High Efficiency Machining through the Employment of Machining Simulation Technology

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In recent years, there have been demands for higher quality, shorter lead time and cost reduction with regard to the manufacturing of products. In addition, high accuracy and efficiency is also required in machining process. However, attempts are still being made to resolve machining process problems based on past experience and trial and error. On the other hand, numerical simulation is being used in machining processes to predict processing phenomena by making use of advances in numerical analysis. This paper shows the possibilities for improving machining efficiency using machining simulation that employs the finite element method, the prediction of chatter vibration in machining through vibration analysis and the optimization of NC programs through cutting forces analysis.

1. Introduction

Recent market demands for ever higher quality products, shorter lead-time, and slashed costs have led to the demand for ever higher precision and efficiency in machining industries. Yet even today, improvements in machining in actual work sites continue to rely upon past experience and trial and error. However, this experimental approach faces limitations in terms of both time and the cost of repeating tests and trial productions. This is particularly true with the sort of products our company handles, such as large structures and jet engine components that use expensive and difficult-to-cut materials, including titanium alloys and nickel base alloys.

Meanwhile, simulation is being increasingly applied to machining, and this is encouraged by advancements in numerical analysis, which have made it possible to predict phenomena involved in the machining process. We have been striving for the development of optimization technology for deriving machining conditions by combining our original machining simulator and commercially available general-purpose software. This paper provides case examples of our initiatives.

2. Machining simulation technology

2.1 FEM-based cutting simulation

Cutting simulation employing the finite element method (FEM) can help to derive the internal stress of the materials and edge tools, as well as the temperature of the edge of cutting tools that are hard to measure in experiments. Thus, simulation promises greater understanding of cutting phenomena and effective improvements of cutting technique. Accordingly, we have introduced AdvantEdge® in our company. Obtaining the physical properties of materials to be used for the simulation is difficult. But this software has default data (i.e., pre-installed data) in its database, which allows for simulation with over 100 kinds of materials. However, in many cases, sufficient precision cannot be ensured from the default data. Higher precision simulations are pursued by obtaining the physical properties of materials from the results of various material tests stored in our company. This adds to our know-how.

Figure 1 shows an example of comparisons of cutting force errors between the results from experiment and analysis performed with the facemill (ϕ 32 mm, 2-fluted tool) for SCM440H. Analysis results were compared between cases when the default data of AdvantEdge® was used and when the obtained physical property of the material was used. In this example, when the obtained data was used, we were able to keep the cutting force errors between the results from experiments and analysis to no more than 20% in the X, Y, and Z directions as the cutting was performed.

2.2 Simulation for prediction of cutting forces

FEM-based simulations can only analyze cutting phenomena over extremely short periods of time because of the shortness of its allowable analysis time. In general, however, cutting conditions change from moment to
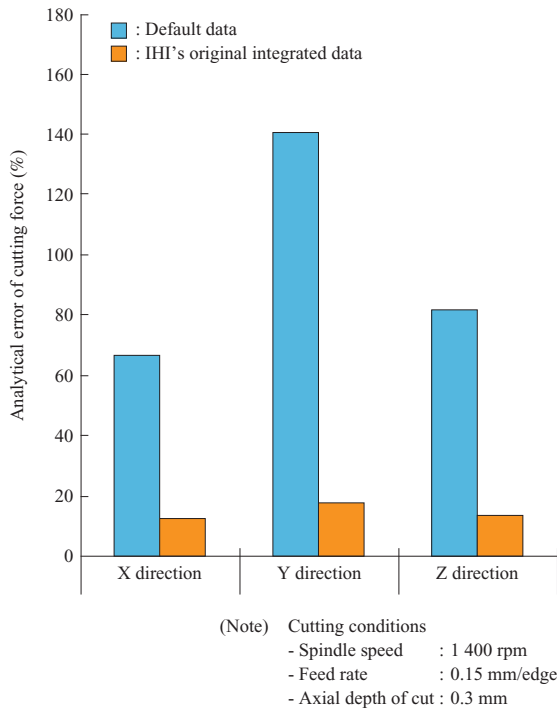
Fig. 1 Comparison of material properties for analytical errors related to cutting force

Fig. 2 Example of application of a method to avoid machining chatter

moment in the machining process of actual products, which requires simulation technology for the entire process. We have introduced the ProductionModule® for prediction of the cutting forces. This software optimizes the feed rate in the Numerical Control (NC) program by prediction of the cutting forces for the entire process by simulation based on the cutting force coefficients obtained from experiments and by entering the cutting force as an optimization variable. An example of application of this software is discussed later in detail.

2.3 Simulation for predicting and avoiding chatter vibrations

There are several types of problematic chatter vibrations during the cutting process. Adequate countermeasures must be taken by identifying the exact type of vibration. We have introduced CUTPRO®, software capable of predicting regenerative chatter vibrations, in order to predict and avoid the regenerative chatter vibrations caused by fluctuation in chip thickness, which are the biggest challenges in the actual cutting process. In addition, we have created a program to predict forced chatter vibrations caused by the periodic impact force associated with intermittent cutting[1]. In this way we are striving for the development of our own technology for making a coupled analysis of both types of chatter vibrations and successfully avoiding them without compromising the efficiency in the cutting process. **Figure 2** shows an example of the application to the machining process.

Element test results and contact conditions of the tool and work during the cutting process are used to calculate ① stability lobes of regenerative chatter vibrations predicted by CUTPRO®, ② occurrence prediction range
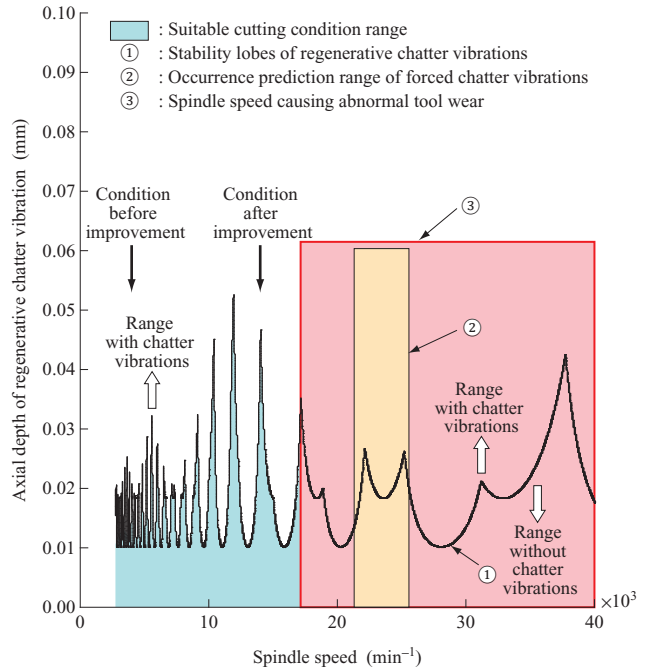
of forced chatter vibrations predicted by the program, and ③ spindle speed causing abnormal tool wear. Consideration of these three phenomena helps not only to avoid regenerative chatter vibrations, but also to identify spindle speed and axial depth of cut that can avoid both the forced chatter vibration range and the range associated with abnormal tool wear. In the example shown in **Fig. 2**, improvement was made to the initial conditions by increasing the spindle speed to successfully avoid chatter vibrations and abnormal tool wear. As a result, the efficiency of the cutting process increased threefold from the previous level.

3. Case example of application of simulation for prediction of cutting forces in practice

This chapter introduces a case example of a particularly practical and immediately effective use of ProductionModule® applied in the prediction of a cutting force and optimization of the NC program.

3.1 Optimization technology for the NC program

In recent years, our company has frequently employed the five-axis control machining center and small-diameter ball end mills for the cutting process of components with complex shapes such as jet engine components for aircraft and turbocharger components for automobiles. There is a limit to how much one can pursue higher efficiency by relying only on experience and intuition because of the complicated contact condition between the tool and the work and the complexity of the NC programs. In addition, it is difficult for the conventional functions of Computer Aided Manufacturing (CAM) to stably achieve selected optimal cutting conditions during 5-axis simultaneous machining process of a complex shape.

As a simple example of a ball end mill in use, **Fig. 3** shows an analysis of the contact length in the axis direction by the NC program based on CAM. In this example, the contact length in the axis direction rises sharply at the moment of reversing the feed direction of the ball end mill. Excessive cutting force is applied to the tool in the part experiencing the sharp rise in the contact length in the axis direction, which can trigger problems such as chipping of the edge of the cutting tool. In the actual cutting process, it is difficult to appropriately modify the program to adjust for such a sudden change in cutting conditions. This leaves no other alternative but to minimize the feed amount of the entire program, which inevitably prolongs the processing time.

Figure 4 shows an example of optimization of the NC program, wherein the feed rate is adjusted while tangential force is chosen as an optimization variable. **Figure 4-(a)** shows the previous state optimization. With respect to the processing machine and tool stiffness, a difference from the allowable upper limit of tangential force is observed because the tool's capacity is not sufficiently raised up in some parts and exceeding the upper limit in the other. In contrast, as a result of optimization as shown in **Fig. 4-(b)**, the feed rate is adjusted to stably maintain the tangential force at the upper limit in order to optimize the NC program. Feed rate adjustment can be made for each line

of the NC program (further division is possible), making pinpoint adjustment possible. Usually, there are many parts with a low cutting force in the NC program output by CAM. This often makes it possible to simultaneously extend the tool life and enhance precision by smoothing out the cutting force, as well as reduce machining time. In the example shown in **Fig. 4**, a 59% reduction in machining time was achieved.

3.2 Case example of application

An example of application of this technology to impeller processing is introduced. Tangential force is chosen as the optimization variable in order to set the standard condition based on the results from the analysis of tangential force according to the previous cutting condition. After excluding momentary peak values, half of the maximum value in the remaining part was set as the standard condition of tangential force (condition 1). Two more conditions were added that raise the target value of tangential force from the standard condition. Optimization was performed with a total of three conditions for test production. **Table 1** lists target values of optimization variables for each process. Figures of conditions 2 and 3 are shown in proportion to the figure of condition 1. Target values were set low in processes ④ and ⑤, which greatly affect machining precision. Feed rate in process ⑥ with sufficiently small axial depth of cut is set constant with reference to the
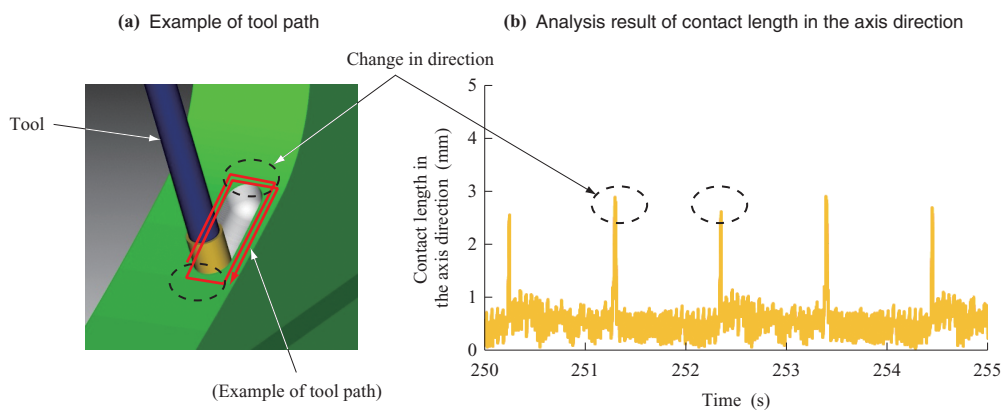
(a) Example of tool path   **(b)** Analysis result of contact length in the axis direction

Fig. 3   Analysis case involving the axial depth of cuts in ball-end milling

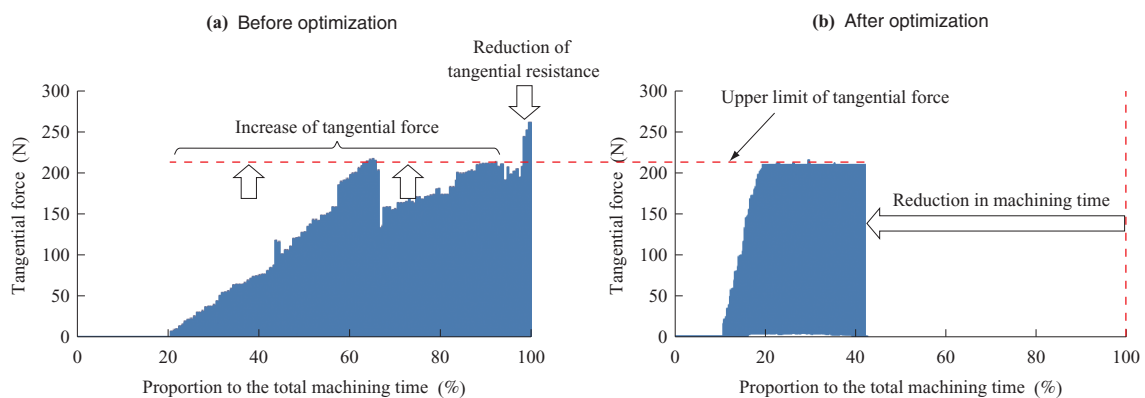**(a)** Before optimization   **(b)** After optimization

Fig. 4   Example of NC program optimization

Table 1 Optimization variables and target values

Process	Optimization variable	Target value of optimization variable			
		Proportion to standard condition	Condition 1	Condition 2	Condition 3
①	Tangential force	1.0	1.0	1.3	1.7
②		1.0	1.0	1.3	1.7
③		1.0	1.0	1.3	1.7
④		0.17	1.0	1.5	2.0
⑤		0.027	1.0	1.5	2.0
⑥		0.67	1.0	1.0	1.0

analysis results.

Figure 5 shows the results from the analysis of the rate of reduction in machining time as compared to the existing NC program corresponding to each condition. In processes ④ and ⑤, machining time increases under condition 1 with a low target value of tangential force. However, in terms of the entire set of processes, it was predicted that the machining time can be reduced under all conditions.

The machining precision improved in comparison to the previous cutting conditions prior to optimization even under condition 3, which achieved the greatest reduction in machining time. The required specifications could be thus satisfied. Enhancement of machining precision could probably be achieved by suppressing excess cutting force to prevent work deformation. In the trial production under condition 3, machining time was shortened by 23% in comparison to the previous machining conditions prior to optimization.

3.3 Future tasks

At present, it is often difficult to quantitatively set the target value of optimization variables without applying past data or element test data. This case example required three trial productions. Further trial and error would be necessary, were it not for the existing machining conditions that are confirmed to achieve a certain level of precision and reasonable machining time. Quantitative definition of the target values of optimization variables without trial productions will further require both a simulator capable of calculating variables with sufficient precision and the technology to theoretically define the upper limit of target values for the variables.

4. Conclusion

This paper demonstrated the effectiveness of the optimization method involving an NC program that employs machining simulation as an alternative to the conventional optimization of processing conditions depending on past experience and trial and error at machining work sites. In a case example of application of this method, machining time was reduced by increasing the feed speed in the part with room for increase in cutting force while suppressing the cutting force in the other part to maintaining stable processing quality.
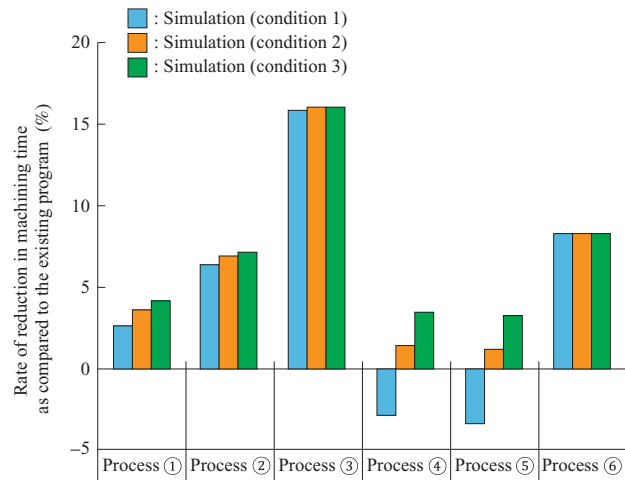

Fig. 5 Comparison of cutting conditions for the rate of reduction for machining time for the current NC program

In recent years, element technologies are advancing with machining tools, NC, manual tools, CAM, and so forth, in order to speed up and enhance the performance of machining. We are also experiencing cases of components with complex shapes that have so far only been manufactured by casting and machine pressing, but which can now be manufactured by machining.

Meanwhile, demand for quicker delivery and for cost reduction is mounting, under the conditions of diversifying customer needs and the advent of variable-mix variable-volume production in addition to the historically strong yen and rise of emerging economies. In order to meet these demanding market needs, we must achieve dramatic cost reduction by developing an innovative technology to achieve higher efficiency that goes beyond the level of improvement.

As one of the means toward this end, machining simulation technology is expected to continually play a crucial role in order to take full advantage of the full potential of advanced element technologies. Simulations help us to capture machining processes numerically and unravel related phenomena based on theory and logic. In this manner, the development of innovative processing methods, tools, and conditions can be made more efficient and speedy while reducing the need for tests and trial production. We intend to continuously contribute our innovative machining technologies toward the development of new products and systems, and thereby serve as a driving force for progress in our society.

REFERENCES

(1) N. Suzuki, T. Ikada, R. Hino and E. Shamoto : Comprehensive Study on Milling Conditions to Avoid Forced/Self-Excited Chatter Vibrations Journal of the Japan Society for Precision Engineering Vol. 75 No. 7 (2009. 7) pp. 908-914