Measurement-based modelling of cutting forces in micro-milling of Inconel 718

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Abstract: Due to its superior properties, nickel-based superalloy Inconel 718 can meet the requirements of micro parts with the high strength at high temperatures which have three-dimensional geometry structure like stepped surface, deep-hole, thin wall and so on. However, Inconel 718 is difficult to cut. Now, there are few researches on the cutting forces in micro-milling of Inconel 718, and the micro-milling mechanism of nickel-based superalloy is almost blank, while the prediction and control of micro-milling forces is important to reveal the micro-milling mechanism of nickel-based superalloy, to realise processing parameter optimisation, to reduce the tool wear, etc... To predict the cutting forces during micro-milling Inconel 718 process, coated carbide tools are used to micro-milling micro groove on Inconel 718, and the orthogonal type experiments are adopted. The influences of cutting parameters on cutting forces are studied. The micro-milling forces prediction model is built based on the experimental results, which can be used to predict the cutting forces during micro-milling of Inconel 718 nickel-based superalloy. To prove the validity of the built model, the significance test and fitting degree test are conducted.

Keywords: micro; milling; forces; parameters; Inconel 718.


Biographical notes: Xiaohong Lu is an Associate Professor at the Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, China. Her research activities include micro-milling technology, project management, precision measurement technology and performance monitoring of machine tools. She has published more than 40 papers in reputable academic journals and conferences.
1 Introduction

The micro parts which have complex and micro 3D geometrical shapes are increasingly needed in aerospace, energy and power, biomedicine and other fields with the development of technology. Some of them, such as blade of ultra-micro-turbine engine, micro-rocket engine nozzles and injection metal die of micro-fluidic chip, are required to bear not only the high working temperature but also high strength and corrosion conditions. Nickel-based superalloy Inconel 718 is suitable for those parts, because it has high strength, resistance to oxidation and corrosion resistance in high temperature environment. So, Inconel 718 superalloy is a typically difficult to cut material and is used widely in aviation and space industries (Jafarian et al., 2014), but its machinability is considered to be very poor (Li and Wang, 2013; Huang, 2010). If Nickel-based superalloy is applied to create ultra-micro-turbine engine blades which have three-dimensional structures with proper micro fabrication techniques, it can improve aerodynamic performance of the blades, solve the life problems of creep and reduce complexity of the progress. Hence, it is important to conduct research on the machinability of Inconel 718 micro-parts.

Kaya et al. (2011) and Pawade and Joshi (2012) convinced the machinability of Inconel 718. Ucun et al. (2013) focused on tool wear research during the Inconel 718 micro-milling process. Mian et al. (2011) found both chip thickness and cutting velocity is main factor that affect the micro-machining size effect. Cutting forces determine the power consumption and deformation of system during processing, meanwhile, they directly affect the generation of cutting heat, tool wear, tool breakage, tool life and machining accuracy. Many scholars have researched on cutting forces of traditional processing Inconel 718. Pawade et al. (2011) researched the influences of milling
direction, feed rate, cutting speed, depth of cut, etc., on cutting forces in traditional ball end milling and built the force model. Chun et al. (2006) established the 3D milling force prediction model of Inconel 718, whose parameters were calibrated based on the cutting experiments.

Investigations on micro-end milling models for different materials during micro-end milling process have been done now. Afazov et al. (2012) investigated the prediction of micro-milling cutting forces in micro-milling AISI H13 steel. Cutting forces model of micro-milling (part materials are NAK-55 steel, graphite and aluminium alloy) was built by Bao and Tansel (2012), which considered the influences of feed rate per tooth, tool run-out, tool radius and tool wear. A series of slot milling experiments on single ferrite base, pearlite base, multiphase ferrite and pearlitic ductile iron were carried out by utilising carbide end milling cutter with 2 flutes, whose diameter is 0.5 mm, by Vogler et al. (2003). The machinability of nickel-based superalloy is testified by the related research results. Researches on micro-end milling forces model of steel, graphite, aluminium alloy, glass and other materials offer reference to research on cutting forces model during micro-end milling nickel-based superalloy process. Nickel-based superalloy is multiphase material, whose micro structure can cause fluctuation of cutting forces and make it difficult to predict the cutting forces during micro-milling nickel-based superalloy. Thus, the research on cutting forces during micro-milling nickel-based superalloy process becomes one of the key issues to be solved.

2 The analyses of factor influence for cutting forces

In order to analyse the factor influence for cutting forces, micro-milling grooving experiments of Inconel 718 are done on the three axis micro-milling machine (see Figure 1), whose working stroke of three axial is 50 mm × 50 mm × 102 mm. The position accuracy is 1 μm. The spindle speed could be adjusted in a wide range: from 40,000 to 140,000 rpm. The machine system is equipped with a Kistler piezoelectric minimise multi-component dynamometer (9256CQ1), which can achieve the measurement of the cutting forces accurately.

Figure 1 The self-developed micro CNC milling machine
Ultrafine particle coated cemented carbide end milling tool with 2 flutes whose diameter is 0.6 mm made by UNION TOOL Co. is adopted. Rounded cutting edge radius $R = 2 \mu m$, the normal rake angle of milling tool $\alpha_0 = 5^\circ$ and working edge length is 0.5 mm.

2.1 Taguchi-type orthogonal experiment design

Referring to the research results of high-speed cutting Inconel 718, we choose the mount of micro-milling cutter overhanging $L$, the micro-cutting depth $a_p$, feed per tooth $f_z$ and spindle speed $n$ as the four experimental parameters. The ranges of these parameters are shown in Table 1. Micro-milling grooving experiment is the standard orthogonal experiment table $L_{25}(5^4)$, as shown in Table 2.

**Table 1** The ranges of these parameters in the micro-milling grooving experiment

<table>
<thead>
<tr>
<th>The mount of micro-milling cutter overhanging $L$(mm)</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed $n$ (r/min)</td>
<td>39,680</td>
<td>49,600</td>
<td>59,520</td>
<td>69,440</td>
<td>79,370</td>
</tr>
<tr>
<td>Micro milling cutting depth $a_p$ (μm)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Feed per tooth $f_z$(μm/z)</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**Table 2** Orthogonal experiment table and the measurement results of the cutting force

<table>
<thead>
<tr>
<th>Serial number</th>
<th>The mount of micro-milling cutter overhanging $L$(mm)</th>
<th>Spindle speed $n$(r/min)</th>
<th>Micro-milling cutting depth $a_p$(μm)</th>
<th>Feed per tooth $f_z$(μm/z)</th>
<th>$F_x$(N)</th>
<th>$F_y$(N)</th>
<th>$F_z$(N)</th>
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</thead>
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<td>0.1884</td>
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<tr>
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<tr>
<td>7</td>
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<tr>
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<td>0.9</td>
<td>0.1738</td>
<td>0.1897</td>
<td>0.24</td>
</tr>
<tr>
<td>17</td>
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<td>0.2531</td>
<td>0.2516</td>
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</table>
Table 2 Orthogonal experiment table and the measurement results of the cutting force (continued)

<table>
<thead>
<tr>
<th>Serial number</th>
<th>The mount of micro-milling cutter overhanging (L) mm</th>
<th>Spindle speed (n) r/min</th>
<th>Micro-milling cutting depth (a_p) μm</th>
<th>Feed per tooth (f_z) μm/z</th>
<th>F_x(N)</th>
<th>F_y(N)</th>
<th>F_z(N)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>18</td>
<td>59,520</td>
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<tr>
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<tr>
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<tr>
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<td>39,680</td>
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<td>1.1</td>
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<td>0.2281</td>
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<tr>
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<tr>
<td>25</td>
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<td>0.9</td>
<td>0.3511</td>
<td>0.4235</td>
<td>0.4538</td>
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</tbody>
</table>

Image about chip morphology with the mount of micro-milling cutter overhanging L = 12 mm; spindle speed n = 39,680 r/min; axial depth of cut a_p = 15 μm; feed per tooth f_z = 3.0 μm/z is shown in Figure 2 and long strip chip are obtained.

Figure 2 Chip morphology (see online version for colours)

The processing length of groove is 30 mm with dry cutting and air-cooler during experimental processing. Kistler 9256CQ1 is used to measure the cutting forces.

2.2 The factors of influencing cutting forces

F_x, F_y and F_z are cutting forces of different directions. In the micro-milling grooving orthogonal experiment, X direction is the cutting feed direction, and Y direction with perpendicular to the feed direction is the main cutting force direction, as shown in Figure 3. The experiment results (see Table 2) indicate that the main cutting forces are larger than feed forces within the scope of the same experimental cutting parameters.
2.2.1 The influence of mount of micro-milling cutter overhanging on cutting forces

It can be seen from Figure 4, when the mount of micro-milling cutter overhanging varies between 12 mm and 16 mm, cutting forces are little influenced by the mount of micro-milling cutter overhanging; as the extended length of micro-milling cutter increases, cutting forces first increase and then decrease, the variation trend of which is quite slow. When the mount of micro-milling cutter overhanging varies between 16 mm and 20 mm, cutting forces are highly influenced. With the increasing of the mount of micro-milling cutter overhanging, cutting forces $F_x$ and $F_y$ first increase and then decrease, and cutting force $F_z$ gradually increases. Adopting minor mount of micro-milling cutter overhanging can reduce elastic deformation of micro-milling cutter effectively and is helpful for improving system rigidity and stabilising milling states.

2.2.2 The influence of spindle speed on cutting forces

Cutting forces gradually increase with spindle speed increasing during traditional high-speed milling Inconel 718. However, during the micro-milling Inconel 718 process, when spindle speed varies between 39,680 r/min and 59,520 r/min, spindle speed has little influence on cutting forces (shown in Figure 5). As spindle speed increases, cutting
forces $F_x$ and $F_y$ first increase and then decrease while cutting force $F_z$ first decreases and then increases. The change law may be that: with the low rotational speed, the cutting temperature is relatively low, so the separation of the chips from the workpiece is mostly brittle fracture; under cutting force, the enlarging cracks are constantly being created along the tangential direction of cutter, which makes cutting force of $Z$-direction decline. When spindle speed varies between 59,520 r/min and 79,370 r/min, it has great influence on cutting forces. As spindle speed increases, cutting forces of $X$- and $Z$-direction increase while cutting force of $Y$-direction first rapidly increases and then slowly decreases. With the raise of cutting speed, cutting temperature gradually increases, and then considering the relatively high stiffness of Inconel 718 under high temperature, the material plastic increases so that the separation of chips transits from brittle fracture to tearing gradually. Under high temperature the material gets more viscid, so fictional resistance between flank of cutter and workpiece is getting larger. Therefore, as rotational speed increase, cutting force raises rapidly and the growth trend is getting slower. As spindle speed further increases, when deformation rate of chips is lower than cutting speed, deform zone of chips narrow down, deformation coefficient decreases; furthermore, with the increase of spindle speed, cutting temperature rises, yield shear strength of metal in chip underlayer decline and friction coefficient decrease. So, it is predicted that with further increase of spindle speed, cutting forces should increase slowly and even gradually turn into the decrease tendency.

**Figure 5** The influence principle curves of spindle speed on cutting forces

2.2.3 The influence of micro-milling cutting depth on cutting forces

During traditional high-speed milling nickel-based superalloy Inconel 718, when axial depth of cut increases, cutting forces increase. Our studies have come to similar conclusions (see Figure 6). In the range of experiment, cutting forces $F_x$, $F_y$, and $F_z$ increase gradually with the increase of cutting depth. The cutting forces only act upon the tool-workpiece contact area. The length of the contact area depends on the axial depth of cut, and the width of the contact area depends on the radial width of cut. The radial width of cut is a constant in micro-milling grooving experiments. Therefore, the length of tool-workpiece contact increases when the axial depth of cut increases. As a result, Micro-milling forces show upward trend. The choice of cutting parameters should ensure the stability of the milling process.
2.2.4 Feed per tooth’s influence on cutting forces

Cutting forces increase with feed per tooth increasing in traditional high-speed milling nickel-based superalloy Inconel 718. However, micro-milling Inconel 718 is different (as shown in Figure 7), because micro-milling process is influenced by minimum chip thickness effect.

In the range of experiment, when feed per tooth increases, cutting forces $F_x$, $F_y$ and $F_z$ first increase and then decrease. Feed per tooth has greater impact on $F_x$ and $F_y$ than on $F_z$. The cutting forces’ change trends in feed per tooth range of 0.3–0.5 μm and 0.9–1.1 μm are much slower than that in the range of 0.5–0.9 μm. Beyond the scope of experiment parameters, with the increasing of feed per tooth, chip thickness will gradually increase, it is predicted that cutting forces should have slow increasing trend.

In micro-machining, tool edge radius is comparable or even more than the uncut chip thickness, which brings the effect of minimum chip thickness. The cutting forces appear obvious increasing trends nearby the minimum chip thickness, for the effect of ductile plowing effect around the round cutting edge zone. When feed per tooth is 0.7 μm, the cutting forces nearby have obvious trends of first increasing and then decreasing, so the minimum chip thickness is approximate $f_z = 0.7$ μm during micro-milling Inconel 718.

The cutting edge radius of the adopted cutter is approximate $R = 2$ μm, so $f_z / R \approx 0.35$, which consistent with the conclusion that the minimum chip thickness to tool edge radius
ratio is approximate 0.2~0.4 (Liu et al., 2006). To reduce the cutting forces, it is advisable to avoid minimum chip thickness, so as to extend the tool life and to increase processing efficiency.

3 Model of micro-milling forces in micro-milling Inconel 718 is established

The influences of the mount of micro-milling cutter overhanging $L$, micro milling cutting depth $a_p$, spindle speed $n$ and feed per tooth $f_z$ on cutting forces are considered in the article. According to the metal cutting mechanism, there is a complex exponential relationship between the cutting forces and cutting parameters. The exponential models of $F_x$, $F_y$, and $F_z$ are given by:

\[
\begin{align*}
F_x &= C_{F_x} \cdot L^{b_{1x}} \cdot a_p^{b_{2x}} \cdot f_z^{b_{4x}} \\
F_y &= C_{F_y} \cdot L^{b_{1y}} \cdot a_p^{b_{2y}} \cdot f_z^{b_{4y}} \\
F_z &= C_{F_z} \cdot L^{b_{1z}} \cdot a_p^{b_{2z}} \cdot f_z^{b_{4z}}
\end{align*}
\]

(1)

where $C_{F_x}$, $C_{F_y}$, $C_{F_z}$ are the cutting force coefficients determined by the work-piece material, machine tool and machine conditions; $b_{1x}$, $b_{2x}$, $b_{3x}$, $b_{4x}$, $b_{1y}$, $b_{2y}$, $b_{3y}$, $b_{4y}$, $b_{1z}$, $b_{2z}$, $b_{3z}$ and $b_{4z}$ are the exponential coefficients of the mount of micro-milling cutter overhanging, axial depth of cut, spindle speed and feed per tooth respectively. In order to determine the coefficients in nonlinear equation (1), it is necessary to take the common logarithm of equations (1) to transform equations (1) into linear equations expressed as equations (2). Based on the cutting force data and processing parameters obtained by experimental measurement, regression analysis is applied to determine the coefficients of the regression equations.

\[
\begin{align*}
\log F_x &= \log C_{F_x} + b_{1x} \log L + b_{2x} \log a_p + b_{3x} \log f_z \\
\log F_y &= \log C_{F_y} + b_{1y} \log L + b_{2y} \log a_p + b_{3y} \log f_z \\
\log F_z &= \log C_{F_z} + b_{1z} \log L + b_{2z} \log a_p + b_{3z} \log f_z
\end{align*}
\]

(2)

The least squares method is applied to estimate the coefficients of the regression equations. The cutting forces of exponential empirical formula for micro-milling Inconel 718 can be expressed as

\[
\begin{align*}
F_x &= 10^{4.7031 \cdot L^{0.3867} \cdot a_p^{0.3464} \cdot f_z^{0.1051}} \\
F_y &= 10^{5.279 \cdot L^{0.4922} \cdot a_p^{0.3149} \cdot f_z^{0.0348}} \\
F_z &= 10^{5.7389 \cdot L^{0.5122} \cdot a_p^{0.2771} \cdot f_z^{0.1145}}
\end{align*}
\]

(3)

4 The cutting force prediction model testing

It is necessary to conduct the significance test of linear relationship for the multiple regressions cutting force model before using it to predict and control. Hypothesis: $H_0: \beta_1 = 0, \beta_2 = 0, \beta_3 = 0, \beta_4 = 0$. F-test is applied during the significance test of linear relationship.
where $n$ is the number of experimental group, $p$ is the number of dependent variables, $n = 25, p = 4$. The deviations sum of square $SS_T$, regression sum of square $SS_R$ and square sum of residual $SS_E$ of the cutting forces $F_x$, $F_y$, and $F_z$ are calculated, and $F$-test is calculated by equation (4). The results of significant $F$-test for regression equations are $F_{0.01}$, $(4, 20) = 4.43 < F_y = 5.75$, so the hypotheses are rejected and the regression equations of cutting forces $F_y$ are significant.

Likewise, $F_{0.01}$, $(4, 20) = 4.43 < F_y = \frac{0.09570/4}{0.07254/20} = 6.6$ and $F_{0.01}$, $(4, 20) = 4.43 < F_z = \frac{0.13677/4}{0.05439/20} = 12.57$. It can be concluded that the regression equations of cutting forces $F_y$ and $F_z$ are significant.

The significance test of regression equation indicates that the regression equations match well with the experimental results on the experimental points.

Application of the regression model parameter range is: $12 \leq L \leq 20$; $39,680 \leq n \leq 79,370$; $15 \leq a_p \leq 35$; $0.3 \leq f_z \leq 1.1$.

5 Conclusions

The influences of the mount of micro-milling cutter overhanging, micro milling cutting depth, spindle speed and feed per tooth on micro-milling forces are studied, and the micro-milling nickel-based superalloy Inconel 718 cutting force model is established. The concrete conclusions are as follows:

1. When the mount of micro-milling cutter overhanging is minor, the fluctuation of forces influenced is minor; when extended length of cutter is large; the fluctuation of forces influenced is large.

2. Under low rotational speed, the cutting forces have a micro fluctuation of first increasing and then decreasing with the increase of spindle speed; under high rotational speed, the cutting forces have a trend that increases rapidly and then gradually slowly with the increase of rotation speed.

3. As micro milling cutting depth increases, cutting forces first increase, then tend to be stable, finally gradually increase. The stationary of the cutting process should be guarantee during the machining.

4. Cutting forces appear first increasing and then decreasing with the increase of feed per tooth. The minimum chip thickness phenomenon appears and the ratio of minimum chip thickness to rounded cutting edge radius is about 0.35.

5. A micro-milling forces model is built based on micro-milling grooving orthogonal experimental results and the significance and fitting degree test have been done, whose results indicate that the cutting force model established can be applied to predict and control micro-milling forces on Inconel 718 within the scope of experiment parameters.
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References


