Effect of Cutting Parameters on Residual Stress for Ti1023 Using FEM and RSM

Jinhua Zhou, Junxue Ren

Key Laboratory of Ministry of Education for Contemporary Design and Integrated Manufacturing Technology, Northwestern Polytechnical University, Xi’an 710072 China

ABSTRACT: Machining induced residual stress has a major influence on the life time of machined parts, especially in their corrosion resistance and fatigue life. In this paper, finite element model (FEM) and response surface methodology (RSM) are applied to investigate the residual stress for machining titanium alloy Ti1023. The process of orthogonal cutting Ti1023 is successfully simulated by FEM using Power-Law constitutive model. The formation mechanism of residual stress is briefly described utilizing elastoplastic theory. Based on the analysis and simulations, the residual stresses profile in cutting and feed direction are successfully explained. Then, RSM is introduced to study the effects of the cutting speed and feed on surface residual stress. The results show that their interactions have no significant influence on surface residual stress. And the cutting speed and feed has strong nonlinear effect on surface residual stress.

1 INTRODUCTION

Residual stresses play a key role in the service life of components. During service, it adds up the stress induced by external load, leading to a real stress higher than the applied stress. Then the fatigue resistance is reduced and possible premature failure during service life will happen (García Navas et al., 2012). In addition, residual stress has important influence on dimensional stability, part distortion, corrosion resistance, and assembly accuracy.

Removing material by machining operation inevitably produces residual stress in manufacture process. Köhler et al. (Köhler et al., 2012) investigated two typical machining process, face milling and peripheral milling. The research results showed that increasing speed leads to increased penetration depth in case of face milling and did not exhibit strong influence on the end milled subsurface. Masmiati (Masmiati and Sarhan, 2015) showed that feed rate, machined surface inclination angle have moderate influence on surface integrity for inclined end milling, while axial depth of cut and cutting have less influence on residual stress. Li et al. (Li et al., 2015) analyzed the effects of depth of cut on the redistribution of residual stress and optimized its profile and magnitude. Dehmani et al. (Dehmani et al., 2013) found that multi-steps cutting has important influence on the residual stress due to the cumulated strain and temperature by finite element simulation. Saini et al. (Saini et al., 2012) reported that the feed and depth of cut are the main influencing factors on residual stress whereas cutting speed and nose radius have mild impact on residual stress for hard turning of AISI H11 tool steel. The results showed that it is possible to produce tailor-made residual stress levels by controlling the tool geometry and cutting parameters. García Navas et al. (García Navas et al., 2012) thought that the orientation of principal residual stress also has significant influence on thin-wall component. In their study, they determined both the magnitude and the orientation of the principle residual stresses by means of X-ray diffraction measurement for turning AISI 4340 steel. Wu and Li (Wu and Li, 2014) showed that cutting residual stress increase with machined surface roughness and main spindle rotational speed, fee, and tool condition have a strong effect on surface residual stress. Wyen et al. (Wyen et al., 2012) found that residual stresses increase with the cutting edge radius especially in up milling, whereas the influence in down milling is less pronounced. Ren et al. (Ren et al., 2015) obtained the optimum cutter geometric parameters, including radial rake angle, primary radial relief angle, and helix angle, simultaneously considering surface roughness and residual stress for ending milling titanium alloy Ti-5Al-5Mo-5V-1Cr-1Fe.

These previous investigations on machining residual stress usually focused on analyzing the profile of residual stress by considering different cutting parameters, cutter structure, and other factors. But the interactions among these factors on machining induced residual stress needs further especial focus. Therefore, the main objective of this research work is to analyze formation mechanism of
residual stress profile and the effect of cutting parameters and their interactions on residual stresses for orthogonal cutting titanium alloy Ti1023.

2 FINITE ELEMENT MODEL

In order to investigate the effects of cutting parameters on the distribution of residual stress, modeling of orthogonal cutting process with FEM is possible and necessary. In the finite element analysis (FEA), material constitutive model is one of the most critical factors for the simulation of machining, which reflects material deformation behavior. Many models were developed such as Johnson-cook, Power-Law, and Bodner-Partom, and so on. In the current study, Power-Law equation is employed for cutting simulation (Jiang et al., 2012). The Power-Law model is widely used to estimate the flow stress for a wide range of strain, strain rates, and temperatures commonly encountered in cutting process.

\[ \sigma(\dot{\varepsilon}, T) = g(\dot{\varepsilon}) \cdot \Gamma(\dot{\varepsilon}) \cdot \Theta(T) \]  

(1)

Where the first term represents strain hardening; the second term indicates the strain rate sensitivity; and the last term reflects thermal softening phenomenon.

The strain hardening function \( g(\dot{\varepsilon}) \) is expressed as follows.

\[
\begin{cases}
  g(\dot{\varepsilon}) = \sigma_0 (1 + \frac{\dot{\varepsilon}}{\varepsilon_p})^{\frac{1}{m}}, \text{when } \dot{\varepsilon} < \dot{\varepsilon}_p \\
  g(\dot{\varepsilon}) = \sigma_0 (1 + \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}})^{\frac{1}{n}}, \text{when } \dot{\varepsilon} \geq \dot{\varepsilon}_p
\end{cases}
\]

(2)

Where the \( \sigma_0 \) is the initial yield stress; the \( \varepsilon_p \) is plastic strain; the \( \varepsilon_p \) is the reference plastic strain; the \( \varepsilon_p \) is the cutoff strain; and the \( n \) is the strain hardening exponent.

The strain rate sensitivity function \( \Gamma(\dot{\varepsilon}) \) is defined as follows.

\[
\begin{cases}
  \Gamma(\dot{\varepsilon}) = (1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})^{\frac{1}{m}}, \text{when } \dot{\varepsilon} \leq \dot{\varepsilon}_i \\
  \Gamma(\dot{\varepsilon}) = (1 + \frac{\dot{\varepsilon}_i}{\dot{\varepsilon}})^{\frac{1}{m}} (1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_i})^{\frac{1}{m} - 1}, \text{when } \dot{\varepsilon} > \dot{\varepsilon}_i
\end{cases}
\]

(3)

Where the \( \dot{\varepsilon} \) is strain rate; the \( \dot{\varepsilon}_0 \) is the reference plastic strain rate; the \( \dot{\varepsilon}_i \) is the strain rate where the transition between low and high strain rate sensitivity occurs; the \( m_1 \) is the low strain rate sensitivity coefficient; and the \( m_2 \) is the high strain rate sensitivity coefficient.

The thermal softening function is given as follows.

\[
\begin{cases}
  \Theta(T) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4, \text{when } T < T_{cut} \\
  \Theta(T) = \Theta(T_{cut}) (1 - \frac{T - T_{cut}}{T_{mel} - T_{cut}}), \text{when } T \geq T_{cut}
\end{cases}
\]

(4)

Where the \( c_0 \) through \( c_5 \) are the coefficients for the polynomial fit; the \( T \) is temperature; the \( T_{cut} \) is the linear cutoff temperature; and the \( T_{mel} \) is the melting temperature.

In this paper, FEA software Advantage is utilized to simulate the orthogonal cutting process. This commercial software integrates the standard tools and adaptive remeshing technology. It can calculate residual stress automatically after machining.

A plane strain coupled thermo-mechanical analysis is performed by using orthogonal assumption. The tool and the workpiece are modeled as an elastic body and elasto-plastic material, respectively. The tool geometry, with carbide alloy body, is defined by a rake angle of 6°, a clearance angle of 12°, and an edge radius of 20\( \mu m \). The triangle element type is used in the simulations. The workpiece is a rectangular block of 5 mm x 3 mm. Very fine elements are defined near the cutting zone and the minimum mesh size is about 2\( \mu m \). The tool is fixed and a velocity along the \( x \) direction is exerted on the workpiece to accomplish the cutting process. Constant coulomb friction factor is taken into account for modeling the friction. No cutting fluid is used in cutting process. The FEM model shown in Figure 1 has been created.

![Figure 1. FEM model of orthogonal cutting.](image)

The variable process parameters are selected as cutting speed and feed rate, while the cutting depth is fixed as 3 mm. Table 1 shows the cutting parameters and their levels.

| Table 1. Cutting parameters and their levels. |
| --- | --- | --- |
| Factor | Low level | Center level | High level |
| Cutting speed (m/min) | 30 | 60 | 90 |
| Feed rate (mm/r) | 0.2 | 0.4 | 0.6 |
| Cutting depth (mm) | 3 | 3 | 3 |
3 RESULTS AND DISCUSSION

Figure 2 has shown the temperature field distribution in the cutting process. The cutting direction is defined as \( x \) direction, while \( y \) direction corresponds to the feed direction. During the machining Titanium alloy Ti1023, adiabatic shear bands with low thermal conductivity are developed in the chip and lead to the serrated chip formation. It can be also observed that the highest temperature located at rake face. This is according with previous researches.

![Temperature field](image)

Figure 2. Temperature distribution of orthogonal cutting.

3.1 Formation mechanism of residual stress profile

Generally, cutting residual stress is considered as elastic stress and developed from thermal and mechanical interact. Formation process of cutting residual stress can be explained from Figure 3.

![Formation mechanism of cutting residual stress](image)

Figure 3. Formation mechanism of cutting residual stress.

The machined workpiece is divided into three layers. The first layer, denoted as \( S \), presents the surface and near surface of workpiece. In this layer, mechanical and thermal effects are very significant. The second layer, denoted as \( D \), corresponds to the subsurface, in which the thermal effect can be neglected. The \( S \) and \( D \) layers are very thin, about several dozens to hundreds of micron in thickness. The third layer, denoted as \( B \), represents the remainder of the workpiece where residual stress magnitudes are negligible. The total strain in \( S \) layer is equal to the sum of the mechanical elastic and plastic components (\( \varepsilon_{S}^{e,m} \) and \( \varepsilon_{S}^{p,m} \)) and the thermal elastic and plastic components (\( \varepsilon_{S}^{e,i} \) and \( \varepsilon_{S}^{p,i} \)). The deformation in \( B \) layer is only caused by cutting forces, therefore the total strain contains the two components of mechanical elastic and plastic components (\( \varepsilon_{S}^{e,m} \) and \( \varepsilon_{S}^{p,m} \)). Only mechanical elastic strain happened in the \( B \) layer. These strain in workpiece can be expressed as follows.

For \( S \):

\[
\varepsilon_{S} = \varepsilon_{S}^{e} + \varepsilon_{S}^{p} = (\varepsilon_{S}^{e,m} + \varepsilon_{S}^{e,i}) + (\varepsilon_{S}^{p,m} + \varepsilon_{S}^{p,i})
\]

(5)

For \( D \):

\[
\varepsilon_{D} = \varepsilon_{D}^{e} + \varepsilon_{D}^{p} = \varepsilon_{D}^{e,m} + \varepsilon_{D}^{p,m}
\]

(6)

For \( B \):

\[
\varepsilon_{B} = \varepsilon_{B}^{e} + \varepsilon_{B}^{p} = \varepsilon_{B}^{e,m}
\]

(7)

Where, the \( \varepsilon_{S} \), \( \varepsilon_{D} \), and \( \varepsilon_{B} \) are the total strain in the \( S \), \( D \), and \( B \) layer, respectively; the \( \varepsilon_{S}^{e,m} \) and \( \varepsilon_{S}^{p,m} \) are the elastic and plastic strain caused by mechanical effect in the \( i \) layer, respectively; and the \( \varepsilon_{S}^{e,i} \) and \( \varepsilon_{S}^{p,i} \) are the elastic and plastic strain caused by thermal effect in the \( i \) layer, respectively.

According to the deformation coordination principle, material in these three layers has the same total deformation. In Figure 3, rigid supports fixed to each end of the layer. One rigid support is fixed and the other one is constrained to translation to obey to the deformation coordination principle (Kurt Jacobus, 2000).

\[
\varepsilon_{S} = \varepsilon_{D} = \varepsilon_{B}
\]

(8)

Equilibrium of structure in the absence of external loading requires

\[
\sigma_{i}^{i} h_{i} A + \sigma_{D}^{i} h_{D} A + \sigma_{B}^{i} h_{B} A = 0
\]

(9)

Where the \( \sigma_{i}^{i} \) is the residual stress in the \( i \) layer; the \( h_{i} \) is the thickness of the \( i \) layer; and the \( A \) is the cross sectional area.

Equation (9) divided \( h_{B} \) leading to

\[
\sigma_{S}^{i} h_{B} + \sigma_{D}^{i} h_{D} + \sigma_{B}^{i} h_{B} = 0
\]

(10)

Generally, the thickness of the machining induced residual stress is very small. So, it is reasonable to assume that the thickness of the \( S \) and \( D \) layers is far less than that of the \( B \) layer, \( h_{S} \ll h_{D}, h_{D} \ll h_{B} \). Then, \( \sigma_{B}^{i} = 0 \) can be obtained from Equation (10).

Substituting Equation (5)~(7) into Equation (8) and using hooke’s law, the Equation (11) can be obtained as follows.
\[
\frac{\sigma_i^r}{E} + \varepsilon_i^r = \frac{\sigma_i^m}{E} + \varepsilon_i^m = \frac{\sigma_i^h}{E}
\] (11)

Then
\[
\begin{align*}
\sigma_s^r &= -E\varepsilon_s^r = -E(\varepsilon_s^m + \varepsilon_s^h) \\
\sigma_D^r &= -E\varepsilon_D^r = -E\varepsilon_D^m \\
\sigma_h^r &= 0
\end{align*}
\] (12)

From Equation (12), it can be observed that the sign of the residual stress opposes the strain developed in the S and D layers. Therefore, if machining induces compressive plastic strain, the workpiece will have a tensile residual stress and vice versa. In addition, the residual stress in the B layer is approximately equal to zero.

Mechanical effect usually produces compressive residual stress, while the thermal effect induces tensile residual stress. Then, \( \varepsilon_s^m > 0 , \varepsilon_D^m > 0 \), and \( \varepsilon_s^h < 0 \). According to above analysis, the cutting residual stress can be classified into two cases as follows.

Case 1: Significant thermal effect, \( |\varepsilon_s^m| > |\varepsilon_s^m| \), then \( \sigma_s^r > 0 , \sigma_D^r < 0 \).

Case 2: negligible thermal effect, \( |\varepsilon_s^m| < |\varepsilon_s^m| \), then \( \sigma_s^r < 0 , \sigma_D^r < 0 \).

Figure 4 shows the two different profiles of residual stress. Dotted lines refer to residual stress from purely mechanical action, while solid line refer to that from combined thermal and mechanical effects. For the case 1, there is tensile residual stress in the surface/near surface, while compressive stress happened in subsurface. For the case 2, both the S and D layers develop compressive residual stress.

![Residual stress distribution](image)

(a) Case 1

(b) Case 2

Figure 4. Possible residual stress distribution.

3.2 Residual stress along feed direction

Figure 5 shows the residual stress distribution along the distance from surface under different level combination of cutting parameters. Tensile stress is observed on the machined surface and near surface in both the directions for all the parameter levels. For the stress in the cutting direction, there is compressive stress in the subsurface, but inconspicuous. For the stress in the cutting direction, obvious compressive can be observed in the subsurface. With the increase of parameter level, tensile residual stress in surface/near surface, compressive residual stress in subsurface, and thickness of residual stress layer have obvious increase. This may be caused by larger cutting force and higher temperature due to the larger feed and the higher cutting speed.

Comparing Figure 4 with Figure 5, it can be found that the residual stress distribution match most closely with case 1. Machining Titanium alloy Ti1023 produces a lot of cutting heat, which leads to compressive deformation in surface/near surface. Then, tensile residual stress happened. So, thermal effect is very obvious for cutting Ti1023. Coupled thermo-mechanical effect is the direct reason for this phenomenon.
In order to further analyze the thermal and mechanical effect in cutting process, cutting temperature and mises stress are extracted in different locations as shown in Figure 2. Those locations are as follows: line a: \( x = -0.022 \text{ mm} \), line b: \( x = 0 \text{ mm} \); and line c: \( x = 0.046 \text{ mm} \). Figure 6 has shown the temperature and mises stress distribution on line a, b and c, respectively. Those curves have similar variation trend. From Figure 6(a), it can be seen that the temperature is close to indoor temperature when the distance from surface is beyond 0.08 mm. It demonstrates that heat affected layer thickness is very thin and subsurface layer do not happen large thermal deformation. In Figure 6(b), the mises stress increases first then decreases along the distance from surface. The surface/near surface present smaller mises stress and the maximum values locate the points below the surface about 0.75~0.1 mm. It is due to that thermal effect weakens the mechanical effect in the near surface. This also proves that the thermal effect for machining Ti1023 alloy can not be ignored.

3.3 Residual stress along cutting direction

Figure 7 shows the surface residual stresses along cutting direction under different combination of parameter level. Those curves display cyclical fluctuation and heterogeneous surface stress can be observed. The maximum fluctuating value of residual stress is \( \Delta \sigma_x = 582.8 \text{ MPa}, \Delta \sigma_y = 512.6 \text{ MPa} \). The inhomogeneity may be induced by period variations cutting force and temperature, or machining chatter. Figure 8 shows the corresponding cutting force and peak tool temperature in cutting process.
4 THE EFFECT OF CUTTING PARAMETERS ON RESIDUAL STRESS

In current study, RSM approach is applied to determine the effect level of the process parameters. Compared to conventional methods, RSM has many advantages including the provision of rapid and reliable experimental data, a consideration of the effects and interactions between factors, reduction in the number of experiments and minimizing experimental costs and time consumption. Second-order polynomial Equation (13) which includes all interaction terms is employed to calculate the predicted residual stress.

\[ \sigma_i = \sum_{j=1}^{k} \sum_{i=1}^{j} c_{ij} x_i x_j \]  

(13)

Where the \( \sigma_i \) is residual stress, the \( X_i \) are the cutting parameters, and \( c_{ij}, c_i, c_j \) are the undetermined coefficient.

Table 2. Central composite design and results.

<table>
<thead>
<tr>
<th>Run</th>
<th>( v ) (m/min)</th>
<th>( f ) (mm/r)</th>
<th>( F_i ) (N)</th>
<th>( F_r ) (N)</th>
<th>( \tau ) (°)</th>
<th>( \sigma_i ) (MPa)</th>
<th>( \sigma_r ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>0.2</td>
<td>380</td>
<td>146</td>
<td>586</td>
<td>64</td>
<td>181</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0.2</td>
<td>347</td>
<td>100</td>
<td>774</td>
<td>141</td>
<td>386</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>0.6</td>
<td>898</td>
<td>194</td>
<td>682</td>
<td>164</td>
<td>216</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>0.6</td>
<td>772</td>
<td>116</td>
<td>953</td>
<td>294</td>
<td>414</td>
</tr>
<tr>
<td>5</td>
<td>17.57</td>
<td>0.4</td>
<td>722</td>
<td>226</td>
<td>565</td>
<td>73</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>102.43</td>
<td>0.4</td>
<td>572</td>
<td>100</td>
<td>913</td>
<td>230</td>
<td>466</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>0.12</td>
<td>230</td>
<td>103</td>
<td>565</td>
<td>149</td>
<td>119</td>
</tr>
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<td>8</td>
<td>60</td>
<td>0.68</td>
<td>881</td>
<td>141</td>
<td>838</td>
<td>276</td>
<td>336</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>0.4</td>
<td>612</td>
<td>123</td>
<td>775</td>
<td>188</td>
<td>336</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>0.4</td>
<td>612</td>
<td>123</td>
<td>775</td>
<td>188</td>
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<td>60</td>
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<td>612</td>
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<td>775</td>
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<td>336</td>
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<td>12</td>
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<td>612</td>
<td>123</td>
<td>775</td>
<td>188</td>
<td>336</td>
</tr>
</tbody>
</table>

The central composite design (CCD) is employed to arrange the experimental processes. The centre points of the experiments are normally repeated to improve the precision of experiments and five centre points are selected in this paper. Axial or star points represent the values both below and above the centre of the two factorial levels and both are outside their range (Razali et al., 2013). The parameters and their levels are shown in Table 1. The design variables are the cutting speed and feed, while the average surface residual stress is selected as performance responds. The data is analyzed using Design Expert 7.0 and the coefficients are interpreted using F test. Three main analytical steps: analysis of variance (ANOVA), regression analysis and plotting of response surface plots are performed to investigate the effect of process parameters on residual stresses. Table 2 lists the experimental design and the corresponding results.

4.1 Effect of parameters on residual stress in cutting direction

Form Table 2, the residual stress in cutting direction changes from 64MPa to 294MPa. The least square regression methodology is used to fit the data to a high order Equation. The modeling of the experimental data is performed using the quadratic model and stepwise regression is used. The final empirical model is as follows.

\[ \sigma_i = -115.24 + 4.91v + 270.38f - 0.02598v^2 \]  

(14)

Equation (14) also shows the term \( v \) and \( f \) have a positive and very significant influence on the response, and the term \( v^2 \) has a negative and significant influence, reflecting nonlinear relationship between residual stress and speed. Positive values mean that the terms increase the response and negative that they decrease it. No interaction terms in Equation (14) indicates that interaction effect can be ignored.

Table 3. Results of ANOVA table for \( \sigma_i \).

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>50270.8</td>
<td>3</td>
<td>16756.8</td>
<td>62.9</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>A-v</td>
<td>23008.5</td>
<td>1</td>
<td>23008.5</td>
<td>86.3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>B-f</td>
<td>23393.4</td>
<td>1</td>
<td>23393.4</td>
<td>87.8</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>V^2</td>
<td>3868.6</td>
<td>1</td>
<td>3868.6</td>
<td>14.5</td>
<td>0.0042</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>16.32</td>
<td></td>
<td>R^2</td>
<td>0.955</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>179.3</td>
<td></td>
<td>R^2_adj</td>
<td>0.939</td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td>9.10</td>
<td></td>
<td>R^2_Pred</td>
<td>0.887</td>
<td></td>
</tr>
</tbody>
</table>

The model and factor significance is investigated using the ANOVA to the 95% of confidence from the F test of distribution and P values. According to the results from Table 3, the model for residual stress in cutting direction shows that \( F_{cal} \) value is higher than \( F_{tab} \) ( \( F_{cal}=62.88>F_{tab} = 2.81 \) ), which demonstrates the significance of the quadratic model. As shown in Table 3, the correlation coefficient \( R^2 \) is 0.9545, indicating that the model explain 95.45% of variance around the mean.

Figure 9. Response surface for stress in cutting direction.
Therefore, the correlation between predict values by the model and experimental data is significant, demonstrating the model is adequate to describe the cutting parameters influences on the residual stress.

The regression coefficients indicate that the feed has strong linear ($P < 0.001$) effects on residual stress. Cutting speed also has strong linear ($P < 0.001$) and significant quadratic ($P < 0.05$) on residual stress. The response surface plot is illustrated in Figure 9. It can be obviously observed that residual stress increases with the increase of cutting speed and feed. At higher cutting speed, the residual stress has lower increase rate when the cutting speed increases to 90m/min. This phenomenon may be understood by the weakening of thermal effect. Higher cutting speed, more heat into chip and less heat into workpiece.

4.2 Effect of parameters on residual stress in feed direction

Form Table 2, the residual stress in cutting direction has a large variation from 79MPa to 386MPa. This demonstrates cutting parameters have important influence on the residual stress. The quadratic model equation, excluding the insignificant term, is given by Equation (15).

$$\sigma_y = -165.18 + 3.96v + 1019.22f - 985.05f^2$$  \hspace{1cm} (15)

Equation (15) shows the term $v$ and $f$ have a positive and significant influence on the residual stress, and the term $f^2$ has a negative and significant influence. There are no interaction terms in Equation (15), indicating that no major interactions between these factors occur. The large coefficients of the quadratic term declare that there is strong nonlinear relationship between residual stress and feed.

The results of ANOVA are shown in Table 4. It can be seen that the empirical model provides a model with a smaller $p$-value (less than 0.001) and a larger $F_{cal}$ value ($F_{cal}=24.13 > F_{tab} = 2.81$). The high correlation coefficient $R^2$ reflects the high reliability of the regression model. The linear term of cutting feed has a very small $p$-value ($P < 0.001$), indicating a very significant effect on response. The effects of linear and quadratic term of feed on response is also significant ($P < 0.05$).

Figure 10 presents the 3D graphic of response surface for residual stress in feed direction. It can be observed that increasing feed promotes a significant increase in the residual stress to a maximum value, and further increase of speed causes a slow increase of the response. The decline of the increase may due to weakening of chip deformation at larger speed, which slows the increment speed of cutting temperature of workpiece. As previous researches, cutting speed promotes a significant increase in the cutting temperature. Since all the residual stresses in these simulations tensile stress, residual stress increases when the cutting speed increase from 30 m/min to 90 m/min.

5 CONCLUSION

The effect of the cutting parameters on residual stress is investigated using FEM and RSM. Some conclusions are summarized as follows.

1. Both surface residual stresses in cutting and feed direction present tensile stresses, when cutting speed ranges from 30 m/min to 90 m/min and feed ranges from 0.2 mm/r to 0.6 mm/r. In addition, the surface residual stresses along cutting direction are inhomogeneous.

2. Thermal effect is very significant for machining titanium alloy Ti1023.

3. Cutting speed and feed have strong nonlinear effect on surface residual stress and the interaction effect between them can be neglected for orthogonal cutting Ti1023.

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