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Rule-based cutting condition recommendation system for intelligent machine tools †

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Abstract

This study relates to a rule-based cutting condition recommendation system for the implementation of intelligent machine tools. For cutting processes, information on the configuration and material of the work-piece, machine tools, and other related tools are essential, similarly as machine tools operators determine appropriate cutting conditions using their own experience along with such details. The development of computer technology has enhanced the intelligence of machine tools, allowing them to automatically calculate and determine relevant cutting data. In this study, a rule-based cutting condition recommendation system is implemented and installed on an open controller for intelligent machine tools. The cutting conditions utilized were provided by tool-makers. The conditions were recommended by classification into high-speed and common speed machining. Efficiency and accuracy has been improved by the implemented system, which is expected to be a key technology for the development of intelligent machine tools.

Keywords: Cutting conditions; Rule-based system; Recommendation system; Intelligent machine tools

1. Introduction

A large number of studies on the development of intelligent machine tools which actively recognize, process, and respond to environmental changes have been conducted. For the actual cutting process, information on the configuration and materials of the work-piece, machine tool, and other tools are necessary for setting up optimal cutting conditions. However, in a conventional CNC process, the cutting conditions, including cutting speed, depth, and feed rate, depend on the operator's experience rather than systematic information. Therefore, conventional methods are not suitable for high productivity, accuracy, and material removal rate. Setting up the right cutting conditions is important because they are the basis for the estimation of time and equipment used in production, such as process and workflow design, as well as actual machining. Taking into consideration the fact that manufacturing trends are shifting from mass production to mass customization, the proper provision of cutting condition data is of significantly greater importance. In general, the actual cutting tests used to optimize cutting conditions require too much time and additional financial costs, hence leading to great inefficiencies in the use of resources. Though cutting conditions can also be extracted from data obtained in earlier experiments and various workability factors in machining, a number of tests are still necessary for application in actual production. To this end, studies are conducted to effectively and efficiently utilize the data in the existing technical information, which is a database listing machining conditions and conditions recommended by tool-makers.

In this study, the cutting conditions for a ball-end mill were optimized by constructing a rule-based

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knowledge base with cutting data and developing a recommendation algorithm for cutting conditions according to the work-piece materials and tool data. The recommendation system was installed in the open controller of a machine tool to test applicability. The knowledge base was constructed with the data provided by tool-makers, providing recommendations classified into high speed and common machining. The system is expected to become a key technology for intelligent machine tools, thereby improving productivity and machining accuracy.

2. Cutting conditions on cutting processes

The performance of a cutting process is determined by the cutting speed of the machine tools and the material removal rate [1]. The cutting conditions guarantee the surface roughness at high productivity and accuracy, as well as tolerance, which requires new tools and appropriate cutting conditions.

As mentioned earlier, the studies on the optimization of cutting conditions include the modeling of ideal conditions through cutting tests and the recommendation of cutting conditions using artificial intelligence with an appropriate knowledge base. Fig. 1 shows the proposed methodologies for obtaining optimized cutting conditions.

Ermer analyzed the impact of parameter errors on the determination of material removal rate at minimum cost [2]. The study describes the impact of measured errors and shows the development of correction factors which enable minimum cost removal rates. The factors are a function for experimental error, cutting conditions from tool life tests, and the Taylor's tool life exponent *n*. Meng proposed a method for calculating optimal cutting conditions that allowed minimum machining time and maximum production [3]. The optimal cutting conditions were determined by applying a variable flow stress machining theory, along with constraints such as machine power, tool plastic deformation, and built-up edge formation, to estimate cutting force and stress. Öktem proposed an effective methodology for determining optimal cutting conditions in milling molds to minimize surface roughness (R_a) [4], which was improved by about 10% after combining a DNA algorithm and response surface methodology (RSM). However, these methodologies are limited in applicability because extensive cutting tests are required to determine the coefficients used to calculate the optimal cutting condition.

To cope with this problem, studies on the application of artificial intelligence coupled with an appropriate knowledge base have been actively conducted. Arezoo performed a study determining the tool selection and cutting condition for machining works that utilized expert systems [5]. The developed system recommends using operators and optimal tool and cutting conditions in conjunction with a knowledge base containing tool data such as tool holders, inserts, and cutting conditions like feed, speed, and depth of cut. Matsumura created a selection system to improve accuracy and surface roughness by first developing

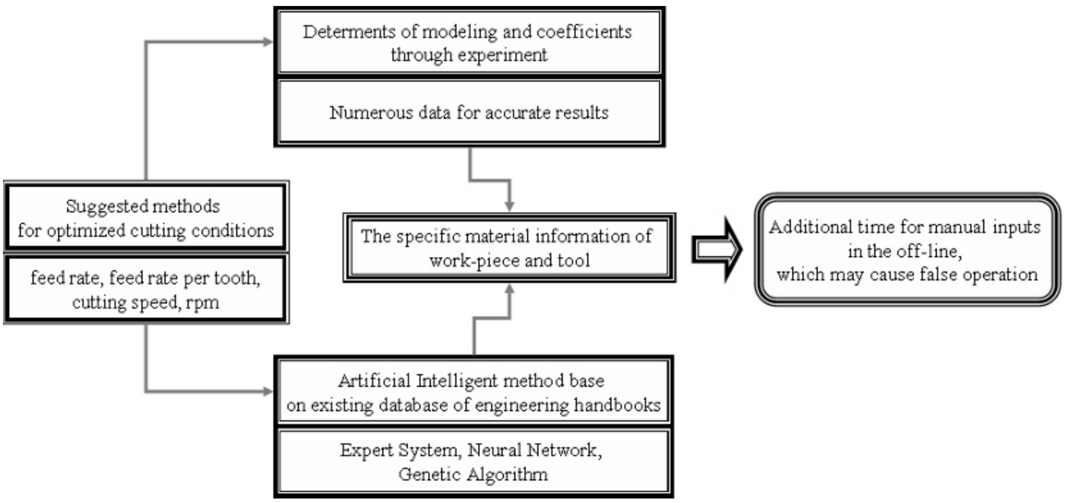

Fig. 1. Suggestion methods for optimized cutting conditions.

numerical expressions for data obtained from experience and references, and then reasoning using logic-based methods to calculate optimal cutting conditions [6].

A more recent method for recommending cutting conditions is the application of artificial intelligence techniques to the existing databases provided by machine tools and/or tool makers. Zuperl determined optimal cutting conditions for low machining cost and high productivity using a commercial database, given relevant restrictions [7, 8]. In the study, a hybrid approach was developed by combining an artificial neural network with an analytical module to improve the accuracy of the predicted result. A method employing generic algorithm has also been studied, where optimal cutting conditions are sought using evaluation functions that can evaluate cutting efficiency and relevant constraint conditions [9].

The cutting conditions obtained from these studies are available offline for PC or in print, and require time for data entry with an increased chance for errors in data input. In this study, a cutting condition recommendation system which can be built in open-type CNC was developed using a basic reasoning system.

3. Factors for cutting condition recommendations

3.1 Optimal cutting conditions for ball-end Mill

An optimized cutting condition can maximize efficiency and economy while maintaining acceptable quality in the machining process. One means of improving the productivity of machining consists of minimizing the production time, which is the sum of the cutting time, the non-cutting time, and the replacement time. Of these factors, cutting time can be minimized by setting up optimal cutting conditions, thereby also improving the surface roughness of the product, which is a measure of machining quality. The cutting conditions to be optimized include the cutting speed, feed rate, feed rate per tooth and spindle speed [10].

Dies and molds are among the products which require intensive cutting processes. According to the dimensions, configuration, and complexity of each individual mold, a process can take anywhere between 1200 to 3800 hours, of which 33% ~ 55% involves NC processing. End mill accounts for about 80% of cutting tools, and the use of the ball-end mill has been increasing, according to the increasing complexity of products. However, due to the dynamic nature of ball-end mills, there have been many theoretical and empirical reports that have suggested recommendations for cutting conditions. Since the tools are shaped like a ball, their stiffness is relatively low and no cutting work is carried out at the vertex. As finishing is required to remove the cusp on the cut surface, the cutting conditions have to be varied according to the process slope (15° is the standard angle) for high-speed cutting [11]. To determine the optimal cutting conditions of ball-end milling, certain factors such as cutting speed, feed rate, feed rate per tooth, and spindle speed have to fall within pertinent allowable ranges.

Cutting speed is the relative speed between tool and work-piece and has the largest impact on tool life and product quality. For example, a mere 50% increase in cutting speed may result in a 90% reduction of the tool's life. Cutting speed also influences feed rate and feed rate per tooth. In end milling processes, feed rate per tooth influences the average thickness of chips while feed rate dictates the total quality of chips made. Cutting speed V is calculated by the Eq. (1) below:

$$V = \frac{\pi \cdot D \cdot n}{1000} (m / \min) \tag{1}$$

where V is cutting speed, D is tool diameter, and n is spindle speed.

Feed rate per tooth is a factor which determines surface roughness and is therefore closely related to the number of teeth. In principle, the number of teeth should not exceed that which is required by the feed per cutter; machine power should also should be taken into consideration. Feed rate per tooth is calculated by the Eq. (2) below:

$$S_z = \frac{S^F}{n \cdot z} = \frac{S_n}{z} (mm / tooth) \tag{2}$$

where S_z is feed rate per tooth, S^F is feed rate per minute, n is spindle speed, and z is number of teeth.

The feed rate of the cutter is the most important factor for work efficiency and should be determined by accounting for the material of the work-piece and tool life. Feed rate is calculated by the Eq. (3) below:

$$S_T = n \cdot S_n = n \cdot z \cdot S_z (mm / \min) \tag{3}$$

where, S_T is feed rate, n is spindle speed, z is number of teeth, and S_z is the feed rate per tooth.

Spindle speed is a determining factor of cutting speed. Although up and down millings also influence cutting speed according to the table feed, the effect is miniscule in comparison to spindle speed. Therefore, engineering data of spindle speed from the tool-maker should be used.

The optimal cutting conditions for ball-end milling should be within allowable ranges. In this study, an algorithm is proposed to recommend cutting speed.

3.2 Proposed algorithm for cutting condition recommendation

Optimal cutting conditions are determined by various factors, including the characteristics of the work-piece, the material and size of tool, and the applied machining method. Fig. 2 presents the algorithm used in determining optimal cutting conditions in this study. The conditions are classified into two categories: high-speed and common machining. For high-speed cutting, data for cutting speed, feed rate, feed rate per tooth, and spindle speed are recommended. In common machining, only feed rate and spindle speed are

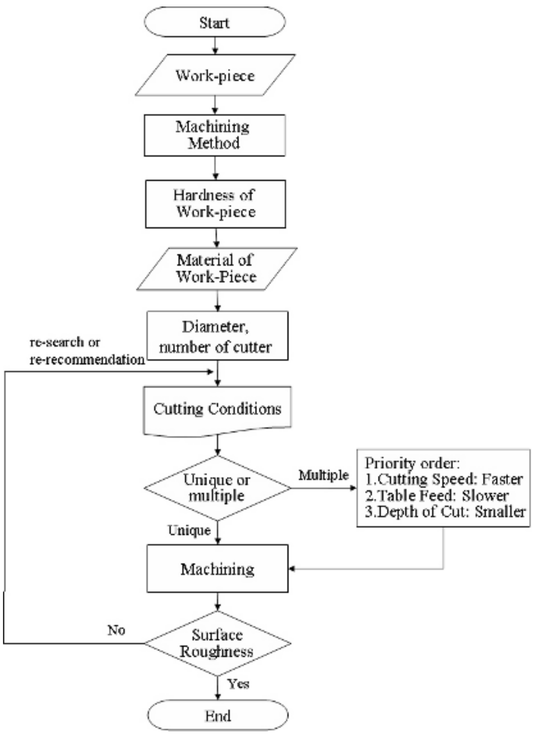

Fig. 2. Flow diagram of optimal cutting conditions for ball-end milling.

recommended. In this study, 'high-speed' means 7000 rpm or higher, while common machining is intermediate cutting and rough cutting.

The operator first selects the work-piece and machining method. For the machining method, the selection was between ball-end milling, high speed cutting or common cutting. The material and hardness of the work-piece, as well as the diameter and number of teeth in the tool are then input. The material of work-pieces are classified into tool steel, alloy steel, high hardened steel, common cast iron, and stainless steel according to hardness. The cutting conditions for aluminum, which is widely used at present, are also provided. The tool diameter range is R0.5-10, and the default number of teeth is 2. When high-speed machining is selected, the angle of the cutting surface slope needs to be selected at above or below 15°, according to the feature of the work-piece.

When such basic data has been entered, the cutting conditions are then recommended. If the recommended conditions are unique, they are then applied; if there are multiple recommendations, the cutting conditions are listed according to priority with due consideration to the weight of the cutting conditions. Faster cutting speed takes top priority among the recommended cutting speeds. If the selected cutting speed is too low, vibrations may occur, reducing precision, thus faster speeds are preferred. The next is feed rate. Lower feed rates are preferred because higher feed rates tend to increase cutting temperature and flank wear. Finally, a smaller depth per cut, which impacts process time, is preferred to achieve appropriate productivity and high process quality. This consequently imrpoves chip removal and reduce cutting resistance. The operator then selects the preferable options from the sorted conditions. After processing, the average surface roughness is measrued. If the surface roughness meets the target value, the conditions are applied. Otherwise, the conditions are again sorted through, or the recommendation process is repeated.

4. Implementation and analysis

For the proposed cutting conditions recommendation algorithm, a cutting conditions recommendation system that can be applied in CNC was fabricated. The open CNC that has been applied in machine tools since the 1990s has brought great changes for intelligent machine tools, shifting focus from hardware to software [12].

Open CNC allows the operator to control the hardware components of machine tools and run application programs via a man-machine interface (MMI) using a standard PC, rather than a dedicated control board. The open CNC used in this study was the Siemens model 840D, whose structure is shown in Fig. 3 [13]. The operating system was Windows XP and the software and MMI utilized was Man Machine Control (MMC) 103. The Numerical Control Kernel (NCK) receives prompts from MMC and provides operating signals for machine tool components. MMC includes a base function unit and a specific function unit; the MMI was set up in the former while user-defined functions were set up in the latter. The cutting condition recommendation system developed in this study was installed in the specific function unit.

Knowledge can be expressed in numerous ways; the application of a methodology that uses rules to express knowledge is one of the most common ways. A rule-based knowledge expression should enable the easy ordering of the results obtained from earlier research and support the user in correct decision-making by making possible the easy modification of the constructed rules whenever necessary [14,15]. Table 1 presents the classification and examples of the rules.

Knowledge can provide more flexible and diverse decision making functionalities than an algorithm method, which give results in accordance with predefined rules and sequences. The knowledge base constructed exclusively for the cutting conditions of the ball-end mill in this study can provide the optimal cutting conditions for cutting processes.

An "if-then" technique was used to construct the knowledge base with existing cutting conditions data. This technique is one of the most popular methods in declarative knowledge representation used in artificial intelligence. It enables the simplified understanding of constructed knowledge, the addition of new

Table 1. Classification and example of rules.

		Definition	Example
Term		Definition of term	Compensative value
Fact		The fact that inter-link one term with another	Compensative values are calculated with temperature
Rule	Constraints	Conditional statement judged as True/False	If temp. is 40℃, the compensative value is 2 *um*.
	Guideline	Recommending conditional statements including judgment as True/False	Temp. exceeding 70℃ is not recommended.
	Action Enabler	Judge as True/False, execute event, message or action	Start-up cooler when temp. exceeds 70℃
	Workflow	Control flow between rule sets	Go to Rule Set 1 to reset compensative value if temp. exceeds 70℃
	Computation	Rule including calculation algorithm	Compensative value = *f*(temp.dxdydz)
	Inference	Judge the condition to set up new factor and influence on the inference	No application of compensative value if temp. is below 15℃. Stop the cooler if there is no compensative value application

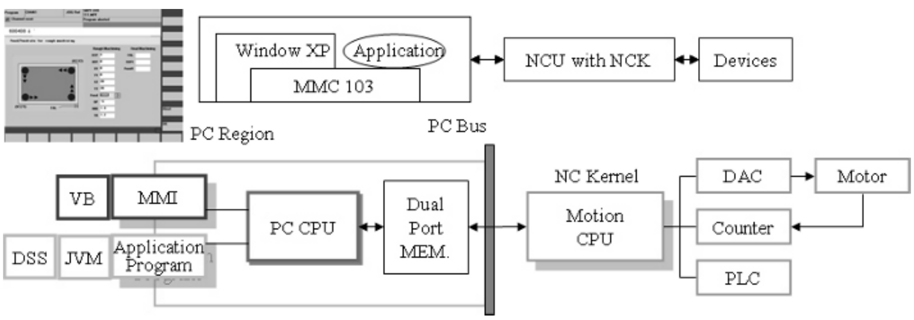

Fig. 3. Structure of open CNC controller.

knowledge and the modification of existing knowledge [16]. Fig. 4 illustrates a typical "if-then" rule set and the structure of the rule. In general, the rule is structured to execute the resultant clauses if the facts in the conditional clauses are met. The rules are organized in the rule set, which are the reasoning units.

An interface engine which includes reasoning logic is required for recommending optimal cutting conditions using the implemented knowledge base. In this study, a commercial interface engine is used in the reasoning process of the technique, thus improving the reliability and speed of reasoning even when the volume of rule sets becomes greater. Fig. 5 illustrates the structure of the cutting conditions recommendation system using the rule-based knowledge base. All software programs, including applications and inference engines, were installed in the specific function unit of the open CNC controller and implemented using Java software. The inference engine supports forward and backward chain reasoning and can process 10,000 rules per second. As it is purely based on

```
Rule_Set for {Class.Input} is
{
    Rule 1 is
            if condition
            then {Class.Output}
    Rule 2 is
            if condition
            then {Class.Output}
    :
    :
}
```

Fig. 4. Structure of rule and rule set.

operates in a hidden layer. The rule base is controlled Java-style architecture, it supports Java open API and in ASCII format for easy modification. The rules were implemented with the data provided by ball-end mill tool makers and the cutting condition equations presented earlier in this paper. The rule wrapper, which is a Java API, converts the inquiry from the application software into text and communicates it to the inference engine, which then reports the reasoning results back to the application software, which interfaces with the operator displaying the inquiry data and the reasoning results on the CNC screen.

Fig. 6 shows a cutting condition recommendation screen in a common process, reporting table feed rate and spindle speed. The cutting conditions of spindle speed of 37501rpm and table feed rate of 189.0 mm/min were recommended for common steel, 2 cutters, hardness 2, and a tool diameter of R1.0. When multiple conditions are recommended, the lower table feed rate for common machining is displayed with the data already sorted by priority.

For a high-speed process, cutting speed, feed rate per tooth, table feed rate, and spindle speed are recommended. As shown in Fig. 7, the angle of the cutting surface (15° standard) is an input factor according to the configuration of the work-piece because of the shape of ball-end mill. When multiple conditions are recommended, they are sorted with priority given to faster cutting speed, and then displayed based on conditions giving lower feed rate per tooth and table feed rate. The depth of cut is determined by the operator, since the chip disposition and cutting characteristics vary by the type of cutting. In general, the depth of cut is 0.5-2.0mm for light cutting, and 4mm or deeper for heavy cutting.

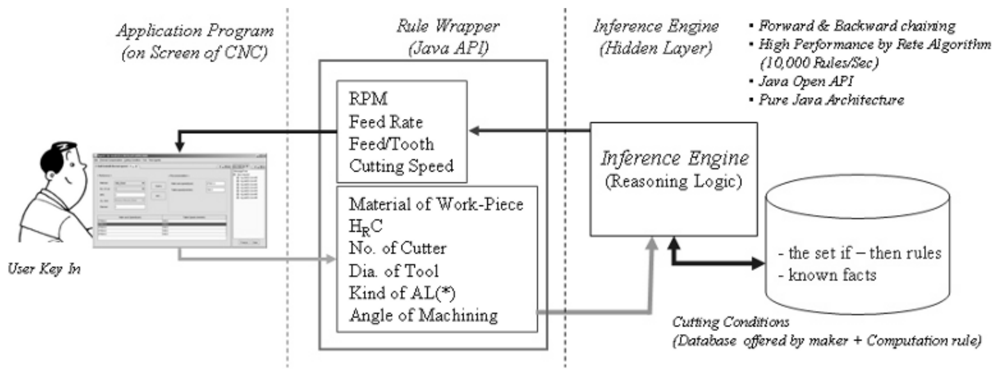

Fig. 5. Cutting condition recommendation system using rule-based knowledge Base.

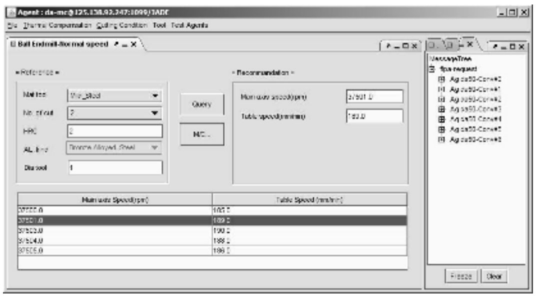

Fig. 6. Recommendation of cutting conditions for common processes.

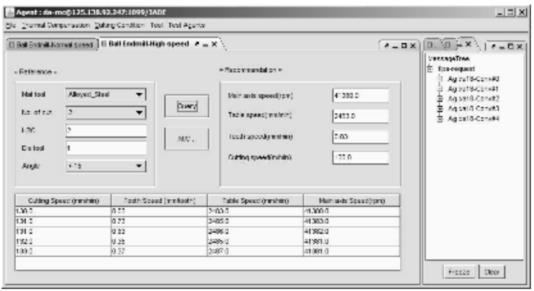

Fig. 7. Recommendation of Cutting Conditions for High-Speed Processes.

Since ball-end milling using multiple cutters is not a simple cutting process that varies from turning or grinding, it is difficult to empirically determine cutting conditions. Therefore, it is not unusual to depend on technical data provided by tool makers. It should be noted that since intelligent machine tools and many operators emphasize short process time, quality problems such as rough surface or damaged layer may be more prevalent in ball-end milling. To prevent such problems from occuring, it is necessary to apply optimized cutting conditions. The cutting condition recommendation system developed in this study can improve productivity and product quality by reducing the time required for manual search and input of cutting conditions, as well as preventing erroneous input.

The reduction of the number of process hours realized by the reduction of the search time for the optimal cutting conditions and the improvement of product quality were analyzed to test the applicability of the cutting condition recommendation system.

As shown in Fig. 8, the general machining process involves work preparation, rough cutting, fine cutting, and finishing, and optimal conditions are applied to each step. A piece of work measuring 100 x 100 mm

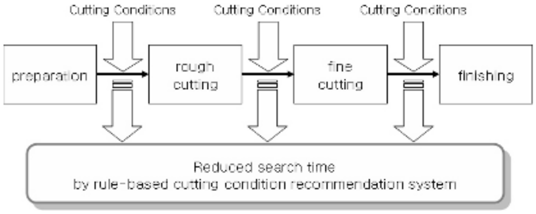

Fig. 8. Reduced search time through recommendation system.

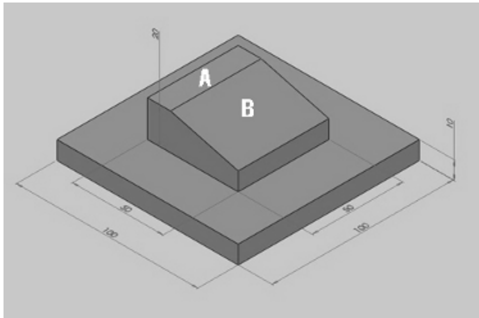

Fig. 9. A piece of work processed according to the cutting conditions recommended system.

was processed in the shape shown in Fig. 9. The machine tool used in the process was a Hi-M 760 of H company, with a maximum speed of 24,000 rpm; the material used to make the work was AL 6061. Rough cutting was carried out in accordance with the following cutting conditions proposed by the recommendation system: spindle speed of 2,500 rpm, feed rate of 480 mm/min, depth per cut of 2.5 mm, and pitch of 7.2 mm; with a diameter of 12mm and a 2-flute end mill; for a total cutting time of 24 minutes and 35 seconds. In the fine cutting, the recommended cutting conditions were as follows: spindle speed of 15,000 rpm, feed rate of 3,000 mm/min, cutting speed of 471 m/min, and a feed rate per cutter of 0.1 mm/tooth; with a diameter of 10 mm and a 2-flute ball end mill. The cutting time for surfaces A and B was 10 minutes and 34 seconds, with a depth of 0.1 mm per cutter and a pitch of 0.1 mm. Meanwhile, it took approximately 5 minutes to the find the appropriate cutting conditions in a data book. This is an average of the times used for loading the NC program and searching for the conditions from the data book. When the cutting conditions were searched on the CNC screen using the recommendation system developed in this study, about one minute was required for each step, which is equivalent to a reduction of 19% of the entire process time.

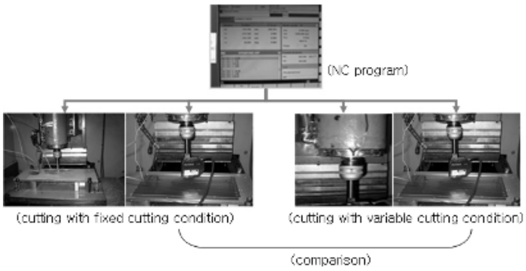

Fig. 10. Measurement of surface roughness achieved by applying the cutting condition recommendation.

The improvement of surface roughness is the most important factor in the improvement of product quality achieved by optimizing cutting conditions. The surface roughness achieved by the processes, where the cutting conditions were set up and fixed at the initial step and modified afterwards, respectively, were measured using a non-contact type of sensor. According to the results shown in Fig. 10, the variations in roughness do not show any significant differences. However, the cutting condition recommendation system proposed in this study could help unskilled machine operators in avoiding the production of products which do not conform to the required standard by applying the recommended cutting conditions.

5. Conclusion

This study involved the implementation of a rule-based cutting condition recommendation system in an open-type CNC to provide an intelligent machine tool. The optimization of the cutting conditions is important since it maximizes the efficiency and quality of the machining works. The rules for the cutting condition recommendation were adopted using the cutting conditions provided by the tool manufacturers, and the rules can be applied through the search function of the reasoning engine on the CNC display. The cutting conditions are recommended within the optimal range by referring to the rule base. In this study, the rule base was built for ball-end mill tools and tested under a real machining process. The results of the application showed an improvement in cutting efficiency and product quality. The recommendation system developed in this study could be used as a core technology in the implementation of intelligent machine tools, and could be used as a knowledge base through the exchange of machining data in network-based machine tools which are expected to be realized in the near future.

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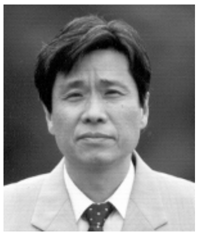

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