モジュラ・ボーリング・ツール・システム支援用 エキスパートシステム*

竹田 晴見**・中島 秀人***・宮内 誠***

Expert System for Modular Boring Tool System*

Harumi TAKEDA**, Hideto NAKAJIMA*** and Makoto MIYAUCHI***

For a build-up type modular tool system used for boring, a boring bar is constructed by combining basic parts such as a shank (or basic holder), accessories, boring head, tip holder, and cutting edge to match the shape and properties of work. The individual basic parts, however, are of such diverse kinds that they provide a vast number of combinations. For this reason, a considerable length of time is required for selection of an optimum combination of basic parts, and this considerably reduces the intrinsic value of the build-up system requiring less time in fine adjustment of cutting edge and tool wear correction.

This paper discusses an expert system developed for higher accuracy and speed in selection of an optimum combination of basic parts for a modular boring tool system. We have only to specify the shape of work, its material quality, etc. in the conversational mode. The expert system will then select an optimum combination of basic parts, and will output the result of selection, cutting rate, feed rate and other boring conditions in a short time.

1. Introduction

Boring is a machining job done to enlarge an existing starting hole to finish it to a required dimensional accuracy. Among the various types of machining jobs, it is one of the hardest because it is most highly dependent on tool design and performance¹. In recent years the boring tool (boring bar) used for a machining center has been transitioning from the conventional microcartridge type in which the shank and boring head are in a single piece to a build-up type modular tool system^{1,2}. The build-up system is finding wider use because it

requires less time in fine adjustment of cutting edge and tool wear correction and can be used for different machines simply by changing shanks.

For a modular tool system, a boring bar is constructed by combining basic parts such as a shank, accessories, boring head, tip holder, and cutting edge. The individual basic parts, however, are of such diverse kinds that they provide a vast number of combinations. For this reason, a considerable length of time is required for selection of an optimum combination of basic parts and this considerably reduces the intrinsic value of the build-up system mentioned above.

Under the circumstances, the authors developed an expert system for accurate and fast selection of an optimum combination of basic parts for a modular boring tool system. This paper describes the configuration of the system. The expert system developed by the authors is intended primarily for use with a modular tool system called the BIG-KAISER CK boring system^{3,4} (abbreviated to the CK boring systems) but is adaptable for use with the other

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** 大阪電気通信大学 Osaka Electro-Communication University ; 18-8 Hatsu-cho, Neyagawa, Osaka 572, JAPAN

*** 大昭和精機株式会社 Daishowa-Seiki Co., Ltd. ; 3-3-39 Nishi Ishikiri-cho, Higashi-Osaka, Osaka 579, JAPAN

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modular tool system in the same way.

2. Modular Boring Tool System^{3,4}

The expert system developed is intended for use with a small-diameter boring tool system for boring of diameters up to 150mm. The CK boring system, the target system for which we made studies to develop the expert system, is briefly described below. The system, as shown in Fig.1 (a), comprises basic parts such as a shank, boring head, accessories, tip holder, throw-away tip (cutting edge), and chamfering tool. A boring bar best suited for work can be configured by combining basic parts that match the boring shape of work, its material quality, etc.

(1) Shanks (Basic Holders)

The length and taper of that portion of a shank which is to be seized by a machining center generally varies among different machining centers. For the CK boring system, five kinds of shanks different in the shape of the portion are available to comply with the MAS standards. For each of the five kinds of shanks, six kinds different in shaft diameter D_s shown in Fig.1 (b) are available. In addition, several kinds different in nominal length L_s are available. Therefore, a total of 39 kinds of shanks are available.

(2) Boring Heads

Boring heads are a part in which a tip holder is to be set. Broadly divided, boring heads include one for rough boring and one for finishing. Rough boring heads include one for through holes and one for blind holes, and six kinds each different in shaft diameter are available respectively. Boring heads for finishing include two kinds for round tip holders used for boring of small-diameters up to 20mm and seven kinds for square tip holders used for boring of diameters up to 150mm. Each of the boring heads has a tip (edge)-adjustable boring range. The range of a boring head overlaps that of another. In other words, multiple boring heads may be selected for a given boring diameter. Hereinafter, the shaft diameter of boring head is referred to as D_h and the nominal length (lengths of tip holder and cutting edge are also contained) referred to as L_h as in Fig. 1 (c).

(3) Accessories

Accessories may be broadly divided into extension adaptors and reduction adaptors. An extension adaptor is used for extending the

(a) An example of boring bar combined

(b) Shank (basic holder)

(c) Boring head (with tip holder and throw-away tip)

(d) Extension adaptor

(e) Reduction adaptor

Fig. 1 Modular boring tool system

length of a boring bar by inserting it between the shank and boring head or between the shank and reduction adaptor or between the boring head and reduction adaptor. Six kinds different in length and shaft diameter are available. In this paper that follows, the effective length of extension adaptor is referred to as L_e as in Fig. 1 (d).

A reduction adaptor is used for intermediately reducing the diameter of a boring bar when there is a difference in work hole diameter by inserting it between the shank and boring head.

Twenty four kinds different in length and shaft diameter are available. Hereinafter, the effective length of reduction adaptor is referred to as L_r , and the length of the portion nearer to the boring head (the thinner portion) referred to as L_{rh} as in Fig. 1 (e).

(4) Tip Holders and Cartridges

Tip holders and cartridges are a part in which a throw-away tip (cutting edge) is to be set. They include two kinds of round tip holders to be set in a boring head for a small-diameter cutting tip holder for finishing, and seven kinds of square tip holders for the corresponding boring heads for boring for diameters up to 150 mm. For a rough boring head, a cartridge is used in place of a tip holder. Cartridges include eight kinds for blind holes and eight kinds for through holes ; each kind of cartridge for a corresponding boring head.

(5) Throw-away Tips

A throw-away tip is a blade edge to be set in a tip holder or cartridge. For rough boring of through holes, two kinds of tips, one for steel and cast iron and one for aluminum, are available. For rough boring of blind holes, two kinds of tips, one for steel and cast iron and one for aluminum, are available. Finishing tips include three kinds ; one for steel, one for cast iron, and one for aluminum.

(6) Chamfering Tools

The chamfering tools are shaped like a ring and can be fitted on boring bar. They allow the chamfering of bores immediately after having bored, without changing the tool. Six kinds different in inside diameter are available.

By the way, a shank, boring head, reduction adaptor, extension adaptor and chamfering tool must have connecting portions identical in diameter (outside or inside diameter) if they are to be coupled together. If the connecting portions are different in diameter, they cannot be coupled together. For this reason, each of the basic parts indicates a number associated with the diameter of its connecting portion to represent connectability (referred to as a C number hereinafter). In Fig. 1 (a) for example, the C number of the boring head and that of the head side end of the reduction adaptor and the C number of the shank and that of the shank side end of the extension adaptor must respectively coincide. As previously stated, six kinds of basic holders different in shaft diameter D_s are available. The value of C number, therefore, ranges from 1 to 6. The larger the shaft diameter, the larger the

value of C number.

Such being the case, the standard combinations of only boring heads and shanks reach approx. 470 kinds. If accessories are added, more than 6000 kinds of combinations are selectable. It is therefore not easy to select out of the so many kinds in a short time an optimum one suitable for a given piece of work.

3. Selecting of Optimum Combination of Basic Parts

This section describes how an optimum combination of basic parts is selected. The expert system essentially searches for basic parts to combine, working in the direction from boring heads toward shanks. The hunting process consists of the selecting blocks shown in Fig. 2.

Fig. 2 Hunting process for optimum combination of basic parts

3.1 Data Entry Block

First this block acquires, in the conversational mode, data on the shape, dimensions, material quality, infeed (whether finish boring or rough boring is to be done), chamfering data (whether chamfering is to be done or not, how much chamfering is to be done), type of machining center, etc. In addition, the entered values are compared with maximum and minimum dimensional values permissible for boring to perform processing to inhibit illegal entries. The expert system is designed for use in applications where boring hole depth L_w is less than 400 mm. In this paper that follows, boring to the size and shape shown in Fig. 3 (boring the L_{w1} area in Fig. 3) is taken as an example.

Fig. 3 An example of boring shape of work

3.2 Boring Head Selecting Block

In this block, a boring head is selected on the basis of the information entered in the data entry block; that is, the size of boring diameter D_1 , infeed, and, when rough boring is to be done, whether the hole is a blind or through hole.

First all boring heads are hunted to select those that have a range of boring diameters, assigned to each boring head in advance, in which boring diameter D_1 of work is included. The boring heads thus selected are further hunted for those in which the following formula holds good among boring diameter D_1 , head diameter D_h , and empirical allowance d_r (6 mm) in the diametric direction.

$$D_h + d_r \leq D_1 \quad (1)$$

In this case, multiple boring heads may be selected. When finish boring is to be done, however, one with the least value of C number is selected to eliminate chips of work easily. For rough boring, one with the largest value of C number is selected to minimize chatter due to rigidity. Generally, it is likely that multiple boring heads different in axial direction length

L_h are selected.

3.3 Retrieval Block For Standard Type Combination Not Using Any Extension Adaptors

If a boring head is selected, an attempt is made to find combinations (called the standard type) that do not use a reduction adaptor. In other words, shanks are selected that have a holding portion that matches the machining center to be used and that have the same C number as that of boring head previously selected. In this case, too, it is likely that multiple shanks different in nominal length L_s are selected.

Combinations in which nominal length L_s of the shanks selected in this manner and effective length L_h of boring head satisfy the following condition

$$L_w + d_a \leq L_s + L_h \quad (2)$$

as shown in Fig. 4 (a) are selected as candidates. Of the combinations, one that has the least value of $L_h + L_s$ is selected as an optimum combination because of minimizing chatter due to rigidity. The d_a in Eq. (2) is an empirical allowance (15 mm) in the axial direction that is required for boring.

On the other hand, when the boring hole is so deep that Eq. (2) cannot be satisfied, an attempt is made by the following block to find the extension adaptor that should be inserted between the selected boring head and shank.

Fig. 4 Standard type combination of boring bar not using any reduction adaptor

3.4 Extension Adaptor Selecting Block for Standard Type Combination

An extension adaptor is selected whose effective length L_e satisfies the following equation

$$L_w + d_a \leq L_s + L_e + L_h \quad (3)$$

and which fits in the diameters of the shank and boring head, or which has the same C number.

In this case, too, it is likely that multiple extension adaptors different in length are selected. Therefore, optimizing is done as described later. If Eq. (3) is not satisfied by use of only one extension adaptor because of its insufficient length, the number of extension adaptors is increased until the condition is met. In this case, the L_e in Eq. (3) should be taken to represent the sum of the effective lengths of all the extension adaptors. If the number of basic parts which constitute a boring bar is increased, the accuracy of the combined boring bar deteriorates. If multiple extension adaptors are selected, therefore, the optimizing block described later selects an optimum combination out of many candidates.

3.5 Shank Selecting Block for Non-standard Type Combination

If none of the standard type combinations can be found that satisfies the requirements, an attempt is made to hunt for combinations using a reduction adaptor(s), or "reduction in stages" combinations.

If the number of reduction stages exceeds 3, however, the accuracy of a combination of boring bar cannot be guaranteed. Therefore, an attempt is made to search for combinations involving a maximum of two reduction stages. For length adjustment, an extension adaptor(s) as well as a reduction adaptor(s) may be simultaneously used.

For reduction in stages, the C numbers of a boring head and reduction adaptor and those of a shank and reduction adaptor must respectively coincide unlike those in a standard combination. In other words, the C numbers of a boring head and shank do not coincide, quite naturally. Therefore, the shanks are searched for those that have a holding portion that matches the machining center to be used and those in which the following equation holds good among shaft diameter D_s of shank, diameter D_2 of work, and allowance d_r .

$$D_s + d_r \leq D_2 \quad (4)$$

Out of these candidates, one that has the largest value of C number is selected to minimize chatter of the boring bar due to rigidity during boring.

If a boring head and shank are successfully selected, then a reduction adaptor identical with them in C number is selected. It is of course likely that multiple reduction adaptors are selected. In this paper that follows, the C number

on the boring head side of a reduction adaptor and the C number on the shank side are referred to as C_{rh} and C_{rs} , respectively.

3.6 One-stage Reduction Selecting Block

For one-stage reduction, four kinds of combinations in Fig. 5 (a) through (d) are envisioned, depending on the number of extension adaptors and inserting positions. In view of boring bar combination accuracy and boring accuracy, the smaller the number of basic parts, the better. For this reason, the combinations in Fig. 5 are checked in the order from (a) to (b) to (c) to (d). If one or more combinations that satisfy the requirements exist in (b) for example, the combinations in (c) and (d) are no longer searched.

If a reduction adaptor is selected as described above, the length L_{rh} on the boring head side of the reduction adaptor is checked to see if the following condition is satisfied. (A combination in Fig. 5 (a))

$$L_{w1} + d_a \leq L_{rh} + L_h \quad (5)$$

Fig. 5 Non-standard type combination of boring bar using a reduction adaptor

If Eq. (5) is not satisfied, an extension adaptor to be inserted between the reduction adaptor and boring head is selected to make sure that the following equation is satisfied. (A combination in Fig. 5 (b)) In the equation, the L_{e1} is the effective length of extension adaptor I.

$$L_{w1} + d_a \leq L_{rh} + L_{e1} + L_h \quad (6)$$

When Eq. (6) is not satisfied by use of only one extension adaptor, two or more extension adaptors are additionally inserted. In this case, too, the L_{e1} in Eq. (6) should be taken to represent the sum of the effective lengths of all the extension adaptors.

If Eq. (5) or (6) is satisfied, to guarantee the good flow of cutting oil, a check is performed to see if the front end angle θ defined in Fig. 6 satisfies

Fig. 6 Definition of front end angle of boring bar

$$\theta < 60^\circ \quad (7)$$

If Eq. (7) is not satisfied, additional extension adaptors are selected until Eq. (7) is satisfied. If Eqs. (5) and (7) are satisfied, a check is performed to see if the following equation (8) is satisfied.

$$L_w + d_a \leq L_s + L_r + L_h \quad (8)$$

where L_w is the depth of boring hole shown in Fig. 3.

If Eqs. (6) and (7) are satisfied, a check is performed to see if the following equation (9) is satisfied.

$$L_w + d_a \leq L_s + L_r + L_{e1} + L_h \quad (9)$$

If Eq. (8) or (9) is satisfied, the combination is treated as a candidate. If Eq. (8) or (9) cannot be satisfied, extension adaptor II to be inserted between the reduction adaptor and shank is selected. In other words, if Eq. (8) is not satisfied, extension adaptor II that satisfies the following equation (10) is selected. (A combination in Fig. 5 (c))

$$L_w + d_a \leq L_s + L_{e2} + L_r + L_h \quad (10)$$

If Eq. (9) is not satisfied, extension adaptor II that satisfies the following equation (11) is selected. (A combination in Fig. 5 (d))

$$L_w + d_a \leq L_s + L_{e2} + L_r + L_{e1} + L_h \quad (11)$$

In Eqs. (10) and (11), the L_{e2} represents the effective length of extension adaptor II. If Eqs. (10) and (11) are not satisfied by a single extension adaptor, the L_{e2} in each of the equations should be taken to represent the sum of the effective lengths of multiple extension adaptors.

3.7 Two-stage Reduction Selecting Block

For two-stage reduction, eight kinds of roughly divided combinations in Fig. 7 (a) through (h) are envisioned. In any of the combi-

Fig. 7 Non-standard type combination of boring bar using two reduction adaptors

Remarks ; R I : reduction adaptor I
R II : reduction adaptor II

nations, an attempt is first made to search for reduction adaptor I in the portion close to the boring head. Reduction adaptor I whose C_{rh} number is equal to the C number of the boring head and whose C_{rs} number is lower in value than (the C number of shank-1) is selected. Generally, multiple pairs of reduction adaptors I and II can exist.

Let the length of reduction adaptor I in the portion close to the boring head be L_{rh1} .

$$L_w + d_a \leq L_{rh1} + L_h \quad (12)$$

If Eq. (12) is not satisfied, extension adaptor I to be inserted between the reduction adaptor I and boring head is selected to make sure that the following equation is satisfied. In the equation the L_{e1} is the effective length of extension adaptor I.

$$L_w + d_a \leq L_{rh1} + L_{e1} + L_h \quad (13)$$

If Eq. (12) or (13) is satisfied, a check is performed to see if the requirement of the front end angle of boring bar in Eq. (7) is met. If it is not met, another extension adaptor is added between reduction adaptor I and boring head to satisfy Eq. (7). The combinations in Fig. 7 (b) through (h) assume that only one extension adaptor exists between the reduction adaptor and boring head, but multiple extension adaptors may be inserted as in the case of single-stage reduction.

If Eq. (12) or (13) and Eq. (7) are satisfied, a check is performed to see if the nominal length of boring bar is larger than $L_w + d_a$. Since the process is the same as in the case of single-stage reduction, only the different conditions in Fig. 7 are shown below.

A combination in (a)

$$L_w + d_a \leq L_s + L_{r2} + L_{r1} + L_h \quad (14-1)$$

A combination in (b)

$$L_w + d_a \leq L_s + L_{r2} + L_{r1} + L_{e1} + L_h \quad (14-2)$$

A combination in (c)

$$L_w + d_a \leq L_s + L_{r2} + L_{e2} + L_{r1} + L_h \quad (14-3)$$

A combination in (d)

$$L_w + d_a \leq L_s + L_{r2} + L_{e2} + L_{r1} + L_{e1} + L_h \quad (14-4)$$

A combination in (e)

$$L_w + d_a \leq L_s + L_{e3} + L_{r2} + L_{r1} + L_h \quad (14-5)$$

A combination in (f)

$$L_w + d_a \leq L_s + L_{e3} + L_{r2} + L_{r1} + L_{e1} + L_h \quad (14-6)$$

A combination in (g)

$$L_w + d_a \leq L_s + L_{e3} + L_{r2} + L_{e2} + L_{r1} + L_h \quad (14-7)$$

A combination in (h)

$$L_w + d_a \leq L_s + L_{e3} + L_{r2} + L_{e2} + L_{r1} + L_{e1} + L_h \quad (14-8)$$

3.8 Optimizing Block

It is believed that the larger the total number of basic parts, the poorer the boring bar combination accuracy. Therefore, if two or more combinations of basic parts selected as described above exist, one with the least number of extension and reduction adaptors is selected.

If two or more combinations with the least number of reduction and extension adaptors exist, one that makes a boring bar with the least effective boring depth (the length from the neck of shank to the front end of bar) is selected.

If two or more combinations still exist, one in which the L/D ratio⁵ is less than 7 and its value the smallest is selected to minimize chatter due to rigidity. Generally, the L/D ratio is defined by the ratio of nominal length L of boring bar to shaft diameter D as shown in Fig. 8. Though the value of less than 5 is used in conventional microcartridge type boring bar, the value mentioned above is empirically used in the CK-boring system, because that diameter of boring bar is sometimes reduced by use of reduction adaptor, in other words, diameter of front end is smaller than that of neck of the bar.

If two or more combinations that satisfy all of the conditions exist, all of them are output as optimum combinations.

Fig. 8 Definition of L/D ratio

3.9 Chamfering Toll and Throw-away Tip Selecting Block

If an optimum combination of basic parts that constitute a boring bar is selected through the processes described above, a chamfering tool that matches the shaft diameter of the boring bar, or a chamfering tool whose C number is the same as the C number of the boring head or shank or reduction, corresponding to the position to be set, is selected, unless the chamfering amount entered in the entry block is zero. In

addition, a throw-away tip best suited for the properties of work and boring conditions is also selected.

3.10 Cutting Speed Calculating Block

If an optimum combination of basic parts is selected and the shape of boring bar completely determined, what has to be done next is to determine infeed, cutting speed, feed rate, etc., based on the type of machining center, properties of work, nominal length of boring bar, etc.

In recent years, thanks to advances in development of materials, many tips now available allow working to be done at a cutting speed of about 200 m/min. In the case of a center lathe, working can be successfully done at any cutting speed best suited for the material quality of tip, as long as the rigidity and horsepower of the machine permit. When working is to be done by the one-sided bar of machining center, etc., however, increasing the nominal length of boring bar increases chatter, making it impossible to cut at the tip maker's recommended cutting speed. In other words, the cutting speed may have to be reduced.

When the bar of machining center is of the vertical type and the boring bar is a combination of only a shank and boring head, and when carbon steel (S45C) is to be cut at the feed rate of 0.05–0.15 mm/rev., the empirically acquired relationships among the effective length of boring bar (the length from the neck of the shank to the front end of boring bar), working diameter and optimum cutting speed are shown in Fig. 9. Similar relationships are empirically known for nickel chromium steel, stainless steel, cast iron and aluminum. Cutting speeds for them are called "standard cutting speeds" in the expert system.

When extension and/or reduction adaptors are used, the cutting speed must be reduced in proportion to their quantity and shank diameter to compensate for reduced rigidity. Such being the case, this block calculates a cutting speed as described below.

If the bar of machining center is of the lateral type, the cutting speed is reduced 5% from the standard speed. If the combination of basic parts contains extension adaptors, the cutting speed is further reduced at a C number dependent ratio shown in Table 1 on a per extension adaptor basic.

If a reduction adaptor is contained and the difference between its C_{rs} and C_{rh} numbers is 1, the cutting speed is further reduced at a C_{rs}

Fig. 9 An example of relationships among boring diameter, nominal length of boring bar, and standard cutting speed
(In the case of carbon steel S45C and feed rate 0.05 to 0.15 mm/rev.)

Table 1 Ratio of cutting speed to be reduced when extension adaptors are included in combination of basic parts (ratio per extension adaptor)

C number of extension adaptor	ratio to be reduced [%]
1	2.0
2	2.0
3	1.5
4	1.5
5	1.0
6	1.0

number dependent ratio shown in Table 2 on a per reduction adaptor basis. If the difference between the C_{rs} and C_{rh} number is more than 2, the cutting speed is further reduced at a C_{rs} number dependent ratio shown in Table 3 on a per reduction adaptor basis. The values shown in Tables 1 through 3 are also empirical values.

When the bar of machining center is of the lateral type and the C number of shank, C_{rs} and C_{rh} number of reduction adaptor are assumed as 6, 6 and 4, respectively, the cutting speed for the

Table 2 Ratio of cutting speed to be reduced when reduction adaptors are included in combination of basic parts and also difference between C_{rs} and C_{rh} numbers is 1. (ratio per reduction adaptor)

C_{rs} number of reduction adaptor	ratio to be reduced [%]
2	2 0
3	1 5
4	1 5
5	1 0
6	1 0

Table 3 Ratio of cutting speed to be reduced when reduction adaptors are included in combination of basic parts and also difference between C_{rs} and C_{rh} numbers is more than 2. (ratio per reduction adaptor)

C_{rs} number of reduction adaptor	ratio to be reduced [%]
2	1 5
3	1 0
4	1 0
5	5
6	5

boring bar shown in Fig.1 (a) for example is given by :

$$\text{Cutting speed} = \text{Standard cutting speed} \times 0.95 \times 0.90 \times 0.95 \quad (15)$$

4. General Discription of System

This expert system is mainly written in Prolog language and uses rule type knowledge expressions (production rule). The section performing calculations and the user interface section involving screen processing, etc., however, are written in C language. Data transfer is achieved by calling the functions written in C language from the program written in Prolog language. The program size is about 400 Kbytes.

As language compilers, Arity Prolog Ver. 4.0 and Lattice C Ver. 3.1 were used. The microcomputer in use is an NEC PC-9801VM with 2M byte cash memory added.

The expert system^{6,7}, as shown in Fig.10, comprises an inference engine (inference mechanism), knowledge base, working memory, knowledge editor, and user interface.

In programs written with conventional programming methods, "knowledge" of some

Fig. 10 Configuration of the expert system

kind is also used. However, such knowledge is implanted in the program and cannot be distinguished clearly. For this reason, it is not easy generally to adapt conventional programs to knowledge revision, addition, etc.

On the other hand, the inference engine, data-base, rule base, and others are separated clearly in an expert system, and knowledge revision, addition, etc., is extremely easy. Moreover, it is said that software development processes can be down to a third by expressing "knowledge" as rules.

In particular, with expanding use of the modular boring tool system, the kinds of basic parts for boring bars are increasing in recent years, and advances are about to be made in machining center high-speed processing. However, changes in boring bar resonance conditions and demand for greater processing precision growing alongside advance in speed are causing the need for drastic changes in "knowledge". Hence, knowledge rule expression have been employed in this system.

4.1 Inference Mechanism

The inference mechanism of the expert system essentially draws forward-looking inferences based on the production rules just like that of an ordinary production system. Since use of a microcomputer is a prerequisite for this system, if contention rules are configured by collating the condition parts of all the rules with the facts on the working memory described below, a considerable length of time will be required before an inference is drawn, and will make it difficult to configure a practical system. Therefore, design strategies were employed to form design blocks by grouping rules according to the scope of application and to prevent collating the condition parts of rules with those not required.

By so doing, the condition part of each rule is also successfully simplified.

Practically, of the blocks for selecting the optimum combination of basic parts shown in Fig. 2, ten blocks excluding the output block correspond to respective rule blocks.

4.2 Knowledge Base

The knowledge base consists of a data base area and rule base area. The data base area consists of a relational data base and a fact base. The relational data base stores data on the individual basic parts, including their model numbers, dimensions of individual portions, etc. and data on the cutting conditions described in 3.10, inventory of basic parts, etc. The fact base stores the default values of working memory, etc. The rule base area consists of meta-rule and rule blocks. The rule base has about 255 rules.

A meta-rule is a group of rules that control the scope of application of rules (production rules) in rule blocks, application sequence, etc. and is written in the following format like ordinary rules.

IF condition THEN driving rule block name

If the content in the condition part compared with the fact written to the working memory match, the rule block concerned is driven.

In more concrete terms, meta-rule controls the process in Fig. 2, that is, the flow of the respective rule blocks. Explicitly, the portion determining the block to be selected next (two portion in Fig. 2 shown in hexagonal shape), is correspond to by meta-rule, depending on the availability of candidate sufficing each block requirement. Implicitly, meta-rule mediates in date and argument transfer between rule blocks. To drive rules by a meta-rule, each rule is declared as described below.

```
Rule (
  Block name
  Rule name
  Condition part
  Action part (results)
)
```

4.3 Working Memory

The working memory stores the result of an inference or a temporary assumption, and indicates the current status in the inference process. The content in the condition part of forward-looking inference rule is collated with the content of the working memory. If they match, the content of working memory is updated by

the action part of the rule to advance to another inference.

4.4 Knowledge Editor

The knowledge editor consists of a data base editor for easier entry of data in the data base area and a rule base editor for easier modification and updating of rules in the rule base area.

4.5 User Interface Section

The user interface section allows entry of data on the shape of work, material quality, etc. in the conversational mode and also has facilities for indication of the result of selection of an optimum combination on the display and also for outputting the data to the printer.

5. Examples of Execution

What are shown here are some examples of optimum boring bar combination selected by use of the expert system to do boring under the conditions shown in Table 4. Fig. 11 shows those results. The results (a) (b) and (c) are corresponding to conditions (a) (b) and (c) in Table 4 respectively. The lengths of time required to obtain the results (a), (b), and (c) are about 5, 13, and 15 seconds respectively.

Table 4 Boring conditions for examples

examples	(a)	(b)	(c)
taper	BT45	BT50	BT50
infeed	finish	rough	finish
material quality	carbon steel	nickel chromium	nickel chromium
type of machining center	lateral	vertical	vertical
shape of work			
D_1 (mm)	40	30	25
D_2 (mm)	50	70	80
L_{w1} (mm)	30	40	60
L_w (mm)	90	150	400
C (mm)	0	5	0
through/blind	through	through	through

C denotes the chamfering amount.

6. Conclusions

Explanations have been given about the expert system which supports selection of an optimum combination of basic parts that constitute a boring bar ideally suited for the boring conditions for a modular boring tool system. For the optimizing block of the system, the empirically acquired condition of less than 7 has been set as the condition concerning the L/D

Expert System for BIG-KAISER Modular Boring Tool System			
parts	type	quantity	stock
shank	BT45-CK3-150	1	○
boring head	EW32-CK3	1	○
tip holder	EB32	1	○
throw-away tip	TPGP080202EL	1	○

$t=0.2 \text{ mm}/\phi$
 $v=180 \text{ m/min}$
 $f=0.07 \text{ mm/rev.}$

(a)

Expert System for BIG-KAISER Modular Boring Tool System			
parts	type	quantity	stock
shank	BT50-CK6-165	1	○
reduction adaptor	CK62-115	1	○
boring head	RW25-33CK 2	1	○
cartridge	RW2533E	1	○
throw-away tip	CCMP070204EFM	1	○
chamfering tool	CR2-42	1	○
chamfering blade	CB 1	1	○

$t=2.5 \text{ mm}/\phi$
 $v=104.0 \text{ m/min}$
 $f=0.25 \text{ mm/rev.}$

(b)

Expert System for BIG-KAISER Modular Boring Tool System			
parts	type	quantity	stock
shank	BT50-CK6-300	1	○
reduction adaptor	CK65-115	1	○
extension adaptor	CK55-60	1	○
reduction adaptor	CK51-100	1	○
boring head	EW20-26CK 1	1	○
tip holder	EB20	1	○
throw-away tip	TPGP080202EL	1	○
chamfering tool	CR2-42	1	○

$t=0.2 \text{ mm}/\phi$
 $v=128.0 \text{ m/min}$
 $f=0.07 \text{ mm/rev.}$

(c)

Fig. 11 Some examples of inference execution results
 (Remarks ; t : infeed, v : cutting speed, f : feed rate)

ratio, but it seems that the chattering condition may vary with the shape and dimensions of basic parts to be combined. It is therefore desirable to make further studies in the future from the standpoint of vibration theory and add calculation routines for finding more detailed conditions.

Furthermore, the expert system has the disadvantage of requiring enormous memories and processing time if the number of rules grow dramatically, if rules are not organized, or there are large number of candidates satisfying the requirements. When expert system is built with microcomputer or other small equipment, these become major problems. For this reason, it is necessary to automate in the future systematic acquisition, organization of knowledge (configuration of a knowledge base in general without contradiction or redundancy) done manually at present.

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