DEVELOPMENT OF A SPRT MILLING TECHNOLOGY FOR NI-BASED SUPER ALLOY

Norikazu Suzuki  
Nagoya University  
Furo-cho, Chikusa-ku  
Nagoya, Aichi, 464-8603, Japan  
nsuzuki@mech.nagoya-u.ac.jp

Yuya Kato  
Nagoya University  
Furo-cho, Chikusa-ku  
Nagoya, Aichi, 464-8603, Japan  
kato@upr.mech.nagoya-u.ac.jp

Eiji Shamoto  
Nagoya University  
Furo-cho, Chikusa-ku  
Nagoya, Aichi, 464-8603, Japan  
eiji.shamoto@mae.nagoya-u.ac.jp

Yukio Naiki  
Mitsubishi Heavy Industries, Ltd.  
1200 Higashitanaka, Komaki, Aichi, 485-8561, Japan

Yuji Takagi  
Mitsubishi Materials Corporation  
1511 Furumagi, Joso, Ibaraki, 300-2795, Japan

ABSTRACT

We conducted milling experiments of Ni-based super alloy by use of the developed milling cutter with Self-Propelled Rotary Tool (SPRT). Experimental results verified that the tool life is increased 12 times as compared with the conventional milling without insert rotation due to tool wear suppressions. Cutting process parameters were also identified by inverse analysis of the cutting forces. The identified parameters may be available for advanced estimations in tool geometry and machining quality. On the other hand, disadvantageous characteristics in ramping process were revealed due to flank face contact.

INTRODUCTION

Ni-based super alloy is frequently used for component parts manufacturing in aerospace and/or power plant industries due to its superior physical and chemical properties. This nature, at the same time, imposes significant difficulty in machining process. As the tool life is extremely short due to excessive tool wear, improvement of the tool wear resistance is a major focus for manufacturing engineers [1]. In order to attain drastic improvement of the tool life in the Ni-based super alloy machining, many researchers have dedicated to apply the rotary cutting technique so far [2]. In the rotary cutting process, the cylindrical insert tool rotates continuously while cutting. The contact region of the tool against the workpiece changes resulting in suppression of the tool wear process. The researchers have contributed to explore the rotary cutting mechanics and to develop practical applications including Ni-based super alloy machining. Significant improvement was achieved in turning process especially with actively-driven-rotary-tool (ADRT) [3], meanwhile the applications to milling process have not been developed, which are interesting considering practical use in industry.

In order to attain rotary milling, the authors have proposed utilization of the self-propelled-rotary-tool (SPRT) mechanism. The force and motion prediction model in rotary milling was developed and a novel milling cutter equipped with compact SPRT has been designed by the authors [4]. In order to verify the fundamental cutting performance of the developed SPRT milling cutter, a series of milling experiments of Ni-based super alloy were conducted in the present study.

TOOL LIFE TEST WITH DEVELOPED SPRT

Fig. 1 shows experimental setup for face milling of Inconel 718 workpiece. Top surface of the workpiece was machined by the developed SPRT milling cutter. The experimental conditions are summarized in Table 1. The continuous motion of the developed SPRT was observed. Fig. 2 compares the flank wear developments in SPRT/conventional milling with an increase of material removal. Comparing the flank wear in Fig. 2, the tool life is improved 12 times longer by using the developed SRPT. Hence, the developed technology can realize high performance machining of Ni-based super alloy.

![Figure 1: Experimental setup.](image)

Table 1: Experimental conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
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<tbody>
<tr>
<td>Cutting speed</td>
<td>30 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.1 mm/tooth</td>
</tr>
<tr>
<td>Axial depth of cut</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Cutting style</td>
<td>Half slotting</td>
</tr>
<tr>
<td>Cooling</td>
<td>Soluble</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Inconel718</td>
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</table>
INVERSE ANALYSIS OF EXPERIMENTAL RESULTS

The cutting edge profile and hardness of the machined surface were investigated through the face milling experiments. The experimental results indicated gradual deteriorations in not only the flank face but also rake face. In addition, gradual increase in the hardness was observed. These results lead into manufacturing quality degradation. Hence, measurement and/or estimation of these state quantities are important in industry. Based on the SPRT milling simulation technique, inverse analysis method of the process was developed by use of the measured cutting force. In the developed method, the cutting parameters are identified to minimize the estimation error in cutting force against the measured one. Fig. 3 shows measured and estimated cutting forces by use of the cutter with a single insert. Measured cutting forces increase with an increase in material removal amount due to deterioration in cutting edge geometry. Analytical results indicate considerable agreement with the measured ones. Hence, it is considered that the variations of the cutting parameters were identified appropriately by utilizing the developed method.

Figure 3: Measured and simulated cutting forces.

Gradual deteriorations in cross-sectional profile of the cutting edge are shown in Fig. 4. Relationship between measured and estimated rake angles demonstrated in Fig. 5 shows correlativity. The measured surface hardness increase also showed strong correlations with the identified parameters, i.e., the nominal rake angle and the shear strength, as shown in Fig. 6. Hence, the developed method may be available for advanced estimations in tool geometry and machining quality.

Figure 4: Measured cutting edge profile deteriorations.

Figure 5: Measured and identified rake angle deteriorations.

Figure 6: Identified shear strength v.s. hardness of machined surfaces.

DISADVANTAGEOUS CHARACTERISTICS IN RAMPING WITH DEVELOPT SPRT

The bottom cutter portion needs to be used in the ramping process due to gradual depth of cut increase. In particular, the inner side of the bottom cutting edge contacts to the workpiece at the backside cutting region that rarely contacts to the workpiece in general face milling. Through analytical investigations, disadvantageous characteristics in ramping process were revealed. Fig. 7 shows calculated relative clearance angle of the SPRT ramping operation at the moment of the backside cutting. An insert angle is defined as a cutting edge angle from the bottom portion. Positive/negative angles represent outer/inner side of the cutting edge. As shown in Fig. 7(a), the relative clearance angle becomes negative even at a ramping angle of 2 deg. In order to avoid flank face contact, a ramping angle needs to be smaller than 0.25 deg, see Fig. 7(b). This fact indicates that the developed SPRT milling cutter causes the flank contact even with a very small ramping angle.

Figure 7: Estimated relative clearance angles at (a) $\theta_{\text{ramp}}$:2deg and (b) $\theta_{\text{ramp}}$:0.25deg.
To clarify the available range of a ramping angle, the ramping experiment was conducted. The experimental conditions are summarized in Table 2. The ramping angle was changed from 0.1 to 0.7 deg. The measured cutting forces are compared to the analytically simulated ones in Fig. 8. The simulated and measured cutting forces corresponds to each other at the small ramping angle of 0.25 deg. However, the cutting force in the experiment significantly increases only at backside cutting region with a ramping angle of greater than 0.25 deg. This is caused by the flank face contact, which is not modelled in the cutting force simulation. Fig. 9 shows average errors between measured and simulated cutting forces at frontside/backside cutting regions. The resultant error increases at a ramping angle greater than the critical ramping angle of 0.25 deg. Hence, the ramping angle should be selected to avoid flank face contact.

Table 2: Experimental conditions.

<table>
<thead>
<tr>
<th>Ramping angle deg</th>
<th>0.1-0.7</th>
</tr>
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<tbody>
<tr>
<td>Cutting speed m/min</td>
<td>30</td>
</tr>
<tr>
<td>Feed rate mm/tooth</td>
<td>0.1</td>
</tr>
<tr>
<td>Axial depth of cut mm</td>
<td>1.0</td>
</tr>
<tr>
<td>Cutting style</td>
<td>Full slotting</td>
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<tr>
<td>Cooling</td>
<td>Soluble</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Inconel718</td>
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</tbody>
</table>

Figure 8: Measured and simulated cutting forces in ramping operation.

Figure 9: Force estimation errors in front/backside cutting region v.s. ramping angle.

CONCLUSIONS

In order to clarify the performance of the developed SPRT milling, a series of cutting experiments were conducted in the present study. The fundamental face milling tests verified that the tool life is improved 12 times longer by using the developed SRPT. By analyzing the measured cutting forces, the cutting edge deterioration and the finished surface hardness were estimated. On the other hand, difficulty in ramping operation was clarified due to the flank face contact at the moment of the backside cutting.

REFERENCES