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To My Wife And My Parents

for all their supports and encouragement
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CHAPTER 1

INTRODUCTION

In manufacturing a discrete part by forging and subsequent machining, the first step is to design the forging*. This is done by modifying the given machined part geometry according to the requirements of the forging process. For this purpose, the necessary forging envelope, corner and fillet radii, and appropriate draft angles are added to the machined part geometry. Further, difficult to forge deep recesses and holes are eliminated and thin and tall ribs are thickened.

Traditionally, this is done by experienced forging designers using empirical forging design guidelines. Throughout the years, a great deal of know-how and experience has been accumulated, in the form of design guidelines, for designing forgings. The design guidelines, governing the geometry modification, vary depending on the type of forging (e.g., blocker-type, conventional, precision, etc.), material (e.g., steel, aluminum, titanium, etc.), equipment (e.g., hammer, mechanical press, hydraulic press, etc.), temperature (hot, cold, etc.), and production lot size, etc.

* Only geometrical aspects of the forging design are considered in this study. "Forging design" and "forging geometry design" are used interchangeably throughout this dissertation.
In recent years, the use of computers to aid design and manufacturing activities in forging has shown that the experience-based intuition and skill of designers can be considerably augmented by computerized analysis and design [1]. Computer-Aided Design (CAD) of forging geometry can now be carried out using interactive graphics [2], however, it is still the designer who provides the design expertise. The inability to computerize the forging design stems from the following major difficulties:

(a) Forging design requires many kinds of knowledge. Since forging process is affected by the type of equipment, material, and tooling used, knowledge about these processing parameters is required for designing forgings. This knowledge, available in the form of design guidelines, is mostly experience based. It consists of quantitative as well as qualitative criteria and the complexity of the design increases when interactions between design guidelines are considered or when conflicting design guidelines occur. The conventional algorithmic approach is weak in handling this type of complex problems.

(b) Forging design requires many problem solving techniques. These techniques can be roughly classified into two distinctive types. The first type deals with geometry manipulation, which is algorithmic in nature and computation intensive. The other type involves with forging design
related decision making (ie. design guidelines selection and application, based on process conditions and geometric complexity), which is symbolic in nature and knowledge and reasoning intensive. It is not sufficient to use only the conventional analytical techniques to computerize forging design.

(c) The process conditions and die design technology that influence the design of forgings change with the improvements of production facilities or advances in technology. The conventional algorithmic approach is too rigid when flexibility and adaptiveness of the system need to be considered.

Inspired by the needs for preserving the gradually disappearing forging design expertise due to attrition, retirement or death, an effort is thus made to develop an Automated Forging Design (AFD) system. The development of such an AFD system is also essential for an integrated Computer Aided Engineering (CAE) system for forging applications, as shown in Figure 1, since forging design represents the initial step in the such an integrated environment. Specifically, the objectives of the current study are to:

(1) capture and bring the experience based forging design knowledge into forging design;
CAD/CAM PROCEDURE OF FORGING DIE DESIGN

Figure 1. Simplified Block Diagram of an Integrated CAE System for Forging and Die Design [3].
(2) identify and incorporate the many kinds of problem solving techniques needed for forging design;

(3) develop and implement a flexible and adaptive AFD system that will design forging geometries automatically.

In view of the above objectives, it is apparent that the computerization of the experience based intuition and skill of forging designers requires an approach more powerful than the classical problem solving techniques. A new problem solving methodology, called "knowledge based systems" approach [4-7], that focuses on ways to bring expert knowledge to problem solving seems to offer a potential solution. The biggest advantage of using this methodology in the development of an AFD system is due to its separation of knowledge (design guidelines, or conversion rules) from the inference mechanism (application of design guidelines). The implication of this separation is that the forging design guidelines can be programmed separately from the geometry handling and the control of information flow. Thus, design guidelines which are a portion of this AFD program, being stored in a separate data base, can be added to or modified with minimal programming effort. In addition, the clarity of the program is enhanced since the rules are not intermixed with the flow control mechanism as in the conventional computer aided design approach.
While the knowledge based approach seems to offer a potential solution for computerizing forging design, many issues needed to be investigated. Among them, the representation of forging design knowledge and forging geometry, the control of forging design knowledge application, and the incorporation of different problem solving techniques are most critical. It is known that an effective representation of domain knowledge and the problem can facilitate easy problem solving. It is also known that an effective control scheme is essential in dealing with any complex tasks. Since many techniques are usually needed for solving a complex task, how to incorporate them in an effective fashion is very important. Thus, in the current study, these issues are addressed.

It would be neither possible nor practical to develop an AFD system which encompasses the design of all types of forgings. Thus, the initial development effort was concentrated on the computerization of the 2D section geometry design for the rib-web type of forgings (such as those shown in Figure 2), forged in closed dies with flash. By restricting the effort to 2D forging section design, the required geometric manipulations are greatly simplified. This 2D approach is logical since the design of forging is usually done in considering planes of metal flow [8], as shown in Figure 3. While the scope was limited in the initial effort, the development was generic in nature so that generalization is possible later.
A. WEB SURROUNDED BY RIBS

B. SERIES OF CROSS RIBS AND WEBS SURROUNDED BY RIBS

C. WEB SURROUNDED BY TAPERED RIBS

D. COMPLEX SHAPE WITH CROSS RIBS AND WEBS OF VARYING SIZES SURROUNDED BY RIBS

Figure 2. Types of Structural Forgings Representative of Increasing Levels of Forging Difficulty [8]
Figure 3. Planes and Directions of Metal Flow During Forging of Two Simple Shapes [8]

(a) Planes of flow, (b) finished forged shape
(c) directions of flow.
In chapter 2, the forging design principles and practices are first reviewed, followed by the discussions of factors that influence forging design. Chapter 2 ends with the discussion of the state of the art in forging design.

The roles of knowledge based systems in mechanical design are identified in Chapter 3. This chapter starts with the discussion of the common characteristics of mechanical design. It then covers the roles of knowledge based systems for mechanical design in general, and for forging design in specific.

Chapter 4 describes a conceptual framework for forging design. The forging design problem is first defined. The important properties of the forging design task are then examined. A model for forging design is proposed at the end of Chapter 4.

A knowledge based approach to forging design, based on the proposed model of chapter 4, is described in Chapter 5. The knowledge acquisition procedure for forging design is first discussed. The frame based and rule based schemes used in representing forging design knowledge and forging design specifications are then described. Next, a hybrid scheme for controlling the forging design process is introduced. The use of these representation and control schemes in performing forging design tasks is then described. Chapter 5 ends with the detail discussions of the basic design steps involved in an "evaluation-modification" cycle for forging design.
The implementation of an AFD and sample results are described in Chapter 6. Overall structure of the AFD system is first given, followed by the descriptions of the basic stages involved in running AFD. In addition, the input requirements and the output information provided by the AFD system are also described. Several forging designs obtained from the AFD are presented at the end of Chapter 6.

Chapter 7 gives the conclusions of this study. The current research is first summarized, followed by a brief description of the major findings from this study. The contributions of this research are then identified. Finally, recommendations for possible extension of this work and the use of knowledge based design approach for other geometry related design problems are given.
CHAPTER 2

FORGING DESIGN

Designing a mechanical component is essentially the process of creating a useful shape with specified properties, that can be produced at an acceptable cost. Forging design, similar to designs to be produced by other metalworking processes, is influenced by the nature of the metal being processed and the capabilities and limitations of the available production equipment. A completed forging design is represented using forging drawing, as shown in Figure 4.

2.1 FORGING DESIGN PRINCIPLES AND PRACTICES

As illustrated in Figure 4, when designing a forging, basic design considerations include the specification of the following:

- Location of parting line
- Orientation of forging plane
- Minimum finish allowance (forging envelope)
- Minimum web thickness
- Minimum rib width
- Draft Angle
- Minimum corner radii
- Minimum fillet radii
Figure 4. Typical Forging Drawing for a Forged Part [9]
As shown in Figure 5, each design consideration corresponds to a key forging design feature that needs to be determined based on the forging material, the capabilities and limitations of the available production equipment, and the type of forging considered.

In the following sections, the design principles and practices of these key design features are briefly described. More detailed discussions can be found in [8-13].

2.1.1 Parting Line

Parting line refers to the planes of separation between the upper and lower parts of a closed die set. The selection of the parting line location and shape is one of the most important decisions in forging design. When selecting the parting line location, the obvious consideration is to allow ease of part removal following the forging operation. However, the choice of optimum parting line position also depends on many interrelated factors, such as selection of forging equipment, initial cost and ultimate wear of dies, the ease of forging, the grain flow, related mechanical properties, and the machining requirements for the finished part. Often, these factors may represent opposing requirements. In actual practice, the parting line is established usually, but not always, through the maximum periphery of the forged part. It may be straight or irregular.
Figure 5. Key Forging Design Features That Need to be Considered When Designing Forgings
Figure 6 illustrates a variety of simple shapes showing undesirable and preferred parting line locations. The preferred choice in Case 1 avoids deep impressions that might otherwise promote die breakage. The preferred choices in Cases 2 and 3 avoid side thrust which could cause die shift. In Case 4, the "satisfactory" location provides the least expensive method of parting, while the "preferred" location, produces the most desirable grain flow pattern. The choice in Case 5 is also based on grain-flow considerations. However, the "desirable" parting line location usually introduces manufacturing problems and is used only when grain-flow is critical in design.

2.1.2 Forging Plane

Forging plane refers to the plane perpendicular to the direction of ram stroke. Side thrusts in the dies are present if the parting line is not parallel to the forging plane. Thus, mismatch between the upper and lower die may occur. A general guideline to reduce side thrust is to locate the forging in the dies, in an inclined position with respect to the forging plane, as illustrated in Figure 7.

2.1.3 Finish Allowance

This design feature includes the machining and tooling allowances, length and width tolerances, and tolerances for die wear, die closure, mismatch, andstraightness. The finish allowance represents the amount of excess metal needed to surround the finished and assembly ready part shape for purpose of cleanup and machining. The
Figure 6. Schematic Diagram of Several Forging Shapes Illustrating Both Undesirable and Preferred Parting Line Locations [10]
Figure 7. If Possible, the Forging Plane Should be Positioned in Such a Way as to Eliminate Side Thrust During Forging [9]
tolerances, however, represent the permissible deviations from dimensional specifications. Figure 8 shows how these allowances are applied to the finished part to obtain the forging outline.

**Machining and tooling allowance**

A forging that is to be machined all over is given a minimum stock allowance to ensure that the machined part is contained in the forging. This stock allowance is applicable to all metals. This allowance is generally related to the largest dimension of the forging and is first applied over the entire finish machined forging before other allowances or tolerances.

**Length and Width Tolerance**

Length and width tolerances allow for variations in dimensions measured in a plane parallel to the parting line of the dies. These tolerances include allowances for shrinkage, die sinking and die polishing variations. They are usually 0.003 in. per inch and apply to all dimensions of length and width including diameters.

**Die Wear Tolerance**

Die dimensions vary as a result of grinding and polishing of the die cavity to repair operational damage or die wear. This damage includes gouges and scratches caused by tongs, abrasion caused by material flow during forging, plus damage caused by scale and lubricant
Figure 8. Forged Section Showing Application of Allowances and Tolerances. Magnitudes of Allowances and Tolerances are Exaggerated for Ease in Reading Illustration [11].

(Note: Draft Allowance is Treated as a Separate Design Feature in the Current Study).
Die wear varies according to the material being forged. It is not necessary to add an allowance for die wear to the forging envelope since the finished part can always be obtained as the forging "grows" larger as the dies wear out.

Die Closure Tolerance

Die closure tolerances allow for thickness variations of forging as affected by the closing of forging dies. They represent the variation in any dimension crossing the parting line of the forging and are applied in a direction perpendicular to the major forging plane. The required tolerances generally depend on the type of metal being forged and the total plan area at the parting line.

Mismatch Tolerance

Mismatch tolerances apply to the axial alignment of two opposing impression dies. These tolerances are a measure of the lateral displacement of a point in one die from a corresponding point in the opposite die in any direction parallel to the forging plane. Mismatch tolerances are applied separately and are independent of all other tolerances. They are based on the weight and/or overall length of the forging.
Straightness Tolerance

Straightness tolerances allow for slight and gradual deviations of surfaces and center lines from the specified contour, which may result from post-forging operations, such as trimming, cooling from forging and heat treating. Straightness tolerances are applied to all surfaces except ends. The required tolerances generally depend on the type of metal and the shape of part being forged.

2.1.4 Web Thickness

The web of a forging is the relatively thin, plate-like element of the forging that lie between, and serves to connect, ribs and other forged elements projecting from surfaces of the web. While a small reduction in thickness of large webs accounts for sizable forging weight reduction, thin webs require considerably greater forging pressure than heavier sections because they are exposed to greater frictional forces per unit volume, and also because they cool more rapidly. Thus, there are practical limits on the minimum web thicknesses. Generally speaking, the minimum dimensions of webs depend on the size of the forging (expressed as projected plan area at the parting line) and on the average web width. Webs usually have a width-to-thickness ratio less than 3. When forging webs which have a width-to-thickness ratio approaching 3 to 1, the die pressure can be substantially decreased by tapering the web to open in the direction of lateral metal flow, as shown in Figure 9.
Figure 9. Design of Web Geometry to Reduce Die Pressure [13]
2.1.5 Rib Width

A rib is a wall-like projection that is located either at the periphery or on the inside of a forging. The producibility of ribs depends mainly on their height and width. A higher and thinner rib usually requires greater forging pressure. The width limits on thin ribs are imposed in much the same manner as those for webs. They are influenced by the metal being forged and by the forging geometry. The choice of fillet radii and location of the rib play important roles in forging a sound, vertical rib. The location of the parting line also influences the possible rib geometry. In general, the rib height should not exceed eight times the rib width. Most forging companies prefer to work with rib height-to-width ratios between 4:1 and 6:1. In addition, a rib should never be wider than the thickness of the web from which it is forged. If attempted, the flow of material to fill the rib may cause a defect in the web opposite the based of the rib, as shown in Figure 10.

2.1.6 Draft Angle

Draft refers to the taper given to internal and external sides of a closed die forging to facilitate its removal from the die cavity, and in certain instances, to aid in achieving desired metal flow. Draft is normally expressed as an angle from the direction of ram stroke. Depending upon the workpiece material and the forging equipment used, draft angles vary. The most common draft angles are 3 degrees for materials such as aluminum and magnesium and 5 to 7 degrees for steels
Figure 10. Forging Defect will Occur if Rib Width ($W$) is Greater Than Web Thickness ($T$) [13]
and titanium. For steel forgings, it is common to apply a smaller draft angle on the outside surface than on the inside, because the outside surface will shrink away from the die during cooling and permit removal of forging. Whenever possible, constant standard draft angles are adopted for reducing die design and manufacturing cost. In addition, by changing the location of parting line and the orientation of forging plane, a forging may have natural draft. This is illustrated in Figure 11. By taking advantage of the natural draft, the amount of metal removal required can thus be reduced.

2.1.7 Corner radius

A corner radius is formed by the intersection of two surfaces with an included angle (within the forging) that is less than 180 degrees, or excluded angle (outside the forging) that is greater than 180 degrees. Sharp corner radii usually cause premature die failure and require greater forging pressures to fill the die cavity. A general guideline is to establish a minimum radius based on the height of the rib from the parting line. Because of the differences in forging characteristics, the magnitude of the minimum corner radii depend upon the material of the forging. Figure 12 shows the recommended size of corner radius for aluminum forgings. Whenever possible, the same corner radii are adopted on all corners of a given forging in order to reduce die machining costs and larger radii are used at rib ends to permit cavity fill without excessive difficulty.
a. Natural draft inherent in part design

b. Natural draft provided by changing parting line

Figure 11. Several Typical Shapes Exhibiting Natural Draft [10]
Figure 12. Recommended Size of Corner Radius for Aluminum Forgings [9]
2.1.8 Fillet Radius

A fillet radius is formed by the intersection of two surfaces with an included angle (within the forging) that is greater than 180 degrees, or excluded angle (outside the forging) that is less than 180 degrees. Liberal fillets on forgings permit the forging stock to flow along the die contours more easily during the forging process. The sizes of fillet radii required are governed by the step height from the surface where the fillet occurs to the adjoining surface level. Again, the minimum fillet radii differ among materials. Figure 13 shows the recommended size of fillet radius for aluminum forgings.

2.2 FACTORS INFLUENCING FORGING DESIGN

Many factors influence the design of the key design features described in the previous section. These factors include:

- Forging type (precision, conventional, blocker, etc.)
- Forging material (aluminum, titanium, etc.)
- Forging geometry (complexity, thickness of ribs & webs, etc.)
- Forging equipment (hammer, mechanical or hydraulic press)
- Forging and die temperature
- Production lot size

In the following sections, the effects of these factors on forging design are briefly described. More detailed discussions on this subject can be found in [2,8,10-12].
Figure 13. Recommended Size of Fillet Radius for Aluminum Forgings [9]
2.2.1 Forging Type

Forging designs can be classified into four general categories: (1) Blocker type designs; (2) Conventional designs; (3) Close tolerance designs; and (4) Precision designs.

The first three categories represent designs that are progressively closer to the finish machined part outline, and accordingly, progressively require an increasing number of die impressions and forging steps. The blocker types are used primarily for limited quantity aircraft applications and are characterized by generous contours, large radii, draft angles of 7 degrees or more, and liberal finish allowances. The conventional designs have more refined details, standard draft (3 to 7 degrees), smaller radii and finish allowances, and specific dimensional tolerances that can be achieved on most conventional forging equipment. Close tolerance designs are generally considered as those having shallow draft (3 degrees), little or no finish allowance, and dimensional tolerances of less than half those specified for conventional designs. Close tolerance forgings are normally forged in conventional equipment but usually require complex tooling and added operations such as coining.

Precision forgings are engineered and tolerated to require little, if any, subsequent processing. They are characterized by 0 to 1 degree draft angles, thin sections, small radii, and excellent surface condition, and often feature multiple parting lines, permitting optimum grain flow control. Precision forging usually requires the use of split
tooling, special forging techniques, and specialized forging machinery.

2.2.2 Forging Material

In close die forging, a material must satisfy two basic requirements: (a) the flow strength must be low so that die pressures are kept within the capabilities of practical die materials and constructions, and (b) the forgeability must be adequate so that the material will undergo desired deformation without failure. For different materials, the flow strength and forgeability characteristics are different. Thus, the design of the above mentioned forging features is greatly influenced by the type of material to be forged. In general, the more difficult to forge a material is, the less shape definition a forging has. For example, owing to difficulties in forging, nickel alloys allow for less shape definition than aluminium alloys.

2.2.3 Forging Geometry

The main objective of forging design is to ensure adequate metal flow so that desired part geometry can be obtained without any external or internal defects. Metal flow is greatly influenced by part or die geometry. Often, several preforming operations are needed to achieve gradual flow of the metal from an initially simple shape into the more complex shape of the final forging. In general, spherical and blocklike shapes are the easiest to forge in impression dies, while parts with long, thin sections or projections (webs and ribs) are more difficult to forge because they have more surface area per unit volume.
Thus, the design of forging geometry is not only affected by the geometric properties (e.g., volume, plan view area, part length, etc.), but also complexity of the forging part. In addition, the design of forgings for structural shape is generally more complex than for axisymmetric shapes because "U" and "H" shaped rib and web portions are common to most of them.

2.2.4 Forging Equipment

Forging equipment can generally be categorized into two classes: hammers, and presses (mechanical, hydraulic, screw, etc.). While a hammer forces metal to assume the shape of the die cavities by the application of repeated blows, a press performs the same function with a single stroke. Many forging shapes can be produced by either hammers or presses, but the processing characteristics of each type of equipment influence: (a) the contact time between the material and the dies under load; (b) the rate of deformation; (c) the production rate; and (d) the part tolerances.

High forging speed, that is characteristic of hammers and mechanical presses, reduces die contact time, thereby reduces the chill effect. However, it increases the rate of deformation, thereby increases resistance to deformation in strain rate sensitive materials, offsetting the advantages of less die contact time. The longer die contact time that is characteristic of hydraulic press operations has a marked cooling effect on the workpiece, which increases resistance to deformation and therefore increases loads. However, in forging certain
deformation rate sensitive materials in dies with intricate contours, the slower speeds maintained under constant pressure can be advantageous. In many hydraulic presses, speed and pressure can be controlled. Because of the repetitive stroke position of the ram, the mechanical press provides opportunity for consistent forging results, and offers high productivity and accuracy without requiring for special operator skills.

Due to its influences on forging processes, the forging equipment greatly affects the design of forgings. Many forging design guidelines, such as those for finish allowance and draft angle requirements, are highly dependent of the equipment used for the forging operation.

2.2.5 Forging and Die Temperature

Flow strength and forgeability of a material are highly temperature dependent. In general, increasing forging temperature increases forgeability and decreases flow strength and therefore promotes or improves metal flow during forging. In addition, the use of heated dies improves die filling and reduces forging pressures. This is due to the fact that hot dies do not chill the surface layers of the workpiece so drastically. Consequently, the effects are more noticeable when dies are heated close to the workpiece temperatures. Temperature changes in the workpiece increase with time as well as with the temperature differential between the die and the billet. Therefore, heated dies offer more advantages when forging with hydraulic presses
than with hammers and mechanical presses.

Due to their effects on the metal flow behavior, the initial workpiece and die temperatures greatly influence the design of forgings. A more intricate part shape can be forged without causing forging defects if proper temperatures are selected. The initial temperatures also affect the tolerance specifications on the forging due to thermal expansion during forging and shrinkage after cooling.

2.2.6 Production Lot Size

The production lot size has a great effect on the specified tolerances. If the production size is large, die wear is the main reason for changing the dies. In this case, the forging is designed in such a way that relatively little material movement is allowed, so that the die wear is not significant. Nevertheless, it may be practical to build more elaborate tooling to eliminate the need for subsequent machining since the higher cost of tooling can be offset by the large number of parts, forged using that tooling.

If production lot size is small, die cost per forging become very significant since these costs need to be amortized over a small number of parts. As a result, some of the preforming steps may be eliminated. A generously contoured forging with liberal finish allowances and tolerances may be, in these cases, far more economical than a forging design that is closer to finish machined part.
Another important factor that will affect the forging design is the preform (or blocker) shape. In general, the design of preform (or blocker) shape is done based on the forging design. In actual practices, iterations between these two design activities may be necessary to ensure a sound forging design. In the current study, the forging design is considered to be "fixed" and not subject to change. Thus, the number and the geometry of the blocker shapes must be selected such that the desired forging can be produced.

As mentioned earlier, the effects of the above described factors upon the forging process are inter-dependent. For example, the forging temperature is generally determined by the forging material used. Thus, a forging designer needs to consider not only the individual effects of the process variables, but their combined effects as well.

2.3 THE ART OF FORGING DESIGN

Traditionally, forgings are designed by experienced forging designers. Starting from a finished part specification, including part geometry and processing conditions, a forging designer modifies the part geometry, section by section, to facilitate forging without increasing excessively material usage and machining. Based on empirical design rules, each key design feature is evaluated and established. The establishment of design features is an iterative process. From time to time, approximations need to be made for certain geometric parameters in order to establish certain design features. At a later stage, these
approximated parameters are evaluated to ensure their validity. The affected design features are then re-evaluated and re-established if necessary.

The task of forging design is best described with an example. An aluminum 7075 conventional forging for a pylon bulkhead fitting (Figure 14) is chosen from reference [11] as an example. After machining, this part has an overall length, width, and height of 8.76, 5.56 and 3 inches respectively. In addition, its plane view area is 40 square inches and its weight is 3.5 lbs. The forging geometry design for this part is briefly described below.

**Establish Parting Line**

The selection of the parting line locations is usually the first step in designing a forging from a machined part. It is common practice to establish the parting line through the center of the maximum periphery of the forging in order to avoid deep and narrow die impressions. A straight parting line is preferred to minimize die sinking costs. The mid-web location of the parting line on the example forging allows the use of a flat parting line. It is to be noted that the concept of webs does not materialize until the forging plane is established. Here, we made an assumption that the forging plane will also pass through the maximum periphery.
Figure 14. Perspective and Side Sectional Views of a Conventional Forging for Pylon Bulkhead Fitting (Machined Contours in Phantom) [11]
Establish Forging Plane

The forging plane is usually established based on the locations of the parting line. In this example part, the forging plane is established to be parallel to the parting line. The assumption made about the locations of webs in establishing the parting line seems reasonable. Thus, parting line needs not be re-established.

Determine Datum Planes

Mutually perpendicular datum planes are established in the length, width, and thickness directions as origins of dimensions for the forging. The so-called "tooling points" define the datums and are used as fixture contact points for dimensional inspection and subsequent machining operation. In the example part, the length and width datums are established at the outside surfaces of the side wall, and will be used as reference for calculating the shrinkage allowances. It is to be noted that the tooling points can not be determined until the forging envelope is established. Here, we are making an assumption about the location of the tooling points.

Estimate Forging Geometry Parameters

Forging allowances are usually established based on forging part geometry parameters (length, width, area, and weight). Since these parameters can not be computed until the forging design is completed, it is necessary to make an estimate of these parameters, at this stage,
based on the machined part geometry. These estimates need not be very accurate since the tolerances are based on broad variations of the parameters. But, it is necessary to check their validity later to ensure that correct forging allowances are included in the forging envelope.

Estimated overall forging length and width are generally obtained by adding an amount of stock to the machined part typical for the size forging being designed. In this example part, 0.15 inch is added to length and width directions. This addition gives an estimated overall length and width of the example part of 8.91 and 5.71 inches respectively. Based on these estimates, the forging plan view area can be approximated. In this example part, an estimated forging plan view area of 42 square inches is obtained.

It is very difficult to estimate the weight of the forging before the forging envelope is added. One way to circumvent this difficulty is to delay the approximation of the forging weight until the forging envelope is established. This is possible since forging weight is generally not the only factors that affect the allowance requirements. However, a check needs to be made at later stages of design to determine whether the forging weight has any effect on the forging allowances established.
Establish Forging Envelope

Once the parting line, the forging plane, and the datum planes are determined, preliminary forging allowances are added to the machined part geometry. This is generally done by considering each forging section individually. Based on the estimated forging geometry parameters (length, width, plan area) and empirical design rules, the forging designer applies machining, tooling, straightness, mismatch, die closure, and shrinkage allowances to all the sections in the form of a forging allowance envelope, as indicated in Figure 8. In this example part, an allowance of 0.2 inches is to be applied to all surfaces in length and width direction. An allowance of 0.165 inches is added to all unconfined web surfaces.

Establish Web Thickness

A check of the forging web thickness is made to ensure that all webs meet the minimum thickness requirements. The minimum web thickness varies depending on the forging difficulty of the material used. In this example part, a thickness of 0.25 inches is used as a minimum forgeable web thickness for AL7075. Since all webs meet this minimum requirement, no stock is added to the webs.
Establish Rib Width

Similar to web thickness, a check of the forging rib width is made to ensure that all ribs meet the minimum width requirements. In this example part, no change is necessary since all ribs meet the minimum requirement of 0.50 inches, and a maximum rib height-to-width ratio of 2.5 to 1.

Estimate Forging Weight

An approximate forging weight is calculated manually at this stage. A check is then made to ensure the established mismatch allowance, that is affected by the forging weight, is adequate. In this example part, the estimated forging weight (42 pounds) yields the same mismatch allowance requirement. Thus, no modification to the forging geometry is necessary.

Establish Corner Radii

Based on the heights of the ribs and the given material, a minimum corner radius is determined for all corners. In order to reduce the cost of frequent cutter changes during die sinking, a single minimum corner radius of 0.16 inches is selected for all corners in this example part.
Establish Draft Angle

To facilitate the removal of the forging from the dies, a minimum draft angle must be selected. This example part has an 8 degree draft angle on side ribs, where available, and a 3 degree draft angle elsewhere, except the blend draft shown in Figure 14 (section C-C).

Establish Fillet Radii

Based on the step heights of the ribs, a minimum fillet radius is determined for all fillets. For the example part, a minimum fillet radius of 0.5 inches is selected for all fillets.

Summary of Forging Design

At this point, all the key design features have been evaluated and modified if necessary. A final check is required to ensure the validity of the approximations and assumptions made during the design process. The geometric parameters are computed and they are checked against the design rules applied. In the example part, none of the actual forging parameters changes any of the allowances applied to the forging envelope. If any allowances had changed, the forging design would have been modified to reflect these changes and a new set of geometric parameters would be calculated. This iterative procedure is repeated until no design changes are found to be necessary.
As seen from the above example, the task of forging design involves not only geometry manipulation but also design decision making. Based on the part geometry and processing conditions, the designer selects and applies the most appropriate guidelines to design a key forging feature. The part geometry is then updated and the same procedure is repeated until all the design features are evaluated and established.

It should be noted that the design sequence described above is not unique. During the process of forging design, some key forging features may be designed independently of the others. For example, the design of the finish allowances generally does not affect the selection of the draft angle. However, there are restrictions on the sequence of design steps for other key design features. For example, the design of the draft angles can not be made until the forging plane orientation is determined.

Some restrictions on the design sequence are due to geometry modification considerations, that is, the design decision of a key forging feature does not affect that of the other feature. For example, the design of corner radii does not affect that of draft angles. However, corner radii are usually established before the draft angles since draft angles are generally established in such a way that they are tangent to the corner radii. Other design sequence restrictions are due to forging design considerations, that is, the decisions on a design feature do affect that of the other feature. For example, corner radii are determined based on rib heights which are in turn affected by the
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finish allowances. Thus, corner radii are generally established after the finish allowances are decided.

There are general guidelines for establishing a sequence for various forging design steps. However, such guidelines vary between individual designers and for various part geometries. For example, deep and narrow grooves in a machined part may be removed first by evaluating the minimum radii requirements prior to the application of various allowances. Another example involves the design sequence for the parting line and the forging plane. In order to allow natural drafts, the selection of forging plane orientation may be done before that of parting line locations. In addition, the design sequence is also affected by the design guidelines used. For example, if a design guideline, that determines the magnitude of corner radii based on the draft angle, is used, the draft angle may need to be determined first before the corner radii are evaluated and modified. Since forging design sequence affects the final forging geometry, the importance of establishing the design sequence can not be overlooked.

At present, Computer-Aided Design (CAD) of forging geometries can be carried out using interactive graphics, however, it is still the designer who provides the design expertise. That is, only the geometry manipulation activity is automated. In order to automate the forging design, the experienced-based and knowledge-intensive forging design decision making activities should also be computerized. The "knowledge based systems" approach seems to offer a potential solution. Due to the differences in computing requirements for automating these two distinct
activities, however, schemes for representing and manipulating part geometry, design knowledge and design activities must be investigated.
CHAPTER 3

KNOWLEDGE BASED DESIGN

The use of computers exhibits a trend of four ascending levels of sophistication [14]. Computers' initial use was for "data processing", in which number crunching is the major task. The next level was "information processing", in which related data items are processed in a structured manner. Semantic meanings are added into information items in "knowledge processing". The ultimate level, the "intelligence processing", will allow new knowledge to be acquired through computer learning from large scale knowledge data bases. For scientific and engineering applications, computers are still being used mostly for data processing and/or information processing. Nevertheless, knowledge and intelligent processing will be the main thrust for the years to come because no one can formulate at one time the enormous amount of knowledge needed, and also because sequential reasoning impedes optimization involving many parameters. To probe further the better use of computers in engineering design*, one needs to study the progress made by the Artificial Intelligence (AI) research.

The goal of AI is to develop computer programs that can solve problems normally thought to require human intelligence. AI differs

* Engineering design is, for the scope of this dissertation, restricted to problems in mechanical design in general and forging design in specific.
from the classical problem solving in the emphasis of symbolic reasoning, instead of numeric operations. Among the important techniques that emerged from early AI research were general methods for representing information in symbolic data structures, general methods for manipulating these structures, and heuristics for searching through them. The early hope that a relatively small number of powerful general mechanisms would be sufficient to generate intelligent behavior gradually waned when they fell short of providing a basis for constructing programs that solve complex practical problems such as mechanical design. The growing recognition of the many kinds of knowledge required, including general problem solving techniques and domain specific pragmatic knowhow, has led to the design and the use of knowledge based systems (KBS)* [7].

What distinguishes a KBS from an ordinary application program is, mainly, the separation of knowledge representation from its use. In most KBSs, the model of problem solving in the application domain is explicitly in view as a separate entity, or knowledge base, rather than appearing only implicitly as part of the coding of the program. This knowledge base is manipulated by a separate, clearly identifiable control strategy. Such a system architecture has the attraction of generality and a certain kind of modularity. Due to its strong emphasis

* The distinction between "knowledge based systems" and "expert systems" is not clear. An expert system can be defined as a computer program that uses knowledge and problem solving techniques on a skill level comparable to those of human experts. To reflect the emphasis of knowledge in these systems, the term "knowledge based system" is used in this dissertation.
on the task specific knowledge for solving the problem, a KBS is most valuable in experience based technologies, such as mechanical design, which rely on the judgement and experience of skilled designers for decision making. By capturing this experience in a systematic and logical manner, a KBS can provide permanent availability and wider accessibility of human expertise to industries at any given time.

While the KBS approach has been applied in various problem domains [6], most notably in diagnosis, little has yet been done in mechanical engineering design. Aquesbi, et al [15] describe a KBS for computer aided mechanical design based on pattern directed inference procedures. Their approach focuses on applying large amount of situation specific knowledge rather than a weak method (eg. generate and test) using general knowledge about the design task. Dixon and Simmons [16] describe a model based on "redesign" for doing mechanical design and illustrate it for a standard V-Belt drive design. Their approach, essentially "generate and test", generates an alternative design when a failure in a design occurs. Brown and Chandrasekaran [17] present a model based on "plan refinement" and illustrate it for an air cylinder design. Their approach focuses in structuring design knowledge in a hierarchical form for a limited class of routine design problems. Mittal, et al [18] extend Brown and Chandrasekaran's approach by incorporating a more powerful problem solver that can control the search through a large and complex design spaces in an efficient manner.
The techniques used in KBS are powerful in many ways and have proven successful in several applications. One question is: "What is the role of KBSs for mechanical design in general and for forging design in specific?". Before addressing this question, some special features of the mechanical design process that could affect the application of KBS technology are addressed.

3.1 Characteristics of Mechanical Design

Mechanical design is a highly complex activity, one for which AI has only relatively weak theories of, especially for more creative design activity. What makes the application of KBSs to mechanical design so difficult lies in the requirements of both large amount of domain specific knowledge as well as considerable problem solving skill. To cope with the complexity, a designer needs to factor the design into subtasks which are seldom independent.

Most of the mechanical design problems are ill-structured, that is, they lack well defined goals. Although some characteristics of the goal may be known (from design specifications), there is no unique solution. Due to the differences in acceptability criteria used, different designers will come up with different solutions, each with some strong points and some weaknesses, but all meeting the design specifications.
The mechanical design process involves iterative decision making. The solution to a problem results from integrating and satisfying all the constraints in a long series of decision making steps. Constraints are imposed or recognized during the course of the design. Thus, rough design and backtracking occur during this design process. From time to time, plausible assumptions need to be made in order to continue the design process. These assumptions must be checked to ensure their validity at the later stages of design. In addition, constraints need to be relaxed when all design fails.

The solution space of mechanical design problems are usually very large and tentative reasoning is very important because simplifying assumptions are frequently invoked to reduce the magnitude of the problem. Effective and efficient techniques for searching through the large solution space and reformulating the assumptions are required.

Analysis is usually a part of mechanical design. Designers have the option at any stage to investigate an available alternative in more detail. This investigation may take the form of minor debugging, refinement, modification, approximate engineering analysis, feasibility study, or the use of a formal, sophisticated technique such as finite element analysis (FEA). However, the analysis techniques are not always known or accessible to a designer and sometime not easy to use (eg. FEA). The process decisions of when, how and what to apply these analysis tools can have a great effect on the final design solution.
Many of the mechanical design problems require reasoning about spatial and geometrical properties of the system being design. This reasoning demands considerable computing resources and powerful representation schemes.

Last but not the least, human factors play very important roles in the mechanical design. A designer calls repeatedly on his experience, intuition, common sense, and engineering values during the process of design. These human factors must be taken into account as an integral part of the design process.

3.2 Roles for KBS in Mechanical Design

Given the diversity and complexity of the mechanical design tasks performed by designers, one needs to be explicit about the role of a computer based tool (eg. a KBS or a CAD system) in the overall spectrum of design tasks. Typically, the design of mechanical parts proceeds in stages [19]:

(1) Conceptual Design - decide the basic method and structure of the design solution;

(2) Basic Design - decide the layout and structure of the design solution;

(3) Detail Design - decide the minute specifications of the parts;

(4) Production Design - Generate the necessary data for the production;
The early stage deals with conceptual design, which involves selection of overall method, structure, environment, and functional requirements. The basic design stage deals with decomposing a large problem into more tractable sub-problems, finding partial solutions to the requirements, trying to satisfy different constraints and requirements, and modifying previous decisions. It is in these first two stages that the layout and structure of the design solution are synthesized and evaluated. The detail design stage involves making more commitments about the spatial and geometrical properties of the part being designed. During the production design stage, all the necessary data for the production (e.g., production method and schedule, tooling and material specifications, etc.) are generated. Before the part design is released for actual production, prototypes are built and tested to ensure the validity and feasibility of the design.

It is to be noted that the activities during each design stage are not just acted on and completed on their own before any other stage is considered. Each design stage reflects the general confidence building and problem solving nature of the design itself. Thus, such a process cannot be described as a set of sub-activities connected by unidirectional communications. The connections are instead seen as a network of communications - "pipelines" in which information flows continuously in both directions, between all elemental activities [20]. In addition, design analysis should be considered as an integral part of the design process. In order to investigate design alternatives and/or
to evaluate the design solutions (either partial or entire solution), various design analysis tools may be used. The design process is thus controlled by encouraging the rapid exchange of ideas and responses during all stages of design.

The development of computer based design techniques has been directed towards providing a complete geometric description of an object initially, and then moving on to the generation of manufacturing instructions. Systems are thus configured to represent and record the geometrical entities (e.g., geometry modeling systems), to confirm the proposed design (e.g., analysis tools for stress, kinematic, dynamics, etc.), and to generate the engineering information for production (e.g., drafting, NC tape generation, and process planning, etc). This approach to design recognizes only part of the role performed by the designer. Design is not simply the production of shapes, it is the development of those shapes to satisfy the functional requirements under various manufacturing constraints. Thus, in order to provide a better support for the designer, computer based design techniques must be developed to automatically generate design solutions and test against the major constraints of shape, function, and manufacturing. That is, design should be performed by the machine, but guided by the designer [21]. This human-aided machine design approach differs from the machine-aided design approach in which the human does the design and the machine provides support tools without understanding the design decision.
To automate the design process, one needs to understand the process better. To this purpose, better models of design need to be developed. Yoshikawa [22] presents two design models based on general design theory, with consideration of a real designer's memory structure. Mostow [21] suggests that a comprehensive model of design should address the representation of goals, states, decisions and rationales for decisions; control of the design process; and the role of learning in design. While developing better design models is the key research problem in AI-based design, the general consensus is the utilization of KBS approach in automating the design process.

The primary reason for using KBS approach in automating design is to facilitate the representation and manipulation of the many kinds of knowledge required for design in a unified manner. Due to the complex nature of the mechanical design process, it is not feasible, if not impossible, to formulate the entire design process using the conventional (algorithmic) approach. Thus, the KBS approach is expected to play a major role in capturing the "knowledge and reasoning intensive" nature of the mechanical design process. For example, KBS approach can be used to perform a knowledge-guided search to select overall structure of the design solution from a large space of possible structures based on the product requirements. A top down, knowledge-guided "design refinement" approach may be used to generate the structure of design solution by dynamically decomposing the design activities, exploring available design alternatives and evaluate design decisions based on the design requirements (shape, function,
manufacturing). The knowledge-guided control may be implemented to coordinate the design activities and direct the flow of the information between all activities.

3.3 Roles for KBS in Forging Process Design

Forging is a fine blend of art and science, requiring many critical decisions by the forging designer far in advance of actual part production. The design of the forging process proceeds in stages. Given a set of finished part specifications (including part geometry, material, desired mechanical properties, etc.), a forging designer first determines forging processing methods (e.g., upsetting, impression die forging, roll forging, etc.) and associated processing conditions (e.g., equipment, temperature, tolerances, etc.). Based on these design requirements, the forging geometry is then designed, followed by the design of finisher dies. If intermediate forging operations are required, the blockers and associated dies are designed. During the process of design, various analyses (e.g., Finite Element Analysis) are performed to ensure the validity of the forging and die designs, and/or to evaluate the alternative designs. Similar to any mechanical design, the forging design procedure iterates until a final design which satisfies all the constraints of part shape, function and manufacturing is obtained.
Although the application of computer aided design techniques in forging process design has shown progress in recent years [2], it is still limited to the use of commercially available CAD/CAM systems to model the part and die geometries and to prepare NC tapes for die sinking purpose, and the use of analysis tools to evaluate and validate forging designs. Similar to other mechanical design tasks, the forging process design is very complex and knowledge intensive. What distinguishes the forging process design from other mechanical designs is its use of large amount of highly experienced based knowledge. Due to its emphasis on the unified treatment in representing and utilizing different kinds of knowledge, the KBS approach is expected to make contributions in preserving the forging process design know-how that otherwise could be lost by attrition, retirement and death.

Specifically, KBSs may contribute to the forging process design in the following areas:

(1) Selection of forging method and appropriate processing conditions. A knowledge-guided search may be used to select the optimal (or sub-optimal) forging method based on the finished part requirements. The selection of optimal material processing conditions, such as die material, equipment, die speed, temperature, material interface, etc., requires good engineering judgement and experience. By integrating numerical analysis from various tools (eg. FEA) with symbolic reasoning from KBS, optimal conditions can be determined.
Effective and efficient search strategies may be needed in searching through various design databases, such as material database, design method database, etc.

(2) Design of forging geometry and finisher dies. To automate forging and finisher die design, the design knowhow needs to be computerized. The use of KBS approach for forging design is investigated in this study. The KBS approach may also be used to design flash requirements for finisher dies.

(3) Design of blocker and dies. The KBS approach may be used to determine the number of blocking operations required. For the design of blocker geometry, a current effort is being made [23]. Again, the flash design for blocker dies may be computerized by using KBS approach.

(4) Design of preform. While the volume of a preform can be obtained from that of the blocker, the design knowhow for optimal preform shape may be computerized by using KBS approach.

(5) Use of analysis tools. The critical problems in using analysis tools involve with "when to use", "what to use", and "how to use". Good engineering judgement is usually required to determine "when" to use "what" analysis tools. A pattern invoked approach may be used to address these problems. The
problem of "how to use" is very much dependent on the type of analysis tools to be used and how the analysis tool is designed. For FEM analysis, the preparation of the large amount of data is a tedious and sometime error prone process. This is especially true for defining the FEM mesh, which is very time consuming and skill intensive. Using KBS approach, this effort may be reduced. In addition, KBS approach may be used to interpret the FEM simulation results and make design or refinement recommendations.

The application of KBS to forging process design represents a new problem solving strategy for engineering problems. Due to the knowledge and computing intensive nature of forging process design, the use of KBS approach for this application needs to consider not only the representation and application of design knowledge, but also the incorporation of many different problem solving techniques. It is expected that the new strategy will preserve the gradually disappearing forging process design expertise, and advance the forging technology, which in turn will provide the much needed productivity gains for the forging industry.
CHAPTER 4

CONCEPTUAL FRAMEWORK FOR FORGING DESIGN

As discussed earlier, forging design is very complex and requires many kinds of knowledge and problem solving techniques. In this chapter, the forging design problem is first defined, followed by further examination of the significant properties of the forging design task. A conceptual forging design model is then proposed to guide the development of an Automated Forging Design (AFD) system.

4.1 Forging Design as a Geometry Design Task

The task of forging design is to modify the part geometry so as to satisfy the constraints imposed by the finished part shape and the forging operations based on specified processing conditions. During the process of modification, key forging design features, detailed in section 2.1, are evaluated and modified if necessary. The design of these key features are very knowledge intensive and usually affected by various interacting forging process parameters (eg. material, forging type, equipment, temperature, lot size, etc.), as described in section 2.2. The task of forging design is further complicated by the many possible design sequences of these key features, as described in section 2.3.
Forging design is similar to many mechanical design activities that involve the design of part geometries. Given the specifications of the desired finished part geometry and forging process conditions, a forging designer uses experience-based knowhow to generate an optimal forging part geometry that can be produced by the intended forging and subsequent machining operations. Depending on the design objectives, the criteria for an optimal forging design vary. For example, if material saving is the primary design goal, a set of design rules that facilitate close tolerance forging design is used. If better mechanical properties are required, a different set of design rules that produce good material flow is used.

As required by typical mechanical design activities, design iterations are also necessary for forging design. A forging design cycle starts with the selection of a basic layout of the forging design based on the design goals. Key design features are then evaluated and modified. The design cycle ends when all the key design features are established. If the completed forging design fails to meet the intended design goals, the same design cycle is repeated. This design process iterates until a satisfactory forging design is obtained.

Design iterations may also occur during each design cycle. Since most of the design rules used by the forging designers are based on parameters of the forging geometry, such as the forging length, weight, etc., plausible estimates need to be made for these parameters in order to start and continue the design process. At later stages of the design cycle, these parameters need to be checked and iterations may
be required to ensure the validity of the design. A designer generally refines, instead of redesigns, the forging geometry during the iterations. There are general rules for making estimates about these parameters and they may be viewed as rules for reducing design refinements, hence, design iterations.

Also similar to other design tasks, forging design requires the establishment of a design sequence. As described in section 2.3, a designer usually evaluates and modifies key forging design features in sequence. Since the order of forging design sequence affects the final forging design, the knowledge of how to establish a proper sequence of design tasks is important in forging design.

Due to its emphasis on the spatial and geometrical properties of the part being design, forging design should be treated as a geometry design task that contains elements of design constraint satisfaction, design iterations and establishment of a design sequence. While there are CAD tools that assist designers in creating and assessing forging geometry, it is the designer that provides the design expertise in generating the satisfactory design. Thus, the goal of this study is to computerize the forging design process. The main issue needed to be addressed in automating this process is how to capture, represent and utilize the geometry design and planning knowledge that reflects the essence of forging design process.
4.2 Characteristics of the Forging Design Task

As described in the previous section, forging design is a geometry design task. There are many other properties that distinguish forging design task from other type of design task. Some of them are unique, others are not. Although most of these properties were described earlier, important ones are summarized below for convenience of discussions.

Forging design task can be decomposed into subtasks, each corresponding to a key design feature described in section 2.1. While this decomposition reflects the way the designer performs the forging design, these subtasks are not independent. That is, the design decision made in one subtask may either directly or indirectly affect that to be made in the other subtask. The indirect effect is propagated from the previous subtasks to the subsequent subtasks through the part geometry. The need for this decomposition arises from the inability of the designer to analyze the effect of all elements of the design on each other. Thus, this approach reduces a complex forging design problem into more manageable subproblems.

Forging part geometry can be decomposed into and designed by subcomponents. Virtually all forging designs can be broken down into components formed either parallel (web) or perpendicular (rib) to the fundamental forging plane. In addition, the design of each key design feature can be done by considering these components one by one since the same design principles are used for designing the same type of
components. The implication of this decomposition is that a complex part geometry can be designed as easily as a less complex part.

Forging design requires multiple representation and problem solving schemes. As described in section 2.3, forging design involves not only design decision making but also geometry manipulation. Due to the differences involved in problem solving, these two activities require two different knowledge representation and manipulation schemes. Since these two activities interact with each other, the transformation between these representations is also necessary.

Acceptable forging design is not unique. Non-unique solutions usually exist for most of the mechanical designs, especially for those that deal with geometrical design. Since forging design is mostly experience based, design rules used by designers do vary. Even with the same design guideline, the geometry manipulation performed by designers may not be identical. To facilitate design variations, debugging as a design problem solving strategy may be employed. That is, it may be more efficient to produce an acceptable design and then modify it (to accommodate variations), than to insist on a first solution without further modifications.
4.3 A Forging Design Model

A problem solving model is a scheme for organizing reasoning steps and domain knowledge to construct a solution to a problem. That is, it provides a conceptual framework for organizing knowledge and a strategy for applying that knowledge. With this model, the different problem solving techniques required can be identified and considered. In this section, a problem solving model for forging design is developed so as to guide the computerization of this process.

As discussed in the previous sections, a forging designer usually decomposes the task of forging design into subtasks, each corresponding to a key forging design feature. These subtasks are performed, in sequence, by evaluating and modifying each forging feature based on the design specifications and design knowhow for that feature. Since these subtasks are not independent, the order of the design sequence influences the final forging design. It is known that the order of design sequence varies between individuals and part geometries. It is also known that refinements are required to ensure the validity of forging design due to the nature of forging design guidelines used. Thus, it seems logical to model forging design by using a hierarchical network structure.

Using such a structure, the hierarchical natural of the forging design tasks and their interactions can be represented. In addition, by organizing the forging design knowledge based on this structure, the application of this knowledge can be efficiently
manipulated by a simple control strategy, such as a data driven scheme.

As shown in Figure 15, the forging design model contains four conceptual levels: design applications, design phases, design tasks, and design steps. While major activities in these levels are represented by nodes, their interactions are indicated by connecting lines. Major components in these levels and their relationships are described below.

**Level 1 - Design Applications**

At this top level, there are three major applications: forging geometry design, forging process design, and forging tooling design. In the forging process design, type of forging operations and its associated processing conditions such as equipment, temperature, lubricants, etc., are determined. In the forging tooling design, the type of forging dies, the die material and the die geometries are determined. In the forging geometry design, the geometry of the forging is determined. Since forging geometry design is the main emphasis in this study, the other two designs are not discussed here. That is, the forging process and tooling are assumed to be pre-determined. However, it is to be noted that the forging geometry design is greatly affected by the process and the tooling as described in Chapter 2, and several iterations may be needed before an optimal forging design is obtained.
Figure 15. A Forging Design Model (in Hierarchical Network Form) Developed in the Current Study
LEGEND

Level 1 - Design Applications
T1 : Forging Geometry Design
T2 : Forging Process Design
T3 : Forging Tooling Design

Level 2 - Design Phases
T11 : Pre-Design Phase
T12 : Design Phase
T13 : Refinement Phase

Level 3 - Design Tasks
T111: Parting Line Design
T112: Forging Plane Design
T113: Forging Length Estimate
T114: Forging PVA Estimate
T115: Forging Weight Estimate
T121: Finish Allowance Design
T122: Web Thickness Design
T123: Rib Width Design
T124: Corner Radii Design
T125: Draft Angle Design
T126: Fillet Radii Design
T131: Finish Allowance Refinement
T132: Web Thickness Refinement

Level 4 - Design Steps
I1 : Geometry Decomposition
I2 : Geometry Modification
I3 : Geometry Construction
I4 : Geometry Verification

Figure 15. (Continued)
The forging geometry design activity at this level can be treated as a geometry transformation process that converts the finished part geometry to the forging geometry while satisfying the forging production constraints and the specifications provided by the user.

**Level 2 - Design Phases**

Three basic design phases a designer goes through in designing forgings can be conceived at this level. They are Pre-Design, Design, and Refinement phases. Based on the design specifications, basic layout of the forging design is determined in the Pre-Design phase. In additions, geometric parameters of the intended forging design are estimated. Key forging design features are then evaluated and modified, if necessary, in the Design phase. The design deviations due to estimated parameters are corrected in the Refinement phase. If the completed forging design does not satisfy the design goals, this design procedure is repeated. The forging design process terminates when a satisfactory forging design is obtained.

This rationalization seems to capture both the "design refinement" and the "redesign" elements of the forging design process. The design refinement starts after a preliminary forging design is completed. The redesign starts when the current design cycle fails to generate a forging design that meets the intended design goals. From the implementation point of view, this rationalization offers many advantages. Among them, the simplification of design task management and the reduction of required geometry manipulations are most essential.
The task management is simplified because backtracking is not needed during each design cycle (since design refinement is performed after a preliminary forging design is completed). Less geometry manipulations are required because part geometry is refined, instead of redesigned, during each design cycle.

The partition of forging design tasks using this rationalization reflects the apparent functional differences performed in each phase. It also represents the different types of the problem solving activity involved in each phase. In Pre-Design phase, no geometry modification is performed and all tasks performed consider the forging part as a whole. In Design phase, the part geometry is modified and all tasks can be performed by considering components of the part one by one. In Refinement phase, part geometry is refined if necessary and all tasks need to consider the part geometry not only as a whole but also by components. As will be described in the next chapter, this partition facilitates the uniform treatment of design tasks under each phase.

**Level 3 - Design Tasks**

At this level, the tasks performed in each design phase are considered. These tasks correspond to key forging design features described in section 2.1.
In Pre-Design phase, these tasks include: parting line locations selection, forging plane orientation determination, forging length estimation, forging plan view area (PVA) estimation, and forging weight estimation. Depending on the part geometry, either the forging plane orientation or the parting line location is determined first. The orientation of the forging plane is usually determined by the location of the parting line. However, the selection of the parting line location is highly dependent on the forging plane orientation. Thus, several iterations between the parting line design and the forging plane design may be required.

Once the basic forging design layout is determined, forging geometry parameters that will be used in the Design phase are estimated. A logical order for estimating these parameters is to estimate the length first, followed by the PVA and weight. The reasons for this sequence are that the PVA may be approximated by a function of the length, and the weight may be approximated by a function of the PVA and cross sectional area. This may be true for axisymmetric parts or certain structural parts with relatively uniform cross section geometry. However, for more complex structural parts, the complexity of the part geometry will affect the form of these functions. Thus, design heuristics that are used by the designers to estimate these geometric parameters are essential. It should be emphasized here that the more accurate these estimates are, the less iterations are required in the design refinement phase.
The tasks performed in Design phase include the establishment of finish allowances, minimum web thickness, minimum rib width, minimum corner radii, minimum draft angle, and minimum fillet radii. The finish allowance design task can be further decomposed into subtasks that determine required allowances for machining, tooling, straightness, mismatch, closure, and shrinkage. Since these tasks are not independent, the forging designed using different sequences may not be the same. According to general design rules, finish allowances are usually applied first. Since the thickness of a web affects the heights of adjacent ribs, the minimum web thickness is established prior to the establishment of those design features that are influenced by the rib height. These include minimum rib width, minimum corner radii, and minimum fillet radii. However, the minimum web thickness also depends on the rib width. Thus, iterations between rib width design and web thickness design may be required to ensure validity of the design. In most cases, minimum corner radii are established after the minimum rib width is ensured. Due to geometry manipulation considerations, the minimum draft angle is often established after minimum corner radii are established.

In the Refinement phase, the magnitudes of the finish allowance and web thickness are determined. The finish allowance refinement task can further be decomposed into subtasks that reflect requirements for straightness, mismatch, closure, and shrinkage allowances. Again, the finish allowance refinement is generally performed first. If any geometry modification is made when performing
these refinement tasks, the refinement process is repeated. This refinement process is iterated until no geometry modification is necessary during the refinement cycle.

**Level 4 - Design Steps**

At this level, the basic design steps performed by each task are considered. Due to the differences in problem solving involved, the design steps performed by the tasks in Pre-Design phase are different from those in Design and Refinement phases.

In the Pre-Design phase, each task requires distinct design steps, governed by the design heuristics used. In addition, these tasks are likely to go through an evaluation step first. In this step, design alternatives are evaluated against the design criteria (e.g. minimizing forging weight) and the part geometry. The reason for this evaluation is because an infinite number of design alternatives exist for these tasks. Based on the results of this evaluation, a candidate design is selected and used. Finally, the selected design is validated. This design process is iterated until a satisfactory design for the task is obtained.

For tasks in Design and Refinement phases, a series of design steps are performed. These are geometry decomposition, geometry modification, geometry construction and geometry verification steps. These design steps are performed in sequence and they represent a complete "evaluation-modification" task design cycle. For certain
tasks, some steps are not performed. For example, if all ribs satisfy the minimum width requirement, part geometry is not modified and the geometry construction step need not be performed. The functions performed by these design steps are described below.

As described in section 4.2, a forging can be decomposed into subcomponents and the design of this forging can be done by considering these subcomponents one by one. Thus, geometry decomposition is first performed. This "divide and solve" strategy is usually employed by forging designers and is essential when dealing with a complex forging part design. Another important function performed during this decomposition step is the transformation of part geometry representation for geometry manipulation to that for the design decision making.

In the geometry modification step, key forging features are designed. The design of these features involves the evaluation and modification of all component sections. Based on the component geometry and forging requirements, an evaluation is made to determine whether the component geometry needs to be modified. If needed, the component geometry is modified based on forging design knowhow. Another important function performed in this design step is the reverse transformation of part geometry representation due to the required geometry manipulations.

If any component geometry is modified, the part geometry needs to be re-constructed based on the modified component geometry. This is performed in the geometry construction step. The major reason for this geometry reconstruction is to propagate the proper effect of a forging
feature design to the next feature design. Certain geometric parameters of a component (e.g. the height of a rib from the adjoining web surface), used in designing key forging design features, can not determined solely from the component after the geometry modification. Also, component sections are sometimes subject to major changes, such as the disappearance of a narrow web section. Thus, the part geometry reconstruction is necessary. Another reason for re-constructing the part geometry is to verify the part geometry after the geometry modification.

Two major functions are performed in the geometry verification step. One is to ensure the validity of the part geometry after geometry modification. When designing forging geometry at the component level, certain forging geometry requirements can not be considered. For example, a "non-smooth" surface may occur when two neighboring fillet radii are too large. This type of geometry consistency checking and modification needs to be made. The other function is to allow user to make changes for a non-typical design. In order to accommodate design variations, the designed part geometry needs to be presented to the user and to allow the user to make necessary changes.
CHAPTER 5

KNOWLEDGE BASED APPROACH TO FORGING DESIGN

As described in Chapter 4, forging design is a geometry design task which involves many kinds of knowledge and problem solving techniques. Further examination of the forging design task led to the development of a hierarchical network model to deal with the complex problem solving activities involved. In this chapter, a knowledge based approach to forging design, based on this model, is described.

In the following sections, the procedure used in acquiring forging design knowledge is first described, followed by the discussion of the representation for this design knowledge and the forging design specifications. The control of the forging design process is then described. The last section deals with the use of this knowledge based approach in performing design tasks.

5.1 Forging Design Knowledge Acquisition

One of the most important phases of any knowledge based system development is knowledge acquisition. This is the process whereby detailed knowledge is acquired from the knowledge sources for representation in a knowledge base inside the computer. Many approaches to knowledge acquisition have been suggested. Some approaches emphasize the elicitation of knowledge from human experts. These include
approaches that acquire problem solving knowledge by: talking to experts and obtaining from text books; transferring the expertise from the experts to the system interactively; or transcribing the problem solving process so as to extract relevant material. Other approaches offer ways of bypassing human experts. These include the use of algorithmic methods to analyze large bodies of data to produce rules automatically [24], and the use of heuristics in generating rules [25].

In the current study, the first type of knowledge acquisition approach was used. That is, forging design knowledge was obtained from the experts and handbooks. This knowledge acquisition process is summarized below.

In order to better understand the diversity of problem solving in forging design, the author started out by reviewing handbooks and literature that were compiled by experts in forging design. The materials reviewed include those in references [2, 8-13]. A set of representative forging designs were then collected and studied. While they contain many useful forging design knowhow, the information compiled did not address the detailed steps a forging designer goes through in designing forgings.

To capture the problem solving process involved in forging design, forging design experts were asked to perform a detailed forging design according to a selected set of design specifications. They were asked to record, in detail, the design rules and the actual design sequence used. Based on the information provided by the designers, an
outline of the forging design process that the designers followed was prepared.

To validate this outline, the author used this outline and the design rules compiled to design a forging based on a new set of specifications. It was found that many required geometry manipulations were not clearly defined. In many cases, the manipulation of geometries using conventional (analytical) approaches proved to be incorrect. For example, one common way of smoothing adjoining surfaces is to reduce the radii, nevertheless, this treatment violates the minimum radii requirement of the forging design.

A prototype system based on Prolog was then built [26] to determine the adequacy of the knowledge compiled. During the development of this prototype, it was found that some of the knowledge obtained was not operationally useful since computational processes for making similar decisions were not specified. For example, in order to reduce die sinking costs, constant corner radii are usually used. This design guideline is not operationally useful since it does not specify the magnitude of the required radius.

After many interactions between the author and the forging designers, a final outline was established and this outline was used to guide the development of forging design model, hence, the current version of automated forging design system.
5.2 Frame & Rule-Based Design Knowledge Representation

A variety of knowledge representation formalisms have been developed. Among them, rule-based, frame-based and logic-based schemes are most notable. Rule-based systems [27] evolved from a more general class of computational models known as production systems [28]. Instead of viewing computation as a pre-specified sequence of operations, production systems view computation as the process of applying transformation rules in a sequence determined by the data. A classical production system has three major components: (1) a global data base that contains facts or assertions about the particular problem being solved; (2) a rule base that contains the general knowledge about the problem domain in an "IF <condition> THEN <action>" form; and (3) a rule interpreter that carries out the problem solving process. The rule-based scheme facilitates modular, uniform and natural representation of knowledge. But, it is inefficient in knowledge application and hard to follow the flow of control in problem solving. The inefficiency results from the high overhead required by the strong modularity and uniformity of the representation. The difficulties in following the control flow are due to the isolation of the rules and the uniform size of rules [6]. In additions, the rule-based scheme is not adequate for the representation of objects and their inter-relationships.
The frame-based scheme [29] is a generalization of semantic nets that allows rich linkages between facts [30]. A frame is an encoding of knowledge about an object, including not only properties and values, but also pointers to other frames and attached procedures for computing values. The pointers indicate semantic links to other concepts, e.g., material-of, and also indicate more general concepts from which properties may be inherited, e.g., subtask-of, and more specialized concepts to which its properties may be manifested, e.g., has-subtask. In addition, the frame based scheme allows ways to specify default values for pieces of information about an object when that information is not explicitly given. The frame-base scheme provides a concise structural representation of objects and their relations. It also provides "automatic" inferences as part of each assertion and retrieval operations because the taxonomic relationships among frames enable descriptive information to be shared among multiple frames (via inheritance), and because the internal structure of frames enables semantic integrity constraints to be automatically maintained [31]. The frame-based scheme, however, provides no direct facilities for declaratively describing how the knowledge stored in frames is to be used.

A logic-based representation scheme [32] is one in which knowledge about the world is represented as assertions in logic, usually first order predicate logic or a variant of it. This mode of representation is normally coupled with an inference procedure based on theorem proving. The rigor of logic is an advantage in specifying
precisely what is known and how the knowledge will be used. A disadvantage has been difficulty in dealing with imprecision and uncertainty of plausible reasoning [27].

It should be noted that all these schemes easily allow specification of conditional rules. While these three schemes represent the basic frameworks for representing knowledge, the nature of the problem solving usually requires more flexibility than the above schemes can provide. In those cases, variations to the basic framework do occur. Further, there have been implementations that used mixed representation scheme. The basic idea is to increase the breadth of what one can represent easily while maintaining the advantages of having stylized representations.

In the current study, a mixed representation scheme, that combines the advantages of rule-based and frame-based schemes, is used to represent forging design knowledge. Due to its generality, compactness, modularity and intelligibility, the rule-based scheme is used to represent the cognitive activities of forging design process. The inadequacy of rule-based scheme in defining objects, e.g. forging design subtasks, and static relationships among objects is handled by the frame based-scheme. That is, the forging design guidelines are represented in the form of rules, embedded in frames, and a frame-based scheme is also used to describe the objects referred in the rules and to provide the generic deductive capability about those objects that does not need to be explicitly dealt with in the rules.
In addition, to represent the large amount of forging design knowledge, the organization of this knowledge is very important. The problem is not only one of efficiency but also one of focus and control. For this purpose, the frame-based scheme is used to partition, index, and organize the forging design knowledge. This facilitates the easy construction and understanding of forging design rules, and the control of when and what particular collections of rules are to be used.

In the following sections, the use of this mixed scheme in representing the forging design tasks and forging design rules is described. Since knowledge pertinent to the forging resources, such as material properties and forging process characteristics, is essential for the forging design, its representation using the frame-based scheme is also described.

5.2.1 Representation of Forging Design Tasks

As described in section 4.3, the many tasks involved in forging design can best be organized in a hierarchy according to their level of abstraction. A forging design task hierarchy, based on the forging design model, is depicted in Figure 16. The major function performed by the higher level tasks (e.g. Design) in this hierarchy is to determine the sequence for the lower level design tasks. The lower level tasks perform forging geometry design.
Figure 16. The Forging Geometry Design Task Hierarchy
This structural representation of forging design tasks can easily be handled by frame constructs. For this purpose, each design task is represented by a frame that contains slots for attribute descriptions. Since all design tasks share many similar properties, it is proper to define a "prototype" that contains the prototypical characteristics of the forging design tasks. The individual design task can thus be made an "instance" of the "prototype" frame, so as to inherit the prototypical characteristics, while allowing the specification of individual characteristics. This can be done by defining and using a structural link, INSTANCE, to allow the flow of all information from the "prototype" to individual design tasks. The hierarchical relationship between design tasks can be represented by defining and using a structural link, SUBTASK-OF (with reverse link, HAS-SUBTASK). It should be noted that the SUBTASK-OF link does not allow any information flow between individual design tasks.

The prototype frame, AFD-TASK, that contains 10 slots is shown in Figure 17. The "goal" slot contains the goals of the task to be achieved. Each goal is represented by a symbol, such as TO-ESTABLISH-MISMATCH-ALLOWANCE, and it may be used by the AFD to select the proper set of design guidelines. The "subtask-of" slot contains the upper level task to which this task belongs. For example, MISMATCH-ALLOWANCE-DESIGN is a subtask of FINISH-ALLOWANCE-DESIGN. The "subtask-of" slot of the MISMATCH-ALLOWANCE-DESIGN frame will contain the symbol FINISH-ALLOWANCE-DESIGN. The "has-subtask" slot contains pointers to those subtasks that may be performed under this task. For example, FINISH-
Figure 17. The Prototype AFD Task Frame
ALLOWANCE-REFINEMENT and WEB-THICKNESS-REFINEMENT are subtasks of REFINEMENT, these two symbols are contained in the "has-subtask" slot of the REFINEMENT frame.

The "task-agenda" slot contains those design tasks (indicated by the frame names) that need to be performed in order to complete this task. The "priority" slot contains the priority of the task. The priority of a task is represented by a numerical value. The lower the value of the priority is, the higher priority this task has. As will be discussed later in section 5.4, the "task-agenda" and "priority" slots facilitate the control of the forging design process using an agenda-based scheme.

The "has-rule" slot contains the pointers to the available design rules for this task. As will be discussed later in section 5.2.2, a forging design guideline will be encoded in an "IF-THEN" rule form, embedded in a frame. The names of the frames that contain the design rules for a task will be contained in the "has-rule" slot of the task frame. The "status" slot contains the current status of the task, e.g., nil, suspended, or completed.

The "to-refine" slot indicates if this design task needs to be refined later. The need for later refinement is indicated by a symbol T. The "to-validate" slot contains the estimated forging design parameters, such as forging weight, that need to be validated. The "confirmed" slot contains those design parameters that have been confirmed. Special symbols can be used to represent these design
parameters, such as WEIGHT for forging weight, LENGTH for forging length and PVA for forging plan view area.

It is to be noted that a NIL is specified for all slots of the prototype AFD-TASK frame. That is, a default of "no value" is given for all attributes of the AFD-TASK. Through inheritance, each individual design task will contain all the characteristics (slots) of this prototype without explicitly specifying them. This is illustrated in Figure 18. The contents of MISMATCH-ALLOWANCE-DESIGN after design rules are loaded is given in Figure 18a. The total inheritance of properties from AFD-TASK is indicated in the "instance" slot, while the structural relation to FINISH-ALLOWANCE-DESIGN is indicated in the "subtask-of" slot. The "goal" slot indicates that this task is to establish mismatch allowance. The available design rules are indicated by pointers, e.g. D-MM-001, under the "has-rule" slot. Based on the values given in these slots, design decisions are made. The values of these slots, e.g., "status" slot, will be updated to reflect the effects caused by the application of design rules. As can be seen from Figure 18b, the value of the "status" slot is changed to COMPLETED upon completion of this task. Since a design rule that uses estimated forging length and weight values was applied, LENGTH and WEIGHT were added to the "to-validate" slot, and the value of "to-refine" was set to T. After refinement is performed, LENGTH and WEIGHT are added to the "confirmed" slot, and "to-refine" is set to NIL, as shown in Figure 18c.
Figure 18. An Example AFD Task Frame to Demonstrate how it can be Manipulated:
(a) After Associated Design Rules are Loaded;
(b) After the Design Task is Completed;
(c) After the Refinement Task is Completed.

(a) (MISMATCH-ALLOWANCE-DESIGN
(INSTANCE afd-task)
(GOAL to-establish-mismatch-allowance)
(SUBTASK-OF finish-allowance-design)
(HAS-RULE d-mm-001 d-mm-002 d-mm-003))

(b) (MISMATCH-ALLOWANCE-DESIGN
(INSTANCE afd-task)
(GOAL to-establish-mismatch-allowance)
(SUBTASK-OF finish-allowance-design)
(HAS-RULE d-mm-001 d-mm-002 d-mm-003)
(STATUS completed)
(TO-REFINE t)
(TO-VALIDATE length weight))

(c) (MISMATCH-ALLOWANCE-DESIGN
(INSTANCE afd-task)
(GOAL to-establish-mismatch-allowance)
(SUBTASK-OF finish-allowance-design)
(HAS-RULE d-mm-001 d-mm-002 d-mm-003)
(STATUS completed)
(TO-REFINE nil)
(TO-VALIDATE length weight)
(CONFIRMED length weight))
5.2.2 Representation of Forging Design Guidelines

As mentioned in section 5.2, the rule-based scheme provides a natural means for representing experience-based forging design knowhow in the form of rules. Due to efficiency, focus, and control considerations, these rules can best be organized, based on the task they perform, in a hierarchy as described in section 5.2.1. To represent these rules and their relationships to the tasks, the frame based scheme is most effective. Thus, a combination of rule-based and frame-based schemes is used to represent forging design guidelines.

Due to the similar characteristics of the design rules, a prototype design rule frame can be defined. This prototype frame, AFD-RULE, is shown in Figure 19. The name of the frame is used as the pointer to be attached to the designated task. The "description" slot contains the description of the design rule. It can be used by the system to explain the reasoning of the forging design process. The "rule-of" slot contains the task to which this design rule belongs, and it also enables the attachment of the name of this design rule to the task frame. The "priority" slot contains the default priority used in conflict resolution. The lower the priority value is, the higher the priority this design rule has. The "status" slot contains the current status of the rule, e.g., NIL or APPLIED.

The "condition" slot contains the pre-conditions that are to be matched against the known facts by the rule interpreter. The pre-conditions can be any combinations of Lisp statements. The
(AFD-RULE
  (DESCRIPTION <Description of the rule; NIL>)
  (RULE-OF <Task to which the rule belongs; NIL>)
  (PRIORITY <Priority value of the rule; NIL>)
  (STATUS <Rule status; NIL>)
  (CONDITION <Preconditions; NIL>)
  (ACTION <Actions; NIL>))

Figure 19. The Prototype AFD Rule Frame
evaluation of these conditions should generate a non-nil result if this rule is to be fired. The "action" slot contains the consequence or actions to be performed. Again, they can be any combination of Lisp statements or procedures that generate proper effects. In particular, it can result in the generation of new facts, such as parting line locations, or modification of old facts, such as changes of part geometry.

Since forging design involves not only geometry design but also design sequence planning, two types of rules need to be represented. One type performs geometry design, while the other type performs task sequence planning. Nevertheless, the described prototype frame can be used to represent both types of rules. The uniform treatment of geometry design and planning knowledge allows the embodiments of implicit problem solving knowledge in a knowledge module. Such a module, containing a cluster of rules for both design and planning knowledge, can be treated as an autonomous unit. For a complex task, such as forging design, this capability should prove to be very useful.

The representation of the knowledge for establishing the task sequence is illustrated by a finish allowance planning rule, D-FA-004, shown in Figure 20. The fact that this frame is to inherit all the characteristics of the prototype frame is indicated in the "instance" slot. The "rule-of" slot enables this rule to attach to the FINISH-ALLOWANCE-DESIGN task frame. That is, D-FA-004 will be placed under the "has-rule" slot of the FINISH-ALLOWANCE-DESIGN frame. The priority of
(D-FA-004
 (DESCRIPTION "D-FA-004: Change task to establish mismatch allowance")
 (INSTANCE afd-rule)
 (RULE-OF finish-allowance-design)
 (PRIORITY 104)
 (STATUS nil)
 (CONDITION (neq 'mismatch-allowance-design 'status 'completed))
 (ACTION (setf next-afd-task 'mismatch-allowance-design)))

Figure 20. An Example Rule for Establishing the Forging Design Sequence
this guideline is 104 and the rule has not been applied yet. The condition and action pair can be interpreted as "IF mismatch allowance design task is not completed; THEN the next task is to perform the mismatch allowance design". NEQ, shown in the "condition" slot, is a predicate that returns T when the "status" slot of the MISMATCH-ALLOWANCE-DESIGN frame has a value of COMPLETED.

The representation of geometry design knowledge is illustrated by a mismatch allowance design rule, D-MM-001, shown in Figure 21. Again, this rule is an instance of AFD-RULE and it is attached to MISMATCH-ALLOWANCE-DESIGN frame. The priority of this rule is 101 and this rule has not been applied yet. The condition and action pair can be interpreted as "IF mismatch allowance design is not completed, and forging material is aluminum; THEN establish mismatch allowance based on the given table, request later refinement of this allowance by validating LENGTH and WEIGHT, and change the status of mismatch allowance design task to COMPLETED". In the "action" slot, the ESTABLISH-MISMATCH-ALLOWANCE is a Lisp function that establishes mismatch allowance for the forging part. NEW-VALUE and ADD-VALUES are utility functions provided by the frame based system to change or to add values to the specified slot of the specified frame, respectively.
(D-MM-001 :DB :NONE)

(Description: "D-MM-001: For aluminum forging, establish mismatch allowance based on the following table:

<table>
<thead>
<tr>
<th>Length</th>
<th>15</th>
<th>50</th>
<th>100</th>
<th>250</th>
<th>250+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>5</td>
<td>50</td>
<td>200</td>
<td>1000</td>
<td>1000+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length</th>
<th>0.02</th>
<th>0.06</th>
<th>0.10</th>
<th>0.14</th>
<th>0.16</th>
</tr>
</thead>
</table>

(Instance afd-rule)
(Rule-Of mismatch-allowance-design)
(Priority 101)
(Status nil)

(CONDITION (and (neq 'mismatch-allowance-design 'status 'completed))
  (equalp (get-material-type) 'aluminum)))

(ACTION (and (establish-mismatch-allowance
  '(15 50 100 250 1000)
  '5 20 200 1000 10000)
  '(0.02 0.06 0.10 0.14 0.16))
  (new-value 'mismatch-allowance-design 'to-refine t)
  (add-values 'mismatch-allowance-design 'to-validate
    '(forging-length forging-weight))
  (new-value 'mismatch-allowance-design 'status 'completed))))

Figure 21. An Example Forging Geometry Design Rule
5.2.3 Representation of Forging Resources

In forging design, the knowledge about the properties and availability of forging resources is essential in generating satisfactory design. This may include, but is not limited to: (1) characteristics of forging equipment, such as speed and capacity of the forging press; (2) forging material properties, such as temperature and flow behavior; and (3) forging process capabilities, such as precision, isothermal, conventional forgings. Often, this knowledge may be represented in tables and stored in conventional data bases. Nevertheless, these data bases lack proper interface with any knowledge based design systems. Since this knowledge greatly affects the design of forgings and are usually referred in design rules, it needs to be represented in a form that can be effectively accessed by the design rules. For consistency considerations, a logical choice is the frame based representation scheme for this study.

As shown in Figure 22, a hierarchical structure is used to represent the many resources needed in forging design, according to the level of abstraction. While non-terminal nodes represent sets of objects, terminal nodes represent individual objects. The set-element relationships are indicated by connecting arcs. In this hierarchy, the top level is the forging resources, the second level contains forging material, equipment, and process. The third level contains various types of materials, equipment and processes. The fourth level further classifies types of materials and equipment.
Figure 22. The Forging Design Resource Hierarchy
Each node in this resource hierarchy is represented by a frame and the set-element relationship is represented by a structural link IS-A. A material frame, AL7075, is shown below:

(AL7075
  (IS-A Aluminum)
  (Density 0.101)
  (Temperature 700))

Since AL7075 is an aluminum alloy, it will inherit all the common properties of the ALUMINUM, hence, that of the MATERIAL and RESOURCES. The individual properties of AL7075, such as density and forging temperature, can still be specified in the frame.

It is to be noted that the current representation of the forging resources is by no means complete. Nevertheless, other types of materials, equipment and processes can be easily added to this hierarchy to reflect the available resources. In addition, the system can be further expanded to allow the design of the forging process. For example, with the addition of a forging load calculation module and the inclusion of the equipment capacity in the resource hierarchy, the system can be used to select the proper forging equipment. This aspect will not be elaborated upon due to the scope of the current study.

For the forging geometry design application, the incorporation of this resource hierarchy not only reduces the input requirements, but also facilitates input data checking. For example, material density that is essential in calculating forging weight can be obtained from this hierarchy. Data given by the user can be checked against this hierarchy for their correctness. In addition, this hierarchy reduces
the complexity of the design rules, and sometimes, even reduces the amount of design rules required. For example, some forging design rules are dependent of a class of forging materials, e.g., aluminum. With the automatic inference provided by the frame constructs, this resource hierarchy infers from a user input of "AL7075" to the "aluminum".

5.3 Frame-Based Part Representation

For forging geometry design application, the process and geometry related design specifications need to be represented. The process related specifications include those forging conditions, as described in section 2.2, that affect the forging geometry. The geometry related specifications include the part geometry and special geometry design considerations, such as minimum draft angles and corner radii, etc.

The representation of process related design specifications and special geometry design considerations can be easily done by using the frame-based scheme. As will be detailed later in section 5.3.1, each specification can be treated as a special property of the forging part. These special properties can then be represented as attributes of the part representation so that they may be accessed by the design rules for making design decisions.
The representation of the part geometry needs further investigation. Since the current study is limited to 2D forging section design, the part geometry is represented in terms of forging sections. A forging section can be described by its boundary. This boundary needs not be connected as for example in the case when holes exist inside the forging section. Since each boundary can be decomposed into a set of non-overlapping closed curves, the description of the forging section can also be accomplished with closed curves.

There are many techniques available to describe closed curves. One can compare these different techniques only in the context of intended applications. As mentioned in section 4.2, forging design involves not only geometry manipulation but also design decision making. Due to differences in problem solving, the evaluation of representation techniques for forging part geometry should consider not only these two distinct tasks, but also the transformation between them.

For the purpose of geometry manipulation, a closed curve can be described by a polygonal approximation. That is, a closed curve is approximated by a series of curved or linear segments. There are several variations to this technique. One simple scheme is to approximate the curve by using linear segments only. While essential for graphic display purpose, this approach is neither compact nor unique. For a more compact and accurate representation, curved segments, such as arcs, are incorporated into the description. One scheme to represent curved segments is to treat them as separated entities. For example, an arc may be represented by its starting,
ending, and center points. The other scheme is to treat curved segments as part of linear segments. That is, a closed curve is described by its vertices in a specified order (either clockwise or counter-clockwise), while each vertex is represented by its X, Y coordinates and the associated corner radii. For convenience of discussions, this approach shall be termed as "XYR scheme" and the section geometry description based on this approach as "XYR".

The XYR scheme offers many advantages for forging design applications. It is not only general, i.e. it can be used to approximate most of the forging sections, but also concise, i.e. it can represent a forging section in a more brief form than the other schemes mentioned above. The most important advantage comes from the ease of geometry manipulation in forging geometry design. Since curved segments are treated as part of linear segments, the establishment of finish allowances can be done by constructing parallel linear segments. The establishment of draft angles can be done by shifting these linear segments according to the angles specified. The modification of radii can be done easily by changing the R coordinates.

For forging design decision making, the XYR scheme is not effective since forging designers work at a higher conceptual level, dealing with shapes and features. That is, they usually decompose the forging section into ribs and webs, and makes design decisions based on the height, width, length, radius, and angle of these components. For this purpose, the forging section should be described in terms of these geometric entities. From an implementation point of view, this type of
description is also attractive since it reduces the complexity of design rules by ignoring the superfluous detail of the section geometry. Again, for discussion purposes, this approach shall be termed as "ENTITY scheme" and the section geometry description based on this approach as "ENTITY".

The basic steps involved in a "evaluation-modification" task design cycle, as described in section 4.3, can be treated as transformations between XYR and ENTITY. That is, section XYR is first transformed to component XYR and then component ENTITY in the geometry decomposition step. The component ENTITY is then evaluated and modified, if necessary, by applying proper design rules, and the modified ENTITY is transformed back to the component XYR, in the geometry modification step. The modified component XYR is transformed back to section XYR in the geometry construction step. Finally, the new section XYR is validated in the geometry verification step. This design cycle is iterated until a satisfactory forging design is obtained. Thus, the effectiveness of information exchange between these two schemes is very important.

For the transformation from XYR to ENTITY, the XYR scheme is attractive. The length, width and height entities can be calculated directly from the axial distance between two vertices (corners) of XYR. The radius entity can be obtained directly from the R coordinate of XYR. The angle entity can be easily calculated from the linear segment of XYR. For the transformation from ENTITY to XYR, the XYR scheme is also attractive. As mentioned earlier, the increase of length, width, and
height can be done by parallelly shifting the linear segments outward. The change of angle can be done by shifting the linear segment according to specified angle. The change of radius can be easily done by modifying the R coordinate.

Based on the above discussions, the XYR and ENTITY are effective geometry representations for the forging geometry design application. Thus, they are used in the current study. For the representation of part geometry, the fact that a forging part is usually decomposed into subcomponents and the design of this forging part is done by designing these subcomponents one by one, should also be considered. For this purpose, the scheme used to represent the forging part geometry should not only allow the multiple representations of the forging section and its components, but also the structural relations between the section and components. The frame-based scheme satisfies these requirements since multiple representations can be easily included in the same frame under different slots and structural links can be used to represent the structural relations.

Since the frame-based scheme provides an effective means for representing both process related and geometry related design specifications, it is used in the current study. As shown in Figure 23, a forging part can be hierarchically decomposed to sections, and hence, ribs and webs. Nodes in this forging part hierarchy are represented by frames while their structural relationships are represented by structural links. These structural links are SECTION-OF (HAS-SECTION as the reverse link), RIB-OF (HAS-RIB as the reverse link), and WEB-OF
Figure 23. The Forging Part Hierarchy
(HAS-WEB as the reverse link). The RIB-OF and WEB-OF links also enable the attachment of rib and web frames to the section frame so that ribs and webs may be accessed by the forging design rules from the section frame. In the following sections, the representations of forging part, forging section, ribs, and webs using the frame based scheme are described.

5.3.1 Representation of the Forging

At the forging level, process and geometry related design specifications need to be represented. Since the current study is limited to 2D section geometry design, 3D part geometry is not included. A forged part frame PART-1, shown in Figure 24, illustrates the use of the frame based scheme in representing these specifications.

In PART-1, "part-id" slot contains the identification code for the part being designed. General notes about this forging part are given in "description". The type of forging part geometry, eg. axisymmetric or structural, is specified in "part-type". The type of forging process to be used, eg. conventional or precision, is specified in "forging-type". The type of forging material to be used, eg. Ti64 or Al7075, are specified in "material-type". The type of forging equipment to be used, eg. hydraulic or mechanical press, is specified in "equipment-type". The forging temperature is specified in "temperature". Number of forgings to be made is specified in "lot-size". Since only the geometric aspect of the forging design process is emphasized in the current study, these attributes are treated
(PART-1
(PART-ID afd001)
(Description "AL7075, Conventional")
(PART-TYPE structural)
(FORGING-TYPE conventional)
(MATERIAL-TYPE AL7075)
(EQUIPMENT-TYPE hydraulic)
(Temperature 700)
(LOT-SIZE 200)
(ESTIMATED-FORGING-LENGTH 12.5)
(ESTIMATED-FORGING-PVA 106.2)
(ESTIMATED-FORGING-VOLUME 371.9)
(ESTIMATED-FORGING-WEIGHT 37.56)
(CALCULATED-FORGING-LENGTH nil)
(CALCULATED-FORGING-PVA nil)
(CALCULATED-FORGING-VOLUME nil)
(CALCULATED-FORGING-WEIGHT nil)
(MIN-MACHINING-ALLOWANCE 0.060)
(MIN-TOOLING-ALLOWANCE 0.030)
(MIN-MISMATCH-ALLOWANCE 0.060)
(MIN-CLOSURE-ALLOWANCE 0.015)
(MIN-SHRINKAGE-ALLOWANCE 0.030)
(MIN-STRAIGHTNESS-ALLOWANCE 0.030)
(MIN-WEB-THICKNESS 0.200)
(MIN-RIB-WIDTH 0.125)
(MIN-CORNER-RADII 0.063)
(MIN-FILLET-RADII 0.125)
(MIN-DRAFT-ANGLE 5.0)
(HAS-SECTION section-1))

Figure 24. A Part Frame Containing Design Specifications for an Example Part
as forging design specifications.

The estimated and calculated values for overall forging length, forging plan view area, volume and weight, are also included in the part frame. The estimated values are necessary since design guidelines are generally based on forging geometry. The estimated values, either provided by the user or generated by experience based rules, are used in generating preliminary forging designs, subject to later refinement. The calculated values are obtained from the preliminary design. The differences between the calculated and estimated values are used as the basis for design refinement. It is to be noted that the inclusion of forging volume is for the purpose of forging weight calculation, i.e., either volume or weight, but not both, is needed. In addition, the calculated values can be obtained only for parts that can be modelled by the rotational or translational sweeping since the current study is limited to 2D forging section design.

Also included in the part frame are slots for the minimum requirements of various allowances, rib width, web thickness, radii, and draft angle. The inclusion of these slots serves many purposes. One purpose is to allow the user to override the design decision made by the system. This is very important since special design considerations are usually needed. For example, in order to reduce die sinking costs, constant corner radii are usually established even though smaller radii can be established for some corners. By providing this capability, design variations due to these special considerations can thus be handled. Another purpose is to store the minimum requirements
established by the design rules during the design phase, so that they can be used by the refinement rules during the refinement phase.

5.3.2 Representation of Forging Section

Since a forging section can be decomposed into ribs and webs, the structural relations between the section and its components need to be represented. In addition, multiple representations of part geometry are needed due to tasks involved in forging geometry design. In the current study, the frame based scheme is used in representing the section geometry. This is illustrated by a section frame SECTION-1, shown in Figure 25.

In SECTION-1, the description of the input geometry, i.e. the finished section geometry after subsequent machining operations, is specified in the "machined-section-xyr" slot. The description of the output geometry, i.e. the designed forging section geometry, is stored under the "forging-section-xyr" slot. Since these two geometries are to be used for the purpose of geometry manipulation, they are represented by using the X Y R scheme and their vertices are ordered in a clockwise direction.

The "center-line" slot contains the description of the center line of the section geometry using the X Y R scheme. The center line is described by a series of linear segments that pass through centers of all webs of the section geometry. The concept of center line coincides with that of the parting line. However, since the parting line may not
Figure 25. A Section Frame Containing Section Geometry for an Example Part
be always established at the center of webs due to special design considerations, the center line, instead of parting line, is used as the basis for the decomposition of the section geometry and the measurement of geometric entities, eg. rib height.

The "parting-line" slot contains the description of the parting line using the XYR scheme. The parting line for forging section design are described by two linear segments. As shown in Figure 26, only the outside portions of the parting line are included in the description. There are many reasons why internal portions are not included. First of all, the internal portions do not exist in physical space. In forging geometry design, they appear in conceptual space for the purpose of geometric entity measurement. Secondly, they may not be a good measurement reference since they are not unique due to special design considerations as mentioned earlier. Thirdly, they can not be determined based on a forging section alone. Thus, they are not included in the description and the center line is used instead for measuring geometric entities.

The "forging-plane" slot contains the description of the forging plane. For forging section design, it can be described by a linear segment. The "tooling-point" slot contains the X and Y coordinates of a tooling point needed in establishing shrinkage allowance for forging section design. The centroid of the forging section is stored in "forging-section-centroid". It is used to determine whether a draft is internal or external. The length and area of the forging section are stored in "forging-section-length" and
Figure 26. Parting Line of an Example Section, Generated by AFD
"forging-section-area" respectively. They may be used to aid a user to estimate the forging length and forging weight for structural parts. The decomposed subcomponents are described in "has-rib" and "has-web". These two slots represent the structural relations between the section and its subcomponents. Also, they allow design rules to access these subcomponents from the forging section frame.

5.3.3 Representation of Ribs and Webs

For designing the forging geometry, several items need to be included into the description of a rib and a web. First of all, since ribs and webs are subcomponents of a forging section, the structural relations between them and the section need to be represented. Secondly, their geometries should be represented. As discussed earlier, the geometry description should include both XYR and ENTITY representations.

A rib frame RIB-1, shown in Figure 27, illustrates the use of the frame based scheme to represent a rib. Since all ribs have the same attributes, a prototype rib frame RIB was established. The total inheritance of attributes from RIB to RIB-1 is indicated in the "instance" slot. The relation between the rib and the forging section is specified in "rib-of" slot. For the purpose of geometry manipulation, ribs are classified into various types, based on their relative locations in the forging section. This classification will be discussed later in section 5.5.1. The symbol, R, specified in the "type" slot indicates that this rib is a standard center rib. The
Figure 27. A Rib Frame Containing a Rib Geometry for an Example Part
geometry representation of this rib using XYR scheme is specified in the "vertices" slot. For the apparent space saving consideration, pointers, instead of actual X, Y, R coordinates, are used. These pointers point to the corner points specified in the "forging-section-geometry" slot of the section frame, SECTION-1.

The remaining slots represent the rib geometry using ENTITY scheme. The width of the rib is specified in the "width" slot. The height of the rib, measured from the center line, is specified in the "height" slot. The step heights, measured from the adjoining web surfaces, are specified in the "step-height" slot. Again, pointers are used to represent corners and they are contained in the "corner" slot. The "fillet" slot contains the fillets of the rib. For each fillet, two values are specified. The first value is the pointer and the second value indicates whether this fillet is confined or unconfined. The drafts of the rib are specified in the "draft" slot. To allow geometric variations for a rib type, all linear segments of a rib geometry are treated as drafts. This deviation from the definition of the draft will not cause any problems since a draft needs to be modified only if its angle does not satisfy the minimum requirement. The linear segments that are not drafts will not be modified since their angle would have been larger than the minimum requirement. Two values are used to describe a draft. The first value indicates whether this draft is external or internal, while the second value specifies the draft angle.
The representation of a web is similar to that of a rib. The use of the frame based scheme to represent a web is illustrated by a web frame WEB-1, shown in Figure 28. Again, a prototype web frame WEB was established and the total inheritance of attributes from WEB to WEB-1 is indicated in the "instance" slot. The relation between the web and the forging section is specified in "web-of" slot. The type indicator, 3, specified in the "type" slot indicates this is a side web. The X-Y-R geometry representation of this web is specified in the "vertices" slot. As in the rib frame, pointers are used to represent corners. The remaining slots represent the web geometry using ENTITY scheme. The length and thickness of the web is specified in the "length" and "thickness" slots, respectively. The height of web, measuring from the center line, is specified in the "height" slot. Again, pointers are used to represent corners of side webs and they are contained in the "corner" slot. As in the rib frame, drafts are represented in the "draft" slot.

5.4 Hybrid Design Process Control

To facilitate forging design process control, forging design knowledge is organized based on the forging design model presented in section 4.3. For such a model, one needs to control not only the design activities in a task, but also the transitions from the higher level task to the lower level task, from the lower level task to the higher level task, and between tasks at the same level. Since forging design
Figure 28. A Web Frame Containing a Web Geometry for an Example Part
guidelines are represented in rules, the control needed for activities within a task involves the manipulation of design rules. For this purpose, a data driven scheme is employed.

The data driven scheme reasons forward from an initial state toward a goal. That is, the user initially enters all the information about the problem into the dynamic data base and the rules are then applied to "reason forward" from the data to the conclusions. Since its reasoning is based on the information contained in the dynamic data base, this scheme responds quickly to the changes of data. This feature is attractive for the forging design application because: (1) the forging geometry is evolving over the course of design; (2) design changes may be made by the user due to special design considerations; and (3) new data may be provided to the user to guide the forging design. One common shortcoming of the data driven scheme is that its behavior can sometimes appear to be aimless if the rules are not favorably ordered. This shortcoming is overcome, in the current study, by properly ordering and grouping forging design rules based on the forging design model.

The task transition control involves the application of forging design sequence knowledge. The advantages of making the task specific knowledge modular and explicit can be extended to control knowledge as well. This approach is attractive for forging design applications. Being the control knowledge for the forging design knowledge, the design sequence planning knowledge affects the final forging design. By making this knowledge explicit, the forging design
system can adapt its design rule selection strategy to the design sequence variations between individual designers and design specifications. In addition, the system can be further expanded to cover other aspects of forging design, e.g., forging process design.

Thus, in the current study, the design sequence knowledge is made explicit by encoding it as rules. Similar to the control of activities in a design task, the data driven scheme can also be used to control the transitions between forging design tasks. By using the same format to represent both the forging design rules and the forging sequence rules, the same rule interpreter can be used to manipulate both types of rules. Under this data driven control, the forging design process starts with the selection of a most favorable design sequence rule based on the current status of the system and of the forging design tasks. Once applied, this rule determines the design task to be performed. A most favorable design rule from this design task is then selected based on the design specifications and the part geometry. The application of this design rule may change the part geometry and/or status of the design task, which may affect the selection of the next design sequence rule. Again, a design sequence rule is selected. The same process is iterated until no design sequence rule is applicable or a satisfactory forging design is obtained.

In order to provide a more flexible task transition control, an agenda based scheme is also employed. An agenda based scheme can be considered as a special case of event driven control. It determines the next design task (event) based on the precedence relations, represented
by priority values, of the required tasks or subtasks (events) contained in a task agenda. As described in section 5.2.1, the tasks need to be performed are contained in the "task agenda" slot of the task frame, and the priority of a task is defined in the "priority" slot of the task frame. Conceptually, the subtasks needed to be performed for a task and their associated priority values constitute a design plan for this task.

To facilitate the transition control for the forging design model, any tasks can be contained in the "task-agenda" of a task. That is, a task can activate any task as long as the latter is contained in the "task-agenda" and has a higher priority. Also, the contents of the "task-agenda" and the priority values of the tasks can be changed dynamically, either by the rules or the user, during the design process. By manipulating these values to reflect the required subtasks (or tasks) and their significance for a design task, a flexible and powerful task transition control can thus be achieved. In addition, the agenda based control not only reduces the amount of required design sequence planning rules, but also facilitates easy handling of the required design iterations.

For this hybrid control scheme, the control data are stored in a control block. As shown in Figure 29, this control block can be implemented by using the frame based scheme. The "AFD-initialization" specifies whether the system is initialized. The "AFD-input" indicates whether a complete design specification is given. The "AFD-design" indicates whether the forging design process is completed. The next design task is specified in the "AFD-next-task". The "conflict-set"
(AFD-CONTROL
  (AFD-INITIALIZATION completed)
  (AFD-INPUT completed)
  (AFD-DESIGN nil)
  (AFD-NEXT-TASK mismatch-allowance-design)
  (CONFLICT-SET (101 2 d-mm-001)
                  (102 2 d-mm-002)
                  (102 1 d-mm-003))
  (RULES-APPLIED tm001 ... d-fa-004)
  (LOW-PRIORITY 932))

Figure 29. Major Control Data (Stored in a Frame) Used by the AFD
contains the descriptors of applicable rules for the next design task. The first value of the rule descriptor is the priority of the rule. The second value specifies the number of pre-conditions. The third value specifies the name of the rule. The "rules-applied" contains rules applied thus far. The "low-priority" specifies a low priority value to be assigned to the rule that will be applied next. By updating the priority values of rules applied, lower priority rule can thus be selected and applied after the higher priority rule is applied.

A rule interpreter based on the above described hybrid control scheme is developed. This rule interpreter performs pieces of problem solving activities in the following iterative sequence:

(1) If "AFD-design" of the control block has a value T, i.e. the forging design process is completed, no more design activity is allowed.

(2) Next design or sequence planning task is determined. The selection of next task is based on the "priority" of the current task and the tasks contained in the "task-agenda" of the current task. The "AFD-next-task" of the control block is updated to the highest priority task, and this task is removed from the "task-agenda" if necessary. If no task exists in the task agenda, the current task is the next task.
(3) Applicable design or planning rules are determined. This is done by evaluating all the rules available to the next task one by one. The available rules can be accessed from the "has-rule" of the next task. For a data driven control scheme, the pre-conditions of the rule are evaluated to determine its applicability. For each applicable rule, a 3-tuple rule descriptor, which contains the priority, number of pre-conditions, and name of the rule, is placed in the "conflict set" of the control block. If there are any applicable rules for the next task, the control goes to (5).

(4) Next design or planning task is updated. If there is any task in the task-agenda of the next task, the next task is changed to the highest priority task in the agenda and the control goes to (2). If there is no task in the agenda and the next task is not the top level task, the next task is changed to the higher level task, and the control goes to (2). The higher level task can be accessed from the "subtask-of" of the next task. If there is no task in the agenda and the next task is the top level task, the rule interpreter halts and a design failure message is issued.

(5) Next design or planning rule is determined. This is done by selecting the most applicable rule, from the conflict set, based on two conflict resolution criteria. The "rule order" criterion is first used. That is, the rule in the conflict
set with the highest priority is chosen. If more than two rules satisfy the "rule order" criterion, the "generality order" criterion is the used. That is, the most specific rule is chosen. The more pre-conditions a rule has, the more specific this rule is. If both criteria fail, a rule is chosen arbitrarily.

(6) The selected rule is applied. This is done by performing the actions specified in the rule, adding the name of this rule to the "rules-applied" in the control block, and changing the status of this rule to APPLIED. In addition, the priority of this rule is set to the low priority value specified in the control block, and the low priority value in the control block is updated.

As seen from the behavior of this rule interpreter, the control of forging geometry design is done by a data driven scheme. The control of forging design sequence planning can be done by using either the same data driven scheme or the agenda based scheme. When the data driven scheme is used, the transition knowledge from higher level to lower level tasks, and between tasks at the same level is encoded as rules. The processing sequence is determined by in a "step by step" fashion. That is, only the next design step is determined, followed by the forging geometry design activities. It is to be noted that the transition from the lower level to the higher level tasks is performed automatically.
When the agenda based scheme is used, the transition knowledge may also be encoded as rules. A default design sequence can be defined by placing required subtasks into the task agenda and specifying the proper priority value for that task. Rules, that manipulate these default subtasks and priority values, are necessary for handling variations to the default sequence and iterations of design steps. The basic difference between this scheme and the data driven scheme is that the processing sequence is determined a priori. That is, the design sequence for all the required subtasks is first determined, followed by the forging geometry design activities.

It should be emphasized that the grouping of forging design rules into "modules", within which the rules are ordered for the purpose of conflict resolution, deviates from the spirit of production systems since only those rules in the selected "module" can fire [33]. However, this grouping offers many advantages. First, it is "natural" for the user to write forging design rules as a group working toward a single forging design goal. This grouping restricts the context of the rules, which in turn facilitates the application of these rules. The ordering of rules also reduces the complexity of the rule since redundant pre-conditions are not needed to ensure the proper rule activation sequence. This is also critical to system performance due to the reduction of pattern matching required.
5.5 Evaluation-Modification Design Cycle

In the previous sections, the representation of forging design knowledge and forging design specifications, and the control of forging design process are discussed. In this section, the use of these representation and control schemes in performing forging design tasks is described. More specifically, the incorporation of many problem solving techniques, in a cooperative fashion, to automatically design the forging geometry is addressed.

As described in previous sections, each task in the forging design task hierarchy (Figure 16) is represented by a frame. To facilitate control, the forging design knowledge is partitioned and organized according to this hierarchy. The forging geometry design knowledge is represented in the form of rules (embedded in frames) and attached to the lower level tasks. The design sequence knowledge is attached to the higher level tasks. This sequence knowledge may be explicitly represented as rules, or implicitly stored under "task-agenda" and "priority" slots of these task frames.

Since design iterations are required for certain tasks, this iteration knowledge may be attached to the respective higher level tasks. To reduce the number of iterations, iterations should be limited to the lowest possible level in the forging design task hierarchy. For example, the refinement of forging design may be done by iterating over the refinement tasks instead of the tasks in Pre-Design, Design and Refinement phases. This approach may introduce redundant subtasks, but
it will reduce the complexity of design task control and enhance the modularity of the design knowledge representation.

In addition to determining design sequence and iteration for the lower level tasks, higher level tasks may also perform forging geometry modifications. For example, due to similarity of the required geometry manipulations for establishing various allowances, the lower level allowance design tasks (e.g. TOOLING-ALLOWANCE-DESIGN) only determine the required allowances. The actual modification of forging geometry to include all the necessary allowances is done by FINISH-ALLOWANCE-DESIGN. This approach will reduce the geometric manipulation requirements.

Based on the design sequence knowledge and the current status of the forging design tasks, a design task is selected. For tasks in the Pre-Design phase, applicable rules are selected and applied, based on the forging design specifications stored in the part frame (eg. PART-1) and the section geometry stored in the section frame (eg. SECTION-1). The result from each rule application (eg. parting line location or estimated forging weight) is shown to and validated by the user. Upon completion of each task, the values of the corresponding slots in the part or section frames are updated, and a completion mark is recorded in the "status" slot of the selected task frame. The Pre-Design phase is completed when all the necessary tasks are performed.
For tasks in the Design phase, applicable forging feature design rules are selected and applied, based on the forging part geometry and design specifications stored in the forging part hierarchy (section 5.3). The modified part geometry after each rule application is shown to and validated by the user. Upon completion of a design task, the modified section geometry in the section frame is updated and a completion mark is recorded in the "status" slot of the corresponding task frame. If estimated forging geometric parameters are used, a T is marked in the "to-refine" slot and these parameters are recorded in the "to-validate" slot of the corresponding task frame. The Design phase is completed when all the design tasks are performed.

For tasks in the Refinement phase, the geometric parameters (e.g., weight) that need validation can be obtained from the "to-validate" slot of the corresponding feature design task frame. For this purpose, new estimates of these parameters need to be made. For axisymmetric parts, new estimates can be calculated from the designed forging geometry. For structural parts, new estimates may be obtained from the user. Based on the original and new estimates and design specifications, applicable refinement rules are selected and necessary geometry refinements are made. Upon completion of each task, the modified section geometry in the section frame is updated, and a completion mark is recorded in the "status" of the corresponding task. It is to be noted that only those forging features that were designed based on the estimated forging geometric parameters need to be refined. In addition, iterations may be required when a forging feature is
refined since each refinement will change the overall section geometry. The Refinement phase is completed when all the geometric parameters are validated and no further refinement is necessary.

Due to similarity of the design activities involved, the same sequence of design steps can be applied to all the tasks in the Design and Refinement phases. The design steps involved in these tasks include: (1) geometry decomposition - the decomposition of forging section geometry to section components; (2) geometry modification - the modification of section component geometries to satisfy forging operation requirements based on given design specifications; (3) geometry construction - the construction of the forging section geometry based on the modified component geometries; and (4) geometry verification - the verification of the forging section geometry. By decomposing the design activities involved in these tasks into these steps, a uniform treatment of these design tasks can be obtained. In addition, similar design activities for these tasks need not be re-defined. For each design or refinement task, only the geometry modification needs to be developed separately.

This series of design steps represent a complete "evaluation-modification" cycle for a forging design or refinement task. The design steps are performed in sequence. Nevertheless, not all steps need to be performed for all tasks for a given set of design specifications. When geometry modification is not made for a task, geometry construction is not performed.
5.5.1 Geometry Decomposition

As described in section 4.2, a forging can be decomposed into subcomponents and the design of this forging can be done by considering these subcomponents one by one. Thus, section geometry is first decomposed into components, i.e. ribs and webs, in this design step. For the purpose of design decision making, as described in section 5.3, the component geometry is best represented in ENTITY form. Thus, the transformation of component geometry from XYR to ENTITY form is also performed in this design step.

To decompose a forging section into ribs and webs, these components need to be recognized first. For geometric feature recognition, the syntactic approach has attracted considerable attention due to its abilities to handle pattern structures and their relationships. In [34], Choi outlines the use of syntactic pattern recognition in identifying elementary machined surfaces for process planning in machining centers. In [35], Jakubowski uses a syntactic approach to describe the shape of those mechanical parts modelled by the rotational or translational sweeping. In [36], Staley et al. use syntactic pattern recognition to classify holes from 2-D cross-sectional descriptions extracted from a 3-D solid geometric data base.

The syntactic approach is based on the theoretical framework of formal language theory [37]. It is capable of describing a large set of complex patterns (e.g. forging section geometry) using small sets of simple pattern primitives (e.g. the orientation of linear segment) and
of grammatical production rules. As an analogy to the language theory, patterns in the syntactic paradigm are regarded as sentences in a language, which is defined by a formal grammar. Formally, a grammar G is defined as a 4-tuple \((V_t, V_n, P, S)\), where \(V_t\) is a set of terminal symbols (the pattern primitives), \(V_n\) is a set of non-terminal symbols (the sub-patterns), \(P\) is a set of production or rewrite rules (the structural components of a pattern), and \(S\) is the start symbol. The recognition process is accomplished by a syntax parsing of the string of primitives (terminal symbols) representing the pattern (features).

Due to its capabilities in extracting knowledge about the shape and features of a part geometry, a syntactic approach is used in the current study to extract the ribs and webs from the forging section. While most of the researches emphasize in applying syntactic method to extract features from machine parts, little has been done to apply this technique to recognize forging part features, particularly for the purpose of forging design. In an earlier study [26], a syntactic method using line orientations as the pattern primitives was attempted to extract forging design features from a forging section. While able to extract design features for some typical forging sections, the attempt was found to be very sensitive to the orientation of the forging section. Thus, in the current study, types of vertices, instead of line orientations, are used as pattern primitives. Following the formal definition, the grammar G for the forging features can be defined as:
\[ G = (V_t, V_n, P, S) \]

\[ V_t = [a, b, c] \]

\[ V_n = [S, RW, RIB, WEB, R, A, B, C, D, E, W, 1, 2, 3, 4, 5] \]

\[ S = S \]

\[ P = [S \rightarrow <RIB><RW>; <WEB><RW> \]

\[ RW \rightarrow RIB; WEB; <RIB><RW>; <WEB><RW> \]

\[ RIB \rightarrow R; A; B; C; D; E \]

\[ WEB \rightarrow W; 1; 2; 3; 4; 5 \]

\[ R \rightarrow baab \]

\[ A \rightarrow caab \]

\[ B \rightarrow baac \]

\[ C \rightarrow bab \]

\[ D \rightarrow cab \]

\[ E \rightarrow bac \]

\[ W \rightarrow bb \]

\[ 1 \rightarrow cb \]

\[ 2 \rightarrow bc \]

\[ 3 \rightarrow cab \]

\[ 4 \rightarrow bac \]

\[ 5 \rightarrow cac; caac] \]

where \(<a>\) is a corner, as defined in section 2.1,

\(<b>\) is a fillet, as defined in section 2.1,

\(<c>\) is a parting line end point,

\(<S>\) is a forging section,

\(<RW>\) is any combinations of ribs and webs,
<RIB> is any type of rib: R, A, B, C, D, E,
<WEB> is any type of web: W, 1, 2, 3, 4, 5.

The different types of ribs and webs are shown in Figure 30. It is to be noted from the above rewrite rules that, the same pattern is used for both rib type "D" and web type "3", and the same pattern is used for both rib type "E" and web type "4". In actual implementation, patterns "cab" and "bac" are classified as web type "3" and "4", respectively, by the pattern parser. They are included in the rule set for convenience of discussions. These patterns are later classified in their proper types based on the orientation of the line segment that connects both endpoints. This further classification is illustrated in Figure 31. In addition, in order to allow variations of rib types "R", "A", "B", and web type "5", another rewrite rule, "<aaa> -> <aa>", that removes redundant "a"s may be included. Thus, "baaab" can also be classified as a type "R" rib.

To illustrate the decomposition of a forging section into its component ribs and webs, using the above described syntactic approach, an example forging section is given in Figure 32. The pattern string that describes this forging section is also given in this figure. Based on the above rewrite rules, four "R" type and one "A" type ribs, and three "W" type, two "4" type and one "3" type webs, are recognized. The component ribs and webs recognized are then used as the basis for decomposition of this forging section, as shown in Figure 33.
(a) Various types of Ribs: R - baab, A - caab, B - baac,
    C - bab, D - cab, E - bac

Figure 30. Various Types of Ribs and Webs, Recognizable by AFD
(b) Various Types of Webs: \( W \) - \( bb \), 1 - \( cb \), 2 - \( bc \), 3 - \( cab \), 4 - \( bac \), 5 - \( caac \)

Figure 30. (Continued)
Figure 31. Further Classification of Patterns: "cab" and "bac"
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Figure 32. Pattern String and Recognized Rib/Web Components of an Example Forging Section
Figure 33. Decomposed Forging Section Geometry Based on The Components Recognized in Figure 32
Once a forging section is decomposed, as mentioned at the beginning of this section, the geometric representation of the components needs to be transformed from XYR to ENTITY form. As described in section 5.3.3, the ENTITY representation for a rib include: width, height, step height, corner, fillet and draft. The ENTITY representation for a web include: length, thickness, height, corner, and draft. The geometric parameters, such as length, width, height, step height, thickness, and draft angle can be easily calculated for reasons given in section 5.3. Since corner, and fillet are used as pattern primitives, they can be determined directly from the pattern string. Whether a fillet is confined or unconfined can also be easily determined from the neighboring pattern primitive. That is, if the neighboring primitive is "b", it is confined; otherwise, it is "unconfined".

Based on this decomposition scheme, knowledge about various types of ribs and webs can be easily extracted from a forging section. It should be noted that this scheme does not distinguish a rib from a step, and a web from a deep recess. That is, a step is treated as a rib and a recess is treated as a web. This classification satisfies the design application for the current study. In case when they need to be distinguished, they can be further classified based on the height and length of these components.
5.5.2 Geometry Modification

In geometry modification, a task selected in Design or Refinement phase is performed. This task deals with the design or refinement of a key forging feature. The design (or refinement) of a key feature starts with the selection of a most appropriate rule from the rule set associated with this key feature, based on the design specifications and the forging geometry. The selection of the most appropriate rule, as described in section 5.4, is based on rule and generality order. That is, the highest priority and the most specific design (or refinement) rule is selected.

Based on the design (or refinement) requirement specified in the selected rule, a section component, i.e. rib or web, is selected for evaluation. The evaluation is done by comparing the requirement against the value of a geometric entity, associated with this design (or refinement) task, of this component. For example, if a design rule calls for minimum draft angle of 7 degrees, this value is compared with the draft angle of a rib or web. If a component does not satisfy the requirement given in the selected rule, the component geometry is modified.

Due to distinct problem solving requirements for design decision making and geometry manipulation, the modification of component geometry is done in two steps. First, the value of the geometric entity, associated with the design task, of the component is modified. The XYR representation of component geometry is then modified to reflect
the change of the geometric entity.

The modification of component in X Y R form can be done easily, as shown in Figure 34. To establish finish allowances or to increase web thickness, linear segments of the component geometry are shifted outward, while remaining parallel to the original segments, by the amount specified, as shown in Figure 34a. The refinement of finish allowances or web thickness is done similarly. To increase rib width for internal ribs, as shown in Figure 34b, the linear segment that corresponds to the top surface of a rib is extended on both sides by half of the increment required. For side ribs, also shown in Figure 34b, the linear segment is extended toward the internal side by the amount of increment required, in order to save material. To change draft angle, as shown in Figure 34c, the linear segment corresponding to the draft is modified to the angle specified while maintaining tangency to the corner arc. To increase corner or fillet radius, the R coordinate of the associated vertex is modified to meet the minimum requirement while maintaining "typical" cutter dimensions. For example, a radius of 0.621 inches is adjusted to 0.625 inches. In addition, in order to maintain the proper allowance requirement after the increase of corner radius, linear segments may be shifted outward, as illustrated in Figure 34d.

It is to be noted that the geometry entity evaluation and geometry modification are performed for one component at a time. The procedure iterates until all the components are evaluated and modified if necessary. If no geometry modification is made, the design (or
a. Establish Finish Allowances (left), and Increase Web Thickness (right).

b. Increase Rib Width

c. Establish Draft Angle

d. Before (left) and After (right) the Adjustment of a Rib Geometry to Maintain Proper Allowance.

Figure 34. Various Geometry Modifications Performed in XYR Form
refinement) for this key forging feature is completed. That is, the "evaluation-modification" cycle for this task is completed. It is to be noted that not all the components need to be evaluated for all design and refinement tasks. For example, only webs need to be evaluated for web thickness design or refinement.

5.5.3 Geometry Construction

In this step, the section geometry is modified so as to reflect any changes made in geometry modification step. This can be accomplished in various ways. A forging section geometry is represented by its boundary in X,Y,R form. Therefore, one way to modify the section geometry is to directly change its linear segments and associated radii, that are affected by the modified components. This modification is done such that the linear segments and radii match the corresponding ones in the modified component geometry. In this case, some linear segments may be modified by simply replacing the coordinates of their endpoints with the coordinates of the corresponding ones in the modified component. For those linear segments that connect two neighboring components, the coordinates of their endpoints may need to be changed so that the orientations and locations of these linear segments match those of the corresponding ones in the modified component.
While this approach works well for some forging sections, its geometry coverage is limited. This is because some linear segments or components in the machined section may be buried inside the forging section. For example, a deep recess may be removed during forging design. Thus, a more general approach is needed. In the current study, a constructive geometry scheme is used.

The constructive geometry scheme has been widely used to model various types of geometries, especially for solids, due to its abilities in providing an unambiguous and informationally complete representation of a geometry [38]. The basic idea is that complicated geometries can be represented as various ordered "additions" and "subtractions" of simpler geometries by means of the Boolean set operators, i.e. union, difference, and intersection. The Boolean operations are usually "regularized" in some way in order to prevent the creation of unrealistic features, such as dangling faces and edges [39].

To use the constructive scheme for modifying the forging section geometry, this modification should be treated as a geometry construction activity. This conceptual shift is possible and logical since forging design is performed at the component level and a new design can be constructed from the new geometries of these components. By using the constructive scheme, the difficulties associated with the approach that modifies geometry directly, can be overcome. Due to its inherent properties, the Boolean operation "union" will bury those linear segments and components that are lost during forging design.
To construct the modified forging section, in the current study, the Boolean operation "union" is used to add two geometries. In order to ensure the validity of the resulting section geometry without considering the sequence of these "addition" operations, a modified component is added to the original forging section first, as illustrated in Figure 35. In this figure, a modified rib is added to the original section. Another modified component is then added to the resulting section obtained from the previous operation. The modified forging design is obtained when all the modified components are added. The use of the original forging section as the backbone for the "addition" operation is valid since the current forging design process always adds material to the previous design. This approach also reduces the number of "addition" operations since components that are not modified need not be added.

The constructive scheme for the forging geometry construction mentioned above is based on the "union" operation. As shown in Figure 36a, the "union" of two geometries is done by traversing the vertices of a geometry, in clockwise direction, starting from a vertex that does not lie inside the other geometry. When a common point is encountered, the vertices of the other geometry are traversed. This process continues until the starting point is re-visited. This technique works well for most of the cases. However, it fails when the vertex of a geometry lies at the boundary of the other geometry, as shown in Figure 36b. This can be resolved by using the switching point, instead of the common point, as the basis for changing the geometry for traversing. A switching
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Figure 35. Before (left) and After (right) the "Addition" of a Modified Rib to the Forging Section
a. "Common Point" as the Basis to Change Geometry for Traversing

b. Traverse Fails when Vertices of one Geometry Lie on the Boundary of the Other Geometry

c. "Switch Point" as the Basis to Change Geometry for Traversing

Figure 36. Traverse Method Used to "Add" two Geometries
point is defined as a common point that has a large radius, measuring from the current to the next linear segments, for the other geometry, as illustrated in Figure 36c.

5.5.4 Geometry Verification

Two major functions are performed in the geometry verification step. One is to ensure the validity of the part geometry after geometry modification. Another is to allow design variations due to non-typical design. While the former function can be and should be automated, the latter function can be accomplished through the use of interactive computer graphics.

To validate the forging section geometry, the blending of neighboring arcs is most critical. Since forging geometry design is performed at component level, the interface surfaces between these components need to be made smooth. For example, non-smooth surface caused by two large neighboring fillet radii needs to be modified. This type of geometry consistency checking and modifications can be handled by the guidelines for forging geometry manipulation, implemented in rule form. Nevertheless, due to algorithmic nature of the required operations, it was felt proper to automate them by using the analytical geometry approach.
Three types of arc blendings may be automated. They are: (1) corner-corner, (2) fillet-fillet, and (3) corner-fillet types. As shown in Figure 37, the first type of geometric inconsistency was caused by two large neighboring corner arcs. This type of arc blending can be done by increasing the rib width so that a full radius can be constructed. The increase of the width for internal ribs is done by moving both side surfaces outward. For apparent material saving consideration, the increase of width for side ribs is done on internal side only.

The second type of geometric inconsistency, as shown in Figure 38, is caused by two large neighboring fillet arcs. Since the minimum fillet radius requirement is usually determined by the step height, this type of arc blending can be done by reducing the step heights so that a full radius can be constructed. To avoid adding too much volume to the forging section, the reduction of the step heights and fillet radii should be done by increasing the web thickness to the level when a full radius is possible, while maintaining the original aspect ratio between the fillet radius and step height. An absolute minimum for the fillet radius should also be enforced. When this is not possible, the deep and narrow recess is removed from the section, as shown in Figure 38b.

The third type of geometric inconsistency, as shown in Figure 39, is caused by large corner and fillet arcs. This type of arc blending can be done by changing the corner point coordinates. The new point coordinates are determined by locating a line which is tangent to the two neighboring arcs.
(a) Increase Width on Both Sides for Internal Rib

(b) Increase Width on Internal Side for Side Rib

Figure 37. Geometry Modification for Two Larger Corner Radii
(a) Reduce Radii so that a Full Radius Can be Constructed

(b) Eliminate Deep Recess when a Minimum Radius can not be Constructed

Figure 38. Geometry Modification for Two Large Fillet Radii
Figure 39. Geometry Modification for Large Corner and Fillet Radii:
(a) Before Modification, (b) After Modification.
To allow design variations, the design results should be first presented to the user. These may include: modified section geometry, parting line locations and tooling point. For reference purpose, the machined section geometry should also be included. The presentation of these geometries can best be made in computer graphics due to human's unique ability to process pictorial information. To allow a user to inquire about the design details, such as corner radii and draft angle, interactive computer graphics should be used to facilitate the interaction between the user and the display system.

The interactive computer graphics is also essential for making design changes by the user. Thus, the display system should provide facilities to allow the user to modify all the key forging design features, such as draft angle, corner radii, etc. Since a forging designer works at a higher conceptual level, the interactive computer graphics system for forging design display and modification application should interact with the designer in terms of design features. For example, draft angle, instead of line angle, should be used.

Due to these requirements, a forging design display and modification system was developed. This specialized interactive graphics system displays: geometries of machined section and forging section, parting line and tooling point. An example display by this system is shown in Figure 40. In this figure, the machined section is indicated by dashed lines and the forging section is represented by solid lines. In addition, the parting line is represented by a different type of dashed lines, and the tooling point is represented by
Figure 40. Forging (Solid) and Machined (Dashed) Geometries Displayed by the AFD Display Module
a circle. This system also provides detail information about these sections in response to the user's request. This information includes: (1) perimeter, area and centroid of a section; (2) draft angle; (3) coordinates of a corner and the associated radius; and (4) thickness, height, width, and length of a rib or web.

The design modification capabilities provided by this system include the modifications for parting line, forging plane, draft angle, corner and fillet radii, and finish allowances. In addition, it also allows the modification of the coordinates of the corners for a section. The operators used to modify corners include: move, delete, and add. Thus, this capability facilitates not only the change of the overall shape but also the creation of a section geometry. The command hierarchy of this display and modification system is given in Table 1.

In order to ensure the validity of the modification operation, the modified or created section geometry will go through the entire geometry verification procedure. That is, the blending of arcs will be performed if necessary. The geometry verification step is completed when a validated section geometry is not further modified.
Table 1. AFD Graphics System Command Hierarchy

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machined Section</td>
<td>Exit</td>
<td></td>
<td>Exit</td>
</tr>
<tr>
<td></td>
<td>Draft Angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geom. Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width/Thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X Y R Coordinates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modify</td>
<td></td>
<td>Exit</td>
</tr>
<tr>
<td></td>
<td>Forging Plane</td>
<td></td>
<td>Add</td>
</tr>
<tr>
<td></td>
<td>Draft Angle</td>
<td></td>
<td>Delete</td>
</tr>
<tr>
<td></td>
<td>Width/Thickness</td>
<td></td>
<td>Move</td>
</tr>
<tr>
<td></td>
<td>Radius</td>
<td></td>
<td>Construct</td>
</tr>
<tr>
<td></td>
<td>Vertex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forging Section</td>
<td>Exit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angle</td>
<td></td>
<td>Exit</td>
</tr>
<tr>
<td></td>
<td>Coordinates</td>
<td></td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>Modify</td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>Parting Line</td>
<td>Exit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angle</td>
<td></td>
<td>Exit</td>
</tr>
<tr>
<td></td>
<td>Coordinates</td>
<td></td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>Modify</td>
<td></td>
<td>Right</td>
</tr>
<tr>
<td>Tooling Point</td>
<td>Exit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coordinates</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modify</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redraw</td>
<td>Exit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 6

IMPLEMENTATION AND RESULTS

Based on the knowledge based approach presented in Chapter 5, an automated forging design (AFD) system is implemented. In this chapter, the actual implementation of this AFD system is described. Several example designs generated by this system are also given.

6.1 The Automated Forging Design (AFD) System

A modular approach was taken to implement the AFD system. As shown in Figure 41, the AFD system consists of a Forging Design Data Base and 4 main modules, namely, AFD Control, AFD Input, AFD Design and AFD Output Modules. The Forging Design Data Base contains forging design specifications, such as forging part geometries, forging processing conditions and special forging design considerations. It is used as a working memory and its information can be accessed by all AFD system modules. The AFD Control Module performs AFD system initialization and overall execution controls. The AFD Input Module accepts forging design specifications from the user. It also checks for validity of the input data. The AFD Design Module designs a forging geometry based on the knowledge based approach described in Chapter 5. The AFD Output Module outputs design results to files.
Figure 41. Architecture of the AFD System
The AFD Design Module can further be divided into Geometry Design Module and Geometry Manipulation Module. These two modules work in cooperative fashion to design the forging geometry. That is, the Geometry Design Module performs forging design decision making by applying the most appropriate forging design guidelines based on the given design specifications and the forging geometry. The Geometry Manipulation Module modifies forging geometry based on the necessary geometry modifications determined in the Geometry Design Module. The modified forging geometry is then used by the Geometry Design Module for making design decisions. This process is iterated until a satisfactory forging design is obtained.

As shown in Figure 42, the Geometry Design Module consists of a Forging Design Knowledge Base, a Forging Resource Knowledge Base, a Forging Design Control Module, and a Forging Design Control Data Block. The Forging Design Knowledge Base contains the forging design task hierarchy (Figure 16), forging geometry design guidelines, and forging design sequence guidelines. These guidelines are represented in rule form, described in section 5.2.2. Rules that perform the same design task are attached to that task in the hierarchy. The Forging Resource Knowledge Base contains knowledge, about the available forging resources, that are essential for forging design. This information is represented in a hierarchy, as described in section 5.2.3. The hybrid forging design control scheme, described in section 5.4, is implemented in the Forging Design Control Module. The Forging Design Control Data Block contains essential control data that will be used by the Control
Figure 42. Architecture of the AFD Geometry Design Module
The Forging Geometry Manipulation Module performs all geometry manipulation and graphics related activities during the forging geometry design process. As shown in Figure 43, it contains modules for establishing: parting line, forging plane, finish allowance, draft angle, rib width, web thickness, corner radii, and fillet radii. It also contains a postprocessing module for forging section decomposition, construction, and verification, and an interactive graphics module for forging design display and modification.

Due to the diversity of problem solving activities involved in forging design, different kinds of programming languages and tools are used to implement the AFD system. They include a knowledge based system development tool (Knowledge Craft) from Carnegie Group, a symbolic language (VAX Lisp) from Digital, a procedural language (Fortran 77) from Digital, and a command language (DCL) from Digital. It is to be noted that the selection of the type of languages and tools are based mainly on the functional requirements of the forging design activities. For example, forging geometry manipulation, due to its algorithmic nature, is best handled by a procedural language, such as Fortran. Forging design decision making, due to its symbolic manipulation requirements, is best done by a symbolic language, such as Lisp. Nevertheless, the selection of a particular language and tool is strongly affected by the accessibility of the software and the VAX computing environment.
Figure 43. Architecture of the AFD Geometry Manipulation Module
Knowledge Craft, written in Common Lisp [40], is a frame based system. It provides an integrated knowledge representation and problem solving environment [41]. Its frame based language also allows the representation of user-definable relations, meta-knowledge and demons. A variety of problem solving techniques are integrated into the frame based representation. They include: a logical programming language (Prolog), a rule-based programming language (OPS-5), an object programming language based on message sending paradigm, and agenda mechanism for event based simulations. In the AFD system, Knowledge Craft is used to implement the Forging Design Data Base, Forging Design Knowledge Base, Forging Resource Knowledge Base, and Forging Design Control Data Block. More specifically, the frame constructs of Knowledge Craft are used to represent the forging design specifications, forging task hierarchy, forging design rules, forging design resource hierarchy and design control data.

VAX Lisp [42] is an extended implementation of the Common Lisp language. In the AFD system, VAX Lisp is used to implement the AFD Control, AFD Input, AFD Output, AFD Design, Geometry Design, and Forging Design Control Modules. More specifically, VAX Lisp programs and functions are developed to control the execution of AFD system, to input forging design specifications, to output forging design results, and to control the forging design activities. In addition, miscellaneous functions that are referred in the design rules are implemented in VAX Lisp. Important extensions, provided by the VAX Lisp, are also used in the AFD system. For example, "SPAWN" is used to transfer control from
the Geometry Design Module to the Geometry Manipulation Module.

Forging geometry manipulation and graphics related modules are implemented in Fortran. The activation of these modules is controlled by a command procedure, implemented by using DCL (Digital Command Language). For efficiency, the data communication between Geometry Design and Geometry Modification modules are accomplished through files.

For each forging design session, the AFD system will likely go through four major stages. They are: initialization, input, design, and output stages. The "initialization" stage starts when the AFD system is loaded into the Lisp environment. In this stage, the forging design task and resource hierarchies are initialized. The design specifications are then provided by the user in the "input" stage. Based on the given design specifications, the forging geometry design is performed in the "forging geometry design" stage. In the "output" stage, the forging geometry designed is saved in a file. While these stages are to be performed in sequence, these four stages, implemented in the AFD system, can be performed in any sequence as long as it is valid. For example, the AFD system allows a user to switch from the "design" stage to the "input" stage for changing design specifications. But, the AFD system will not allow a user to enter the "design" stage unless a set of valid design specifications is given. In the following sections, major activities performed during these four stages are described.
6.1.1 Initialization Stage

This stage starts with the specification of the type of terminal in use. This information is essential since various types of graphics terminals are supported by the interactive graphics module. The AFD system is then loaded into the VAX Lisp environment. To conserve memory, not all the AFD system modules are loaded at this stage. For example, design rules are not loaded until they need to be accessed, and geometry manipulation modules are not loaded until they are used.

Once the AFD system is loaded, the task hierarchy, design control data block, and forging part hierarchy are initialized. Since a forging section is not yet given, the forging part hierarchy is only partially established. The system initialization is done by establishing or restoring defaults for pre-determined slots or frames. Upon the completion of this stage, a completion mark is recorded in the "AFD-initialization" attribute of the AFD Control Data Block.

It is to be noted that the AFD system needs not be re-loaded for subsequent sessions for different forging section designs. But, the AFD system needs to be initialized for each design session since some slots may contain values that are not valid for the new forging section.
6.1.2 Input Stage

During input stage, the forging design specifications are given. The design specifications to be provided by the user include machined section geometry, associated forging process conditions, and special design considerations. These data can be either read in from a file or specified by the user interactively. When reading from a file, each type of data contains a keyword that defines the type of data. This approach greatly facilitates the flexibility of input data. These keywords and their meaning are briefly described in Table 2. An example input data file, using this keyword format, is shown in Figure 44.

As can be seen from this Table, the AFD system input data can be roughly classified into three categories. The first category contains forging process related input data, such as forging type, material type, etc. The valid forging geometries for the AFD system include structural or axisymmetric types. The valid types of forging processes, forging materials, and forging equipments are those that are defined in the Forging Resource Knowledge Base. The part identification code is optional. If specified, it will be displayed by the interactive graphics module of the AFD system. The forging temperature needs not be specified if the default value defined in the Forging Resource Knowledge Base is to be used.

The second category contains geometry related input data. Since the AFD system is to design forging section geometry starting from machined section geometry, machined section geometry needs to be
Table 2. AFD System Input data

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(1) Forging Process Related Data</strong></td>
<td></td>
</tr>
<tr>
<td>PART-TYPE</td>
<td>Forging geometry type; eg. structural</td>
</tr>
<tr>
<td>FORGING-TYPE</td>
<td>Forging process type; eg. conventional</td>
</tr>
<tr>
<td>MATERIAL-TYPE</td>
<td>Forging material type; eg. AL7075</td>
</tr>
<tr>
<td>EQUIPMENT-TYPE</td>
<td>Forging press type; eg. hydraulic-press</td>
</tr>
<tr>
<td>LOT-SIZE</td>
<td>Production quantity</td>
</tr>
<tr>
<td>* TEMPERATURE</td>
<td>Forging temperature</td>
</tr>
<tr>
<td>* PART-ID</td>
<td>Part identification code</td>
</tr>
<tr>
<td>* DESCRIPTION</td>
<td>General notes about this forging</td>
</tr>
<tr>
<td><strong>(2) Forging Geometry Related Data</strong></td>
<td></td>
</tr>
<tr>
<td>MACHINED-SECTION-XYR</td>
<td>Machined section geometry in XYR form</td>
</tr>
<tr>
<td>TOOLING-POINT</td>
<td>Tooling point</td>
</tr>
<tr>
<td>* ESTIMATED-FORGING-LENGTH</td>
<td>Estimated forging length</td>
</tr>
<tr>
<td>* ESTIMATED-FORGING-PVA</td>
<td>Estimated forging plan view area</td>
</tr>
<tr>
<td>* ESTIMATED-FORGING-WEIGHT</td>
<td>Estimated forging weight</td>
</tr>
<tr>
<td><strong>(3) Special Design Considerations</strong></td>
<td></td>
</tr>
<tr>
<td>* PARTING-LINE</td>
<td>Parting line for the section</td>
</tr>
<tr>
<td>* FORGING-PLANE</td>
<td>Forging plane</td>
</tr>
<tr>
<td>* MIN-MACHINING-ALLOWANCE</td>
<td>Minimum machining allowance</td>
</tr>
<tr>
<td>* MIN TOOLING-ALLOWANCE</td>
<td>Minimum tooling allowance</td>
</tr>
<tr>
<td>* MIN-MISMATCH-ALLOWANCE</td>
<td>Minimum mismatch allowance</td>
</tr>
<tr>
<td>* MIN-CLOSURE-ALLOWANCE</td>
<td>Minimum closure allowance</td>
</tr>
<tr>
<td>* MIN-SHRINKAGE-ALLOWANCE</td>
<td>Minimum shrinkage allowance</td>
</tr>
<tr>
<td>* MIN-Straightness-ALLOWANCE</td>
<td>Minimum straightness allowance</td>
</tr>
<tr>
<td>* MIN-WEb-THICKNESS</td>
<td>Minimum web thickness</td>
</tr>
<tr>
<td>* MIN-RIB-WIDTH</td>
<td>Minimum rib width</td>
</tr>
<tr>
<td>* MIN-CORNER-RADII</td>
<td>Minimum corner radii</td>
</tr>
<tr>
<td>* MIN-FILLET-RADII</td>
<td>Minimum fillet radii</td>
</tr>
<tr>
<td>* MIN-DRAFT-ANGLE</td>
<td>Minimum draft angle</td>
</tr>
</tbody>
</table>

Note: * - Optional input data
<table>
<thead>
<tr>
<th>PART-ID</th>
<th>afd001</th>
</tr>
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<tbody>
<tr>
<td>DESCRIPTION</td>
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<td>FORGING-TYPE</td>
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<td>MATERIAL-TYPE</td>
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<tr>
<td>EQUIPMENT-TYPE</td>
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<tr>
<td>LOT-SIZE</td>
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<td>MACHINED-SECTION-XYR</td>
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</tr>
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<td>0 2 0</td>
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</tr>
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<td>2 2 0</td>
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<td>11 2 0</td>
<td></td>
</tr>
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<td>12 2 0</td>
<td></td>
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<td>4 -1 0</td>
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</tr>
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<td>0 -1 0</td>
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</tr>
</tbody>
</table>

Figure 44. An Example Input File for the AFD System
specified. As described in section 5.3, the input data for this geometry is to be represented by its boundary curves using the XYR form in the clockwise direction. Since the tooling point is used to determine the shrinkage allowance for the forging section, X and Y coordinates of the tooling point that will affect this allowance need to be specified. The estimated values for forging length, PVA, and weight may be given as the input data. If not provided, these estimates will be either generated by the AFD system for axisymmetric parts, or requested from the user for structural parts, during the design stage.

The third category contains special design considerations for all key forging design features. For structural parts, the locations of parting lines and the orientation of forging plane may be affected by the neighboring sections. Thus, they may be given as input data even though they may be determined during the design stage. The minimum values for the key design features, such as draft angle and corner radii, may be used to override the values stored in the design rules. For example, if minimum draft angle is given, this value is compared with the minimum value determined by the draft angle design guidelines, and the larger minimum value will be used.

The provided input data is validated before they are stored in the Forging Design Data Base. In addition, the AFD system provides facilities to allow the user to examine and modify these specifications. Upon completion of the input stage, a completion mark is recorded in the "AFD-input" attribute of the AFD Control Data Block.
6.1.3 Design Stage

During the design stage, the forging geometry is designed based on the given design specifications. This is done by performing all the necessary design tasks under each design phase, as described in section 5.5. These tasks are performed in a design sequence determined by the sequence knowledge stored in the Forging Design Knowledge Base. A design task is performed by selecting and applying the most appropriate rules from the Forging Design Knowledge Base based on the design specifications and forging geometry stored in the Forging Design Data Base. The forging geometry is then modified according to the necessary changes specified by this rule. For each task in Design and Refinement phases, the "evaluation-modification" task design cycle, described in section 5.5, is performed. At the completion of each design task, the contents of the Forging Design Data Base are updated and the modified geometry is presented to the user in graphics form. The design stage is completed when a satisfactory forging section geometry is obtained.

To facilitate the control of the forging geometry design process, a step by step design option is also provided by the AFD system. Once selected, this option displays the selected design rule for a design task before it is applied. A user can either reject or accept the selection. If accepted, this design rule is applied and the modified forging section is presented to the user in graphics form. If the current selection is rejected, another selection is made by the AFD system by searching through the Forging Design Knowledge Base for the
next best design rule. This process continues until a design rule is accepted by the user.

To make the design rationale explicit, an explanation facility is also provided by the AFD system. This facility displays all the design rules applied thus far in a reverse order. That is, the most recent design rule applied is displayed first.

### 6.1.4 Output Stage

During the output stage, design results are saved in files for further processing. Two output files are provided by the AFD system. One file stores all the design rules applied. Another file stores the geometry related results. The design rules output file contains all the design rules applied according to their application order. The contents of this file is illustrated by an example file, given in Figure 45.

For reference purposes, input data provided by the user and major design parameters used by the AFD system are also included in the geometric result file. As shown in Table 3, this output file is similar to the input file. It uses the same keyword format and contains all the keywords given in the input file. The extra data contained in the output file include the forging section geometry in X,Y,R form, and calculated forging section length, area, and centroid. Also can be seen from this Table, the "part-id" and "description" are the only data that may not appear in the geometric result file.
TM001: Perform AFD pre-design tasks

P-001: Parting line not given, establish parting line next

P-PL-002: Establish parting line at the flat surface if possible; at the center of webs, otherwise.

P-002: Forging plane not given, establish forging plane next

P-FP-003: Eastablish forging plane so that it intersects parting-line at 0.5 inch beyond the endpoints; Back drafts are removed

P-FL-002: Estimate forging length, based on machined section length

P-FV-002: Request forging PVA estimate from user

P-FW-002: Request forging weight estimate from user

P-006: AFD Pre-Design tasks completed, Perform AFD Design tasks

D-001: Establish finish allowances next

D-MA-001: Determine machining allowance (.06 inches)

D-FA-007: Establish finish allowance based on determined allowances

D-002: Evaluate/Modify minimum web thickness next

D-007: AFD design tasks completed, Perform AFD refinement tasks

R-SA-001: Evaluate/Refine straightness allowances for conventional aluminum/steel forging, per rule D-SA-001

R-004: Part design not refined, AFD refinement tasks completed

TM004: AFD forging geometry design completed

Figure 45. An Example Rule Output File Generated by the AFD System
Table 3. AFD System Output data

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(1) Forging Process Related Data</strong></td>
<td></td>
</tr>
<tr>
<td>PART-TYPE</td>
<td>Forging geometry type; eg. structural</td>
</tr>
<tr>
<td>FORGING-TYPE</td>
<td>Forging process type; eg. conventional</td>
</tr>
<tr>
<td>MATERIAL-TYPE</td>
<td>Forging material type; eg. AL7075</td>
</tr>
<tr>
<td>EQUIPMENT-TYPE</td>
<td>Forging press type; eg. hydraulic-press</td>
</tr>
<tr>
<td>LOT-SIZE</td>
<td>Production quantity</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Forging temperature</td>
</tr>
<tr>
<td>* PART-ID</td>
<td>Part identification code</td>
</tr>
<tr>
<td>* DESCRIPTION</td>
<td>General notes about this forging</td>
</tr>
<tr>
<td><strong>(2) Forging Geometry Related Data</strong></td>
<td></td>
</tr>
<tr>
<td>MACHINED-SECTION-XYR</td>
<td>Machined section geometry in XYR form</td>
</tr>
<tr>
<td>FORGING-SECTION-XYR</td>
<td>Forging section geometry in XYR form</td>
</tr>
<tr>
<td>TOOLING-POINT</td>
<td>Tooling point</td>
</tr>
<tr>
<td>ESTIMATED-FORGING-LENGTH</td>
<td>Estimated forging length</td>
</tr>
<tr>
<td>ESTIMATED-FORGING-PVA</td>
<td>Estimated forging plan view area</td>
</tr>
<tr>
<td>ESTIMATED-FORGING-WEIGHT</td>
<td>Estimated forging weight</td>
</tr>
<tr>
<td>FORGING-SECTION-LENGTH</td>
<td>Calculated forging section length</td>
</tr>
<tr>
<td>FORGING-SECTION-AREA</td>
<td>Calculated forging section area</td>
</tr>
<tr>
<td>FORGING-SECTION-CENTROID</td>
<td>Calculated forging section centroid</td>
</tr>
<tr>
<td><strong>(3) Major Design Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>PARTING-LINE</td>
<td>Parting line for the section</td>
</tr>
<tr>
<td>FORGING-PLANE</td>
<td>Forging plane</td>
</tr>
<tr>
<td>MIN-MACHINING-ALLOWANCE</td>
<td>Minimum machining allowance</td>
</tr>
<tr>
<td>MIN-TOOLING-ALLOWANCE</td>
<td>Minimum tooling allowance</td>
</tr>
<tr>
<td>MIN-MISMATCH-ALLOWANCE</td>
<td>Minimum mismatch allowance</td>
</tr>
<tr>
<td>MIN-CLOSURE-ALLOWANCE</td>
<td>Minimum closure allowance</td>
</tr>
<tr>
<td>MIN-SHRINKAGE-ALLOWANCE</td>
<td>Minimum shrinkage allowance</td>
</tr>
<tr>
<td>MIN-STRAIGHTNESS-ALLOWANCE</td>
<td>Minimum straightness allowance</td>
</tr>
<tr>
<td>MIN-WEB-THICKNESS</td>
<td>Minimum web thickness</td>
</tr>
<tr>
<td>MIN-RIB-WIDTH</td>
<td>Minimum rib width</td>
</tr>
<tr>
<td>MIN-CORNER-RADII</td>
<td>Minimum corner radii</td>
</tr>
<tr>
<td>MIN-FILLET-RADII</td>
<td>Minimum fillet radii</td>
</tr>
<tr>
<td>MIN-DRAFT-ANGLE</td>
<td>Minimum draft angle</td>
</tr>
</tbody>
</table>

Note: * - These data appear only if they are specified in the Input.
Similar to the input file, data in this output file can be classified into three categories. The first category contains all the process related data, such as forging type. The second category contains geometry related data, such as forging section geometry. The third category contains the major design parameters, such as minimum corner radii. These parameters correspond to the special design considerations in the input file. Nevertheless, the value for a major design parameter may not be the same as that of the corresponding design consideration. This is because the data contained in these design parameters are the actual values used in designing the forging section. An example geometry result file, using this keyword format, is shown in Figure 46.

Due to their similarity, the geometry result file may be used as the input file for AFD system to allow alternative designs. To implement this option, the status of the AFD system, particularly the status of design tasks, needs to be recorded in the output file.

6.2 Example Designs

To demonstrate how the AFD system works, a complete forging section geometry design session is first described. Several design results generated by the AFD system are then shown to illustrate the capabilities of the system.
PART-ID: afd001
DESCRIPTION: "AL7075, Conventional"
PART-TYPE: structural
FORGING-TYPE: conventional
MATERIAL-TYPE: AL7075
EQUIPMENT-TYPE: hydraulic-press
TEMPERATURE: 700
LOT-SIZE: 200
TOOL-POINT: 0.0 0.5
ESTIMATED-FORGING-LENGTH: 12.5
ESTIMATED-FORGING-PVA: 106.25
ESTIMATED-FORGING-VOLUME: 79.25
ESTIMATED-FORGING-WEIGHT: 37.56
FORGING-SECTION-CENTROID: 6.277 0.321
FORGING-SECTION-LENGTH: 13.0043
FORGING-SECTION-AREA: 85.4794
MIN-MACHINING-ALLOWANCE: 0.06
MIN-TOOLING-ALLOWANCE: 0.03
MIN-MISMATCH-ALLOWANCE: 0.06
MIN-STRAIGHTNESS-ALLOWANCE: 0.030
MIN-CLOSURE-ALLOWANCE: 0.015
MIN-SHRINKAGE-ALLOWANCE: 0.030
MIN-WEB-THICKNESS: 0.200
MIN-RIB-WIDTH: 0.125
MIN-CORNER-RADII: 0.063
MIN-FILLET-RADII: 0.125
MIN-DRAFT-ANGLE: 5.000
MACHINED-SECTION-XYR: 22
        0.0000  2.0000  0.0000
       2.0000  2.0000  0.0000
       2.0000  5.0000  0.0000
        . . . . . . . . . . . . . .
FORGING-SECTION-XYR: 24
         -0.41856 0.50000 0.00000
         -0.27197 2.17556 0.15625
          1.45840 2.17556 0.87500
        . . . . . . . . . . . . . .
PARTING-LINE: 4
         -0.41856 0.50000 0.00000
         -1.41856 0.50000 0.00000
          12.58572 0.50000 0.00000
          13.58572 0.50000 0.00000
        TOOLING-POINT: 0.00000 0.50000
        FORGING-PLANE: 0.0 0.0 1.0 0.0

Figure 46. An Example Geometry Output File Generated by the AFD System
A set of design specifications, used to demonstrate the forging design session, is shown in Figure 47. The AFD system and user interaction for this design session is illustrated in Figure 48. After the AFD system is loaded and initialized, the AFD main menu is displayed. By selecting the "Input" option, the AFD input menu is displayed. These design specifications are then read into the AFD system using the "File Input" option. The validity of these input data are checked upon exiting from the input option.

After selecting the "Design" option from the AFD main menu, the AFD design menu is displayed. As can be seen from this menu, the next design task is activated by selecting the "Continue Design Tasks" option. The "One-step" switch is used to control the mode of design. If this switch is set to ON, the forging geometry design will be done in a step by step fashion, as described in section 6.1.3. The design rules applied can be examined by selecting the "Examine Rules Applied" option. The current section geometry can be displayed by selecting the "Display Part Geometry" option. By repeatedly selecting the "Continue Design Tasks" option, the forging section geometry is designed, based on this given set of design specifications, in the following order:

1. Enter Pre-Design Phase

2. Establish Parting Line
   The parting line is established so that it passes through the maximum periphery of the section and the center of webs, as shown
Figure 47. Design Specifications for the Demonstration Forging Section
* * * Provide forging design specifications, through a file
* * *

AFD Main Menu

0 - Exit
1 - Input Part Geometry
2 - Design Forging Geometry
3 - Output Designed Geometry

AFD Input Mode

0 - Exit
1 - File Input
2 - Display/Modify Part Specifications
3 - Display/Modify Section Specifications

Enter INPUT file name: AFD001.DAT

AFD Input Mode

0 - Exit
1 - File Input
2 - Display/Modify Part Specifications
3 - Display/Modify Section Specifications

AFD Input Checking in Progress...
AFD Input OK

* * *
* Design Forging Geometry
* *

AFD Main Menu

0 - Exit
1 - Input Part Geometry
2 - Design Forging Geometry
3 - Output Designed Geometry

Figure 48. Interactions Between the AFD System and the User for the Demonstration Forging Section Design (User Responses are Underlined)
Design Forging Geometry in "continuous" mode

AFD Design Mode

0 - Exit
1 - Toggle one-step switch (OFF)
2 - Continue Design tasks
3 - Display Part Geometry
4 - Examine Rules Applied

Parting Line Established.
Display Result [Y]? N

Examine forging guideline used

AFD Design Mode

0 - Exit
1 - Toggle one-step switch (OFF)
2 - Continue Design tasks
3 - Display Part Geometry
4 - Examine Rules Applied

P-PL-002: Establish parting line at the flat surface if possible;
at the center of webs, otherwise.

More applied rule (Y/N)? N

Figure 48. (Continued)
Design forging geometry in "one-step" mode

AFD Design Mode
----------------------------------------
0 - Exit
1 - Toggle one-step switch (OFF)
2 - Continue Design tasks
3 - Display Part Geometry
4 - Examine Rules Applied 1

AFD Design Mode
----------------------------------------
0 - Exit
1 - Toggle one-step switch (ON)
2 - Continue Design tasks
3 - Display Part Geometry
4 - Examine Rules Applied 2

P-002: Establish forging plane next
Apply this rule (Y/N)? Y

P-FP-003: Establish forging plane so that it intersects parting-line at 0.5 inch beyond the endpoints; Back drafts are removed
Apply this rule (Y/N)? Y

Forging Plane Established.
Display Result [Y]? N

Figure 48. (Continued)
Output Forging Design Results

AFD Main Menu
==================================
0 - Exit
1 - Input Part Geometry
2 - Design Forging Geometry
3 - Output Designed Geometry

Output part geometry and processing conditions...
Enter OUTPUT file name: AFD001.OUT

Output forging design guidelines applied...
Enter OUTPUT file name: AFD001.RULE

Figure 48. (Continued)
in Figure 49a.

3. Establish Forging Plane

The forging plane is established in such a way that it intersects with the parting line at 0.5 inches beyond the ends of the forging section, as shown in Figure 49b.

4. Enter Design Phase

Since estimated forging length, PVA, and weight are given as input data, Pre-Design phase is completed, and tasks in Design phase are performed next.

5. Establish Finish Allowances

Various allowances (in inches) are determined and applied to this section geometry. They include:

- Machining Allowance = 0.060,
- Tooling Allowance = 0.030,
- Mismatch Allowance = 0.060,
- Closure Allowance = 0.015,
- Shrinkage Allowance = 0.030,
- Straightness Allowance = 0.030.

The section geometry after the finish allowance application is shown in Figure 49c.

6. Establish Web Thickness

For this section geometry, the minimum web thickness is 0.2 inches.
Figure 49. Design Evolution of the Forging Geometry (for the Design Specifications Given in Figure 47) as Generated by the AFD System.
FORGING PLANE ESTABLISHED

Figure 49. (Continued)
ALLOWANCES ESTABLISHED

Figure 49. (Continued)
CORNER RADIi ESTABLISHED

Figure 49. (Continued)
DRAFT ANGLE ESTABLISHED

Figure 49. (Continued)
FILLET RADIi ESTABLISHED

Figure 49. (Continued)
FORGING GEOMETRY

Figure 49. (Continued)
Since all webs in this section exceed this thickness minimum requirement, no modification of the section geometry is necessary.

7. Establish Rib Width
For this section geometry, the minimum web thickness is 0.125 inches. Since all ribs in this section exceed this minimum requirement, no modification of the section geometry is necessary.

8. Establish Corner Radii
For this section geometry, the corner radii are determined by rib heights, with a minimum radius of 0.063 inches. In addition to changing the corner radii, the linear segments of the section geometry are also modified to maintain the minimum allowance requirements around the corners, as shown in Figure 49d.

9. Establish Draft Angle
A 5 degree angle is applied for all drafts in this section. The drafts meeting at the parting line endpoints are adjusted in such a way that 5 degree angle is maintained. The modified section geometry is shown in Figure 49e.

10. Establish Fillet Radii
For this section geometry, the fillet radii are determined by the step heights, with a minimum radius of 0.125. Deep recesses are made shallow so that the construction of a full radius is possible. The modified section geometry is shown in Figure 49f. It should be
noted that constant fillet radii are not enforced in this design.

11. Enter Refinement Phase
All the design tasks under Design phase have been performed and a preliminary forging section design is obtained. Since estimated forging length, PVA and weight were used in determining straightness allowance, mismatch allowance, closure allowance, and minimum web thickness, they need to be validated.

12. Refine Finish Allowance
New estimates for forging length, PVA, and weight are obtained. They are used to determine the extra allowances required for the forging section. No modification for this section geometry is performed since the original and new estimates generate the same amount of finish allowances.

13. Refine Web Thickness
The new estimates for forging length, PVA, and weight are also used to determine the minimum web thickness required for the forging section. No modification for this section geometry is performed since all webs in this section exceed the new minimum thickness requirement.

14. Complete Forging Design
No iteration of the refinement tasks is required since no change is made to the section geometry in steps 12 and 13. Thus, the forging
geometry design is completed, as shown in Figure 49g.

It is to be noted that the above description of the forging design process is a simplified version of the actual design process performed by the AFD system. Nevertheless, it does show the major activities performed by the AFD system. For an actual forging design session, accurate estimates may not be obtained easily. Thus, many iterations may be needed before a satisfactory design can be obtained.

Once the forging geometry design is completed, the designed forging geometry and design rules applied can then be saved in files by selecting the "Output Designed Geometry" option.

By using the same set of design specifications with a different forging type, i.e. "blocker" instead of "conventional", the AFD system generates a different section geometry, as shown in Figure 50. The principle design changes are enlargement of the corner and fillet radii, and more generous finish allowances. This alteration in section design resulted in a forging that can be completed in blocker-type dies, thereby eliminating the conventional finishing operation. Other design feature, including parting line locations and draft angle, remained unchanged.

The same effect can be seen from another section geometry design with the same set of design specifications, except the material type is changed from Al7075 to Ti-64. The Ti-64 provides a favorable ratio of strength to weight at elevated temperature, while it is more difficult to forge than Al7075. The Ti-64 section designed by the AFD
Figure 50. Forging Section Geometry Generated by the AFD System Based on Design Specifications Given in Figure 47. (Except the Forging Type)
system is shown in Figure 51. Compared to the AL7075 section, the TI-64 section has more generous radii and finish allowances. In addition, a 7 degree, instead of 5 degree, draft angle is used for TI-64 section. These differences in section designs are due to the forgeability of the material used.

Two example designs, generated by the AFD system, are used to demonstrate how the AFD system can be used to explore the alternative parting line designs. These sections use the same set of design specifications, as shown in Figure 52a. The only difference is the parting line location. Figure 52b shows the designed forging section when the parting line is established at the center of webs. Figure 52c shows the forging section when the parting line is established at the top surface. If forging weight is the main design criterion, the section shown in Figure 52b is less desirable since its design requires more forging weight. Nevertheless, the section shown in Figure 52c is more difficult to forge and the die sinking costs may be higher because its design has a deeper impression. To obtain an optimal design, design criteria, such as weight or die costs, need to be determined first. Design rules that make design decisions based on these criteria can then be included in the AFD system. In addition, iterations between several design tasks, eg. parting line design and forging plane design in this case, may be required. Thus, the iteration knowledge needs also be encoded and included in the AFD system.
Figure 51. Forging Section Geometry Generated by the AFD System Based on Design Specifications Given in Figure 47. (Except the Material Type)
PART-ID
DESCRIPTION
PART-TYPE
FORGING-TYPE
MATERIAL-TYPE
EQUIPMENT-TYPE
LOT-SIZE

AFD005
"Parting Line Design Alternatives"
Axisymmetric
Conventional
AL7075
Hydraulic-Press
200

(a) Design Specifications

Figure 52. Use of AFD System to Explore Parting Line Design Alternatives
(b) Not Desirable Design

(c) Desirable Design

Figure 52. (Continued)
Another two example designs, generated by the AFD system, are used to demonstrate the use of the AFD system to explore the alternative forging plane designs. The same set of design specifications, shown in Figure 53a, is used to design these two sections. The only differences are the orientation of forging plane and the location of parting line. Figure 53b shows the "L" shaped forging design that requires extra material for the drafts. Figure 53c shows the "V" shape design that has natural drafts. Again, if forging weight is the main design criterion, the section shown in Figure 53b is less desirable since its design requires more forging weight. Nevertheless, the section shown in Figure 53c requires more expensive tooling since a flat die can be used in producing the lower section shown in Figure 53b. To obtain an optimal design for this case, the required design iterations may include all tasks in the Pre-Design and Design phases since the draft angle is usually established at the later stage of Design phase. In addition, when designing forging geometry to allow natural drafts, possible die shift should be avoided. For this purpose, a die force calculation module may be included.

The above examples demonstrates the capabilities of the AFD system in designing forging geometries. With limited forging design knowledge, the current version of AFD system is capable of generating acceptable (but not necessarily optimal) designs for rib-web type of forgings. Nevertheless, the AFD system structure allows easy implementation of additional forging design knowledge. By including knowledge for optimal forging design, the AFD system can be a powerful
Figure 53. Use of AFD System to Explore Forging Plane Design Alternatives
**Figure 53. (Continued)**

- **L SHAPE DESIGN**
- **V SHAPE DESIGN**

(b) Not Desirable Design

(c) Desirable Design
tool to aid the designer in designing forging geometries.
CHAPTER 7

CONCLUSIONS

This chapter concludes the presentation for the current study. The current study is first summarized, followed by the discussions of major findings related to this study. The contributions of this research are then identified. The last section gives recommendations for similar studies and possible new research related to this work.

7.1 Summary of Research

The computerization of forging geometry design is essential in preserving the gradually disappearing design knowhow and providing the much needed productivity gains for the forging industry. It is also essential for the development of an integrated CAE system for forging design and manufacturing. It is known that effective knowledge representation and problem solving schemes are needed to facilitate the computerization of the "knowledge" and "computing" intensive forging design task. Thus, using a combination of knowledge based and algorithmic techniques, an automated forging design (AFD) system was developed to computerize the forging section geometry design for structural or axisymmetric parts.
The AFD system separates the forging design decision making from the forging geometry manipulation. Due to its algorithmic nature, the geometry manipulation is done by using analytical geometry techniques. Due to its symbolic manipulation nature, the design decision making is accomplished using knowledge based design techniques. These two are used simultaneously to generate a forging design.

The problem solving model of the AFD is a highly structured special case of data driven reasoning. This is due to characteristics of the forging design task, which deals with the design specifications and evolving forging geometry. In addition to using data driven reasoning as a design knowledge application strategy, the AFD prescribes the organization of the forging design knowledge, the forging design tasks, and the forging part specifications.

In AFD, a forging part is represented in a rib-web hierarchy. The forging design tasks are organized in a hierarchical network structure, which reflects the conceptual model of forging design. The forging design knowledge is encoded as rules and partitioned into independent modules of knowledge. Each module corresponds to a forging design task. The knowledge modules perform the geometry design using the corresponding set of rules. These rules activate the necessary geometric manipulation modules to perform actual geometry modifications.

Data driven reasoning is applied within this overall organization of the task and part hierarchy, and task-specific design knowledge. The next module of knowledge to apply is determined
dynamically, one step at a time, resulting in the incremental generations of the forging design. The choice of a module of knowledge (or task) is based on an agenda based scheme. That is, the next design task is selected based on the current status of the system, and priority of the design tasks contained in the agenda of the current design task.

At each step of knowledge application, a most favorable design rule is selected and applied. This selection is based on the rule and generality order. For tasks in Design and Refinement phases, an "evaluation-modification" design cycle is performed for each task. This design cycle starts with the decomposition of the section into rib and web components, followed by the design modifications of these component geometries. Next, the section geometry is re-constructed from these component geometries. The modified section geometry is then validated. A forging design is completed when a satisfactory design is obtained, or when all the necessary design tasks are successfully performed.

In order to allow design variations, an interactive computer graphics facility is also provided by the AFD system. This specialized graphics system not only displays the design results, but also allows a user to modify the section geometry. In addition, it interacts with a user in the forging designer's language, to provide a user friendly interface.

It is to be noted that, similar to other knowledge based systems, the effectiveness and the usefulness of the AFD system depends upon the completeness of the design knowledge base. The current
research demonstrates how a "computing" and "knowledge" intensive task, such as forging design, may be computerized.

7.2 Summary of Findings

During the development of the AFD system, several observations were made. They are summarized as below.

(1) Knowledge based approach is feasible for the computerization of certain geometric design tasks which use experience based design knowhow. This is demonstrated by the AFD system, that is capable of designing various forging geometries. Also, the importance of the problem solving model can not be over-emphasized. The effectiveness and efficiency of the AFD system depends greatly on the problem solving model for the forging design. For example, by introducing a redundant task, such as draft angle design in the Pre-Design phase, design iterations to optimize forging weight may be reduced.

(2) For many design tasks, multiple representations of the object being designed are required. This is because various problem solving tools, used in designing an object, require different representation schemes to allow efficient data manipulations. For example, the AFD system represents the forging geometry in XYR form for geometry manipulation, and ENTITY form for design decision
(3) Decomposition is essential for solving complex design problems, but how to decompose is problem specific. In AFD, forging design is decomposed into a hierarchy of tasks, and forging geometry is decomposed into a rib-web hierarchy. The forging design task hierarchy determines the forging design model. The decomposition of the forging geometry greatly affects the modification of the forging geometry.

(4) A frame based scheme is effective for representing objects (or concepts) and their relationships. It also facilitates multiple representations of an object. In addition, due to its automatic inference capabilities, the frame based scheme facilitates easy implementation of the forging design task and forging part hierarchies in the AFD system. In an earlier implementation, Prolog was used to represent the forging design tasks and forging geometry. In this case, the relationships between tasks needed to be explicitly coded as "predicates". Such a representation was neither compact nor structured.

(5) Interactive computer graphics is essential for any geometric design tasks. Due to humans' unique ability in handling pictorial information, interactive computer graphics provides the most natural form of user-system interactions. Also, it is critical for system development, especially during the debugging stage.
(6) Special implementation considerations need to be made for the development of a knowledge based system. Often, they may affect the problem solving strategy used. For example, VAX Lisp is a very powerful symbolic language, however, it is relatively slow as compared to most of the procedural language, such as Fortran, and is very memory intensive. In order to overcome these deficiencies, Fortran, instead of VAX lisp, is used to implement the geometry manipulation tasks in the AFD system. This necessitates the data transformation between the geometry manipulation tasks and design decision making tasks. In order to reduce the number of data transformations, design activities are arranged in such a way that geometry manipulations are performed only when they are absolutely necessary.

7.3 Contribution of Research

Major contributions of the current research are given below.

(1) The forging geometry design task performed by a forging designer is formalized with a hierarchical network model. Various design tasks associated with forging geometry and their inter-relationships are identified. In addition, design knowledge and problem solving techniques associated with these design tasks are also identified. By representing these design tasks in a structure that reflects the conceptual model of forging design, the computerization of forging
geometry design is thus possible.

(2) The feasibility in using a knowledge based approach to computerize the "computing" and "knowledge" intensive forging design task is demonstrated. Based on the forging design model developed, an AFD system was developed. In AFD, the experienced based forging design knowhow is encoded as rules. Using a data driven problem solving scheme, the applications of these rules result in the incremental generations of forging design. The AFD is capable of designing various forging section geometries for structural or axisymmetric parts.

(3) The use of different problem solving techniques in solving a complex forging geometry design problem, in a cooperative fashion, is demonstrated. The AFD system developed in this study incorporates knowledge based techniques for computerizing forging design decision making, and analytical geometry techniques for automating forging geometry modifications. They work in cooperative fashion to generate a forging design. That is, the forging design decision making modules determine the necessary geometry manipulations. The geometry manipulation modules modify the forging geometry, which in turn, affect decision making in forging design.
7.4 Future Research Problems

This section contains recommendations for possible future research problems. The possible extensions to the AFD system are first identified. The recommendations for the use of knowledge based design approach for similar design problems are then described.

The first extension to the AFD system is the inclusion of more forging design knowledge. Currently, the AFD system contains 117 forging design rules. Most of these rules are for "conventional" or "blocker" types of forging design of aluminum and titanium parts. Design rules for other types of forging materials can be easily added to the AFD system due to the separation of geometry design and geometry modification, and due to the uniform design knowledge representation and manipulation used. Nevertheless, the inclusion of design rules for "precision" type of forging designs is more difficult. This is due to the characteristics of precision forging, which uses multiple dies and allows undercut. To use the AFD system for precision forging design, the geometry manipulation modules need to be modified to allow multiple parting lines and back-drafts.

The second extension to the AFD system is the inclusion of forging design optimization knowledge. For this purpose, the design criteria, such as forging weight, need to be defined first. Usually, the criteria for different forging designs vary due to special design considerations. In addition, conflicting criteria may exist. For example, forging weight and material flow behavior, sometimes, represent
two conflicting criteria. Thus, to facilitate forging design optimization, design criteria and design optimization heuristics need to be included in the AFD system. This may be done by placing design criteria in the "goal" slots of the task frame, and by encoding optimization heuristics as design rules.

The third extension to the AFD system is the forging part geometry design in 3D space. It is obvious that no physical object exists in 2D space. The current section geometry design approach by the AFD system is complete for forging parts that can be modelled by the rotational or translational sweeping, i.e. axisymmetric or uniform section geometry structural parts. For some structural parts with non-uniform section geometries, the AFD system may not be adequate. To allow AFD to design these forging parts, the geometry representation of the forging parts needs to be modified, and 3D geometric manipulation capabilities should be provided. For this purpose, the solid geometric modelling scheme may be used. That is, a forging part is composed by its rib and web components. These components can be represented by prototypes with varying width, height, thickness and radii. The same AFD part hierarchy can be used and additional attributes may be included in the rib and web frames. The geometric parameters of these components can then be modified by the design rules stored in the forging design knowledge base. The forging part geometry is obtained by performing the Boolean operation "union" on these components. By incorporating a commercially available solid modeller (e.g. GEOMOD) in the AFD system for solid geometry manipulation, a 3D AFD system can be constructed.
The fourth extension to the AFD system is to allow a complete forging process design. The present AFD system is limited to the forging geometry design. However, it may be expanded to cover the process condition and die design. The forging die design can be done by incorporating a flash design module and a forging load estimation module into the AFD system. The process condition design can be done by expanding the Forging Resource Knowledge Base of the AFD system. A total design system for forging application will require many iterations over these design modules and more complex optimization knowledge.

While the use of knowledge based design approach for forging geometry design is emphasized in this study, the same approach can be applied to other similar design problems. They include, but are not limited to, the casting design and injection molding design. The common link to these designs is the geometry. Due to process limitations, such as solidification in casting and injection molding, the parts produced by these methods may require subsequent finishing operations (e.g. machining). Also, the design of the casting or molding parts is very knowledge and computing intensive. The design knowledge is usually experience based and various analyses may be performed during the design process. Thus, similar approach taken in the AFD system may be used. The findings summarized in section 7.2 should be very useful for taking this approach. It should be emphasized here that the design tasks and objects associated with any of these applications need to be represented in the structure that reflects the conceptual model of the design process for the application.
REFERENCES


