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Simulation Analysis of Ti6Al4V Cutting Under Liquid Nitrogen Cryogenic Cooling

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Abstract: Liquid nitrogen cryogenic cooling technology has great advantages in cutting machining. A thermodynamic finite element model of liquid nitrogen cryogenic cooling based on the plane strain assumption is established to observe the changes in cutting force and tool temperature corresponding to different cutting parameters (feed rate and cutting speed) under liquid nitrogen cryogenic cooling conditions. Existing tests verified the accuracy of the simulation model, and the prediction error of the simulation model was controlled within 10%. Analyzing the data obtained from the simulation model, it is found that a lower tool temperature is obtained when the cutting parameters are selected to be lower values; under the conditions of liquid nitrogen cryogenic cooling and dry cutting machining, the effect of the cutting speed on the cutting force is not obvious, while the effect of the feed volume on the cutting force is more significant; under the conditions of different cutting parameters, the tool temperature as well as the cutting force are lower under the conditions of liquid nitrogen cryogenic cooling compared to the dry cutting machining method.

Keywords: Liquid nitrogen cryogenic cooling; Finite element; Cutting force; Tool temperature.

1. Introduction

With the development of aerospace and medical industries, Ti6Al4V is more widely used, Ti6Al4V has excellent physical properties but also brings difficulties in processing [1]. Due to its poor thermal conductivity, the accumulation of heat generated during the cutting process accelerates the wear of the tool, the use of cutting fluid in the cutting process can reduce the cutting temperature to a certain extent, and improve the tool life, but the cutting fluid commonly used in the industry has a different degree of damage to the environment [2]. Liquid nitrogen cryogenic cooling is an environmentally friendly cooling technology [3], which can rapidly reduce the temperature of the cutting area with sufficient flow rate, and at the same time improve the tool-worker contact properties, which also plays an important role in reducing the cutting force and surface stress, and also improves the tool life and machining quality.

Xu Zuodong et al [4] combined low-temperature micro-lubrication and vibratory cutting and found that the new cutting method demonstrated superior cutting performance. Hu Bo et al [5] analyzed the influencing factors of cutting force in low-speed orthogonal planing and found that the cutting parameters have more obvious influence than the tool geometry parameters. In order to improve the machining efficiency, Xu Qing et al [6] increased the milling feed under liquid nitrogen cryogenic cooling and found that the cryogenic cooling can reduce the cracking of the tool. Lu Jiafeng et al [7] investigated the effect of liquid nitrogen flow rate on the cutting performance of the tool by milling test. Zhao Di et al [8] designed a new toolholder configured with cryogenic cooling medium, which to a certain extent meets the needs of modern industry for cryogenic cooling cutting. Sahoo et al [9] investigated the spraying effect of different types of cooling medium nozzle equipment and comprehensively analyzed the changing law of cutting force under different tool coatings. Shokrani [10], in order to improve the life of the tool and the machining efficiency as much as possible, proposed A new hybrid cryogenic cooling method.

In the research carried out on cutting Ti6Al4V under cryogenic cooling conditions, more experimental studies were used and less cryogenic cooling cutting models were established. Therefore, the Ti6Al4V liquid nitrogen cryogenic cutting model was established using the finite element method, and the orthogonal cutting process was analyzed using the material model proposed by Johnson-Cook, which comprehensively considered the material deformation and heat exchange in the cutting process, and investigated the effects of cutting parameters and cooling conditions on the cutting force and tool temperature.

2. Cutting Process of Ti6Al4V

2.1. Cutting process analysis

The actual turning process is shown in Fig. 1(a) cutting motion process analysis diagram, in order to facilitate the analysis, the rotary motion of the workpiece is converted to linear motion as shown in Fig. 1(b). From the simplified cutting model, it can be seen that the workpiece is subjected to a uniform force perpendicular to the Y-axis, assuming that there is no deformation in the Y-axis direction, i.e., the strain in the Y-axis direction is zero.

$$\gamma_{xy}=\frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0\ ,\quad \gamma_{zy}=\frac{1}{2}\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)=0$$

Substituting the above equation into Hooke's law gives:

$$\sigma_y=\mu(\sigma_x+\sigma_z) \tag{1}$$

Therefore, the constitutive equation of the Ti6Al4V cutting model under the plane strain assumption is:

$$\varepsilon_x = \frac{1-\mu^2}{E}(\sigma_x - \frac{\mu}{1-\mu}\sigma_z) \quad (2)$$

$$\varepsilon_z = \frac{1-\mu^2}{E}(\sigma_z - \frac{\mu}{1-\mu}\sigma_x) \quad (3)$$

$$\gamma_{xz} = \frac{1}{G}\tau_{xy} = \frac{2(1+\mu)}{E}\tau_{xz} \quad (4)$$

Where, ε is strain, σ positive stress, τ shear stress, γ shear strain, μ Poisson's ratio, E elastic modulus, G shear modulus.

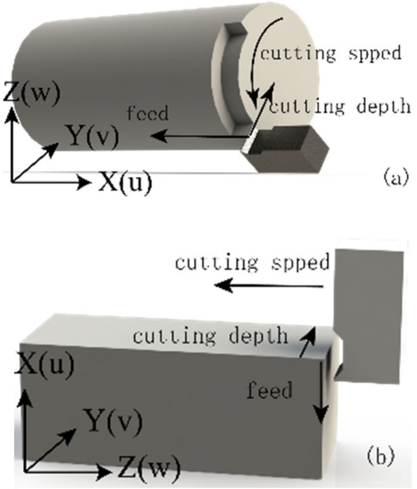

Figure 1. Cutting Process Analysis

2.2. Heat exchange during cutting

Titanium alloy due to its low thermal conductivity, the accumulation of heat in the cutting process aggravates the wear of the tool, so a reasonable analysis of heat transfer in cutting has an important impact on the accuracy of the model. There are mainly three forms of heat exchange in the cutting process, the heat mainly comes from the plastic deformation of the material occurring in the deformation zone, part of the heat flows to the tool or the cooling medium in the form of heat transfer, and the other part is taken away by the chips; the other part of the heat comes from the mutual friction between the tool and the workpiece, which is related to the friction of the tool-worker; the environmental impact on the cutting process of the heat through the convection heat transfer coefficient is calculated, and the heat transfer coefficient is set to 20℃ for the environment, and the convection heat transfer coefficient is set to 20℃ for the environment and 20 ℃ for the environment. The ambient temperature is set to 20℃, and the convective heat transfer coefficient is 20 $W/(m^2 \cdot K)$. Liquid nitrogen cryogenic cooling is mainly through changing the ambient temperature, convective heat transfer coefficient and friction effect on cutting, the tool - worker friction coefficient is 0.25, the ambient temperature is set to -196 ℃, the convection coefficient is related to the liquid nitrogen injection device and the flow rate, here take 20000 $W/(m^2 \cdot K)$.

3. Ti6Al4V Finite Element Model

3.1. Material model

Here the isomorphic model proposed by Johnson-Cook is chosen to describe the effect of thermal changes in the material on the dynamic behavior of the processed material. The Johnson-Cook isomorphic equation is:

$$\left(A + B\varepsilon_p^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)\right] \quad (5)$$

Where: A is the yield strength under quasi-static conditions; B is the hardening strain parameter; $\dot{\varepsilon}_p$ is the equivalent plastic strain; n is the hardening index; C is the strain rate enhancement parameter; $\dot{\varepsilon}$ is the equivalent plastic strain rate; $\dot{\varepsilon}_0$ is the reference strain rate of the material; T_0 is room temperature; T_{melt} is the melting point of the material; $m$is the thermal softening parameter。Here the parameters obtained by Seo [11] are chosen as：$A, B, n, C, m, T_0, T_{melt}$ in order：997.9,653.1,0.45,0.0198,0.7,20ºC,1605 ºC。Other thermodynamic parameters are shown in Table 1.

Table 1. Material thermodynamic parameter

materials	Ti6Al4V	WC
densities (Kg/m^3)	4430	15700
Young's modulus (Gpa)	113.8	650
Poisson's ratio	0.342	0.25
heat conductivity $(W/m \cdot K)$	7.3	59
Expansion(K^{-1})	8.6×10^{-6}	5.6×10^{-6}

3.2. Cutting separation guidelines and contact behavior

During metal cutting, the material reaches the failure criterion under the shearing and squeezing action of the tool, and then the material breaks and falls off, in order to accurately describe this process, Cockcroft and Latham [12] related the damage of the workpiece to the equivalent crack length:

$$\int_0^{\bar{\varepsilon}} \sigma^* d\bar{\varepsilon} = D_{Ti} \quad (6)$$

Where $\bar{\varepsilon}$ is the effective strain, σ^* is the principal stress (MPa), D_{Ti} is the material constant.

During the cutting process, the tool and the workpiece are mainly categorized into bonded and sliding contact. Özel et al [13] described bonded and sliding contact as:

$$\tau_f = \begin{cases} mk, \mu p_i \geq mk \\ \mu p_i, \mu p_i < mk \end{cases} \quad (7)$$

where k is the shear yield stress of the working material, m is the shear friction coefficient, τ_f is the friction stress, μ is the Coulomb friction coefficient, and p_i is the interfacial pressure.

Comprehensive analysis of the above, the use of DEFORM finite element calculation software, based on the assumption of plane strain, the establishment of two-dimensional finite element cutting model, the tool geometry parameters remain unchanged, the relevant parameters are shown in Table 2. In order to ensure the accuracy of the calculation, the tip of the tool and the cutting part of the local mesh as shown in Fig. 2, the minimum mesh for the cutting depth of 1/20, the maximum mesh 0.1mm. to the tool- workpiece model to add motion constraints and thermal boundary conditions to ensure that the normal movement of the tool.

Table 2. Cutting parameters and tool geometry

batch number	1
cutting speed(m/min)	30m/min
feed(mm/r)	0.06,0.28
Cutting length (mm)	2.5mm
Rack angle (°)	15
Clearance angle (°)	2
Cutting edge radius (mm)	0.02

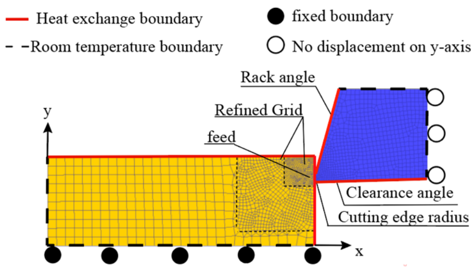

Figure 2. Ti6Al4V finite element model

4. Simulation Results and Discussion

4.1. Simulation model accuracy analysis

Fig. 3 and Fig.4 show the trend graphs of cutting force changes and temperature distribution cloud graphs corresponding to different feeds at a cutting speed of 30m/min, from which it can be seen that an increase of 0.22mm/r in feed increases the cutting force by 291N and the cutting temperature by 60°C. Fig. 5 gives the experimental results of Ducobu[17] et al. The relevant cutting parameters are the same as the parameters in Table 2, and the comparison reveals that the main cutting force of the finite element model is basically the same as that of the test, and the errors under the feed of 0.06 mm/r and 0.28 mm/r are 4.76% and 4.3%, respectively.

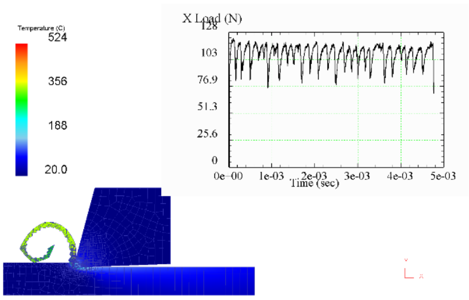

Figure 3. Feed (0.06mm/r)

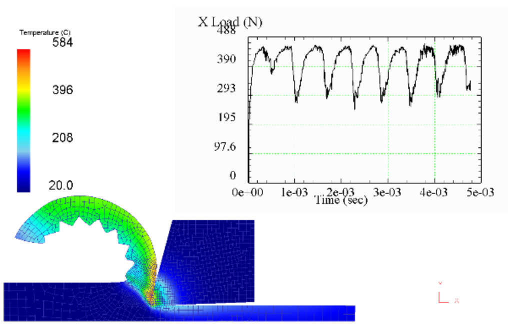

Figure 4. Feed f (0.28/mm)

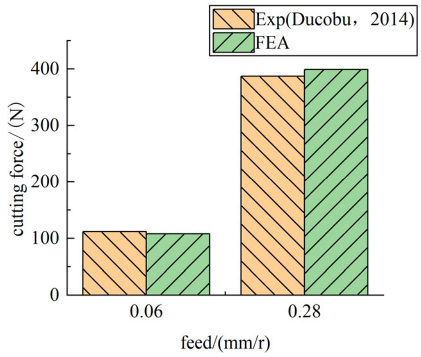

Figure 5. Comparison of test and simulation values for different feeds

Fig.6 and Fig.7 show the trend graphs of cutting forces and temperature cloud graphs corresponding to dry cutting and liquid nitrogen cryogenic cooling under the conditions of 145 m/min cutting speed and 0.096 mm/r feed. From the graphs, it can be seen that liquid nitrogen cryogenic cooling exhibits lower cutting temperatures and the overall range of fluctuation of cutting forces is reduced for the same cutting speed and feed conditions. Figure 8 gives the test data of Jerold [18] et al. In his test, the cutting speed is 145m/min, the feed is 0.096mm/r, the tool material is PCBN tool, the tool is clamped by the ISO PCLNR 2020 K12 cage, and the same parameters are set, the simulation results obtained are shown in Fig. 8, and a comparison of the simulation values and the test values shows that the results are basically the same, liquid nitrogen cryogenic cooling exhibits a lower cutting temperature, and the overall fluctuation range of the cutting force is reduced. The simulation results are shown in Fig. 8, comparing the simulation values with the test values, the results are basically the same, the errors of liquid nitrogen cryogenic cooling and dry cutting are 7.8% and 5%, respectively.

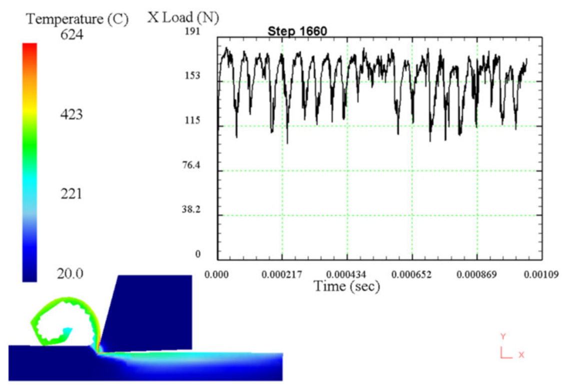

Figure 6. Dry cutting

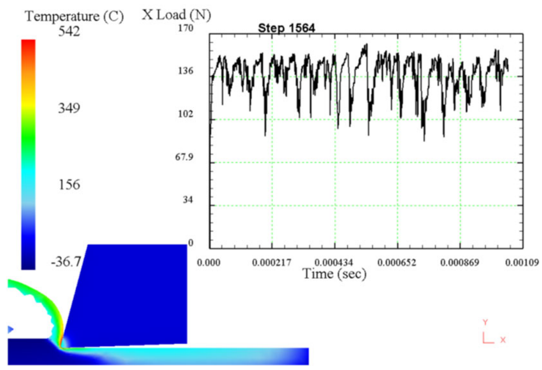

Figure 7. Cryogenic

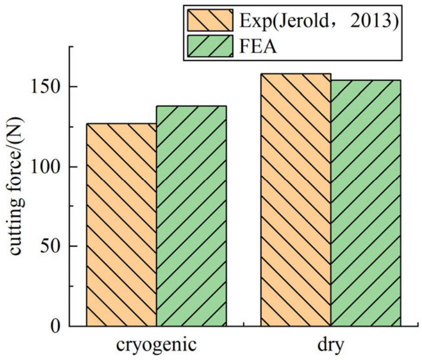

Figure 8. Comparison of experimental and simulated values for different cooling methods

4.2. Cutting force influencing factor analysis

Intercepting the average value of cutting efforts in both directions during the cutting stabilization phase. The cutting combined force is calculated as $F=\sqrt{F_X^2+F_Y^2}$ 。 Fig. 9 and Fig. 10 show the cutting force values for different feeds at 30m/min and 145m/min cutting speeds, respectively, from which it can be found that the feeds affect the cutting force in a regular manner, and that cryogenic cooling with liquid nitrogen has the effect of reducing the cutting force. Comparison of Fig. 9 and Fig. 10 shows that no significant change is observed with the increase in cutting speed.

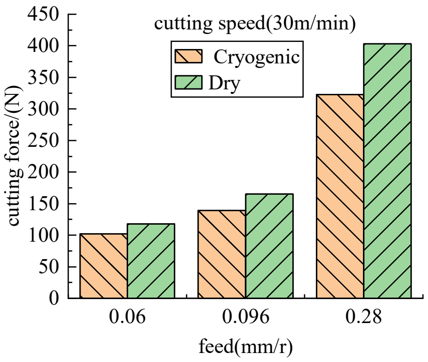

Figure 9. Cutting force at 30m/min cutting speed

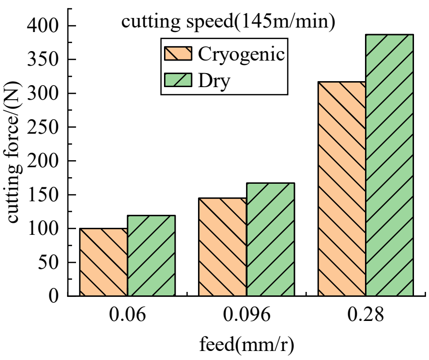

Figure 10. Cutting force at a cutting speed of 145m/min

4.3. Analysis of tool temperature influencing factors

Fig.11 and Fig.12 show the tool temperatures corresponding to different feeds and different cooling methods at 30m/min and 145m/min cutting speeds. As can be seen from the figures, the relationship between the influence of feed and cutting temperature, liquid nitrogen cryogenic cooling has a significant effect on reducing the tool temperature. Comparison of the two graphs shows that the cutting speed has a significant effect on the maximum tool temperature.

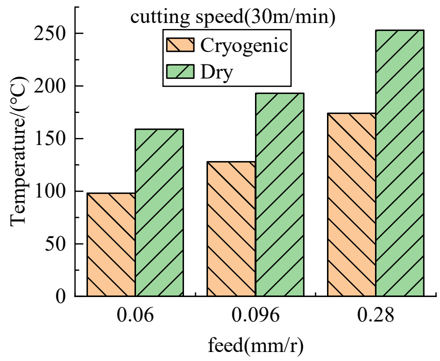

Figure 11. Cutting Temperature at 30m/min Cutting Speed

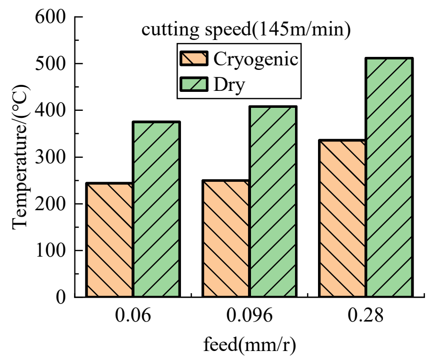

Figure 12. Cutting Temperature at 145m/min Cutting Speed

4.4. Influence of convective heat transfer coefficient on cutting force and tool temperature

The boiling point of liquid nitrogen is -196°C, so the ambient temperature is often set to -196°C when simulating liquid nitrogen cryogenic cooling. Under the effect of liquid nitrogen cryogenic cooling, the friction between the tool-worker and the heat dissipation relationship between the tool-worker model and the environment are changed, and the cooling effect is simulated by setting the friction coefficient, ambient temperature and convective heat transfer coefficient in the simulation model. As can be seen in Fig. 13, the effect of the convective heat transfer coefficient on the cutting force and cutting temperature in the -196°C environment, the cutting force was kept near 130N under three convective heat transfer coefficient gradients, and the tool temperature was about 300°C, and no significant changes were observed.

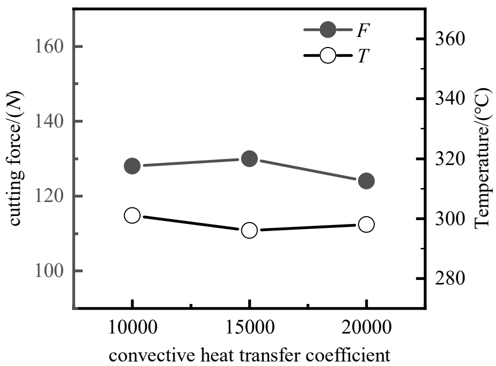

Figure 13. Effect of convective heat transfer coefficient

4.5. Effect of coefficient of friction on cutting forces and tool temperature

As can be seen from Fig. 14, the friction coefficient between the tool and the workpiece has a significant effect on the cutting force and cutting temperature at -196°C, and the smaller the friction coefficient, the better the cooling effect.

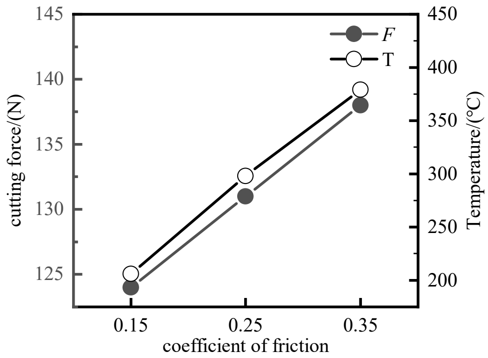

Figure 14. Effect of coefficient of friction

5. Conclusion

DEFORM finite element software was used to establish a Ti6Al4V cutting model based on the plane strain assumption, and the effects of the cutting parameters on the cutting force and the maximum tool temperature were analyzed under the condition of liquid nitrogen cryogenic cooling. The following conclusions were obtained: (1) The two-dimensional cutting model established is accurate and effective, and the error between the simulation value and the test value is within 10%. (2) The feed has a significant effect on cutting force and tool temperature, and the cutting speed has a greater effect on tool temperature and a smaller effect on cutting force. (3) Compared with dry cutting, the cutting force and tool temperature under liquid nitrogen cryogenic cooling machining are lower. (4) Liquid nitrogen cryogenic cooling technology mainly through the reduction of the cutting environment temperature and improve the tool - work friction relationship on the cutting process to have an effect.

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