The Simulation of Cutting Force and Temperature Field in Turning of Inconel 718

Yang Zhenchao¹, Zhang Dinghua¹, Huang Xinchun¹, Yao Changfeng¹, Liang Yongshou¹, Mao Ying²

¹Key Lab of Contemporary Design and Integrated Manufacturing Technology, Ministry of Education, Northwestern Polytechnical University, Xi'an, China
²Osin Technology Corporation, Beijing, China
yang966122@126.com

Abstract: Finite element method (FEM) is a powerful tool to predict cutting process variables such as temperature field which are difficult to be obtained from experimental methods. The turning process of Inconel 718 is simulated by AdvantEdge which is professional metal-cutting processing finite element software. The effects of cutting speed, feed and cutting depth on cutting force and temperature field are analyzed. The results show that cutting forces decrease with cutting speed increasing, and increase with feed and cutting depth, and the influence of cutting depth on cutting forces is significant. The maximum temperature in the cutting zone located on the rake face at a distance of about 0.01 mm from the tool tip. As cutting speed and feed increase, the maximum temperature in the cutting area increases. The influence of cutting speed on cutting temperature is significant, but the cutting depth has little impact on temperature.

Keywords: Inconel 718, turning, cutting parameter, cutting force, temperature field

1. Introduction

Inconel 718 is a high strength, thermal resistant Nickel-based superalloy that plays an extremely important role in gas turbines engines, aircraft, marine, industrial and vehicular gas turbines, space vehicles, rocket engines, nuclear reactors, submarines, stream production places and other high temperature applications. However, Inconel 718 is also known to be one of the most difficult materials to machine because of its high hardness, high strength at high temperatures and low thermal conductivity. The main reasons for the difficulty in machining this alloy are as follows [1,2]: (1) high work-hardening at machining strain rates; (2) abrasiveness; (3) toughness, gumminess and a strong tendency to weld to the tool and to form a built-up edge; (4) low thermal properties leading to high cutting temperatures; and (5) a tendency for the maximum tool-face temperature to be close to the tool tip.

Assessment of machinability of the superalloys has been a topic research over the last three decades. It is observed that most of the efforts are directed towards assessing the life of cutting tools and disclosing tools wear mechanisms in machining of Inconel 718 [3,4], and in recent years, the surface generated during machining of Inconel 718 has been a subject research of a number of investigations [5-7]. These include analysis and/or evaluation of surface roughness, surface morphology, microhardness, residual stress and microstructure. Besides, cutting force during machining of Inconel 718 has been investigated by some authors [8,9]. However, machining of Inconel 718 remained a difficult problem.

Improper selection of cutting parameters such as cutting speed, feed, and cutting depth in turning of Inconel 718 may cause cutting tools to wear quickly and even to break, which leads to the poor surface quality and anti-fatigue performance of Inconel 718. This paper builds a finite element model for the turning of Inconel 718 using the commercial general purpose machining software AdvantEdge. The effects of cutting speed, feed, and cutting depth on cutting forces and cutting temperature in turning of Inconel 718 are investigated. The evidence for selection of turning parameters and studying surface integrity of Inconel 718 will be provided.

2. Finite Element Model

2.1 Workpiece Material Constitutive model

The turning of Inconel 718 is modeled as an orthogonal cutting process assuming plane strain conditions. A schematic of the tool-workpiece configuration is as shown in Fig. 1, where the \( v \) is the cutting speed, \( f \) is the feed. The tool was modeled as a rigid body because of the significantly high modulus of cemented carbide tool material compared to that of Inconel 718.

Fig. 1 Cutting model used for numerical simulations

The commercial finite element package AdvantEdge from Third Wave Systems is used for the numerical simulations. AdvantEdge is a Lagrangian finite element package used for two-dimensional modeling of orthogonal cutting. The element topology used is a six-noded quadratic triangle element with three corner and three midsize nodes. Continuous adaptive remeshing is used to correct the problem of element distortion due to high deformations. The larger elements are refined and smaller elements coarsened at regular intervals.

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For the model, Inconel 718 is assumed to behave in a ductile manner. The material behavior is modeled by using the constitutive equation,

\[
(1+\dot{e}_p/e_0)^{m_1} \left(1+\dot{e}_p/e_0\right)^{-m_2} [\sigma / \left(e^{\dot{e}_p}\right)] = \sigma_{\text{eff}} + s,
\]

where \(\sigma\) is the effect Mises stress, \(g\) is the flow stress, \(e^{\dot{e}_p}\) is the accumulated plastic strain, \(e^{\dot{e}_{\dot{e}_p}}\) is the accumulated plastic strain rate, \(e_0\) is the threshold strain rate which separates the two regimes. In calculations, first \(e^{\dot{e}_p}\) is computed according to \(1\), and switch to \(2\) if the result lies above \(e_0\).

A power hardening law with linear thermal softening is adopted. This gives

\[
g = \beta \cdot \left(T - T_0\right) B_{\text{H}} \left(1+\dot{e}_p/e_0 Defaults^\right)^{1/2}
\]

where \(n\) is the hardening exponent, \(T\) is the current temperature, \(T_0\) is a reference temperature, \(a\) is a softening coefficient, and \(S_0\) is the yield stress at \(T_0\).

### 2.2 Cutting Conditions

The workpiece material used in this paper is Inconel 718. The chemical composition of the workpiece material confirms to the following specification (wt.%): 0.4 Al; 3.0 Mo; 19.0 Cr; 0.18 Si; 0.04 C; 18.5 Fe; 0.9 Ti; balance Ti. The mechanical properties are shown in Table 1.

<table>
<thead>
<tr>
<th>Mechanical properties of Inconel 718</th>
</tr>
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<tbody>
<tr>
<td>Ultimate tensile strength(MPa)</td>
</tr>
<tr>
<td>Yield strength(MPa)</td>
</tr>
<tr>
<td>Elastic modulus(GPa)</td>
</tr>
<tr>
<td>Hardness(HV100)</td>
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<tr>
<td>Density (g cm(^{-3}))</td>
</tr>
<tr>
<td>Melting point(℃)</td>
</tr>
<tr>
<td>Thermal Conductivity(W/mK)</td>
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</tbody>
</table>

The studied cutting condition in this paper is listed in Table 2.

### 3. Results and Discussion

#### 3.1 Simulation Process

Fig. 2 shows the cutting forces in X and Y directions and peak tool temperature at different cutting times, when \(v = 30\) m/min, \(f = 0.2\) mm/r, \(a_p = 0.5\) mm. It can be seen from the figure \(F_x\) is twice as magnitude as \(F_y\). At the beginning of cutting, two direction cutting forces all increase rapidly to a maximum and then come into the stable phase gradually. At the end of cutting, forces decrease and reduce to zero finally when the cutting process finished. The peak tool temperature rises rapidly with cutting beginning, and then reaches to a steady state. In this paper, cutting force values are extracted from the value in the stable phase.
3.2 Effect of Cutting Speed

The other cutting parameters are set as follows when researching the effect of cutting speed: feed=0.2mm, cutting depth=0.5mm.

Fig. 4 shows the effects of cutting speed on cutting forces. Cutting forces in X and Y directions decrease as the cutting speed increases. The reason is that cutting temperature increases with cutting speed, the increasing cutting temperature leads to the decrease of the deformation coefficient and friction coefficient of workpiece material decreases of the workpiece material, which reduces the cutting forces.

Fig. 5 shows the temperature field distributions on rake and relief face under different cutting speed at the same time. The maximum temperature is located on the rake face of the tool, with a distance of about 0.01 mm from the tool tip. The maximum temperature increases with cutting speed increasing, and varies from 629 °C at 15m/min to 902 °C at 60m/min. This is because the power and the heat generated per unit time increase with the cutting speed, in addition, strong friction occurs between chip and rake face, producing a large amount of friction heat. Thus, the above factors contribute the rise of the maximum temperature in the cutting zone.

3.3 Effect of Feed

The other cutting parameters are set as follows when researching the effect of feed: cutting speed=40m/min, cutting depth=0.5mm.

Fig. 6 shows the effects of feed on cutting forces. It is observed that the cutting force increases with feed per tooth. This is due to an increase of chip load tooth as the feed per tooth increases.
Fig. 7 shows the temperature field distributions on rake and relief face under different feed at the same time. The maximum temperature increases with feed, and varies from 740 °C at 0.1mm/r to 885 °C at 0.4mm/r. There are two reasons: on the one hand, the metal removals rate increases and the chip deformation coefficient decreases with the feed increasing, which leads to the cutting power under the same cutting volume decline. And on the other hand, the tool-chip contact length and the cutting heat carried off by chip increase at the mean time. The result is that the temperature increases with the feed increasing, but slowly.

Fig. 7 The temperature distributions under different feed.

### 3.4 Effect of cutting depth

The other cutting parameters are set as follows when researching the effect of: cutting speed = 40 m/min, feed=0.2mm.

Fig. 8 shows the effect of cutting depth on cutting forces. It is observed that the cutting force increases with cutting depth increasing because of the area of cut per tooth increasing.

Fig. 8 The effect of cutting depth on cutting forces

Fig. 9 shows the temperature field distributions on rake and relief face under different at the same time. As can be seen from the chart, depth of cut has little impact on cutting temperature, because with the increase of cutting depth, cutting force increases, the cutting heat generated also increased, but at the same time, the length of the work involved in cutting edge also increased, improving the cooling conditions, thus cutting temperature did not change significantly.

Fig. 9 The temperature distributions under different cutting depth

### 4. Conclusion

The turning process of Inconel 718 is simulated by the commercial general purpose machining software AdvantEdge and the influences of cutting speed, feed and cutting depth on cutting force and temperature are analyzed. In the experimental range, the following conclusions are based on the results above:

1. The cutting forces decrease with cutting speed increasing, and increase with feed and cutting depth increasing. The influence of cutting depth on cutting forces is significant.
2. The maximum temperature in the cutting zone is located on the rake face of the tool, with a distance about 0.01 mm from the tool tip.
3. The maximum temperature in the cutting area increases with cutting speed and feed per tooth increasing. The temperature in other places of the rake and relief face has a same changing regularity.
4. The influence of cutting speed on cutting temperature is significant, but the cutting depth has little impact on temperature.

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