Research article

Analysis and prediction of residual stresses based on cutting temperature and cutting force in rough turning of Ti–6Al–4V

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ABSTRACT

Turning is a typical machining process, which is widely used in the manufacturing process of parts. The residual stress introduced by turning has a significant influence on the mechanical properties, fatigue performance, and service safety, and is one of the key factors affecting the fatigue life of parts. Conventional residual stress prediction models based on cutting parameters cannot consider all the influencing factors of turning and are strongly dependent on the specific cutting environment and tool, so they have limitations. Therefore, a residual stress analysis and prediction method based on cutting temperature and cutting force is proposed in this paper for the rough turning process of Ti–6Al–4V. Firstly, the sensitivity analysis of turning residual stress is carried out on eight cutting variables to determine the key cutting variables affecting the residual stress. Subsequently, the influence of the above key variables on residual stress is analyzed from the perspective of cutting temperature and cutting force. Finally, the residual stress prediction model based on cutting temperature and cutting force is established. The results show that the three variables that have the greatest influence on residual stresses are friction coefficient, tool edge radius, and cutting speed. The friction coefficient and tool edge radius affect the thickness of the residual stress layer. The cutting speed has little effect on the thickness of the residual stress layer, but increasing the cutting speed will lead to the transformation of residual stress to tensile stress. The relative error between the predicted value and the simulated value of residual stress is less than 6%, indicating that the prediction model has high accuracy and can effectively predict the residual stress. The prediction method proposed in this paper is not limited by the specific turning condition and provides a new perspective for the analysis and prediction of turning residual stress.

1. Introduction

Ensuring the operation safety of aero-engine has always been the goal pursued in the process of engine development. Once the aero-engine life-limited part fails, it will bring catastrophic consequences to the whole aircraft, so the importance of ensuring its safety is beyond doubt. To ensure the safety of life-limited parts, the Federal Aviation Administration issued the Advisory Circular 33.70 (FAA, 2009) which contains requirements applicable to the design and life management of life-limited parts. The residual stress introduced by machining has a significant influence on the mechanical properties, fatigue performance, and service safety, and is one of the key factors affecting the fatigue life of parts (Guo and Warren, 2008; Jafarian et al., 2015). Therefore, AC 33.70 proposed that the residual stress should be considered in the manufacturing plan of the life-limited parts (FAA, 2009).

Turning is a typical machining process, which is widely used in the manufacturing process of life-limited parts, and is one of the sources of residual stresses in life-limited parts. With the development of simulation technology, finite element technology is widely used in metal turning. Rao et al. (2013) investigated the effects of turning parameters on cutting force and pointed out that feed rate and depth of cut had significant effects on cutting force. Mali et al. (2020) established a mathematical model between cutting parameters and cutting force through multiple regression analysis. Abou-El-Hossein and Kops (2017) explored the influences of cutting parameters on cutting temperature, showing that excessive depth of cut and cutting speed led to high cutting temperatures.
which adversely affected tool life. Ji et al. (2021) discussed the influence of flank angle on cutting force and cutting temperature in the C45 material turning process, concluding that cutting force and cutting temperature decreased with the increase of flank angle. Mabrouki et al. (2008) studied the dry turning process of aeronautical aluminum alloy A2024-T351. The results showed that the contact between chip and workpiece and the tool feed movement produced a bending load on the chip. Therefore, when the chip began to curl, it would break on the rake face. Sun et al. (2009) revealed the influences of different cutting parameters on chip formation and showed that the slippage angle of the segmented chip was larger than that of the continuous chip. In addition, some researchers studied tool wear during machining. Li (2012) systematically introduced the research progress of tool wear theory and numerical simulation and pointed out that Hidden Markov Models (HMMs) could be used to evaluate tool wear. Toubhans et al. (2020) further introduced the influence of tool wear into the local formulation, thereby establishing the Inconel 718 cutting force model considering the effect of tool wear.

Many experiments and simulations have been carried out to investigate the residual stress induced by machining. Brinksmeier et al. (1982) analyzed the causes of residual stresses in machining, showing that the residual stress was the result of a combination of mechanical and thermal effects. Besides, the typical residual stress distributions for processes such as turning and grinding were given. Ulutan and Ozel (2011) reviewed the machining-induced surface integrity of titanium and nickel alloys, focusing on the machining-induced surface residual stress. Chen et al. (2004) explored the influence of flank face wear on residual stress in the turning process of Ti-6Al-4V and pointed out that with the increase of flank wear, surface residual stress became more tensile due to increased temperature. Ozel and Ulutan (2012) further conducted Ti-6Al-4V face turning experiments and finite element simulations to explore the effects of tool edge radius and coating on residual stress, concluding that the residual stress became more compressive with increased tool edge radius, but more tensile at the surface when coated. Niestony et al. (2014) reported that the accuracy of residual stress prediction was related to the constitutive model of the material. Pan et al. (2018) further established a modified Johnson-Cook constitutive model to consider the microstructural attribute changes of titanium alloy Ti-6Al-4V during machining. Abboud et al. (2016) pointed out that there is a conflict between residual stress and surface roughness in the finish turning of titanium alloy, indicating that both compressive residual stress and roughness increased with the increase of the feed rate.

Although extensive research has been carried out on the turning process, some aspects still need to be improved. Firstly, there are many influencing factors in the turning process, which makes it impossible to consider all the cutting factors in a single residual stress prediction model and the influence degree of each cutting factor on the residual stress is not clear. Secondly, the existing residual stress prediction models based on cutting parameters are strongly dependent on the specific cutting environment and cutting tool. After changing the cutting environment, the applicability of the prediction model is unclear. In summary, it is necessary to further optimize the establishment method of turning residual stress prediction model.

To solve the problems mentioned above, this work selects the key cutting parameters by sensitivity analysis method, analyzes the influence of key turning parameters on residual stress from the perspective of cutting force and cutting temperature, and then establishes the residual stress prediction model of titanium alloy Ti-6Al-4V based on cutting force and cutting temperature. The rest of this paper is structured as follows: The simulation method of turning residual stresses is presented in Sec. 2. The accuracy of the simulation method is validated through experiments in Sec. 3. The sensitivity of cutting variables is analyzed and the residual stress prediction model is established in Sec. 4. The main conclusions are summarized in Sec. 5.

2. Simulation method of cutting residual stresses

2.1. Geometric model

The commercial software DEFORM-2D™ is used to model the turning process of titanium alloy Ti-6Al-4V. In this paper, the plane strain model is used to simplify the simulation process. When the cutting width is greater than 5 times the cutting thickness, it can be regarded as a plane strain problem (Kumar et al., 2020; Salio et al., 2006). In the plane strain state, a two-dimensional (2D) model can be used instead of a three-dimensional (3D) model for simulation to improve the calculation efficiency and reduce the time cost.

In the process of 2D modeling of oblique cutting, the equivalent plane method is used to consider the effect of inclination angle in oblique cutting. The accuracy of the equivalent method is verified by comparing the simulation results based on the equivalent plane modeling with the experimental results (Li et al., 2009, 2011; Wang et al., 2018). In summary, the two-dimensional finite element model based on the equivalent plane is adopted in this paper to simulate the turning process, and the schematic diagram of the cutting modeling method is shown in Figure 1.

2.2. Material constitutive model

There are many constitutive models to describe material properties, such as Johnson-Cook model (Johnson and Cook, 1983), Steinberg-Guinan model (Steinberg et al., 1980), Zerilli-Armstrong model (Zerilli and Armstrong, 1987), Follansbee-Kocks model (Follansbee and Kocks, 1988), etc. Nevertheless, cutting is a complex deformation process with large strain, large strain rate, and high temperature, so the selected constitutive model should fully reflect the influence of the above factors on flow stress. Johnson-Cook model introduces the parameters representing the above effects, which can describe the cutting properties of titanium alloys well and is one of the most widely used models (Shrot and Baker, 2012). Besides, the material parameters in this model are relatively easy to obtain. Therefore, the Johnson-Cook model is adopted in this paper, which can be given in Eq. (1):

$$\sigma = [A + B \left( \frac{\varepsilon}{T_o} \right)^n] \left[ 1 + C \ln \left( \frac{T}{T_o} \right) \right] \left[ 1 - \left( \frac{T - T_o}{T_m - T_o} \right)^{\frac{m}{e}} \right]$$

where $\sigma$ is the flow stress, $\varepsilon$ is the equivalent plastic strain, $T$ is the equivalent plastic strain rate, $T_o$ is the reference plastic strain rate, $T$ is the temperature of the workpiece, $T_o$ is the room temperature, $T_m$ is the melting temperature of the material, $A$ is the yield strength, $B$ is the hardening modulus, $C$ is the strain rate sensitivity coefficient, $n$ is the strain hardening coefficient and $m$ is the thermal softening coefficient. The constitutive model parameters of Ti-6Al-4V alloy are shown in Table1.

2.3. Material fracture criterion

The selection of fracture criterion is the key to determining the accuracy of finite element simulation. There are many fracture criteria describing the fracture behavior of materials, such as Rice&Tracey criterion (Rice and Tracey, 1969), Oyane criterion (Oyane et al., 1980), Cockcroft & Latham criterion (Cockcroft and Latham, 1968), etc. Titanium alloys have ductile fracture characteristics. Cockcroft & Latham criterion can describe the fracture behavior of titanium alloy well and has been adopted by a large number of researchers (Umbrello, 2008). Cockcroft & Latham criterion can be expressed by Eq. (2):

$$\int_0^\infty \sigma' \, d\varepsilon = c$$

where $\sigma'$ is the effective stress, $\varepsilon$ is the strain, and $c$ is a constant.
where $\sigma^*$ is the maximum principal stress, $\gamma$ is the equivalent strain, $\gamma_f$ is the effective fracture strain, and $c$ is the critical damage value, which is 240 in this study (Bai et al., 2017; Berger et al., 2021; Zhou et al., 2022).

2.4. Friction model

In order to describe the friction effect during cutting, a shear friction model based on the constant shear hypothesis is used, namely $\tau = \mu \tau_0$, where $\tau$ is shear stress, $\mu$ is friction coefficient and $\tau_0$ is shear yield stress. $\tau_0$ is expressed as $\tau_0 = \frac{\sigma_0}{\sqrt{3}}$, where $\sigma_0$ is yield normal stress of the material (Filice et al., 2006, 2007).

2.5. Simulation setup

The workpiece is modeled as an elastic-plastic body to analyze the residual stress (Wang et al., 2006), and the workpiece material is Ti-6Al-4V. The tool is modeled as a rigid body and the material is tungsten carbide. The local dynamic adaptive mesh refinement method is used for the workpiece to balance the accuracy and efficiency of analysis. The material parameters of the workpiece and tool are from the DEFORM software material database.

The cutting model and boundary conditions in the finite element simulation are shown in Figure 2. The bottom surface of the workpiece is fixed in the Y direction, and moves relative to the tool at the cutting speed $V$ in the X direction. The tool is completely fixed. Heat transfer calculations inside the tool and the workpiece, as well as between the tool with the workpiece and the chip, are considered. The contact surface between the tool and the workpiece is set as the third boundary condition, that is, the convective heat transfer with the environment, the ambient temperature is 20°C, and the convective heat transfer coefficient is 20W/m²K. The other surfaces of the tool and the workpiece are set as the first boundary condition and the temperature is set as the ambient temperature. The heat transfer coefficient of the tool-workpiece contact zone is 40000 W/m²K. A local heat exchange window is set to simulate the cooling effect of the coolant, with the coolant temperature of 20°C and the convective heat transfer coefficient of 1000W/m²K.

3. Simulation method validations by experiments

To verify the accuracy of the simulation method, the turning experiments of titanium alloy Ti-6Al-4V were carried out. Firstly, the geometric model parameters were obtained by experimental measurement, and the friction coefficient was determined according to the chip morphology. Subsequently, the simulation model was established based on the above parameters. The simulation results were compared with the experimental results, which proves the accuracy of the simulation method.

3.1. Determination of simulation model parameters

3.1.1. Geometric model parameters obtained by experimental measurements

In the machining of the Ti-6Al-4V aero-engine compressor disk, a margin of 30mm was reserved for cutting into a ring part for rough turning experiments. The outer and inner diameters of the ring part are 480mm and 420mm, respectively, as shown in Figure 3. The rough turning experiments were carried out on a CK500A CNC lathe machine. The cutting insert type WNMG 080408-CF and tool holder type MWLN3232P08 were used for machining, as shown in Figure 4. The cutting speed was 25rpm, the feed rate was 0.25mm/r, and the depth of cut was 3mm, which were selected according to the recommendations of the tool supplier.

The geometric parameters of the cutting insert and tool holder were measured by Alicona Infinite Focus SL 3D shape measuring instrument

| A (MPa) | B (MPa) | C | m | n | $T_m$ (°C) | $T_0$ (°C) | $\tau_0$ (s⁻¹) |
|--------|--------|---|---|---|-----------|-----------|-------------|
| 870    | 990    | 0.011 | 1 | 0.25 | 1650       | 20        | 1           |

Table 1. Johnson-Cook constitutive model parameters of Ti-6Al-4V alloy.

Figure 1. Schematic diagram of cutting modeling method.
Figure 4 (a) and ATOS Capsule 3D blue light measuring system (Figure 4 (b)), respectively, as shown in Figure 4. The measurement results are shown in Table 2.

3.1.2. Friction coefficient obtained by chip morphology

Chip morphology is an important indicator to reflect the characteristics of the machining process, because the extrusion and friction between tool and workpiece, as well as the generation of cutting heat, will ultimately be reflected in the chip morphology. Correspondingly, the friction coefficient can be determined according to the chip morphology when other cutting conditions are determined. By adjusting friction coefficients, the chip morphologies under different friction coefficients are simulated. When the simulated chip morphology agrees with the experimental result, the target friction coefficient can be obtained (Umbrello, 2008).

Figure 5 shows the chip morphologies obtained by experiment (Figure 5 (a)) and simulation (Figure 5 (b)), respectively. It can be seen from Figure 5 that the simulated and experimental chip morphologies are similar, and both show the characteristics of serrated chips due to adiabatic shear failure of Ti–6Al–4V. Table 3 shows a quantitative comparison between the two. The relative errors of chip pitch and chip tooth height are less than 17%, which is within the acceptable range. Therefore, the target friction coefficient was determined to be 0.8 for the turning simulation.

3.2. Comparison between experimental and simulated residual stresses

In this paper, residual stress refers to circumferential residual stress. The results show that the radial and shear residual stresses are neglected compared to the axial and circumferential residual stresses (Leppert and Peng, 2012; M’Saoubi et al., 1999). Meanwhile, the circumferential residual stress is usually greater than the axial residual stress in the outer layer of the machined surface. In addition, the circumferential residual stress is one of the key input parameters of the damage tolerance analysis.
method of aero-engine life-limited parts, which has a significant influence on the performance of the parts. Therefore, only circumferential residual stress is analyzed and discussed in this study.

3.2.1. Residual stresses obtained by simulation

The simulation calculation was carried out according to the model parameters obtained in Section 3.1. The variations of cutting forces (Figure 6 (a)) and cutting temperatures (Figure 6 (b)) with time during the cutting process were extracted, as shown in Figure 6. When the cutting time is between 0.00358 and 0.00513 s, the cutting is in a stable state. This time period is defined as the change cycle of physical quantities (cutting force, cutting temperature). The cutting force and cutting temperature are obtained by averaging the corresponding physical quantities in the above time period. In this study, cutting temperature refers to the maximum temperature of the tool.

As shown in Figure 7, to avoid the residual stress on the machined surface being affected by the boundary or cutting zone, the machined surface being affected by the boundary or cutting zone, the machined
The surface far away from the boundary and cutting zone is selected as the extraction zone of residual stress. To reduce the error, the residual stress values of 100 surface points were extracted uniformly from this region and averaged as the target residual stress value. According to the above method, the target residual stress value in the above time period is -519.57 MPa.

3.2.2. Residual stresses obtained by experiment

The X-ray diffraction (XRD) technique is used to measure the surface residual stress in the cutting direction. The measuring equipment is an X-ray stress analyzer (X-3000) produced by AST-Stresstech. Eight measuring points are evenly distributed on the ring part, as shown in Figure 8.

The surface residual stress measurement results are shown in Table 4. There is no significant difference in the residual stress value of each measuring point, indicating good machining quality. According to the data in Table 4, the normal distribution, \( X \sim N(\mu, \sigma^2) \), is fitted in MATLAB. The estimated values of the normal distribution coefficient are as follows: \( \mu = -507.6525 \), \( \sigma = 13.2455 \), that is, the average surface residual stress measured by experiment is -507.6525 MPa. The relative error between simulation and experimental results is 2.3%, which is within the acceptable range. Therefore, the simulation method in this paper is reliable.

4. Results and discussion

In this section, the sensitivity analysis of cutting variables to residual stress is carried out first. Subsequently, the influence of key variables on residual stress is analyzed from the perspective of cutting temperature and cutting force. Finally, the method for establishing the residual stress

| Chip morphology | Average pitch (μm) | Average tooth height (μm) |
|-----------------|-------------------|--------------------------|
| Experiment      | 355               | 125                      |
| Simulation      | 410               | 117                      |
| Error (%)       | 16.9              | 6.4                      |

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Figure 5. Experimental and simulated chip morphologies (a) experiment, (b) simulation.

Table 3. Comparison of experimental and simulated chip morphologies.

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| Simulation      | 410               | 117                      |
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Figure 6. Variations of cutting forces (a), and cutting temperatures (b), with time.
prediction model considering cutting temperature and cutting force is proposed.

4.1. Sensitivity analysis of cutting variables

When performing sensitivity analysis on a variable, other variables need to be temporarily treated as constants, which is similar to the control variable method commonly used in experiments. The sensitivity coefficient $S_{AF}$ of the variable is calculated by Eq. (3):

$$S_{AF} = \frac{\Delta A/A}{\Delta F/F}$$  \hspace{1cm} (3)

where $\Delta F/F$ is the change rate of factor $F$, and $\Delta A/A$ is the corresponding change rate of evaluation index $A$ when factor $F$ changes $\Delta F$.

Residual stress is affected by many turning variables. Typical turning variables are selected in this section as follows: rake angle, flank angle, tool edge radius, coating thickness, friction coefficient, cooling condition, cutting speed, and feed rate. According to the actual machining process and literature data (Çelik and Fidan, 2022; Liu and Liu, 2018; Pan et al., 2018), the reference and value range of the above cutting variables are selected, as shown in Table 5.

The sensitivity ranking of cutting variables is shown in Table 5. The three variables that have the greatest influence on residual stresses are friction coefficient, tool edge radius, and cutting speed. These variables are the key factors affecting the cutting residual stress. This conclusion can guide experimental designs. For example, the residual stress is very sensitive to the tool edge radius, which means that optimizing the tool edge radius can better improve the residual stress.

| Parameters                     | Reference Range | Sensitivity | Ranking |
|--------------------------------|-----------------|-------------|---------|
| Friction coefficient          | 0.3             | 3.3654      | 1       |
| Convective heat transfer coefficient of coolant (W/m²K) | 1000–4800 | 0.0472 | 8       |
| Coating thickness (μm)        | 0–6             | 0.2476      | 5       |
| Rake angle (°)                | 4–6             | 0.0768      | 7       |
| Flank angle (°)               | 6–8             | 0.2589      | 4       |
| Tool edge radius (μm)         | 20–80           | 0.4977      | 2       |
| Cutting speed (m/min)         | 25–65           | 0.4736      | 3       |
| Feed rate (mm/r)              | 0.25–0.65       | 0.2071      | 6       |

Table 5. Cutting variable values and sensitivity ranking.
4.2. Influence of mechanical and thermal effects on residual stress

Residual stress is the result of a combination of mechanical and thermal effects. This section uses univariate analysis to explore the influence of mechanical and thermal effects on residual stress.

4.2.1. Influence of mechanical effect on residual stress

To investigate the influence of mechanical effect (cutting forces) on residual stress, the heat transfer option is turned off in the DEFORM software to keep the workpiece and tool temperature always at ambient temperature (20°C). The cutting force and residual stress are analyzed by varying the tool edge radius. As shown in Figure 9, the surface compressive residual stress increases first and then decreases as the cutting force increases, without considering the cutting heat. This is because mechanical effects cause two types of plastic deformation which have two opposite effects on the direction of residual stress:

① Type I: During the turning process, the workpiece material is squeezed by the rake face, resulting in compressive plastic deformation of the machined surface in the cutting direction. Under the interaction of the compressive plastic deformation of the machined surface and the inner undeformed material, the tensile residual stress (+σ) is generated in the surface layer and the compressive residual stress (-σ) is generated in the inner layer.

② Type II: During the turning process, the workpiece material is subjected to the extrusion and friction of the flank face, which causes tensile plastic deformation of the machined surface in the cutting direction. Under the interaction of the tensile plastic deformation of the machined surface and the inner undeformed material, the compressive residual stress (-σ) is generated in the surface layer and the tensile residual stress (+σ) is generated in the inner layer.

Compare Type I and Type II plastic deformations: when the former is larger, tensile residual stress is generated on the machined surface, and conversely, compressive residual stress is generated.

4.2.2. Influence of thermal effect on residual stress

To investigate the influence of thermal effect on the residual stress, only the workpiece model is established in DEFORM software to exclude the effect of cutting force. The finite element model and boundary conditions are shown in Figure 10. After heating is complete, cool the workpiece to room temperature. The maximum temperature and residual stress of the workpiece are analyzed by varying the heat flux. As shown in Figure 11, the surface residual stress appears as tensile stress under the thermal effect, and both the maximum temperature of the workpiece and the surface tensile residual stress increase significantly with the increase of heat flux. This is because the surface temperature of the workpiece is high, while the inner temperature is low, resulting in

Figure 9. Variation of cutting force and residual stress with tool edge radius without cutting heat.

Figure 10. Finite element model and boundary conditions.
uneven temperature distribution. The surface layer of the workpiece has a tendency of volume expansion at high temperatures, but is constrained by the inner layer, so thermal stress is generated in the surface layer. When the thermal stress exceeds the yield limit of the material, compressive plastic deformation occurs in the surface layer. When the workpiece is cooled to room temperature, the volume contraction of the surface layer is constrained by the inner layer, resulting in tensile residual stress on the metal surface.

Similarly, due to the strong plastic deformation and friction generated by cutting, the surface temperature of the workpiece is high, while the inner temperature is low, resulting in uneven temperature distribution. Consequently, the residual stress tends to transform into tensile stress as the thermal effect increases during cutting.

The residual stress of the machined surface is the result of the combined effect of the above factors. The magnitude and direction of residual stress are determined by dominant factors. Therefore, surface residual stresses can be either tensile or compressive stresses.

4.3. Influence of key cutting variables on residual stress

Based on the studies in Sections 4 and 4.2, this section analyzes the influence of key cutting variables on residual stress. The residual stress value under the reference condition in Section 4.1 is taken as a reference to normalize the residual stress under other working conditions.

Five residual stress extraction paths are set in the depth direction of the machined surface, and the residual stress values at the same depth

Figure 11. Variation of the maximum temperature and residual stress of the workpiece with heat flux without cutting force.

Figure 12. Effect of friction on residual stress.
are averaged to obtain the residual stress distribution in the depth direction.

4.3.1. Influence of friction on residual stress

Figure 12 shows the variation of residual stress with friction coefficient. When the friction coefficient is between 0.4 and 0.6, the residual stress is significantly affected by friction. With the increase of friction, the absolute value of surface compressive residual stress increases gradually. This indicates that residual stress induced by mechanical effect dominates at low temperature, promoting the compressive stress on the machined surface. In addition, the surface residual stresses corresponding to the friction coefficients of 0.3 and 0.4 are almost the same, because the cutting forces and cutting temperatures are almost the same (Figure 13). The same is true for friction coefficients of 0.6 and 0.7, respectively. It is also observed that the absolute value of residual stress increases by 320% when the friction coefficient increases from 0.4 to 0.5. However, when the friction coefficient increases from 0.7 to 0.8, it only increases by about 100%. This shows that the increase of friction has two opposite effects on the direction of residual stress: 1) The friction between the tool flank and the machined surface increases, resulting in increased tensile plastic deformation of the machined surface, thus promoting the generation of compressive residual stress (Type II mechanical effect plays a leading role.); 2) The increase of cutting heat promotes the generation of tensile stress (thermal effect). When the friction coefficient reaches
above 0.7, the cutting temperature has reached a high level (Figure 13), so the thermal effect is enhanced, which confirms the above analysis.

Figure 14 shows that friction affects the thickness of the residual stress layer. The thickness of the residual stress layer increases with the friction coefficient. This is because both cutting force and cutting temperature increase with the increased friction coefficient, and both promote the increase of residual stress layer thickness. In addition, as the friction coefficient increases, the thickness of the compressive residual stress layer decreases. This is because with the increase of cutting temperature, the depth of temperature influence increases, which accelerates the direction transformation of residual stress. It can be seen from Figure 14 that the residual stress curves corresponding to friction coefficients of 0.3 and 0.4 almost coincide, which also confirms the previous analysis, namely, the thermal and mechanical loads of the two are almost the same.

4.3.2. Influence of tool edge radius on residual stress

Figure 15 describes the effect of tool edge radius on residual stress. When the tool edge radius increases from 20 μm to 40 μm, the absolute value of compressive residual stress increases rapidly. When the tool edge radius is 40 μm, the absolute value of residual stress reaches the maximum, which is about 340 MPa. This reflects the enhanced Type II mechanical effect, as the mechanical effect plays a dominant role at this time. As the tool edge radius increases, the sharpness of the tool decreases, the extrusion and friction effects increase, the degree of plastic deformation of the metal increases, and therefore the surface...
Compressive residual stress increases. In other words, the increase of tool edge radius promotes the formation of surface compressive residual stress to a certain extent. However, when the tool edge radius exceeds 40μm, the absolute value of compressive residual stress decreases slightly. This is because the increase in tool edge radius increases the friction between the tool and the workpiece, causing increased friction heat, which tends to transform the compressive residual stress into tensile residual stress.

Figure 16 indicates the variations of cutting temperature and cutting force with tool edge radius. It can be seen that the cutting force and cutting temperature increase with the tool edge radius, especially when the tool edge radius increases from 40μm to 60μm, the cutting temperature increases sharply. This means that an excessively large tool edge radius results in increased tool wear. In conclusion, machining with a tool having a medium tool edge radius (20–40μm) is beneficial for maintaining low cutting forces and tool temperatures, extending tool life, and obtaining surface compressive residual stresses.

As shown in Figure 17, the maximum compressive residual stress value and the maximum tensile residual stress value of the residual stress distributions along the depth direction. The medium tool edge radius (20–40μm) is beneficial to keeping the cutting force and tool temperature at a low level and obtains the surface compressive residual stress. This is consistent with the conclusion of Hua et al. (2005). Therefore, the tool edge radius should not be too large in the tool design.

As shown in Figure 17, the maximum compressive residual stress value and the maximum tensile residual stress value of the residual stress distributions along the depth direction.
layer have the same variation trend and both increase with the tool edge radius. The reason is that residual stress is the self-balanced stress that remains in the workpiece. It is also observed that the tool edge radius affects the thickness of the residual stress layer. The thickness of the residual stress layer increases with increasing tool edge radius due to enhanced mechanical and thermal effects (both cutting force and cutting temperature increase with increasing tool edge radius). Furthermore, as the tool edge radius increases, the thickness of the residual compressive stress layer increases, which means that the transition from compressive to tensile stress is slowed down. This is because the enhanced mechanical effect (cutting force) affects the deeper sub-surface layer.

4.3.3 Influence of cutting speed on residual stress

Figure 18 shows the variation of residual stress with cutting speed. As the cutting speed increases, the surface residual stress tends to transform into tensile stress, and the absolute value of compressive residual stress decreases approximately linearly. When the cutting speed increased by 20 m/min, the absolute value of residual stress decreased by nearly 40%. The main reason is the significant increase in cutting temperature (Figure 19), i.e., the enhanced thermal effect, which promotes the transformation of compressive stress to tensile stress.

It can be seen from Figure 20 that the cutting speed has little effect on the thickness of the residual stress layer. This is due to the poor thermal effect.
conductivity of Ti-6Al-4V, so the temperature increase cannot be transmitted to the inside of the workpiece in a short time. The surface layer of the workpiece is the compressive residual stress, and the subsurface layer is the tensile stress. With the increase of cutting speed, the surface compressive residual stress corresponding to the above three cutting parameters at different levels are selected as the basic data for establishing the residual stress prediction model, as shown in Table 6.

### 4.4. Residual stress prediction model

The conventional residual stress prediction model is established based on cutting parameters. However, this approach has certain limitations. Firstly, there are many influencing factors in the turning process, including but not limited to the eight variables in Section 4.1, so it is not possible to consider all the cutting factors in a single residual stress prediction model. Secondly, the existing residual stress prediction models based on cutting parameters are strongly dependent on the specific cutting environment and cutting tool. After changing the cutting environment, the applicability of the prediction model is unclear. Unlike cutting parameters, cutting force and cutting temperature are the result of the combined effect of turning factors. The residual stress prediction model established by cutting force and cutting temperature can consider more cutting influencing factors, such as cutting environment and tool changes. Therefore, the residual stress prediction model can be established from the perspective of cutting force and cutting temperature.

The sensitivity analysis results in Section 4.1 show that the three parameters that have the greatest impact on residual stress are: friction coefficient, tool edge radius, and cutting speed. This means that physical quantities such as residual stress can be significantly changed by adjusting the above parameters. Therefore, the cutting temperature, cutting force, and surface residual stress corresponding to the above three parameters at different levels are selected as the basic data for establishing the residual stress prediction model, as shown in Table 6.

The residual stress prediction model is established through multiple regression analysis, which is given by Eq. (4):

$$ f(x, y) = 0.031x^2 + 0.0244y^2 - 0.0403xy - 8.9909x - 3.3729y + 1.7970 	imes 10^3 $$  \hspace{1cm} (4)

where $x$ is the cutting temperature and $y$ is the cutting force.

The significance test of the regression effect was carried out on the model. The $p$-value of the model is less than 0.01 ($p = 0.0019 < 0.01$), indicating that the regression effect is very significant. The coefficient of determination (goodness of fit) $R^2$ of the model is 0.9576 ($R^2 = 0.9576$), indicating a good fit.

To further verify the reliability of the residual stress prediction model, the residual stresses under other cutting parameters not covered in

### Table 6. Basic data for establishing residual stress prediction model.

| Serial number | Cutting parameters | Cutting temperature (°C) | Cutting force (N) | Residual stress (MPa) |
|---------------|--------------------|--------------------------|-------------------|-----------------------|
| 1             | f0.3-r20-v25       | 209.25                   | 215.12            | -129.15               |
| 2             | f0.4-r20-v25       | 224.82                   | 222.32            | -127.56               |
| 3             | f0.5-r20-v25       | 441.18                   | 404.30            | -542.34               |
| 4             | f0.3-r40-v25       | 242.41                   | 242.51            | -338.29               |
| 5             | f0.3-r60-v25       | 322.99                   | 429.72            | -327.63               |
| 6             | f0.3-r60-v45       | 234.04                   | 188.25            | -81.41                |
| 7             | f0.5-r60-v25       | 315.36                   | 183.74            | -31.29                |
| 8             | f0.5-r40-v25       | 477.30                   | 540.46            | -392.03               |
| 9             | f0.5-r60-v25       | 486.59                   | 559.86            | -278.88               |
| 10            | f0.5-r80-v25       | 480.14                   | 591.72            | -104.27               |

* Take “f0.3-r20-v25” as an example to explain the meaning of cutting parameters in the above table. “f0.3-r20-v25” means that the friction coefficient is 0.3, the tool edge radius is 20μm, and the cutting speed is 25 m/min. Other cutting parameters are consistent with the reference working condition in Section 4.1.
Table 6 were predicted. The comparison between the predicted and simulated values of residual stress is shown in Figure 21. As can be seen from Figure 21, the relative error between the predicted value and the simulated value is small, and the absolute value of the relative errors is less than 6%. This indicates that the prediction model has high accuracy and can effectively predict the residual stress.

Figure 22 shows the relationship between cutting temperature, cutting force, and residual stress. The flatter the surface, the less effect this factor has on residual stress. On the contrary, this factor has a greater effect on residual stress. It is obvious that both cutting temperature and cutting force have significant effects on residual stress. As shown in Figure 22, cutting temperature promotes the transformation of residual stress to tensile stress, which is consistent with the conclusion in Section 4.2.1. Under the two types of plastic deformation caused by mechanical effects, the residual stress induced by cutting force tends to transform to compressive stress and then to tensile stress, which further confirms the conclusion in Section 4.2.2.

5. Conclusions

The sensitivity of cutting influencing factors to residual stress was studied and the variation of residual stress under different cutting conditions was explained from the perspective of cutting force and cutting temperature. Finally, a residual stress prediction model was established based on the cutting force and cutting temperature in the turning process. The main conclusions are summarized as follows:

1. The influencing factors of the cutting process are systematically studied, and the sensitivity ranking of residual stress to different cutting parameters is given. Within the parameters studied in this paper, the three parameters that have the greatest influence on residual stress are friction coefficient, tool edge radius, and cutting speed.

2. The friction coefficient and tool edge radius affect the thickness of the residual stress layer, while the cutting speed has little effect on the thickness of the residual stress layer. However, increasing the cutting speed will lead to the transformation of residual stress to tensile stress. Machining with a tool having a medium tool edge radius (20–40μm) is beneficial for maintaining low cutting forces and tool temperatures, extending tool life, and obtaining surface compressive residual stresses.

3. The influence of a single mechanical effect or thermal effect on residual stress is investigated. The results show that the thermal effect promotes the generation of surface tensile residual stresses. Mechanical effect induces two types of plastic deformation: compressive plastic deformation induced by the rake face and the tensile plastic deformation induced by the flank face. These two types of plastic deformations promote the generation of surface tensile residual stress and compressive residual stress, respectively.

4. A residual stress prediction model was established based on cutting force and cutting temperature, and the model prediction effect was examined. The relative error between the predicted and expected values is less than 6%, indicating that the model can effectively predict the residual stresses.

The analysis in this paper is based on the actual turning of the aero-engine titanium alloy disk. To further explore the generation and adjustment mechanism of residual stress, there are still some issues to be solved. For example, the change of material microstructure during cutting, real-time adjustment method of friction coefficient, more advanced friction model, etc. These topics are all the emphases of our future research.

Declarations

Author contribution statement

Guo Li: Conceived and designed the experiments; Analyzed and interpreted the data.

Wanqiu Lu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Shuchun Huang: Performed the experiments; Wrote the paper.

Xingyu Zhang: Performed the experiments.

Shuiting Ding: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.
Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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