Development of Grinding Condition Determination System Using Knowledge Digital Modeling Technology

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By digitally modeling the knowledge of experts, we have developed technology enabling anyone to easily perform high-precision machining. This model has a network structure and can comprehensively express the knowledge of experts. Based on this technology, we have developed two systems. The support tool for turning has contributed to more efficient training for new employees. Meanwhile, the grinding condition determination system, TAKUMI NEURON, has enabled processing equivalent to that of experts by optimization of grinding conditions according to production volume and reduction of study/examination period.

Key Words*: knowledge digital modeling technology, network structure, grinding knowledge model, TAKUMI NEURON*

1. Introduction

Due to the projections for a decrease in the total population, declining birthrates, and an aging population in 2025, the Japanese manufacturing sector must face the fact that labor shortages and lack of skilled workers in particular will become more serious. Therefore, it is necessary to improve the efficiency with which knowledge is transferred from skilled workers through workplace education processes.

A mixture of various type of knowledge, including tacit knowledge possessed by workers, explicit knowledge summarized in documents or textbooks, and processing data from machines and other equipment, are found on production sites. Based on their own experience, skilled workers combine these various types of knowledge to solve tasks. The main hurdle for knowledge transmission is that these thinking processes are idiosyncratic to each worker.

Therefore, we believe that a system that can allow anyone to solve tasks by applying related knowledge in accordance with skilled workers' thinking process is needed. To that end, it is necessary to digitize the multifaceted knowledge at worksites so that it can be expressed in the same frame, and then experts' ways of thinking must be codified so that they can be visualized as digital models of knowledge.

2. Modeling Knowledge with Digital Technology

2. 1 Development of Knowledge Model

A variety of knowledge representation methods, such as expert systems that digitize experts' knowledge and learning-type inference tools like machine learning, exist and see use. However, it is difficult to fully describe knowledge in expert systems, and machine learning models are effectively black boxes, so the process by which solutions are derived is unclear. These methods also require rebuilding of models each time the problem-solving task changes, so it is difficult for them to satisfy the demand we have identified for novel knowledge representation systems.

To meet this demand, we have collaborated with Toyota Central R&D Labs., Inc. to develop a Knowledge Model system that can comprehensively represent the knowledge at production sites and explain the processes by which solutions are derived.

These Knowledge Models are built by capturing all of the knowledge of the target field as explicit knowledge (**Fig. 1**). Technical terms are defined as factors and connected in a network structure. Data values are then set for each factor, and knowledge is explicitly saved by representing the relationships between the factors with connection conditions.

In other words, the model represents various types of knowledge as factors and data values, and the thinking processes of skilled workers as the connection orders and conditions of the factors. Qualitative or quantitative information can be used to set factors' data values and their connection relations. Various connection relations

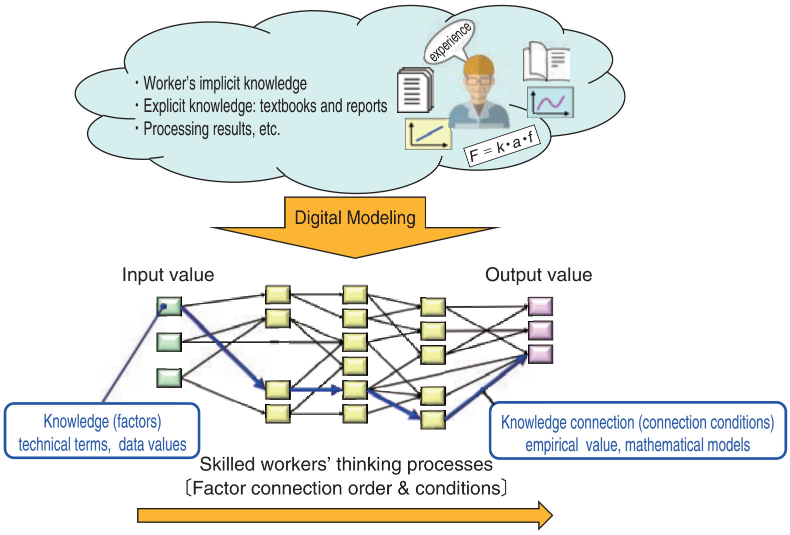

Fig. 1 Conceptual diagram of knowledge model

are created from the empirical data values and rules based on the skilled workers' knowledge, and the contribution between connected factors and connection relations is defined by mathematical models. This unique knowledge network structure can comprehensively represent the knowledge of skilled workers while operating as a white box that allows others to understand the process from input to output.

Furthermore, by constructing a Knowledge Model in a given field once and extracting information by specifying input/output factors, it is possible to utilize a knowledge model to solve various tasks and also to learn about skilled workers' ways of thinking. Since these Knowledge Models are built based on the knowledge of skilled workers, they can be built even with small amounts of data.

2. 2 Utilization for Manufacturing Education

2. 2. 1 Support Tool for Turning

Using the knowledge model structure we developed, we created a turning knowledge model for outer diameter lathe processing. The turning knowledge model was built using a knowledge network that extracted factors related to turning, such as workpieces, tools, machining conditions, and processing results, based on input from skilled workers and teaching materials, and then connecting the factors according to the thinking processes of these skilled workers. When less skilled workers encounter problems during the turning process, it is possible to input information about the workpiece and tool being used into the turning Knowledge Model to determine the recommended machining conditions according to the work materials and required accuracy.

Based on the turning Knowledge Model, we developed a support tool that can predict machining results including abnormalities from the machining condition. With this tool, the connections of the knowledge network can be visually confirmed, and knowledge is then transmitted by tracing the relationships of each factor.

2. 2. 2 New Employee Education Training

From 2019, a prototype of the support tool was used for new employee education training (**Fig. 2**). At the practical training, inexperienced new workers (18 workers in 2019 and 24 workers in 2020) used this tool to accomplish the "verifying the difference in machining characteristics by work material" task.

Fig. 2 Practical use in manufacturing education process

At the training in 2019, we compared and verified the difference of two different materials: carbon steel for machine structure which is used at training every year, and aluminum alloy with which the new workers were unfamiliar. We then analyzed the factors of the built-up edge that occurs during processing of aluminum alloys and examined countermeasures.

The practical training in 2020 included high carbon chrome bearing steel, alloy tool steel, and chrome-molybdenum steel in addition to the materials used in 2019. For each material, we examined its machinability and the process efficiency limits that do not cause abnormalities during machining.

Through this practical training, new workers were able to select a wide range of processing conditions and formulate countermeasures according to each task and situation without relying on instructors. At the same time, by examining the relationships between and contribution of factors, they were able to cultivate an understanding of countermeasures and deepen their knowledge, helping them to gain the "ability to think and act".

As shown in **Fig. 3** and **Fig. 4**, using this support tool contributed to improvements in educational training efficiency, such by allowing for an expansion of the curriculum and by reducing training time by about 60%.

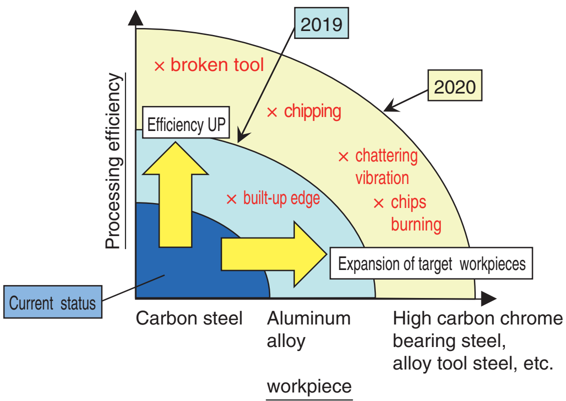

Fig. 3 Training curriculum content

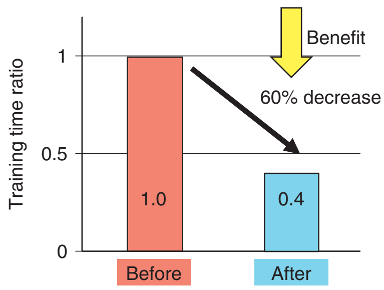

Fig. 4 Problem-solving time

3. Grinding Condition Determination System—TAKUMI NEURON

3. 1 Challenges at Grinding Production Site

Grinding processes generate more heat than cutting processes, so it is easier to cause thermal deterioration of workpieces. In addition, even though high machining accuracy is required, machining accuracy is greatly affected not only by the grinding conditions but also by the grinding wheel dressing conditions and correction timing. Setting grinding conditions is a difficult task that relies on the knowledge and skills of skilled workers.

Inexperienced new workers are not able to set the optimum grinding conditions, so they set higher load grinding conditions compared to skilled workers, resulting in shorter grinding wheel life. Finishing processes may also be set longer than necessary. Additional time is consumed while considering grinding conditions and performing repeated trial grinding and measurement, and then further modifying the conditions.

3. 2 Modeling Grinding Knowledge

In order to solve these tasks, a grinding Knowledge Model was developed by extracting the knowledge of skilled grinding workers. For the cam lobe and journal parts of the camshaft grinding system (**Fig. 5**), which are highly evaluated by customers among grinding machines, we developed a grinding condition determination system called TAKUMI NEURON.

By inputting the specifications such as workpiece, grinding wheel, and required accuracy, TAKUMI NEURON can calculate grinding conditions such as work spindle rotation speed, feed rate, and infeed amount, that satisfy the required cycle time, as well as the predicted machining accuracy, grinding wheel correction conditions, and grinding wheel life (truing interval) (**Fig. 6**). The algorithm of the grinding Knowledge Model contains important knowledge, theory, and information for calculating grinding conditions, such as the mechanical performance of the grinding machine, and the grinding wheel performance information, such as grinding wheel life and sharpness (grinding force) (**Fig. 7**).

Fig. 5 Camshaft grinding system

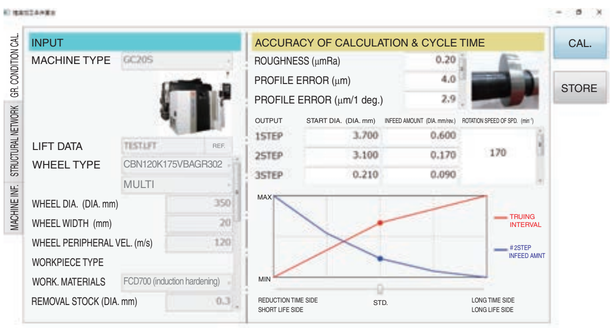

Fig. 6 Grinding condition determination system-TAKUMI NEURON

Fig. 7 Cam lobe grinding knowledge model

Based on our accumulated grinding technology and knowledge, we weight the connections of the Knowledge Model by clarifying the thinking processes of skilled workers. As a result, this system can predict the optimum grinding conditions and machining accuracy, and customers can determine whether the required values are met without test grinding. Grinding conditions such that "anyone can easily perform machining at the same level as skilled workers" can be selected regardless of experience.

3. 3 Processing at the Same Level as Skilled Workers

Aiming for the same machining accuracy with an actual cam lobe, we compared the grinding machining time of the grinding conditions selected by mid-level, highly-skilled workers and TAKUMI NEURON. In the case of using FCD as a workpiece material, TAKUMI NEURON was able to calculate the grinding conditions with the same machining time as a skilled worker and compared to a mid-level worker the machining time was reduced by 22% (**Fig. 8**). Similarly, when the material was steel, it was possible to reduce the machining time by 39% compared to a mid-level worker, and machining time was almost the same as that of skilled workers (experts) (**Fig. 9**). In all cases, the machining accuracy was equivalent to that of a skilled worker.

Even when the material of the workpiece was changed, it was able to calculate the same grinding conditions as skilled workers, based on the characteristics of the material. This shows that TAKUMI NEURON can be used as a system so that "anyone can easily perform machining at the same level to that of a skilled worker".

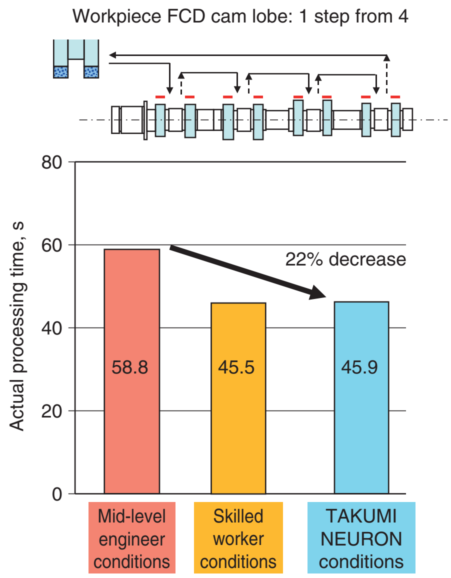

Fig. 8 Comparison of machining time between skilled worker, mid-level worker and TAKUMI NEURON (FCD cam lobe)

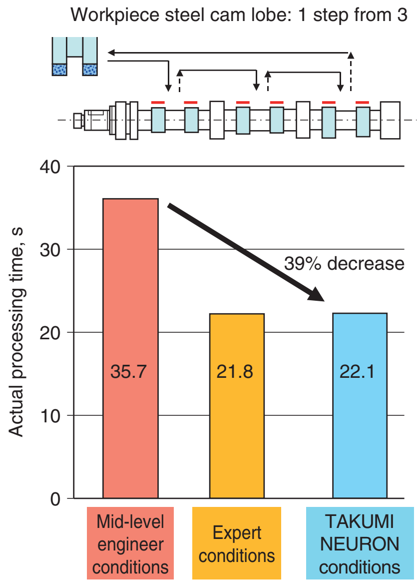

Fig. 9 Comparison of machining time between skilled worker, mid-level worker and TAKUMI NEURON (Steel cam lobe)

3. 4 Selection of Grinding Conditions and Reduction of Examination Time According to Production Volume

In addition, this system can output multiple grinding conditions at once, e.g. standard grinding conditions, conditions that improve productivity, and conditions that extend the grinding wheel life. For each of these conditions, it is possible to compare the cycle time and grinding wheel life simply by moving a slider on a graph in the TAKUMI NEURON screen. By confirming this, customers can easily select the optimum conditions according to their production volume.

For cam lobes, we compared the standard grinding conditions with the conditions that reduce cycle time to improve productivity and conditions that extend grinding wheel life (**Fig. 10**). When productivity is most important, the conditions for improving productivity by 1.3 times (0.7 times the actual machining time) were output, as compared to the standard grinding conditions. Similarly, when grinding wheel life is more important, conditions for extending the grinding wheel life by 1.3 times were output. Since the machining accuracy is the same for all conditions, it is possible to flexibly choose whether to prioritize productivity or grinding wheel life without changing the machining accuracy. With this function, it is possible to shorten the grinding condition examination time for new mass-produced products, and also to easily change the grinding conditions due to changes in production volume even at sites without experienced workers.

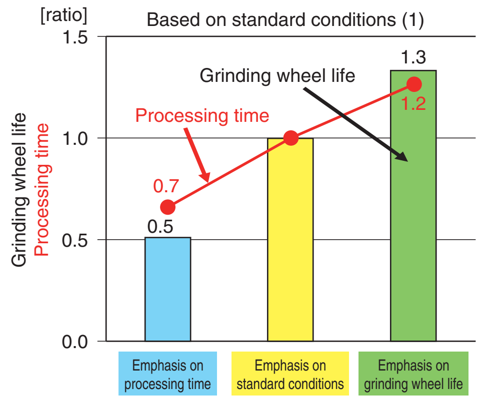

Fig. 10 Comparison of by TAKUMI NEURON results

3. 5 Reduction of the Examination Time before Processing

The procedure to determine the grinding conditions for workpieces before mass production includes:

(1)Check if there are records of results for similar workpieces.

(2)Adjust the grinding conditions based on the differences between the targeted workpiece and past results of similar workpieces.

(3)Perform trial machining and measurements, compare the machining accuracy and machining time with the target values, and perform machining again.

For mid-level workers, steps (2) and (3) are repeated many times, while skilled workers adjust the grinding conditions once or twice. If there is no reference to work from, the number of trials will increase further. TAKUMI NEURON can significantly reduce the time required to select conditions (**Fig. 11**). According to the results of our investigation, the required time is 75% shorter than for mid-level workers and 50% shorter than for skilled workers. This makes it possible to reduce setup times of plant production lines and preparation times for prototype workpieces.

When using TAKUMI NEURON, it is also possible to perform preliminary verification when considering a grinding wheel change. Previously, grinding wheels proposed by the grinding wheel manufacturers were compared with the conventional grinding wheel on the operating line. To evaluate whether targets would be reached under the grinding condition of the production line, it was necessary to process and evaluate large quantities of products. Using this system, on the other hand, the customer can easily select a grinding wheel suitable for the required accuracy and cycle time on the application by comparing to the conventional grinding wheel. This makes it possible to reduce the significant amount of time that was previously required to select a grinding wheel.

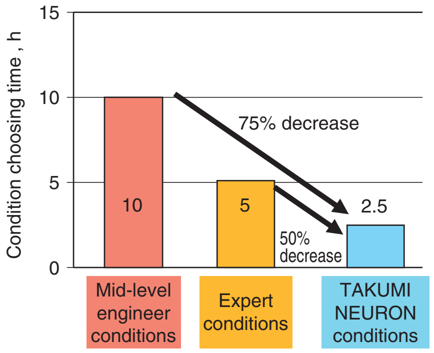

Fig. 11 Reduction of condition selection time by TAKUMI NEURON

4. Conclusion

In the future, we will continue to promote the digital modeling of skilled workers' knowledge related to the grinding processes for various workpieces. We will then expand the applicable range of workpieces to mass-produced products such as reduction gears, eccentric shafts for compressors, motor shafts for EVs, and the high-precision processed products of high-mix low-volume.

The Knowledge Model used in TAKUMI NEURON will continue to evolve from the current fixed method to the changeable method (**Fig. 12**). The Knowledge Model in TAKUMI NEURON will be automatically updated by taking in the state data of the machine during machining and the measurement data of the workpiece during and after machining, and also adding customized rules for each customer. We hope to contribute to the world's manufacturing by calculating the optimum grinding conditions in a timely fashion for each machine used by our customers.

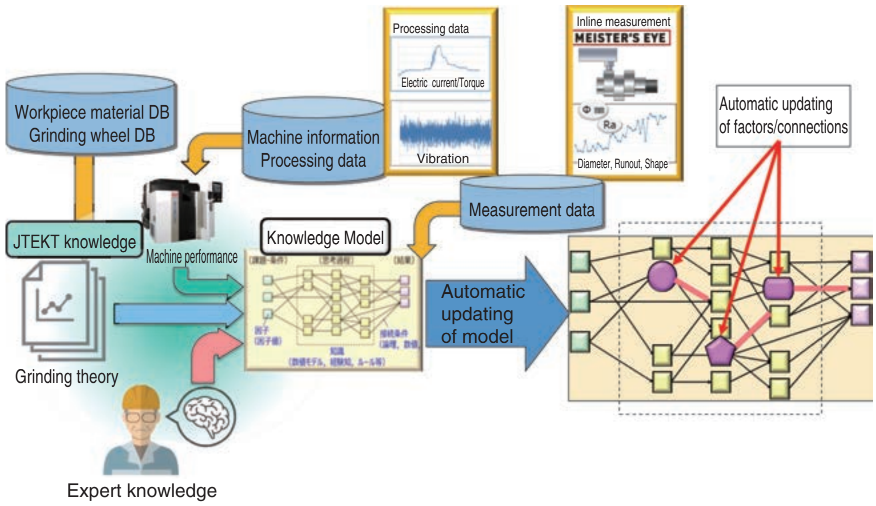

Fig. 12 Ideal vision for TAKUMI NEURON


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