A Knowledge-Based System for the
Design of Round Broaches

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Master of Science

by
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Chapter One

Introduction

1.1 Broaching

Broaching is a metal removal process whereby a multi-tooth cutting tool is either pushed or pulled through or along the surface of a workpiece. Broaching is similar to planing, and is competitive with other machining processes such as milling and boring. The primary difference between broaching and other metal removal processes lies in the design of the broach tool.

In its simplest form, a broach tool is a slightly tapering round or flat bar with rows of cutting teeth located along the tool axis [Fennimore and Schultz, 1976]. Figure 1.1 shows a typical round pull type broach. Frequently, a broach tool will consist of three distinct cutting sections - rough, semifinish, and finish, with each successive tooth increasing in height from the first roughing tooth to the first finishing tooth. This increase in height, commonly referred to as the rise or cut per tooth, is seldom uniform throughout the broach. Usually, the rise or cut per tooth is greater in the roughing teeth than in the semifinishing. The first finishing tooth serves
Figure 1.1: Typical round pull-type broach
to remove the final increment of stock, with the remaining teeth used for sizing. However, as the broach wears, the first finishing tooth will no longer be able to completely remove the final increment of stock, and hence the second tooth will be engaged. This process continues until the last finish tooth is no longer capable of sizing the part, at which time the broach becomes undersized and is discarded.

The design of a broach differs from other traditional machine tools in that the feed is built directly into the tool. In particular, the increase in tooth height from tooth to tooth represents the feed, whereas in other machining processes such as milling, the feed is controlled by the milling machine. Also, this unique feature of broaching often translates into one of its major strengths, the ability to rough and finish cut in a single stroke.

There are basically two types of broaching, internal and external. In internal broaching, there must be a starting hole in the workpiece through which the broach is either pushed or pulled. An exception to this rule would be blind hole broaching, whereby a recess, larger than the broached hole, is provided at the bottom of the hole for chip collection [Linsley, 1961]. Internal broaches are capable of producing round, hexagonal, square, or other
irregularly shaped holes such as splines, keyways and spirals to name a few.

In external broaching, the broach is usually pushed or pulled along the surface of the workpiece. In some instances, however, the broach can be held stationary while the workpiece is pushed or pulled along the broach tool surface. There are virtually no limitations to the number of different contoured surfaces which can be produced by this method.

The major difference between internal and external broaching lies in the design of the broach. The basic structure of the teeth is the same, however, external broaches usually have teeth on only one side of the broach. One limitation of both internal and external broaching is that the surfaces to be broached must be parallel to the direction of broach travel. One exception to this rule is in the production of helical gear teeth, whereby the broach is twisted while passing the workpiece surface.

Both internal and external broaching are used to machine parts of various sizes and composition. Applications may range from cutting small keyways to machining engine block surfaces. According to Hamm et al
[1983], broaching has been used on both ferrous and non-ferrous metals, plastics, hard rubber, wood, composite materials, and graphite.

1.2 Broaching Machines

There are basically two main types of broaching machines, vertical and horizontal. Each machine is equally capable of performing both internal and external broaching operations. According to Hamm et al [1983], the selection of a broaching machine for a particular application is usually dependent on the type of broach tool used, the production requirements, capacity in terms of ram force, broaching power requirements, and the available production floor space to name a few.

Vertical machines offer the advantage of better space utilization provided the machine height does not exceed that of the ceiling. Also, they have "... generally better cutting fluid dispersement and chip removal facilities [Hamm et al, 1983]." Additionally, vertical broaching machines may be better suited for situations in which broach tool chatter is a problem. This is due to the fact that the broach can be attached to the broaching machine ram, which is massive enough to absorb these vibrations and insure
accurate size and finish [Linsley, 1961].

Horizontal broaching machines provide the advantage of long stroke lengths for greater stock removal, and have the ability to handle larger and heavier workpieces. However, most broaching machines produced and in service today, are vertical [Hamm et al, 1983].
1.3 STATEMENT OF RESEARCH

1.31 Statement of Need

Broaching, if used properly, is a highly productive, economical, precise, and extremely versatile process. At its best, broaching is capable of production rates as much as 25 times faster than traditional metal removal methods. This most likely stems from the ability to rough and finish cut in a single stroke. Also, with reasonably thin workpieces, broaching provides the capability of processing more than one part at a time by stacking the pieces and machining them simultaneously. Additionally, workpieces can consistently be held within exacting tolerances. Broaching also produces superior surface finishes which in turn frequently eliminate the need for grinding. As previously mentioned, almost any conceivable contoured surface can be created as long as the workpiece surface to be cut or machined remains parallel to the direction of broach travel.

Unfortunately, despite these advantages, broaching has not been utilized as much as other machining processes such as milling and boring. This can probably be attributed to several inherent economic weaknesses of broaching. First,
being a specialized process, broaching requires a high capital investment in both machinery and workholding devices. Also, due to their unique designs, broach tools are generally designed for job-specific tasks. They are usually not interchangeable, but rather designed for a particular operation on a particular part for a specific machine. Second, the lead time required to design and fabricate a broach commonly runs between 10 to 12 weeks [Savage, 1988]. Unless production volumes are high, broaching can be difficult to economically justify. This point is accentuated by the availability of alternative processes, although usually slower, that can accomplish the same machining operation at a lower cost.

1.32 Objective

The objective of this research is to lower the cost of broach tools by reducing the time required to design and fabricate them. The proposed methodology for effecting this time reduction involves the computerization and integration of the round-hole broach design and manufacturing process (see Figure 1.2). Before discussing this methodology, however, a brief description of the broach design problem is given.
FIGURE 1.2: Framework for developing a computer-integrated broach design system.
In designing a round-hole broach, a number of constraints must be satisfied. First, the maximum stress a broach tool is subjected to cannot be greater than that which will cause the broach to fail in either compression (push broach) or tension (pull broach). Secondly, the deflection of the broach teeth cannot exceed the maximum allowable deflection. Thirdly, the force required to push or pull a broach cannot exceed the maximum tonnage rating of the broaching machine. The fourth constraint states that the length of a broach should not exceed 75 times the diameter of the finishing teeth for round pull-type broaches, and 25 times the finishing teeth diameter for round push-type broaches [Van DeMotter, 1988]. Although there is no theoretical limit to the length of a broach, this rule of thumb can prevent much unnecessary breakage. The fifth constraint states that the length of a push or pull-type broach cannot exceed the stroke length of the broaching machine. Additionally, the length of the cutting section of the broach must be greater than the thickness of the part through which the broach is to be passed. Finally, the volume of metal to be removed must not exceed the total volume of the cavities between successive teeth.

As shown in Figure 1.2, the first step of the process is the development of a knowledge-based system for the design of broaches. According to Walters and Nelsen [1988],
a knowledge-based system is designed to "...capture the problem solving expertise of a human being - an expert in a highly constrained problem area, called a problem domain - and represent this person's knowledge or expertise in a computer..." Knowledge-based systems offer a multitude of advantages. The following list is just a sample:

1) They relieve the burden on the expert - the expert is free to direct his/her time to more creative endeavors.

2) They facilitate the process of knowledge distribution - the knowledge can be easily accessed by non-experts.

3) They are capable of handling large quantities of complex data - as the amount of knowledge increases, the knowledge-based system becomes even more effective.

4) They are usually capable of explaining the solution strategy to the user.

5) They do not get sick.

6) They do not retire.

According to Walters and Nelson [1988], Knowledge-based systems are usually composed of three sections:

1) Knowledge base - the collection of all
pertinent facts, rules of thumb, and experiences that are specific to the problem domain.

2) Inferencing Engine - the reasoning portion of the knowledge-based system. It controls the selection and application of knowledge and facts in the knowledge base.

3) Interface - the portion of the system that interfaces with the user and the knowledge or data base.

The construction of a knowledge-based system, then, is the integration of its component parts for the purpose of assimilating and representing the expert's knowledge.

The second stage of the framework involves Computer-Aided Drawing (CAD). According to Groover [1980], "CAD is any design activity that involves the effective use of computers to create or modify an engineering design." The objective of this step is to create an interface which could directly link the knowledge-based system to a conventional CAD software package. The basis for the interface hinges on the development of a methodology for generating Drawing Interchange Files (DXF) directly from the knowledge-based system. A DXF file is basically an ASCII file structure used to represent geometric data. Most conventional CAD packages have the capability to both generate and read DXF
files.

The product of the second step - a DXF file, is the input for the third step - CAM. CAM or Computer-Aided Manufacturing, is broadly defined by Groover [1980] as "the effective utilization of computer technology in the management, control, and operations of the manufacturing facility through either direct or indirect computer interface with the physical and human resources of the company". For the purposes of this research, CAM will be narrowly defined as the indirect computer interface with physical and human resources. In particular, the boundary of CAM will be restricted to the computer generation of NC part programs. The programming function will be of two types: 1) the generation of the tool path data, and 2) the generation of machine language through a postprocessor.

The first program makes geometric checks and solves the geometric problems associated with path definition and path calculation [Fennimore and Schultz, 1976]. Software packages that perform this function are generally available. The general instructions generated by this step must then be translated into machine readable code specific to the CNC or NC machine tool system used. This step is the function of the postprocessor.
The next stage in the computerization and integration process is the physical manufacture of the broach tool. This is the culmination of all previous stages; it provides the ability to physically prototype on a real time basis.

The final step is the testing and analysis of the prototype. During this stage, the user physically tests the broach under real life conditions. This step provides feedback as to whether or not the knowledge-based system is effectively modeling the experts knowledge. If not, the knowledge-based system can be altered to reflect these changes. In addition, testing affords the designer the opportunity to gain further knowledge of the broach design process.

It is worthy of noting that the process of computerizing and integrating the broach design and fabrication process is iterative. That is, all aspects of the system should be continually updated to reflect the present level of broach design knowledge. This process should continue as long as research into broaching continues.

It is believed that the computerization and integration of the broach design and fabrication process could reduce the time required to design and fabricate broaches by:
1) streamlining the design process by enabling the computer to make all design decisions and calculations with a minimum of user inputs.

2) virtually eliminating the time required to generate engineering drawings.

3) eliminating the process of manually determining the tool path data for manufacturing the broach.

4) eliminating the process of converting the tool path data into an instruction set readable by the CNC machining center.

In addition to the time savings, it is viewed that this process could offer the potential to increase the marketability of broaching through the ability to react to customer orders on a real time basis. It could also provide the ability to increase and standardize the knowledge required to manufacture broaches.
1.4 THESIS ORGANIZATION

Due to the multitude of tasks involved in the computerization and integration of the broach design and fabrication process, this thesis will only concentrate on the first two stages - the development of a knowledge-based system and the CAD interface. In addition, this thesis will only cover round-hole broaching.

Chapter Two discusses the acquisition of expert knowledge and the proposed system model of the round-hole broach design process. Chapter Three is a detailed discussion of the program and programming methodology employed. Chapter Four details the development and coding of the CAD interface. A full explanation of DXF files is included in this chapter. Finally, Chapter Five is a discussion of the conclusions and recommendations.
CHAPTER TWO

Knowledge Engineering

2.1 Introduction

According to Martin and Oxman [1988], Knowledge Engineering is "...the process of reducing a large body of knowledge to a definitive set of rules and facts through both the construction of a knowledge base and the inference procedures required for interpreting that knowledge." This phase is the foundation of the knowledge-based system development process. The primary tasks performed in the knowledge engineering process are: (1) Knowledge Acquisition and (2) Knowledge Representation.

This chapter will focus on the first of the two tasks - knowledge acquisition. Knowledge representation is the focus of Chapter Three.

2.2 Knowledge Acquisition

Knowledge Acquisition is the acquisition of knowledge, experience, and rules of thumb from the human expert [Martin and Oxman, 1988]. The major phases in the knowledge
The acquisition process are:

1) Acquire knowledge from direct and indirect sources.
2) Develop a model of the system based on the knowledge obtained.
3) Check for areas of missing knowledge.
4) Acquire missing knowledge if possible.
5) Re-Iterate the above steps until the knowledge base is reasonably complete.

As stated above, two sources of information were used in the procurement of expert knowledge - indirect and direct. Indirect knowledge is information from public sources such as books, trade papers, articles, handbooks and any other documentation on the subject under study. A complete listing of the indirect sources used is provided in the bibliography. The purpose of using indirect sources of knowledge is to develop an understanding of the problem domain before consulting direct sources - experts.

The second source for knowledge acquisition revolved around expert interviews. The interviews were of two types: (1) on site visits and (2) telephone conversations.

Before continuing with the methodology used to obtain expert knowledge, it is worth mentioning an important
obstacle in the knowledge acquisition process. In particular, the broaching industry represents a small portion of the domestic manufacturing base. According to Schroeder and Seals [1988], broaching equipment - machines and tooling, only represent 1% of the machine tool market. They also imply that the broaching industry is highly competitive and subsequently of proprietary nature. They note that the lack of standards throughout the industry complicates broaching design, raises costs, and makes learning about broaching more difficult. Consequently, it is a cumbersome task to ascertain specific broach tool design knowledge.

In order to obtain expert knowledge, it was first necessary to select appropriate experts. The selection of the experts was based upon the recommendations of Terry et al of the Ohio University Broaching Research Laboratory. They recommended three experts, of which two indicated a willingness to actively participate. The two experts participating were Mr. Christopher Van De Motter, Manager of Engineering of the Ohio Broach and Machine Company, Willoughby, Ohio and Mr. Robert Savage, Vice President of the Hassey / Savage Company, Turners Falls, Massachusetts. One on site visit and numerous telephone interviews were conducted with Mr. Van De Motter. Telephone interviews were the only conversation medium used with Mr. Savage. It would
have been more beneficial to conduct several on site visits with both parties; unfortunately, financial restrictions prohibited this.

The second stage of the knowledge acquisition process was to model the round-hole broach design process based upon information provided by both direct and indirect sources. Two tools of the Structured Analysis methodology were used to develop a round-hole broach design system model:

(1) **Data Flow Diagrams (DFD)** - a network representation of a system which portrays the system in terms of its component parts, with all interfaces among the components indicated [DeMarco, 1979].

(2) **Data Dictionary (DD)** - a set of definitions of data flows, data elements, files, data bases, and processes referred to in a leveled DFD set [DeMarco, 1979].

Structured Analysis is basically a systems engineering modeling technique which uses the tools previously defined to create a Structured Specification of the system. The model consists of several diagrams which depict the required processes and the information flows between the processes.
The basic modeling strategy is to: (1) create a simple system model consisting of one process or transformation and all the flows going both in and out, (2) decompose the processes until they can be reasonably described in terms of primitive constructs - a process commonly referred to as leveling [DeMarco, 1979], (3) show all information flows between transformations, (4) create a descriptive narrative of all processes, and (5) create a Data Dictionary defining all flows, elements, files, and processes.

The purpose of utilizing the Structured Analysis technique was to create a comprehensible model of the complex broach design system. The technique of decomposition facilitated the process of recognizing and analyzing the procedures involved in the broach design process. It also afforded a simplistic and comprehensible approach for tracking the information or knowledge flow. Finally, it provided a means for checking design completeness and consistency.

Before continuing, a brief description of the notation used in the Data Flow Diagrams and the Data Dictionary is provided below.

The Data Flow Diagrams consist of the following four elements:
(1) Arrows - show the direction of information flow
(2) Circles - represent processes or transformations
(3) Parallel lines - represent files of information

The Data dictionary uses the following notation in its definitions [DeMarco, 1979]:

= means IS EQUIVALENT TO
+ means AND
() means the enclosed component is OPTIONAL

Contained in the ensuing pages are Data Flow Diagrams of the round-hole broach design process accompanied by descriptive narratives, and a Data Dictionary. The descriptive narrative defines the processes in terms of their system purpose or function. Chapter Three will detail the logic of the system model.

Context Diagram - Generate Broach Design

Figure 2.1 represents the context diagram, which is the first level of the Data Flow Diagram set. It depicts all of the flows that enter and exit the round-hole broach design system. The user is the source and the sink of the system inputs and output.
FIGURE 2.1: CONTEXT DIAGRAM
Level 0 Diagram

Figure 2.2 is the first decomposition of the system. It shows that the system is composed of five processes: (1) Generate Teeth Specifications, (2) Generate Pilot Designs, (3) Determine Force Requirements, (4) Determine Broach Length, and (5) Generate Final Output.

Diagram 1.0 - Generate Teeth Specifications

Figure 2.3 is the decomposition of the first transformation - Generate Teeth Specifications. This process consists of four subsequent transformations:

(1) Determine Tooth Geometry
(2) Determine Cut Per Tooth
(3) Determine Number of Teeth
(4) Generate Chip Breaker Specification

The first process, Determine Tooth Geometry, performs the function of generating the form of the individual teeth from the geometry file based on the length of cut provided by the user. The geometry file consists of six elements: pitch, length of cut, land width, gullet depth, face angle radius, and circle area.
FIGURE 2.2: LEVEL 0 DIAGRAM
FIGURE 2.3: DIAGRAM 1.0
The second transformation, Determine Chip Per Tooth Roughing, generates the chip per tooth for the roughing teeth. The chip per tooth represents the amount of material that one broach tooth removes per side. Two values of the chip per tooth are calculated in this transformation, the theoretical maximum chip per tooth roughing, and the standard chip per tooth roughing. The standard chip per tooth is equal to 0.00125 inches [Van De Motter, 1988]. Additionally, this process compares the two chips per tooth and selects the appropriate value. The length of cut, the circle area, and the workpiece material constitute the inputs into this process.

The function of the third process, Determine Number of Teeth, is to calculate the number of broach teeth required to remove the specified amount of material. This process determines the number and chip per tooth of the semifinishing teeth, the number of finishing teeth, the chip per tooth of the first finishing tooth, and subsequently the total number of broach teeth required. The inputs into this process include the length of cut, the required surface finish and tolerances, the starting and finish-hole diameters, and the chip per tooth roughing.

A detailed description of how the number and the chip per tooth of the semifinishing and finishing teeth are
determined is provided in Chapter Three. Chapter Three also discusses how the workpiece material type effects this process.

The fourth transformation, Generate Chip Breaker Specification, functions to determine the number of chip breakers needed based on the tooth diameter, the number of teeth, and the material being broached. All round broaches require chipbreakers, otherwise the chips would form continuous rings in the tooth gullets. One exception to this rule is if cast iron or hard brass is broached; they form flakes rather than continuous chips.

Diagram 2.0 - Generate Pilot Designs

As can be seen in Figure 2.4, this process consists of two additional transformations - Determine Shank Specifications, and Determine Rear Pilot Specifications.

The purpose of Process 2.1 is to generate the shank specifications based on the user inputs. The shank specification is composed of three elements for pull broaches: the pull end, the neck, and the front pilot (see Figure A.1 of Appendix A). The type of pull end is selected by the user, while the dimensions are generated from the pull-ends design file. The shank on push broaches only
FIGURE 2.4: DIAGRAM 2.0
consist of the front pilot.

Transformation 2.2, Determine Rear Pilot Specifications, is functionally responsible for generating the rear pilot specification and the follower end if required. Figure A.2 of Appendix A represents the possible broach-end designs for both pull and push-type broaches. The inputs into this process include the broach-type, the length of cut, the finish-hole diameter, and the pull-end design.

Diagram 3.0 - Determine Force Requirements

This process is leveled into three additional transformations: Determine Maximum Allowable Force, Determine Required Force, and Compare Maximum to Required (see Figure 2.5).

The first transformation, Determine Maximum Allowable Force, calculates the theoretical maximum force that the broach can withstand based on the smallest cross sectional area of the broach and the yield strength of the broach tool material. The force calculations are dependent on the type of broach being designed - pull or push type.
FIGURE 2.5: DIAGRAM 3.0
Process 3.2, Determine Required Force, calculates the force required to either push or pull the broach through the workpiece. The chip per tooth for the roughing teeth, the starting hole diameter, the maximum number of teeth in contact with the workpiece at a given time, and the broaching constant (C) are the major determinants in this calculation.

The third transformation, Compare Maximum to Required, compares the maximum force allowable to the required force. Additionally, the required force is compared to the tonnage rating of the broaching machine. If the maximum allowable force is less than the required force, or if the required force is greater than the machine tonnage rating, the broach design is determined to be insufficient. If not, the design is deemed correct to this point in the round-hole broach design process.

Transformation 4.0 - Determine Broach Length

The function of this process is to calculate the broach length. The inputs into this process include the pilot dimensions, the number of teeth, and the pitch. After the length is determined, it is compared against one of the two rules listed below (Van De Motter, 1988):

1) The length of a pull type broach must not exceed
75 times the diameter of the finishing teeth.

(2) The length of a push type broach must not exceed 25 times the diameter of the finishing teeth.

If either of the above rules is broken, the broach design is determined to be invalid.

Transformation 5.0 - Generate Output

This process is the final transformation in the broach design system. All functions performed by the previous transformations are assembled to form the output of the broach design process - the round-hole broach design.

Data Dictionary

The following is a dictionary defining all the data flows, data elements, and data files contained in the Data Flow Diagrams.

Data Flows

Broach Design = teeth specification
                 + broach length
                 + pilot designs
                 + required force
Broach Tool Material = material type
   + tensile yield strength

Broach Type = push type
   OR pull type + retrievable OR non-retrievable

Broaching Machine Description = stroke length
   + machine tonnage

Chipbreaker Specification = number of chipbreakers/tooth
   + number of roughing teeth
   + number of semifinishing teeth

Chip per Tooth = chip per tooth roughing
   + chip per tooth semifinishing
   + chip per tooth first finishing

Follower End Type = automatic shank type
   OR tapered

Hole Specifications = length of cut
   + starting-hole diameter
   + finish-hole diameter
   + tolerances
   + surface finish
Number of Teeth = number of roughing teeth 
+ number of semifinishing teeth 
+ number of finishing teeth

Pilot Designs = pilot type 
+ pilot dimensions

Pilot Type = shank specification 
+ rear pilot specification

Pull End Type = automatic shank type 
OR key type

Rear Pilot Specification = rear pilot dimensions 
+ (follower end type 
+ follower end dimensions)

Shank Specification = front pilot dimensions 
+ (pull end type 
+ pull end dimensions 
+ front neck dimensions)

Teeth Specification = tooth geometry 
+ number of teeth 
+ chip per tooth
+ chip breaker specification

Tooth Geometry = pitch
   + land width
   + gullet depth
   + hook angle radius
   + back of tooth radius
   + circle area

Workpiece Material = material type
   + ( hook angle
      + backoff angle
      + broaching constant)

Files

Material = material type
   + hook angle
   + backoff angle
   + broaching constant

Pull End Designs = pull end type
   + dimensions
Tooth Geometry = length of cut
    + pitch
    + land width
    + gullet depth
    + face angle radius
    + back of tooth radius
    + circle area

Data Elements

Back of Tooth Radius - the radius on the back of the tooth in the chip space.

Backoff Angle - relief angle back of the cutting edge of a broach tooth.

Broach Length - the overall length of the broach.

Chipbreaker - notches in the broach teeth which divide the width of chips, facilitating their removal.

Chip per Tooth - the depth of cut which determines chip thickness.

Circle Area - the area commonly referred to as the chip space; equal to \((3.14159/4) \times D^2\)
where $D = \text{gullet depth.}$

Finish-Hole Diameter - the diameter of the finished hole in the workpiece.

Follower End - the retrievable end of a retrievable pull type broach, or the tapered end of a non-retrievable pull-type broach.

Front Pilot - the guiding portion of the broach; it serves as a check to assure that the starting-hole diameter is not undersized.

Gullet Depth - the depth of the gullet of a broach tooth.

Hook Angle - angle of the cutting edge of a broach tooth.

Hook Angle Radius - the radius just below the cutting edge that blends into the back of the tooth radius.

Land Width - thickness of the top of a broach tooth.

Machine Tonnage - the maximum pulling or pushing capacity of a broaching machine (given in tons).
Pitch - distance from the cutting edge of one tooth to the corresponding point on the next tooth.

Pull End - the end of the broach which is coupled to the puller of the broaching machine: it is used to pull the broach through the workpiece.

Stroke Length - the length of the broaching machines maximum stroke.

Surface Finish - the desired smoothness or surface texture of the broached hole.

Tolerances - the accuracy to which the finished hole is to be produced by the broach.

At the culmination of the system modeling process, three steps remained in the knowledge acquisition phase of the broach design process.

The third and fourth steps in the knowledge acquisition process were to recognize and obtain missing information. The major means for recognizing missing data was accomplished through the examination of the DFD's. Processes without information flows or visa versa were good indicators of missing knowledge or of misunderstanding of
the broach design process. The acquisition of missing knowledge was performed through telephone interviews with the experts mentioned previously.

The final phase of the knowledge acquisition process was to re-iterate the previous steps until the knowledge base was believed to be relatively complete. The Data Flow Diagrams represent the current level of round-hole broach design knowledge. It is important to mention that the knowledge acquisition process is never complete. New information should be added to the knowledge base as it is discovered through the life cycle of the project.
Chapter Three

Knowledge Representation

3.1 Introduction

As mentioned previously, Knowledge Acquisition is the acquisition of the knowledge, experiences, and rules of thumb from a human expert for a particular problem domain. Knowledge Representation, simply put, is the codification of this subject domain knowledge so that the knowledge can be used by a computer-based system [Martin and Oxman, 1988].

Before discussing the codification of the round-hole broach design system, a brief description of the programming style employed is warranted. According to Taylor [1988], there are three basic programming styles: (1) function-based or procedural, (2) object-oriented, and (3) rule-based.

The function-based programming method is a style frequently used for coding highly procedural, structured, and quantitative problems. In a pure function-based program, functions or subroutines receive control of the computer when they are called. Arguments or data are passed to functions, a calculation or procedure is performed, and
the arguments are returned to the main module.

Developing programs on the basis of associating data and programmed behavior with the objects in an application system is termed object-oriented programming [Walters and Nelsen, 1988]. Unlike procedural languages where data is passed to procedures, objects in an object-oriented language are asked to perform operations on themselves [Pascoe, 1986].

Rule-based programming is a methodology frequently used with expert system shells. Rules of the "if X then Y" form are used to represent the knowledge, where "X" is the premise and "Y" is the conclusion. The rules are generally arranged in a non-sequence dependent order where the firing of rules depends on the starting condition and the inferencing mechanism used. This programming style is commonly used when the knowledge to be represented is qualitative and/or symbolic in nature.

The procedure-based programming style was selected for the codification of the broach design knowledge-based system. This style was selected for the following reasons: (1) procedure-based languages are widely available, and generally run more efficiently in a PC environment [Martin and Oxman, 1988], (2) procedure-based languages are highly
transportable and generally inexpensive, and (3) the round-hole broach design process is quantitative and highly procedural.

Microsoft QuickBASIC version 4.0 was selected for the codification process. It was chosen due to the wide variety of features offered including: (1) fully structured CASE SELECT and IF...THEN...ELSE statements, (2) SUB and FUNCTION procedures which allow groups of program code to be placed in subprograms that the main program can call repeatedly, (3) fully recursive procedures, (4) the ability to define data types made up of any combination of integer, real, and string variables, and (5) a user friendly full screen editing window with automatic syntax checking and pop down menus.

The remainder of this chapter will focus on the coding of the knowledge-based system.

3.2 Knowledge-Based System Coding

A modular approach to program development was used to code the knowledge-based system for the purpose of increasing maintainability and readability of the program. Complex non-modular programs tend to be difficult to read and virtually impossible to debug. In their purest form,
modular programs should afford the programmer the ability to add and delete modules without interfering with program execution.

The program developed for the broach design application consists of a main module and several external modules. The main module contains the coding of the knowledge-base and the user interface. The external modules contain the coding of the round-hole broach design process. There are eight external modules: (1) Determine the Tooth Geometry, (2) Determine the Chip per Tooth Roughing, (3) Determine the Pilot Specifications, (4) Determine the Number of Teeth, (5) Determine the Pulling Force, (6) Determine the Push Force, (7) Determine the Broach Length, and (8) Determine Chip Breakers. The following section contains a narrative description and the pseudocode of each module.

3.21 Process Module Description

Main Module

As stated previously, the main module contains the coding of the knowledge-base and the user interface. The knowledge-base contains the standard broach design data provided in Tables 1 through 4 located in Appendix A. The user interface consists of a series of initial broach
design questions, along with questions relating to the type of output required. The questions are arranged in four sections relating to: (1) the type of broaching and broaching machine employed, (2) the workpiece geometry, required tolerances, and required surface finish, (3) the workpiece and broach tool material, and (4) the type of output required.

The first section requires from the user the type of broach being designed, either push or pull-type. Additionally, questions are asked regarding the stroke length and the tonnage rating of the broaching machine employed.

Section two prompts the user to input the length of cut, the starting-hole diameter, the finish-hole diameter, and the tolerances and surface finish required on the broached hole.

The third section inquires that the user select the workpiece material and broach tool material types from the menus provided. Table 1 in Appendix A lists the various workpiece materials contained in the knowledge-base. If either material is not contained in the data base, the user is prompted to enter the material types from the keyboard. If the workpiece material is selected from the menu, the
user is prompted to input values for the hook and backoff angles from the recommended ranges. If the workpiece material was entered from the keyboard, the user is asked to input values for the hook and backoff angles as well as the material broaching constant (C), where C represents the machinability of the material.

The final section of questions prompts the user to enter whether or not they would like a print out of the broach design specifications and if they would like to create a CAD readable file. A description of the CAD readable file is provided in Chapter Four. Appendix A contains sample printouts of design specifications for four different broach designs.

Additionally, the main module consists of call statements to the other program modules. The pseudocode of the main module is provided below.

Main Module Pseudocode
BEGIN Program
ENTER the broach type (push or pull)
ENTER the broaching machine stroke length
ENTER the broaching machine tonnage rating
IF broach type = pull
    THEN GOTO pull
ELSE GOTO continue questions

ENDIF

Pull:

ENTER the puller type (automatic or key type)

Will you be using an automatic retriever?

Continue Questions:

ENTER the starting hole diameter

ENTER the finishing hole diameter

ENTER the length of cut

ENTER the required surface finish

ENTER the required tolerances

ENTER the workpiece material type

IF workpiece material is within workpiece file

THEN SELECT the hook angle (rough) from the recommended range

SELECT the hook angle (finish) from the recommended range

SELECT the backoff angle from the recommended range

ELSE

ENTER the workpiece material type

ENTER the hook angle (rough)

ENTER the hook angle (finish)

ENTER the backoff angle

ENTER the broaching constant (C)

ENDIF
ENTER the broach tool material type
CALL Determine tooth geometry
CALL Determine the chip per tooth roughing
IF broach type = push
    THEN GOTO push
ENDIF
CALL Determine the pilot specifications
CALL Determine the number of teeth
CALL Determine the pulling force
CALL Determine the broach length
CALL Determine chip breakers

Push:
CALL Determine the number of teeth
CALL Determine the push force
CALL Determine the broach length
CALL Determine chip breakers
Would you like a print out of the design specifications?
    IF answer = yes
    THEN
        print the specifications
    ENDIF
Would you like to create a CAD readable file of the broach tool?
    IF answer = yes
    THEN

create the CAD readable file
ELSE
END Main Program
END IF
END Main Program

Module 1 - Determine Tooth Geometry

This module performs the function of generating the form of the individual teeth based on the length of cut and the starting-hole diameter input by the user. After the length of cut is input, it is matched to the length of cut in the tooth form file. From the tooth form file, the associated pitch, land width, gullet depth, hook angle radius, and circle area are retrieved (see Figure 3.1). For a definition of each parameter, please refer to the data dictionary provided in the previous chapter.

The next step is the calculation of the gullet depth as a percentage of the starting hole diameter. This calculation is then compared against the following rule [Van De Motter, 1988]:

IF the gullet depth is more than 1/6 of the starting hole diameter
THEN the gullet depth must be reduced
Figure 3.1 - typical broach teeth

BTR - Back of tooth radius
C/T - chip per tooth
GD - gullet depth
HA - hook angle
HAR - hook angle radius
LW - land width
P - pitch
RA - rake angle
The purpose of this rule is to prevent the tooth from failing under the load for which it was designed. If the gullet depth is indeed greater than 1/6 of the starting-hole diameter, then it is reduced until it is less than or equal to 1/6 of the starting hole diameter, or until the gullet depth reaches the minimum value contained in Table 2 of Appendix A. If the value for the gullet depth reaches the minimum, the broach design is invalid based on the initial inputs of the user. If the gullet depth is less than or equal to 1/6 of the starting hole diameter, the associated circle area and hook angle radius are retrieved from the tooth form file. The pitch and land width retain their initial values. The pseudocode associated with this module is given below.

Module 1 Pseudocode

Variable Declaration

\[
\begin{align*}
CA &= \text{circle area (in.}^2\text{)} \\
GD &= \text{gullet depth (in.)} \\
HAR &= \text{hook angle radius (degrees)} \\
LW &= \text{land width (in.)} \\
PT &= \text{pitch (in.)} \\
STD &= \text{starting hole diameter}
\end{align*}
\]

End Variable Declaration

1. Match the length of cut entered by the user with the
length of cut in the tooth geometry file

1. Get PT
2. Get LW
3. Get GD
4. Get HAR
5. Get CA

2. Calculate GD as a percentage of STD

IF GD > 1/6 of STD

THEN

DO

choose a GD one increment smaller than the current GD in the geometry file

LOOP UNTIL GD <= 1/6 of STD

1. Get the new GD
2. Get the new HAR
3. Get the new CA

ELSE

the design is invalid based on the initial conditions provided by the user

ENDIF

END Determine Tooth Geometry

Module 2 - Determine the Chip per Tooth Roughing

The chip per tooth for round-hole broaches is
equivalent to 1/2 of the cut per tooth, where the cut per tooth represents the amount of material that a broach tooth removes on diameter. For instance, if the amount of material that a tooth removes equals 1 inch, the chip per tooth would equal 1/2 inch (see figure 3.2). The determination of the chip per tooth is based on the standard chip per tooth and the theoretical maximum chip per tooth. The standard chip per tooth equals 0.00125 inches, and represents the standard initial value used when determining the chip per tooth for a broach design [Van De Motter, 1988]. The theoretical maximum chip per tooth is calculated as follows [Hamm et al, 1983]:

\[
\text{MAX} = \frac{\% \text{CA}}{\text{LC}}
\]

where,

\[
\text{CA} = \text{circle area (in.}^2\text{)} - \text{the available chip space},
\]

\[
\text{LC} = \text{length of cut (in.)}.
\]

The percentage of the circle area used is dependent on the workpiece material type, and is determined by the following rule [Savage, 1988]:

IF the workpiece material is cast iron or brass

THEN use 10% of the circle area

ELSE use 12% of the circle area
Chip per Tooth = A
Cut per Tooth = 2A

Figure 3.2
The reason for using a smaller percentage of the circle area for brass and cast iron is due to their chip forming nature - they form flakes rather than continuous chips.

The standard chip per tooth roughing is then compared against the maximum. The following rule is used to determine the appropriate chip per tooth:

IF the standard chip per tooth is less than the maximum
THEN the chip per tooth equals the standard
ELSE the chip per tooth equals the maximum

The rationale for this rule is to guarantee that the chip per tooth never exceeds its theoretical maximum, otherwise the tooth would have a higher probability of failing under the cutting forces. The pseudocode for this module is provided below.

**Module 2 Pseudocode**

**Variable Declaration**

- CA = circle area (in.²)
- CTR = chip per tooth roughing
- LC = length of cut (in.)
- MAX = maximum chip per tooth roughing
- PI = 3.14159
SCTR = standard chip per tooth roughing

End Variable Declaration

IF the workpiece material = cast iron OR brass

THEN

use 10% of CA

ELSE

use 12% of CA

ENDIF

SCTR = 0.00125

1. Calculate MAX

MAX = % CA / LC

2. Compare MAX against SCTR

IF MAX < SCTR

THEN

CTR = MAX

ELSE

CTR = SCTR

ENDIF

END Determine Chip per Tooth Roughing

Module 3 - Determine Pilot Specifications

This module consists of two processes, the determination of the shank specifications and the determination of the rear pilot specifications.
The purpose of the first process is to generate the shank specifications based on the user inputs. The shank specification is composed of three elements for pull broaches: the pull end, the neck, and the front pilot. Its purpose is to engage the puller. The front pilot acts as a "GO" "NO GO" gauge to insure that the starting-hole diameter is not undersized. The type of pull end used is selected by the user, either automatic shank type or key type. Figure A.1 of Appendix A illustrates both designs. The pull-end design used is selected by choosing a design which is slightly smaller in diameter than the front pilot. Tables 3 and 4 of Appendix A illustrate each design and provide accompanying dimensional data.

The shank on a push broach only consists of the front pilot, where the front pilot serves to guide the broach in place and to insure that the starting-hole diameter is not undersized (see Figure A.1 of Appendix A). The front pilot dimensions are a function of the length of cut and the starting hole diameter. In particular, the front pilot length is calculated by adding 1/8 inch to the length of cut, and the diameter is determined by subtracting 0.003 inch from the starting hole diameter [Van De Motter, 1988]. The reason for designing the front pilot longer than the length of cut is to insure that the broach teeth will not be engaged in the workpiece prematurely. The front pilot is
designed slightly smaller than the starting-hole diameter to insure that the front shank can pass through the broach unobstructed.

The second process functions to generate the rear pilot specification and the follower end if required (see Figure A.2 of Appendix A). The rear pilot dimensions are determined in the same fashion as the front pilot. The specification of the follower end is dependent on the type of broach being designed. For example, push broaches do not have a follower end, and for pull-type broaches, the follower end is specified based on whether or not the broach is retrievable. For retrievable broaches, the dimensions for the follower end are the same as those of the pull end. If the broach is not retrievable, the follower end is set to equal 1/2 in.

Module 3 Pseudocode
Variable Declaration

\[
\begin{align*}
FDIA & = \text{finish-hole diameter (in.)} \\
FE & = \text{follower end} \\
FN & = \text{front pilot neck length (in.)} \\
FPD & = \text{front pilot diameter (in.)} \\
FPL & = \text{front pilot length (in.)} \\
LC & = \text{length of cut (in.)} \\
RN & = \text{rear pilot neck length (in.)}
\end{align*}
\]
RPL = rear pilot length (in.)
STD = starting-hole diameter (in.)

End Variable Declaration

1. Calculate FPL
   FPL = LC + 1/8

2. Calculate FPD
   FPD = STD - .003

3. Calculate RPL
   RPL = FPL

4. Calculate RPD
   RPD = FDIA - .003

5. Determine puller type and size
   IF puller type = automatic
       THEN
       get puller from the automatic puller
       file that is slightly smaller than FPD
   ELSE
       get puller from the key type puller file
       that is slightly smaller than FPD
   ENDIF

6. Determine follower end type and size
   IF broach is retrievable
       THEN
       FE = same as automatic pull end
   ELSE
       FE = 0.5 inches
RN = 0.375 inches

ENDIF

END Determine Pilot Specifications

Module 4 - Determine the Number of Teeth

This module functions to calculate the number of broach teeth required to remove the user specified amount of material.

The number of finishing teeth is dependent on the tolerances required on the workpiece, and the number of semifinishing teeth needed depends on the user specified workpiece surface finish. The following two rules are used to determine the number of finishing and semifinishing teeth [Van De Motter, 1988]:

**IF**
the required tolerances > 0.001

**THEN**
the number of finishing teeth = 4

**ELSE**
the number of finishing teeth = 6

**IF**
required surface finish >= 250 microns

**THEN**
the number of semifinishing teeth = 0

**ELSEIF**
the required surface finish >= 63 microns
AND the required surface finish <= 250 microns

**THEN**
the number of semifinishing teeth = 3
The number of roughing teeth required is determined in the following stages. First, the amount of material to be removed by the broach is calculated. Second, the number of roughing teeth needed to remove as much of the material as possible is determined. For example, if the amount of material to be removed equalled 0.014 inches and the chip per tooth roughing equalled 0.00125, then the number of roughing teeth would equal 11.2 teeth. Third, the amount of material left over from the previous step is calculated. Setting the number of roughing teeth equal to 11, the amount of material left over would equal 0.00025 inches. This amount is then divided by the number of semifinishing teeth plus one, where the extra tooth represents the first finishing tooth. This value represents the chip per tooth for the semifinishing teeth and the first finishing tooth. The following rule is used to test this value [Savage, 1988]:

IF the semifinishing chip per tooth < .0003 AND the workpiece material = stainless steel THEN the chip per tooth roughing must be recalculated
ELSEIF the semifinishing chip per tooth < .0001 AND the workpiece material = any THEN the chip per tooth roughing must be recalculated
ELSE the number of roughing teeth should be calculated

At first glance, this rule may seem confusing. The reasoning behind it is to prevent the chip per tooth semifinishing from becoming too small, in which case the teeth will gaul the workpiece surface rather than take a clean "bite" out of it [Van De Motter, 1988]. The chip per tooth roughing is reduced in order to provide a reasonable amount of material for the semifinishing teeth to remove. Once the constraint that states that the chip per tooth semifinishing must be greater than or equal to .0003 for machining stainless steel and greater than or equal to .0001 for machining any other type of material is satisfied, the number of roughing teeth is calculated based on the following formula [DeGarmo et al, 1988]:

\[
NUMR = \frac{(AMT - (NUMS \times CTS) - CTS)}{CTR}
\]

where,

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMR</td>
<td>the number of roughing teeth,</td>
</tr>
<tr>
<td>AMT</td>
<td>the total amount of material to be removed,</td>
</tr>
<tr>
<td>NUMS</td>
<td>the number of semifinishing teeth,</td>
</tr>
<tr>
<td>CTS</td>
<td>the chip per tooth semifinishing,</td>
</tr>
<tr>
<td>CTR</td>
<td>the chip per tooth roughing.</td>
</tr>
</tbody>
</table>

Additionally, if the chip per tooth roughing was
reduced, the required force $F$ must be recalculated to reflect this change.

Module 4 Pseudocode

Variable Declaration

\begin{align*}
\text{AMT} & = \text{total amount of material to be removed (in.)} \\
\text{AMTL} & = \text{amount of material to be removed by the semifinishing teeth (in.)} \\
\text{AMTS} & = \text{amount of material to be removed by the roughing teeth (in.)} \\
\text{CTR} & = \text{chip per tooth roughing (in.)} \\
\text{CTS} & = \text{chip per tooth semifinishing (in.)} \\
\text{FDIA} & = \text{finish-hole diameter (in.)} \\
\text{NR} & = \text{number of roughing teeth needed to remove most of the material} \\
\text{NUMF} & = \text{number of finishing teeth} \\
\text{NUMR} & = \text{number of roughing teeth} \\
\text{NUMS} & = \text{number of semifinishing teeth} \\
\text{STD} & = \text{starting-hole diameter (in.)} \\
\text{SURF} & = \text{required surface finish (micro in.)} \\
\text{TOL} & = \text{required tolerances (in.)}
\end{align*}

End Variable Declaration

1. Determine NUMF

\begin{align*}
\text{IF TOL} & > .001 \\
\text{THEN}
\end{align*}
NUMF = 4
ELSE
NUMF = 6
ENDIF

2. Determine NUMS
IF SURF >= 250
THEN
NUMS = 0
ELSE IF SURF > 63
THEN
NUMS = 3
ELSE
NUMS = 4
ENDIF

3. Determine NUMR
AMT = (FDIA - STD) / 2
NR = INT(AMT / CTR)
AMTL = (AMT - (NR * CTR)
CTS = AMTL / (NUMS + 1)
IF CTS < .0003 AND material = stainless steel
THEN
CTS = .0003
AMTS = AMT - ((NUMS + 1) * CTS)
CTR = AMTS / INT((AMTS / CTR) + 1)
NUMR = (AMT - (NUMS * CTS) - CTS) / CTR

1. Re-calculate required force


\[ F = 3.14 \times D \times N \times CTR \times C \]

ELSE IF CTS < .0001

THEN

DO

CTR = CTR - .00001
NR = INT(AMT / CTR)
AMTL = (AMT - (NR \times CTR)
CTS = AMTL / (NUMS + 1)
LOOP until CTS > .0001 or
CTR < .00025
NUMR = AMT - (NUMS * CTS) - CTS) / CTR

1. Re-calculate required force

\[ F = 3.14 \times D \times N \times CTR \times C \]

ELSE

NUMR = (AMT - (NUMS * CTS) - CTS) / CTR

ENDIF

END Determine number of teeth

Module 5 - Determine the Pulling Force

The function of this module is to determine the force required to pull the broach through the workpiece, and to compare this value against the theoretical maximum pulling force and the tonnage rating of the broaching machine used.

The calculation of the minimum force required to pull
the broach through the workpiece is based on the following equation [Hamm et al, 1983]:

\[ F = 3.14 \times \text{STD} \times N \times \text{CTR} \times C \]

where

- \( F \) = minimum pulling force required (lbs.),
- \( \text{STD} \) = hole diameter before broaching (in.),
- \( \text{CTR} \) = chip per tooth for roughing teeth (in.),
- \( N \) = maximum number of teeth engaged in the workpiece at one time,
- \( C \) = empirical broaching constant representing the machinability of the workpiece material (psi).

The theoretical maximum pulling force \( (P) \) that the broach can withstand without failing at the smallest cross sectional area of the broach is calculated as the product of the minimum broach cross sectional area and the tensile yield strength of the workpiece material. The minimum cross sectional area is either at the pull end or at the root of the first broach tooth.

After the force calculations are completed, the required pulling force \( (F) \) is compared to the maximum allowable pulling force \( (P) \), and to the tonnage rating of the broaching machine \( (T) \). The following rule is used for the comparison [Van De Motter, 1988]:
IF F is at least 20% less than P
AND F is less than T
THEN the broach design is deemed valid at this stage in the broach design process

However, if either of these conditions is not met, the design must be altered to satisfy both constraints if possible. By examining the variables associated with the calculation of the required pulling force, only one variable, the chip per tooth (CTR), can be altered. The broaching constant (C) and the starting hole diameter (STD) are predetermined by the user. The maximum number of teeth in contact with the workpiece material at one time (N) usually equals three, and the reduction of this variable could adversely decrease the stability of the broach as it passes through the workpiece.

If it becomes necessary to reduce the required pulling force, the chip per tooth is systematically decreased. After each reduction, the subroutine determine the number of teeth is called to recalculate the chip per tooth semifinishing. The rationale for calling this subroutine is to insure that the chip per tooth semifinishing does not become too small. This process is continued until either the constraints are satisfied or until the chip per tooth reaches a predetermined minimum. If the chip per tooth
reaches the minimum value before the force constraints are satisfied, the broach design is deemed invalid.

Module 5 Pseudocode

Variable Declaration

\[
\begin{align*}
A &= \text{minimum cross sectional area (in.}^2) \\
C &= \text{broaching constant (psi)} \\
CTR &= \text{chip per tooth roughing (in.)} \\
F &= \text{required force (lbs.)} \\
N &= \text{number of teeth in contact with workpiece at one time} \\
P &= \text{maximum allowable pulling force (lbs.)} \\
PED &= \text{minimum pull end diameter (in.)} \\
PI &= 3.14159 \\
RD &= \text{root diameter at first tooth (in.)} \\
STD &= \text{starting-hole diameter (in.)} \\
T &= \text{tonnage rating of the machine (lbs.)} \\
Y &= \text{tensile yield strength of the broach tool material (psi)}
\end{align*}
\]

End Variable Declaration

1. Calculate the minimum cross sectional area of the broach

   IF the minimum is at the pull end

   THEN

   \[ A = (PI/4) \times PED \]

   ELSE
\[ A = \left( \frac{\pi}{4} \right) \times RD \]

END IF

2. Calculate the maximum allowable pulling force

\[ P = A \times Y \]

3. Calculate the required force

\[ F = 3.14 \times D \times N \times CTR \times C \]

4. Compare \( F \) to \( P \) and \( F \) to \( T \)

IF \( F < (0.8 \times P) \) AND \( F < T \)

THEN

the design is valid

ELSE

DO

  A. Reduce CTR
  B. CALL determine number of teeth
  C. Re-calculate \( F \)
  D. Compare \( F \) to \( P \) and \( F \) to \( T \)

LOOP until \( F < (0.8 \times P) \) AND \( F < T \) OR

until CTR reaches its minimum

END IF

IF CTR reached its minimum AND \( (F > (0.8 \times P)) \)

OR \( F > T \)

THEN

the design is invalid

ELSE

the design is valid up to this point in

the design process
END IF

END Determine the pulling force

Module 6 - Determine the Push Force

This module determines the force required to push the broach through the workpiece, and compares this value against the theoretical maximum and the tonnage rating of the machine.

The force required to push the broach through the workpiece is calculated in the same manner as the required pulling force.

The theoretical maximum load that a push broach can withstand without failing at its smallest cross sectional area is calculated using the following equation [Hamm et al, 1983]:

\[ PL = \frac{Y \times RD^4}{L^2} \]

where,

- \( PL \) = the maximum allowable load (lbs.),
- \( Y \) = the tensile yield strength of the broach tool material (psi),
- \( RD \) = root diameter at 1/2 \( L \) (in.),
- \( L \) = length from push end to first tooth (in.).
The required load (F) is then compared against both the maximum allowable load (PL) and the tonnage rating of the machine (T). The same rule applied in the previous module is used to make the force comparison:

\[
\begin{align*}
\text{IF} & \quad F \text{ is at least 20\% less than } PL \\
\text{AND} & \quad F \text{ is less than } T \\
\text{THEN} & \quad \text{design is valid at this point in the broach design process.}
\end{align*}
\]

If either of these constraints is not satisfied, then the same process described for pull-type broaches is employed to possibly correct the design.

Module 6 Pseudocode

Variable Declaration

\[
\begin{align*}
\text{CTR} & = \text{ chip per tooth roughing (in.)} \\
C & = \text{ broaching constant (psi)} \\
F & = \text{ required force (lbs.)} \\
FDIA & = \text{ finish-hole diameter (in.)} \\
GD & = \text{ gullet depth (in.)} \\
L & = \text{ length from push end to first tooth (in.)} \\
N & = \text{ number of teeth in contact with workpiece at one time} \\
PL & = \text{ maximum allowable load (lbs.)} \\
PI & = 3.14159
\end{align*}
\]
RD = root diameter at 1/2 L (in.)
STD = starting-hole diameter (in.)
T = tonnage rating of the machine (lbs.)
Y = tensile yield strength of the broach tool material (psi)

End Variable Declaration

1. Determine DR
   \[
   DR = \frac{(FDIA - STD)}{2} - GD
   \]
2. Determine the maximum allowable load
   \[
   PL = \frac{Y \times DR^4}{L^2}
   \]
3. Determine the required force
   \[
   F = 3.14 \times STD \times N \times CTR \times C
   \]
4. Compare F to PL and F to T
   IF \[ F < (0.8 \times PL) \text{ AND } F < T \]
   THEN
   the design is valid
   ELSE
   DO
   A. Reduce CTR
   B. CALL determine number of teeth
   C. Re-calculate F
   D. Compare F to P and F to T
   LOOP until \[ F < (0.8 \times P) \text{ AND } F < T \text{ OR } \]
   until CTR reaches its minimum
   END IF
IF CTR reached its minimum AND (F > (.8*P)) OR F > T) THEN
   the design is invalid
ELSE
   the design is valid up to this point in the design process
ENDIF

END Determine Push Force

Module 7 - Determine Broach Length

The function of this module is, simply put, to calculate the total broach length. The broach length is calculated by adding the lengths of the three sections of a broach - the front shank, the teeth, and the broach end.

For pull-type broaches, the front shank consists of the pull end, the front neck, and the front pilot. The broach end consists of the rear pilot, the rear neck, and the follower end. If the broach is retrievable, the follower end is equivalent to the pull end. If not, the follower end usually equals 1/2 inch. For push broaches, the front shank consists only of the front pilot, and the broach end consists solely of the rear pilot.
The calculation of the length of the teeth section is constant for both pull and push-type broaches, and equals the product of the number of teeth and the tooth pitch. After the broach length has been determined, it is analyzed by the following rule:

\[
\text{IF push broach length} > 25 \times \text{finish-hole diameter OR pull broach length} > 75 \times \text{finish-hole diameter}
\]
\[
\text{THEN the design is invalid}
\]

Although there is no theoretical maximum to the length of a broach, this rule can prevent unnecessary tool breakage [Van De Motter, 1988].

Module 7 Pseudocode

Variable Declaration

\[
\begin{align*}
\text{BL} & = \text{total broach length (in.)} \\
\text{FDIA} & = \text{finish-hole diameter (in.)} \\
\text{FE} & = \text{follower end length (in.)} \\
\text{FN} & = \text{front pilot neck length (in.)} \\
\text{FPL} & = \text{front pilot length (in.)} \\
\text{NUMF} & = \text{number of finishing teeth} \\
\text{NUMR} & = \text{number of roughing teeth} \\
\text{NUMS} & = \text{number of semifinishing teeth} \\
\text{LS} & = \text{total length of pull end section (in.)}
\end{align*}
\]
LR = total length of broach end section (in.)
PEL = pull end length (in.)
PIT = tooth pitch (in.)
RN = rear pilot neck length
RPL = rear pilot length (in.)

End Variable Declaration

1. Calculate LS
   LS = FPL + PEL + FN
2. Calculate LR
   LR = RPL + RN + FE
3. Calculate BL
   BL = LS + PIT*(NUMF + NUMS + NUMR) + LR
4. Check broach length (push type)
   IF BL >= 25 times FDIA
      THEN
      the broach design is invalid
   ENDIF
5. Check broach length (pull type)
   IF BL >= 75 times FDIA
      THEN
      the broach design is invalid
   ENDIF

END Determine Broach Length
Module 8 - Determine Chip Breakers

This module functions to determine the number of chip breakers needed based on the tooth diameter and the material being broached. Chip breakers are slots or grooves ground into the surface of the broach teeth. With round-hole broaches, chips form continuous rings around the teeth as the broach passes through the workpiece. The chip breakers perform the function of breaking the chips in order to prevent the chips from lodging in the tooth gullet. All round broaches require chip breakers unless the workpiece material is cast iron [Savage, 1988]. This exception is due to the nature of cast iron - it forms flakes rather than continuous chips.

According to Savage [1988], chip breakers should be placed 1/8 in. to 3/16 in. apart, and staggered from tooth to tooth. In addition, they should be 3/64 in. wide X 3/64 in. deep for all teeth except the last semifinishing tooth and the finishing teeth.

Module 8 Pseudocode

Variable Declaration

\[
\begin{align*}
    \text{CB} & = \text{chip breakers per tooth} \\
    \text{CBS} & = \text{chip breaker size} \\
    \text{STD} & = \text{starting hole diameter (in.)}
\end{align*}
\]
End Variable Declaration

1. Determine CB

IF workpiece material <> cast iron

THEN

   CB = STD/(1/8)

ELSE

   CB = 0

END IF

2. Determine CBS

CBS = 3/64 in. X 3/64 in. for all teeth except

last semifinishing tooth and finishing teeth

END Determine Chip Breakers
CHAPTER FOUR

Computer-Aided Design Interface

4.1 Introduction

According to Groover [1984], Computer-Aided Design involves any type of design activity which makes use of the computer to develop, analyze, or modify engineering drawings. Conventional CAD systems are based on interactive computer graphics (ICG), where ICG denotes a two component user-friendly system - the computer and the user. The computers purpose is to transform design data from the user into the form of pictures and symbols. This process offers several advantages including: (1) design drawing standardization, (2) manufacturing data base generation, and (3) higher quality designs.

Despite these advantages, Mr. Robert Savage of the Hassey/Savage Company stated that the time necessary to transfer design specifications into a working drawing was greater when a CAD system was employed then when manual documentation methods were used. Although CAD does offer more effective documentation, the bottom line in a small industry such as broaching is that time is money.
To offset the time consuming task of translating the design specifications generated by the knowledge-based system into a working drawing of a broach tool, a CAD interface was developed. It is believed that this interface will substantially decrease the design time as well as afford the designer the ability to realize the advantages inherent in Computer-Aided Design. The remainder of this chapter will discuss the CAD interface and the method employed for its development.

4.2 Computer-Aided Design Interface Development

The creation of the CAD interface involved two major tasks: (1) the determination of the format that conventional CAD packages utilize to represent geometric data, and (2) the creation of a mechanism in the knowledge-based system capable of reproducing this format for a particular design.

Through the inspection of two CAD software packages, AutoCAD and CADKEY, it was observed that both packages represent geometric data in a standard format. One format used is termed DXF, meaning "drawing interchange file" format. Simply put, a drawing interchange file is an ASCII text file with a file type of ".DXF". It is a mechanism whereby drawings created in one CAD software package can be
used with different versions of the same software, or with different software packages altogether. Additionally, the drawing interchange file is a mechanism for transferring geometric data to Computer-Aided Manufacturing software packages as well as to finite element structural analysis programs.

In a drawing interchange file, drawings are represented in terms of entity definitions. Entities represent standard geometric building blocks such as lines, arcs, circles, polygons, etc. The definition accompanying each entity consists of its two dimensional coordinates. For instance, a line would be represented as follows:

```
LINE
X1
Y1
X2
Y2
```

where,

- LINE represents the entity,
- X1 and Y1 represent the starting position,
- X2 and Y2 represent the ending position of the line.

The second task in developing the CAD interface involved the creation of a mechanism in the knowledge-based
system capable of reproducing this format for particular round-hole broach designs. The methodology employed was to reduce the broach into its smallest entities - lines, and arcs, and then to create a generic file structure whereby different designs could be represented using the same file.

The structure of a broach was broken down into three sections, the front portion of the broach, the teeth, and the end of the broach. The cutting section or teeth of a broach are the same for both push and pull-type broaches. The front and rear portions, however, differ depending on the broach type. Subsequently, the following structure was developed indicating the sections needed in the drawing interchange file to properly represent all possible round-hole broach designs developed by the knowledge-based system.

1. Front Section
   A. Pull
      1. Automatic shank type
      2. Key type
   B. Push
2. Teeth
   A. Roughing
   B. Semifinishing
   C. Finishing
3. Rear Section
A. Pull
1. Retrievable
2. Non-retrievable

B. Push

Figure A.1 of Appendix A represents the two possible front sections of a pull-type broach that the knowledge-based system is capable of generating. As can be seen from the figure, the front section of a pull-type broach consists of three components - a pull-end, a front neck, and a front pilot. Push-type broaches consist of only the third component, a front pilot. Through inspection of each design, it is evident that the front portion of a broach can be broken down into a series of lines, with only the key-type puller containing arcs.

In order to provide the drawing interchange file with the capability of generating each design, the first portion of the DXF file was separated into three sections of code for: (1) the automatic shank type puller, (2) the key-type puller, and (3) the front pilot of a push-type broach. For example, if the designer specified an automatic pull-type shank, only the portion of code representing this particular design would be executed. Additionally, the code was structured so that each design could be generated independent of the particular design dimensions. In other
words, any design contained in the tables of Appendix A could be created. In order to build in this flexibility, the DXF code had to be structured accordingly. In particular, the entities (lines or arcs) of a particular design were specified according to their order of execution. For instance, the creation of the triangle in Figure 4.1 would be accomplished by executing the three entity statements in a predefined order. Within each entity (a line for example) is its definition in terms of "X and Y" coordinates. These coordinates were represented in terms of variables, with the values of these variables coinciding with the dimensions of a particular design. The following line is an example of this point:

```
LINE
X1 = A1
Y1 = B1
X2 = A2
Y2 = B2
```

where the length and position that the line assumes in the "XY" plane is a function of the values sent to the variables A1, B1, A2, and B2.

Figure 4.2, reprinted from Chapter 3, represents the
Possible Sequence of Execution

LINE 1
X1 = A1
Y1 = B1
X2 = A2
Y2 = B2

LINE 2
X1 = A2
Y1 = B2
X2 = A3
Y2 = B3

LINE 3
X1 = A1
Y1 = B1
X2 = A3
Y2 = B3

Figure 4.1
Figure 4.2 - typical broach teeth

BTR - Back of tooth radius
C/T - chip per tooth
GD - gullet depth
HA - hook angle
HAR - hook angle radius
LW - land width
P - pitch
RA - rake angle
basic structure of broach teeth, regardless of tooth type - roughing, semifinishing, or finishing. As can be seen from this figure, broach teeth can be described in terms of the pitch, hook angle, chip/tooth, rake angle, gullet depth, hook angle radius, and the back of tooth radius. These parameters of broach teeth usually vary from design to design. Additionally, the chip/tooth, hook angle, and rake angle often vary between the roughing, semifinishing, and finishing teeth sections of a specific broach design. Consequently, the drawing interchange file must have built in flexibility to respond to these variations. The same principal discussed in the preceding section was used to generate flexibility in the DXF. Namely, the entity statements necessary to produce a broach design were sequentially coded according to the required order of execution.

The cutting teeth section of the DXF was separated into three parts for roughing, semifinishing, and finishing tooth form generation. Within each section, broach tooth parameters (i.e. pitch) were passed from the knowledge-based system to variables located in the entity definitions. A loop structure was utilized to reduce the number of entity statements required. For example, once a tooth form was described in terms of a series of entity definitions, these definitions were placed in a loop and iterated according to
the number of teeth required. This process was repeated for the three broach teeth sections until all teeth were properly represented.

Figure A.2 of Appendix A represents the three possible rear portions of a round-hole broach that the knowledge-based system is capable of generating based on the type of broach being designed. The same principles discussed in the previous sections were employed to provide the drawing interchange file the flexibility necessary to effect each design. This section was divided into three parts, with each part containing sequentially ordered entity statements.

4.3 Computer-Aided Design User Interface

The CAD interface was developed to limit the amount of user interaction necessary to effect the translation of a round-hole broach design specification into a working drawing. Upon the completion of the knowledge-based system design activities, the user is required to perform the following steps to create a CAD drawing of the broach tool:

1. Reply yes to the question, "Would you like to create a CAD readable file?"
2. Exit the knowledge-based system software package and access CADKEY, AutoCAD, or any other CAD
software package capable of reading DXF files.

(3) "Call up" the DXF file while using the CAD software.

Once the DXF file has been accessed by the CAD program, the user is free to analyze, modify, or perform any other action on the drawing. As stated previously, this system eliminates the manual function of creating a drawing based on textual design specifications. Also, it affords the user the ability to realize the advantages inherent in Computer-Aided Design without the burden of time constraints. Finally, the drawing interchange file format is compatible with most CAM and finite element analysis software packages. This development sets the stage for full scale integration of the design and fabrication process.
Chapter Five

Conclusions and Recommendations

The objective of this research effort was to reduce the time and capital resources required to design round-hole broaches through the development of a knowledge-based system. The research resulted in a software package which performs the following two functions:

(1) It computerizes the round-hole broach design process.

(2) It provides an interface for conventional CAD software packages with "DXF" capabilities.

The software developed successfully reduces the time required to design round-hole broaches of both the push and pull type. In particular, the knowledge-based system software package executes the design process in approximately 3 minutes. To manually perform the identical tasks of the knowledge-based system, it would take approximately 45 minutes to an hour.

The execution of the CAD interface can be accomplished in approximately 1.5 minutes. This time will vary depending on the computing power of the computer being used.
Dileberto and Sexton [1989] estimate that the time required to perform the same function manually on a CAD software package would take approximately 2.5 to 3 hours, depending on the number of broach teeth.

Recommendations

Although the knowledge-based system developed offers the advantages of time savings and transportability, it is by no means a perfect system. The following is a list of recommendations developed to increase the effectiveness of the broach design and fabrication system:

(1) The remaining steps in the broach design and fabrication framework should be completed if the ability to physically prototype on a real time basis is to be realized. These steps include interfacing with CAM software, developing an interface with a postprocessor, the physical manufacturing of round broaches, and system updating to reflect the state of the art in broach tool design and fabrication.

(2) The knowledge-base should be improved through consultation with expert broach designers. For instance, information regarding the effect that the condition of the workpiece has on broach design would enhance the systems
effectiveness. This process would greatly improve the accuracy of the knowledge-based system since a knowledge-based system is only as useful as the knowledge base.

(3) Since round-hole broaches represents only a small portion of the broach tool market, it is recommended that the knowledge-based system be expanded to include design knowledge for different types of both internal and external broaches.

(4) The current research in finite element analysis should be incorporated in the knowledge-based system to provide a more accurate method for analyzing the rigidity of a broach tooth when it is subjected to the cutting forces.

(5) The system should be made more user friendly through the creation of an explanation mechanism to explain to the user the design rules used by the system.

(6) In addition to the design function performed by the knowledge-based system, a mechanism for trouble shooting insufficient designs should be created to aid the user in modifying an existing broach design.
Through the completion of the above tasks, the broach design and fabrication system could potentially provide the broaching industry with a tool capable of reaching non-traditional markets. For instance, the time and capital savings realized could make broaching an economical metal removal process in a job shop environment. Additionally, the transportability of the knowledge-based system could potentially provide the broaching industry with the ability to enter foreign markets without expending excessive capital and human resources. In particular, since the design knowledge is contained in the knowledge-based system, non-technical representatives of a broaching firm could transport the broach design knowledge without expensive training or the services of an expert designer.
References


Savage, R., Vice President, Hassay/Savage, Turners Falls, Massachusetts, 1989.


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<th>Hook Angle Finishing</th>
<th>Backoff Angle</th>
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Table 1

(Partially reprinted from the Tool and Manufacturing Engineers Handbook, 1983)
## Standard Tooth Forms

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### Table 2

(Reprinted from the Tool and Manufacturing Engineers Handbook, 1983)
**Standard Automatic Pull Ends**

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Table 3
(Courtesy of The Ohio Broach and Machine Company, 1988)
### Table 4

(Reprinted from Broaching - Tooling and Practice, 1961)

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**Standard Key Type Pull Ends**
Figure A.1- (a) key-type pull end,  
(b) automatic shank-type pull end  
(c) front pilot of a push broach.
Figure A.2 - (a) non-retrievable end (pull-type),
(b) retrievable end (pull-type),
(c) rear pilot (push-type)
Appendix B
### INITIAL CONDITIONS

- **Broach type =**
- **Puller type =**
- **Machine stroke length =**
- **Machine tonnage rating =**
- **Length of cut =**
- **Starting hole diameter =**
- **Finishing hole diameter =**
- **Surface finish =**
- **Tolerances =**
- **Workpiece material =**

### DESIGN RESULTS

- **Pull per tooth for roughing teeth =**
- **Pull per tooth for semifinishing teeth =**
- **Pitch =**
- **Land width =**
- **Gullet depth =**
- **Back of tooth radius =**
- **Hook angle radius =**
- **Hook angle roughing =**
- **Hook angle semifinishing =**
- **Hook angle finishing =**
- **Backoff angle roughing =**
- **Backoff angle semifinishing =**
- **Backoff angle finishing =**
- **Number of finishing teeth =**
- **Number of semifinishing teeth =**
- **Number of roughing teeth =**
- **Max allowable pulling force =**
- **Minimum required force =**
- **Broach length =**

- **Pull =**
  - Automatic shank
  - 50 in.
  - 10 tons
  - 2 in.
  - 1 in.
  - 1.017 in.
  - 64 micro in.
  - .001 in.
  - Zinc

- **Chip per tooth for roughing teeth =**
- **Chip per tooth for semifinishing teeth =**
- **Pitch =**
- **Land width =**
- **Gullet depth =**
- **Back of tooth radius =**
- **Hook angle radius =**
- **Hook angle roughing =**
- **Hook angle semifinishing =**
- **Hook angle finishing =**
- **Backoff angle roughing =**
- **Backoff angle semifinishing =**
- **Backoff angle finishing =**
- **Number of finishing teeth =**
- **Number of semifinishing teeth =**
- **Number of roughing teeth =**
- **Max allowable pulling force =**
- **Minimum required force =**
- **Broach length =**

- .001000 in.
- 1.129946E-04 in.
- .5 in.
- .156 in.
- .164 in.
- .5 deg.
- .095 in.
- 6 deg.
- 6 deg.
- 2 deg
- 1 deg.
- 1 deg.
- 4
- 3
- 8
- 17734 lbs.
- 4738 lbs.
- 17.86419 in.
Figure B.1: Non-retrievable pull broach (automatic shank type)
**INITIAL CONDITIONS**

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<td>Machine stroke length</td>
<td>10 tons</td>
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<tr>
<td>Machine tonnage rating</td>
<td>1 in.</td>
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<tr>
<td>Length of cut</td>
<td>2 in.</td>
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<td>Starting hole diameter</td>
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<td>Finishing hole diameter</td>
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<td>Surface finish</td>
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<td>Workpiece material</td>
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**DESIGN RESULTS**

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<td>Pitch</td>
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<td>Land width</td>
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<tr>
<td>Gullet depth</td>
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Figure B.2: Retrievable pull broach (automatic shank type)
**INITIAL CONDITIONS**

- **Broach type** = Pull
- **Puller type** = key type
- **Machine stroke length** = 50 in.
- **Machine tonnage rating** = 10 tons
- **Length of cut** = 1 in.
- **Staring hole diameter** = 1.5 in.
- **Finishing hole diameter** = 1.517 in.
- **Surface finish** = 300 micro in.
- **Tolerances** = .01 in.
- **Workpiece material** = SAE 1340

**DESIGN RESULTS**

- **Chip per tooth for roughing teeth** = .00125 in.
- **Chip per tooth for semifinishing teeth** = 9.999801E-04 in.
- **Pitch** = .343 in.
- **Land width** = .11 in.
- **Gullet depth** = .13 in.
- **Back of tooth radius** = .343 deg.
- **Hook angle radius** = .068 in.
- **Hook angle roughing** = 12 deg.
- **Hook angle semifinishing** = 12 deg.
- **Hook angle finishing** = 1 deg.
- **Backoff angle roughing** = 1 deg.
- **Backoff angle semifinishing** = 1 deg.
- **Backoff angle finishing** = 1 deg.
- **Number of finishing teeth** = 4
- **Number of semifinishing teeth** = 0
- **Number of roughing teeth** = 6
- **Max allowable pulling force** = 60382 lbs.
- **Minimum required force** = 7948 lbs.
- **Broach length** = 11.48712 in.
INITIAL CONDITIONS

Broach type =
Machine stroke length =
Machine tonnage rating =
Length of cut =
Starting hole diameter =
Finishing hole diameter =
Surface finish =
Tolerances =
Workpiece material =

DESIGN RESULTS

Chip per tooth for roughing teeth =
Chip per tooth for semifinishing teeth =
Pitch =
Land width =
Bullet depth =
Back of tooth radius =
Hook angle radius =
Hook angle roughing =
Hook angle semifinishing =
Hook angle finishing =
Backoff angle roughing =
Backoff angle semifinishing =
Backoff angle finishing =
Number of finishing teeth =
Number of semifinishing teeth =
Number of roughing teeth =
Max. allowable load =
Minimum required force =
Broach length =

Push
50 in.
16 tons
1.5 in.
2.5 in.
2.525 in.
100 micro in.
.00005 in.
Incoloy

.001 in.
1.25011E-04 in.
.437 in.
.14 in.
.184 in.
.457 deg.
.075 in.
15 deg.
15 deg.
13 deg.
3 deg.
3 deg.
6
3
12
12,419 lbs.
9420 lbs.
12.724 in.