO	FEATURE	ACRONYM
1	Vertical Line	V-LINE
2	Right Hand Horizontal Line	RHH-LINE
3	Left Hand Horizontal Line	LHH-LINE
4	Left Hand Inclined Line	LHI-LINE
5	Right Hand Inclined Line	RHI-LINE
6	1st Quarter Arc	FQ-ARC
7	4th Quarter Arc	FQ-ARC
8	3rd Quarter Arc	TQ-ARC
9	2nd Quarter Arc	SQ-ARC

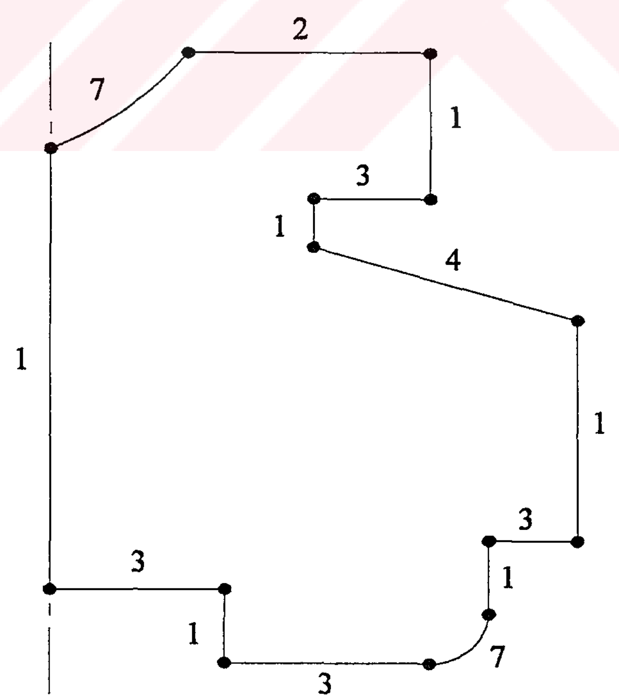


Figure 6.10. Sample Drawing Showing Group Codes

Table 6.2. Group Codes and Coding of Figure 6.10.

Entity	10	20	11	21	40	50	51	Code	Acronym
Line	138.73	165	180	165				2	RH-LINE
Line	180	165	180	135				1	V-LINE
Line	180	135	160	135				3	LHH-LINE
Line	160	135	160	125				1	V-LINE
Line	160	125	205	110				4	LHI-LINE
Line	205	110	205	65				1	V-LINE
Line	205	65	190	65				3	LHH-LINE
Line	190	65	190	50				1	V-LINE
Arc	180	50			10	270	0	7	FQ-LINE
Line	180	40	145	40				3	LHH-LINE
Line	145	40	145	55				1	V-LINE
Line	145	55	115	55				3	LHH-LINE
Line	115	55	115	145.45				1	V-LINE
Arc	115	145.45			60	294.62	324.31	7	FQ-LINE

Code order from top point of Figure 6.10 to bottom and from bottom point to top is:

Series:	2-1-3-1-4-1-3-1-7-3	1-3-1-7
	From TP to BP	BP to TP

The reason for separating codes, from TP to BP and BP to TP, is the difference in forgeable geometry rules. Because geometry rules are different for both inner and outer side of the product geometry.

This coding system helps the designer for forgeable geometry to determine the undercuts. Undercut means unforgeable area in near net shape forging. Since each code represents an entity, the expert system which is formed by IF-THEN rules evaluate these codes. Then, program decides the given shape whether it is forgeable or not. The developed system determines the unforgeable sections and also eliminates the unforgeable area. Finally, program advises the forgeable geometry. Some previous studies determined the geometry for turning operations. But, this section of study differs itself from previous studies in that not only determining geometry but also determining unforgeable section and generating to forgeable section.

In coding system, outer and inner sides of the shape are examined individually since their forgeable rules are slightly different.. For outer side, 3-5-7 and 9 coded entities may cause some problems. Maximum diameter side of the shape must be on top for unilateral shapes and therefore, shape geometry gets smaller from top to bottom.

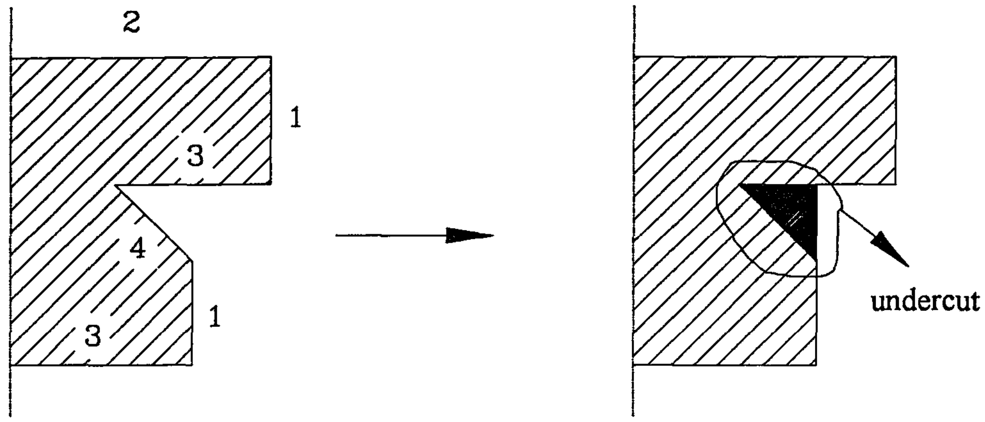
For bilateral shape maximum diameter is not top and bottom portion of the shape. For bilateral shape, If any entity enlarge the shape, then previous entities must be controlled. In other word, any entity getting smaller the shape is critical and following codes must be checked. For example, code 3 means shape is getting smaller. Thus, following codes in the series are checked. Rule for code 3 is as follows:

```
RULE-OUT3-A
IF          Any X value exists bigger than end point of 3ex in the
            series after code 3
THEN        There is unforgeable area                 AND
            Recoordinate 3ex by Nex                   AND
            Remove block from 3ex to Nex              AND
            Add 1 into series instead of this block
```

In order to clarify the coding system, a short nomenclature should be introduced. This is:

N: Nth number of code
s: Start point of entity
e: End point of entity
x: X coordinate
y: Y coordinate

Following Figure 6.11, formed by lines, illustrates sample shape as an example for forgeable geometry.



Final Product Shape Forgeable Shape

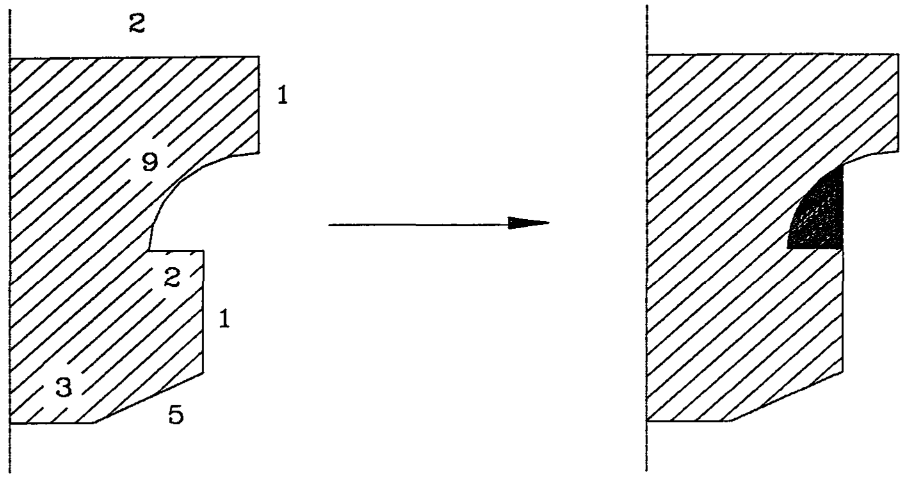
Figure 6.11. Generation of Forgeable Geometry

Series of above figure is: 2 – 1 – 3 – 4 – 1 – 3

In Figure 6.11, there are six codes and all X and Y coordinates of codes are already stored in program memory. Firstly, FORGAX tries to find the code 3 in the series, starting from the beginning. After this code 3, it checks that is there any X coordinate bigger than 3ex or not in the series. In this figure, 4ex is bigger than 3ex. Once "Make Forgeable Part" command is given to the program, it says that there is an unforgeable area (undercut) and then it generates forgeable shape by using related RULE from knowledge base. One of the related rules was given above named by RULE-OUT3-A

According to the rule it omits the digit 4 from series and puts 1 instead of it.
New series is formed by: 2 – 1 – 3 – 1 – 1 – 3

Following Figure 6.12 illustrates an another shape with an arc entity as an example. For forgeable shape, FORGAX uses similar rules that have shown above. The difference is; when line 1 is extended to the entity 9, the coordinate of intersection point with line and arc must be defined. For this purpose, a simple mathematical calculation has been carried out.



Final Product Shape Forgeable Shape

Figure 6.12. Generation of Forgeable Shape

Series of above figure is: 2 – 1 – 9 – 2 – 1 – 5 – 3

Computer program finds first code 3 in the series. Since code 3 is the last code, there is no problem from forgeable geometry perspective. Then it tries to find code 9. If the program finds code 9, it checks to find any x value bigger than 9ex. If there is Nex bigger than 9ex, in this case it checks to find Nex, which is greater or equal to 9sx. In this figure, 2ex is bigger than 9ex AND 9sx is bigger than 2ex. Therefore it says that there is unforgeable area and it generates the figure into forgeable shape by using following RULE. If program can not find code 9, it stops the execution and gives the final coding series.

```
RULE-OUT9-A
IF          Any X value exists bigger than end point of 9ex in the
            series after digit 9
THEN        There is unforgeable area          AND
            Recoordinate 9ex by Nex            AND
            Remove block from 9ex to Nex       AND
            Add 1 into series instead of this block
```

According to the above rule, program omits the digits after 9 to Nex from series and puts 1 instead of it.

New series is formed by: 2 – 1 – 9 – **1** – 1 – 5 – 3

6.7. CASE STUDY for FORGEABLE GEOMETRY

Following Figure 6.13 illustrates a rather complex final product shape for an axisymmetric component. The numbers on the figure show the entity codes.

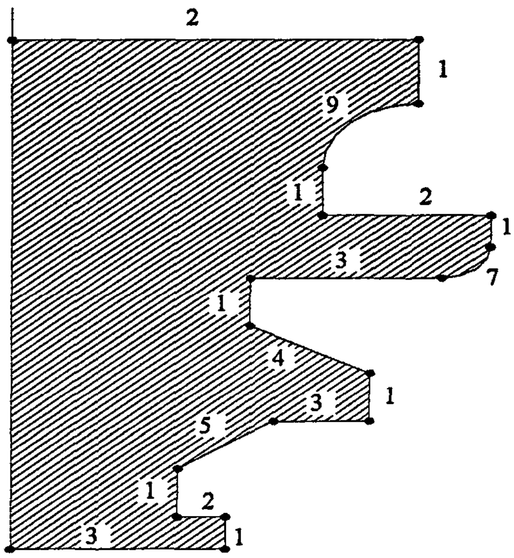
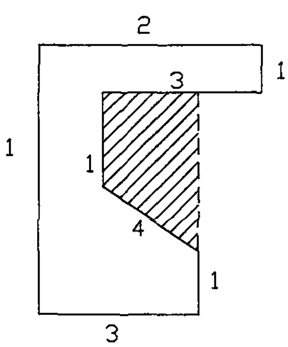


Figure 6.13. Generation of Forgeable Geometry

Series of above figure: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – 1 – 4 – 1 – 3 – 5 – 1 – 2 – 1 – 3

Firstly computer program FORGAX tries to find code 3 from the beginning of the series. When it finds code 3, it tries to find code 4 and then 4ex is checked whether it is greater than 3ex or not. Therefore FORGAX executes the related rule.

RULE-34-B



IF 3sx > 4ex

THEN

- Remove codes from 3 to 4 (except 3) **AND**
- Add 1 instead of removed codes **AND**
- Co-ordinate 1, by the following:

1sx=4ex 1ex=4ex **AND**

1sy=3sy 1ey=4ey

- Change ex value of code 3 by the following:

3ex=4ex

Codes of 1 and 4 are omitted and code 1 is added instead of 1 and 4. Added code, 1, is co-ordinated by 1ex = 2sx and 3ex is recoordinated by 3ex = 2sx. Series is changed by following in new order and generated shape is shown in Figure 6.14

First series of figure is: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – [1 – 4] – 1 – 3 – 5 – 1 – 2 – 1 – 3

New series: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1 – 2 – 1 – 3

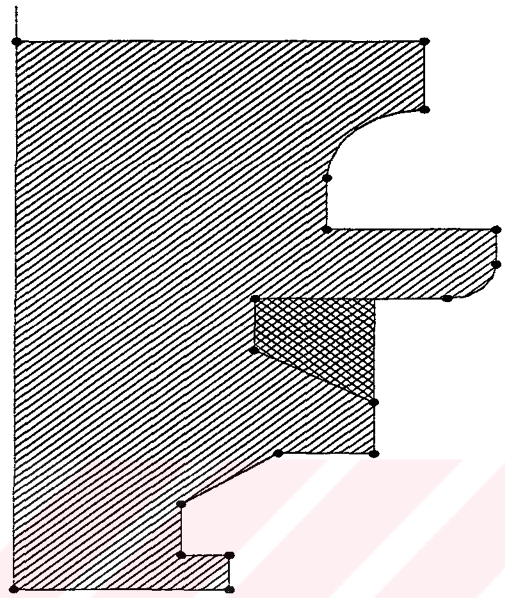
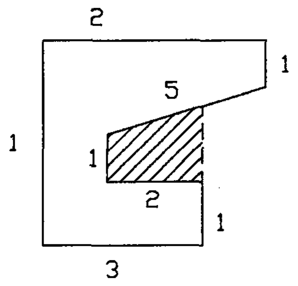


Figure 6.14 1st Generation of Case Study

After this operation program returns the first code and it checks code 3 again but, in this case there is no unforgeable area since there is no point which has X value is greater than 3ex. Then it checks 2nd and 3rd 3 in the series. Again after these codes it cannot find unforgeable area. Therefore, in the series there is no more code 3, which can cause any problem from forgeable geometry point of view.

As a second step, therefore, program checks the series to find code 5. In the series there is code 5 and after that, code 2 is exist. End point co-ordinate of code 2 is bigger than end point co-ordinate of code 5. Hence, FORGAX executes the related rule to eliminate the unforgeable section.

RULE-52-B



IF $5sx > 2ex$

THEN

- Remove codes from 5 to 2 (except 5) **AND**
- Add 1 instead of removed codes **AND**
- Coordinate 1, by the following:

$1sx=2ex$ $1ex=2ex$ $1ey=2ey$ **AND**

$$1sy = 5sy - \left[\frac{(5sx - 2ex) - (5sy - 5ey)}{5sx - 5ex}\right]$$

- Change ex and ey value of code 5 by the following:

$5ex=2ex$ $5ey=1sy$

New code series is formed by;

Previous series: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1 – 2 – 1 – 3

New series: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1– 1 – 3

In the following Figure 6.15 new generated shape can be seen.

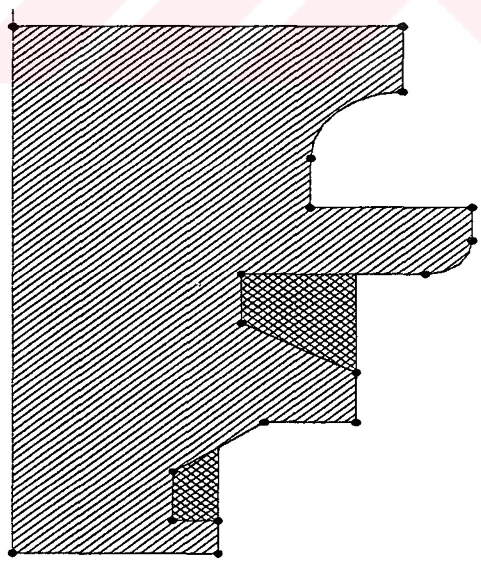


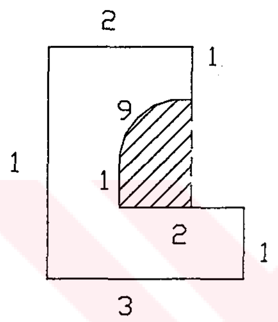
Figure 6.15. 2nd Generation of Case Study

After this generation program again checks the codes 3, 5, 7 and 9 whether the codes 2, 4, 6 and 8 are coming or not. In the third stage, FORGAX finds code 9 and in the series end point co-ordinate of code 2 is greater than starting point co-ordinate of code 9. Therefore, related rule is operated. Codes 9 and 1 are omitted. From 1ex to entity 2 a LINE is drawn and 2sx is co-ordinated by 2sx = 1ex. New coding series and the related rule will be as follows:

Previous series: 2 – 1 – 9 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1 – 1 – 3

New series: 2 – 1 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1 – 1 – 3

RULE-92-A



IF 9sx ≤ 2ex

THEN

- Remove codes from 9 to 2 (except 2) **AND**
- Add 1 instead of removed codes **AND**
- Coordinate 1, by the following:

  1sx=9sx 1sy=9sy

  1ex=9sx 1ey=2ey **AND**
- Change sx value of code 2 by the following:

  2sx=9sx

In the following Figure 6.16 new generated shape can be seen.

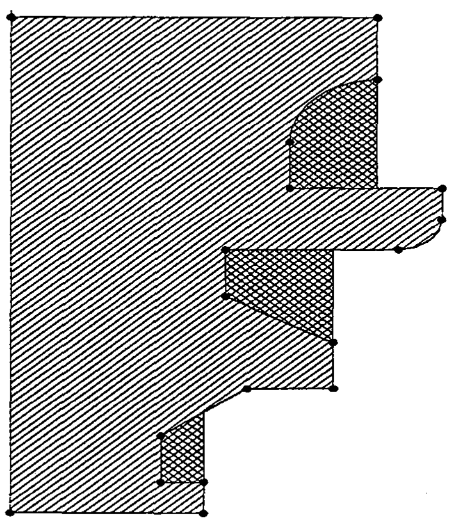


Figure 6.16 3rd Generation of Case Study

Finally computer program FORGAX tries to find codes 3, 5, 7 and 9. Since these codes can also cause problems, program checks unforgeable area. But, after the codes of 3, 5 and 7 there is no unforgeable area. FORGAX stops the program and presents the final coding series. In Figure 6.17 all steps are presented from final product geometry to forgeable geometry for case study.

FINAL CODING SERIES: 2 – 1 – 1 – 2 – 1 – 7 – 3 – 1 – 1 – 3 – 5 – 1 – 1 – 3

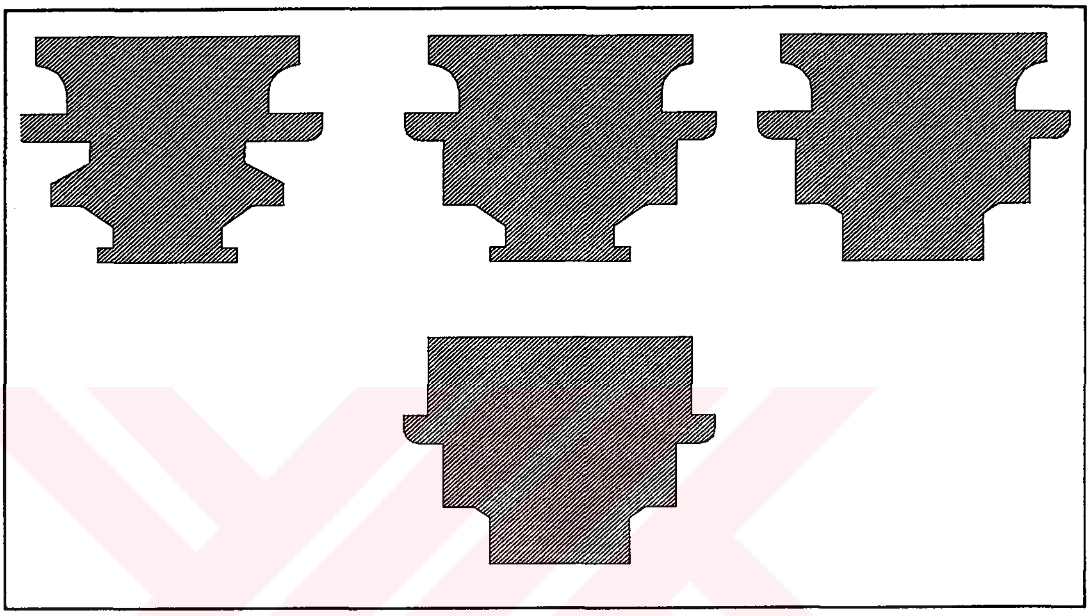


Figure 6.17. All Steps for Forgeable Geometry

Co-ordinates of final digit series are then transformed into DXF file. Then, AutoCAD can read this new DXF file and presents the forgeable geometry. Additionally, Co-ordinates of final geometry can also be transferred into TXT format. AutoCAD can perceive TXT files by writing small program using AutoLISP facility of AutoCAD.

6.8. ALGORITHM for FORGEABLE GEOMETRY

Algorithm for forgeable geometry is formed by certain rules. Especially codes 3, 5, 7 and 9, which are called as key codes, are investigated. Because, these codes get the shape smaller. Apart from these codes there is no problem getting smaller in diameter. However, if diameter gets larger most probably there is an unforgeable area. Therefore algorithm is based on the codes of 3, 5, 7, 9 and checks the codes of 2, 4, 5, 6 whether they are coming after key codes.

Appendix B1 illustrates the algorithm for forgeable geometry for outer side of the shape and Appendix B2 illustrates for inner side of the shape. All related rules for forgeable geometry can be seen in Appendix C.

6.9. CONCLUSION for FORGEABLE GEOMETRY

Computer aided determination of forgeable geometry and therefore forging design has a great importance for preserving the gradually disappearing know-how for forging industry. Therefore, this system has wide applicability since the entities, which are presented in this chapter, represent a large proportion of the total industrial parts.

In this part of study it is illustrated that how forgeable geometry is determined and computerised by using knowledge based approach. After the identification of geometry, the design rules have been stored in the knowledge base in such a way that every industry (designer) can define and add its own values. This means that this knowledge, that is the valuable resource of the company, will not be lost for any personal reasons and will retain and can be modified for a long time.

The developed system, helps the user to determine the optimum forgeable geometry in design process and therefore, reduces the design time. This coding system makes the system easier, more understandable and more practical. Additionally, output of coding system can be exported to the other programming languages by external interface of the system.

CHAPTER 7

FORGING LOAD ESTIMATION

7.1. INTRODUCTION

In this chapter, forging load estimation methods are summarised and Upper Bound Elemental Technique (UBET) is expressed in detail. All elemental regions, velocity fields and forging load calculation formulae are presented in this chapter.

7.2. ANALYTICAL APPROACHES

Design process provides the required geometry and necessary mechanical properties. After the determination of part geometry, die shape is determined by considering the machining allowances and taking into account of forging load. At this stage, the forging and its die are designed so as to fill the die cavity completely. The power and energy requirements for making the finished forging are also determined at this stage.

Closed die forging is a very complex forming process from the point of view of the mechanics of deformation or metal flow. It is difficult to analyse, because of some factors such as non-steady state and non-uniform metal flow, the variable interface friction, and heat flow between the material being deformed and the dies, all of which present a real challenge to evaluation.

The analysis of the forging process must include the factors such as the maximum load requirement by the equipment, the maximum stress distribution on the surface of the dies, and the total energy necessary to complete the deformation.

In metal forming, there are no exact solutions that can be used for practical purposes. Therefore, methods of analysis giving results with various degrees of approximation must be used.

There are four basic analytical approaches used in the analysis of the forging process. These are:

1. The slip line field method
2. The finite element method
3. Elementary slab (Equilibrium) method
4. Bound approach (Upper Bound, Lower Bound)

7.2.1. The Slip Line Field Method

The modelling methodology based on plane-strain rigid plastic, *slip-line theory* has been employed by many researchers, with various types of slip-line models having been developed. In most of these a further assumption has been made that the work material is perfectly plastic (non-hardening) and this tradition is continued in the latest papers. The most significant reason for using the slip-line method lies in that, compared to the finite element method, the use of the slip-line theory can show much more clearly the pattern of the flow of the material over the whole range of the shear deformation zone.

Slip line analysis is based upon a deformation field that is geometrically consistent with the change in shape of the region being deformed. Although equilibrium conditions are observed within the field being considered, equilibrium outside the field is ignored and may not apply.

A slip line field is a two dimensional vector diagram which shows the direction of the maximum shear stress at any point along a line. These lines have the property of satisfying static equilibrium, the prevailing yield condition, and a possible flow field everywhere in the plastic zone of the metal being deformed without any reference to the plasticity equations and strain rates. Slip lines have the property that the shear strain is a maximum and the linear strain is zero tangent to their direction.

7.2.2. The Finite Element Method

Finite Element Method (FEM) have been applied in various studies of deformation in metal forming process, such as preform design in rolling [26, 122], precision forging [58], complex forming [73], forging defects [5], material flow [33], and closed die forging [74].

This method is based upon trial function methods once their difficulties have been overcome as follows:

a) To facilitate the satisfaction of boundary conditions, pointwise discretisation is used. The solution can be expressed in terms of nodal values and interpolation shape functions.
b) Piecewise discretisation is employed in order to simplify the assumed trial solution. The domain is divided into a number of subdomains (Finite Elements) and the equations for each subdomain can be derived. The equations for the whole domain can therefore be assembled from those of the subdomains.

The finite element analysis of a real problem usually requires a large amount of data and results in a large system of equations which cannot be solved without the aid of a digital computer. There are many large finite element programming systems on the market such as ANSYS, DYNA, ADINA, NASTRAN, ALGOR, IDEAS, ABAQUS and etc.

In Finite Element Method, the deformation region is divided into several so-called stream function elements. The stream function for each element is produced by an interpolation function and the nodal points are specified by the stream function value, which is the volume rate [73].

7.2.3. Elementary Slab (Equilibrium) Method

The slab and upper bound methods are the most widely used methods for closed die forging. *Slab (equilibrium) method* assumes that the stresses on a plane perpendicular to the direction of metal flow. A slice or slab of infinitesimal thickness is selected and a force balance is made.

In the slab method, which is also called freebody equilibrium method, the friction hill method, and the elementary slab method, the equilibrium of a slab of the deformed body is considered, in which a simplified stress distribution such as plane strain is assumed for the slab. The governing equations in the direction of the principal stresses are solved, and an approximate solution for the forming forces and stress is obtained. The slab method neglects the effect of friction stress upon the internal stress distribution and thereby introduces errors of an unknown magnitude. It has been successfully applied to many practical problems, especially by using modular and numerically interactive computer techniques. Although approximate, it is a very powerful tool in predicting forming stresses, loads, and, in some cases, even metal flow.

In the slab or equilibrium method, a representative volume element in the body of the material or workpiece undergoing plastic deformation is isolated and the behaviour of this element is observed as it moves along the work zone of the pass. Since the element continues to form an integral part of the body or workpiece,in conjuction with the rigid dies or tools, it must remain constantly in the state of force equilibrium throughout its entire period of deformation. The behaviour of the element reflects the whole of the workpiece and can therefore be analyzed by considering the equilibrium of the forces acting at any instant of deformation.

7.2.4. The Upper Bound Technique

One of early study was carried out by Kudo [64, 65] for theoretical analysis of the experimental tests. It was chosen for its simplicity. He described a general method of analysis that could be used to analyse forging and extrusion type processes to produce predictions of forming loads. The method was based on the upper bound technique for which Prof. W. Johnson had demonstrated prolifically its value in examining a wide range of metal forming processes. The concept of a *unit rectangular deforming region* was introduced by Kudo thus developing a generalisation of the approach. This had been suggested by others but Kudo was the first researcher to present comprehensive details of the method. This work became the seed corn for the research into forging analysis [74].

By the mid of 1970s, computing facilities had become readily available in university engineering departments and so McDermott and Bramley [66, 70] set about reworking Kudo's method, developing additional element types that would accommodate the taper and radius features commonly encountered in industrial forgings.

Tuncer [13], studied this method for precision forging of hollow parts. For describing metal flow, he used velocity field. Based on this velocity field deformation, shear and friction energies are computed and added together to give total forming energy and also forming load.

A one of final study was also carried out by Bramley [74] for upper bound elemental technique. The tetrahedral upper bound analysis was presented which enables a more realistic flow simulation to be achieved. In this approach, the forging was divided into eight basic elemental regions. The boundaries of these regions may be considered as either rigid tools or as rigid parts of adjacent elements of the workpiece. Since the part of this work, *forging load calculation*, is based on Upper Bound Elemental Technique (UBET), the detail of this approach is presented in the following section.

7.3. GEOMETRY DECOMPOSITION from UBET PERSPECTIVE

In using Upper Bound Elemental Technique, geometry should be recognised and simplified in order to make the calculations easy. In this approach, the forging shape is broken down into basic, elemental regions. The forging load estimation is then made for each region separately. The results can be put together in building block manner to obtain the load required for the deformation of rather complex forging. In the following some different geometry decomposition approaches are outlined.

Kim and Im [34] used a line segment and area segment by modifying the final product geometry as shown in Figure 7.1.

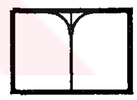
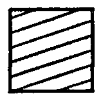
Type	Geometry	Type	Geometry
horiz_line		cone	
vert_line		convex	
tapered_line		concave	
convex_line		bolt	
concave_line		thread	

Figure 7.1. Schematic Description of Line and Area Segment

Based on the given input data, the geometry group of the final product is determined, the geometry group representing a family of geometry types that can be produced by similar forging sequences. For indicating the line segment, the coordinates of the starting and ending points are given and for arcs the coordinate of the center location and the arc radius is given. In the system, the given input data using a line segment are transformed into the area segment.

Tang et. al.[36], decomposed the geometry by pattern recognition approach. Using this approach, the forging section geometry, represented by a sequence of vertices, is first encoded, with each character representing the type of the corresponding vertex. They defined three possible vertex types, depending on whether it is located at a fillet, a corner, or on the parting line. Ribs and webs are then recognised as specific sequences of vertex types in encoded section geometry. Figure 7.2 illustrates the use of this approach to recognise the forging section.

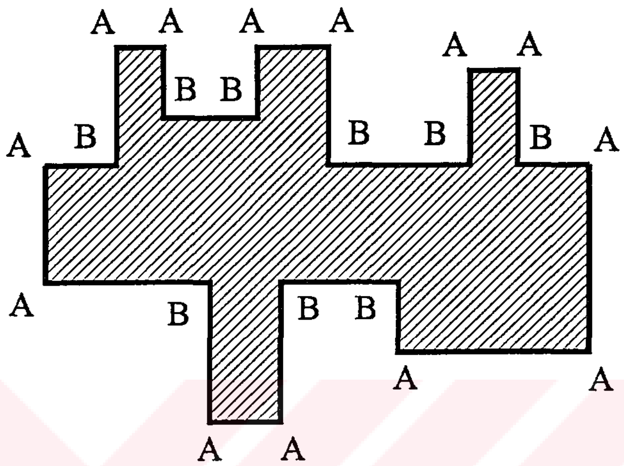


Figure 7.2. Pattern String of Forging Section

Based on the encoded pattern string, five ribs (four "R" type and one "A" type) are recognised. The component ribs (R) and webs (W) recognised are then used as the basis for decomposition of the forging section as shown in Figure 7.3. It should be noted that this scheme does not distinguish a rib from a step or a web from a deep recess. That is, a step is treated as a rib and a recess is treated as a web.

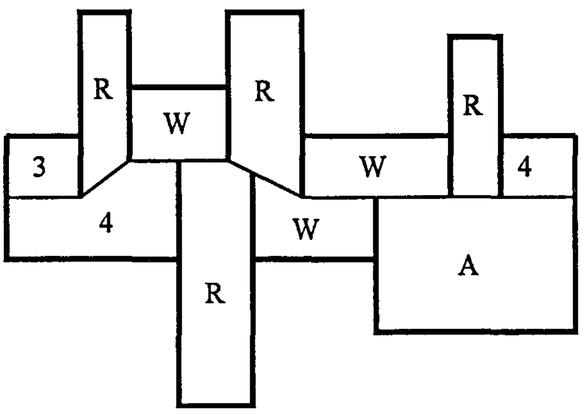


Figure 7.3. Decomposed Forging Section Geometry [36]

The latest geometry decomposition is developed by Bramley [74] by the cooperation with Prof. B. Avitzur, for interactive computing and improved graphical representation resulted in an automatic subdivision technique which is shown in Figure 7.4. He developed general rectangular and triangular elements with only orthogonal flows over their boundaries. This arrangement carries the disadvantage in not predicting dead zones as part of the solution, a feature embodied in Kudo's original elements.

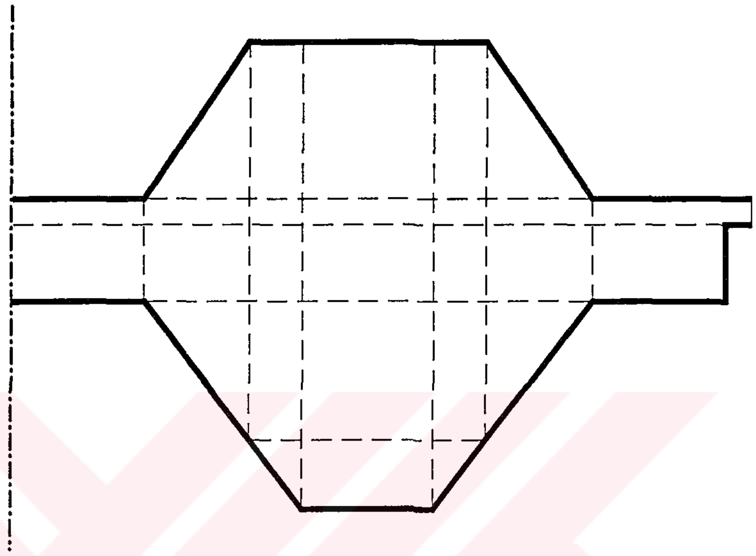


Figure 7.4. Automatic Element Subdivision

It works by projecting inwards from the co-ordinating points defining the cross section, two orthogonal lines which terminate when they meet another boundary orthogonally and reflect at 90^0 if they meet an inclined surface. This generates the requisite field of singly connected triangular and rectangular elements. The velocity boundary conditions for all the elements could not now be determined a priori and thus they became the pseudo-independent variables in the upper bound power calculation. This conveniently removed the requirement for manual subdivision but incurred the risk of generating excessively large numbers of elements and a corresponding high computing overhead.

In the latest extension of UBET, McDermott and Bramley [66, 70, 74] have divided the shape into eight basic simple regions as shown in Figure 7.5. The regions, shown by 1, 3, 5, 7, are deformed in such a manner that their top surface descends vertically due to an external force with a unit velocity thus causes the inner side surface to move inwards as a straight line. The surroundings to these regions may be considered as either rigid tools or as rigid parts of surroundings workpiece, no flow being allowed across the remaining faces in contact with either tool or workpiece. The second type of deformation occurring in the remaining four regions is that shown in Figure 7.5 (2, 4, 6, 8), which differs from the first mode only in that the inner surface does not move whilst the outer cylindrical surface moves radially outwards, remaining cylindrical.

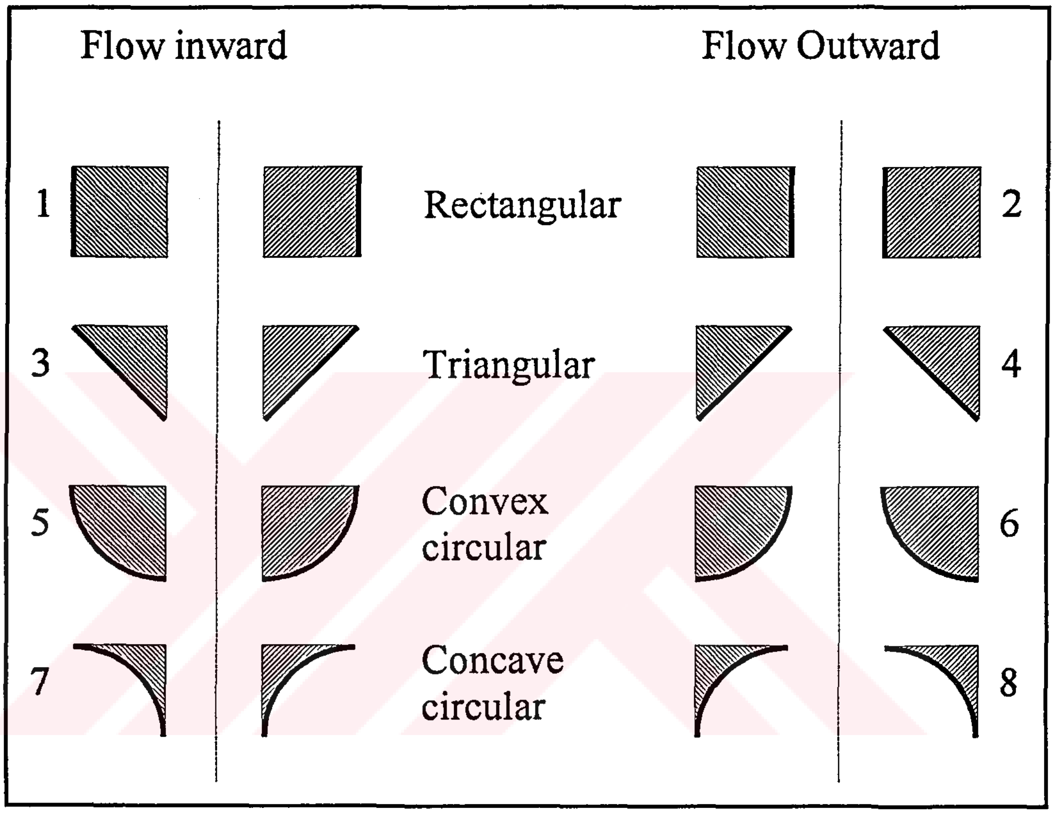


Figure 7.5. Eight Basic Elemental Regions

7.4. GEOMETRY DECOMPOSITION in the PRESENT WORK

In the present work, a similar Bramley approach is used. But our study differs from the previous studies in that, elemental regions are taken into account so that each element contacts to each other or to die completely. By this way, friction factor can be included into the calculations in correct manner. In Figure 7.6. Bramley approach, by dividing the shape into regions, is shown.

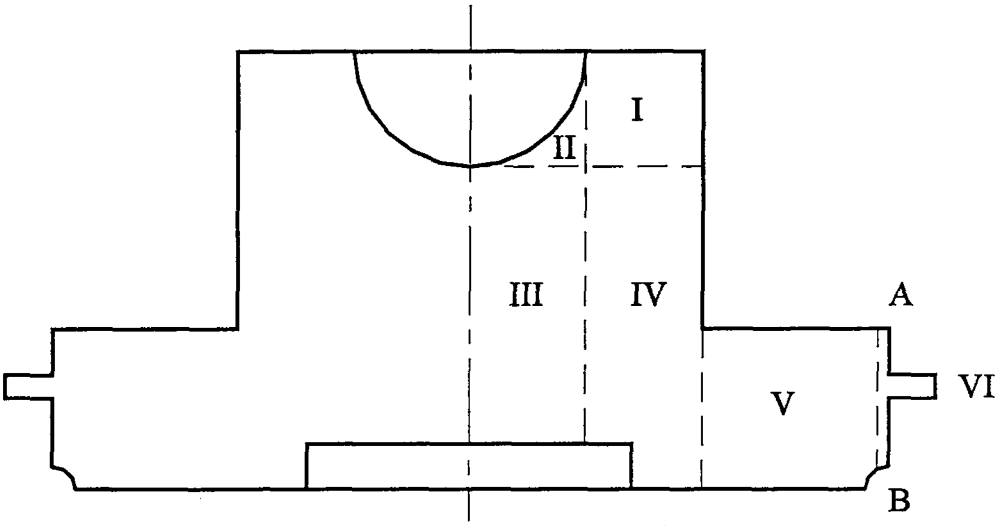


Figure 7.6. Cross Section of Forging Divided into Regions [76]

Figure 7.6. shows a smooth transition of flow in regions I to IV, but not V and VI. To include these regions, the material is considered to fill an infinitesimal element gap, AB, as shown at the right edge of the shape to maintain a continuity of analysis. At the moment of filling the die cavity, the metal in region V would flow outward to close this gap. The regions can be represented as an elemental regions stated before in Figure 7.5. These are:

- The regions I and IV are rectangular inward flow type,
- The regions III, V, VI are rectangular outward flow type,
- The region II is concave circular outward flow type.

As it is seen from the Figure 7.6. regions does not contact each other completely. For example a part of region IV get contact with the die while the other part get contact with the region V. Since metal flow is directly related with the friction regions must be divided in such a manner that one of it's side should contact with the die or material. The velocity boundary conditions for all the elements could not now be determined a priori and thus they became the psuedo-independent variables in the upper bound power calculation.

This problem is overcame in this part of the thesis. According to the work, firstly, outer side of the forging is examined. Triangular and circular regions are removed from the forging weather it is inward or outward flow. And then, all their coordinates are transferred into related table. By this way, forging remains with only rectangular regions as shown in Figure 7.7.

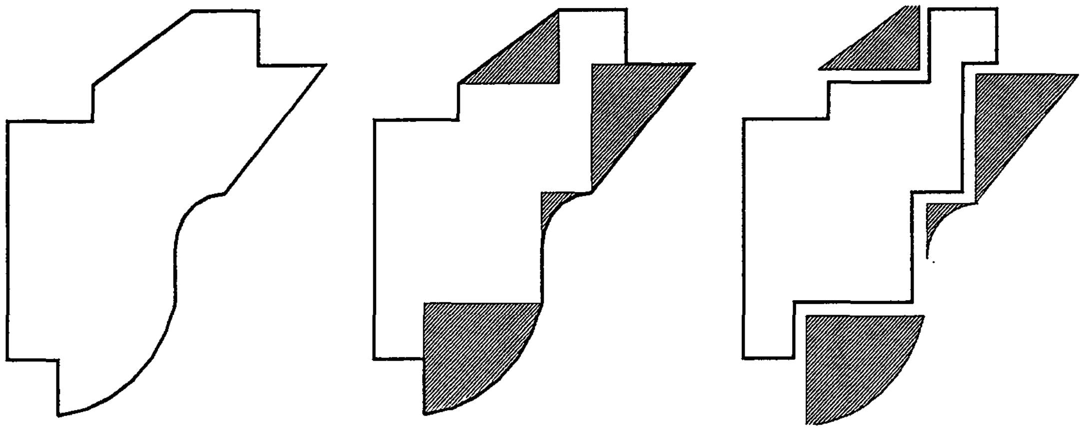


Figure 7.7. Elimination of Rectangular and Circular Regions

This arrangement eliminates the disadvantage in not predicting dead zones, a feature embodied in Kudo's original elements and Bramley's approach.

The newly generated forging is projected inwards from the co-ordinating points defining the cross section. A projected line is drawn in both horizontal and vertical directions from the all corners.

A one of comparative divided geometry between Bramley approach and the present work is illustrated in Figure 7.8 a and b. It is obviously seen that number of divided regions are more smaller than previous work. In Figure 7.8.a there are 75 different regions. But in the new approach, as it is seen in Figure 7.8.b, arcs and triangular regions are removed and therefore, remaining same shape is divided into 22 regions. It is almost one fourth of the previous study. This ratio changes with complexity of the shape. This means that the less number of regions require shorter computation time for load calculation and makes it easy.

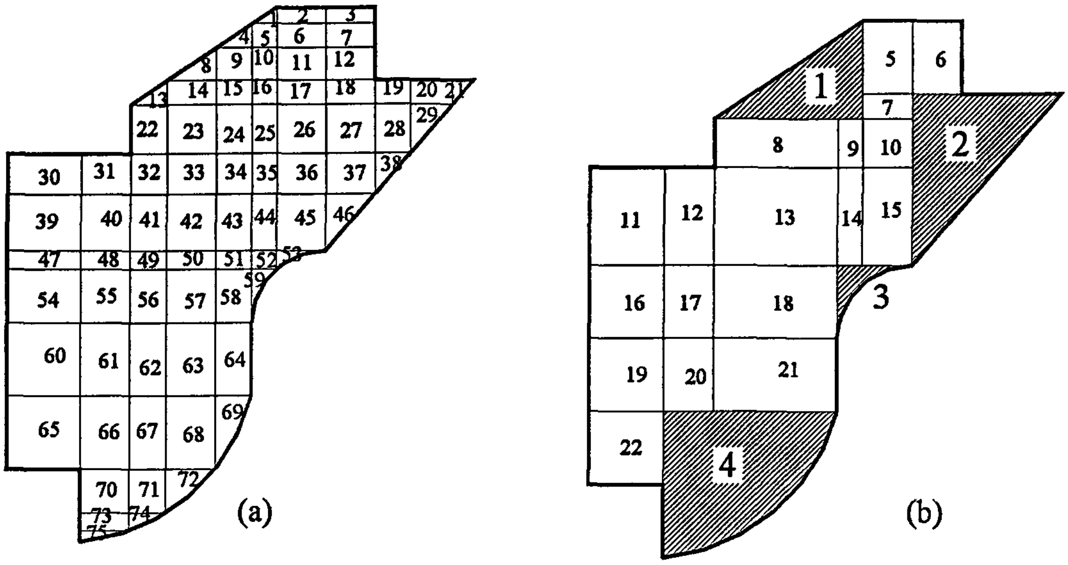


Figure 7.8. Generation of Elemental Regions
a) Bramley Division of Geometry
b) Present Division of Geometry

The analyses of the geometry is completed in the above procedure to produce the basic elements for the forging, which is shown in Figure 7.8. The one side of all elements contacts only with material or die and punch.

For each of these eight regions shown in Figure 7.5, a general admissible velocity field should be derived to obtain internal energy dissipation. In the following example, velocity field for a triangular region with inward flow is derived.

7.5. VELOCITY FIELD

In obtaining the velocity fields for each of the above basic regions, it is assumed that the radial velocity $\dot{u} = du/dt$ is independent of the axial direction Z (in order to facilitate calculation of the internal rate of energy dissipation and to allow connection with neighbouring deforming regions) and the inlet and outlet velocities from any region boundary are constant along the boundary.

In Figure 7.9, definition of the parameters for inward flow of a triangular region is shown. The derived formulae are taken from Mielnik [63].

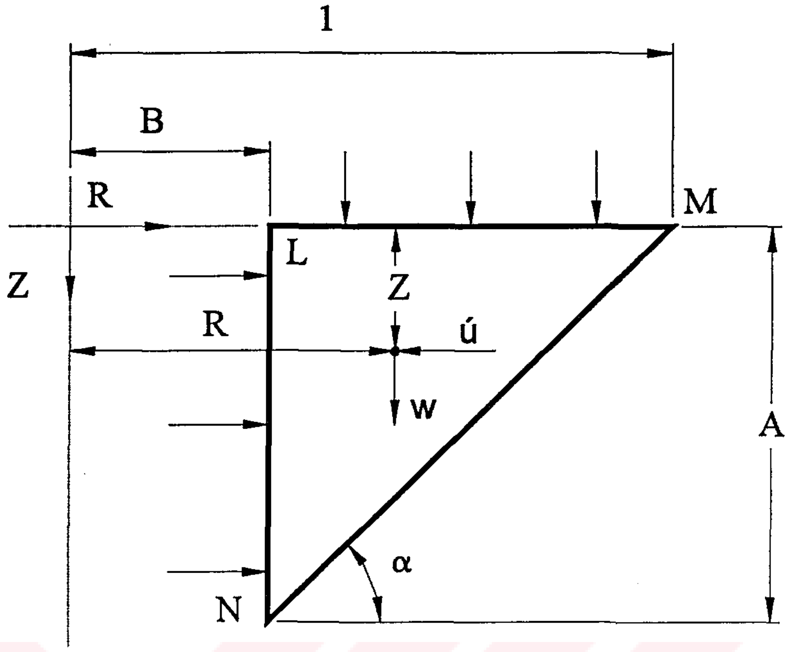


Figure 7.9. Parameters for Inward Flow of Triangular Region

By considering volume constancy;

$$\dot{\varepsilon}_R + \dot{\varepsilon}_\theta + \dot{\varepsilon}_Z = \frac{\partial \dot{u}}{\partial R} + \frac{u}{R} + \frac{\partial \dot{w}}{\partial Z} = 0$$

Since $\dot{u}$ contains only R as a variable then $\dot{w}$ must contain both R and Z, but since R and Z are independent variables the above equation dissolves into like that;

$$\frac{d\dot{u}}{dR} + \frac{\dot{u}}{R} = f(R) \tag{7.1}$$

$$\frac{\partial \dot{w}}{\partial Z} = -f(R) \tag{7.2}$$

where f(R) is an arbitrary function of R. Equation (7.2) leads to

$$\dot{w} = -Zf(R) + g(R)$$

and by using the boundary conditions that

$$\dot{w} = 1 \text{ at } Z=0$$

g(R) is reduced to 1, so that

$$\dot{w} = -Zf(R) + 1 \tag{7.3}$$

On the other hand, the general solution of equation (7.1) is

$$\dot{u} e^{\int \frac{dR}{R}} - f(R) e^{\int \frac{dR}{R}} dR = C$$

and therefore,

$$\dot{u} = \frac{\int f(R)RdR + C}{R} \tag{7.4}$$

Along MN, the resultant velocity vector must be parallel to MN from continuity requirement, provided that the region below MN is at rest. This requires that;

$$\frac{\dot{w}}{\dot{u}} = -\tan\alpha \qquad \text{along} \qquad \frac{Z}{1-R} = \tan\alpha \tag{7.5}$$

Substituting equations (7.3) and (7.4) into equation (7.5) we have

$$R(1-R)(\tan\alpha)f(R) - R = \tan\alpha\left(\int f(R)RdR + C\right) \tag{7.6}$$

Differentiation of this with respect to R leads to

$$\frac{df(R)}{dR} + \frac{1-3R}{R(1-R)} f(R) = \frac{\cot\alpha}{R(1-R)} \tag{7.7}$$

The general solution of this is;

$$f(R) = \frac{-\cot\alpha}{2R} + \frac{C1}{R(1-R)^2} \tag{7.8}$$

Substituting equation (7.8) into equation (7.6), we have

$$C = \frac{-\cot\alpha}{2}$$

hence, from equation (7.4)

$$\dot{u} = \frac{-\cot\alpha}{2}(1+\frac{1}{R}) + \frac{C1}{R(1-R)} \qquad (7.9)$$

The boundary condition that $\dot{u} = -\cot\alpha$ at R=1 requires that C1=0. This is also required to avoid infinite $\dot{u}$ at R=1.

Finally, velocity field for inward flow of triangular region can be written as:

$$\dot{u} = \frac{-\cot\alpha}{2}\left(1+\frac{1}{R}\right)$$ radial velocity field for triangular region

$$\dot{w} = \frac{\cot\alpha}{2}\left(\frac{z}{R}\right)+1$$ axial velocity field for triangular region

By using similar methods it is possible to derive velocity fields for remaining regions. In the following, the equation of velocity fields for both radial and axial directions are given.

Inward flow of rectangular region:

Radial velocity field: $$\dot{u} = \frac{-(1-R^2)}{2AR} \qquad (7.10)$$

Axial velocity field: $$\dot{w} = \frac{-Z}{A} \qquad (7.11)$$

Outward flow of rectangular region:

Radial velocity field: $$\dot{u} = \frac{R^2 - B^2}{2AR} \qquad (7.12)$$

Axial velocity field: $$\dot{w} = \frac{-Z}{A} \qquad (7.13)$$

Inward flow of triangular region:

Radial velocity field: $$\dot{u} = -\frac{\cot\alpha}{2}\left(1+\frac{1}{R}\right) \tag{7.14}$$

Axial velocity field: $$\dot{w} = \frac{\cot\alpha}{2}\left(\frac{z}{R}\right)+1 \tag{7.15}$$

Outward flow of triangular region:

Radial velocity field: $$\dot{u} = \frac{\cot\alpha}{2}\left(1+\frac{B}{R}\right) \tag{7.16}$$

Axial velocity field: $$\dot{w} = -\frac{\cot\alpha}{2R}z+1 \tag{7.17}$$

Inward flow of convex circular

Radial velocity field $$\dot{u} = \frac{\left(R^2-1\right)}{2R\sqrt{1-2B+2BR-R^2}} \tag{7.18}$$

Axial velocity field $$\dot{w} = \frac{z\left(R^3-3BR^2+4BR-R-B)\right)}{2R^{3/2}\sqrt{1-2B+2BR-R^2}}+1 \tag{7.19}$$

Outward flow of convex circular

Radial velocity field $$\dot{u} = \frac{R^2-B^2}{2R\sqrt{B^2-2B+2R-R^2}} \tag{7.20}$$

Axial velocity: $$\dot{w} = \frac{z\left(R^3-3R^2-B^2R+4BR+B^2\right)}{2R^{3/2}\sqrt{B^2-2B+2BR-R^2}} \tag{7.21}$$

This type of approach, however, was found applicable to the regions numbered by 7 and 8 (shown in Figure 7.5), because of the contradictory conditions obtained at the tangential intersections of the two straight line boundaries with the curves. Therefore, in order to overcome this, an approximate solution was initiated consisting of four triangles which linked together to give a 10% overestimate in material volume but 5% underestimate in outlet velocity.

7.6. FORGING LOAD and ENERGY CALCULATION

In the analyses of the axisymmetric forging shapes, flow fields are divided into simple elements (Figure 7.5) and for each element the kinematically admissible velocity field is constructed. Since the whole part is divided into regions, the boundaries of these regions may be considered as either rigid tools or as rigid parts of adjacent elements of the workpiece.

For each of these eight regions shown, a general admissible velocity field, one which is a distribution of particle velocities which is kinematically compatible within itself and the externally applied forces, is considered as shown in the example shown in Figure 7.10 for the outward flow of a rectangular region. The parameters A, B, R and Z are defined in this figure.

The die design of a near net shape forging process requires the estimation of maximum forging load and the necessary forging internal energy. To determine the total internal energy, the required forging load for each region must be determined. The kinematically admissible velocity field for each element is derived by satisfying the external boundary conditions.

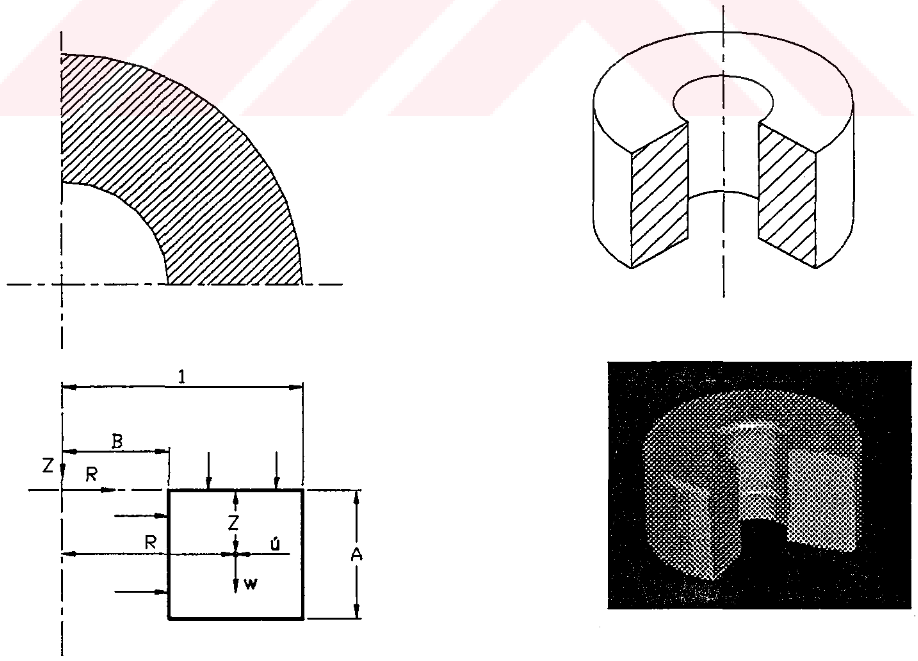


Figure 7.10. Outward Flow of Rectangular Region

Once the velocity components for any of the eight basic regions are known then by definition;

$$\dot{\varepsilon}_R = \frac{\partial \dot{u}}{\partial R} \qquad \dot{\varepsilon}_Z = \frac{\partial \dot{w}}{\partial z} \qquad \dot{\varepsilon}_\theta = -\left(\dot{\varepsilon}_R + \dot{\varepsilon}_Z\right)$$

$$\dot{\gamma}_{RZ} = \frac{\partial \dot{u}}{\partial z} + \frac{\partial \dot{w}}{\partial R}$$

Since all the strain rates are obtained, the rate of internal energy dissipation can now be calculated for that particular field according to Hill's equation:

$$\dot{E} = \sqrt{\frac{2}{3}}\sigma_y \int_v \left(\dot{\varepsilon}_R^2 + \dot{\varepsilon}_\theta^2 + \dot{\varepsilon}_Z^2 + \frac{1}{2}\dot{\gamma}_{RZ}^2\right)^{1/2} dV + \sigma_y \int_S m\dot{S}\,ds \qquad (7.22)$$

where;

$\dot{E}$: The rate of internal energy dissipation

σ_y: The flow stress of the metal being forged

$\dot{\varepsilon}_R$: The strain rate in the radial R direction

$\dot{\varepsilon}_Z$: The strain rate in the axial Z direction

$\dot{\varepsilon}_\theta$: The strain rate in the circumferential θ direction

$\dot{\gamma}_{RZ}$: The shear strain rate in the R-Z plane

m : The friction factor at the region boundaries

$\dot{S}$: The rate of relative slip at the boundaries

s : Surface of the velocity discontinuity

V: Volume of the workpiece

The first integral $\int_V$ in the above equation is carried out throughout the entire volume of the workpiece which is deformed continuously, and the second integral $\int_s$ is carried out over all surfaces of velocity discontinuity on the workpiece-tool and the inter-region boundaries. The value of $\dot{E}$ for any particular region, can now be expressed nondimensionally by dividing by the product of the flow stress, surface area of pressing and the pressing speed of that unit region.

The upper bound solution for the mean extrusion pressure, over the whole cross-sectional area of the billet could be expressed by:

$$\frac{P}{\sigma_y} = \frac{\dot{E}_t}{\frac{\pi D_t^2}{4} V_t} \tag{8.23}$$

In computer analysis, in order to determine the forging load to deform any of the eight regions, the required parameters are:

a) Type of region
b) Yield stress of material being deformed
c) Pressing speed
d) Internal and external radii of the region
e) Height
f) Friction factors

The analysis of a forging, can now be completed by dividing the forging shape into basic regions, entering the required data for each region and summing to find the total load.

The analysis is completed in the above manner to produce the elements for the forging. The following Figure 7.11 shows a cross section of an axisymmetric forging shape. Subdivision of the forging into elemental shapes are shown in Figure 7.12.

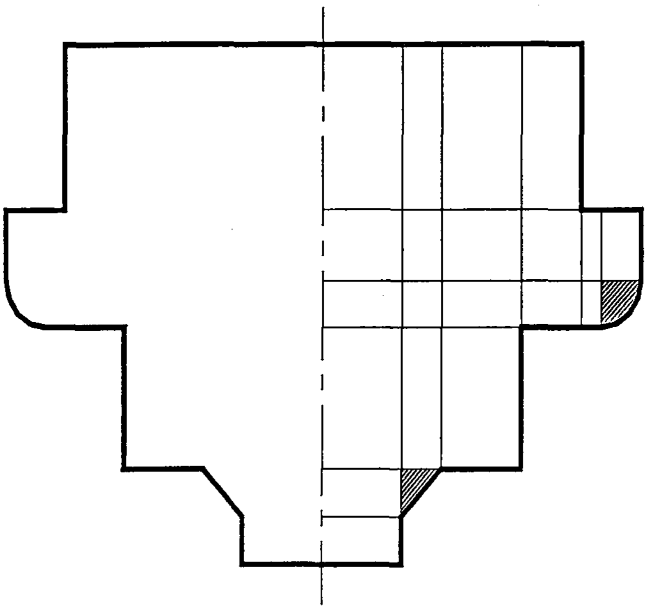


Figure 7.11 Cross Section of an Axisymmetric Forging

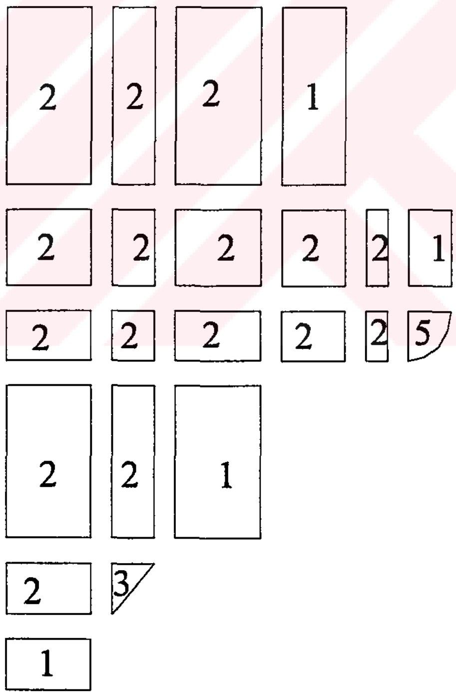


Figure 7.12 Subdivision of Forging

A computer program illustrating the total forging load calculation is shown in Figure 7.13. As it is seen from this flowchart, the obtained forging shape is divided into basic regions.

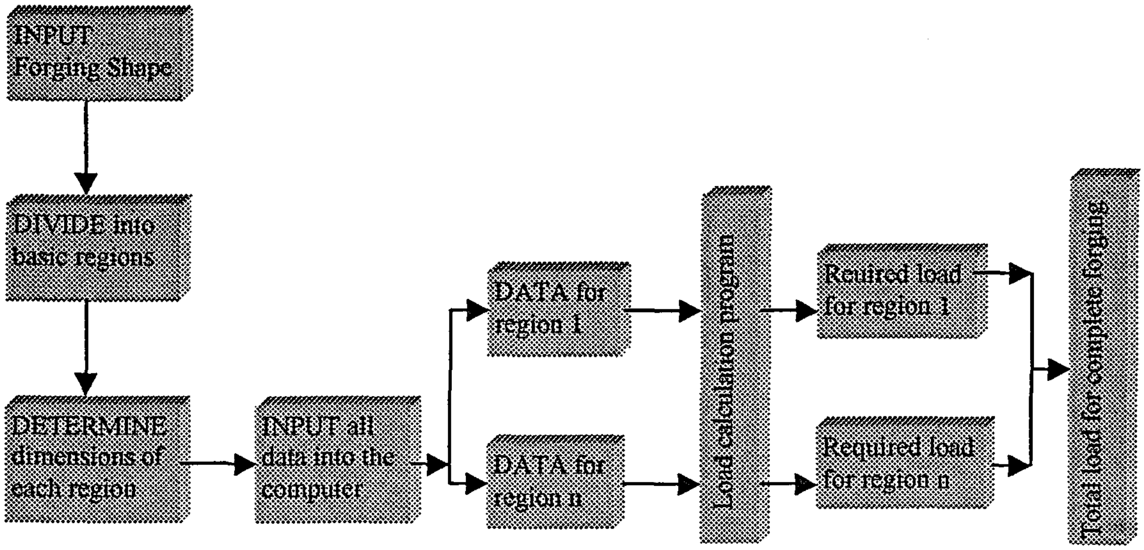


Figure 7.13 Total Load calculation Program

According to the region, velocity field is derived and related data, which are stated before in this text, for each region is input into the computer. By using the load calculation program, load to deform the each region is calculated. Summation of all load gives the required total load for complete forging.

CHAPTER 8

DIE STRESSES and DIMENSIONAL ACCURACY

8.1. INTRODUCTION

In this chapter, all of the factors affecting die accuracy are explained. Die stresses and geometry correction factors to maintain dimensional accuracy are also discussed in detail.

8.2. DIMENSIONAL ACCURACY OF AXISYMMETRIC PARTS

The load carrying capacity and life of any forged product is greatly affected by its dimensional accuracy. Dimensional accuracy is one of the prime goals in near net shape forging. To establish near net shape forging as an economical production technique, it is necessary to analyse the factors which affect dimensional accuracy.

To give an idea of precision of forged parts, the current commonly accepted value of dimensional tolerances give an idea about final forging die dimension. The factors effecting the accuracy of precision forming can be divided into two main groups; one is related to the equipment and the other one is related with the process itself. The main factors which are affecting the accuracy are explained briefly in the following sections.

8.2.1. Equipment Considerations

In order to improve the accuracy in product shape, size and surface properties, the accuracy of the equipment and control of the working process are essential [77].

There are two methods to maintain machine accuracy [30]:

- Design structure; that minimizes the deformation when working load are applied, to increase rigidity of the equipment.
- Properly detect and correction of errors resulting from the deformation of loaded tools during working. This method is not suitable for forging processes where measurements are very difficult to take during the forming process, the former may then be regarded as more suitable.

A considerable amount of distortion occurs in both the press construction and in the driving elements when these are subjected to working loads. Figure 8.1 illustrates the longitudinal elongation of a mechanical press when subjected to full capacity loading [127].

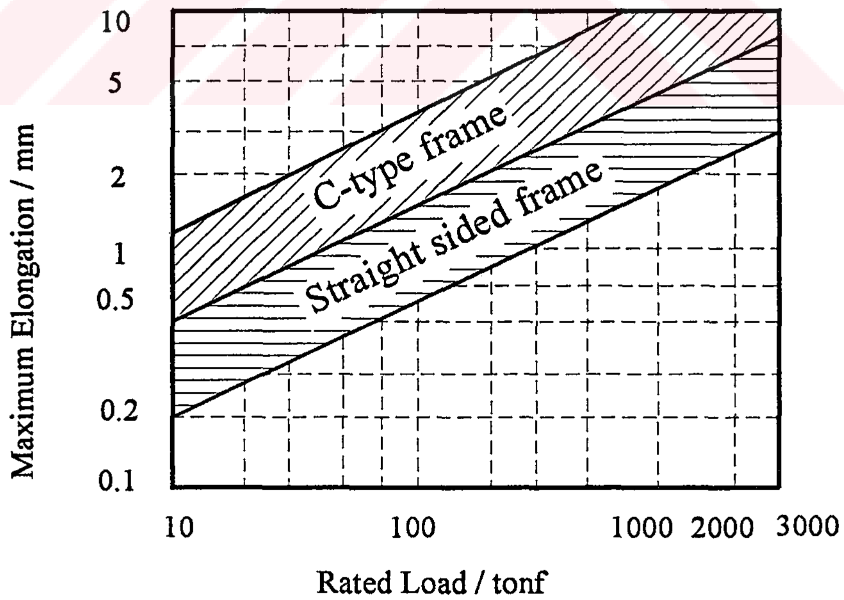


Figure 8.1. Longitudinal Elongation of a Mechanical Press [127]

8.2.2. Tools

Product accuracy is dependent on tool accuracy, which must take account of the deformation and wear of the tools. Since tool components are elastic, they distort to greater or lesser degrees under the working pressure. Deformation is also closely related to temperature distribution, whilst wear is related to surface roughness of the die, temperature and lubricants. When tool design is inadequate, extremely high working loads may be required to attain satisfactory filling of the die cavity, which can cause deformation or failure of the tool.

Product accuracy is also dependent on the properties of the workpiece material. The mechanical properties of the material stock are determined by its chemical composition and previous thermal and mechanical treatments. Redistribution of temperature due to heat generation during working, which depends on flow stress, specific weight and specific heat, induces metal flow and local dimensional instability. Material surface roughness and compatibility with the tool material are important from the viewpoint of surface accuracy [30].

8.3. DIE STRESSES

The structural analysis of the die and the prediction of stresses and elastic deflections, is useful from two points of view:

- The elastic deflections of the die can be the reason for not achieving desired geometrical tolerances in the forged part, especially if the strict requirements of today's precision forging have to be fulfilled.

- In hot forging, die stresses, consisting of mechanical contact and thermal stresses, govern die fatigue, surface cracking, and crack growth; and consequently, they influence die life, geometrical tolerances and profitability.

The stresses in dies arise mainly from the high level of internal pressure during forging. However, the pressure is not constant over the whole length of the die. Since it is concentrated in the portion of the die that is in contact with the deforming workpiece, the pressure will vary during forging and the length of the pressurised region will change also.

8.4. ANALYSIS of the FORGING DIE GEOMETRY CORRECTIONS

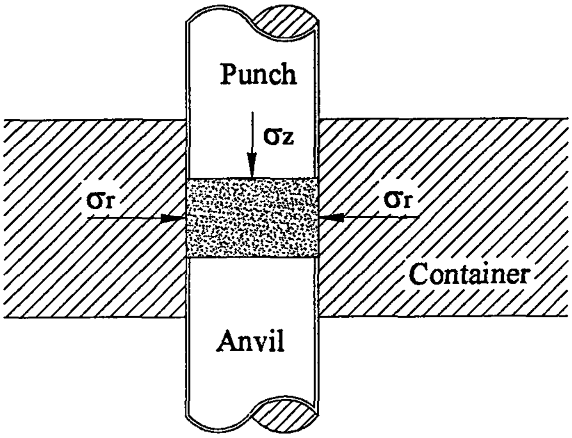
The dimension of the forging is different from the die because of the following factors:

1. The die insert is shrink fitted into the outer ring causing a contraction of the die cavity.
2. In hot forging, the die may be heated prior to forging and further heated by the hot billet during forging. This causes the die insert to expand.
3. Under forging loads, due to forming stresses, the die cavity expands elastically.
4. Post-forging contraction occurs during cooling from forging temperature to room temperature.
5. In electrodischarge machining of the die components, spark gap occurs between electrode and workpiece. This increases the die cavity size.

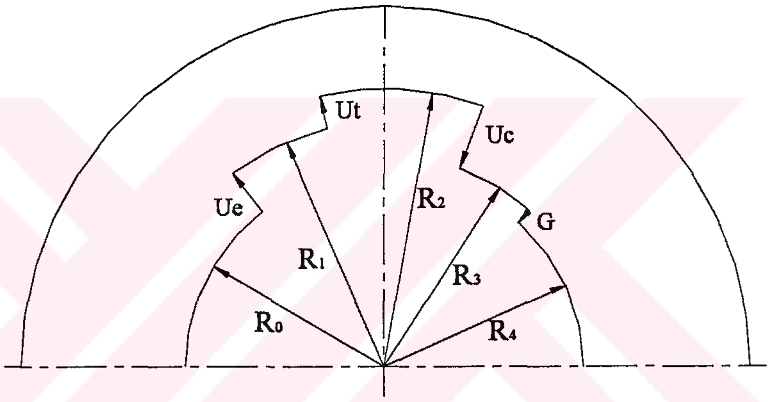
Hence, to obtain the desired accuracy in forged product, each of the geometrical variations listed above has to be estimated and the die geometry has to be corrected accordingly.

Figure 8.2.a shows a schematic representation of cylinder being the simplest axisymmetric forging in a completely closed die cavity and Figure 8.2.b shows half section of a circular forging inside a die container. A billet is placed in the die and deforms under axial compression exerted by the punch and radial flow is constraint by the die wall.

The equations in this chapter are taken from Eyercioğlu and Sadeghi [30, 128].



a) Schematic Representation of an Axisymmetric Forging



b) Half Section of a Circular Forging Inside a Die Container

Figure 8.2. Schematic Representation of Axisymmetric Forging and Die Container

Die geometry correction factors can be stated as follows [30, 128]:

1. Elastic Die Expansion (Ue): As it is seen from Figure 8.2, the radius of the workpiece is assumed to be equal to original die radius R_0. Under a forging load the die will expand elastically and consequently the final forging radius R_1, will be greater than original die radius R_0, by an amount U_e.

$$R_1 = R_0 + U_e$$

2. Thermal Die Expansion (Ut): For forging at elevated temperatures, dies are preheated. Also some heat is transferred from hot billets to the colder die during forging. Therefore, the die will expand by an amount U_t, compared to its original size and the workpiece radius R_2, is given by;

$$R_2=R_0+U_e+U_t$$

3. Thermal Product Contraction (Uc): In warm and hot forging the product will shrink during cooling. Therefore its final radius will be decreased by an amount U_c as shown in Figure 8.2.b. The final product radius R_3, is given by;

$$R_3=R_0+U_e+U_t-U_c$$

4. Spark Gap: Die cavities for precision forging are normally produced by electrodischarge machining and electrode dimensions are different from that of the die cavity due to the spark gap. Therefore the electrode radius R_4, should be smaller than the die cavity by an amount of G, as shown in Figure 8.2.b.

$$R_4= R_0+U_e+U_t-U_c -G$$

8.5. CALCULATION FORMULAE

For a short cylinder with bore radius a, outside radius b, under a uniformly distributed internal pressure P_i, and external pressure P_o, with no axial pressure on its faces, Lame's equations give principal stresses σ_r and σ_θ at any radius as [30];

$$\sigma_r = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} - \frac{P_i - P_o}{r^2}\,\frac{a^2 b^2}{b^2 - a^2} \qquad (8.1)$$

and

$$\sigma_\theta = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} + \frac{P_i - P_o}{r^2}\,\frac{a^2 b^2}{b^2 - a^2} \qquad (8.2)$$

The amount of radial displacement of an element (Ur) at any radius r, can be determined using elastic stress-strain relation;

$$\varepsilon_\theta = \frac{1}{E_d}(\sigma_\theta - \upsilon_d \sigma_r) \qquad \text{and} \qquad \varepsilon_\theta = \frac{U_r}{r}$$

then,

$$U_r = \frac{r}{E_d}(\sigma_\theta - \upsilon_d \sigma_r) \tag{8.3}$$

Substituting σ_r and σ_θ into equation (8.3) gives,

$$U_r = \left(\frac{1-\upsilon_d}{E_d}\,\frac{P_i a^2 - P_o b^2}{b^2 - a^2}\right) r + \left(\frac{1+\upsilon_d}{E_d}\,\frac{a^2 b^2 (P_i - P_o)}{b^2 - a^2}\right)\frac{1}{r} \tag{8.4}$$

Where E_d and ν_d are Young's modulus and Poisson's ratio of the die insert material.

8.5.1. Calculation of the Elastic Die Expansion (Ue):

In order to calculate the changes in workpiece dimensions due to elastic deflection of the die, the elastic-plastic deformation of the workpiece has to be considered.

Assuming that the workpiece is stressed uniformly by the die and always remains cylindrical and at the maximum forging load. The die deflection is elastic and uniform along its axis, and ignoring the friction on workpiece-die interfaces, total variations in workpiece dimensions can be calculated as follows;

a) Changes in workpiece dimensions when the punch load is applied: Assuming a cylindrical workpiece with an initial radius r, less than the die bore R_o is inserted inside the die. By applying the punch load on it, two modes of deformation will occur. First, the workpiece will deform elastically and when the punch pressure becomes equal to the yield stress of the workpiece material, plastic deformation starts and simple compression continues until the workpiece touches the die wall. The radial pressure at the die wall (σ_r) becomes non zero and will increase with an increase in the punch pressure (σ_z). In order to calculate the amount of expansion of the die under radial pressure, initially stress free duplex cylinder is considered as shown in Figure 8.3. If it is subjected to internal pressure P_i, an interfacial stress nP_i will be induced at their interface. For continuity across the interface the hoop (tangential) strains for insert and shrink ring must be equal at this point, $\varepsilon_{\theta 1}=\varepsilon_{\theta 2}$.

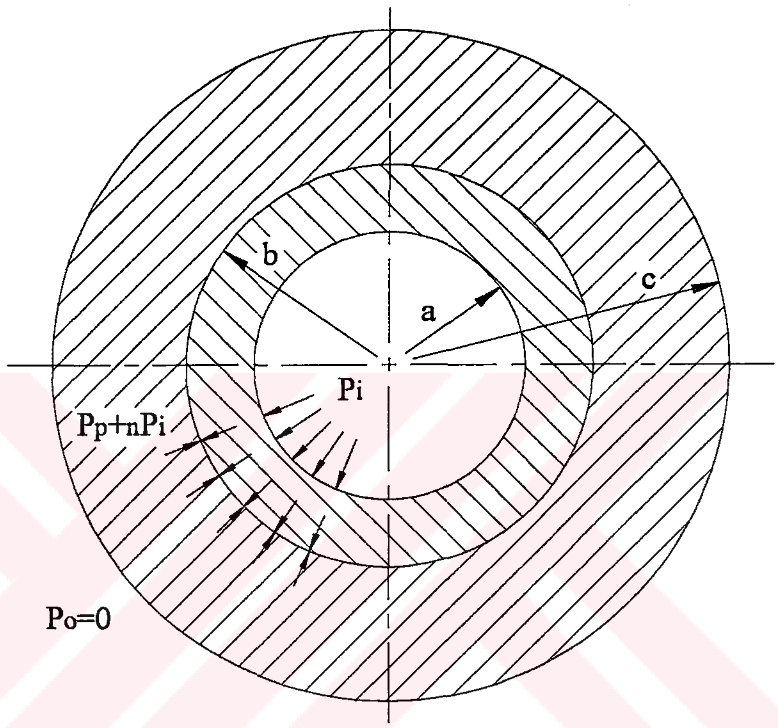


Figure 8.3. A Shrink Fit Assembly of a Die Insert and Outer Ring [30]

where
$$\varepsilon_{\theta 1}=\frac{P_i\left(1-\frac{nb^2}{a^2}\right)}{\frac{b^2}{a^2}-1}\,\frac{1-\upsilon_{d1}}{E_{d1}}+\frac{P_i(1-n)}{\frac{b^2}{a^2}-1}\,\frac{1+\upsilon_{d1}}{E_{d1}}$$

$$\varepsilon_{\theta 2}=\frac{nP_i}{\frac{c^2}{b^2}-1}\,\frac{1-\upsilon_{d2}}{E_{d2}}+\frac{nP_i\left(\frac{c^2}{b^2}\right)}{\frac{c^2}{b^2}-1}\,\frac{1+\upsilon_{d2}}{E_{d2}}$$

therefore;

$$n = \frac{2\frac{E_{d2}}{E_{d1}}\left(\frac{c^2}{b^2}-1\right)}{x+y\left(\frac{b^2}{a^2}\right)+z\left(\frac{c^2}{b^2}\right)+w\left(\frac{c^2}{a^2}\right)} \qquad (8.5)$$

where;

$$x = -\left(1-\upsilon_{d2}+\frac{E_{d2}}{E_{d1}}(1-\upsilon_{d1})\right)$$

$$y = 1-\upsilon_{d2}-\frac{E_{d2}}{E_{d1}}(1-\upsilon_{d1})$$

$$z = -\left(1+\upsilon_{d2}-\frac{E_{d2}}{E_{d1}}(1+\upsilon_{d1})\right) \qquad \text{and}$$

$$w = 1+\upsilon_{d2}+\frac{E_{d2}}{E_{d1}}(1-\upsilon_{d1})$$

The subscripts 1 and 2 refer to die insert and shrink ring respectively. The radial displacement of the die bore (i.e., where r = a) ;

$$U_a = \frac{a\left(a^2(1-\upsilon_{d1})+b^2(1+\upsilon_{d1}-2n)\right)P_i - 2ab^2P_p}{E_{d1}\left(b^2-a^2\right)} \qquad (8.6)$$

b) Changes in workpiece dimensions when the punch load is removed: When the maximum load exerted is on the workpiece, the radial stress will be greater than its yield strength. After reaching such a condition, if the punch load is removed, the die will compress the workpiece plastically until the radial stress on the workpiece is reduced to twice its shear yield stress (Sy). By using Tresca's yield criterion, the relationship between the radial stress (σ_r) and (σ_z) the punch pressure is;

$$\sigma_r = \sigma_z + 2Sy$$

The total amount of radial expansion of the workpiece (U), at the end of this stage, can be calculated by substituting $\sigma_r = P_i = 2Sy$ into equation (8.6) as;

$$U_a = \frac{a\left(a^2(1-\upsilon_{d1}) + b^2(1+\upsilon_{d1} - 2n)\right)2S_y - 2ab^2P_p}{E_{d1}\left(b^2 - a^2\right)} \qquad (8.7)$$

c) Changes in workpiece dimensions during ejection: At the end of forging process, the punch pressure is zero and the radial stress ($2S_y$) is still acting on the workpiece. On ejection, its radius will expand elastically and the amount of recovery (s) can be calculated by assuming a cylindrical state of stress ($\sigma_r = \sigma_\theta$) and by putting $\sigma_z = 0$;

$$\varepsilon_\theta = \frac{s}{r} \qquad \text{and} \qquad \varepsilon_\theta = \frac{1-\upsilon_w}{E_w}\sigma_\theta$$

then, substituting r = a and $\sigma_\theta = 2Sy.a$

$$s = \frac{1-\upsilon_w}{E_w}2S_y\, a \qquad (8.8)$$

where E_w and ν_w are the Young's modulus and Poisson's ratio of the workpiece material. The total change in the workpiece dimensions due to elastic die expansion is;

$$U_e = U_a + s$$

$$U_e = \frac{a\left(a^2(1-\upsilon_{d1}) + b^2(1+\upsilon_{d1} - 2n)\right)2S_y - 2ab^2P_p}{E_{d1}\left(b^2 - a^2\right)} + \frac{1-\upsilon_w}{E_w}2S_y\, a \qquad (8.9)$$

8.5.2. Calculation of the Thermal Die Expansion (Ut):

In hot forging, dies are preheated to prevent cracking of the die components and to reduce the cooling rate of the workpiece. Some heat is transferred from the workpiece during forging which further heats the die. The combination of these two sources of heat causes the die to expand.

The temperature distribution along the radius of the die with a preheat temperature of Tp and bore diameter of Ti is given in Figure 8.4. The preheat temperature is assumed constant throughout the die, but the heat transferred from the workpiece produces an outward heat flow with radial temperature gradient (the axial temperature gradient is neglected).

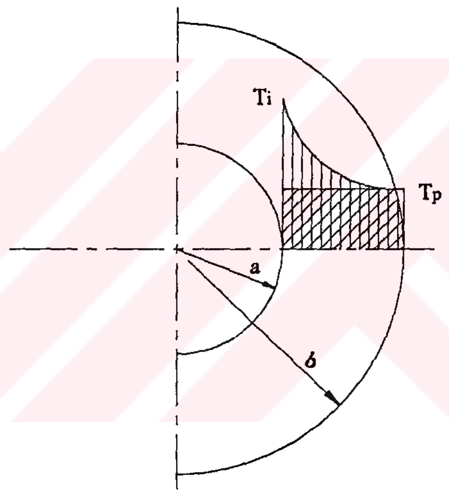


Figure 8.4. Temperature Distribution Along the Die Radius in Hot Forging

Assuming uniform preheating of the die wall will expand freely. The magnitude of the radial expansion (U_{tp}), at any radius can be determined as;

$$U_{tp} = r\,\alpha_d\,(T_p - T_r) \tag{8.10}$$

Where T_r is room temperature, T_p is preheat temperature and α_d is the coefficient of thermal expansion of the die material.

For an axisymmetric steady state system with purely radial heat flow, the temperature distribution is given by the well-known logarithmic law. If (T_i-T_p) is the temperature increase on the inner surface of the die and assuming that the corresponding temperature increase on the outer surface is zero ($T_o - T_p = 0$), where T_i is bore temperature as hown in Figure 8.5. The temperature T at any radius r due to outward heat flow is;

$$T = -\frac{\delta T}{(b-a)} r + \frac{(T_i - T_o)}{(b-a)} b \qquad (8.11)$$

where $\left(T = -\frac{\delta T}{(b-a)}\right)$ represents the temperature gradient along the radius.

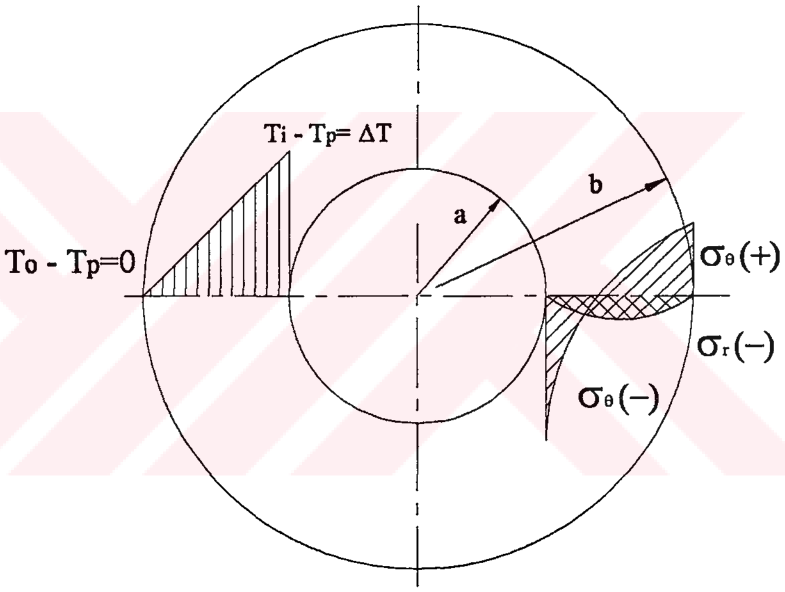


Figure 8.5. Radial and Tangential Stress Distributions due to Outward Temperature Gradient [30]

The radial and tangential stress induced by this temperature gradient is given by the following equations;

$$\sigma_{rt} = \frac{\alpha_d E_d \delta T}{3(b-a)} \left(\frac{a^2 b^2}{a+b} \frac{1}{r^2} - 2r + \frac{b^3 - a^3}{b^2 - a^2} \right) \qquad (8.12)$$

and

$$\sigma_{\theta t} = \frac{\alpha_d E_d \delta T}{3(b-a)}\left(\frac{-a^2b^2}{a+b}\frac{1}{r^2} - r + \frac{b^3-a^3}{b^2-a^2}\right) \tag{8.13}$$

Substituting these equations into equation 3.3, the radial displacement at any radius r due to thermal stresses can be found as;

$$U_{ts} = \frac{-\alpha_d \delta T}{3(b-a)}\left[\frac{-(1+\upsilon_d)a^2b^2}{a+b}\frac{1}{r} + (2\upsilon_d - 1)r^2 + \frac{(1-\upsilon_d)(b^3-a^3)}{b^2-a^2}\right] \tag{8.14}$$

Total die expansion (U_t) due to temperature, will then be

$$U_t = U_{tp} + U_{ts} \tag{8.15}$$

8.5.3. Calculation of the Thermal Product Contraction (Uc):

The amount of shrinkage after hot forming operations depends on the working temperature and coefficient of thermal expansion of the forged material. Assuming that shrinkage takes place radially, and the finish forging temperature is uniform, the amount of radial contraction at any radius is;

$$U_c = r\,\alpha_w\,(T_f - T_r) \tag{8.16}$$

Where T_f is the forging temperature, α_w is the coefficient of thermal expansion of the workpiece, and r is the radius of the workpiece before contraction.

In order to achieve close dimensional tolerances on forgings die dimensions should be closely controlled. From the foregoing it is apparent that a knowledge of the magnitude of the above factors should be obtained before appropriate die and electrode die and electrode dimensions can be determined.

It is assumed that in axisymmetric completely closed die forging after removing the applied load, all dimensional changes take place in radial direction. In order to study the basic mechanics of dimensional variations in a precision forging process, the case of a solid cylinder forged at room and elevated temperatures in a cylindrical die is considered. A theoretical analysis of the dimensional accuracy of such a forging is presented by determining the above factors. Therefore, it is thought that the results of this analysis can be applied to any axisymmetric precision forging process.

8.6. APPLICATION of the CORRECTION FACTORS to the FORGING GEOMETRY

Using the analysis given in the previous section, it is assumed that dimensional changes of the forging takes place in radial direction. Also, from the foregoing theory, for a given forging condition the extend of this movement is proportional to the magnitude of that radius. Therefore, the following expressions can be written [30];

$$\frac{dr}{r} = \frac{dr_b}{r_b} = \frac{dr_p}{r_p} = \frac{dr_t}{r_t} = k \qquad (8.17)$$

The factor k is constant for given conditions and can be calculated for a point n as;

$$k = \frac{(U_e + U_t - U_c - G)_n}{r_n} \qquad (8.18)$$

Then the magnitude of any radius of the final forging is;

$$r' = r + dr = r(1 + k) \qquad (8.19)$$

Using the above analysis, the parameters affecting forging dimensions were calculated and for a given condition the profile of the die was determined. A program has been written to make these calculations and to create the corrected forging product for die. Die insert and shrink ring dimensions (Figure 8.78) are stated in the following equations.

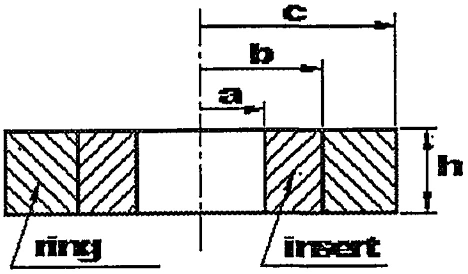


Figure 8.6. Die Insert and Shrink Ring Dimensions

The determination of die insert and shrink ring dimensions have vital importance in die design. Equations from 8.20 to 8.27 give the formulae for these dimensions.

$$b = \frac{a}{Q_1} \tag{8.20}$$

$$c = \frac{a}{Q} \tag{8.21}$$

$$z = \frac{b.S_y}{E}\left(\frac{1}{K_1} - Q_1^2\right) \tag{8.22}$$

$$Q = Q_1.Q_2 \tag{8.23}$$

$$Q_1 = \sqrt{\frac{1}{2}\left(1 + \frac{1}{K_1}\right) - PP} \tag{8.24}$$

$$Q_2 = Q_1.\sqrt{K_1} \tag{8.25}$$

$$PP = \frac{P_i}{S_{ydie}} \tag{8.26}$$

$$K_1 = \frac{S_{yring}}{S_{ydie}} \tag{8.27}$$

Where;

a= Die insert inner radius

b= Die insert outer radius

c= Shrink ring outer radius

z= Interference

P_i= Inner Pressure

8.7. DIE DESIGN CONSIDERATIONS

Since the die for precision forging gets very high radial pressure during the process, it considerably deforms in the radial direction. This radial deformation of the die becomes an important factor influencing the dimensional accuracy of the product. In order to obtain the product with highly accurate dimension, it is therefore essential to acquire some information on the elastic deformation of the die and the product. Finally, Process and die designs are carried out using these information. [123]

In hot forging, during deformation, both dies apply pressure on workpiece to deform. Due to this deformation, the temperature of the dies and the workpiece increases. The temperatures of the die and workpiece are also affected by the friction condition between die workpiece interface. It is observed that temperature has a significant effect on the flow stress of a material. To calculate forging load, it is necessary to take into account the temperature change during hot forging. These factors were encountered in the previous sections.

The major problem associated with precision forging is related mainly to the control of billet volume. Inevitable billet volume variations dealt with in two ways. If the die cavities are completely closed, variation in elastic deformation of tooling and forging machines occur, resulting in dimensional variations of forgings [13]. In such cases overloading and failure is likely. A tool set designed to overcome this problem by limiting transmittable forging loads has been described by Dean [131]. The most common approach to limiting overloading is to ensure that at least one surface of the forging is unconstrained by cavity walls.

8.7.1. Basic Considerations

The main consideration of this study is the design of completely closed dies, either by shape is given by punch and die or only in die. In this thesis, basic regions are used for determining forging load calculation. Convex regions are found inapplicable to velocity fields, because of the contradictory conditions obtained at the tangential intersections of the two straight line boundaries with the curved.

Following Figure 8.7 shows the general assembly of the die shape used in this work.

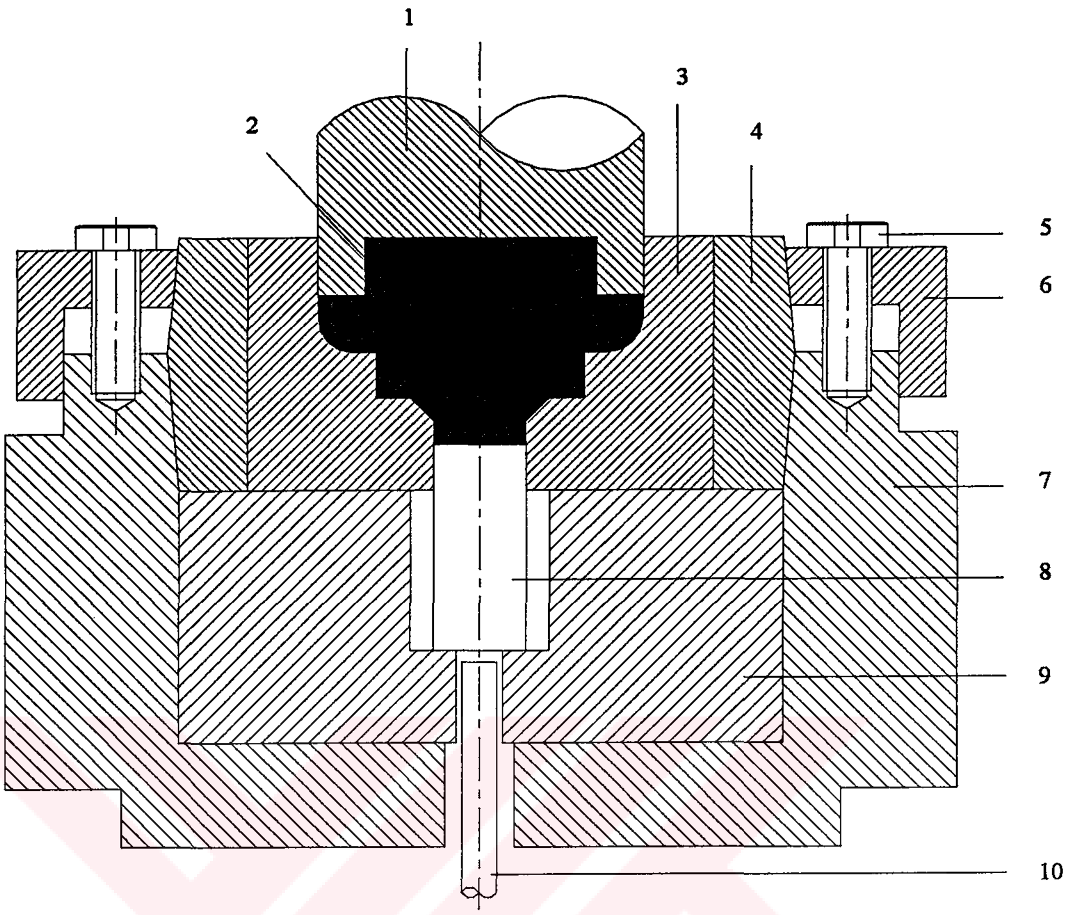


Figure 8.7. General Assembly of Die Shape

Die shape consists mainly 10 parts:

1. Punch	4. Shrink ring	7. Bolster	10. Ejector rod
2. Product	5. Bolt	8. Ejector	
3. Die insert	6. Die clamp ring	9. Ejector seat	

The punch is shown as a single unit and detail of punch is not given. The punch forms the top surface of a cavity and is attached to the moving ram of a forging machine. The ejector is used to remove the product from the die without deforming them and for easy removal of scale and lubricant deposits. Ejector is also used to give the shape to the bottom side of the product.

Die insert forms the inner side of the die (die cavity). Since die insert is subjected to forging load, friction load and temperature, its material must be chosen so that it resists to all required conditions. In order to increase the resistance against internal pressure, it is usual to make an insert shrink fitted into one or more shrink rings. The compressive stress imposed by the *shrink ring* has cumulative effect at the bore of the die insert. Therefore, resultant tensile stress on the bore, caused by the forging loads transmitted through the forging part, can be substantially reduced.

8.7.2. Process Characteristic

An important feature of completely closed forging dies is how the workpiece is deformed to fill the die cavity. For the simple shapes, the deformation mode can be identified by the order of filling of top and bottom corners of the cavity. Figure 8.8 shows a workpiece enclosed in die cavity with the punch and ejector.

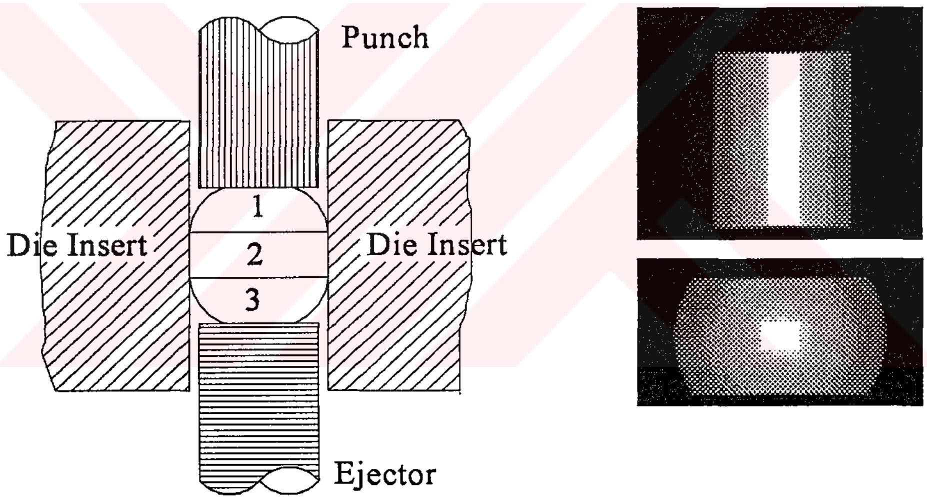


Figure 8.8. Barrelling of Workpiece

The workpiece height, initially, get smaller until the outermost side of workpiece touches to the die wall while the punch is moving downward. Barrelling almost start at the middle of the workpiece. Therefore, friction between the die wall and workpiece plays an important role for the required forging load. After that point, the volume of the part shown by number 2 in Figure 8.8 starts to increase due to the increment in its height. That means more forging load is required. In the final stage, corners of the product remains a little bit circular.

Another aspect of net shape forging is extrusion of workpiece material through the punch clearance when the bottom of the die corner is filled. This fin formation is undesirable before complete die filling, because when the fin starts it continues to form at an approximately constant extrusion load. Therefore, the pressure in the die cavity can not be increased to fill the unfilled areas, and also dimensional accuracy can not be obtained due to material loss in the fin formation. In the following Figure 8.9, there are two workpiece which show the fin formation.

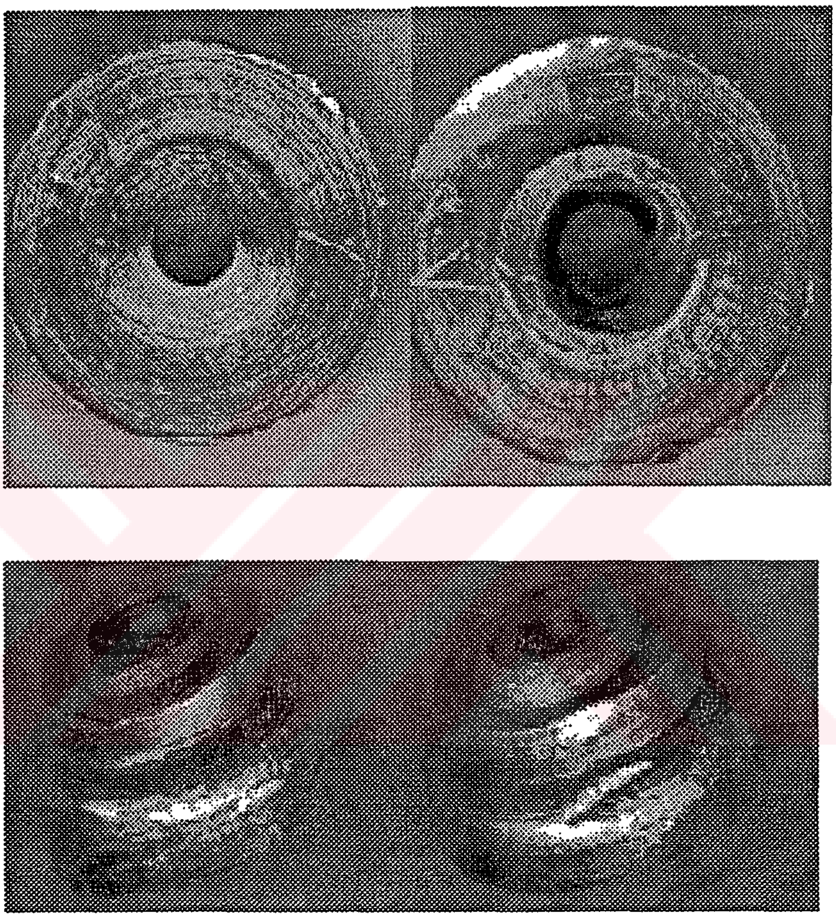


Figure 8.9. Experimental Work Showing Fin Formation

8.7.3. Die Materials

The material property requirements for hot forging dies can be divided into two groups; one associated with manufacture and the other with service performance. Different requirements are often incompatible, so that final material selection represents a compromise solution [30].

The manufacturing requirements may be summarised as follows;

- Low first cost
- Ease of machining
- Simplicity of heat treatment
- Good hardenability

The performance requirements are;

- High hot strength
- High wear resistance
- High mechanical fatigue resistance
- Good thermal fatigue resistance
- Good brittle fracture resistance

To meet these requirements a family of special tool steel has been developed. Chromium type hot work tool steels are generally preferred as a die material for hot forging. Their predominant properties are high hardenability, excellent toughness and greater ductility, even at the cost of wear resistance.

8.7.4. Die Life

Die life depends on various factors. But three of them are essential. These are:

- Erosion
- Friction
- Die heating

When dies with non penetrating punches or ejectors are used erosion between the elements are inhibited. Consequently, die life in these dies is expected to be increased.

If the forging workpiece is tall or contact area between workpiece and die wall is large, then it causes to friction and therefore reduces the die life.

The contact time between the workpiece and the die before and after the forging is important as it affects die temperature. Therefore this time should be as short as possible [13, 132].

8.7.5. Die Element Configuration

In die element configuration three main die components are necessary. They are; punch, ejector and die insert. Cross section of these main components for basic regions (explained in Chapter 7) are shown in the following figures from Figure 8.10 to Figure 8.12.

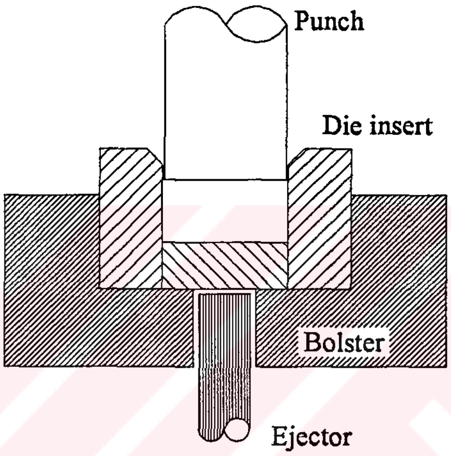


Figure 8.10. Die Geometry for Rectangular Region

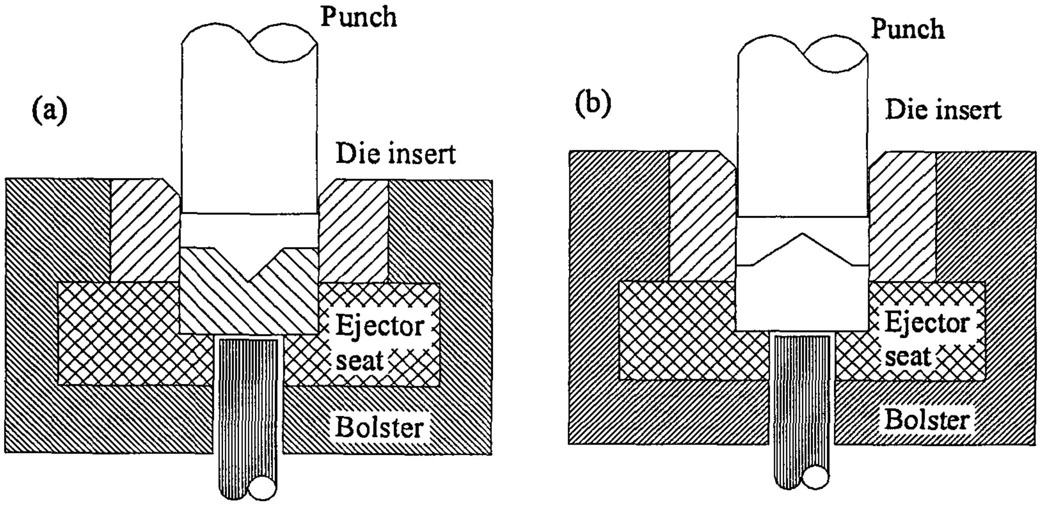


Figure 8.11. Die Geometry for (a) Inward and (b) Outward Triangular Region

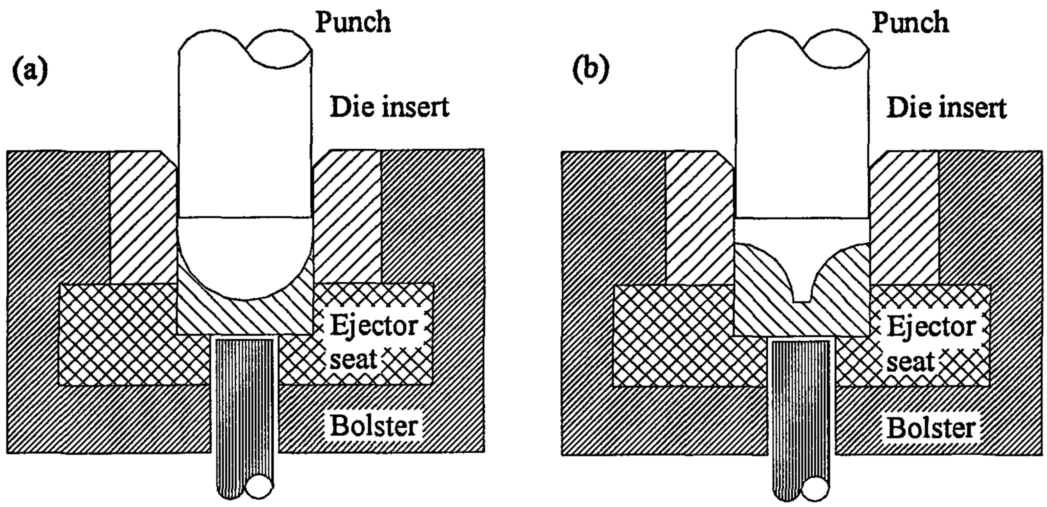


Figure 8.12. Die Geometry for Circular Region
(a) Inward Convex Region
(b) Inward Concave Region

The basic function of the tooling is that relative movement of punch and ejector deforms the workpiece and movement of them are restricted with the volume of the workpiece.

In this chapter, an attempt has been made to enhance the accuracy of axisymmetric parts. It is noted that dimensions of the die cavity are different from the finished product dimensions due to the some factors. These factors, called die geometry correction factors, are formulated and explained in detail. Die insert radius, shrink ring radius and interference are also formulated and put into account.

CHAPTER 9

EXECUTION of the PROGRAM

9.1. INTRODUCTION

This chapter is devoted for the explanation of the execution of the developed program. Capabilities and facilities of the program for users are presented in detail. Due to the complexity of the program, capabilities are given in individual titles. At the end of this chapter one example is given to make the program steps more clear.

9.2. INTRODUCTION to the PROGRAM

The developed expert system is named by EX-AFORD in the abbreviation of "Expert System for Axisymmetric Forging Dies". This expert system is mainly covered by eight groups. These groups are presented in the main screen by pull-down menus which is shown in Figure 9.1. The content of each group were given in previous sections.

The developed expert system was written in Borland C++ language and AutoCAD was used as a graphical environment. The execution of program can be carried out in PC computers.

9.3. GENERAL OUTLOOK of the PROGRAM

EX-AFORD can be executable by either running Borland C++ program, loading the directory which stores the program and running ORNEK.EXE or by just double clicking ORNEK.EXE from Windows environment. When the program is executed, after an opening introduction screen a user friendly pull down menu appears as shown in Figure 9.1. EX-AFORD have eight menu items, titled by;

- File
- Geometry Formation
- Load calculation
- Stress Calculation
- Material Database
- Die Drawing
- Rules
- Help

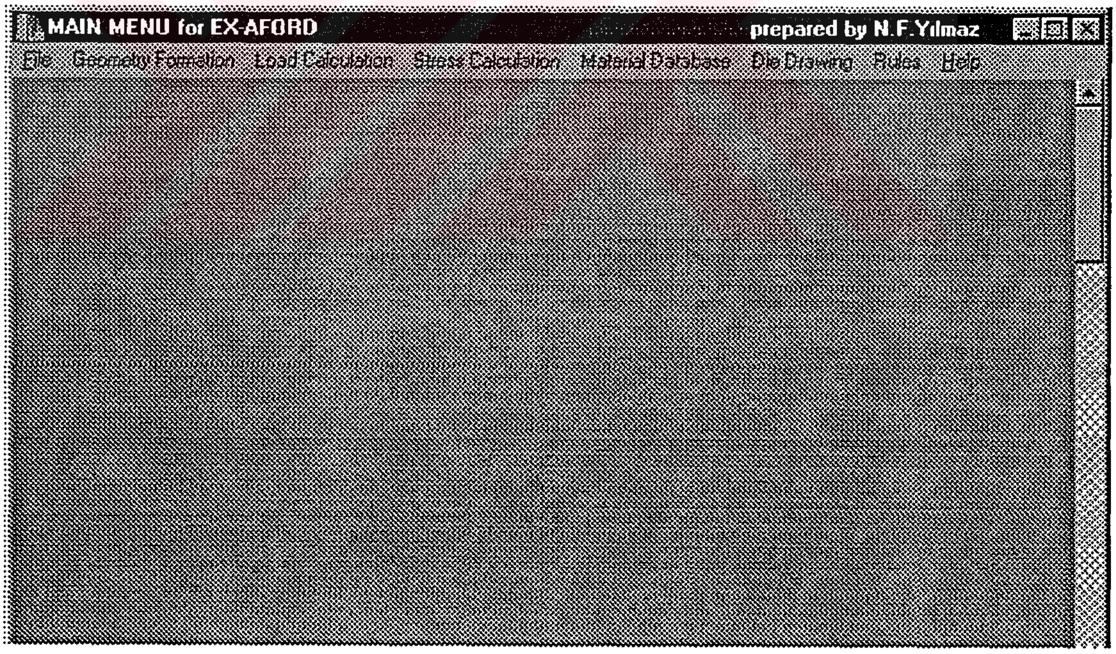


Figure 9.1. Main Screen of EX-AFORD

They can be selected by mouse or keyboard. Since each menu contains sub menus, user should know the program menu tree. This tree is shown in Figure 9.2.

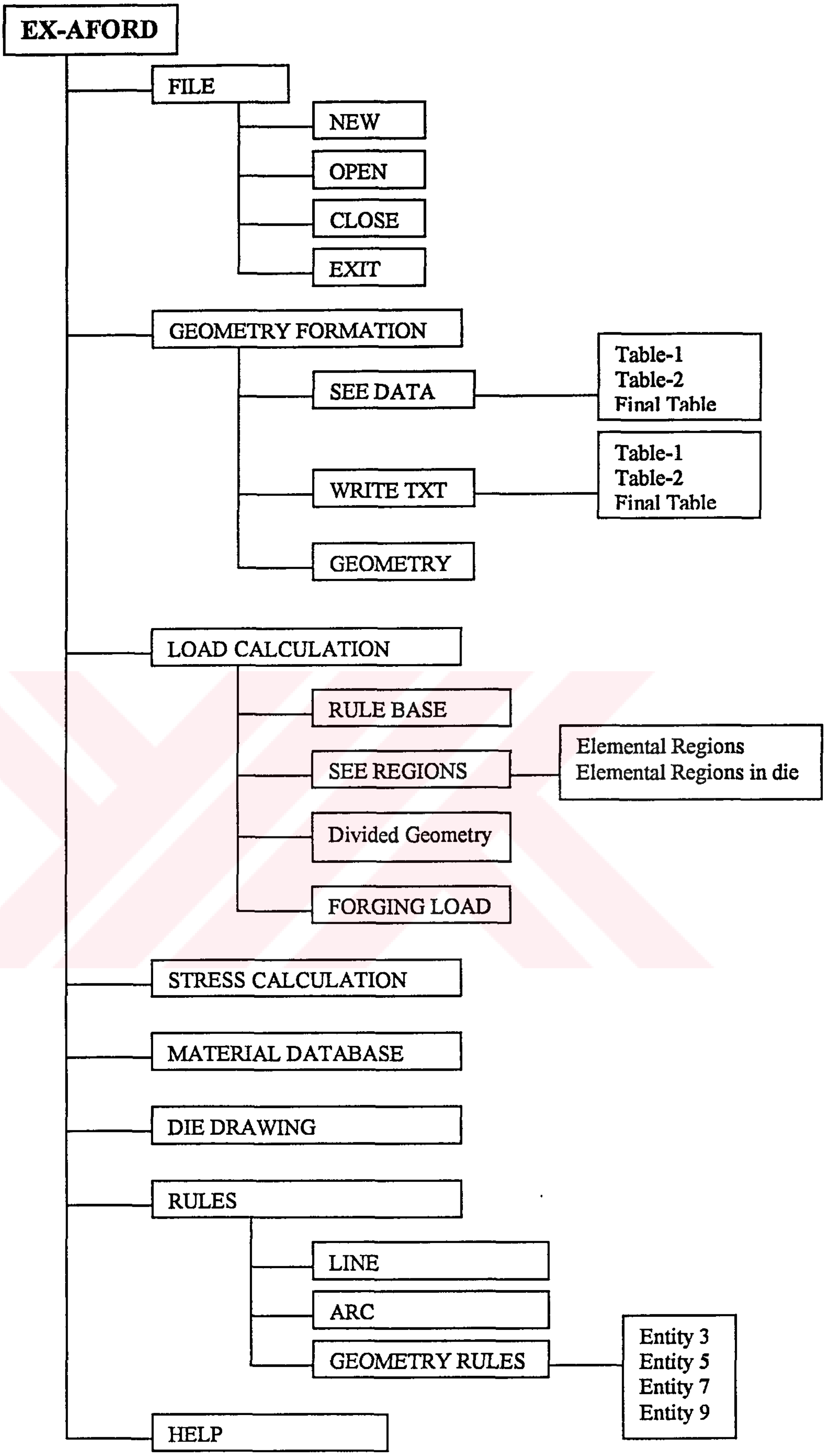


Figure 9.2. Menu Tree for EX-AFORD

In the following figures from Figure 9.3 to 9.10 the constituents of each menu are shown.

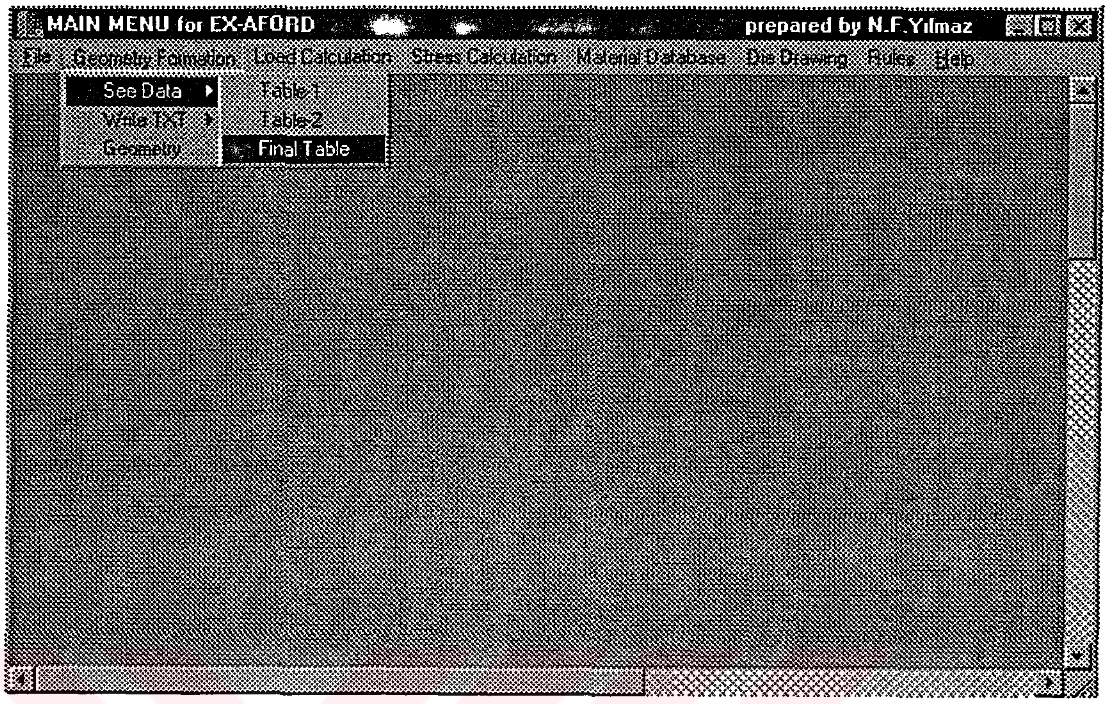


Figure 9.3. “Geometry Formation - See Data” Pull-down Menu

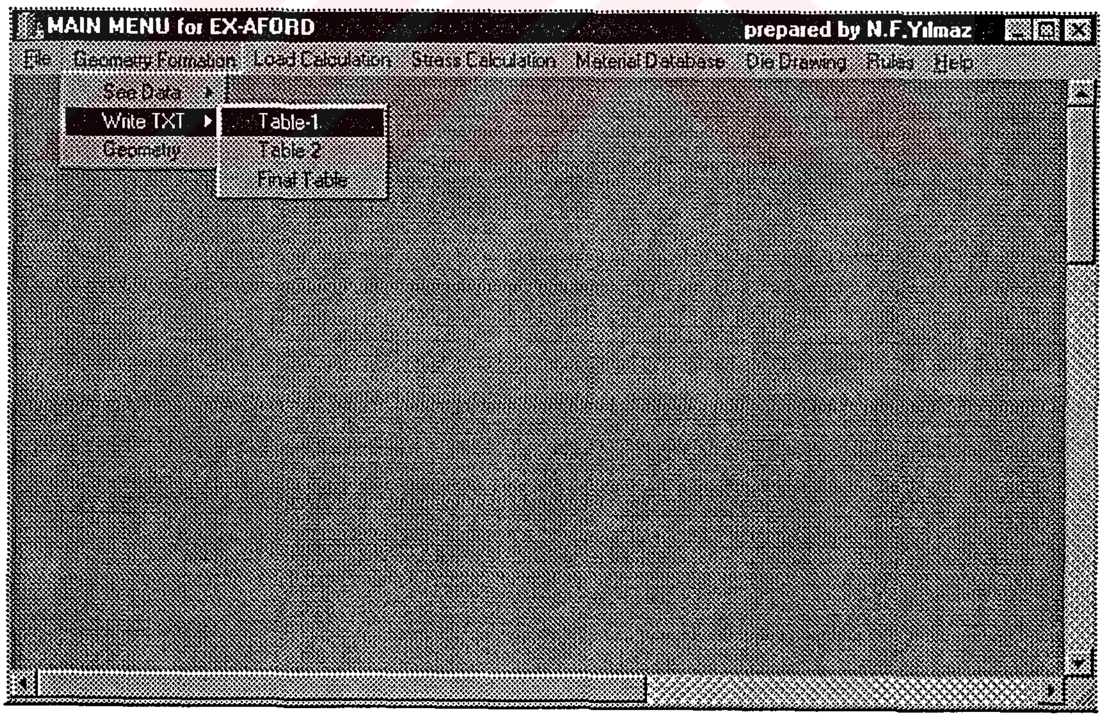


Figure 9.4. “Geometry Formation - Write TXT” Pull-down Menu

When "Geometry" button is clicked following Figure 9.5 appears on screen. This menu is used for feature recognition.

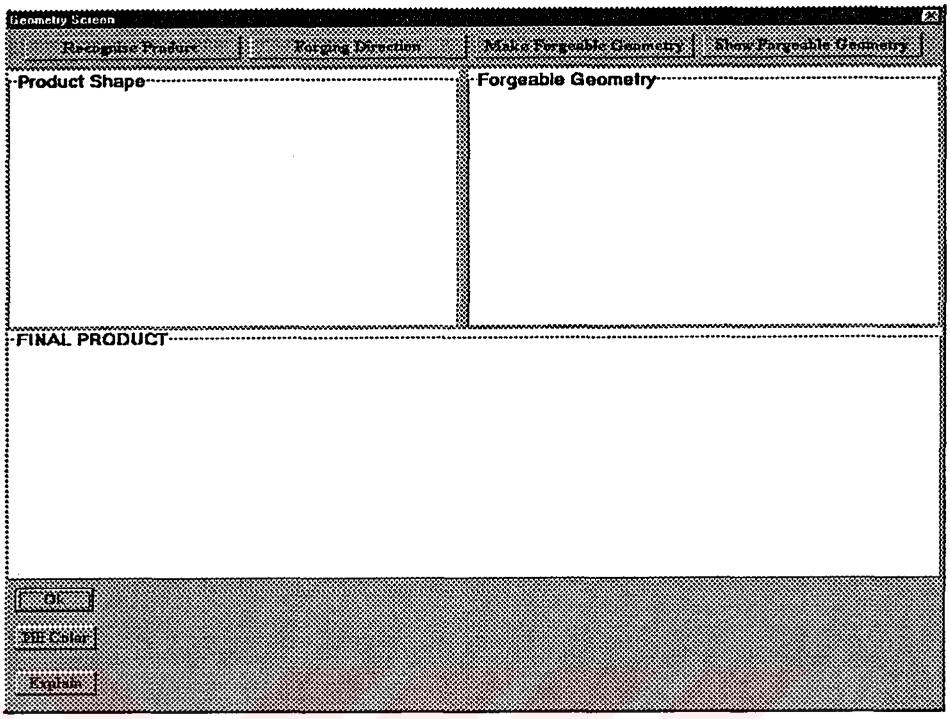


Figure 9.5. "Geometry Formation – Geometry" Pull-down Menu

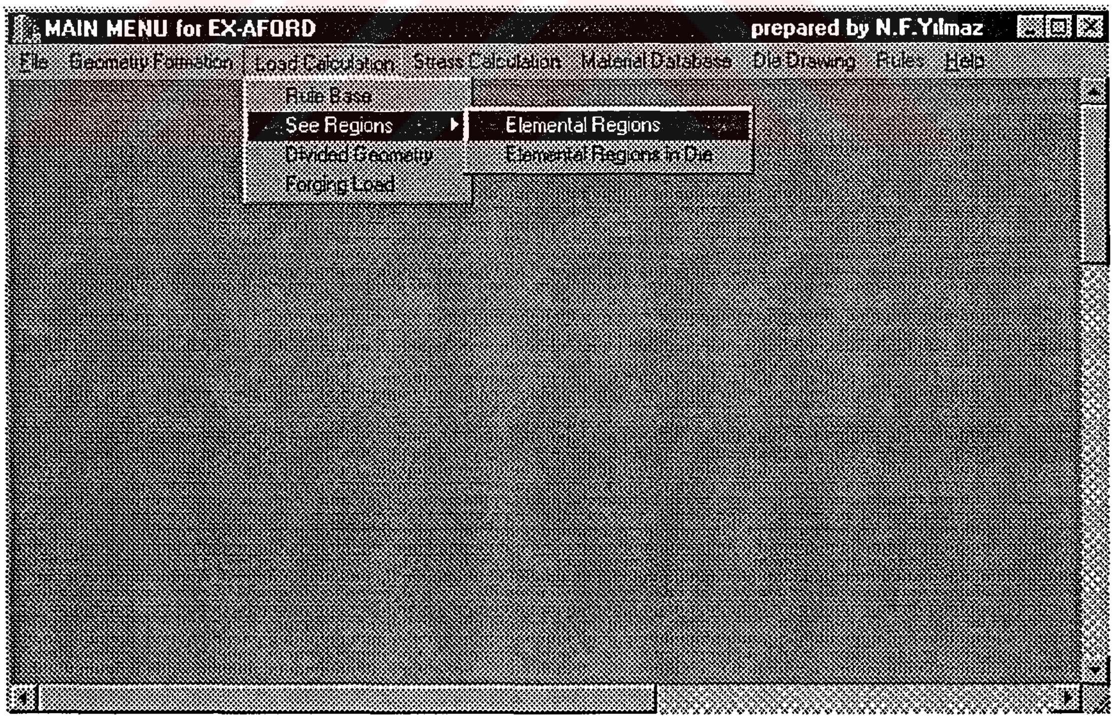


Figure 9.6. "Load Calculation" Pull-down Menu

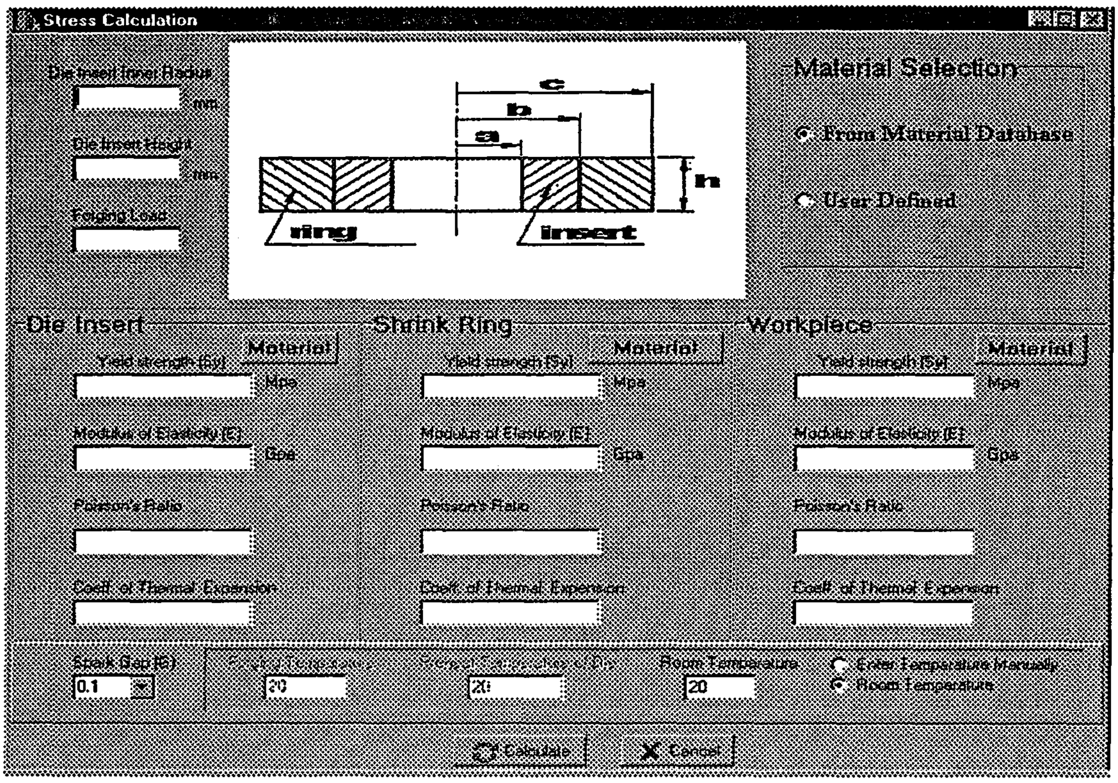


Figure 9.7. "Stress Calculation" Pull-down Menu

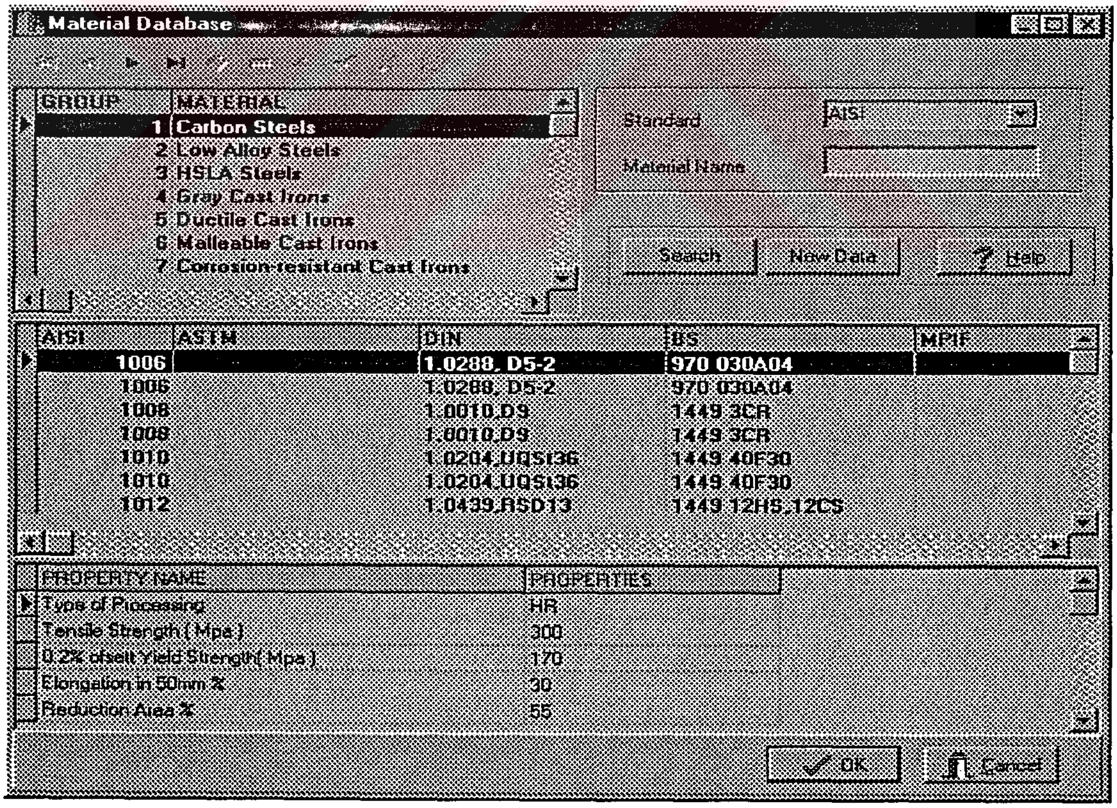


Figure 9.8. "Material Database" Pull-down Menu

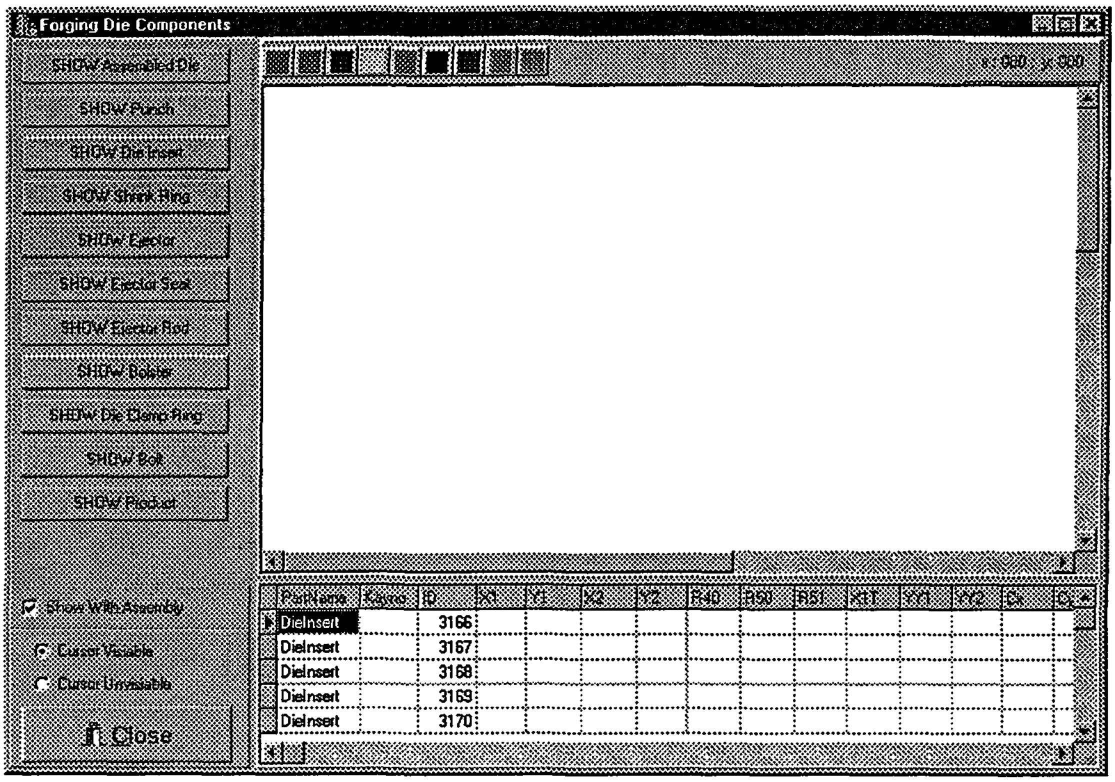


Figure 9.9. "Die Drawing" Pull-down Menu

Figure 9.10. "Rules" Pull-down Menu

9.4. EXECUTION of the PROGRAM

Once the finished product is drawn, it is converted in DXF format in order to activate feature recognition module. By the help of program, this file is extracted and all entity co-ordinates are put into table in drawing order. File name is selected from "File" menu by clicking the "Open" button (Figure 9.11).

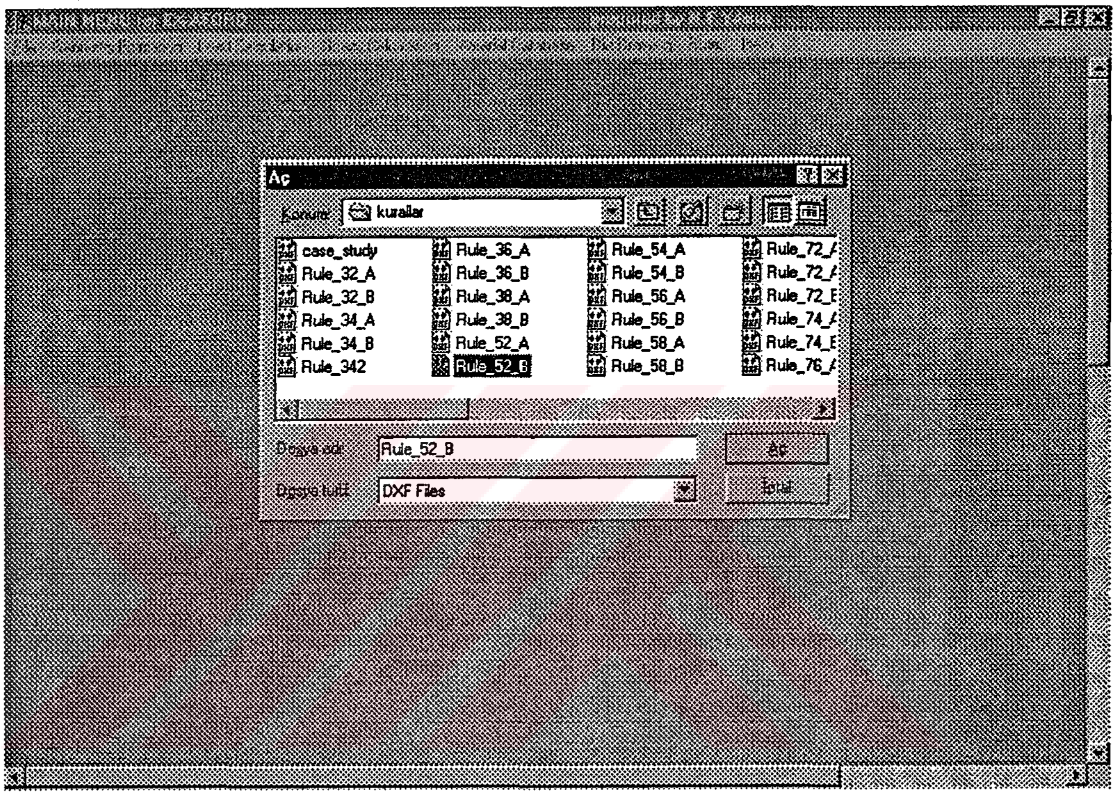


Figure 9.11. Open File Screen

9.4.1. Geometry Formation

The execution sequence of program is important. User must follow certain instructions either by given in this text or by aid of "HELP" menu. After opening the file, as a second step, "Geometry" button must be activated which is located into "Geometry Formation" menu (Figure 9.3). Figure 9.5 covers all geometry functions. Functions of each button is given in the following;

- **Recognise Product:** Feature recognition module is started to execute by clicking this button. This button reads DXF file of the selected file and put the entity co-ordinates into Table-1. This Table-1 can be seen laterally from "See Data", if it is desired.
- **Forging Direction:** This button is not necessary for the execution of the program. This facility can be used in order to see that the product is unilateral or bilateral which is explained in detail in chapter 6.
- **Make Forgeable Geometry:** This button must be activated after "Recognise Product" button. Final product geometry may not be forgeable in closed die. Therefore, it must be checked that whether it is forgeable in closed die or not. If not, by clicking this button new forgeable geometry is created and all related data of the product are transferred into "Final Table", which can be seen laterally from "See Data", if it is desired.
- **Show Forgeable Geometry:** This button enables the user to see the *"Product Shape"*, *"Forgeable Geometry"*, and the *"Final Product"* in the graphical representation (Figure 9.12). By this way, stages from initial geometry to final product shape can be seen.

The program criterion is based on rule based system. In order to determine forgeable geometry, the newly generated coding system called FORGAX, which is the part of EX-AFORD, is applied. Maximum diameter side of the shape must be at the top for unilateral shapes. Therefore, the shape geometry gets small from top to bottom. For bilateral shape the maximum diameter is neither the top nor the bottom portion of the shape. Hence, the shape is given by the punch and remaining part is given by in the die. In this part of the program undercuts are eliminated and new geometry is proposed.

From expert system perspective, it is known that "inference engine" is the knowledge processor which looks at the problem description and tries to find solution. It can be considered as a program that applies domain knowledge to known facts to draw conclusions. Inference engines are domain independent such that they apply domain knowledge to case specific application. The explainer is used to find out how a solution was obtained from an expert system and which individual steps were taken. The user can communicate with the explainer to obtain a report about the operation of the expert system. If the user desires, he can obtain intermediate data and information on how the knowledge was used.

As it is seen from the Figure 9.12 "**Explain**" button activates the inference engine and finds out how a solution is obtained and represents the rules which is used for forgeable geometry.

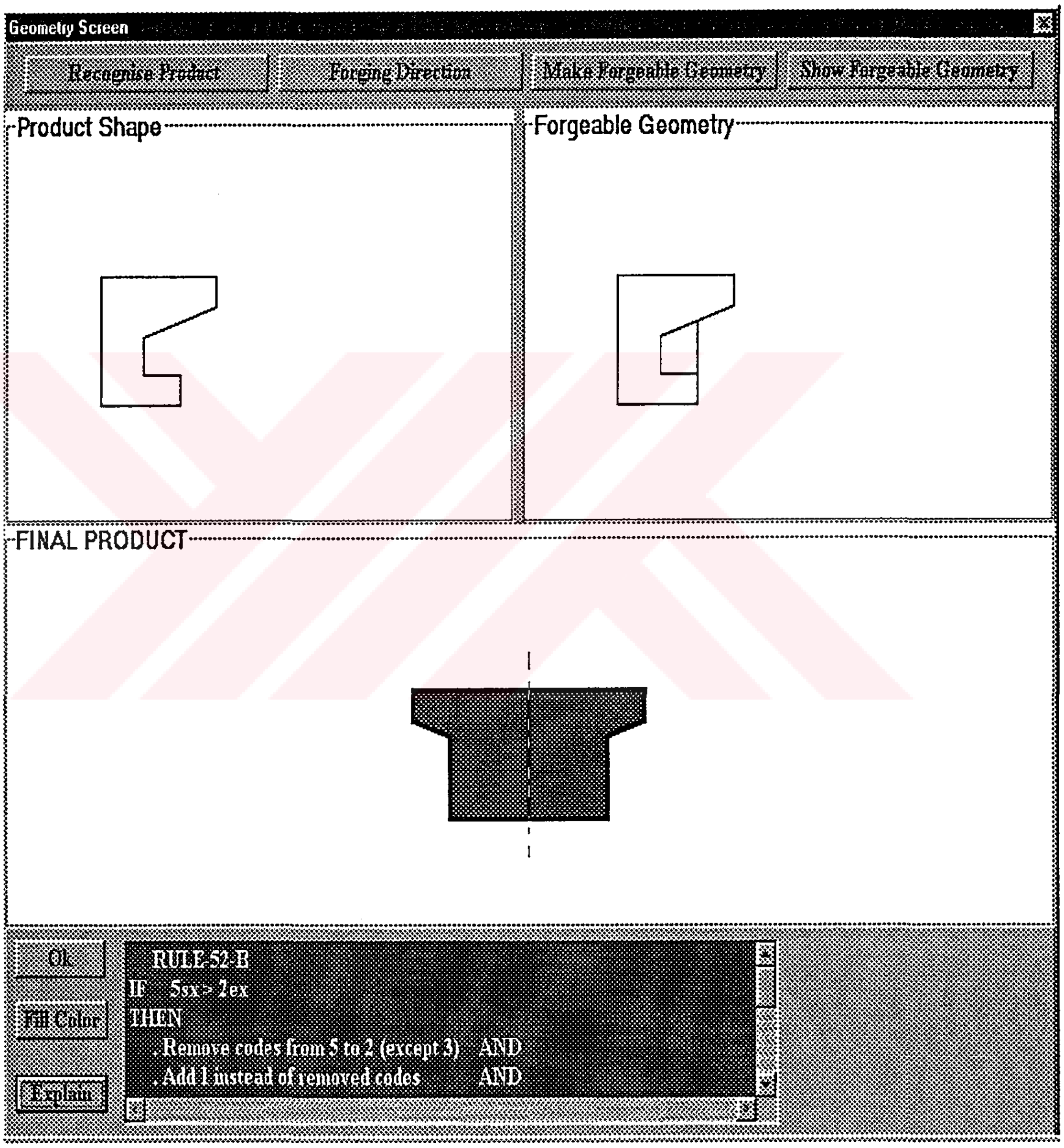


Figure 9.12. "Show Forgeable Geometry" Screen

"Write TXT" button, shown in Figure 9.13, which is located into "Geometry Formation" menu is useful in order to export the data, (Table-1, Table-2 and Final Table) in TXT format. This facility enables the user to get data from program and to use in other softwares, like AutoLISP.

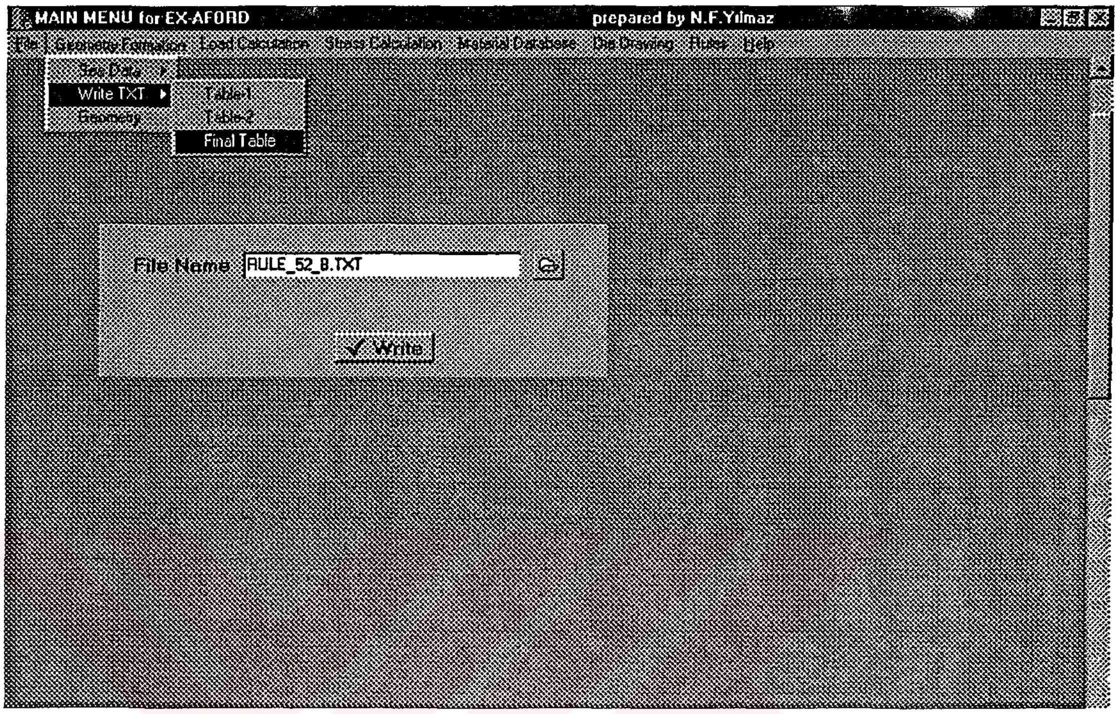


Figure 9.13. "Write TXT" Screen

9.4.2. Load Calculation

"Load Calculation" menu must be activated after geometry formation procedures, explained in the previous section. "Load Calculation" pull-down menu involves four sub-menus. "Forging Load" button has vital importance, while the other three options are not necessary for execution of the program. They are aimed for knowledge only.

Rule Base: This button is added to the program in order to add, delete or change any forging load rule. This section is postponed in future work and recommended for future study.

See Regions: This menu covers two sub-menus. "Elemental Regions" button enables the user to see the regions which are skeleton of the forging load calculation (Figure 9.14). "Elemental Regions in Die" button is only for seeing regions in closed die. These two are dependent on user's choice whether to be used or not.

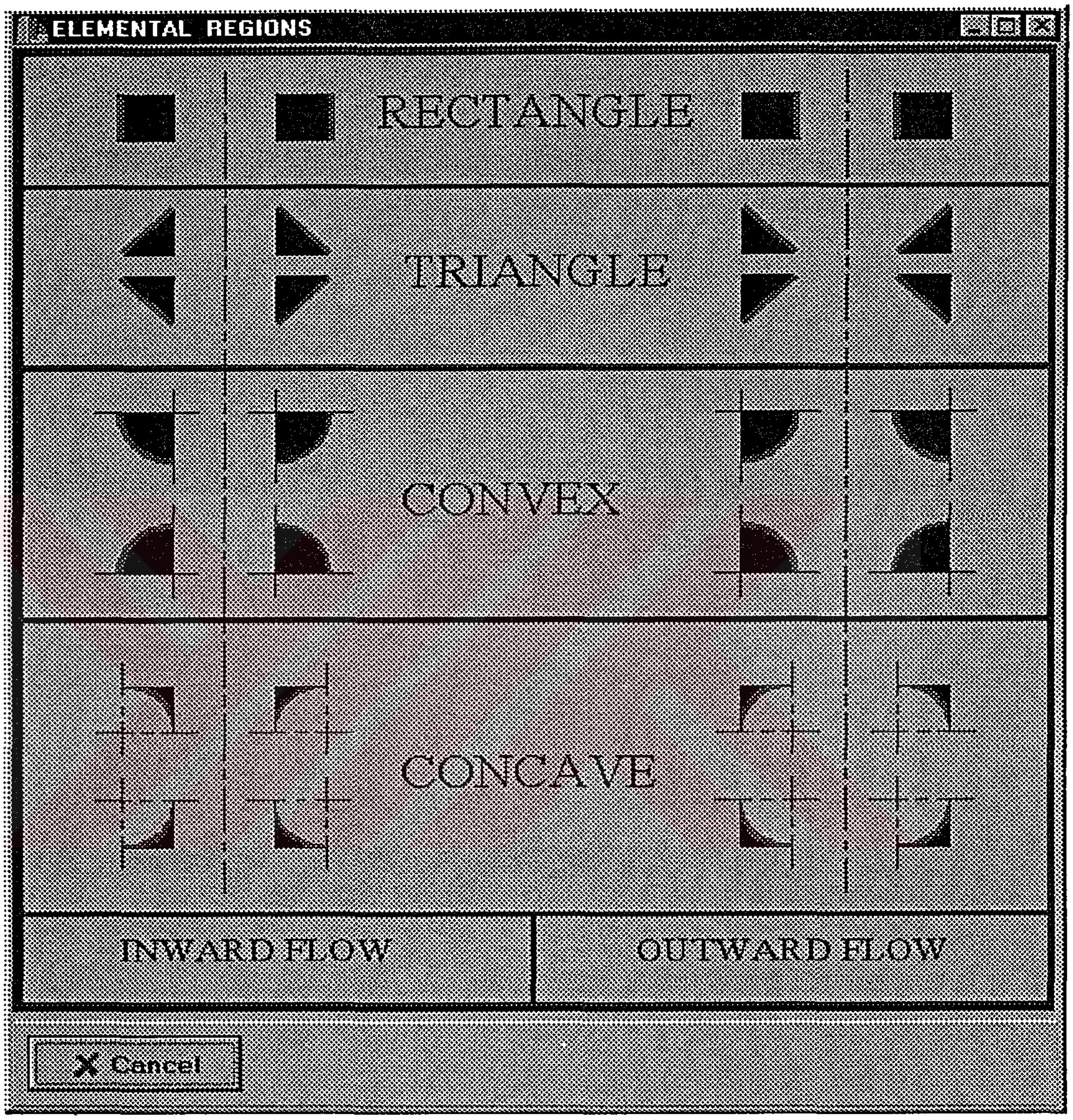


Figure 9.14 "Elemental Regions" Screen

Divided Geometry: In order to calculate the forging load geometry is divided into regions which were explained in chapter 7. This menu presents the geometry in divided position.

Forging Load: During forging die design this button is necessary to be activated. The sequence of this button comes after feature recognition immediately. As it is seen from Figure 9.15, dialog box appears on the screen by asking the flow stress of the material and lubrication condition. Flow stress of the material must be entered by user or if it was entered and recorded into material database, it can also be recalled by clicking "Select Material" radio button. For lubrication, there are five options. Friction factors between material to material or material to punch&die are given to the program by these options. "Manual Entry" is aimed for expert users. If other four options are not corresponding the frictional requirements user can enter his own value by this option.

When "Compute Load" button is clicked all geometric values are taken from "Geometry Formation" module automatically and placed them at the bottom of the dialog box. Middle right side of the dialog box is devoted to divided geometry. Numerical values are going to be given in the proceeding section as a case study.

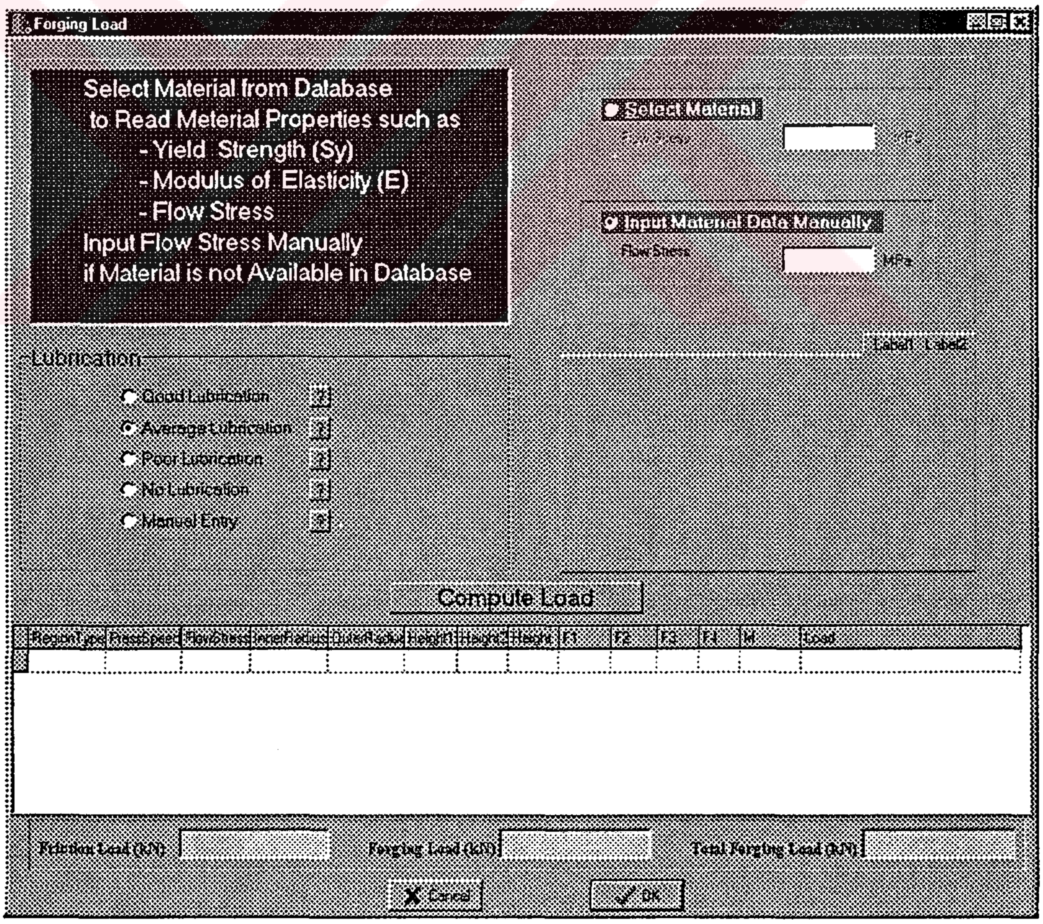


Figure 9.15 "Forging Load" Dialog Box

9.4.3. Stress Calculation

In die design process, the diameter of die insert and shrink ring plays an important role. Stress calculation comes after determination of forging load, immediately. In order to do this, following Figure 9.16 appears on screen if "Stress Calculation" button is clicked. The related calculation formulae were given in chapter 8. Stress calculation dialog box contains lots of blank fields. From these fields, "Die insert Inner radius, Die Insert Height and Forging Load" are filled automatically by taking the values from previously executed "Forging Load" menu.

User must select the materials to be used for each of "Die Insert, Shrink Ring and Workpiece. Material selection can be done by either "From Material Database" or "User Defined" options. If user wants to enter material properties manually, he/she must select "User Defined" section.

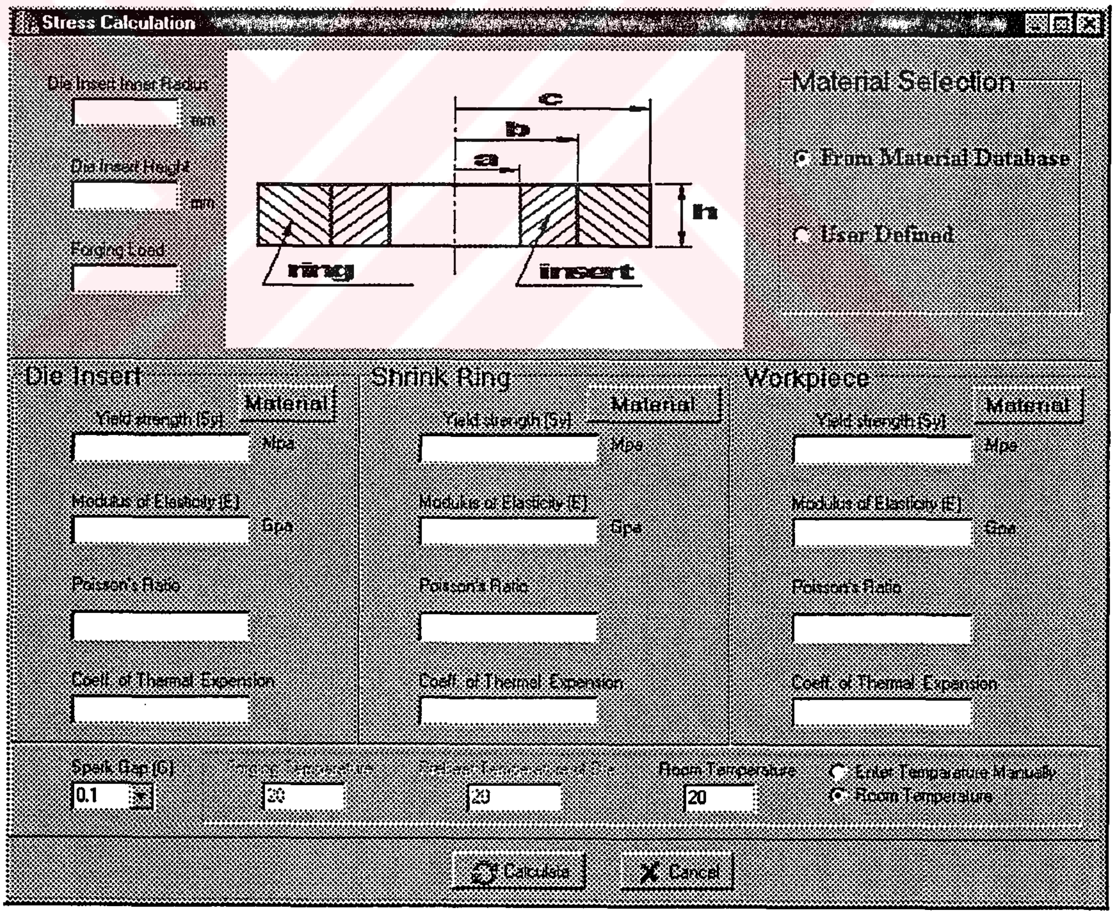


Figure 9.16. "Stress Calculation" Screen

At the bottom of the dialog box, a field is separated for spark gap and forging temperature. All available fields must be filled. If one of the required field remains empty the following message is seen (Figure 9.17).

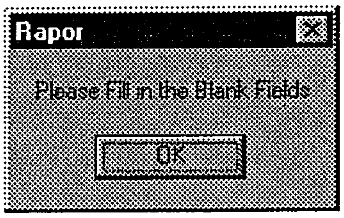


Figure 9.17. "Fill in Blanks" Alert Message

During stress calculation if selected die insert material is weaker than shrink ring material following message, Figure 9.18, appears on the screen.,

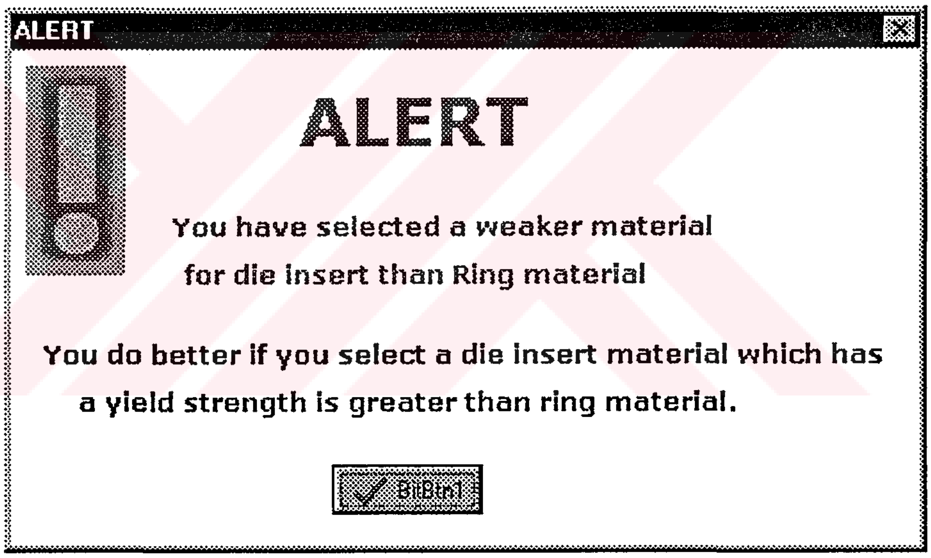


Figure 9.18. "Weaker Material" Alert Message

Additionally, program checks that die failure error occurs or not. In the case of that if the selected die insert material does not resist the forging load, program calculates the required material which has to be yield strength and alerts the user by the following message, Figure 9.19.

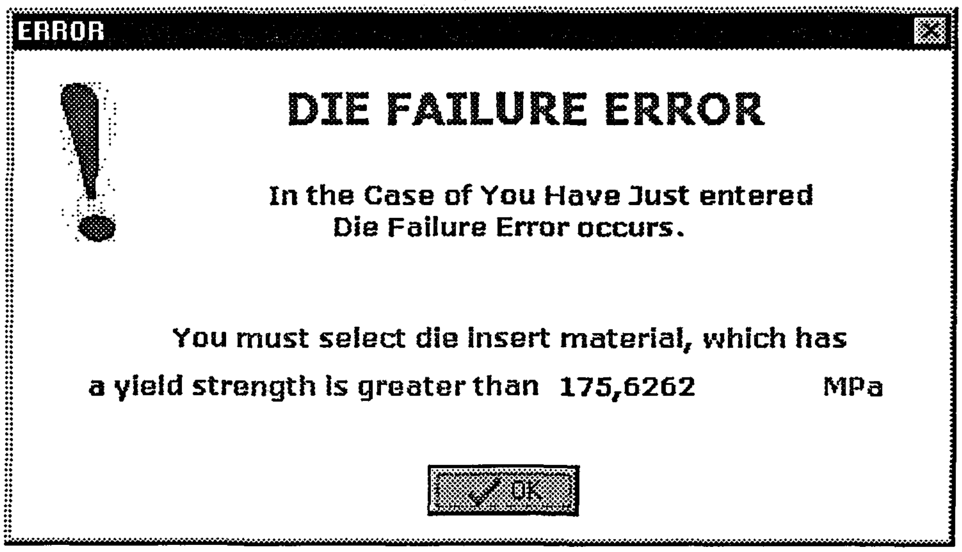


Figure 9.19. "Die Failure Error" Alert Message

9.4.4. Material Database

The prepared material database has wide range of mechanical properties of ferrous and non ferrous materials. The material properties were taken from Metals Handbook of American Society Testing and Manufacturing (ASTM)" [129]. Material database was prepared in such a way that, expert user can add, delete or change any value at any time. Program is available to extend to cover all type of materials.

Material database program consists of three main parts. These are:

- **Main Page:** Material selection is carried out from this main screen. As it is seen from Figure 9.20, main page is formed by three section. The upper left side is separated for material group selection and middle part of the main page is separated for the designations of the materials. The bottom side of the main page shows the available properties of selected material. Such as tensile strength, yield strength, modulus of elasticity, poisson's ratio and etc.

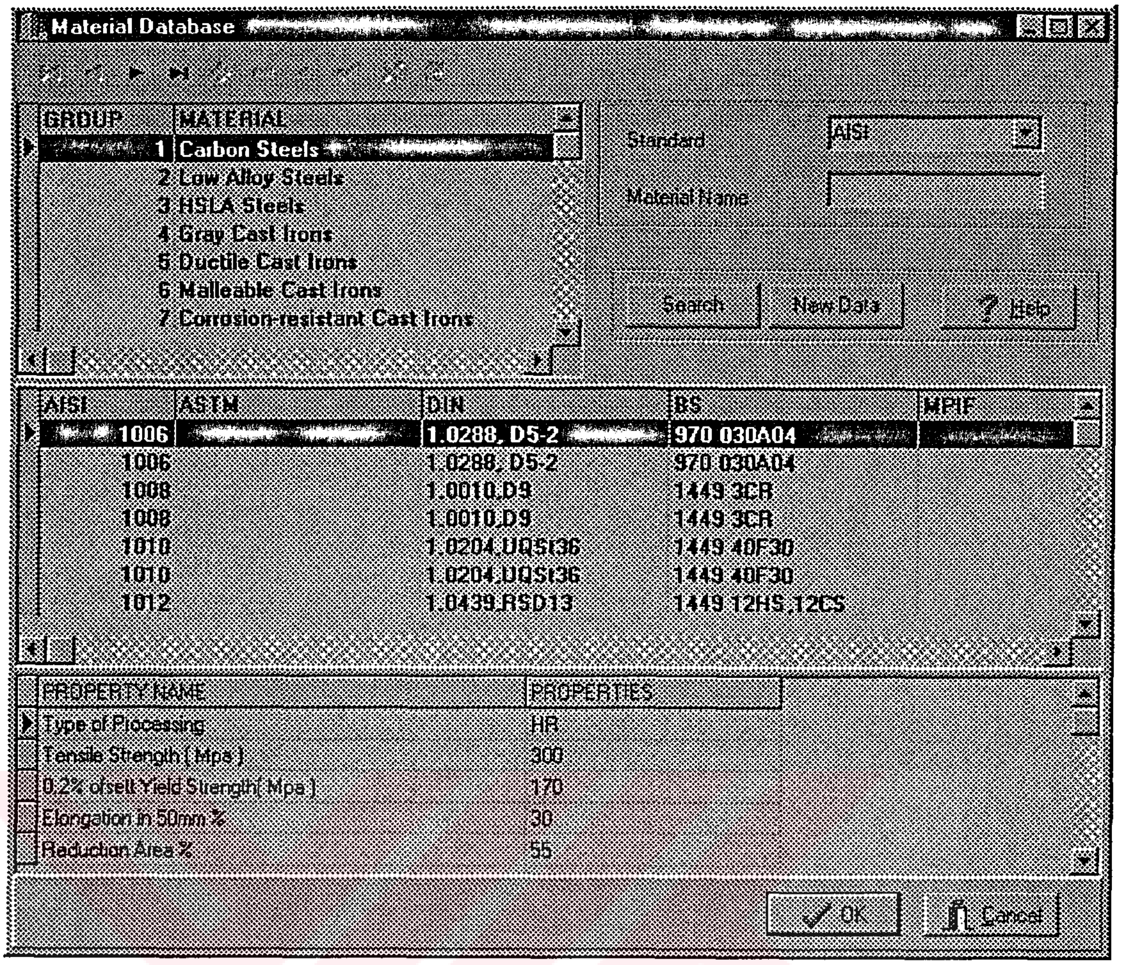


Figure 9.20. Material Database Main Page

- **Search:** Upper right side of the main page has two options. One of them is "Search" button. If "Standard" and "Material Name" fields are filled and "Search" button is clicked, all materials are listed which belongs to selected group. (Figure 9.21)

If "Material Name" field remains blank, program can not activate the searching facility and give an alert message in order to fill in the blanks.

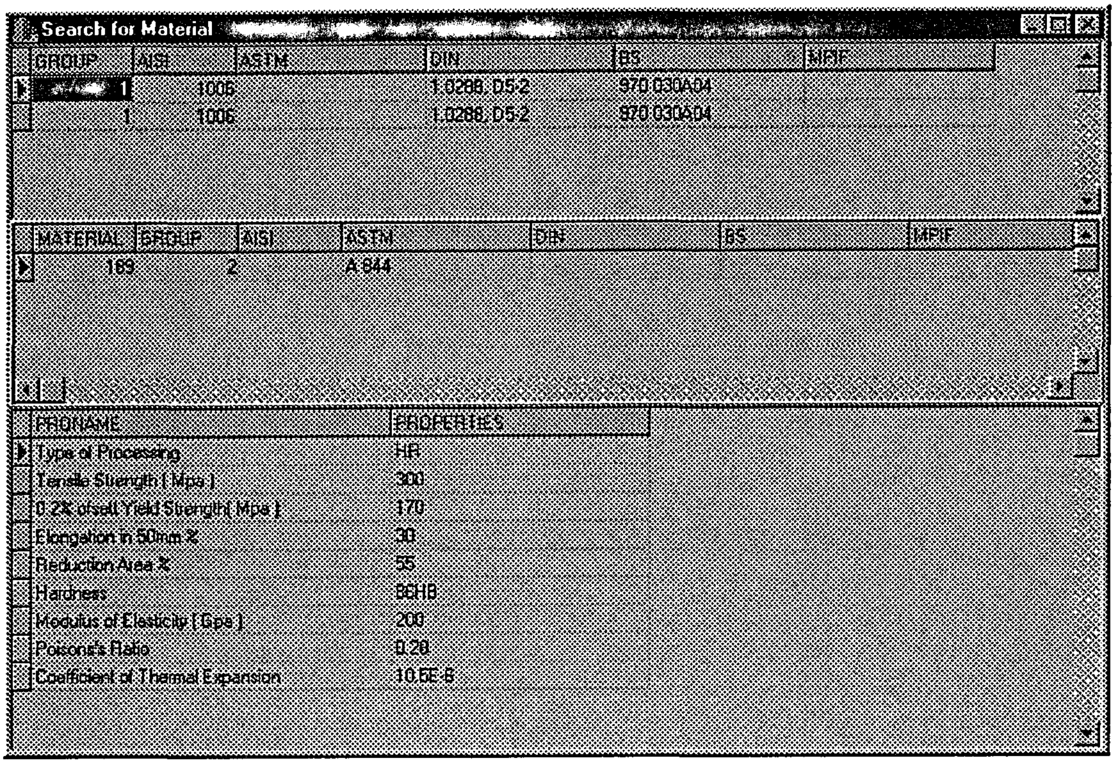


Figure 9.21. “Material Search” Screen

- **New Data:** This button is used for entering new material, material group or editing an existing one. But, in order not to deform the database this section is aimed for expert users and therefore, password is required. Expert entrance is shown in Figure 9.22.

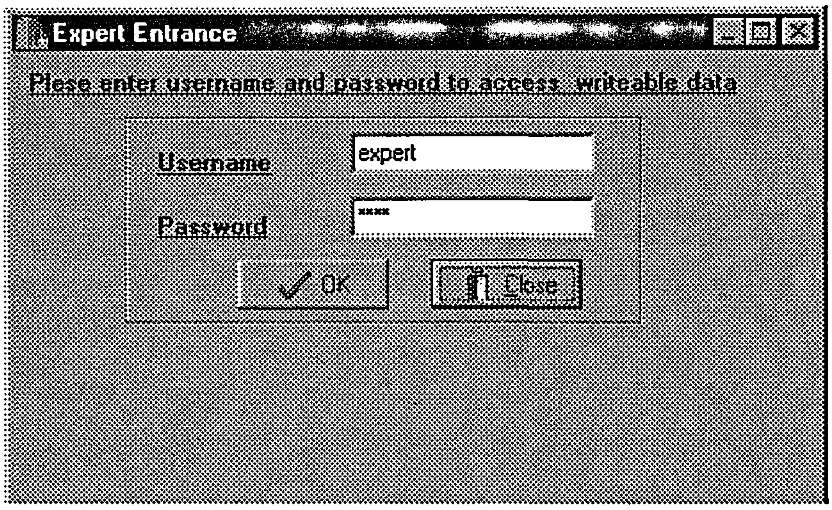


Figure 9.22. Expert Entrance Screen

After expert entrance, screen shown by following Figure 9.23 appears. The user can use the buttons upper side of the table to change or add data. For example, if the user wants to record a new data to the material group table, he must click button and enter the value. In order to record the entered value button must be clicked. If user wants to delete any data from table, only selecting the data and pressing button is enough to delete.

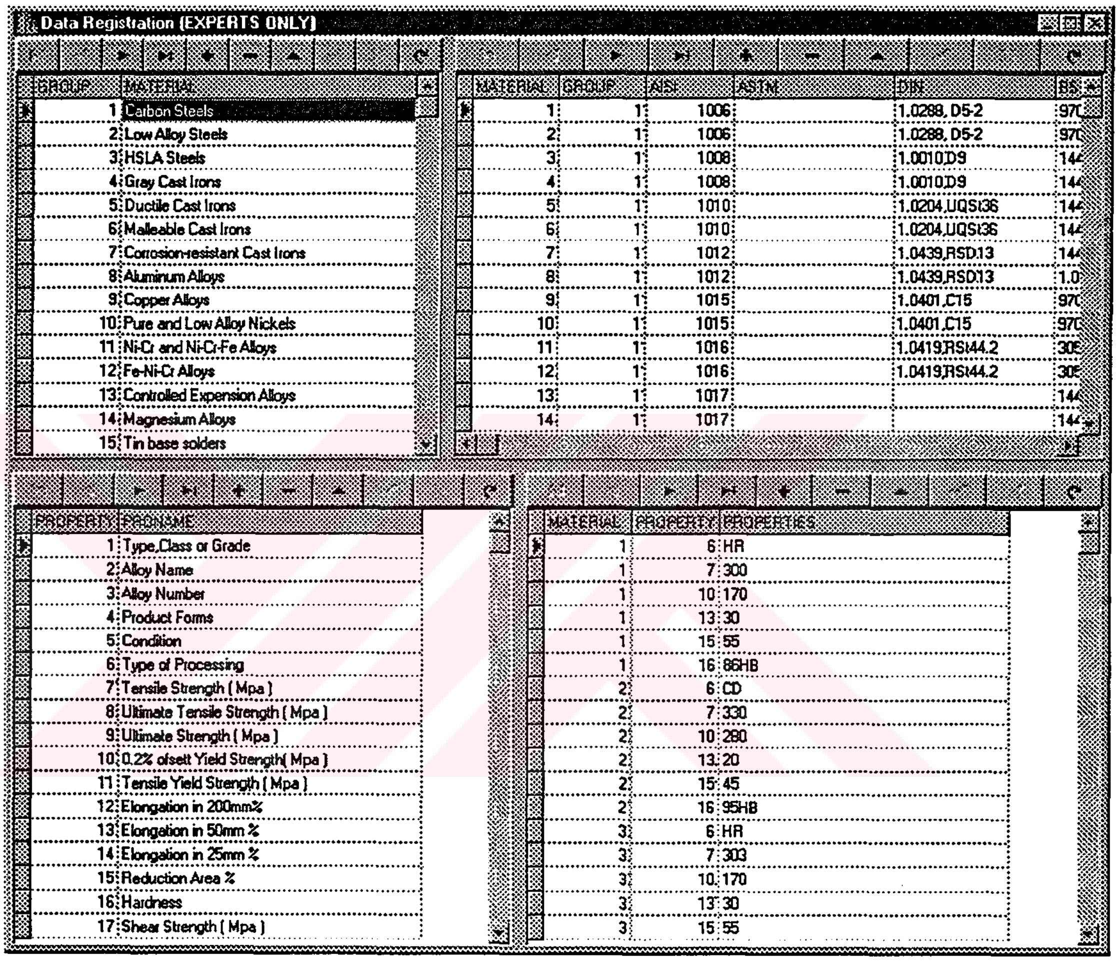


Figure 9.23 "New Data" Screen for Expert Users

9.4.5. Die Drawing

Die design process is ended by the drawing of proposed die assembly. After all calculations, stated in the previous sections, die drawing forms the final step. "Die Drawing" menu provides the die assembly and drawing of each part. Figure 9.24 shows die drawing menu.

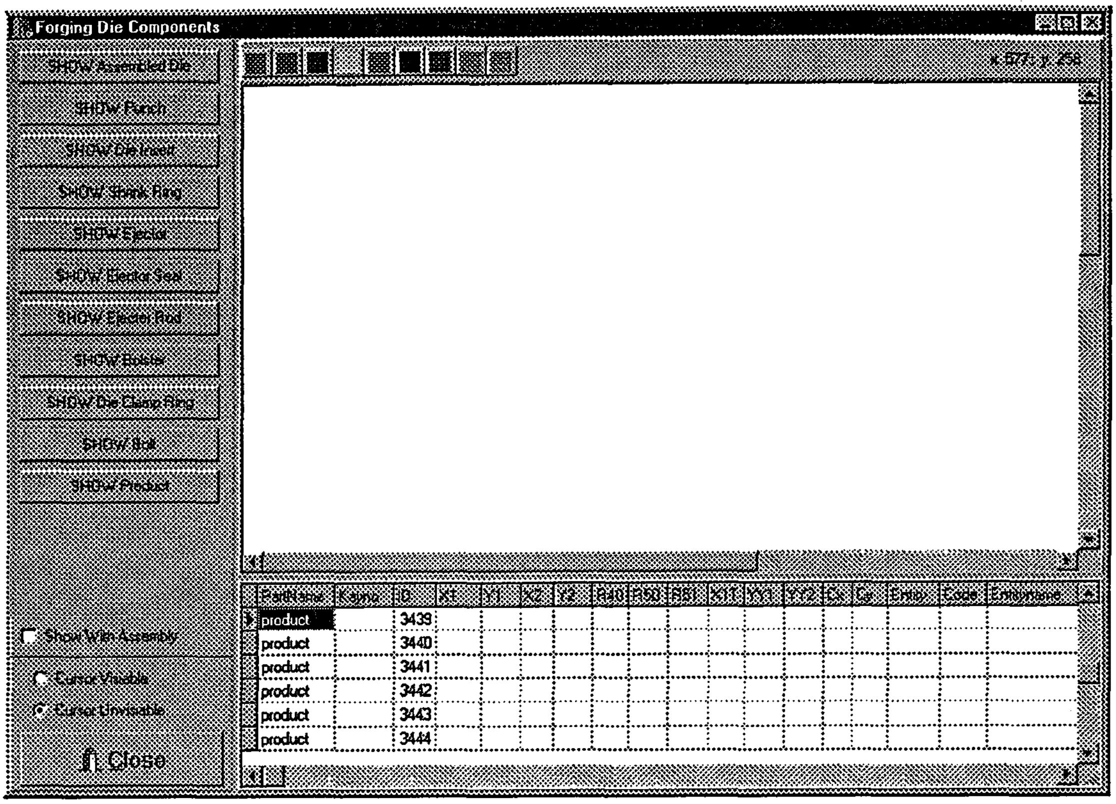


Figure 9.24. "Die Drawing" Screen

As it is seen from above figure, there are eleven buttons at the upper left hand side of the screen. "SHOW Assembled Die" button shows the whole drawing of the die with punch. Each button is activated in order to see the die part individually. The toggle "Show with assembly" utility located at the lower left hand side of the screen enables the user to see individual parts with assembly or not. "Cursor visible" and "Cursor Invisible" radio buttons are used for following each line and seeing the values of selected part.

Color palette presents an additional visual presentation. User can follow each entity or part by one these colors.

Right hand side of the screen is divided into two parts. Upper side is used for graphical representation of die parts. On the other hand, lower side of the screen presents all values related with the die parts.

9.4.6. Rules

This section of the program only serves the user to give idea about the rules. Since program has rule-based structure, user can see rules whenever he wants.

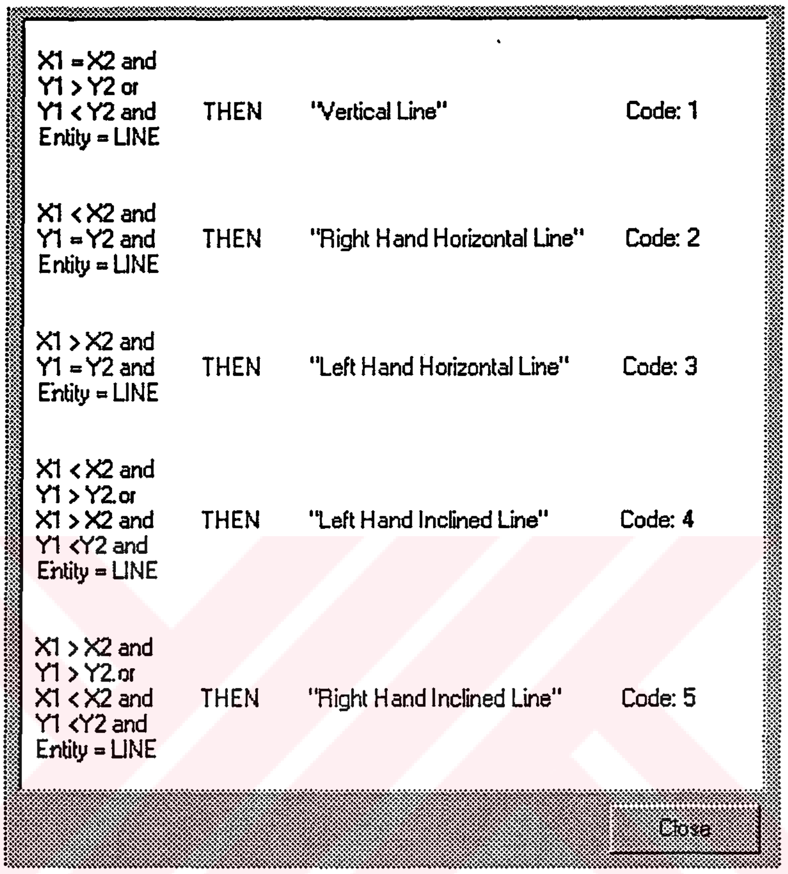


Figure 9.25. “Rules” Menu for Line Entities

A one of rule table is shown in Figure 9.25. All these rules are stored in knowledge base. During the execution of the program, especially geometry formation, most of the design considerations were based on these rules.

CHAPTER 10

EXPERIMENTAL STUDY and PROGRAM GENERATION

10.1. INTRODUCTION

In this chapter, experimental works which were carried out with different shapes will be explained. Friction effect and workpiece material compression test are also given in this chapter. Program generation is given and experimental results are compared with program output.

10.2. EXPERIMENTATION

In the experiments a hydraulic press which has a capacity of maximum 600 kN was used. Lots of experiments were carried out. U-shaped, T-shaped and taper shaped products were obtained.

During the experiments aluminium and lead were used as a workpiece and the die container was made of steel. Ring test was done for aluminium to determine the friction condition. Experiments were carried out at room temperature. Therefore it can be said that aluminium is forged at cold forging conditions and since recrystallisation temperature of lead is about room temperature, lead is forged at warm forging condition. Three different sizes of cylinders were forged from aluminium billets. Products which have a dimension of 40mm in outside diameter and 30mm in height were obtained from stock bars and hollow bars. For the other experiments lead was used.

10.2.1. Disc Forging

In order to determine the stress-strain curve for aluminium used for forging cylinders at room temperature, disc forging compression test was done. A billet with 25mm diameter and 32.1mm high was forged between two plates. Incremental compression was performed and after each loading, reduction of area and corresponding load were calculated and recorded. Reduction in height versus load graphic is shown in the following Figure 10.1 and stress-strain curve is shown in Figure 10.2.

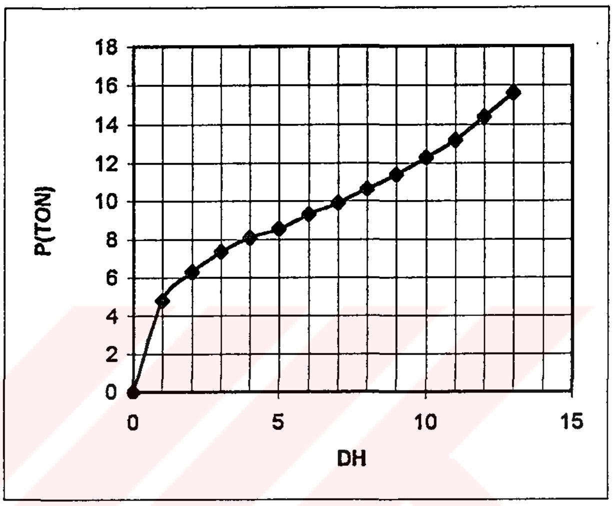


Figure 10.1 Disc forging for Aluminium

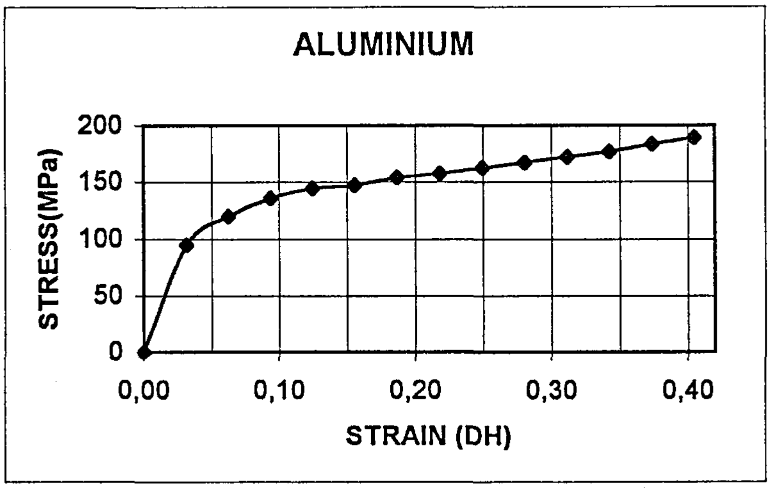


Figure 10.2 Stress-Strain Curve for Aluminium

10.2.2. Ring Compression Test

In order to determine the friction factor (m), the ring compression test has gained wide acceptance. This technique utilises the dimensional changes of test specimen to arrive at the magnitude of friction factor. When a flat ring specimen is plastically compressed between two platens, increasing friction results in an inward flow of the material, while decreasing friction results in an outward flow of the material as schematically shown in Figure 10.3.

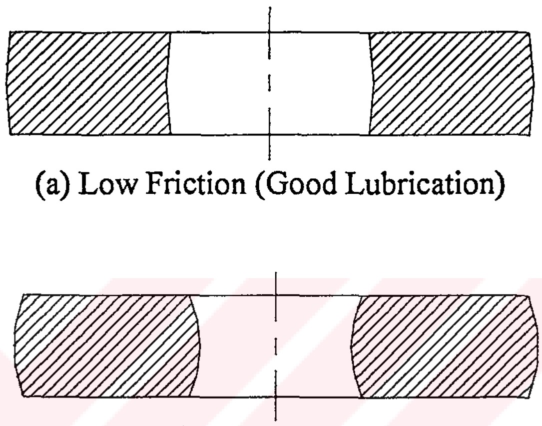


Figure 10.3. Friction Effect on Metal Flow in Ring Compression Test

For a given percentage of high reduction during compression test, the corresponding measurement of the internal diameter of the test specimen provides a quantitative knowledge of the magnitude of the prevailing friction coefficient at the die and workpiece interface. If the internal diameter of specimen increases during the deformation, that means friction is high. Using this relationship *friction calibration curve* in terms of "m" can be generated by relating the percentage decrease in internal diameter with the percentage deformation in height. As recommended in the literature [133], once the reduction in both the internal diameter and the height of the ring are known, "m" can be found from the appropriate charts regardless of material being deformed and test conditions. The most common ring geometry used is 6:3:2 where the first number denotes the external diameter and second number represents the internal diameter of the ring specimen while the last number denotes the thickness of the ring specimen [134].

From this perspective, ring compression tests were carried out for aluminium. Related data are presented in Table 10.1. % ΔH and % ΔD values are obtained by the following equations and friction coefficient "m" is found from Figure 10.4.

Table 10.1 Aluminium Ring Test Data

	Lubricated	Dry (Ground)	Dry (Rough)
D_{o1} (mm)	30	30	30
D_{o2} (mm)	37.7	38.5	38
D_{i1} (mm)	15.2	15.2	15.2
D_{i2} (mm)	14.8	13.5	11.2
H1 (mm)	10	10	10
H2 (mm)	5.65	5.35	5.3
% ΔH	43.5	46.5	47
% ΔD	2.63	11.18	26.3
Load (Ton)	25	30	35
m	0.25	0.4	0.6

$$\%\Delta H = \frac{H_1 - H_2}{H_1} * 100 \qquad \%\Delta D = \frac{D_{i1} - D_{i2}}{D_{i1}} * 100$$

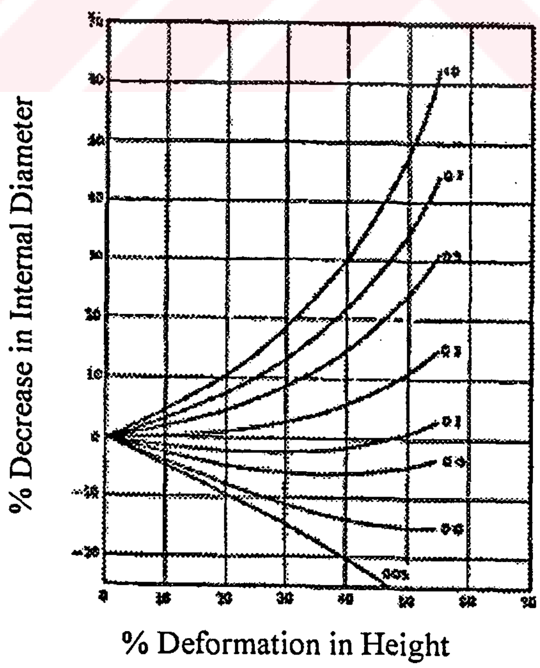


Figure 10.4. Friction Calibration Curve in Terms of *m* [134]

10.2.3. U-Shaped Forging

U-Shaped forging is shown in Figure 10.5. This product is tried to be obtained from different sizes of specimens by keeping their volume constant.

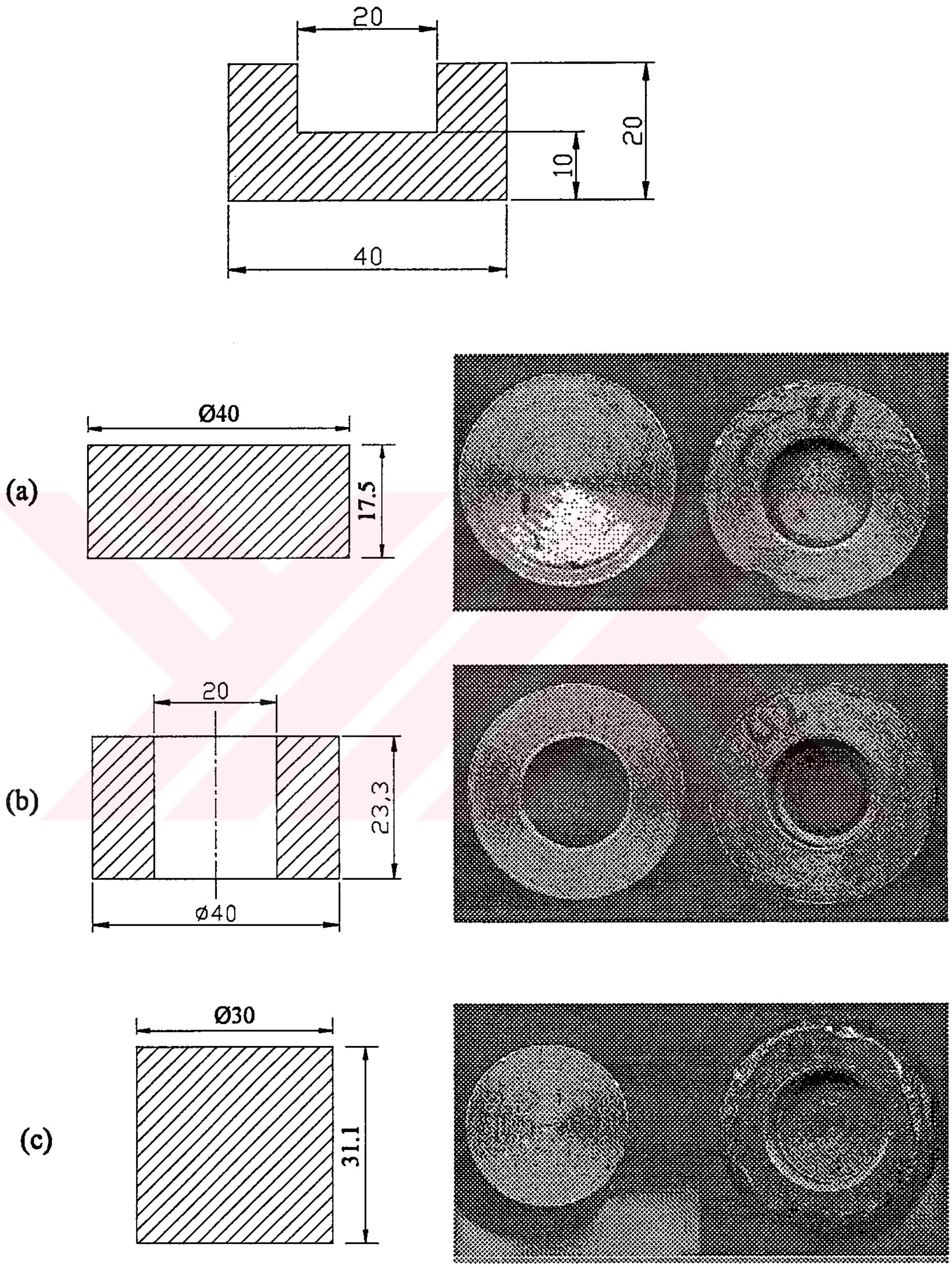


Figure 10.5 U-Shaped Product with different Sizes of Specimen

Figure 10.5 shows the dimensions of the U-shaped forging produced from three different sizes of billets. The first one is tried to be forged from solid cylindrical bar and product was obtained in 26 tons of load. The second one (Figure 10.5.b) is subjected to 55 tons of load, but inner side of the specimen could not be filled. In the third one both upsetting and extrusion type metal deformation exist. In this case product is obtained in 40 tons of load.

10.2.4. T-Shaped Forging

T-Shaped forging is shown in Figure 10.6. This product is tried to be obtained from three different sizes of specimens by keeping their volume constant.

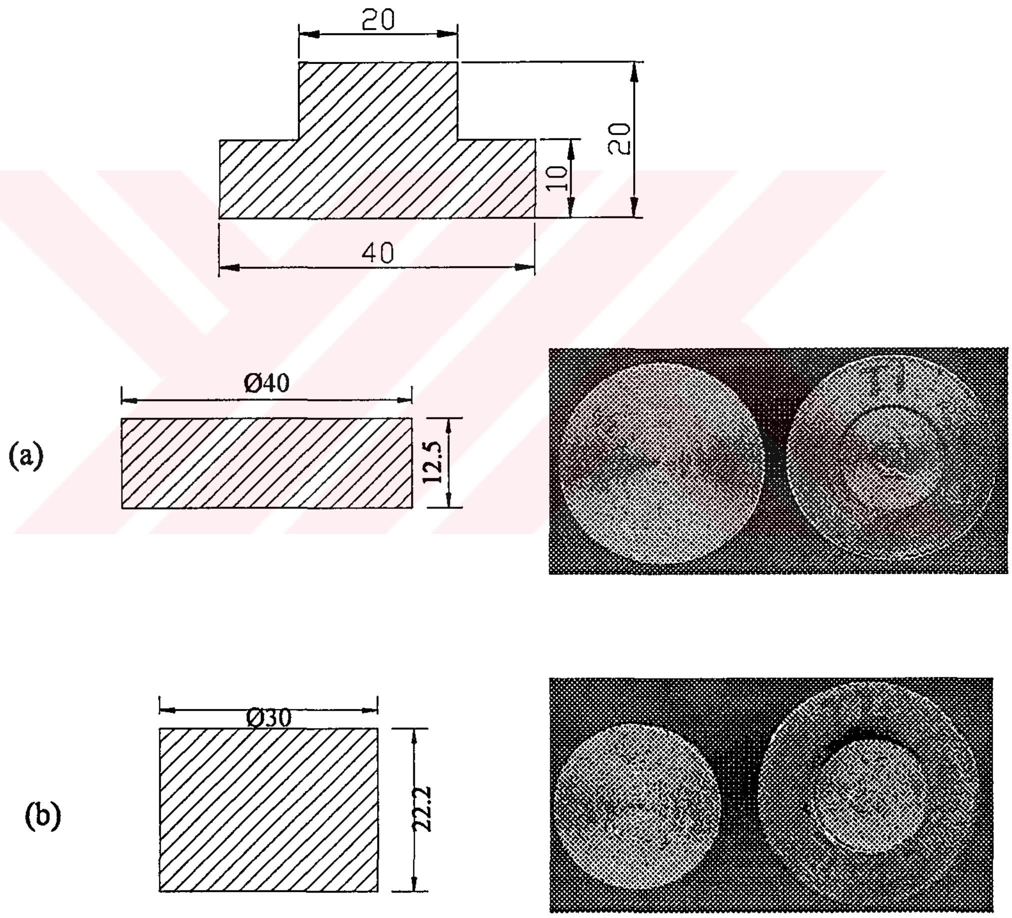


Figure 10.6 T-Shaped Product with different Sizes of Specimen

(c)

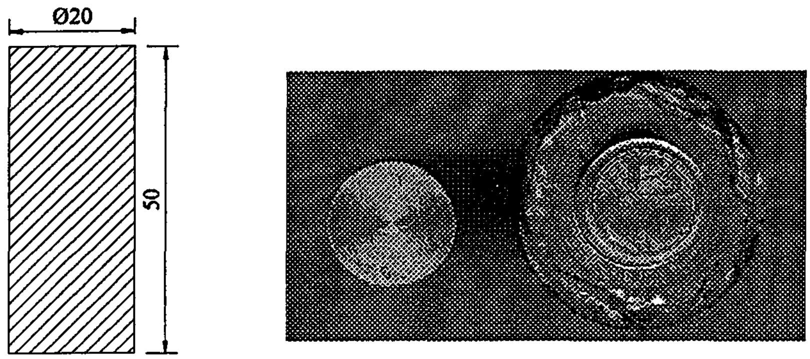


Figure 10.6 T-Shaped Product with different Sizes of Specimen (Cont.)

Figure 10.6 shows the dimensions of the T-shaped forging produced from three different sizes of billets. Although 55 tons of load was applied, Figure 10.6.a shows that T-shaped product could not be obtained and die cavity could not be filled completely. But the second one was subjected to 40 tons of load and the die cavity was almost filled. The third specimen has a same diameter with the smaller part of the shape. 26 tons of load was enough to obtain this product.

10.2.5. Taper Shaped Forging

Taper shaped forging is shown in Figure 10.7. This product is tried to be obtained from different sizes of specimens by keeping their volume constant.

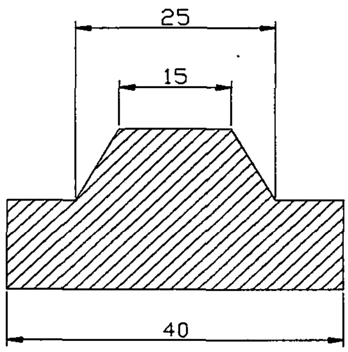


Figure 10.7 Taper Shaped Product with different Sizes of Specimen

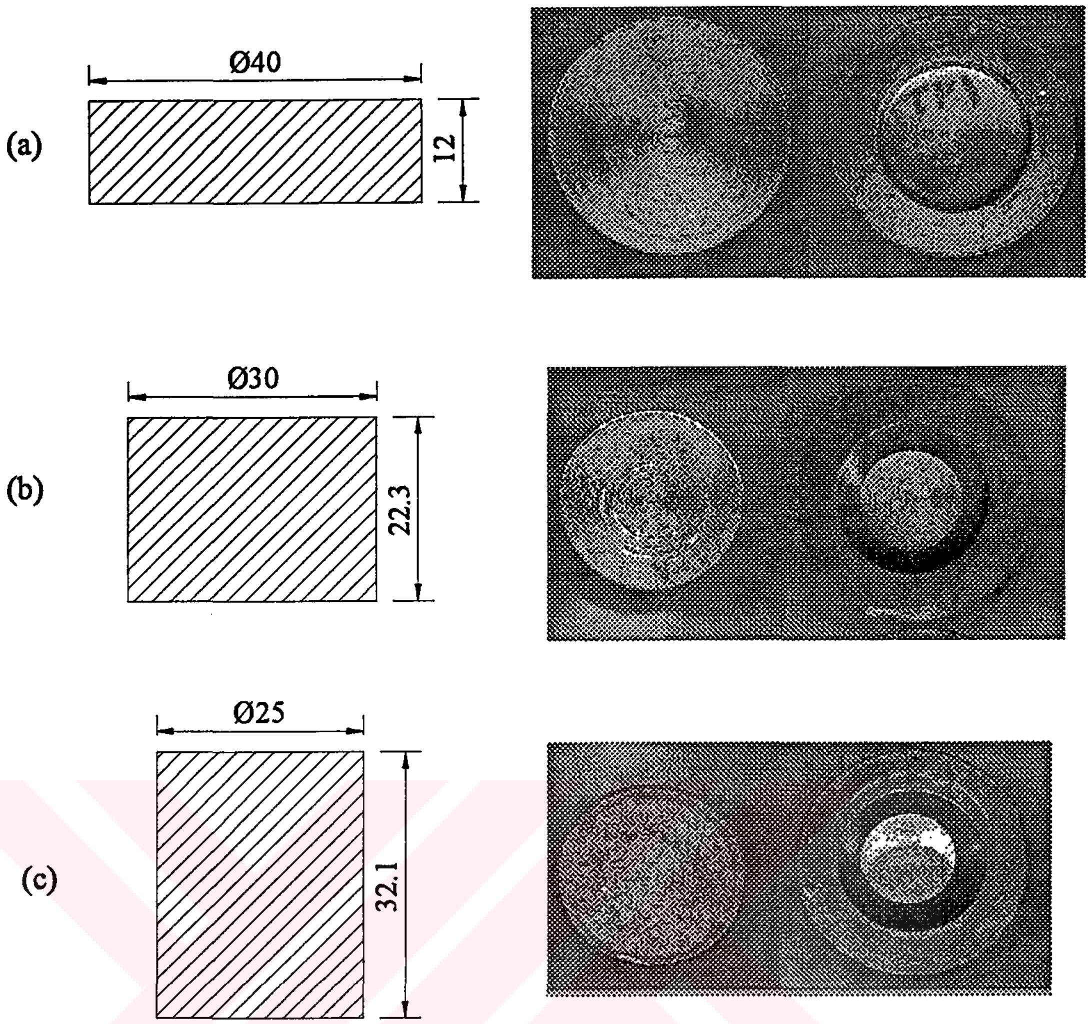


Figure 10.7 Taper Shaped Product with different Sizes of Specimen (Cont.)

Figure 10.7 shows the dimensions of the taper shaped forging produced from three different sizes of billets. Figure 10.7.a shows that taper shaped product could not be obtained by 55 tons of load since the preform is subjected to completely extrusion mode of deformation. But in the second trial 30mm diameter of billet was used and the product is obtained in 35 tons of load (Figure 10.7.b). In this forging top of the taper couldn't be formed completely. The third specimen, having a diameter of 25mm, was subjected to 24 tons of load and the required product was obtained in almost its desired dimensions.

These experiments show that the product can be obtained in different forging loads depending on the billet geometry due to the fin formation, upsetting or extrusion mode of deformatioon and friction effect.

10.3. PROGRAM GENERATION AND OUTPUT for LEAD

The usage of the program, namely EX-AFORD, has been introduced in chapter 9 in detail. In this section, an example is given from beginning to end by explaining all steps. These steps will be as follows:

- Drawing of finished product
- Transfer of geometry into DXF format
- Recognition of the product
- Development of the forgeable geometry
- Forging load calculation
- Die stress calculation
- Drawing of die assembly

Drawing of the finished product is prepared in AutoCAD environment. Since the part is rotationally axisymmetric, it is enough to draw only one portion of part. In this work, right portion is used. In the following Figure 10.8 drawn part can be seen.

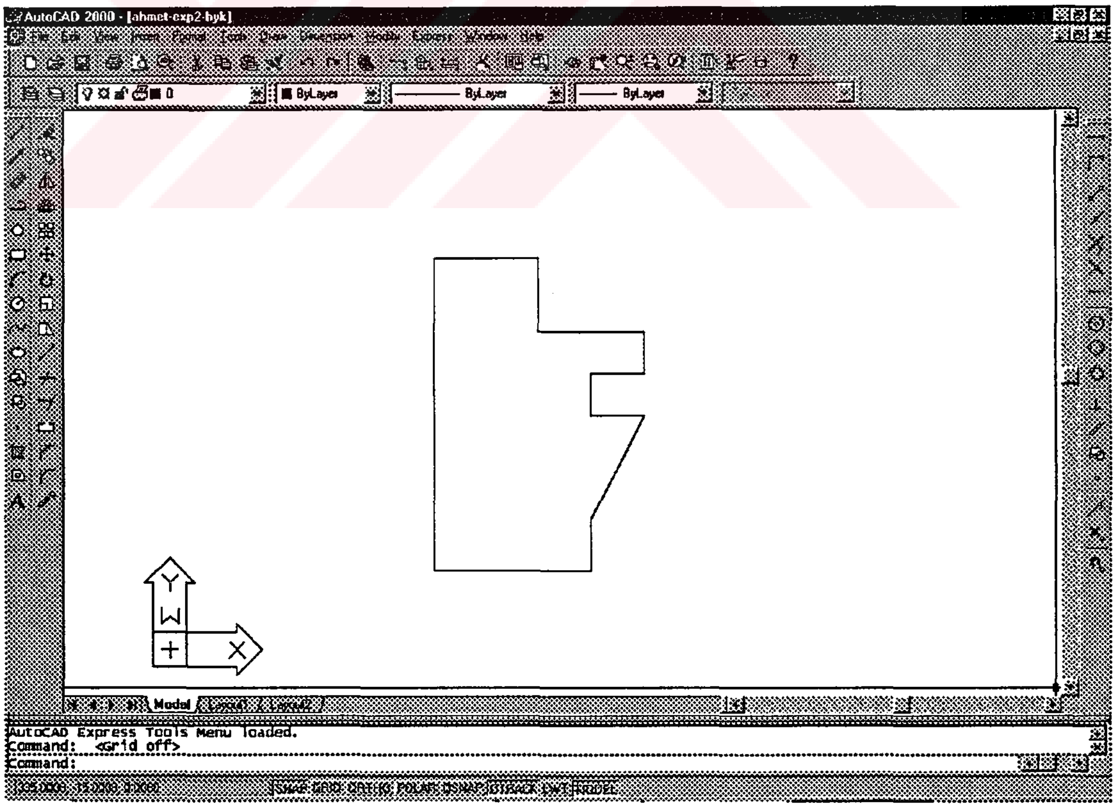


Figure 10.8. Right Hand Portion of Finished Product

Once the part is drawn, it is saved by the extension of "*.DWG". In order to recognize the product by EX-AFORD the drawing must be saved in DXF format. "DXFOUT" command is used for this aim.

DXFOUT command creates a text file which contains all drawing information. Since the text file is quite wordy only ENTITIES section of the DXF file of the part is given in the following Table 10.2. This table represents the co-ordinates of all entities. In order to avoid the complexity of expression, whole DXF table is given in Appendix D.

Table 10.2. ENTITIES Section of Drawn Part

ENTITIES	110.0	45	0.0	AcDbEntity	125.0
0	20	330	11	8	31
LINE	150.0	1F	115.0	0	0.0
5	30	100	21	100	0
40	0.0	AcDbEntity	139.0	AcDbLine	LINE
330	11	8	31	10	5
1F	110.0	0	0.0	115.0	4A
100	21	100	0	20	330
AcDbEntity	143.0	AcDbLine	LINE	135.0	1F
8	31	10	5	30	100
0	0.0	120.0	47	0.0	AcDbEntity
100	0	20	330	11	8
AcDbLine	LINE	143.0	1F	120.0	0
10	5	30	100	21	100
100.0	42	0.0	AcDbEntity	135.0	AcDbLine
20	330	11	8	31	10
150.0	1F	120.0	0	0.0	115.0
30	100	21	100	0	20
0.0	AcDbEntity	139.0	AcDbLine	LINE	125.0
11	8	31	10	5	30
110.0	0	0.0	115.0	49	0.0
21	100	0	20	330	11
150.0	AcDbLine	LINE	139.0	1F	115.0
31	10	5	30	100	21
0.0	110.0	46	0.0	AcDbEntity	120.0
0	20	330	11	8	31
LINE	143.0	1F	115.0	0	0.0
5	30	100	21	100	0
41	0.0	AcDbEntity	135.0	AcDbLine	LINE
330	11	8	31	10	5
1F	120.0	0	0.0	120.0	4B
100	21	100	0	20	330
AcDbEntity	143.0	AcDbLine	LINE	135.0	1F
8	31	10	5	30	100
0	0.0	120.0	48	0.0	AcDbEntity
100	0	20	330	11	8
AcDbLine	LINE	139.0	1F	115.0	0
10	5	30	100	21	100

Table 10.2. ENTITIES Section of Drawn Part (Cont.)

AcDbLine	11	LINE	8	120.0	31
10	100.0	5	0	30	0.0
115.0	21	4C	100	0.0	0
20	120.0	330	AcDbLine	11	ENDSEC
120.0	31	1F	10	100.0	
30	0.0	100	100.0	21	
0.0	0	AcDbEntity	20	150.0	

This DXF table is perceived and entities are extracted by pressing "Recognise Product" button, located at the top of the "Geometry" screen. Once this button is pressed, "Feature Recognition is Completed" response appears as shown in Figure 10.9 a, b. That means, all entity co-ordinates are put into table (Table 10.2). This table can be seen from either "See Data -> Table-1" or "See Data -> Table-2" in detail

(a)

(b)

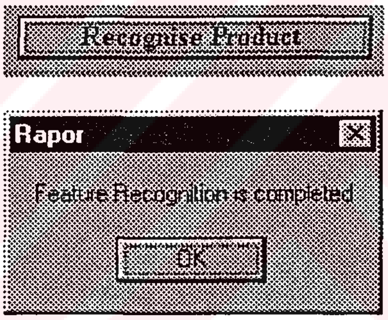


Figure 10.9. Steps for Feature Recognition

(a) Feature Recognition Button

(b) Response Screen for Feature Recognition Button

If user wants to see the type of forging whether it is unilateral or bilateral, it is enough to press following button (Figure 10.10).

Figure 10.10 Forging Direction Button

Table 10.2 Extracted DXF File Showing Entity Properties

Entity	10	20	11	21	40	50	51	Code	Entity Name
Line	100	150	110	150				2	Right hand horizontal line
Line	110	150	110	143				1	Vertical line
Line	110	143	120	143				2	Right hand horizontal line
Line	120	143	120	139				1	Vertical line
Line	120	139	115	139				3	Left hand horizontal line
Line	115	139	115	135				1	Vertical line
Line	115	135	120	135				2	Right hand horizontal line
Line	120	135	115	125				5	Right hand line
Line	115	125	115	120				1	Vertical line
Line	115	120	100	120				3	Left hand horizontal line
Line	100	120	100	150				1	Vertical line

As it is seen from Figure 10.8, final product has unforgeable section for closed die forging operations. The user may not aware of this situation. Therefore, "Make Forgeable Geometry" button must be pressed to eliminate the unforgeable area and to propose the forgeable product. Product shape, forgeable geometry and final product can be seen by pressing "Show Forgeable Geometry" button. These two buttons are seen in Figure 10.11

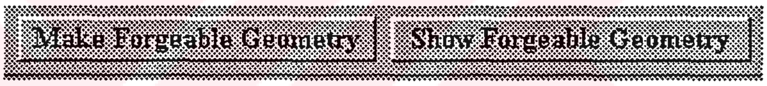


Figure 10.11 Forgeable and Proposed Geometry Buttons

Following Figure 10.12 shows the geometry and presents reasoning strategy. "Explain" button is used for this purpose. Forgeable geometry is determined by certain rules and these rules are stored in knowledge base. At the bottom of the Figure 10.12, the rules that were used during the forgeable geometry process can be seen.

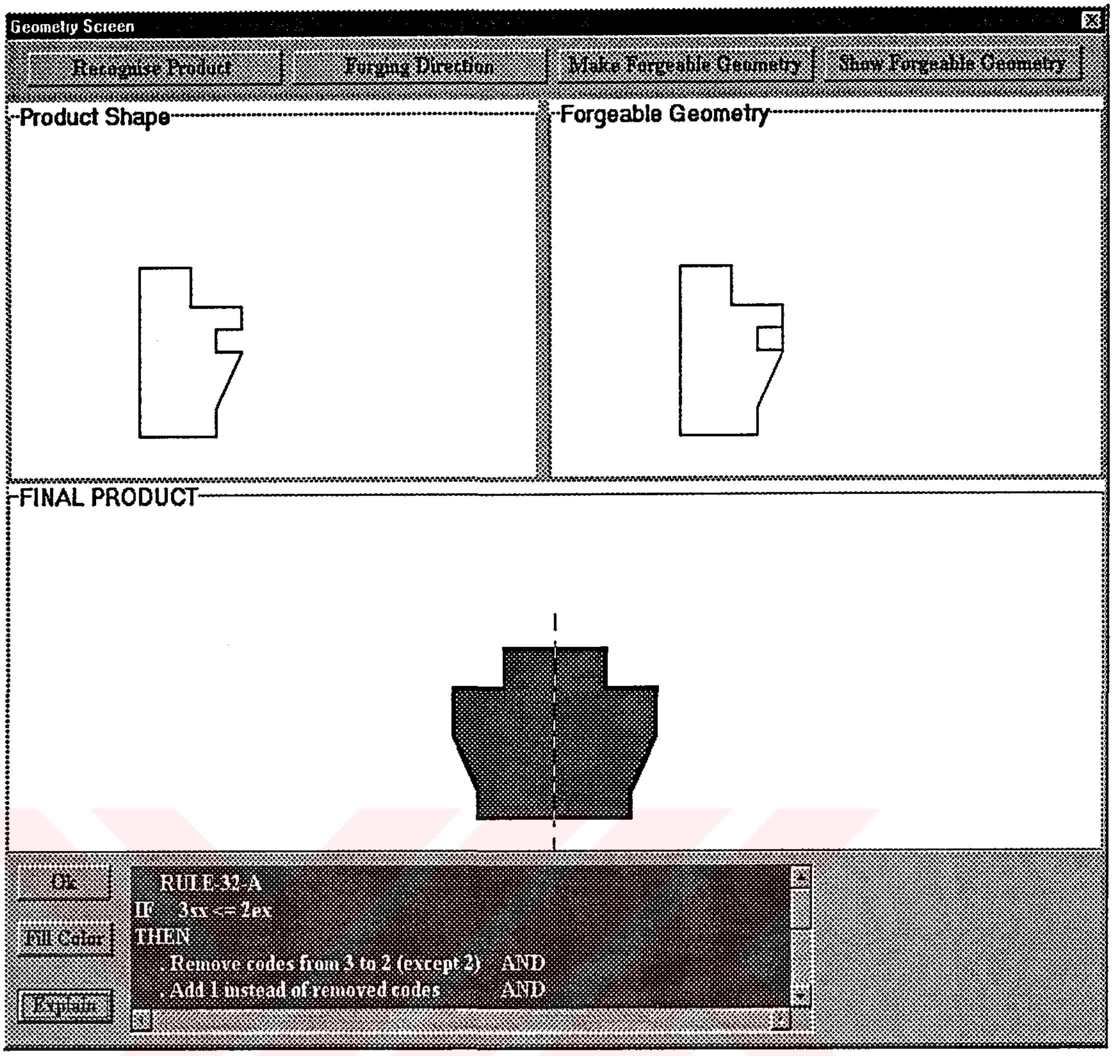


Figure 10.12. Feature Recognition Screen

For the example given above, the rules are presented in the following.

```
RULE-32-B
IF          3sx > 2ex
THEN        Remove codes from 3 to 2 (except 3)
            •  Add 1 instead of removed codes
            •  Co-ordinate 1, by the following:
               1sx=2ex        1ex=2ex
               1sy=3sy        1ey=2ey
            •  Change ex value of code 3 by the following:
               3ex=2ex
```

The next step is forging load calculation. The criteria for load calculation was explained in Chapter 7 in detail. Therefore, in the following, only division of the geometry and forging load table are given. Figure 10.13 shows that geometry is divided into basic regions. Load for friction is calculated for each region individually and summation of them gives the total friction load. Table 10.3 shows required frictional forging load with average lubrication condition. Figure 10.3 also shows the final product shape.

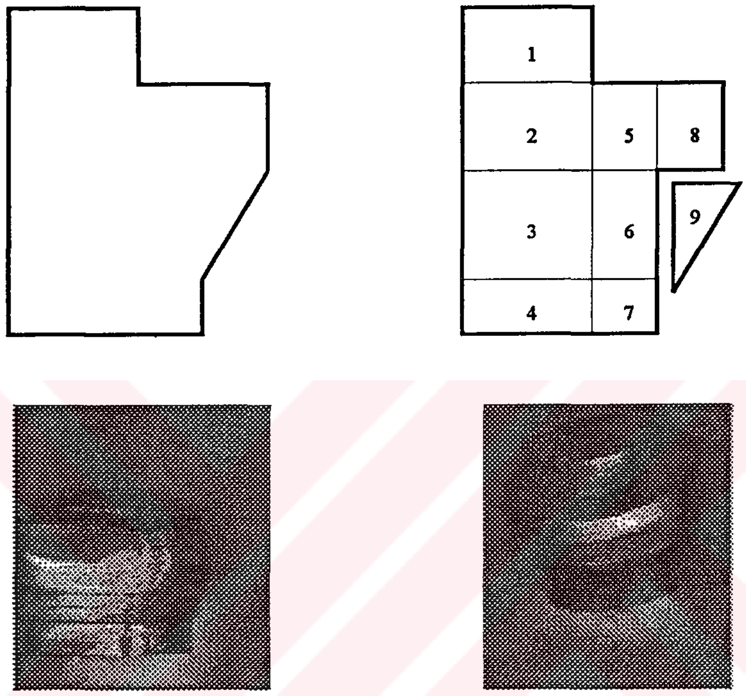


Figure 10.13 Geometry Division for Load Calculation

Due to the strain hardening condition stress-strain curve of the material must be known or flow stress of the material being forged must be in hand. In the experiments lead was used and following equation was derived:

$$\sigma = 120 + 161\varepsilon^{0.95} \tag{10.1}$$

By this way, flow stress of the material was found about 60 MPa. This value is valid for the condition of cold forging at room temperature. By using the following equation frictional forging load is calculated for each region:

$$\left(\frac{2}{3\sqrt{3}} m \frac{R}{A}\right) . \pi R^2 \sigma \tag{10.2}$$

The required forging load is calculated from the following equation:

$$\pi R^2 \sigma \tag{10.3}$$

Table 10.3 Total Forging Load for Friction

Region No	Inner Radius	Outer Radius	Upper Height	Lower Height	F1	F2	F3	F4	M	Load (N)
1	0	10	30	23	0.75	0.75	0.17	0.75	0.605	6267.38
2	0	10	23	15	0.17	0.17	0.17	0.75	0.315	2855.28
3	0	10	15	5	0.17	0.17	0.17	0.75	0.315	2284.23
4	0	10	5	0	0.17	0.17	0.75	0.75	0.46	6671.39
5	10	15	23	15	0.75	0.17	0.17	0.17	0.315	1784.55
6	10	15	15	5	0.17	0.17	0.17	0.17	0.17	770.47
7	10	15	5	0	0.17	0.75	0.75	0.17	0.315	2855.28
8	15	20	23	15	0.75	0.75	0.17	0.17	0.46	3648.42
9	15	20	15	5	0.17	0.75	0.17	0	0.36	2284.23

Total friction load : 29 421,23 N
Forging load : 75 398,22 N
Total forging load : 104 819,45 N

That means, about 10.4 tons of total forging load is required to obtain this product. In the program forging load is calculated 7.5 tons while the friction load is calculated 3.0 tons of load. This small difference is coming from the difference in geometry division.

After the calculation of forging load, the dimensions of the die insert and shrink ring are calculated. Following Figure 10.14 shows material entry table for the calculation of stresses, die insert and shrink ring. The calculated values can be seen by pressing "Calculate" button.

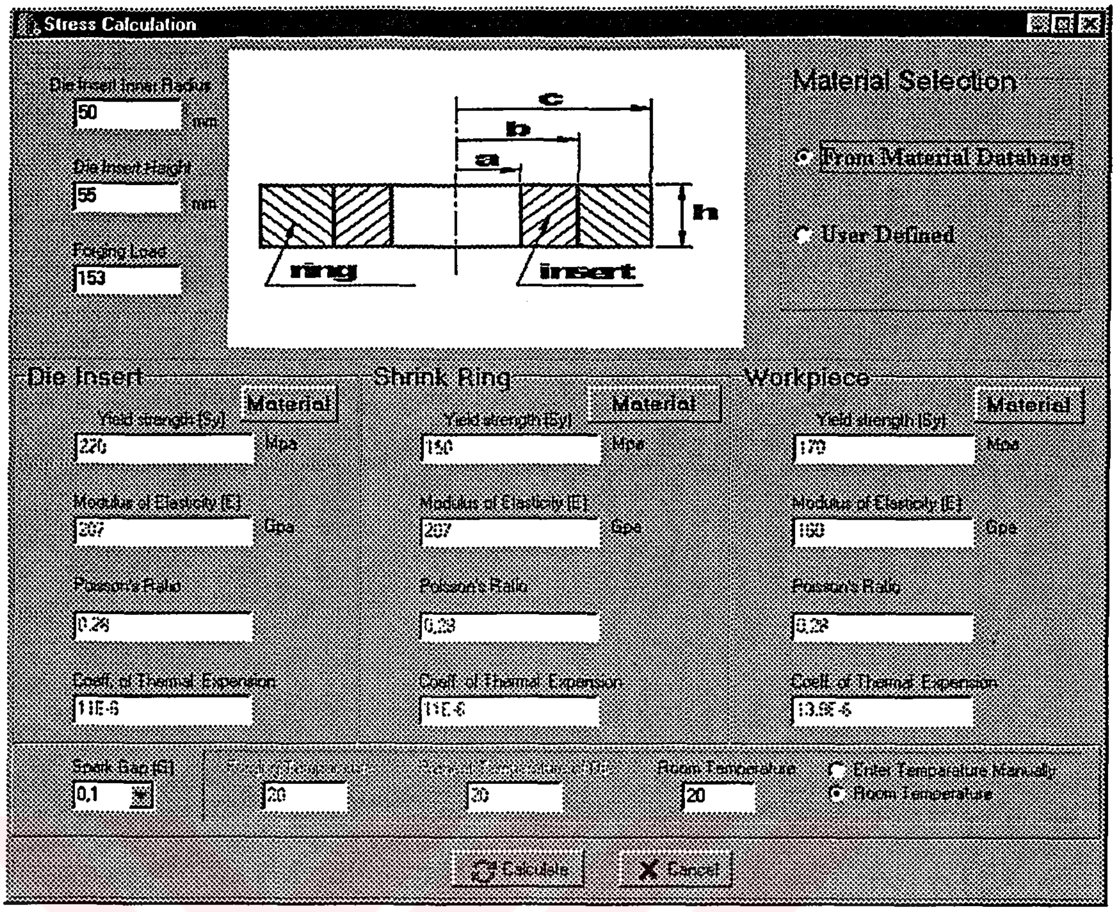


Figure 10.14 Material Entry Table for Die Design

Figure 10.15 represents program outputs for die insert inner radius (a), die insert outer radius (b), shrink ring outer radius (c), die insert height (h) and interference (z) in millimetres.

Geometry correction values are also evaluated and presented on Figure 10.15. Since all related formulae were given in chapter 8, they are not presented again here to prevent repetition.

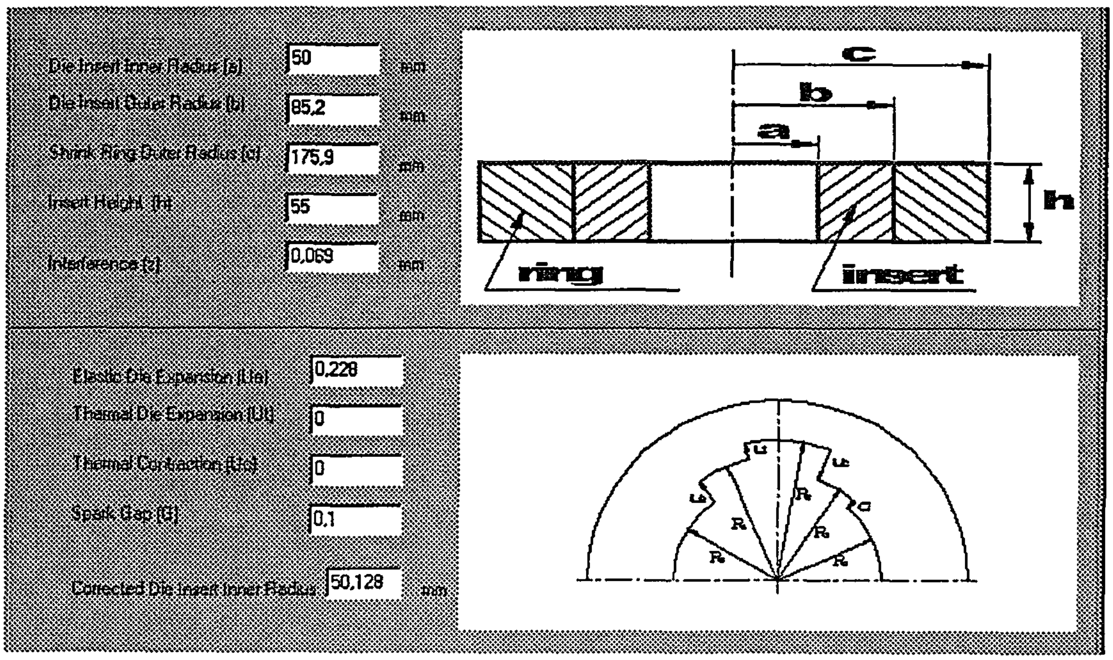


Figure 10.15 Program Output for Die Insert and Ring

Upper left hand side of the Figure 10.15 shows a, b and c in graphical representation. The edit boxes located at middle left hand side of the Figure 10.15 resembles geometry correction factors. Forging Pressure and stress are given at the lower left side of this figure.

Drawing of die assembly forms the final step of the program. “Die Drawing” pull down menu enables the user to see the die assembly. Figure 10.16 shows the print screen of die drawing. Die assembly is composed of 10 components:

- Punch
- Die insert
- Shrink ring
- Ejector
- Ejector seat
- Ejector rod
- Bolster
- Die clamp ring
- Product
- Bolt

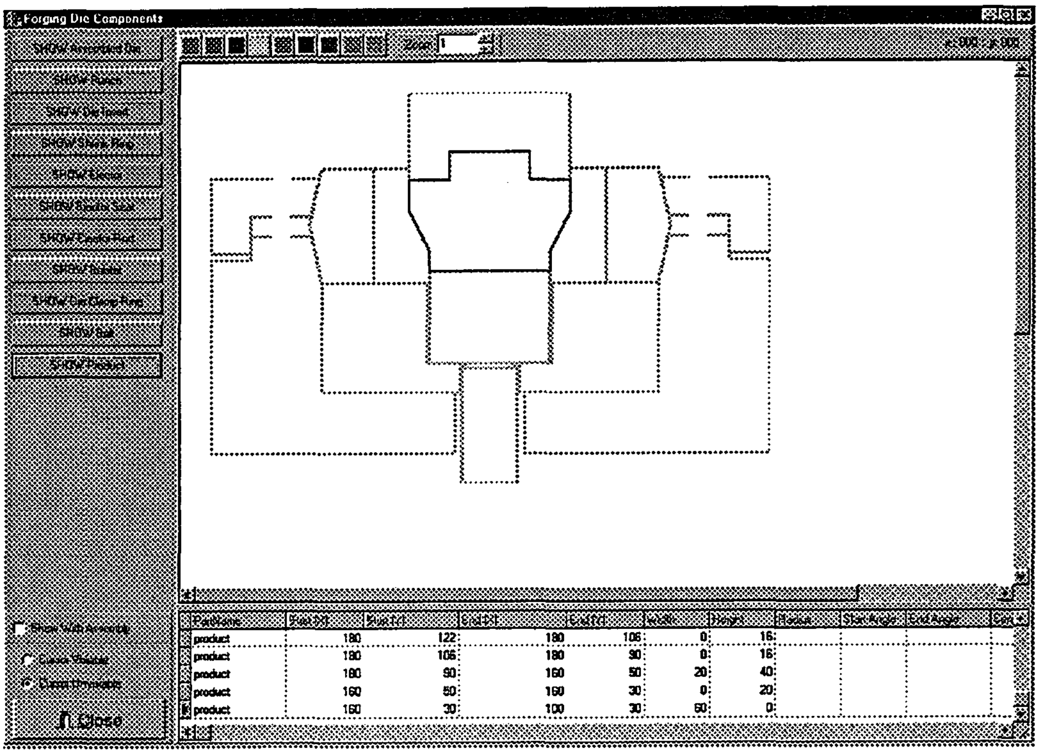


Figure 10.16 Drawing of Die Assembly Screen

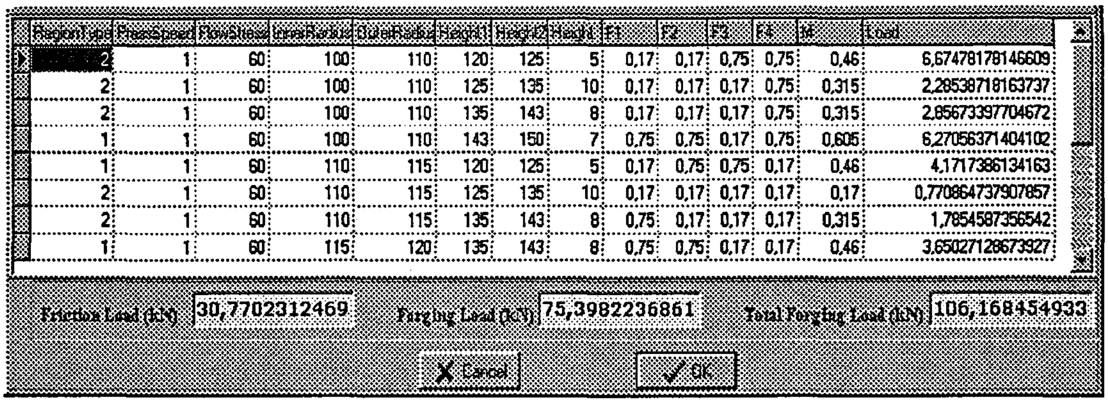
Each part of the die can be seen individually only by pressing related button of left sided ones. Lower right hand side of the screen presents the dimensions of each part. In this section, dimensions of the whole assembly can be seen by checking the "Show With Assembly" check box. Making empty of this box enables the user to see the part geometry and only its dimension.

The calculated forging load is : 75 398.22 N

The calculated friction load is : 30 770.23 N

Total forging load is : 106 168.45 N

Experimental result is : 100 000.00 N



RegionType	PressSpeed	FlowStress	InnerRadius	OuterRadius	Height1	Height2	Height	F1	F2	F3	F4	M	Load
2	1	60	100	110	120	125	5	0,17	0,17	0,75	0,75	0,46	6,67478178146609
2	1	60	100	110	125	135	10	0,17	0,17	0,17	0,75	0,315	2,28538718163737
2	1	60	100	110	135	143	8	0,17	0,17	0,17	0,75	0,315	2,85673397704672
1	1	60	100	110	143	150	7	0,75	0,75	0,17	0,75	0,605	6,27056371404102
1	1	60	110	115	120	125	5	0,17	0,75	0,75	0,17	0,46	4,1717386134163
2	1	60	110	115	125	135	10	0,17	0,17	0,17	0,17	0,17	0,770864737907857
2	1	60	110	115	135	143	8	0,75	0,17	0,17	0,17	0,315	1,7854587356542
1	1	60	115	120	135	143	8	0,75	0,75	0,17	0,17	0,46	3,65027128673927

Friction Load (kN) 30,7702312469 Forging Load (kN) 75,3982236861 Total Forging Load (kN) 106,168454933

Cancel OK

10.4. PROGRAM OUTPUT for ALUMINUM

Experimental studies are checked by prepared program. U-shaped product was obtained in 26 tons of load. By taking flow stress value for aluminium 180 MPa, the calculations and the program outputs (Figure 10.17 to Figure 10.19) will be as follows;

The calculated forging load is : 226 194.67N
The calculated friction load is : 62 684.90 N
Total forging load is : 288 879.57 N
Experimental result is : 260 000.00 N

RegionType	PressSpeed	FlowStress	InnerRadius	OuterRadius	Height1	Height2	Height	F1	F2	F3	F4	M	Load
2	1	180	110	120	130	140	10	0,17	0,17	0,75	0,75	0,46	10,01217267219S
1	1	180	110	120	140	150	10	0,75	0,75	0,17	0,75	0,605	13,16818379948E
1	1	180	120	130	130	140	10	0,75	0,75	0,75	0,17	0,605	39,50455139845E

Friction Load (kN) 62,6849060058 Forging Load (kN) 226,194671058 Total Forging Load (kN) 288,879577064

Figure 10.17. U-Shaped Product Program Output

T-shaped product:

The calculated forging load is : 226 194.67 N
The calculated friction load is : 62 684.90 N
Total forging load is : 288 879.57 N
Experimental result is : 260 000.00 N

RegionType	PressSpeed	FlowStress	InnerRadius	OuterRadius	Height1	Height2	Height	F1	F2	F3	F4	M	Load
2	1	180	110	120	130	140	10	0,17	0,17	0,75	0,75	0,46	10,01217267219S
1	1	180	110	120	140	150	10	0,75	0,75	0,17	0,75	0,605	13,16818379948E
1	1	180	120	130	130	140	10	0,75	0,75	0,75	0,17	0,605	39,50455139845E

Friction Load (kN) 62,6849060058 Forging Load (kN) 226,194671058 Total Forging Load (kN) 288,879577064

Figure 10.18. T-Shaped Product Program Output

Taper shaped product:

The calculated forging load is : 226 194.67 N

The calculated friction load is : 40 846.40 N

Total forging load is : 267 014.10 N

Experimental result is : 240 000.00 N

RegionType	PressSpeed	Flowstress	InnerRadius	OuterRadius	Height1	Height2	Height	F1	F2	F3	F4	M	Load
2	1	180	110	117,5	120	130	10	0,17	0,17	0,75	0,75	0,46	3,434175226564
2	1	180	110	117,5	130	140	10	0,75	0,17	0,17	0,75	0,46	3,434175226564
2	1	180	117,5	122,5	120	130	10	0,17	0,17	0,75	0,17	0,315	3,2566767338332
1	1	180	122,5	130	120	130	10	0,75	0,75	0,75	0,17	0,605	26,968440421347
3	1	180	117,5	122,5	130	140	10	0,75	0,17	0,17	0	0,363	3,7529323212303

Friction Load (kN) 40,8464012145 Forging Load (kN) 226,194671058 Total Forging Load (kN) 267,041072273

Cancel OK

Figure 10.19. Taper Shaped Product Program Output

These experiments and program outputs show that friction load is changing from 15% to 35 % of forging load. Additionally, Program is over estimating total forging load between 10 % to 20 % than experimental results. This can be explained by shape complexity factor. As it is stated by Mielnik [63], empirical formulas such as in the foregoing do not generally contribute very much to a better understanding of the forging process since they are not based on the fundamental phenomena of metal deformation. He states that shape complexity factor can change from 1.2 to 12. In our works it was found that this complexity factor is changing from 1.1 to 2.5.

CHAPTER 11

DISCUSSION AND CONCLUSION

11.1. INTRODUCTION

In this part of the thesis, the developed package is discussed. Conclusions for each module and the recommendations for future work are given in the proceeding sections.

11.2. DISCUSSION

The objective of this study was to develop an expert system for near-net shape axisymmetric forging die design. Some researchers investigated different metal forming techniques by using different approximate methods. However, their studies generally have been concentrated on specific shape or one of industrial parts such as H-Beams, U-Shaped parts, gear, connecting rod and so on. But, in this study a general approach for rotational axisymmetric parts were carried out.

At the beginning of the study, complete CAD/CAM integration for forging dies was desired. But, it was seen that in metal forming there are no exact solutions that can be used for practical purposes and in forging dies are very different and widespread applications. Therefore, the subject was restricted with rotational axisymmetric parts for forging dies.

The sprite of this thesis was based on the Ph.D. studies on process planning [16, 124, 125, 126] which were developed within the Mechanical Engineering Department in the University of Gaziantep. They were started to develop CAD/CAM integration especially on machine tools. In order to found the CAD/CAM group and establish the widespread modular package, each researcher studied on one part of the whole CAD/CAM structure.

In this respect, the design of axisymmetric forging dies and development of expert system have been carried out by this work.

11.2.1. The Need for This Work

The developments in metal forming area bring new technologies together and forces the existing methods to become more efficient. Instead of human based enterprise, today's industry requires computerised technology. They do believe that, they reduce the company's reliance on human experts by capturing expert knowledge and store the knowledge in computers.

Throughout the years, a great deal of know-how and experience has been accumulated in the form of design guidelines for designing forgings. In the search of literature thoroughly, it was recognised that there is not enough analytical method available for the design of forging dies and there is no complete suggestion for the group of forging dies of axisymmetric parts. On the other hand, there is very little work on geometric transition problems from graphical environment and they were not clearly identified. And also deficiency of previous works arises from that only considering one part of forging dies in this field.

This work attempts to utilise DXF standard which can be used for transition of geometrical data between CAD and CAM, suggests individual forging parameters and propose forging die shape.

11.2.2. Used Materials

In order to develop a CAD/CAM package, selection of right working environment and right software have vital importance. Good working environment helps the designer to improve his works, program jobs and handle more complex jobs. If the theoretical works coalesce with the experimental works they become more meaningful. The prepared package, within this work, met with powerful hardware. If capacity of the computer is good enough, software can perform better otherwise not. The software developed in this work is PC based program and it can be executable on any average PC computer.

11.2.3. Inclusion of Expert System

In recent years, numerous programs and programming packages have been developed to solve manufacturing problems.

The expert system is the most famous artificial intelligence tool. Expert systems are the first attempt to simulate human behaviours in industry. In this work, the initial aim was to develop a fully expert system for axisymmetric forging dies. However, the tools for building expert systems were not sufficiently developed in each step of the work. Lots of rules and huge software should be contained since the forging and die design processes have very inclusive and extensive knowledge. Therefore, especially two main parts of the work, which are forgeable geometry and forging load calculation utilise the expert system. Additionally, material database has a wide rage of material type and contains 30 different properties for each material. The remaining part was rule based structured and contains big amount of knowledge.

During study time of the thesis, expert system shells such as VP EXPERT, KES and GOLDWORKS were tried to form the required job. Utilisation of AutoLISP took much of time. It has interrelationship between AutoCAD. It was good at graphic applications but bad at mathematical formulae. MATHEMATICA was also used during load calculation studies. But, unfortunately none of them was sufficient to carry out the desired situation.

Therefore, Borland C++ language was used. This software could handle almost all requirements and it has it's own inference engine. Mathematical calculations and graphical presentation of forging die were achieved by this program.

11.3. CONCLUSION

Computer aided determination of forgeable geometry and therefore forging design has a great importance for preserving the gradually disappearing know-how for forging industry. The developed package has wide applicability since the forging shapes, which are presented in this thesis, represent a large proportion of the total industrial parts.

11.3.1. *Geometric Modelling*

In this step, drawing file of the final product was recognised. The shape, taken from graphical environment (AutoCAD), was converted into DXF format and it was integrated with the system by means of feature recognition module.

In this system, one half of final product shape was inputted to the system by AutoCAD drawing facility. Part geometry was exported from AutoCAD in standard DXF format. It was recognised and all entity co-ordinates are then transferred into table. This made it easier for further verifications on the sequence of the entities and enabled the numerical operations for the determination of forgeable geometry.

11.3.2. Forgeable Geometry

After the recognition of input geometry of the product, it was checked that whether it is forgeable in closed die or not and computerised by using knowledge based approach. Therefore, prepared expert system helps the designer to determine the optimum forgeable geometry in design process and reduces the design time. Some certain rules, which were constructed for forgeable geometry perspective, were adopted to data file. The design rules were stored in the knowledge base, in such a way that, every industry (designer) can define and add its own values. This means that this knowledge, that is the valuable resource of the company, will not be lost for any personal reasons and will retain and can be modified for a long time. At any instant user could require reasoning strategy by "Explain" command.

In this part of study, a new coding system was generated to eliminate the undercuts which can not be forgeable in closed dies. Not only the determination of unforgeable sections but also elimination of the unforgeable area was provided by the prepared program. Therefore, optimum final forgeable geometry was presented by graphically.

11.3.3. Forging Load

It was concluded that total forging load has great importance for forging die design. If forging load is underestimated than actual required load, the die cavity can not be filled completely due to insufficient load. Additionally, if forging load is underestimated than actual required load, this may cause failure in die.

In this thesis, Upper Bound Elemental Technique (UBET) was used to predict the forging load. In order to do this, new geometry decomposition method was developed and geometry was divided into several elemental regions. By this method, since the one side of all elements contacts only with material or die & punch, indefiniteness in friction between the boundaries was overcame. Therefore, the required forging load was calculated so as to fill the die cavity completely. The power and energy requirements for making the finished forging were also determined at this stage. Flow fields were divided into simple elements and for each element the velocity field was constructed. In order to determine the forging load, followings must be known:

- Region type
- Yield stress of billet material
- Press speed
- Inner and outer radii of each region
- Region height
- Friction condition

All these factors were calculated or defined by the program itself. User only inputs the yield stress of the material. The others should be concluded for forging load are:

a) Forging loads for workpiece which flow only inwards are higher than billets which flow only outwards.
b) When two workpiece which have the same diameter but different height, are forged in the same die, the taller one requires less forging load than the other in the early stages where the bulged surface of the workpiece has not yet contacted the die surface. In the second stage of deformation where the corners are filled, the taller one requires much more forging load due to its larger contact area and higher friction force.
c) Dimensional variation of forging due to elastic die deflection decreases when forging temperature increases.
d) For a given die preheat temperature, the higher the forging temperature the greater the increase in forging dimensions due to thermal expansion of die. This is due to the greater amount of heat transferred from hot billet to the colder die at higher forging temperatures.

11.3.4. Die Stresses

Die stresses, such as mechanical contact stresses, thermal stresses, die fatigue, surface cracking and crack growth influence die life and geometrical tolerances.

High level of internal pressure during forging was main reason for die stress. The difficulty was non-uniform distribution of pressure. During forging, stress is concentrated in die at which it is in contact with the deformed billet. Additionally, it was found that total amount of forging load is constant but, energy requirement changes due to the early contact of material to the die wall.

In this study, since cylindrical workpiece were used, both radial and tangential stresses occurs with values which are dependent upon the inner radius of the die insert. Yield stress of forging material plays an important role in plastic deformation. When the punch pressure becomes equal to the yield stress of forging material, the deformation from elastic to plastic starts and simple compression continues until the workpiece touches the die insert. At this stage radial pressure applied to the die insert increases with an increase in the punch pressure.

11.3.5. Die Shape

Since the flash gutter formation is not allowed, an important feature of completely closed dies was found that volume constancy must be maintained between the die cavity and forging workpiece.

Size determination of die insert was carried out after several calculations. Firstly, outside diameter of each section of finished product was recorded. Then, geometry correction factors such as; elastic die expansion, thermal die expansion, thermal product contraction and spark gap are evaluated and added to the finished product size.

Outside diameter of die insert was recorded as an another concluded remark. It is possible arrangement that while one part of workpiece material was getting contact with the die surface, remaining part may not be touching anywhere. Therefore outside diameter of die insert must be calculated by taking most critical section size into account.

Shrink ring diameter was also noticed as an important parameter. Shrink ring firmly surrounds the die insert and its thickness must be well calculated to resist forging load transferred from die insert. It is not definite condition but it is better to choose shrink ring material poorer than insert material due to economical reasons. Correct material selection gives the most appropriate design.

The length of ejector and ejector rod must be well defined to eject the forged product from die. If length of the rod is shorter than die height then, forged product cannot be ejected from the die. This is very important for mass production for time consuming and automatic feeding. The diameter of rod must also be well defined to prevent the buckling problem.

11.3.6. Material Database

In forging die design, it is obvious that material selection has vital importance. The prepared material database has user interactive menu. In this facility, lots of material group were introduced and it was made enable by the user to add, remove or change any of the data without changing the algorithm of the program.

The prepared material database is also capable to be extended to any CAD/CAD applications.

Finally, in this thesis the prepared expert system achieves the following items:

- Rotational axisymmetric parts were handled.
- CAD/CAPP interface from graphical environment based on DXF standard was developed.
- Expert system application was realised for forgeable geometry and forging load calculation.
- Program is made available to extend the knowledge base by adding new rules.
- Determines the most appropriate forging side of the product.
- Generates a new coding system to eliminate undercuts and recommends forgeable geometry.
- Can give outputs of the geometrical data in TXT format for any other purpose.
- New geometry decomposition method was developed using UBET for forging load calculation.
- Experimental studies were carried out for specific geometrical shapes.
- Stresses in forging dies were calculated
- Parametric values for die insert and shrink ring were calculated.
- Geometry correction factors were calculated.
- The proposed die geometry was presented.
- Program is easy to design.

The experience gained from this work can easily be applied to other metal forming techniques and CAD/CAM applications. By making some modifications, the developed package can further be extended and integrated with a previously developed process planning packages which were developed in the Mechanical Engineering Department of Gaziantep University.

11.4. RECOMMENDATIONS for FUTURE WORK

For competitiveness with the other metal forming industries, further developments are required in precision forging, in respect to material utilisation, dimensional control, die design and work planning.

Utilisation of the following items will be useful for extension of the present work:

1. Since initial preform geometry was neglected, preform design can be added. In this thesis all load and energy requirements were calculated by considering the final finished product geometry.
2. Whole part of the work can be introduced with expert system or other one of artificial intelligence tool.
3. In addition to the axisymmetric forging plain symmetric and complex forging die design can be studied.
4. Finite Element simulation for metal flow can be added.
5. In order to eliminate surface finish problem in hot forging, such as oxidation and decarburization, can be eliminated by performing the experiments in protected atmosphere condition.

REFERENCES

1. Lee, I.,B.,H.; Lee, B.,S.; Nee, A.,Y.,C. (1993). Knowledge-based process planning system for the manufacture of progressive dies. *International Journal of Production Research*, **Vol. 31**, No. 2, pp. 251-278.

2. Tang, J.P., Oh, S.I., Lee, F.M. (1985). A Computerised process Design System for Manufacturing Shells and Other Cup-shaped components. *Journal of Applied Metal Working*, **V.4**, N.1.

3. Biglari, F.R., O'Dowd, N.P., Fenner, R.T. (1998). Optimum Design of Forging Dies Using Fuzzy Logic in Conjuction with the Backward Deformation Method. *Int. Journal of Machine Tools & Manufacture*, **V.38**.

4. Sheng,S., Guo, L.Y. (1994). A Die Forging Design Approach for Controlling Metal Flow and its Way and its Application in Practice. *Int. Journal of Machine Tools and Manufacture*, **V.34**, N.2, 161-167.

5. Fujikawa, S., Ishihara, A. (1997). Development of Expert Systems for Forging Processes, Journal of Society of Automotive Engineers of Japan, *Inc and Elsevier Science*. **V.18**, 127-133.

6. Maus, R., Keyes, J. (1991). *Handbook of Expert Systems in Manufacturing.* McGraw Hill, New York.

7. Nelson, M., M., Illingworth, W., T. (1994). *A Practical Guide to Neural Nets.* Addison-Wesley Publishing Co.

8. Sadeghi, M.H., Dean, T.A. (1991). Analysis of Dimensional Accuracy of precision Forged Axisymmetric Components. Journal of Engineering Manufacture. *Proceedings of Institute of Mechanical Engineers*, **V.205**, 171-178.

9. Doege, E., Nagele, H. (1994). FE Simulation of Precision Forging Process of Bevel Gears. *Annals of CIRP*, **V.43**, N.1, 241-243.

10. Lahoti, G. (1997). Precision Forging in Bearing Manufacturing. *Proceedings of the JSTP International Seminar on Precision Forging*, Osaka, pp 8-1 to 8-5.

11. Eyercioğlu, Ö., Dean, T.,A. (1997). Design and Manufacture of Precision Gear Forging Dies. *CIRP International Conference on Design and Production of Dies and Molds*.

12. Mori, K.I., Osakada, K., Aizono, T. (1994). An Expert System for Process Planning in Breakdown Rolling of H-Beams. *Int. Journal of Machine Tools and Manufacture*. **V.34**, 939-948.

13. Tuncer, M. N. (1985). Precision Forging Hollow Parts. *Ph. D. Thesis*, University of Birmingham.

14. National Research Council (1995). Unit Manufacturing Processes- Issues and Opportunities in Research. *Manufacturing Process Research Committee*. National Academy Press,.

15. Altan, T., Kobayashi, S., Oh, S. (1989). Metal Forming and the Finite Element Method. *Oxford University Press*, New York.

16. Dereli, T. (1998). Development of a Process Planning System for Prismatic Parts. *Ph.D. Thesis*, University of Gaziantep.

17. Lengyel, B., Tay, M.L. (1988). Expert System in the Cold Forging of Steel. *Proceedings of the Twenty-seventh International Matador Conference*.

18. Wang, S., Chen, J. (1990). An Expert System for Designing Precision Forging Dies. *International Journal of Production Research*.

19. Brandon, J.A., Huang, G.Q. (1992). Cooperating Expert Systems for CAD/CAM. *Proceedings of the Twenty-ninth International Matador Conference.*

20. Kim, H., S., Im, Y.,T. (1996). An Expert System for Cold Forging Process Design Based on a Depth-First Search, *Journal of Materials Processing Technology.*

21. Chang, T.C. (1985). *An Introduction to Automated Process Planning System*, Prince-Hall Inc., Englewood Cliffs, New Jersey, USA.

22. Ham, I. And Lu, S.C.Y. (1988). Computer Aided Process Planning: The Present and the Future. *Annals of the CIRP*, **Vol. 37**, No.2,

23. Shah, J., et al. (1991). Survey of Feature Based Process Planning and NC Programming Techniques. *Computer Aided Engineering Journal.*

24. Alting, L. And Zhang, H. (1989). Computer Automated Process Planning: State of the Art Survey. *International Journal of Production Research*, **V.27**, N.4.

25. Gupta, T. (1990). An Expert System Approach in Process Planning: Current Development and its Future. *Computers and Industrial Engineering*, **V.18**, N.1.

26. Flaszka, W.G., Paro, J.A., Kivivuori, S.O.J. (1990). Computer Aided Forging Design Using Model Material Simulation. *Journal of Materials Processing Technology.*

27. Hirai, T., et. al. (1992). A Knowledge Based Intelligent CAD System for Cold Forging Design Using Fuzzy Theory. *Proceedings of the twenty-ninth International Matador Conference.*

28. Hyunkee, K., Altan, T. (1992). Computer-aided Part and Processing-sequence Design in Cold Forging. *Journal of Materials Processing Technology.*

29. Gokler, M.I., Dean, T.A., Knight, W.A. (1982). Computer Aided Sequence Design for Hot Upset Forgings. *Proc. 22nd Int. Machine Tool Design Conference.*

30. Eyercioğlu, O. (1995). Developments and Performance Analyses of Precision Forged Spur Gears. *Ph.D. Thesis*, University of Birmingham.

31. Bariani, P., Knight, W.A. (1987). Computer Aided Cold Forging Process Design: Determination of Machine Setting Conditions. *Annals of CIRP*, **V.34**, N.1.

32. Kim, H.K., Altan, T. (1992). Computer Aided Part and Processing-sequence Design in Cold Forging, *Journal of Materials Processing Technology*, **V.33**.

33. Kim, D.Y., Park, J.J. (2000). Development of an Expert System for the Process Design of Axisymmetric Hot Steel Forging. *Journal of Materials Processing Technology*, **V.101**.

34. Kim, H., S., Im, Y.,T. (1995). Expert System for Multi-Stage Cold-Forging Process Design with a Re-designed Algorithm, *Journal of Material Processing Technology*. **V.54**, 271-285.

35. Hartley, P., Sturgess C.E.N., Rowe, G.W. (1986). Expert Systems for Design and Manufacture. *12th AIMTDR Conference*, IIT Delhi.

36. Tang, J., OH, S., Altan, T., Miller, R. (1988). A Knowledge Based Approach to Automate Forging Design, *J. Mater. Shaping Technology*, p 7-17.

37. Wang, S., Chen, J. (1990). An Expert System for Designing Precision Forging Dies. *International Journal of Production Research*. **V. 28**, No. 5, 943-951.

38. Ferguson, B.L., Kuhn, H.A., Trasorras, J. (1987). Expert Software Concepts for Design of P/M Preforms for Precision Forging, *Journal of Material Shaping Technology*, 97-105.

39. Osakada, K., Yang, G. (1991). Application of Neural Networks to an Expert System for Cold Forging. *Int. J. Mach. Tools Manufacture*, **V. 31**, No: 4, 577-587.

40. Mori, K., Osokada, K., Aizono, T. (1994). An Expert System for Process Planning in Breakdown Rolling of H-Beams, *Int. J. Mach. Tools Manufacture*, **V. 34,** No. 7, 939-948.

41. Altan, T., Oh, S., Gegel, H. (1983). *Metal Forming: Fundamentals and Applications*, ASM, Metals Park, Ohio.

42. Fujikawa, S., Yoshioka, H., Shimamura, S. (1992). Cold and Warm Forging Applications in the Automotive Industry, *Journal of Materials Processing Technology*, V.35.

43. Onodera, S., Sawai, K. (1992). Current Cold Forging Techniques for the Manufacture of Complex Precision Near-Net Shapes. *Journal of Materials Processing Technology*, **V.35**.

44. Onodera, S., Sawai, K., (1994). Modern Cold Forging Applications for the Manufacture of Complex Automotive Parts. *Journal of Materials Processing Technology*, **V.46**.

45. Kim, H., Altan, T. (1996). Cold Forging of Steel Practical Examples of Computerised Part and Process Design. *Journal of Materials Processing Technology*, **V.59**.

46. Siegert, K., Kammerer, M., Keepler-Ott, Th., Ringhand, D. (1997). Recent Developments on High Precision Forging of Aluminium and Steel. *Journal of Materials Processing Technology*, **V.71**.

47. Nakano, T., (1994). Modern Applications of complex Forming and Multi-Action Forming in Cold Forging, *Journal of Materials Processing Technology*, **V.46**.

48. Balakrishnan, R., Dwivedi, N. (1988). Knowledge Based Expert system for Forging Die Design. *Proc. 20th Southeastern Symposium on System Theory*, USA.

49. Kuhn, H., Trasorras, J., Ferguson, L. (1988). Automated Design of Net-shape Forming Processes, *Journal of Metals*.

50. Kudo, H. (1990). Towards Net Shape Forming. *Journal of Materials Processing Technology*, **V.32**.

51. Maegaard V. (1992). Cold Forging of Net or Near Net Shape Components. *Journal of Materials Processing Technology*, **V.35**.

52. Chu, C.N., Lee, J.M, Hschyap, R.L. (1993). Skeleton Based Design Analysis of Near Net Shape Products. *CIRP Annals*, **V.42**.

53. Zhao, G., Wright, E., Grandhi, R.V. (1997). Sensitivity Analysis Based Preform Die Shape Design for Net-Shape Forging. *International Journal of Tools Manufacture*, **V.37**, N.9.

54. Rodiger, K., Berg, H., Dreyer, K., Kassel D, Arths,S. (2000). Near Net Shaping in the Hardmetal Industry. *Int. Journal of Refractory Metals & Hard Metals*, **V.18**, 111-120.

55. Doege, E., Thalemann, J., Weber, F. (1992). Hot Forging of Precision Parts. *Journal of Materials Processing Technology*, **V.35**.

56. Lange, K. (1992). Some Aspects of the Development of Cold Forging to a High-tech Precision Technology. *Journal of Materials Processing Technology*, **V.35**.

57. Majerus, J.N., Jen, K.P., Gong, H. (1997). Quantitive Data for Precision, Closed Die, Forging: Internal Deformations and Computer Simulations. *Int. Journal Machine Tools Manufacture*, **V.37**,

58. Osakada, K., Wang, X., Hanami, S. (1997). Precision Forging Process with Axially Driven Container. *Journal of Materials Processing Technology*, **V.71**.

59. Osakada, K., Wang, X., Hanami, S. (1997). Precision Forging of Spline by Flashless Die Forging with Axially Driven Die. *Annals of the CIRP*, **V.46**, N.1.

60. Pale, A.J., Shivpuri, R., Altan, T. (1992). Recent Developments in Tooling, Machines and Research in Cold Forming of Complex Parts. *Journal of Materials Processing Technology*, V.33.

61. Hirschvogel, M., Dommelen, H. (1992). Some Applications of Cold and Warm Forging. *Journal of Materials Processing Technology*, **V.35**.

62. Sheljaskov, S. (1994). Current Level of Development of Warm Forging Technology. *Journal of Materials Processing Technology*, **V.46**.

63. Mielnik, E.M. (1991). *Metalworking Science and Engineering*. McGraw-Hill, Inc.

64. Kudo, H. (1960). Some Analytical and Experimental Studies of Axisymmetric Cold Forging and Extrusion-I. *Int. Journal of Mechanical Science*, **V.2**.

65. Kudo, H. (1961). Some Analytical and Experimental Studies of Axisymmetric Cold Forging and Extrusion-II. *Int. Journal of Mechanical Science*, **V.3**.

66. Osman, F.H., Bramley, A.N., Chobrial, M.I. (1984). Forging and Preform Design Using UBET. *Advanced Technology of Plasticity*, **V.1**.

67. Cser, L., Ziaja, G. (1984). Use of Elemental Upper Bound Technique in CAD. *Advanced Technology of Plasticity*, **V.1**.

68. Kiuchi, M., Karato, A. (1984). Application of UBET to Non-Axisymmetric Forging. *Advanced Technology of Plasticity*, **V.II**.

69. Walker, N.D. (1989). Automated Upper Bound Procedures for Plane Strain Metal Forming Analysis. *J. Mater. Shaping Technology*, **V.7**.

70. Oyekanmi, B.O., Bramley, A.N. Osman, F.H. (1992). The Validation of the Upper Bound Elemental Technique (UBET) in the Prediction of Strain Distributions in Forgings. *Journal of Materials Processing Technology*, **V.30**.

71. Lin, Y.T., Wang, J.P. (1993). A new Upper Bound Elemental Technique Approach to Axisymmetric Metal Forming Processes. *Int. Journal of Machine Tools Manufacture*, **V.33**, N.2.

72. Lee, J.H., Kim, Y.H., Bae, W.B. (1997). A Study on Flash and Flashless-Precision Forging by the Upper Bound Elemental Technique. *Journal of Materials Processing Technology*, **V.72**.

73. Shuqin, X., Yuan, F. (1997). FEM Analysis and Experimental Research on Complex Forming. *Journal of Materials Processing Technology*, **V.69**.

74. Bramley, A.N. (2001). UBET and TEUBA: Fast Methods for Forging Simulation and Preform Design. *Journal of Materials Processing Technology*, **V.116**.

75. Doege, E., Beherns, B. (1997). Development of an Automated Precision Forging Process with Integrated Quality Control. *Proceedings of the I. Conferencia Internacional de Forjamento*. Sao Paulo, Brazil.

76. Lange, K. (1985). *Handbook of Metal Forming*, McGraw Hill.

77. Matsushita, T. (1990). Improvement of Equipment for Close Tolerance Forging and Extrusion in Japan. *Journal of Materials Processing Technology*, **V.24**, 223-238.

78. Körner E., Knödler. (1992). Possibilities of Warm Extrusion in Combination with Cold Extrusion. *Journal of Materials Processing Technology*, **V.35**, 451-465.

79. Sheljaskov, S. (1996). Warm Forging-A Technology for Manufacturing of Precision Components. *Proceedings of the 5th International Conference on Technology of Plasticity*, USA.

80. Shipley, R.J. (1988). Precision Forging. *ASM Metals Handbook-Forming and Forging*, **V.14**, ASM International.

81. Cser, L., Geiger, M., Lange, K., Kals, J.A.G., Hansel, M. (1993). Tool Life and Tool Quality in Bulk Metal Forming. *Journal of Engineering Manufacture*, Proceedings of Institute of Mechanical Engineers, **V.207**, 223-239.

82. Altan, T., Boulger, F.W., Becker, J.R., Akgerman, N., Henning, H.J. (1973). Forging Equipment Materials and Practices. *Metals and Ceramics Information Center*.

83. Hyunkee, K., Altan, T. (1996). Cold Forging of Steel-Practical examples of Computerised Part and Process Design. *Journal of Materials Processing Technology*, V.59, 122-131.

84. Ibhadode, A.O.A., Dean, T.A. (1988). Corner Filling Characteristics in Precision Forging". *Journal of Machine Tools and Manufacture*, **V.28**, N.2, 103-122,.

85. Watkins, M.T. (1975). Metal Forming 1. *Forging and Related Processes*. Oxford University Press.

86. Hirschvogel, M., Dommelen, H.V. (1992). Some Applications of Cold and Warm Forging. *Journal of Materials Processing Technology*, **V.35**, 343-356.

87. Nagahama, T., Enomae, S. (1992). Cold and Warm Forging Press Developments and Applications. Journal of Materials Processing Technology, **V.35**, 415-427.

88. Stevens, R., McInerney, T.M. (1996). Method and Apparatus for Manufacturing a Flashless Metal Connecting Rod. US Patent No.5, 544, 413,.

89. Allada, V., Anand, S. (1995). Feature-Based Modelling Approaches for Integrated Manufacturing: State of the Art Survey and Future Directions. *International Journal of Computer Integrated Manufacturing*, **V. 8**, N.6.

90. Dereli, T., Filiz, İ.H. (1997). Bilgisayar Destekli Tasarım ve Üretim Sistemlerinde Bilgi Değişimi ve Standartları. *Mühendis ve Makine*, **V.38**, N.452.

91. Gülesin, M. (1997). The STEP Standard and Data Exchange Between CAD/CAM systems, *Proceedings of the 1st National Conference on Machine Design Theory and Modern Manufacturing Methods (MATIK)*, Gazi University.

92. Rembold, N., et. al. (1994). *Computer Integrated Manufacturing and Engineering, Addison*, Wesley, UK.

93. Feigenbaum, E.A. (1977). The Art of Artificial Intelligence: I, Themes and Case Studies of Knowledge Engineering. *Proceedings of 5th International Joint Conference on Artificial Intelligence*, 1014-1029.

94. *KES PS Manual.* (1990). Software Architecture and Engineering, Inc.

95. Huang, S.H. and Zhang, H.C. (1995). Neural-Expert Hybrid Approach for Intelligent Manufacturing: A Survey, *Computers in Industry*, **Vol. 26**, pp. 107-126.

96. Badiru, A.B. (1992). *Expert Systems Applications in Engineering and Manufacturing*, Printice-Hall, NJ, USA.

97. Stacey, D. (1994). Intelligent Systems Architecture: Design Techniques. *Artificial Neural Networks for Intelligent Manufacturing* (Edited by Dagli, C.H.), Chapman&Hall, UK, 17-38.

98. Joshi, S., et al. (1988). Expert Process Planning System with Solid Model Interface. *International Journal of Production Research*, **Vol. 26**, No. 5, 863-885.

99. Gulesin, M. and Jones, R.M. (1993). Operation Sequencing in an Expert Process Planning and Fixturing System. *Proceedings of ICES' 93 - Int. Conference on Engineering Software*, 45-50.

100. Vosniakos, L.C., and Davies, B.J. (1993). Knowledge-Based Selection and Sequencing of Hole-Making Operations for Prismatic Parts. *Int. Journal of Advanced Manufacturing Technology*, Springer-Verlag Ltd., **Vol. 8**, 9-16.

101. Arezoo, B. and Ridgway, K. (1990). The Application of Cutting Tools and Conditions for Machining Operations. *Proceedings of 1st Conference on Artificial Intelligence and Expert System in Manufacturing*, IFS Ltd., 113-126.

102. Vitanov, V.I., et.al. (1995). An Expert System Shell for the Selection of Metal Cutting Parameters. *Journal of Materials Processing Technology*, **Vol. 55**, 111-116.

103. Keating, W.G., et al. (1995). Intelligent Tool Selection System. *Journal of Materials Processing Technology*, **Vol. 55**, pp. 91-94.

104. Kusiak, A. (1990). *Intelligent Manufacturing Systems*, Prentice-Hall, USA.

105. Kusiak, A. (1991). Process Planning: A Knowledge-Based and Optimisation Perspective. *IEEE Transactions on Robotics and Automation*, **Vol.7**, No.3, 257-266.

106. Mayer, R.J., et al. (1995). Plan Generation Strategies for a Knowledge-based Automated Process Planning System. *International Journal of Computer Integrated Manufacturing*, **Vol. 8**, No. 6, 399-410.

107. Yılmaz, N.F, Eyercioğlu, Ö. and Dereli, T. (2001). An Expert System for the Determination of Forgeable Geometry in Near-Net shape Manufacturing. *2nd International Conference and Exhibition on Design and Production of Dies and Molds*, Kuşadası, Turkey.

108. Gupta, T. and Ghosh, K.B. (1988). A Survey of Expert Systems in Manufacturing and Process Planning, *Computers in Industry*, **Vol. 11**, 195-204.

109. Kalpakjian, S. (1997). *Manufacturing Processes for Engineering Materials*, 3rd Ed., Addison-Wesley, USA.

110. Dereli, T., Baykasoğlu, A. (2000). Artificial Intelligence in Design and Manufacturing. Journal of Polytechnic, 3/2, 27-60.

111. Hsu, Q.C., Lee, R.S. (1997). Cold Forging Process Design Based on the Induction of Analytical Knowledge. *Journal of Materials Processing Technology*, **V.69**, 264-272.

112. Glynn, D., Lyons, G., Monaghan, J. (1995). Forging Sequence Design Using an Expert System. *Journal of Materials Processing Technology*, **V.55**, 9-102.

113. Osakada, K., Kado, T., Yang G.B. (1998). Application of AI-technique to Process Planning of Cold Foeging. *Annals of CIRP*, **V.37**, 239-242.

114. Yang G.B., Osakada, K. (1990). An Expert System for Process Planning of Cold Forging. *Advanced Technology of Plastics*, **V.1**, 109-115.

115. Im, C.S., Suh, S.R., Lee, M.C., Kim, J.H., Joun, M.S. (1999). Computer Aided Process Design in Cold Former Using a Forging Simulator and a Commercial CAD Software, *Journal of Materials Processing Technology*, **V.95**, 155-163.

116. Tisza, M. (1995). Expert Systems for Metal Forming. Journal of Materials Processing Technology, **V.53**, 423-432.

117. Yang G.B., Osakada, K. (1993). A Review of Expert Systems for Process Planning of Cold Forging. *Manufacturing Rev.*, **V.6**, 101-113.

118. Penchev, T. (1992). Development of an Expert System for Hot Die by Breakdown of the Parts into Groups. *Journal of Materials Processing Technology*, **V.30**, 285-287.

119. Lei, Y., Peng, Y., Ruan, X. (2001). Applying Case-based Reasoning to Cold Forging Process Planning. *J. of Materials Processing Technology*, **V.112**, 12-16.

120. Chul, K., Kim, B.M., Choi, J.C. (2001). Development of an Integrated Computer Aided Process Planning System for Press Working Products. *Journal of Materials Processing Technology*, V.111, 188-192.

121. Lee, I. B. H., Lim, Y. G., Ong, B. L. (1989). Extraction of Technological Information from Feature Oriented Modelling System for Generative Computer Aided Process Planning. *Proceedings of Int. Conference on Productivity.*

122. Joun, M.S., Chung, J.H., Shivpuri, R. (1998). An Axisymmetric Forging Approach to Preform Design in Ring Rolling Using a Rigid-Viscoplastic Finite Element Method. *Machine Tools and Manufacture*, **V.38**, 1183-1191.

123. Park Y.B., Lee K.H. (2001). Study on the Deformation of Die and Product in Closed Die Upsetting. *J. of Materials Processing Technology*, **V.118**, 417-421,.

124. Kayacan, M.C. (1995). Computer Aided Process Planning for Rotational Parts. *Ph.D. Thesis*, University of Gaziantep.

125. Akpolat, A. (1997). Computer Aided Design of Machine Tool Bed Structures. *Ph. D. Thesis*, University of Gaziantep.

126. Görür, G. (1995). Computer Aided Design of the Main Drives of Machine Tools. *Ph.D. Thesis*, University of Gaziantep.

127. Kudo, H. (1978). *Precision Machinery* (Seimitsu Kikai), 409.

128. Sadeghi, M.H. (1989). Precision Forging Axisymmetric Shapes, Straight and Helical Spur Gears. Ph.D. Thesis, University of Birmingham.

129. *Metals Handbook of American Society Testing and Manufacturing* (ASTM)

130. Eyercioğlu, Ö. (1998). Warm Forging for Manufacturing Complex Shapes, *8th International Machine Design and Production Conference*, Ankara.

131. Dean, T.A. (1980). Design Testing and Production Performance of Die Set for Flashless Forging, Proc. *Int. Mech. Eng.*, **V.195**, 15.

132. Jones, D.F. (1951). Die Design and Diemaking Practice, The Industrial Press, New York.

133. Male, A.T., DePierre, V., Saul, G. (1972). The Validity of Mathematical Solutions for Determining Friction from the Ring Compression Test, *Journal of Lubrication Technology*, **V.96**, 389-397.

134. Sofuoglu, H., Gedikli, H. (2002). Determination of Friction Coefficient Encountered in Large Deformation Processes. *Tribology International*, **V.35**, 27-34.

135. Ignizio, J.P., (1991). Introduction to Expert Systems. McGraw-Hill, International Edition, Singapore.

136. Davis, R., Shrobe, H., and Szolovits, P. (1993). What is a Knowledge Representation?. *AI Magazine*, 14(1):17-33.

137. Douglas, J.R., Altan, T. (1972). Characteristics of Forging Presses: Determination and Comparison, *Proceedings of the Matador Conference*, Birmingham, 536-546.

138. Oztaş, A., (1995). The Mitigation of the Effects of Delays in Construction Projects: A Knowledge Based System Approach, *Ph. D. Thesis*, University of Manchester.

139. Aslan, E. (1995). Uzman Sistem Yaklaşımıyla Son İşlemci Tasarımı, *Ph. D. Thesis*, Gazi Üniversitesi.

140. Bozdana, T. (1999). Development of an Expert System for the Determination of Injection Moulding Parameters of Thermoplastics, M. S. Thesis, University of Gaziantep

141. Luce, T. (1992). Using VP-Expert in Business, McGraw-Hill, Watsonville.

142. Gruber, T.R. (1989). The Acquisition of Strategic Knowledge, Academic Press, London.

APPENDICES

APPENDIX A1

DXF GROUP CODE RANGES

Group code	Description
–5	APP: persistent reactor chain
–4	APP: conditional operator (used only with ssget)
–3	APP: extended data (XDATA) sentinel (fixed)
–2	APP: entity name reference (fixed)
–1	APP: entity name. The name changes each time a drawing is opened. It is never saved (fixed)
0	Text string indicating the entity type (fixed)
1	Primary text value for an entity
2	Name (attribute tag, block name, and so on)
3–4	Other text or name values
5	Entity handle; text string of up to 16 hexadecimal digits (fixed)
6	Linetype name (fixed)
7	Text style name (fixed)
8	Layer name (fixed)
9	DXF: variable name identifier (used only in HEADER section of the DXF file)
10	Primary point; this is the start point of a line or text entity, center of a circle, and so on
DXF:	X value of the primary point (followed by Y and Z value codes 20 and 30)
APP:	3D point (list of three reals)
11–18	Other points
DXF:	X value of other points (followed by Y value codes 21–28 and Z value codes 31–38)
APP:	3D point (list of three reals)
20, 30	DXF: Y and Z values of the primary point
21–28, 31–37	DXF: Y and Z values of other points

Group code	Description
38	DXF: entity's elevation if nonzero
39	Entity's thickness if nonzero (fixed)
40–48	Floating-point values (text height, scale factors, and so on)
48	Linetype scale; floating-point scalar value; default value is defined for all entity types
49	Repeated floating-point value. Multiple 49 groups may appear in one entity for variable-length tables (such as the dash lengths in the LTYPE table). A 7x group always appears before the first 49 group to specify the table length
50–58	Angles (output in degrees to DXF files and radians through AutoLISP and ObjectARX applications)
60	Entity visibility; integer value; absence or 0 indicates visibility; 1 indicates invisibility
62	Color number (fixed)
66	"Entities follow" flag (fixed)
67	Space—that is, model or paper space (fixed)
68	APP: identifies whether viewport is on but fully off screen; is not active or is off
69	APP: viewport identification number
70–78	Integer values, such as repeat counts, flag bits, or modes
90-99	32-bit integer values
100	Subclass data marker (with derived class name as a string). Required for all objects and entity classes that are derived from another concrete class. The subclass data marker segregates data defined by different classes in the inheritance chain for the same object. This is in addition to the requirement for DXF names for each distinct concrete class derived from ObjectARX (see "Subclass Markers")

Group code	Description
102	Control string, followed by "{<arbitrary name>" or "}". Similar to the xdata 1002 group code, except that when the string begins with "{", it can be followed by an arbitrary string whose interpretation is up to the application. The only other control string allowed is "}" as a group terminator. AutoCAD does not interpret these strings except during drawing audit operations. They are for application use
105	Object handle for DIMVAR symbol table entry
210	Extrusion direction (fixed)
DXF:	X value of extrusion direction
APP:	3D extrusion direction vector
220, 230	DXF: Y and Z values of the extrusion direction
280-289	8-bit integer values
290-299	Boolean flag value
300-309	Arbitrary text strings
310-319	Arbitrary binary chunks with same representation and limits as 1004 group codes: hexadecimal strings of up to 254 characters represent data chunks of up to 127 bytes
320-329	Arbitrary object handles; handle values that are taken "as is." They are not translated during INSERT and XREF operations
330-339	Soft-pointer handle; arbitrary soft pointers to other objects within same DXF file or drawing. Translated during INSERT and XREF operations
340-349	Hard-pointer handle; arbitrary hard pointers to other objects within same DXF file or drawing. Translated during INSERT and XREF operations
350-359	Soft-owner handle; arbitrary soft ownership links to other objects within same DXF file or drawing. Translated during INSERT and XREF operations
360-369	Hard-owner handle; arbitrary hard ownership links to other objects within same DXF file or drawing. Translated during INSERT and XREF operations

Group code	Description
370-379	Lineweight enum value (AcDb::LineWeight). Stored and moved around as a short. Custom non-entity objects may use the full range, but entity classes only use 371-379 DXF group codes in their representation, because AutoCAD and AutoLISP both always assume a 370 group code is the entity's lineweight. This allows 370 to behave like other "common" entity fields.
380-389	PlotStyleName type enum (AcDb::PlotStyleNameType). Stored and moved around as a short. Custom non-entity objects may use the full range, but entity classes only use 381-389 DXF group codes in their representation, for the same reason as the Lineweight range above.
390-399	String representing handle value of the PlotStyleName object, basically a hard pointer, but has a different range to make backward compatibility easier to deal with. Stored and moved around as an Object ID (a handle in DXF files) and a special type in AutoLISP. Custom non-entity objects may use the full range, but entity classes only use 391-399 DXF group codes in their representation, for the same reason as the Lineweight range above.
400-409	16-bit Integers
410-419	String
999	DXF: The 999 group code indicates that the line following it is a comment string. SAVEAS does not include such groups in a DXF output file, but OPEN honors them and ignores the comments. You can use the 999 group to include comments in a DXF file that you've edited
1000	ASCII string (up to 255 bytes long) in extended data
1001	Registered application name (ASCII string up to 31 bytes long) for extended data
1002	Extended data control string ("{"or "}")
1003	Extended data layer name

Group code	Description
1004	Chunk of bytes (up to 127 bytes long) in extended data
1005	Entity handle in extended data; text string of up to 16 hexadecimal digits
1010	A point in extended data DXF: X value (followed by 1020 and 1030 groups)APP: 3D point
1020, 1030	DXF: Y and Z values of a point
1011	A 3D world space position in extended data DXF: X value (followed by 1021 and 1031 groups) APP: 3D point
1021, 1031	DXF: Y and Z values of a world space position
1012	A 3D world space displacement in extended data DXF: X value (followed by 1022 and 1032 groups) APP: 3D vector
1022, 1032	DXF: Y and Z values of a world space displacement
1013	A 3D world space direction in extended data. DXF: X value (followed by 1022 and 1032 groups) APP: 3D vector
1023, 1033	DXF: Y and Z values of a world space direction
1040	Extended data floating-point value
1041	Extended data distance value
1042	Extended data scale factor
1070	Extended data 16-bit signed integer
1071	Extended data 32-bit signed long

APPENDIX A2

DXF FILE for FIGURE 5.3

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0.0
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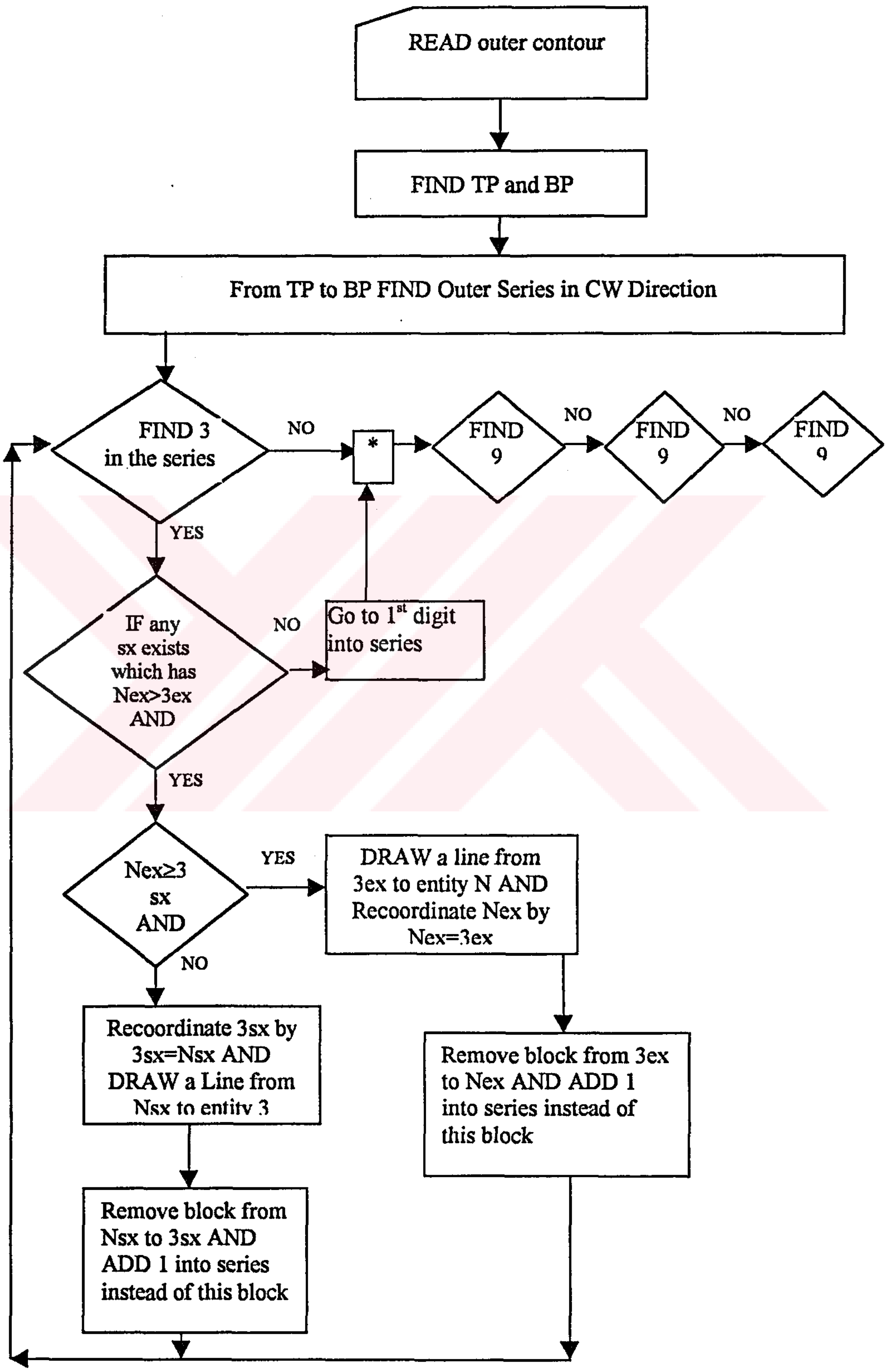
180.0
 20
135.0
 30
0.0
 11
160.0
 21
135.0
 31
0.0
  0
LINE
  5
50
100
AcDbEntity
  8
0
100
AcDbLine
 10
160.0
 20
135.0
 30
0.0
 11
160.0
 21
125.0
 31
0.0
  0
LINE
  5
51
100
AcDbEntity
  8
0
100
AcDbLine
 10
```

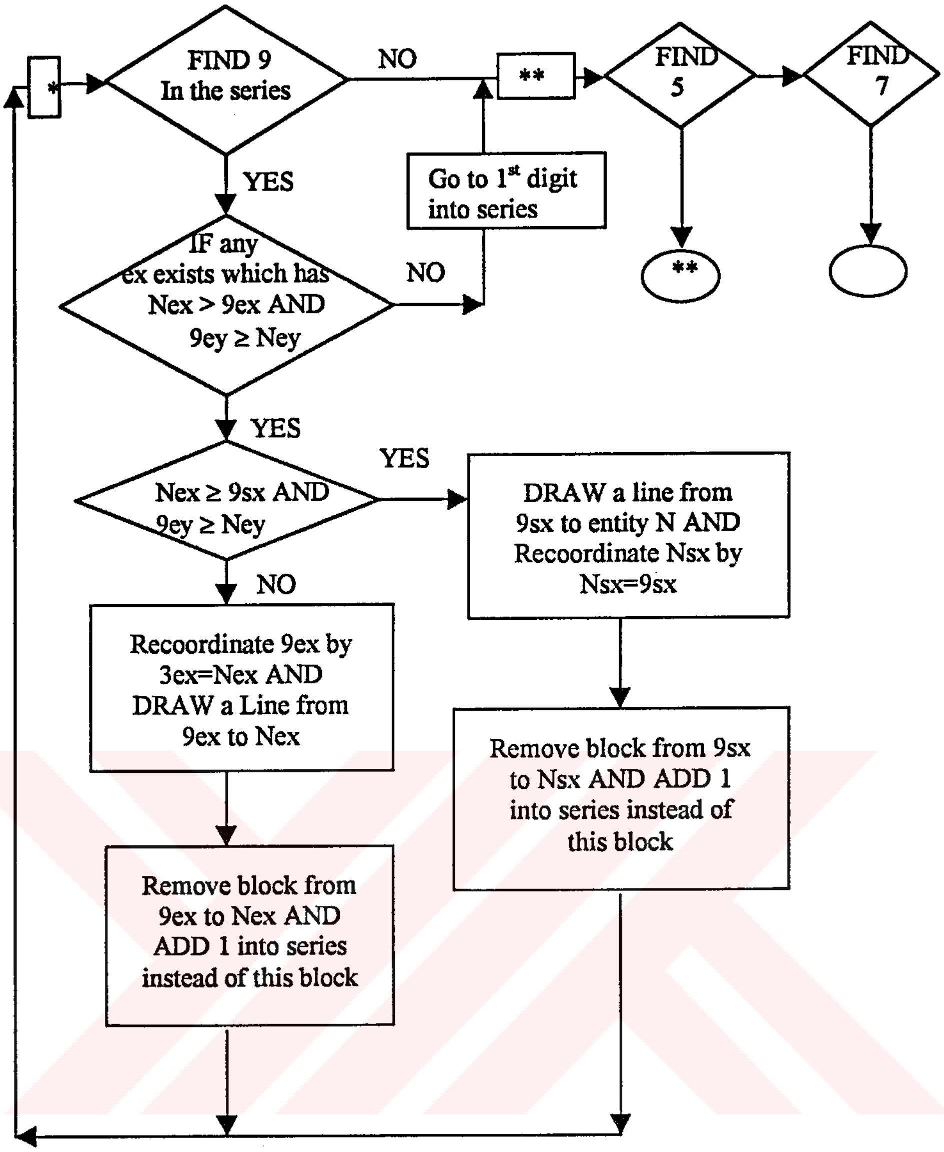
```
160.0
 20
125.0
 30
0.0
 11
205.0
 21
110.0
 31
0.0
  0
LINE
  5
52
100
AcDbEntity
  8
0
100
AcDbLine
 10
205.0
 20
110.0
 30
0.0
 11
205.0
 21
65.0
 31
0.0
  0
LINE
  5
53
100
AcDbEntity
  8
0
100
AcDbLine
 10
205.0
 20
65.0
 30
0.0
 11
190.0
 21
65.0
 31
0.0
  0
LINE
  5
54
100
AcDbEntity
  8
0
100
AcDbLine
 10
190.0
 20
65.0
 30
0.0
 11
190.0
 21
50.0
 31
0.0
  0
ARC
  5
55
100
AcDbEntity
  8
0
100
AcDbCircle
 10
180.0
 20
50.0
 30
0.0
 40
10.0
100
AcDbArc
 50
270.0
 51
0.0
  0
LINE
  5
56
100
AcDbEntity
  8
0
100
AcDbLine
 10
180.0
 20
40.0
 30
0.0
 11
145.0
 21
40.0
 31
0.0
  0
LINE
  5
57
100
AcDbEntity
  8
0
100
AcDbLine
 10
145.0
 20
40.0
 30
0.0
 11
145.0
 21
55.0
 31
0.0
  0
LINE
  5
58
100
AcDbEntity
  8
0
100
AcDbLine
 10
145.0
 20
55.0
 30
0.0
 11
115.0
 21
55.0
 31
0.0
  0
LINE
  5
59
100
AcDbEntity
  8
0
100
AcDbLine
 10
115.0
 20
55.0
 30
0.0
 11
115.0
 21
145.456439
 31
0.0
  0
LINE
  5
5C
100
AcDbEntity
  8
0
  6
CENTER
100
AcDbLine
 10
105.0
 20
175.0
 30
0.0
 11
105.0
 21
30.0
 31
0.0
  0
ARC
  5
5F
100
AcDbEntity
  8
0
100
AcDbCircle
 10
90.0
 20
200.0
 30
0.0
 40
60.0
100
AcDbArc
 50
294.624318
 51
324.314665
  0
ENDSEC
  0
SECTION
  2
OBJECTS
  0
DICTIONARY
  5
C
100
AcDbDiction
ary
  3
ACAD_GROUP
350
D
  3
ACAD_MLINES
TYLE
350
E
  0
DICTIONARY
  5
D
102
{ACAD_REACT
ORS
330
C
102
}
100
AcDbDiction
ary
  0
DICTIONARY
  5
E
102
{ACAD_REACT
ORS
330
C
102
}
100
AcDbDiction
ary
  3
STANDARD
350
1C
  0
MLINESTYLE
  5
1C
102
{ACAD_REACT
ORS
330
E
102
}
100
AcDbMlineSt
yle
  2
STANDARD
 70
     0
  3

 62
     0
 51
90.0
 52
90.0
 71
     2
 49
0.5
 62
   256
  6
BYLAYER
 49
-0.5
 62
   256
  6
BYLAYER
  0
ENDSEC
  0
EOF
```

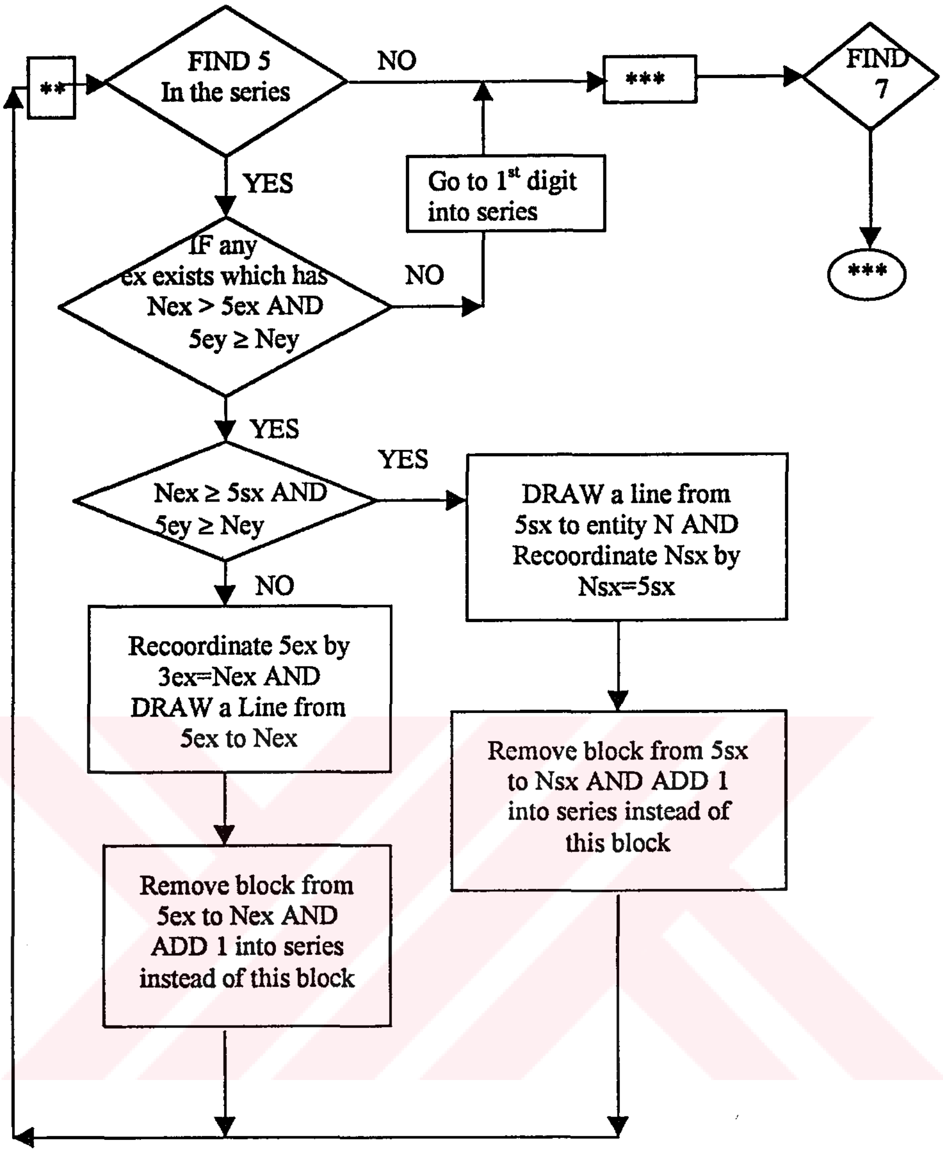
APPENDIX B1

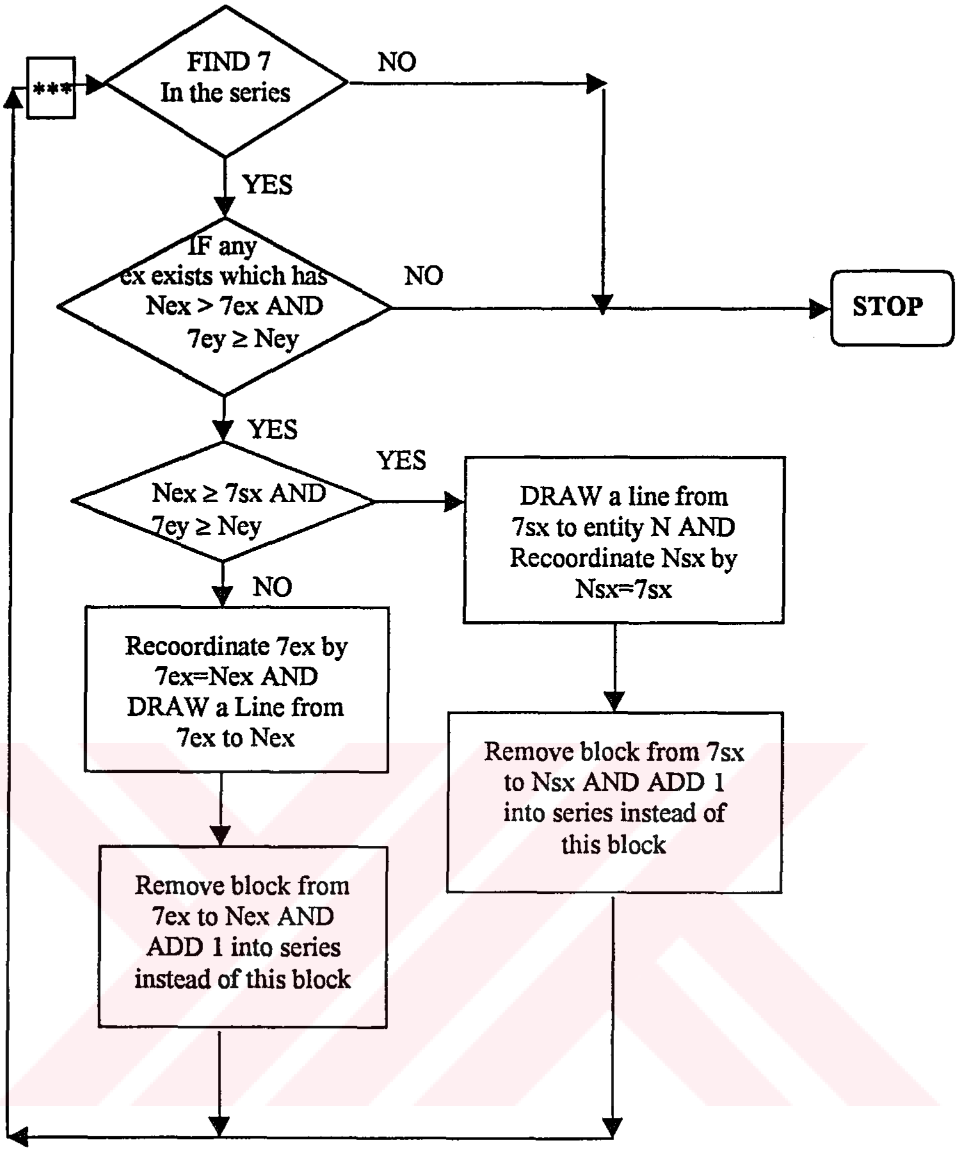
FORGEABLE GEOMETRY FLOWCHART FOR OUTER SIDE





*
FIND 9
In the series
NO
**
FIND
5
FIND
7
YES
Go to 1st digit
into series
IF any
ex exists which has
Nex > 9ex AND
9ey ≥ Ney
NO
**
YES
YES
Nex ≥ 9sx AND
9ey ≥ Ney
DRAW a line from
9sx to entity N AND
Recoordinate Nsx by
Nsx=9sx
NO
Recoordinate 9ex by
3ex=Nex AND
DRAW a Line from
9ex to Nex
Remove block from 9sx
to Nsx AND ADD 1
into series instead of
this block
Remove block from
9ex to Nex AND
ADD 1 into series
instead of this block

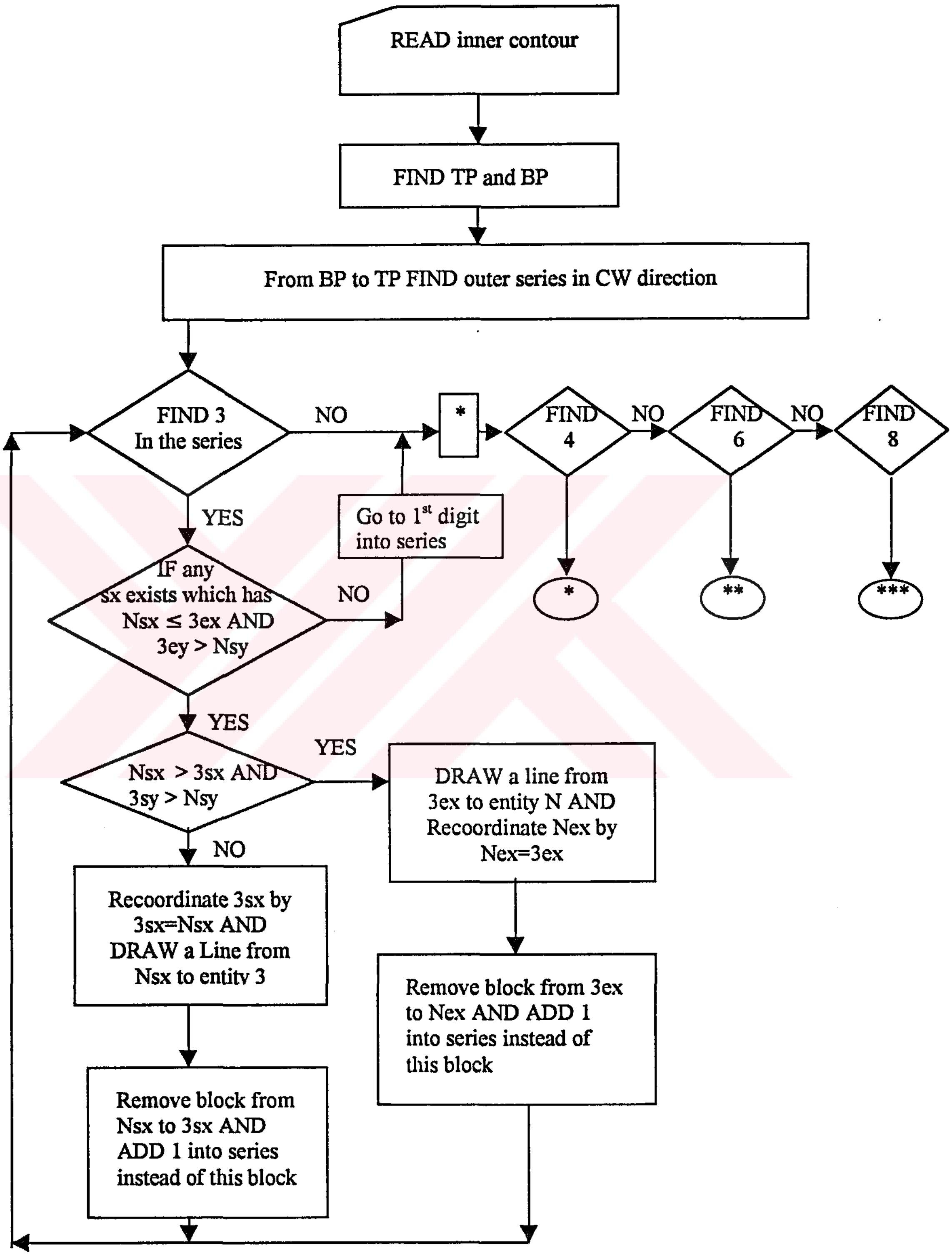

**
FIND 5
In the series
NO
***
FIND
7
YES
Go to 1st digit
into series
***
IF any
ex exists which has
Nex > 5ex AND
5ey ≥ Ney
NO
YES
YES
Nex ≥ 5sx AND
5ey ≥ Ney
DRAW a line from
5sx to entity N AND
Recoordinate Nsx by
Nsx=5sx
NO
Recoordinate 5ex by
3ex=Nex AND
DRAW a Line from
5ex to Nex
Remove block from 5sx
to Nsx AND ADD 1
into series instead of
this block
Remove block from
5ex to Nex AND
ADD 1 into series
instead of this block

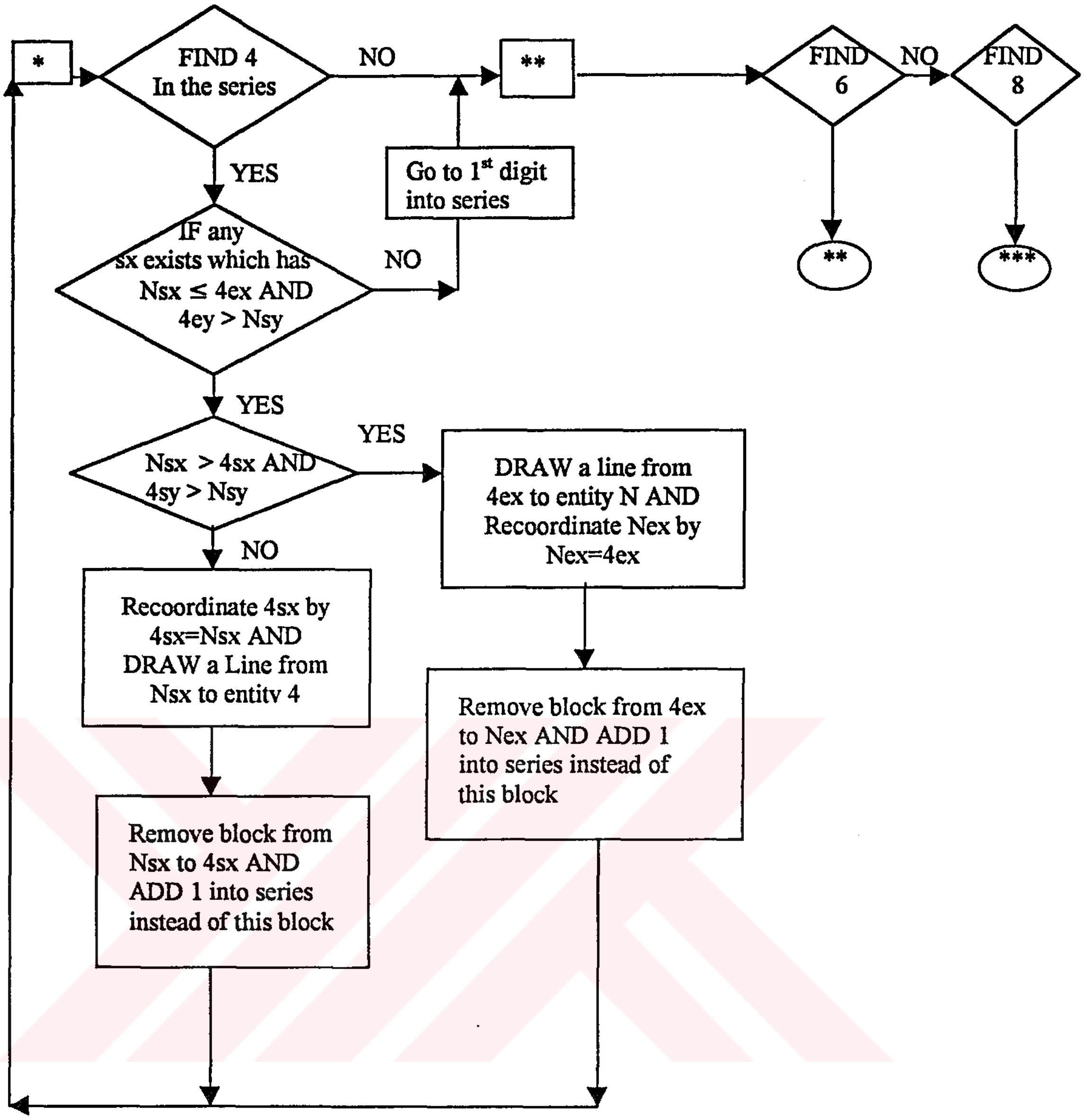


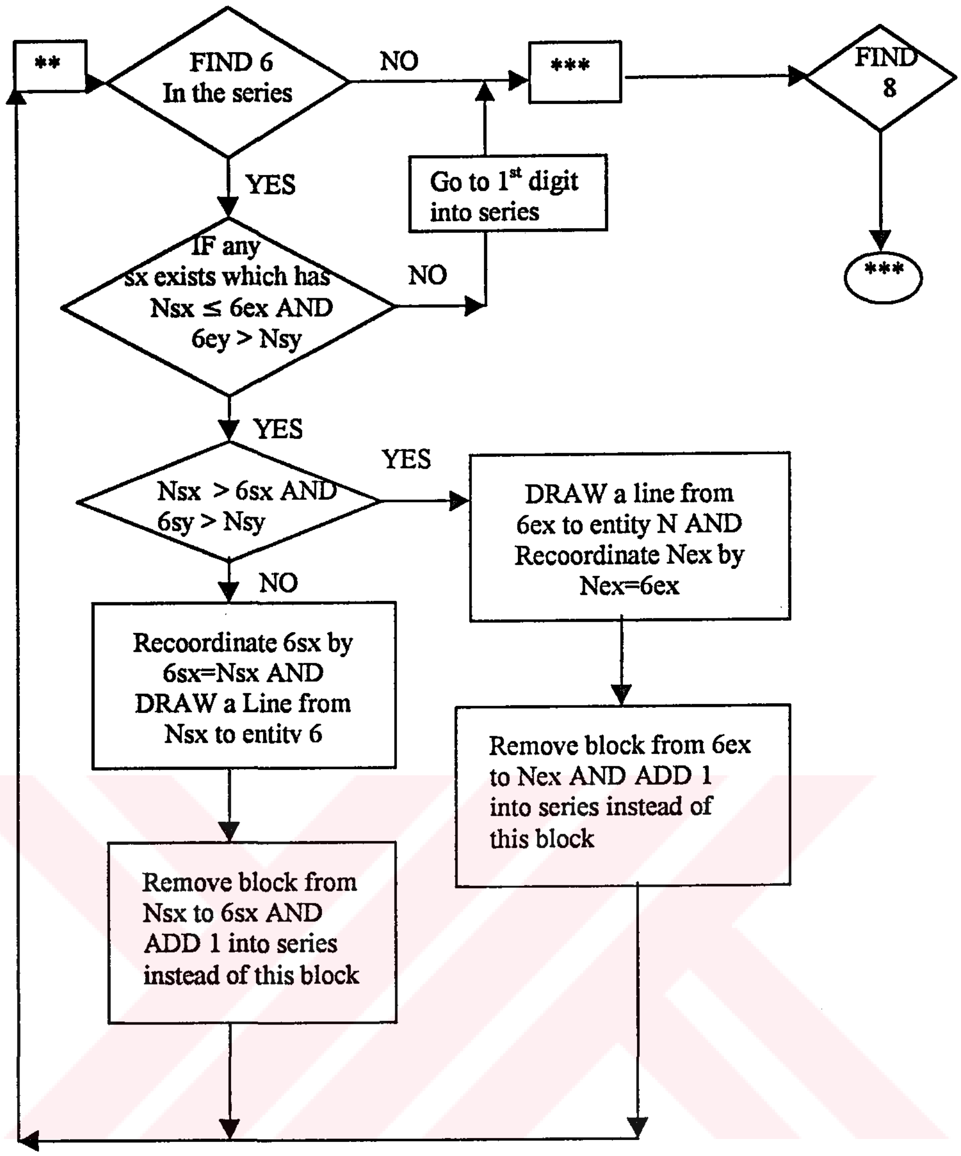
***
FIND 7
In the series
NO
YES
IF any
ex exists which has
Nex > 7ex AND
7ey ≥ Ney
NO
STOP
YES
Nex ≥ 7sx AND
7ey ≥ Ney
YES
DRAW a line from
7sx to entity N AND
Recoordinate Nsx by
Nsx=7sx
NO
Recoordinate 7ex by
7ex=Nex AND
DRAW a Line from
7ex to Nex
Remove block from 7sx
to Nsx AND ADD 1
into series instead of
this block
Remove block from
7ex to Nex AND
ADD 1 into series
instead of this block

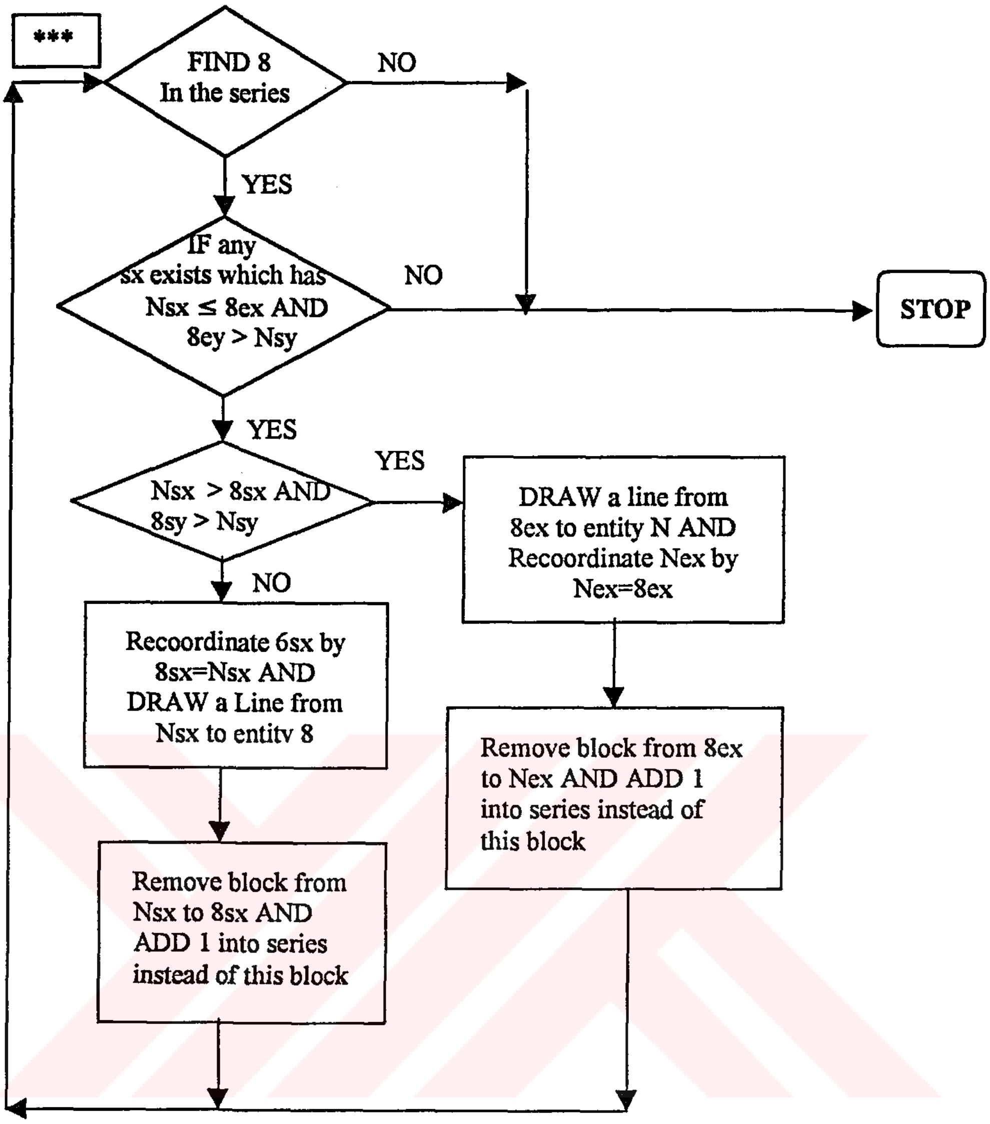
APPENDIX B2

FORGEABLE GEOMETRY FLOWCHART FOR INNER SIDE




*
FIND 4
In the series
NO
**
FIND
6
NO
FIND
8
YES
Go to 1st digit
into series
**
***
IF any
sx exists which has
Nsx ≤ 4ex AND
4ey > Nsy
NO
YES
YES
Nsx > 4sx AND
4sy > Nsy
DRAW a line from
4ex to entity N AND
Recoordinate Nex by
Nex=4ex
NO
Recoordinate 4sx by
4sx=Nsx AND
DRAW a Line from
Nsx to entitv 4
Remove block from 4ex
to Nex AND ADD 1
into series instead of
this block
Remove block from
Nsx to 4sx AND
ADD 1 into series
instead of this block

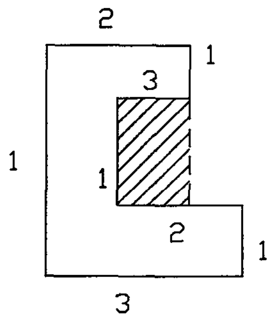

**
FIND 6
In the series
NO
***
FIND
8
YES
Go to 1st digit
into series
***
IF any
sx exists which has
Nsx ≤ 6ex AND
6ey > Nsy
NO
YES
YES
Nsx > 6sx AND
6sy > Nsy
DRAW a line from
6ex to entity N AND
Recoordinate Nex by
Nex=6ex
NO
Recoordinate 6sx by
6sx=Nsx AND
DRAW a Line from
Nsx to entitv 6
Remove block from 6ex
to Nex AND ADD 1
into series instead of
this block
Remove block from
Nsx to 6sx AND
ADD 1 into series
instead of this block


***
FIND 8
In the series
NO
YES
IF any
sx exists which has
Nsx ≤ 8ex AND
8ey > Nsy
NO
STOP
YES
Nsx > 8sx AND
8sy > Nsy
YES
DRAW a line from
8ex to entity N AND
Recoordinate Nex by
Nex=8ex
NO
Recoordinate 6sx by
8sx=Nsx AND
DRAW a Line from
Nsx to entitv 8
Remove block from 8ex
to Nex AND ADD 1
into series instead of
this block
Remove block from
Nsx to 8sx AND
ADD 1 into series
instead of this block

APPENDIX C

FORGEABLE GEOMETRY RULES

RULE-32-A



IF $3sx \leq 2ex$

THEN
- Remove codes from 3 to 2 (except 2) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

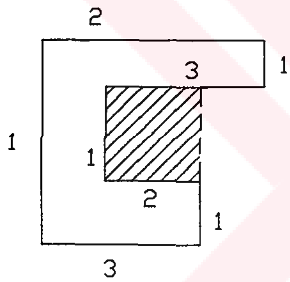
$1sx=3sx$ $1sy=3sy$

$1ex=3sx$ $1ey=2ey$ AND

- Change sx value of code 2 by the following:

$2sx=3sx$

RULE-32-B



IF $3sx > 2ex$

THEN
- Remove codes from 3 to 2 (except 3) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

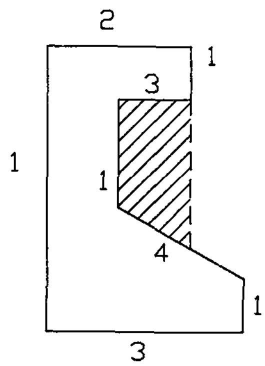
$1sx=2ex$ $1ex=2ex$ AND

$1sy=3sy$ $1ey=2ey$

- Change ex value of code 3 by the following:

$3ex=2ex$

RULE-34-A



IF $3sx \leq 4ex$

THEN
- Remove codes from 3 to 4 (except 4) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

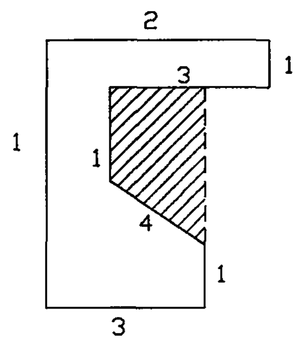
$1sx=3sx$ $1ex=3sx$ $1sy=5sy$ AND

$$1ey = 4ey + \left[\frac{(4sy - 4ey).(4ex - 3sx)}{4ex - 4sx}\right]$$

- Change sx and sy value of code 4 by the following:

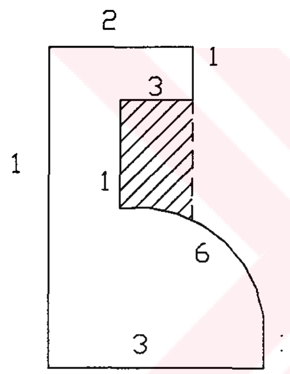
$4sx=3sx$ $4sy=1ey$

RULE-34-B



IF	3sx > 4ex	
THEN	• Remove codes from 3 to 4 (except 3)	AND
	• Add 1 instead of removed codes	AND
	• Coordinate 1, by the following:	
	1sx=4ex 1ex=4ex	AND
	1sy=3sy 1ey=4ey	
	• Change ex value of code 3 by the following:	
	3ex=4ex	

RULE-36-A

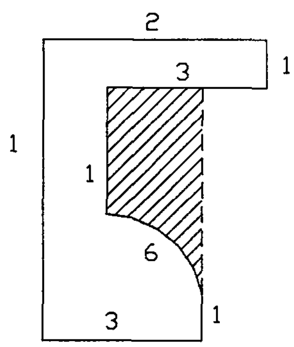


IF	$3sx \leq 6ex$	
THEN	• Remove codes from 3 to 6 (except 6)	AND
	• Add 1 instead of removed codes	AND
	• Coordinate 1, by the following:	
	1sx=3sx 1ex=3sx 1sy=3sy	AND
	$1ey = K6c20 + \sqrt{(K6c40)^2 - (3sx - K6c10)^2}$	

• Change sx and sy value of code 6 by the following:

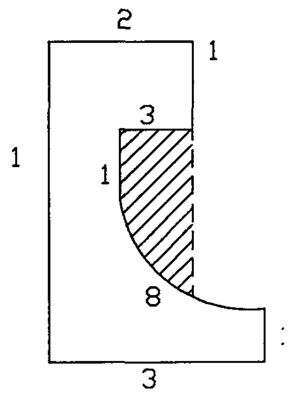
6sx=3sx 6sy=1ey

RULE-36-B



IF	3sx > 6ex	
THEN	• Remove codes from 3 to 6 (except 3)	AND
	• Add 1 instead of removed codes	AND
	• Coordinate 1, by the following:	
	1sx=6ex 1ex=6ex	AND
	1sy=3sy 1ey=6ey	
	• Change ex value of code 3 by the following:	
	3ex=6ex	

RULE-38-A



IF 3sx ≤ 8ex

THEN
- Remove codes from 3 to 8 (except 8) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

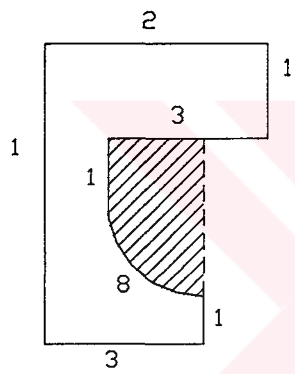
1sx=3sx 1ex=3sx 1sy=3sy AND

$$1ey = K8c20 - \sqrt{(K8c40)^2 - (K8c10 - 3sx)^2}$$

- Change sx and sy value of code 8 by the following:

8sx=5sx 8sy=1ey

RULE-38-B



IF 3sx > 8ex

THEN
- Remove codes from 3 to 8 (except 3) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

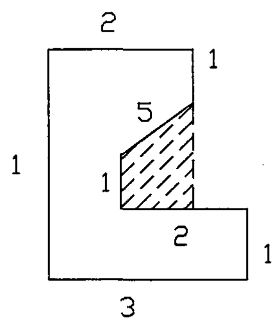
1sx=8ex 1ex=8ex AND

1sy=3sy 1ey=8ey

- Change ex value of code 3 by the following:

3ex=8ex

RULE-52-A



IF 5sx ≤ 2ex

THEN
- Remove codes from 5 to 2 (except 2) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

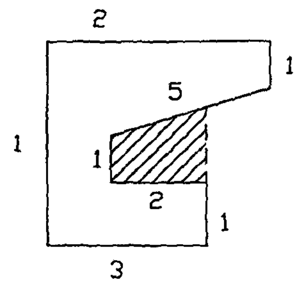
1sx=5sx 1sy=5sy

1ex=5sx 1ey=2ey AND

- Change sx value of code 2 by the following:

2sx=5sx

RULE-52-B



IF 5sx > 2ex

THEN
- Remove codes from 5 to 2 (except 5) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

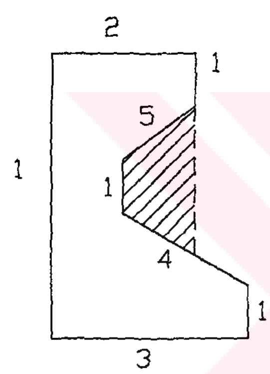
1sx=2ex 1ex=2ex 1ey=2ey AND

$$1sy = 5ey + \left[\frac{(2ex - 5ex) - (5sy - 5ey)}{5sx - 5ex} \right]$$

- Change ex and ey value of code 5 by the following:

5ex=2ex 5ey=1sy

RULE-54-A



IF 5sx ≤ 4ex

THEN
- Remove codes from 5 to 4 (except 4) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

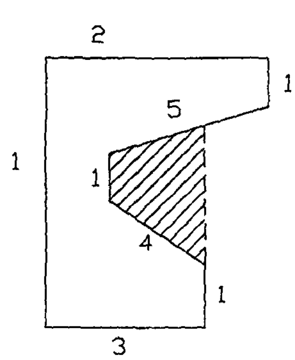
1sx=5sx 1ex=5sx 1sy=5sy AND

$$1ey = 4ey + \left[\frac{(4sy - 4ey).(4ex - 5sx)}{4ex - 4sx} \right]$$

- Change sx and sy value of code 4 by the following:

4sx=5sx 4sy=1ey

RULE-54-B



IF 5sx > 4ex

THEN
- Remove codes from 5 to 4 (except 5) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

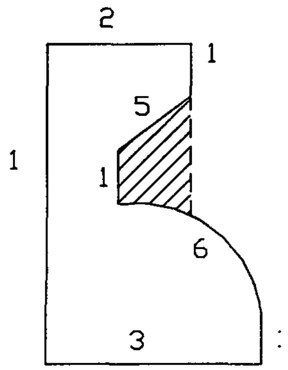
1sx=4ex 1ex=4ex 1ey=4ey AND

$$1sy = 5ey + \left[\frac{(4ex - 5ex).(5sy - 5ey)}{5sx - 5ex} \right]$$

- Change ex and ey value of code 5 by the following:

5ex=4ex 5ey=1sy

RULE-56-A



IF $5sx \leq 6ex$

THEN
- Remove codes from 5 to 6 (except 6) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

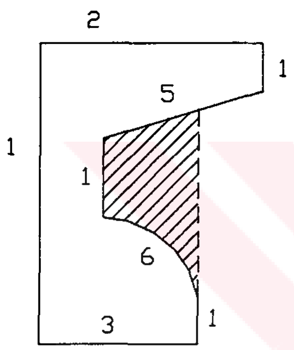
1sx=5sx 1ex=5sx 1sy=5sy AND

$$1ey = K6c20 + \sqrt{(K6c40)^2 - (5sx - K6c10)^2}$$

- Change sx and sy value of code 6 by the following:

6sx=5sx 6sy=1ey

RULE-56-B



IF $5sx > 6ex$

THEN
- Remove codes from 5 to 6 (except 5) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

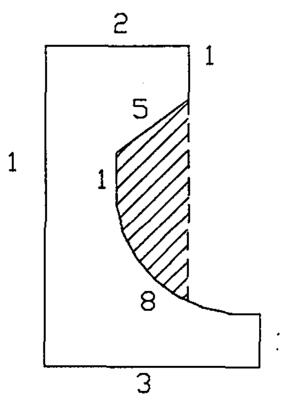
1sx=6ex 1ex=6ex 1ey=6ey AND

$$1sy = 5ey + \left[\frac{(6ex - 5ex).(5sy - 5ey)}{5sx - 5ex}\right]$$

- Change ex and ey value of code 5 by the following:

5ex=6ex 5ey=1sy

RULE-58-A



IF $5sx \leq 8ex$

THEN
- Remove codes from 5 to 8 (except 8) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

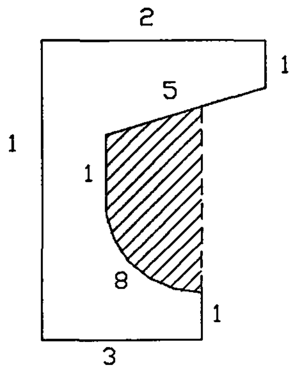
1sx=5sx 1ex=5sx 1sy=5sy AND

$$1ey = K8c20 - \sqrt{(K8c40)^2 - (K8c10 - 5sx)^2}$$

- Change sx and sy value of code 8 by the following:

8sx=5sx 8sy=1ey

RULE-58-B



IF 5sx > 8ex

THEN
- Remove codes from 5 to 8 (except 5) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

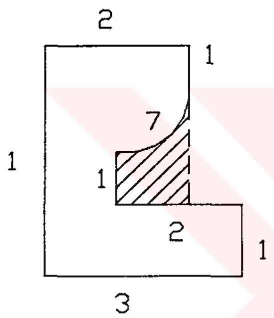
1sx=8ex 1ex=8ex 1ey=8ey AND

$$1sy = 5ey + \left[\frac{(8ex - 5ex)(5sy - 5ey)}{5sx - 5ex}\right]$$

- Change ex and ey value of code 5 by the following:

5ex=8ex 5ey=1sy

RULE-72-A



IF 7sx ≤ 2ex

THEN
- Remove codes from 7 to 2 (except 2) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

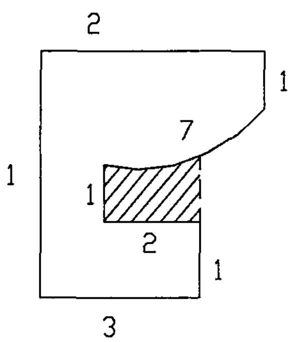
1sx=7sx 1sy=7sy

1ex=7sx 1ey=2ey AND

- Change sx value of code 2 by the following:

2sx=7sx

RULE-72-B



IF 7sx > 2ex

THEN
- Remove codes from 7 to 2 (except 7) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

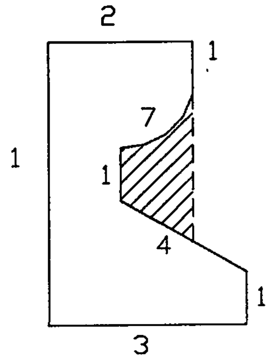
1sx=2ex 1ex=2ex 1ey=2ey AND

$$1sy = K7c20 - \sqrt{(K7c40)^2 - (2ex - K7c10)^2}$$

- Change ex and ey value of code 7 by the following:

7ex=2ex 7ey=1sy

RULE-74-A



IF $7sx \le 4ex$

THEN
- Remove codes from 7 to 4 (except 4) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

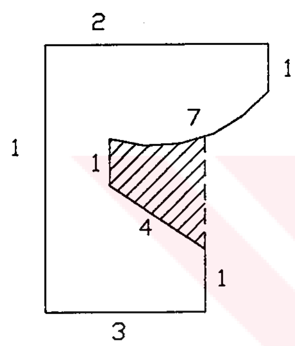
1sx=7sx 1ex=7sx 1sy=7sy AND

$$1ey = 4ey + \left[\frac{(4sy - 4ey).(4ex - 7sx)}{4ex - 4sx}\right]$$

- Change sx and sy value of code 4 by the following:

4sx=7sx 4sy=1ey

RULE-74-B



IF $7sx > 4ex$

THEN
- Remove codes from 7 to 4 (except 7) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

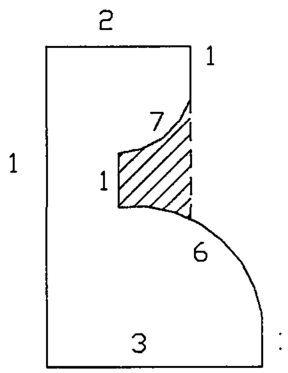
1sx=4ex 1ex=4ex 1ey=4ey AND

$$1sy = K7c20 - \sqrt{(K7c40)^2 - (4ex - K7c10)^2}$$

- Change ex and ey value of code 7 by the following:

7ex=4ex 7ey=1sy

RULE-76-A



IF $7sx \le 6ex$

THEN
- Remove codes from 7 to 6 (except 6) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

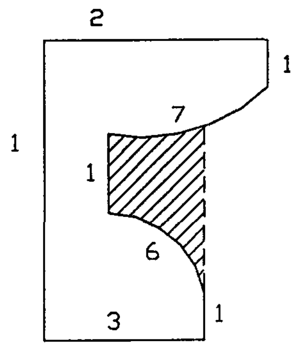
1sx=7sx 1ex=7sx 1sy=7sy AND

$$1ey = K6c20 + \sqrt{(K6c40)^2 - (7sx - K6c10)^2}$$

- Change sx and sy value of code 6 by the following:

6sx=7sx 6sy=1ey

RULE-76-B



IF 7sx > 6ex

THEN
- Remove codes from 7 to 6 (except 7) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

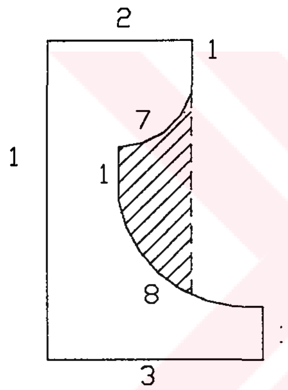
1sx=6ex 1ex=6ex 1ey=6ey AND

$$1sy = K7c20 - \sqrt{(K7c40)^2 - (6ex - K7c10)^2}$$

- Change ex and ey value of code 7 by the following:

7ex=6ex 7ey=1sy

RULE-78-A



IF 7sx ≤ 8ex

THEN
- Remove codes from 7 to 8 (except 8) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

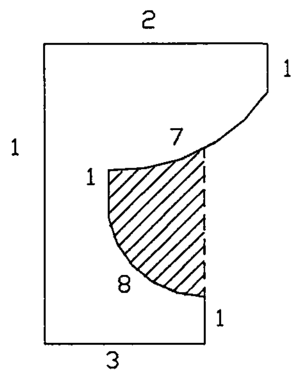
1sx=7sx 1ex=7sx 1sy=7sy AND

$$1ey = K8c20 - \sqrt{(K8c40)^2 - (K8c10 - 7sx)^2}$$

- Change sx and sy value of code 8 by the following:

8sx=7sx 8sy=1ey

RULE-78-B



IF 7sx > 8ex

THEN
- Remove codes from 7 to 8 (except 7) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

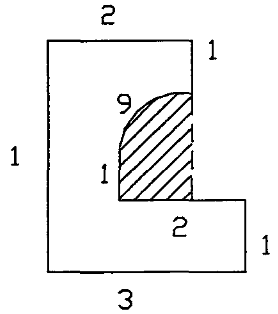
1sx=8ex 1ex=8ex 1ey=8ey AND

$$1sy = K7c20 - \sqrt{(K7c40)^2 - (8ex - K7c10)^2}$$

- Change ex and ey value of code 7 by the following:

7ex=8ex 7ey=1sy

RULE-92-A



IF 9sx ≤ 2ex

THEN
- Remove codes from 9 to 2 (except 2) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

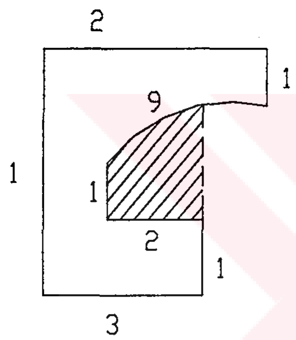
1sx=9sx 1sy=9sy

1ex=9sx 1ey=2ey AND

- Change sx value of code 2 by the following:

2sx=9sx

RULE-92-B



IF 9sx > 2ex

THEN
- Remove codes from 9 to 2 (except 9) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

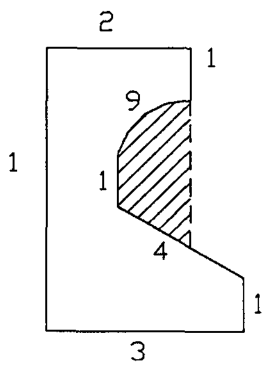
1sx=2ex 1ex=2ex 1ey=2ey AND

$$1sy = K9c20 + \sqrt{(K9c40)^2 - (K9c10 - 2ex)^2}$$

- Change ex and ey value of code 9 by the following:

9ex=2ex 9ey=1sy

RULE-94-A



IF 9sx ≤ 4ex

THEN
- Remove codes from 9 to 4 (except 4) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

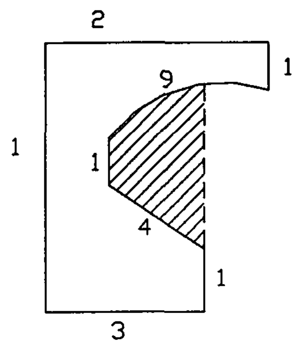
1sx=9sx 1ex=9sx 1sy=9sy AND

$$1ey = 4ey + \left[\frac{(4sy - 4ey).(4ex - 9sx)}{4ex - 4sx}\right]$$

- Change sx and sy value of code 4 by the following:

4sx=9sx 4sy=1ey

RULE-94-B



IF 9sx > 4ex

THEN
- Remove codes from 9 to 4 (except 9) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

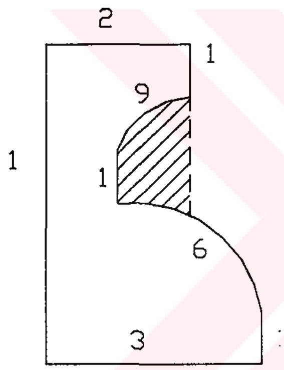
1sx=4ex 1ex=4ex 1ey=4ey AND

$$1sy = K9c20 + \sqrt{(K9c40)^2 - (K9c10 - 4ex)^2}$$

- Change ex and ey value of code 9 by the following:

9ex=4ex 9ey=1sy

RULE-96-A



IF 9sx ≤ 6ex

THEN
- Remove codes from 9 to 6 (except 6) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

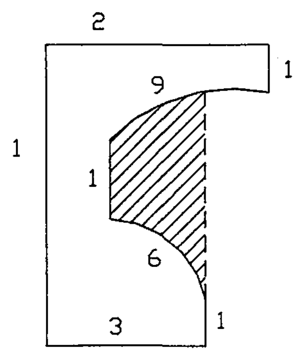
1sx=9sx 1ex=9sx 1sy=9sy AND

$$1ey = K6c20 + \sqrt{(K6c40)^2 - (9sx - K6c10)^2}$$

- Change sx and sy value of code 6 by the following:

6sx=9sx 6sy=1ey

RULE-96-B



IF 9sx > 6ex

THEN
- Remove codes from 9 to 6 (except 9) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

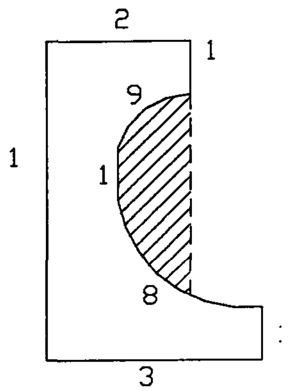
1sx=6ex 1ex=6ex 1ey=6ey AND

$$1sy = K9c20 + \sqrt{(K9c40)^2 - (K9c10 - 6ex)^2}$$

- Change ex and ey value of code 9 by the following:

9ex=6ex 9ey=1sy

RULE-98-A



IF $9sx \leq 8ex$

THEN
- Remove codes from 9 to 8 (except 8) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

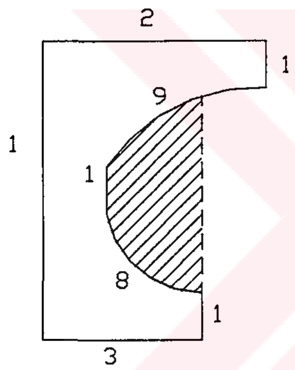
$1sx=9sx$ $1ex=9sx$ $1sy=9sy$ AND

$$1ey = K8c20 - \sqrt{(K8c40)^2 - (K8c10 - 9sx)^2}$$

- Change sx and sy value of code 8 by the following:

$8sx=9sx$ $8sy=1ey$

RULE-98-B



IF $9sx > 8ex$

THEN
- Remove codes from 9 to 8 (except 9) AND
- Add 1 instead of removed codes AND
- Coordinate 1, by the following:

$1sx=8ex$ $1ex=8ex$ $1ey=8ey$ AND

$$1sy = K9c20 + \sqrt{(K9c40)^2 - (K9c10 - 8ex)^2}$$

- Change ex and ey value of code 9 by the following:

$9ex=8ex$ $9ey=1sy$

APPENDIX D

DXF TABLE for FIGURE 10.8

0	9	40	9	$DIMTOFL	0
SECTION	$REGENMODE	1.0	$DIMTOH	70	9
2	70	9	70	1	$DIMSD2
HEADER	1	$DIMASZ	0	9	70
9	9	40	9	$DIMTVP	0
$ACADVER	$FILLMODE	2.5	$DIMSE1	40	9
1	70	9	70	0.0	$DIMTOLJ
AC1015	1	$DIMEXO	0		70
9	9	40	9	9	0
$ACADMAINT	$QTEXTMODE	0.625	DIMSE2	$DIMTIX	9
VER	70	9	70	70	$DIMTZIN
70	0	$DIMDLI	0	0	70
6	9	40	9	9	8
9	$MIRRTEXT	3.75	$DIMTAD	$DIMSOXD	9
$DWGCODEPA	70	9	70	70	$DIMALTZ
GE	1	$DIMRND	1	0	70
3	9	40	9	9	0
ANSI_1254	$LTSCALE	0.0	$DIMZIN	$DIMSAH	9
9	40	9	70	70	$DIMALTTZ
$INSBASE	1.0	$DIMDLE	8	0	70
10	9	40	9	9	0
0.0	$ATTMODE	0.0	$DIMBLK	$DIMBLK1	9
20	70	9	1	1	$DIMUPT
0.0	1	$DIMEXE	9		70
30	9	40	$DIMASO	9	0
0.0	$TEXTSIZE	1.25	70	$DIMBLK2	9
9	40	9	1	1	$DIMDEC
$EXTMIN	2.5	$DIMTP	9		70
10	9	40	$DIMSHO	9	2
100.0	$TRACEWID	0.0	70	$DIMSTYLE	9
20	40	9	1	2	$DIMTDEC
120.0	1.0	$DIMTM	9	ISO-25	70
□	9	40	$DIMPOST	9	2
30	$TEXTSTYLE	0.0	1	$DIMCLRD	9
0.0	7	9	9	70	$DIMALTU
9	Standard	$DIMTXT	$DIMAPOST	0	70
$EXTMAX	9	40	1	9	2
10	$CLAYER	2.5	9	$DIMCLRE	9
120.0	8	9	$DIMALT	70	$DIMALTTD
20	0	$DIMCEN	70	0	70
150.0	9	40	0	9	3
30	$CELTYPE	2.5	9	$DIMCLRT	9
0.0	6	9	$DIMALTD	70	$DIMTXSTY
9	ByLayer	$DIMTSZ	70	0	7
$LIMMIN	9	40	3	9	Standard
10	$CECOLOR	0.0	9	$DIMTFAC	9
0.0	62	9	$DIMALTF	40	$DIMAUNIT
20	256	$DIMTOL	40	1.0	70
0.0	9	70	0.03937007	9	0
9	$CELTSCALE	0	874016	$DIMGAP	9
$LIMMAX	40	9	9	40	$DIMADEC
10	1.0	$DIMLIM	$DIMLFAC	0.625	70
297.0	9	70	40	9	0
20	$DISPSILH	0	1.0	$DIMJUST	9
210.0	70	9	9	70	$DIMALTRND
9	0	$DIMTIH		0	40

 $DIMAZIN 70 0 9 $DIMDSEP 70 44 9 $DIMATFIT 70 3 9 $DIMFRAC 70 0 9 $DIMLDRBLK 1 9 $DIMLUNIT 70 2 9 $DIMLWD 70 -2 9 $DIMLWE 70 -2 9 $DIMTMOVE 70 0 9 $LUNITS 70 2 9 $LUPREC 70 4 9 $SKETCHINC 40 1.0 9 $FILLETRAD 40 10.0 9 $AUNITS 70 0 9 $AUPREC 70 0	9 $MENU 1 9 $ELEVATION 40 0.0 9 $PELEVATIO N 40 0.0 9 $THICKNESS 40 0.0 9 $LIMCHECK 70 0 9 $CHAMFERA 40 10.0 9 $CHAMFERB 40 10.0 9 $CHAMFERC 40 20.0 9 $CHAMFERD 40 0.0 9 $SKPOLY 70 0 9 $TDCREATE 40 2452438.67 9 $TDUCREATE 40 2452438.55 9 $TDUPDATE 40 2452438.68 9 $TDUUPDATE 40 2452438.55 9 $TDINDWG	40 0.00198715 28 9 $TDUSRTIME R 40 0.00198657 41 9 $USRTIMER 70 1 9 $ANGBASE 50 0.0 9 $ANGDIR 70 0 9 $PDMODE 70 0 9 $PDSIZE 40 0.0 9 $PLINEWID 40 0.0 9 $SPLFRAME 70 0 9 $SPLINETYP E 70 6 9 $SPLINESEG S 70 8 9 $HANDSEED 5 4F 9 $SURFTAB1 70 6 9 $SURFTAB2 70 6	9 $SURFTYPE 70 6 9 $SURFU 70 6 9 $SURFV 70 6 9 $UCSBASE 2 9 $UCSNAME 2 9 $UCSORG 10 0.0 20 0.0 30 0.0 9 $UCSXDIR 10 1.0 20 0.0 30 0.0 9 $UCSYDIR 10 0.0 20 1.0 30 0.0 9 $UCSORTHOR EF 2 9 $UCSORTHOV IEW 70 0 9 $UCSORGTOP 10 0.0	20 0.0 30 0.0 9 $UCSORGBOT TOM 10 0.0 20 0.0 30 0.0 9 $UCSORGLEF T 10 0.0 20 0.0 30 0.0 9 $UCSORGRIG HT 10 0.0 20 0.0 30 0.0 9 $UCSORGFRO NT 10 0.0 20 0.0 30 0.0 9 $UCSORGBAC K 10 0.0 20 0.0 30 0.0 9 $PUCSBASE 2 9 $PUCSNAME 2 9 $PUCSORG	10 0.0 20 0.0 30 0.0 9 $PUCSXDIR 10 1.0 20 0.0 30 0.0 9 $PUCSYDIR 10 0.0 20 1.0 30 0.0 9 $PUCSORTHO REF 2 9 $PUCSORTHO VIEW 70 0 9 $PUCSORGTO P 10 0.0 20 0.0 30 0.0 9 $PUCSORGBO TTOM 10 0.0 20 0.0 30 0.0 9 $PUCSORGLE FT 10 0.0 20 0.0 30 0.0 9

$PUCSORGRI	40	9	9	3	4E
GHT	0.0	$PLIMMAX	$LWDISPLAY	AutoCAD	330
10	9	10	290	2000	8
0.0	$USERR5	420.0	0	90	100
20	40	20	9	0	TableRecor
0.0	0.0	297.0	$INSUNITS	280	d
30	9	9	70	0	100
0.0	$WORLDVIEW	$UNITMODE	4	281	ableRecord
9	70	70	9	0	2
$PUCSORGFR	1	0	$HYPERLINK	0	*Active
ONT	9	9	BASE	CLASS	70
10	$SHADEDGE	$VISRETAIN	1	1	0
0.0	70	70	9	HOLDER	10
20	3	1	$STYLESHET	2	0.0
0.0	9	9	1	AcDbHolder	20
30	$SHADEDIF	$PLINEGEN	9	3	0.0
0.0	70	70	$XEDIT	AutoCAD	11
9	70	0	290	2000	1.0
$PUCSORGBA	9	9	1	90	21
CK	$TILEMODE	$PSLTSCALE	9	0	1.0
10	70	70	$CEPSNTYPE	280	12
0.0	1	1	380	0	148.5
20	9	9	0	281	22
0.0	$MAXACTVP	$TREEDEPTH	9	0	104.9
30	70	70	$PSTYLEMOD	0	13
0.0	64	3020	290	CLASS	0.0
9	9	9	1	1	23
$USERI1	$PINSBASE	$CMLSTYLE	9	LAYOUT	0.0
70	10	2	$FINGERPRI	2	14
0	0.0	Standard	2	AcDbLayout	5.0
9	20	9	9	3	24
$USERI2	0.0	$CMLJUST	$VERSIONGU	AutoCAD	5.0
70	30	70	ID	2000	15
0	0.0	0	2	90	5.0
9	9	9	9	0	25
$USERI3	$PLIMCHECK	$CMLSCALE	$EXTNAMES	280	5.0
70	70	40	290	0	16
0	0	20.0	1	281	0.0
9	9	9	9	0	26
$USERI4	$PEXTMIN	$PROXYGRAP	$PSVPSCALE	0	0.0
70	10	HICS	40	ENDSEC	36
0	1.0	70	0.0	0	1.0
9	20	1	9	SECTION	17
$USERI5	1.0	9	OLESTARTUP	2	0.0
70	30	$MEASUREME	290	TABLES	27
0	1.0	NT	0	0	0.0
9	9	70	0	TABLE	37
$USERR1	$PEXTMAX	1	ENDSEC	2	0.0
40	10	9	0	VPORT	40
0.0	-1.0	$CELWEIGHT	SECTION	5	212.423
9	20	370	2	8	41
$USERR2	-1.0	-1	CLASSES	330	1.828
40	30	9	0	0	42
0.0	-1.0	$ENDCAPS	CLASS	100	50.0
9	9	280	1	Table	43
$USERR3	$PLIMMIN	0	DICTIONARY	70	0.0
40	10	9	2	3	44
0.0	0.0	$JOINSTYLE	Dictionary	0	0.0
9	20	280		VPORT	50
$USERR4	0.0	0		5	0.0

51	5	73	100	100	74
0.0	14	0	TablRecord	Table	0
71	330	40	100	70	77
0	5	0.0	TablRecord	1	1
72	100	0	2	0	78
100	TablRecord	ENDTAB	Standard	APPID	8
73	100	0	70	5	140
1	TablRecord	TABLE	0	12	2.5
74	2	2	40	330	141
3	ByBlock	LAYER	0.0	9	2.5
75	70	5	41	100	143
1	0	2	1.0	Record	0.0393
76	3	330	50	100	147
0	72	0	0.0	Record	0.625
77	65	100	71	2	171
0	73	Table	0	ACAD	3
78	0	70	42	70	172
0	40	1	2.5	0	1
281	0.0	0	3	0	271
0	0	LAYER	txt	ENDTAB	2
65	LTYPE	5	4	0	272
1	5	10		TABLE	2
110	15	330	0	2	274
0.0	330	2	ENDTAB	DIMSTYLE	3
120	5	100	0	5	278
0.0	100	Record	TABLE	A	44
130	TablRecord	100	2	330	283
0.0	100	Record	VIEW	0	0
111	TablRecord	2	5	100	284
1.0	2	0	6	Table	8
121	ByLayer	70	330	70	340
0.0	70	0	0	1	11
131	0	62	100	100	0
0.0	3	7	Table	Table	ENDTAB
112	72	6	70	71	0
0.0	65	Continuous	0	0	TABLE
122	73	370	0	0	2
1.0	0	-3	ENDTAB	DIMSTYLE	BLKRECORD
132	40	390	0	105	5
0.0	0.0	F	TABLE	27	1
79	0	0	2	330	330
0	LTYPE	ENDTAB	UCS	A	0
146	5	0	5	100	100
0.0	16	TABLE	7	TablRecord	Table
0	330	2	330	100	70
ENDTAB	5	STYLE	0	TablRecord	1
0	100	5	100	2	0
TABLE	TableRecor	3	Table	ISO-25	BLKRECORD
2	d	330	70	70	5
LTYPE	100	0	0	0	1F
5	TableRecor	100	0	41	330
5	d	Table	ENDTAB	2.5	1
330	2	70	0	42	100
0	Continuous	1	TABLE	0.625	TablRecord
100	70	0	2	43	100
Table	0	STYLE	APPID	3.75	TablRecord
70	3	5	5	44	2
1	Solid line	11	9	1.25	ModelSpace
0	72	330	330	73	340
LTYPE	65	3	0	0	22

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0
BLK_RECORD
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1B
330
1
100
Record
100
Record
  2
Paper_Spac
e
340
1E
  0
BLKRECORD
  5
23
330
1
100
Record
100
Record
  2
Paper_Spac
e
340
26
  0
ENDTAB
  0
ENDSEC
  0
SECTION
  2
BLOCKS
  0
BLOCK
  5
20
330
1F
100
AcDbEntity
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0
100
BlockBegin
  2
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 10
0.0
 20
0.0
 30
0.0
```

```
3
ModelSpace
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ENDBLK
  5
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330
1F
100
Entity
  8
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100
BlockEnd
  0
BLOCK
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1C
330
1B
100
AcDbEntity
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  8
0
100
BlockBegin
  2
PaperSpace
 70
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 10
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0.0
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PaperSpace
  1

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1B
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  8
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BlockEnd
  0
BLOCK
```

```
5
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BlockBegin
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 10
0.0
 20
0.0
 30
0.0
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Paper_Spac
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ENDBLK
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BlockEnd
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  2
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```
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1F
```

```
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0.0
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0
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AcDbLine
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115.0
 21
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 31
0.0

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LINE
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1F
100
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100
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115.0
20
139.0
 30
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```
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LINE
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 21
125.0
 31
0.0
  0
LINE
  5
4A
330
1F
```

100	11	1	330	45	24
AcDbEntity	100.0	0	C	0.0	1.0
8	21	DICTIONARY	100	46	34
0	150.0	5	Dictionary	0.0	1.0
100	31	1A	281	47	15
AcDbLine	0.0	102	1	0.0	-1.0
10	0	{ACAD_REAC	0	48	25
115.0	ENDSEC	TORS	DICTIONARY	0.0	-1.0
20	0	330	5	49	35
125.0	SECTION	C	E	0.0	-1.0
30	2	102	102	140	146
0.0	OBJECTS	}	{REACTORS	0.0	0.0
11	0	330	330	141	13
115.0	DICTIONARY	C	C	0.0	0.0
21	5	100	102	142	23
120.0	C	Dictionary	}	1.0	0.0
31	330	281	330	143	33
0.0	0	1	C	1.0	0.0
0	100	3	100	70	16
LINE	Dictionary	Layout1	Dictionary	688	1.0
5	281	350	281	72	26
4B	1	1E	1	0	0.0
330	3	3	3	73	36
1F	GROUP	Layout2	Normal	0	0.0
100	350	350	350	74	17
AcDbEntity	D	26	F	5	0.0
8	3	3	100	7	27
0	LAYOUT	Model	WithDefaul		1.0
100	350	350	t	75	37
AcDbLine	1A	22	340	16	0.0
10	3	0	F	147	76
115.0	MLINESTYLE	DICTIONARY	0	1.0	0
20	350	5	LAYOUT	148	330
120.0	17	17	5	0.0	1B
30	3	102	1E	149	0
0.0	PLOTSETTIN	{ACAD_REAC	102	0.0	LAYOUT
11	GS	330	REACTORS	100	5
100.0	350	C	330	AcDbLayout	26
21	19	102	1A	1	102
120.0	3	}	102	Layout1	ACDREACTOR
31	PLOTSTYLEN	330	}	70	330
0.0	AME	C	330	1	1A
0	350	100	1A	71	102
LINE	E	Dictionary	100	1	}
5	0	281	PlotSettin	10	330
4C	DICTIONARY	1	gs	0.0	1A
330	5	3	1	20	100
1F	D	Standard	2	0.0	Settings
100	102	350	4	11	1
AcDbEntity	{ACAD_REAC	18	6	420.0	2
8	TORS	0	40	21	4
0	330	DICTIONARY	0.0	297.0	6
100	C	5	41	12	40
AcDbLine	102	19	0.0	0.0	0.0
10	}	102	42	22	41
100.0	330	REACTORS	0.0	0.0	0.0
20	C	330	43	32	42
120.0	100	C	0.0	0.0	0.0
30	Dictionary	102	44	14	43
0.0	281	}	0.0	1.0	0.0

44	12.0	330	147	0	6
0.0	21	1A	1.0	.0	BYLAYER
45	9.0	102	148	36	0
0.0	12	}	0.0	0.0	HOLDER
46	0.0	330	149	17	5
0.0	22	1A	0.0	0.0	F
47	0.0	100	100	27	102
0.0	32	Settings	AcDbLayout	1.0	
48	0.0	1	1	37	0
0.0	14	2	Model	0.0	EOF
49	0.0	4	70	76	ACADREACTO
0.0	24	6	1	0	RS
140	0.0	40	71	330	330
0.0	34	0.0	0	1F	E
141	0.0	41	10	0	102
0.0	15	0.0	0.0	MLINESTYLE	}
142	0.0	42	20	5	330
1.0	25	0.0	0.0	18	E
143	0.0	43	□	102	0
1.0	35	0.0	11	REACTORS	ENDSEC
70	0.0	44	12.0	330	
688	146	0.0	21	17	
72	0.0	45	9.0	102	
0	13	0.0	12	}	
73	0.0	46	0.0	330	
0	23	0.0	22	17	
74	0.0	47	0.0	100	
5	33	0.0	32	MlStyle	
7	0.0	48	0.0	2	
75	16	0.0	14	STANDARD	
16	1.0	49	0.0	70	
147	26	0.0	24	0	
1.0	0.0	140	0.0	3	
148	36	0.0	34	62	
0.0	0.0	141	0.0	256	
149	17	0.0	15	51	
0.0	0.0	142	0.0	90.0	
100	27	1.0	25	52	
Layout	1.0	143	0.0	90.0	
1	37	1.0	35	71	
Layout2	0.0	70	0.0	2	
70	76	1712	146	49	
1	0	72	0.0	0.5	
71	330	0	13	62	
2	23	73	0.0	256	
10	0	0	23	6	
0.0	LAYOUT	74	0.0	BYLAYER	
20	5	0	33	49	
0.0	22	7	0.0	-0.5	
11	102	75	16	62	
	REACTORS	0	1.0	256	
			26		

VITA

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