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Design for Machining Using Expert System and Fuzzy Logic Approach

T.I. Liu, X.M. Yang, and G.J. Kalambur

Design for machining is an essential part of design for manufacturability (DFM). This paper presents a fuzzy logic expert system, SMARTDFM, to help designers obtaining technical information about design for machining. It can help design engineers to consider various machining aspects in the early stage of product design. A hierarchical structure has been established for the knowledge base. This expert system can classify all the components into different component shapes. The design guidelines and their justifications have been built into the expert system. This system also offers graphic display for visualization of the product design.

Backward chaining is used in the inference engine. This system solves the uncertainty of the classification of component shapes using fuzzy reasoning. The design engineers can obtain very specialized guidelines and explanations about design for machining, such as component shapes, accuracy and surface finish, work material and standardization, kinematic design, component assembly, etc. Furthermore, SMARTDFM offers the shortest path for all the questions so that design engineers can get the information about design for machining very quickly. In simple words, SMARTDFM can be used by design engineers to apply design for machining principles efficiently and effectively.

Keywords

design for machining, expert system, fuzzy logic

1. Introduction

DESIGN for manufacturability (DFM) has been used by many companies as a cost-effective way to design and produce products. It is a new generation of design tools that support preliminary as well as detailed design. DFM provides designers with manufacturing information. Many companies have also used DFM to redesign their products (Ref 1-4). DFM can be used for decision making in the design stage.

Computer technology should be used to break down the wall between design and manufacturing engineers as well as to enhance DFM. Although computer-aided design and manufacturing (CAD/CAM) has been widely used, computer-aided DFM has yet to reach its full potential. Design engineers should take advantage of software techniques, better computer hardware, and computer networks. When these tools are used, design engineers can gain access to manufacturing information in the design stage. Thus, design engineers can use complete and effective methodology in the design process, and they can make early and correct decisions that will prevent production problems. In this paper, machining has been considered for product design.

Machining processes are widely used for component manufacture. Most machine tools are designed for the machining operations. To ensure that components are designed adequately, design for machining must be considered.

Expert system offers a powerful tool for DFM. It is a new trend in computer-aided DFM. Expert systems allow engineers to obtain practical solutions for component design quickly and efficiently. Furthermore, many expert systems support fuzzy logic for approximate reasoning. This paper illustrates an expert system, SMARTDFM, which uses fuzzy reasoning for design for machining.

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2. Expert System and Fuzzy Logic

2.1 *Expert System*

The term "expert system" describes a computer-based system that models the decision-making process of a human ex-

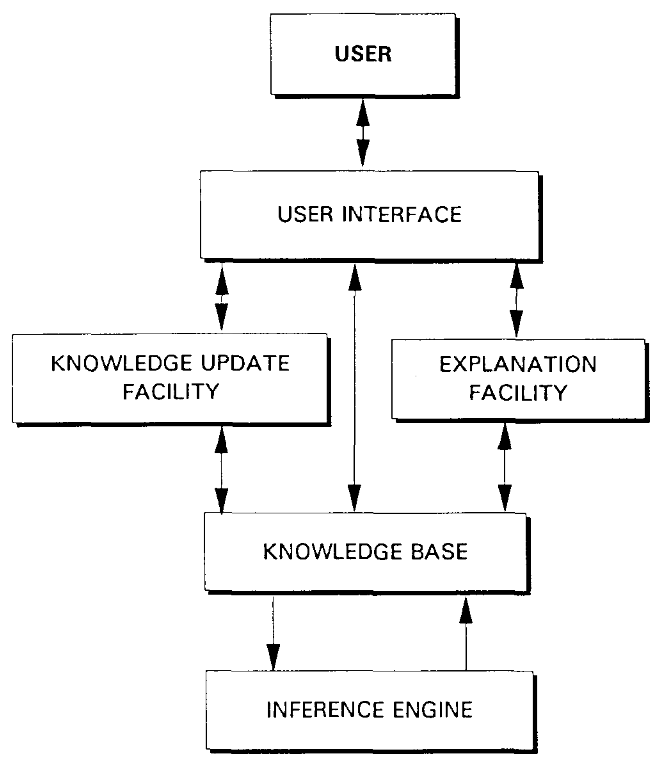

Fig. 1 Typical expert system architecture

pert. The expert system is a branch of artificial intelligence (AI), which has been widely used in product design and manufacturing (Ref 5-7). It attempts to capture the knowledge and expertise of human experts. It also makes extensive use of specialized knowledge to solve problems. A typical expert system is illustrated in Fig. 1; it has two essential parts: (a) knowledge base, and (b) inference engine.

The expert's knowledge about solving specific problems is called the knowledge domain of the expert. Knowledge engineering refers to the acquisition of knowledge from a human expert or other sources and the coding into the expert system (Fig. 2).

One of the popular types of expert systems today is the rule-based system. Rules are popular because of their modular nature and their similarity to the human cognitive process. Rules are made up of English-like sentences or clauses. In their simplest form, rules are defined using an IF-THEN syntax that logically connects one or more antecedent clause with one or more consequent clause:

IF antecedents
THEN consequents

The above rule says that if the antecedents are true, then the consequences are also true.

The significance of the architecture in Fig. 3 is the separation of the knowledge base from the inference engine. The rule base contains the domain expertise. The inference engine consists of a generalized computer program that knows about reasoning strategies and various ways to combine rules and facts, but knows nothing about any particular application. In other words, rules and facts represent what the knowledge is, and the inference engine determines how that knowledge should be analyzed.

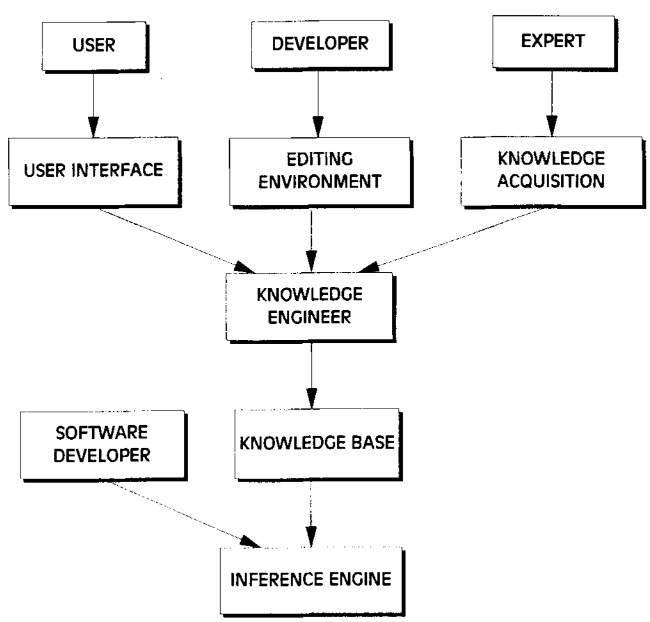

Fig. 2 Development of an expert system

The rules and facts are analyzed by the inference engine. The inference engine uses rules and available facts to assert additional facts. These results, in a series of related rule firings, often are referred to as a chain of reasoning.

In general, expert systems have a number of attractive features: increased availability, reduced cost, reduced danger, permanence, multiple expertise, increased reliability, useful explanation, fast response, steady, unemotional, and intelligent tutor (Ref 8, 9).

2.2 *Fuzzy Logic*

Many expert system shells support fuzzy reasoning. Fuzzy logic was developed by Prof. L.A. Zadeh of the University of California, Berkeley in 1962. By his definition, fuzzy logic is concerned with principles of approximate reasoning (Ref 10-12). Fuzziness indicates the ambiguity contained in the meaning of a word or definition of a concept. Fuzzy logic aims at modeling approximate reasoning, which plays an essential role in the human ability to make decisions in the uncertain and imprecise environment. Fuzzy logic is a well-defined reasoning system that is based on the use of fuzzy sets rather than on the binary values. Fuzzy reasoning is specifically designed to deal with the inexactness (or fuzziness) that is present in the knowledge used by human experts. Design engineers routinely and subconsciously place things into classes for which meaning and significance are well understood but for which boundaries are not well defined. In a fuzzy logic system, only the elements being manipulated are fuzzy; the rules of logic are well defined.

Membership functions span some problem domains, such as length or weight, and show the degree of membership of each value in the problem domain in that function. Membership functions are subjective evaluations and can be in any kind of curve. However, the membership function cannot be assigned arbitrarily. The assignment of the membership function always should be based on the understanding of the real world.

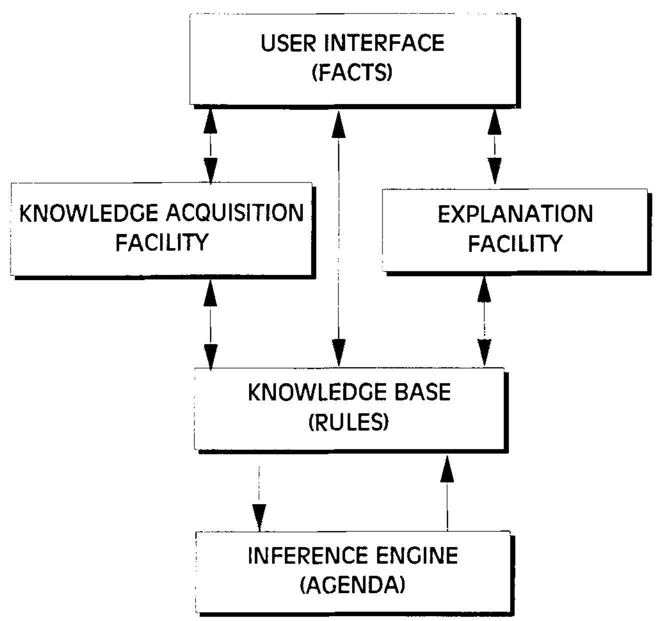

Fig. 3 Structure of a rule-based expert system

The fuzzy set handles ambiguity as seen in the definitions of the fuzzy concept. Let $S = \{s\}$ represent a space of objects. Then a fuzzy set X in S is a set of ordered pairs:

$$X = \{s, f_X(s)\}, s \in S$$

where $f_X(s)$ is the grade of membership of s in X and $f_X(s)$ is a number in the interval [0,1].

Logical inferences are based on if-then rules: "if x is C, then y is D." Fuzzy logic can handle the situation where the membership of x in C is not crisp.

Fuzzy expert systems tend to show some natural degree of robustness to incomplete data, unexpected disturbances, and errors in problem modeling. However, reliable input data and good rule-base design are essential to achieve the solution of a problem efficiently and effectively.

3. Design for Machining Using Expert System

A fuzzy reasoning expert system, SMARTDFM, has been developed and applied to design for machining. Since machining is a very important manufacturing process, design for machining should be considered in the early stage of product design. The information provided to the design engineers by SMARTDFM is concise and complete due to the application of fuzzy logic. Therefore, it is very helpful for product design.

When design for machining is performed, it is important to know how the final component shapes will be cut by machining processes. The complex component shapes lend themselves to an effective classification scheme. In SMARTDFM, applications of fuzzy logic for determining appropriate classification of components have been carried out. The rules used are derived from the length-to-diameter (*L/D*) ratio for rotational components, and from the length-to-width (*A/B*) ratio and the length-to-height (*A/C*) ratio for nonrotational components. Applications of fuzzy logic rules by the estimation of the above ratios can classify various products into different fuzzy sets. Design for machining guidelines are displayed according to which category the component belongs. The inference engine uses fuzzy logic for approximate reasoning, and a correct and concise direction is presented to the design engineers to help them consider various machining aspects in the early stage of product design.

3.1 *Hierarchical Structure of SMARTDFM*

Figure 4 shows the hierarchical structure of SMARTDFM. The expert system shell used is VP-Expert, which offers a combination of powerful features that make it the state-of-the-art PC-based expert system. One of the best features of VP-Expert is its support for computer graphics. It has the ability to execute DOS, COM, and EXE files.

SMARTDFM has the following categories about design for machining for design engineers. Again, each category has its own choices. In other words, it has a decision tree structure:

* How to use SMARTDFM
* SMARTDFM
  ** Standard and work material
  ** Component shapes
    *** General
    *** Rotational component
      **** Disc component
      **** Short cylindrical component
      **** Long cylindrical component
    *** Nonrotational component
      **** Flat component
      **** Long component
      **** Cubic component
  ** Accuracy and surface finish
  ** Kinematic design
  ** Component assembly
* Shortcut references
  ** Standard and work material
  ** General
  ** Rotational component
  ** Disc component
  ** Short cylindrical component
  ** Long cylindrical component
  ** Nonrotational
  ** Flat component
  ** Long component
  ** Cubic component
  ** Accuracy and surface finish
  ** Component assembly
  ** Kinematic design
* Quit

SMARTDFM is designed and developed using the principles of backward chaining and fuzzy logic. The system is developed to be user friendly, and it is menu driven. By responding to the different questions prompted by the system, the user can obtain the answers efficiently and easily. First, the system prompts the user to select one of the different choices (*) either to understand about SMARTDFM, to work systematically in SMARTDFM, or to ask for specific DFM information via the shortest path. If the user selects to work systematically in SMARTDFM, the system asks the user to select a topic (**) of information where expertise or assistance is needed. The inference engine receives the user's selection and searches the knowledge base to match with the facts in order to pass the rule. If the match is made and the conditions are satisfied, the inference engine fires the rule and the results. If more facts are required to satisfy the conditions, the system prompts for more selections (*** and ****) for the users. Depending on the user's input, the inference engine passes all the corresponding rules and displays the conclusions, guidelines, tables, and illustrated graphics.

In order to let design engineers access design guidelines in the fastest manner, "shortcut references" for design for machining were developed. All the relevant topics can be found in this module. Design engineers can always use the shortest path to get the information they need about design for machining.

3.2 *Knowledge Base of SMARTDFM*

The knowledge base file of SMARTDFM contains three basic elements:

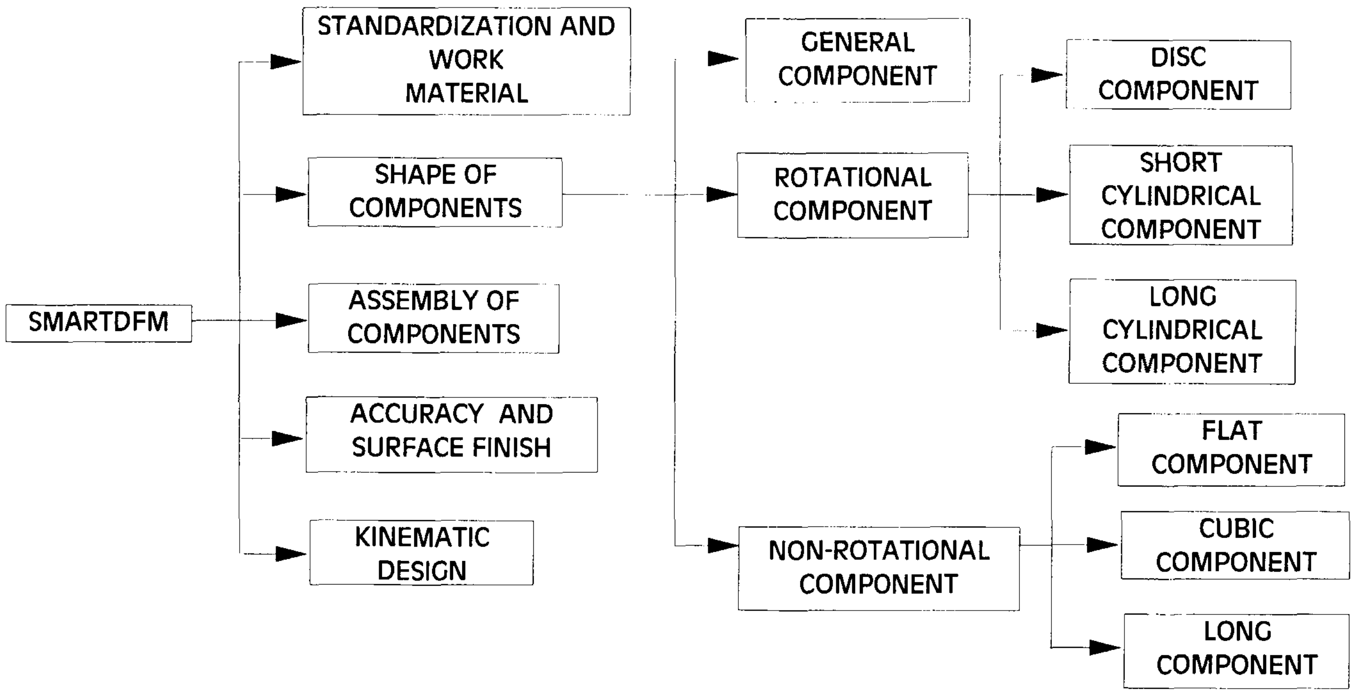

Fig. 4 Hierarchical structure of SMARTDFM

*ACTIONS block
*Rules
*Statements

A fourth element, clauses, is contained within the ACTIONS block or rules of the knowledge base.

The ACTIONS block consists of the keyword ACTIONS, one or more clauses, and a semicolon. This ACTIONS block defines "goals" of the consultation and the sequence of their solution. In other words, the ACTIONS block tells the inference engine what it needs to find out and in what order. This is accomplished with FIND clauses that instruct SMARTDFM to find the value or values of one or more goal variables. In addition to FIND clauses, the ACTIONS block can also contain other clauses specifying other tasks. One example of ACTIONS blocks used in SMARTDFM is:

ACTIONS
FIND Rotational;

Rules with IF/THEN format contain the expertise in design for machining. For example, "If the value for the length-to-diameter ratio is 1.75, then it falls into short cylindrical category of rotational components, then the choice made for "rotational" is "short cylindrical". This information is stated as a rule in the following:

RULE Rotat_CNF (rule name)
IF L_by_D_ratio = 1.75 (premises)
THEN Rotational = Short_cylindrical (conclusion)

In a knowledge base, the rules can occur in any order, but their sequence does affect the path of the inference engine as they move through the knowledge base. Execution speed can be affected by the rule order.

The example shown in Fig. 5 illustrates how a rule contained in the knowledge base of SMART-DFM can help design engineers applying DFM principles for short cylindrical components in their design work. If the rule is passed during a consultation, then a value "short cylindrical" will be assigned to the variable Rotational. The design guidelines to short cylindrical components will be displayed. The DISPLAY clause is used to display messages to the user. When the clause is executed during a consultation, the text within the double quotes is displayed in the window. This clause is very important in SMARTDFM for the conclusion messages. In the example described, the following design for machining guidelines are offered for short cylindrical components:

1. There should be no groove on the surface generated by the cutoff operation.
2. For this kind of component, the diameter of a stepped internal bore should decrease from the exposed end of the workpiece if possible.

3.3 *Fuzzy Reasoning of Component Shapes*

Different design guidelines can be offered by SMARTDFM according to the component shapes. Therefore it is very important to classify components into different categories. Usually, the shape of components can be classified as either rotational or nonrotational.

```
RULE Rotat_CNF

IF        L_by_D_ratio = 1.75

THEN      Rotational = Short Cylindrical

DISPLAY"

     *************************************
     *     ROTATIONAL COMPONENTS         *
     *************************************

Confidence factors for the following components are:

a.  Short Cylindrical Component is 100

Press any key to continue.~".

DISPLAY"

     ****************************************************
     *    ROTATIONAL : SHORT CYLINDRICAL COMPONENTS     *
     ****************************************************
1. There should be no groove on the surface being

   generated by the cutoff operation.


2. For this kind of components, the diameter of a stepped

   internal bore should decrease from the exposed end of

   the workpiece if possible.


         Press any key to continue.~";.
```

Fig. 5 SMARTDFM knowledge base

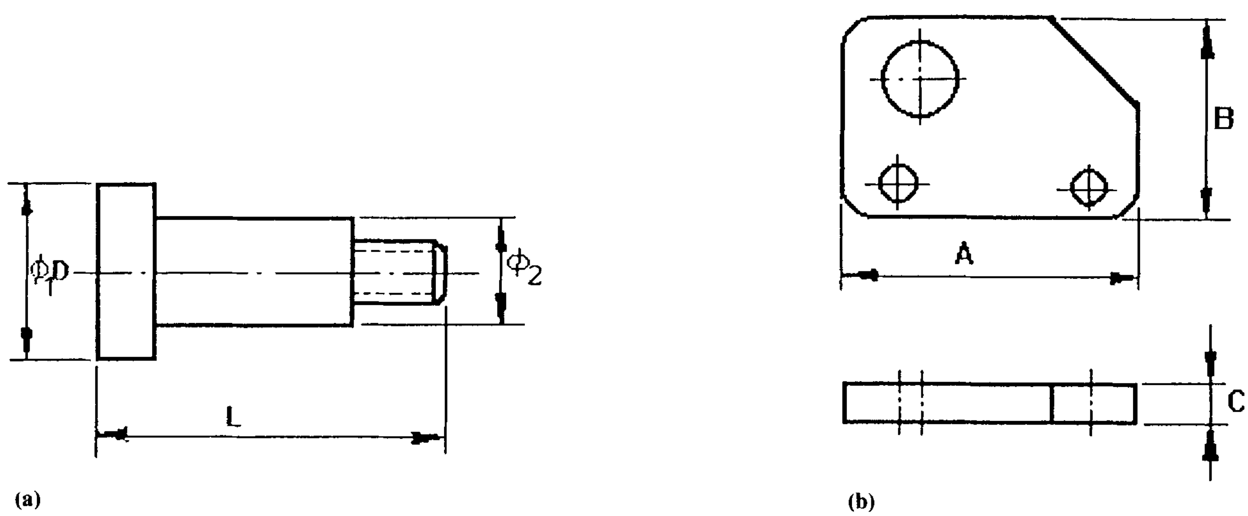

Fig. 6 Basic component shapes. (a) Rotational component. (b) Nonrotational component

If a component shape is rotational, the motion of the tool or workpiece in machining is basically rotation. The basic shape of a rotational component is a plain cylinder with dimension sufficiently large to enclose the final shape.

Components manufactured in the shape of a square, rectangle, plate, or sheet are called nonrotational components. The nonrotational category includes all shapes other than rotational shapes. In machining its basic shape, the motion of the tool or workpiece is linear. The basic shape of a nonrotational component is a right-rectangular prism with dimensions sufficiently large to enclose the final shape. The basic component shapes are shown in Fig. 6.

Many features of rotational and nonrotational components have been taken into consideration by SMARTDFM. The rotational components are further classified to be disc components, short cylindrical components, and long cylindrical components. The nonrotational components are further classified as flat, cubic, and long components.

For rotational components, the boundaries of disc components, short cylindrical components, and long cylindrical components are quite fuzzy. To solve this problem, membership functions are assigned according to the length-to-diameter ratio of the component as shown in Fig. 7, where X-axis represents the length-to-diameter ratio and Y-axis represents the membership function.

For disc components, the membership function is assigned as:

$$
\begin{aligned}
Y &= -100X + 100, && \text{If } 0 < X \le 0.5 \\
Y &= -40X + 70, && \text{If } 0.5 < X \le 1.75 \\
Y &= 0, && \text{If } X > 1.75
\end{aligned}
$$

For short cylindrical components, the membership function is assigned as:

$$
\begin{aligned}
Y &= 100X, && \text{If } 0 < X \le 0.5 \\
Y &= 40X + 30, && \text{If } 0.5 < X \le 1.75 \\
Y &= -40X + 170, && \text{If } 1.75 < X \le 4.25 \\
Y &= 0, && \text{If } X > 4.25
\end{aligned}
$$

For long cylindrical components, the membership function is assigned as:

$$
\begin{aligned}
Y &= 0, && \text{If } 0 < X \le 1.75 \\
Y &= 40X - 70, && \text{If } 1.75 < X \le 4.25 \\
Y &= 100, && \text{If } X > 4.25
\end{aligned}
$$

If the membership function of a component to be disc is between 50% and 60%, then the membership function to be short cylindrical component should be between 40% and 50%. In this circumstance, SMARTDFM will provide design guidelines for both disc component and short cylindrical component. The design engineers can always only look into the guidelines that are more important for practical design. However, if the membership function of a component belonging to disc is higher than 60%, SMARTDFM will only provide design guidelines of disc.

For nonrotational components, the boundary of long components and short components, which consists of flat components and cubic components, is fuzzy. Also, the boundary between flat components and cubic components is fuzzy. First, long components and short components need to be separated. Second, flat components and cubic components need to be dis-

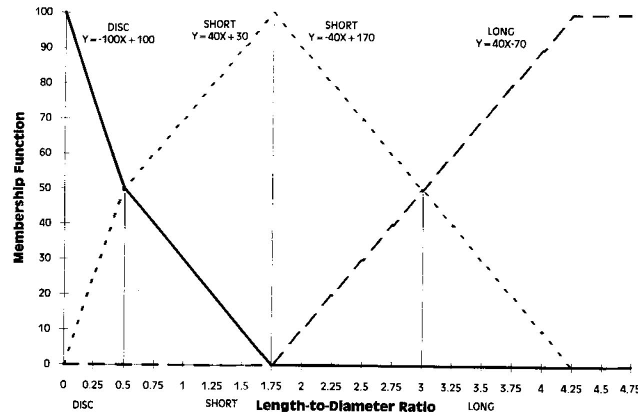

Fig. 7 Membership functions of rotational components

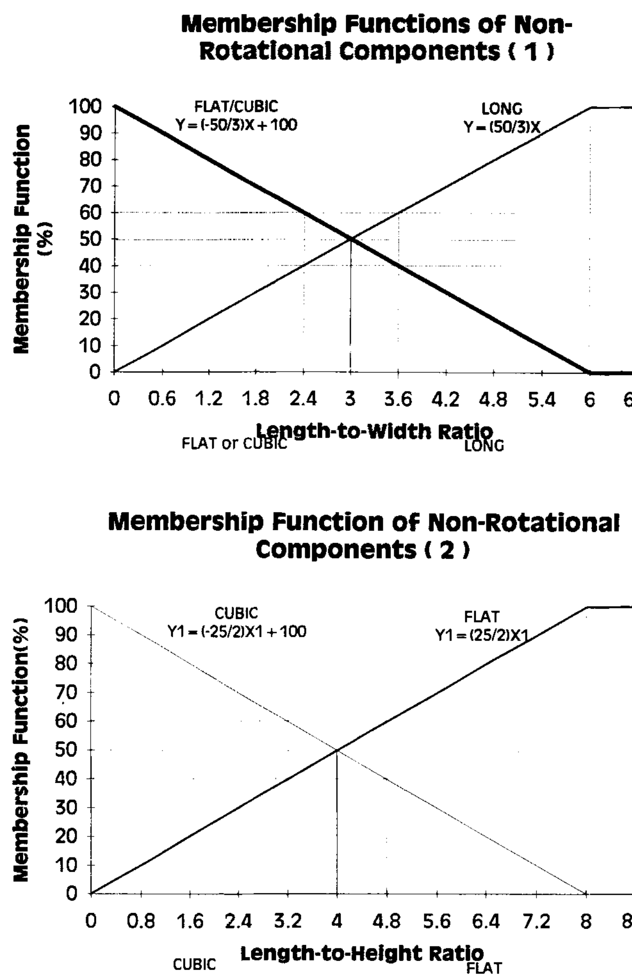

Fig. 8 Membership functions of nonrotational components

tinguished. The classification of three kinds of nonrotational components is more complicated than that of the rotational components. In SMARTDFM, membership functions are assigned according to the length-to-width (A/B) ratio and the length-to-height (A/C) ratio of nonrotational components. Their membership functions are shown in Fig. 8, where X-axis represents the length-to-width ratio or length-to-height ratio and Y-axis represents the membership functions.

For short (flat or cubic) components, the membership function is assigned as:

$$Y = (-50/3)X + 100, \quad \text{If } 0 < X \le 6$$
$$Y = 0, \quad \text{If } X > 6$$

For long components, the membership function is assigned as:

$$Y = (50/3)X, \quad \text{If } 0 < X \le 6$$
$$Y = 100, \quad \text{If } X > 6$$

In order to further classify short components to be either flat or cubic components, the membership function is assigned as:

For cubic components:

$$Y = (-25/2)X + 100, \quad \text{If } 0 < X \le 8$$
$$Y = 0, \quad \text{If } X > 8$$

For flat components:

$$Y = (25/2)X, \quad \text{If } 0 < X \le 8$$
$$Y = 100, \quad \text{If } X > 8$$

For nonrotational components, SMARTDFM can also offer engineers various design for machining guidelines. Depending on the value of length-to-width and length-to-height ratios, SMARTDFM offers design guidelines for flat, cubic, or long components. In case the value of the membership function falls into the fuzzy region, SMARTDFM can display design guidelines for two or even three categories of component shapes. But in the clear-cut region, it displays design guidelines for only one category of component shapes so as to save design engineers' time.

For instance, if the length-to-width ratio of a component is between 3 and 3.6, the value of the membership function of this component belonging to long component is between 50% and 60%. But the membership function of this component to be a short component is between 40% to 50%. In this circumstance, the short component needs to be further classified into cubic or flat components using length-to-height ratio. If this ratio of a component is in the fuzzy region, design guidelines for both cubic and flat components can be displayed to the user. Therefore, engineers can choose design guidelines for up to three different categories of component shapes if they feel it is necessary for the design task. The design engineers can always choose only to look into the guidelines, which is more important for the design by making the choice provided by SMARTDFM.

However, if the membership function of a component belonging to long component is higher than 60%, SMARTDFM only provides design guidelines for long components.

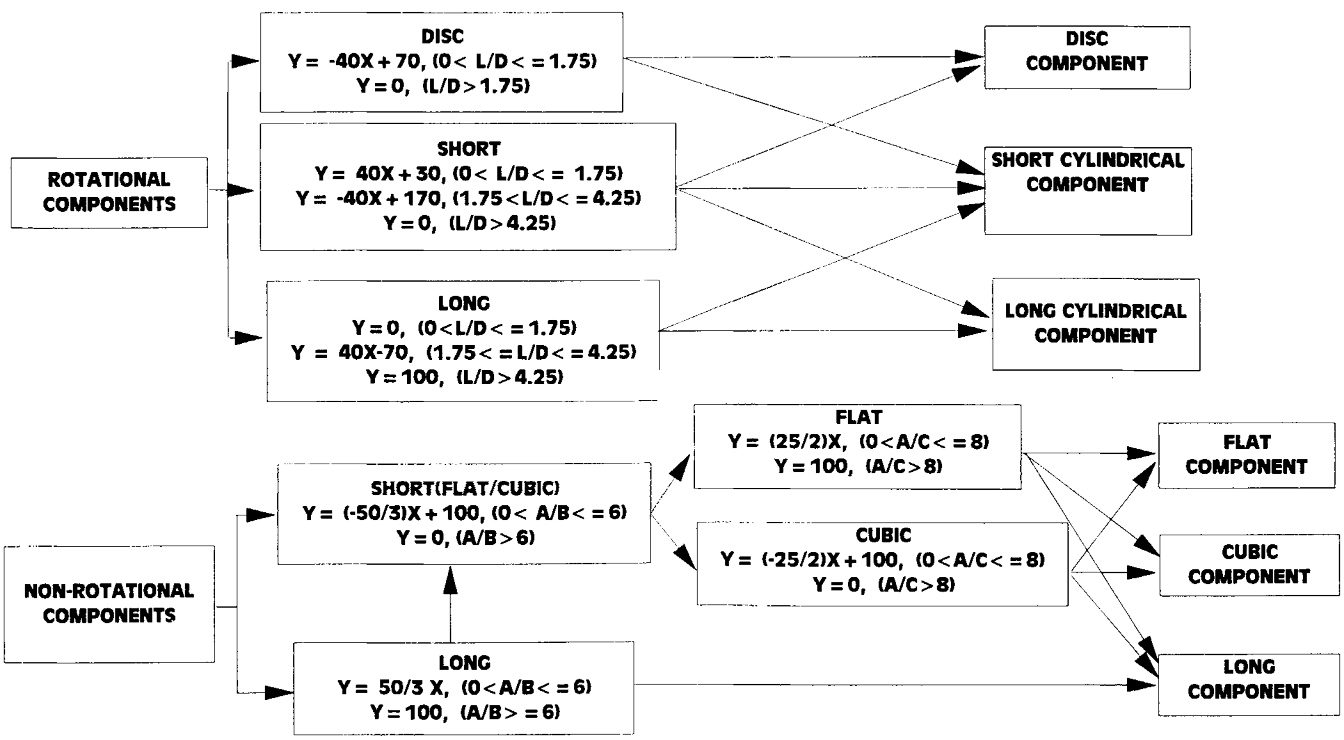

Fig. 9 Membership functions for the classification of component shapes

The reason for providing complete and concise design guidelines for the design engineers is to increase the design efficiency and to help them when considering machining aspects in the design stage. SMARTDFM can provide up to two sets of design for machining guidelines for rotational components and up to three sets of guidelines for nonrotational components in all the "gray" areas so as to provide complete information about design for machining. However, in the clear-cut region, SMARTDFM only provides one set of design guidelines since it is not necessary to provide other irrelevant information. The membership functions for all the component shapes are illustrated in Fig. 9.

4. Application Examples Using SMARTDFM

An illustration of how the inference engine of SMARTDFM is used to determine various categories of components so as to obtain design for machining guidelines is described below. In the knowledge-base, "rotational" has been defined as an ultimate goal variable. The rotational components are classified based on their length-to-diameter ratios. However, there are uncertainties involved during the classification of components. The initial goal for the SMARTDFM is to find the value for Rotational as illustrated below:

```
ACTIONS
FIND Rotational;
```

The inference engine searches the knowledge base for the first rule that can assign a value to the goal variable in its conclusion. RULE Rotat1.1 is the rule:

```
RULE Rotat1.1
IF      CNF_1 ≥ 50 AND
        CNF_1 ≤ 60 AND
        L_by_D_ratio ≤ 0.5
THEN    Rotational = Disc
        Rotational = Short-Cylindrical
DISPLAY"
ROTATIONAL COMPONENTS
Confidence factors for the following components are:
a. Disc Component is {CNF_1}
b. Short Cylindrical Component is {CNF_2}."
FIND Comp_select_d_s;
```

Once the rule is found, the inference engine looks at the first variable named in the premise of the rule. Since the inference engine does not know the value of the membership function in the rule, i.e., premise CNF_1, it looks for the first rule containing CNF_1 in its conclusion. RULE Rotat_CNF_1 is the rule that has CNF_1 in its conclusion:

```
RULE Rotat_CNF_1
IF      L_by_D_ratio ≤ 0.5
THEN    CNF_1 = (100 – (100 * L_by_D_ratio))
        CNF_2 = (100 – CNF_1);
```

Now it has to find the value for L_by_D_ratio which is in the premise of this rule. This sends the inference engine looking for L_by_D_ratio, which eventually causes the ASK statement to display this prompt to the user:

```
ASK L_by_D_ratio:
"Please enter the 'L by D ratio' for the rotational component.";
```

In case the user provides the value 0.5 of the length-to-diameter ratio at the ASK prompt, the inference engine first goes back to RULE Rotat_CNF_1. The values for CNF_1 and CNF_2 are calculated. Since all the conditions are satisfied, RULE Rotat_CNF_1 passes. If the value is not less than or equal to 0.5, the inference engine looks for another rule that satisfies the condition.

Since both CNF_1 and CNF_2 have the value 50 and the length-to-diameter ratio is not larger than 0.5, the inference engine searches the knowledge base and tries to match the fact. If all the conditions are satisfied, the RULE Rotat1.1 passes. The confidence factor for disc component as well as short cylindrical component will be assigned to be 50.

After the design engineer has read the confidence factors for the rotational components, the user will be given the option to select disc, short cylindrical, or both for machining guidelines for the design work.

Since CNF_1 falls into the region where the classification of components is quite fuzzy, the inference engine searches the knowledge base by using the action block, FIND Comp_select_d_s, which means component selection of disc component, or short cylindrical component, or both. Eventually the inference engine will look for the ASK statement:

```
ASK Comp_d_s_choice : "
COMPONENT SELECTION MENU
SELECT one of the following";
CHOICES Comp_d_s_choice :   Disc,
                            Short_Cylindrical,
                            Both;
```

If the designer chooses both, SMARTDFM will display the guidelines for disc and then short cylindrical component as shown in Fig. 10.

The computer graphic such as the display shown in Fig. 11 can help design engineers to visualize principles of design for machining. Some other graphic examples are shown in Fig. 12 to 14.

```
*********************************************
* ROTATIONAL: SHORT CYLINDRICAL COMPONENTS *
*********************************************

1. There should be no groove on the surface being
   generated by the cutoff operation.
2. For this kind of components, the diameter of a stepped
   internal bore should decrease from the exposed end
   of the workpiece if possible.
                Press any key to continue.

                     *********************
                     * ROTATIONAL: DISCS *
                     *********************
1. Design the component so that it is a combination of
   cylindrical surfaces and plan surfaces normal to the
   part axis.  Chamfers and/or tapers can be used.  Try to
   avoid other features which are difficult to produce.
2. Radii for internal corners should be dimensioned
   clearly.
3. The diameters of the internal bore should be reduced
   from the exposed surface while the outside diameters of
   the part should increase from the exposed surface.
4. Try to design the component so that the workpiece does
   not require any machining operation on all surfaces
   which are not exposed in the workholding device.
                  Press any key to continue.
```

Fig. 10 Display two sets of design guidelines

5. Conclusions

A PC-based design for machining expert system, SMARTDFM, has been developed successfully. This package is developed based on the principles of backward chaining and fuzzy reasoning. The design engineers can get important and concise information about design for machining. Not only can the design engineers take into account various machining aspects in the early stage of product design, but they can do it efficiently and effectively so as to save their time and to enhance the design productivity.

SMARTDFM is very user-friendly and is menu driven. This system can offer very specific knowledge in design for machining and is very beneficial for product design.

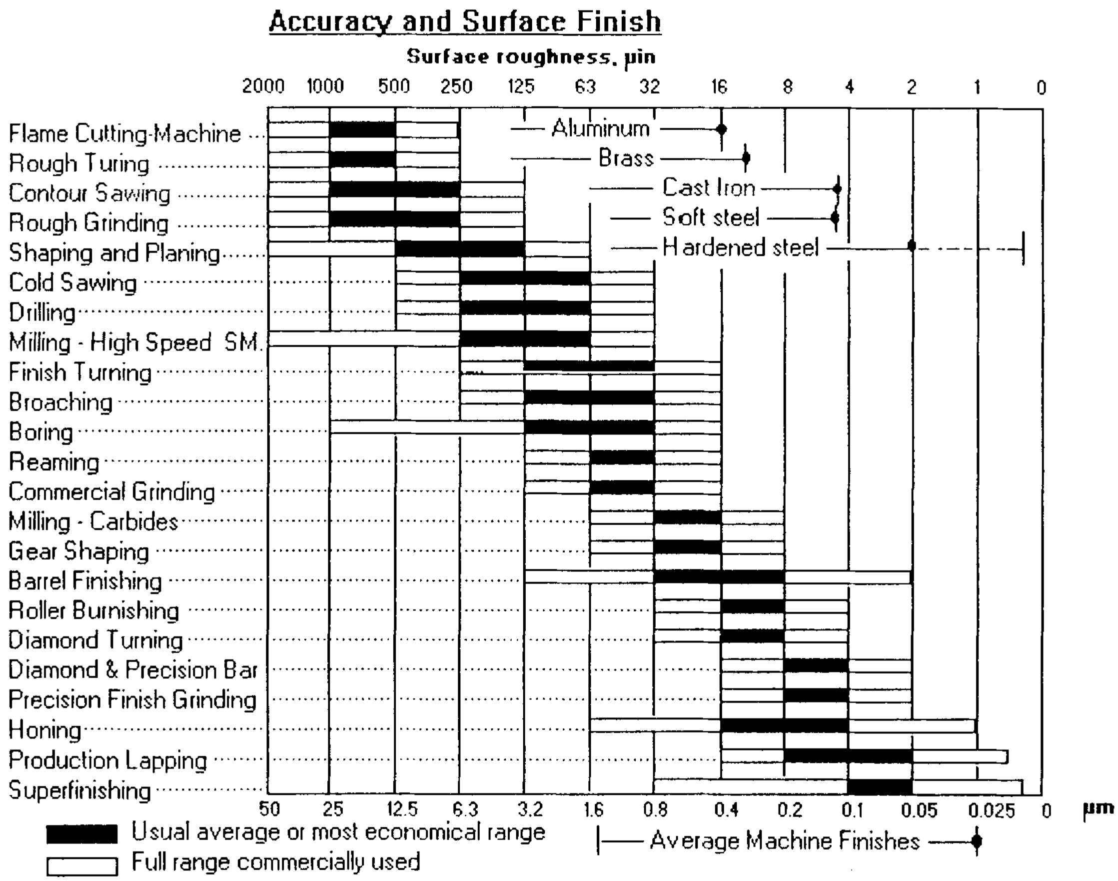

Fig. 11 SMARTDFM guide for accuracy and surface finish

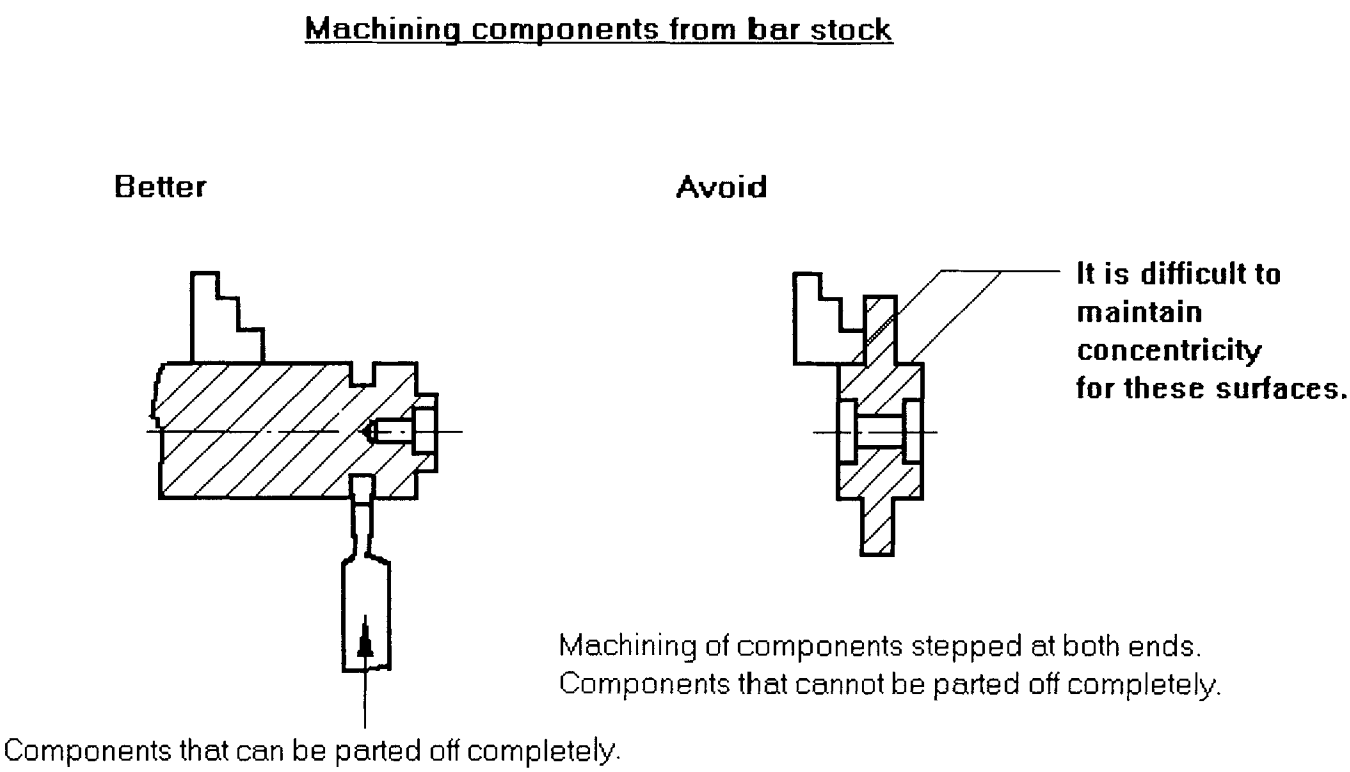

Fig. 12 SMARTDFM graphic display for bar stock

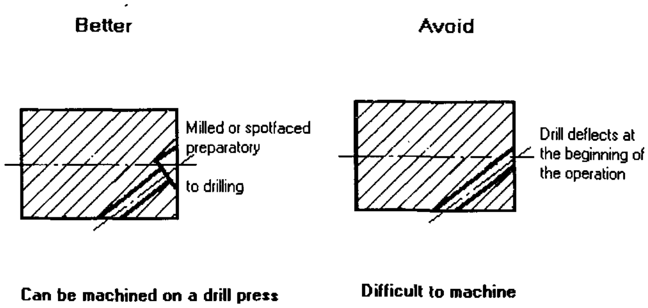

Fig. 13 SMARTDFM graphic display for slant hole drilling

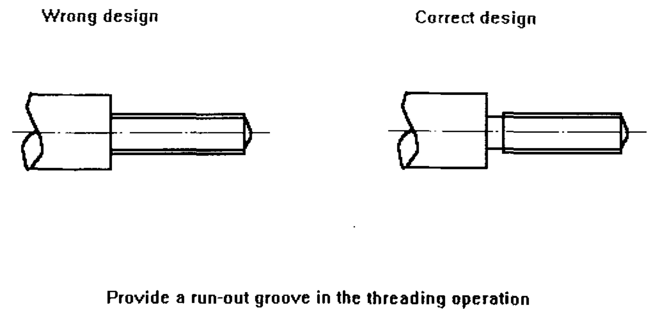

Fig. 14 SMARTDFM graphic display for the threading operation

Acknowledgment

This work is partially supported by the Hornet Foundation and CSUS Mini Grant.

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