

## The effect of cutting speed on residual stresses when orthogonal cutting TC4

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**Abstract.** As one of the most important parameters in metal cutting, cutting speed has a significant influence on residual stress. Finite element method and experiment method are used to study the relationship between cutting speed and residual stress when orthogonal cutting TC4 titanium alloy. The result of simulation and experiment shows that: when the cutting speed is low, the residual stress in axial direction is compressive stress and gradually converts to tensile stress with the increase of cutting speed, but it will convert to compressive stress again if the cutting speed continues to increase; the residual stress in tangential direction is constant to compressive stress and it will decrease with the increase of cutting speed.

### 1. Introduction

As aerospace materials, titanium alloy has a lot of excellent performances, such as low density, high strength-to-weight ratio, excellent temperature resistance, good corrosion resistance. Thus, titanium alloys is often used to manufacture aircraft engine bearing parts and rotating parts. However, the titanium alloys have low elastic modulus, seriously chilled property, high cutting temperature, large cutting force per unit area and serious tool wear, these may have a serious influence on the surface integrity of titanium components. Because of its poor intuitive and imperceptible, residual stress is often overlooked. However, residual stress has remarkable influence for the strength, fatigue life, corrosion resistance, dimensional stability of the structure, especially in the bearing components and the rotating components. The presence of residual stress often results in sudden destruction of the structure and the consequence is often very serious. Therefore, it is very important to deeply understand the relationship between cutting parameters and residual stress.

With the rapid development of computer graphics technology and finite element simulation technology, numerical simulation technology has been widely applied to the study of cutting force, cutting temperature and other metal cutting process. Valiorgue [1] developed a three-dimensional finite element model, by applying a thermal coupling load instead of the model material separation and chips forming to simulate the surface residual stress distribution of fine turning AISI304L; Sima [2] found that the constitutive equations of Ti-6Al-4V has a greatly effects on chip formation; Mohamed [3] studied the effects of four different nose radius on AISI316L orthogonal cutting surface residual stress

high-speed machining process of titanium alloy; Outeiro [4] studied the effect of tool geometry, cutting, cutting thickness and feed on cutting surface residual stress by experimental and numerical methods; Shet [5] studied the effects of the rake angle and the friction coefficient on the machined surface residual stress and strain fields under the orthogonal metal cutting process under plane strain conditions; Lei [6] came up with a new material constitutive model for orthogonal cutting and studied the 1020 steel shear stress field, strain field and temperature field; Xie [7] used the finite element method to simulate the formation of the chip in metal cutting process and studied the effect of the shear banding, cutting force, rake angle on the shear angle, plastic strain field, and distribution of effective stress on tool rake face; Yu [8] using the finite element method to simulate pulling for cutting a workpiece after the stress changes in the surface residual stress; Kim [9] developed two-dimensional steady state orthogonal cutting finite element model based on metal cutting thermal coupling model; ALBERT [10] applied the finite element method to study contact mechanism and the workpiece deformation mechanism between the tool and the workpiece during metal cutting process; Sun [11] established a 3D finite element model according to the thermal-elastic-plastic finite element theory and studied the effect of cutting parameters and tool parameters on aerospace aluminum alloy surface residual stress. Huang [12] studied the effect of several special finite element techniques, such as the chip separation criteria and friction model, on the finite element simulation.

### 2. Numerical simulation procedures

#### 2.1. Material constitutive model

Metal cutting process is a complex thermal elastic-plasticity of nonlinear problems, involving high strain,

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**Table 1.** Johnson-cook material parameters of TC4 [13].

A	B	C	m	n
860	683	0.035	1.0	0.47

high strain rate and high temperature. Therefore, in order to reflect actual machining process, the constitutive model should be chosen under considering the influence of various factors on the flow stress of metallic materials. The Johnson-cook constitutive model is currently the most widely adopted constitutive model for fitting the mechanical properties of metal cutting, the constitutive equation is expressed as Eq. (1):

$$\bar{\sigma} = [A + B(\varepsilon^{pl})^n] \left[ 1 + C \ln \left( \frac{\bar{\varepsilon}}{\bar{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (1)$$

where  $\bar{\sigma}$  is equivalent stress; A, B, C, m, n respectively represent the yield strength, strain hardening coefficient, strain rate hardening coefficient, temperature dependence coefficient and strain hardening exponent under quasi-static conditions,  $\varepsilon^{pl}$  is the equivalent plastic strain,  $\bar{\varepsilon}$  is equivalent plastic strain rate,  $\bar{\varepsilon}_0$  is quasi-static strain rate. Johnson-cook model material parameters for TC4 are listed in Table 1.

## 2.2. Chip separation criteria

Metal cutting process is a process, which chip continuously separated from the workpiece. In order to simulate the mechanical properties of metal cutting the chip separation criterion of simulation process must be determined. Separation rule of metal cutting finite element simulation is mainly divided into geometric criterion and physical standards. Geometric criterion defines the critical distance between tool tip and the element node in tool path, when the distance between the tool tip and node is less than the setting critical value, the node starts to separate. Physical standards define the critical value of physical quantity of simulation model of nodes, such as: stress, strain, strain energy density, when the physical quantity of the node of workpiece model reaches the critical value, the node begins to separate. In order to get better simulation, in this study the Johnson-cook shear failure model of metal cutting chip separation simulation was adopted, as Eq. (1):

$$\omega = \sum \frac{\Delta \varepsilon^{pl}}{\varepsilon_f^{pl}}. \quad (2)$$

## 2.3. Friction model

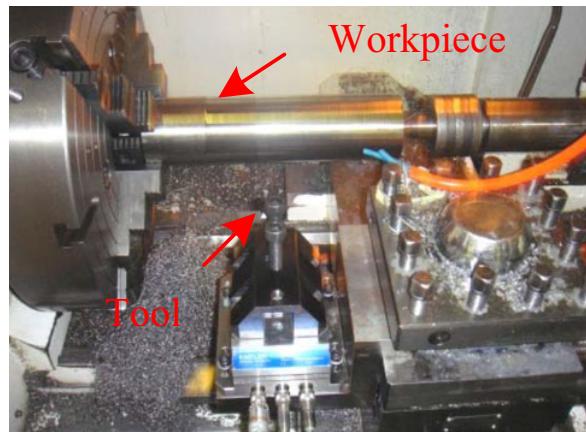
In the metal cutting process, there are two types of friction types: adhesive friction and sliding friction. These two different friction types based on Coulomb friction, we select the correction equation to simulate the friction behavior during the cutting process, as Eq. (3) and Eq. (4):

$$\begin{cases} \tau_f = \tau_s & \text{when } \tau_f \geq \tau_s; \\ \tau_f = \mu \sigma_n & \text{when } \tau_f < \tau_s; \end{cases} \quad (3)$$

$$(4)$$

**Table 2.** Mechanical properties and components of test specimen.

Mechanical properties	state	$\sigma_b$	$\sigma_{0.2}$	$\sigma_5$	$\psi$		
		MPa	MPa	%	%		
Components	M	895	825	10	25		
	Chemical components (%)		others (%)				
	Ti		single	sum			
	Allowance		$\leq 0.1$	$\geq 0.4$			
	Other ingredients (%)						
	Al	V	Fe	C	N	H	O
	5.7	4.0	0.14	0.02	0.04	0.001	0.17

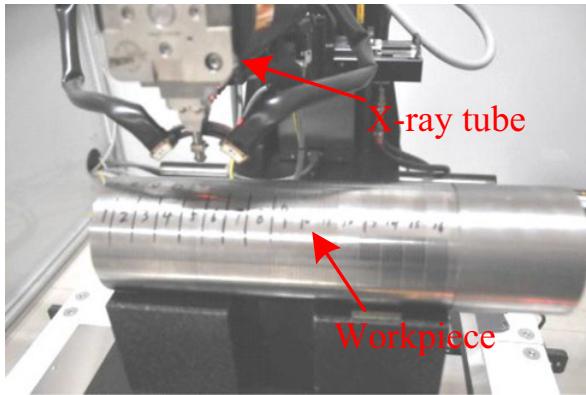
**Figure 1.** The picture of cutting experiment.

where,  $\tau_f$  is friction shear stress,  $\tau_s$  is the critical shear yield stress of the workpiece,  $\sigma_n$  is the normal stress,  $\mu$  is friction coefficient. In the simulation, if the tool and chip contact shear stress is greater than the critical shear yield stress of the workpiece, the point is in the adhesive friction area, otherwise the point is in the sliding friction.

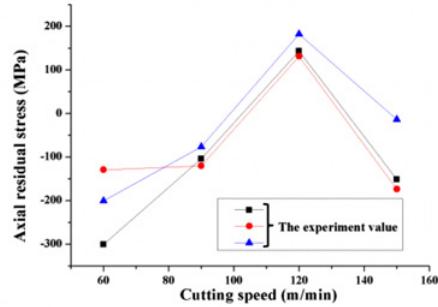
## 3. Experiment and detection method of residual stress

Orthogonal cutting experiments were carried out on HK63 NC numerical control lathe. The test specimen employed in this work were TC4 bar with the dimension of 90 mm  $\times$  350 mm. The mechanical properties and components of test specimen were shown in Table 2.

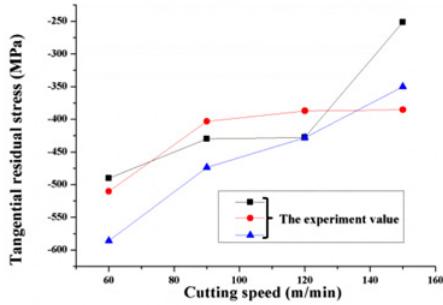
The cutter type been used were LCMF160404-0400-FT CP500. The experiments were carried out with four different cutting speeds (60–90–120–150 m/min) and one cutting depth (0.1 mm). In this paper, the X-ray diffraction technology was used to detect the residual stress. Figure 1 shows the cutting process, and Fig. 2 shows the detection process of residual stress.



**Figure 2.** The picture of residual stress detection.



a. Axial direction



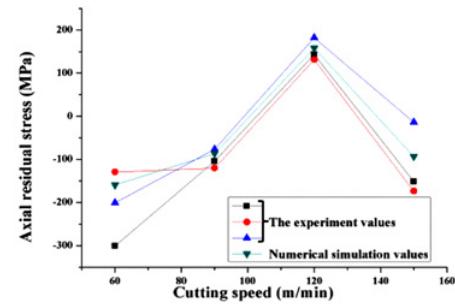
b. Tangential direction

**Figure 3.** The relationship between cutting speed and residual stress.

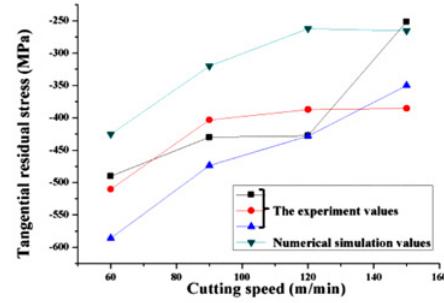
## 4. Results and discussion

In order to ensure the accuracy of detection results, we selected three points on the final surface after each set of experiments. As Fig. 3 shows, the three detection results are very close and have the same tendency. The deviations may be caused by the tiny internal structure difference in different detection position.

When the cutting speed is lower, the residual stress in axial direction is compressive stress, and then gradually changes to tensile stress with the cutting speed increase, but finally it will convert to compressive stress again with the further increase in cutting speed (as it is shown in Fig. 3-a). As we all know, the residual stress are generated by the combination of thermal stress, mechanical stress



a. Axial direction



b. Tangential direction

**Figure 4.** The comparison between simulation and experiments.

and transformation factors. When the cutting speed is lower, the mechanical stress is dominant in the generation of residual stress which results in compressive stress. When the cutting speed goes higher, it seems that thermal stress and transformation will become more and more important.

The residual stress in tangential direction presents compressive stress and it will decrease with the cutting speed increase (as it is shown in Fig. 3-b), due to the temperature increase with cutting speed.

Figure 4 shows the comparison between simulation and experiments.

As Fig. 4 show, the predicted results from numerical simulation are nearly of the same magnitude as the results obtained experimentally. Therefore, this numerical simulation method can be applied to study the relationship between cutting parameters and residual stress.

## 5. Conclusions

A numerical and experimental analysis of residual stress induced by orthogonal cutting of TC4 was performed in this investigation. The numerical results and experiments show good agreements. From the results obtained from this work, the following results can be derived.

- Cutting speed has a significant effect on residual stress.
- When the cutting speed changes from 60 m/min to 120 m/min, the axial residual stress tends to change from compressive stress to tensile stress gradually. When the cutting speed continues to increase, the tensile residual stress will decrease gradually.

- The tangential residual stress presents compressive stress and it will decrease with the cutting speed increase.

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