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Numerical Simulation of Milling Bearing Steel 20CrMnTi Based on Rigid Viscoelastic Variational Principle

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ABSTRACT

Bearing steel 20CrMnTi used in cycloidal gear is a kind of difficult to machine material. Based on the finite element method of rigid viscoplastic, a three-dimensional finite element model that can reflect the actual milling process is established using the finite element software Deform-3D. The milling process of bearing steel 20CrMnTi is simulated. The milling force curve of milling process is obtained and the chip formation process of the milling process is analyzed. The distribution of temperature and stress field of the work piece and the tool is obtained. The effect of milling speed on milling force is researched. The study can provide a theoretical basis for optimization of process parameters in high speed milling bearing steel 20CrMnTi.

Key words: Bearing steel 20CrMnTi, difficult to machine material, milling force, chip shape, numerical simulation

INTRODUCTION

Development of high-quality cycloid reducer has been a hot topic in reducer manufacturing. Cycloid gear is one of the key components of cycloid reducer. At the same time precision machining of cycloid gear is a key technology. Because cycloidal gear material 20CrMnTi is a kind of difficult to machine material, the precision grinder has been used to manufacture cycloid gear in order to ensure accuracy and quality previously. Grinding heat and grinding deformation are relatively large. High-speed milling mechanism of cycloidal gear material 20CrMnTi is studied here in order to provide technical support for milling cycloidal gear. Many scholars have conducted a detailed study of milling. Dong *et al.* (2006) conducted the finite element simulation of milling aluminum alloy. Yang *et al.* (2010) conducted a three-dimensional numerical simulation of cutting force of milling titanium alloy Ti_6Al_4V. Cheng *et al.* (2012) conducted the simulation of milling process with ball end mill based on the software deform 3D. Lu *et al.* (2008) conducted the finite element simulation of milling aerospace aluminum 7075-T7451 using finite element analysis software. Qi *et al.* (2010) conducted the finite element simulation of milling force in the process of high speed milling cycloid. Qi *et al.* (2009) proposed a method of predicting the milling force in side milling cycloid. Tsai and Liao (1999) predicted the milling deformation of the workpiece using the finite element method. A previous study simulated the milling force in the milling process and predicted the distribution of stress and temperature. Wang *et al.* (2014) established a realistic finite element model of milling the material Ti_6Al_4V and conducted the simulation of chip formation process successful. They analyzed the stress and temperature field of workpiece according to stress and temperature contours. The milling process with three-blade cutter was simulated in the study (Li *et al*., 2014). The relationship between milling stress and its process parameters was obtained in order to analyze cutter breakage. Wu *et al*. (2014) conducted the milling tests of carbon fiber composites and studied the variation of milling force. They conducted the regression analysis for the test data of milling force and finally established empirical formula of milling force. Chen *et al*. (2014) constructed the flow stress constitutive model suitable for describing the process of milling 7055 aluminum by tests and established the numerical simulation model with a single tooth using the finite element software deform 3D. The milling force and milling temperature during milling aluminum alloy 7055 was obtained and the impacts of milling speed, feed rate and milling depth on the milling force and milling temperature were analyzed. Bai *et al*. (2014) established the three-dimensional milling models using commercial finite element software ABAQUS in order to study the milling force distribution during thin-walled milling process and obtained the milling force, milling stress and strain distribution. Matsumura *et al*. (2013) presented a force model for milling with cutter axis inclination. The model can predict the chip flow direction and cutting force. Three-dimensional chip flow was explained as a piling up of the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities in the inclined coordinate system with a ball end mill. Tuysuz *et al*. (2013) presented an improved axial cutting force model for 5-axis ball-end milling and proposed a new analytical indentation force model. They studied the effect of tool inclination on chip thickness.

In this study, three-dimensional finite element simulation of milling cycloidal gear material 20CrMnTi is conducted using the finite element software deform-3D. The milling force, chip formation process and the milling temperature in milling process were studied to provide a theoretical basis for the optimization of the milling process parameters.

MATHEMATICAL MODEL FOR FINITE ELEMENT SIMULATION OF MILLING

Finite element variational formula of rigid viscoplastic: The finite element method based on rigid viscoplastic is a finite element method based on variational principle. The basic principle includes the principle of virtual work equivalent integral form and Markov variational principle (Lin and Lin, 1999). Principle of virtual work includes the virtual displacement principle and the principle of virtual stress. The sum of virtual work of external forces and internal forces is equal to zero.Virtual work equation is an important tool of establishing finite element method in the process of plastic machining. The equation of virtual work principle is as follows:

$$\int_V -\delta\dot{\varepsilon}_{ij}\sigma_{ij}dV + \int_V \delta\upsilon_i p_i dV + \int_{S_t} \delta\upsilon_i p_i dS = 0 \quad (1)$$

where, $\delta\dot{\varepsilon}_{ij}$ is incremental strain rate tensor, σ_{ij} is the stress tensor, v is deformable body volume, δv_I is velocity increment, p_i is force, S is force plane, S_t is stress surface.

Variational method is the tool of discussing the functional extremum. Variational method provides a mathematical basis for the finite element method, it is a powerful tool for solving boundary value problems. Markov variational principle is described as the minimum value of the following function in the velocity field that can meet the dynamic condition and speed allowed condition:

$$\Pi = \int_v \bar{\sigma}\dot{\bar{\varepsilon}}dV - \int_{s_p} p\upsilon dS + \int_{s_v} \tau_f \Delta\upsilon dS \quad (2)$$

where, $\bar{\sigma}$ is the equivalent stress, S_p is the surface of force boundary, τ_f is a frictional force between the work piece and the tool border, Δv is the relative sliding velocity between work piece boundary and tool, S_v is the volume surface of role, p is role stress, $\bar{\varepsilon}$ is equivalent strain rate and v is speed. Volume in compressible condition is introduced using Lagrange multipliers. The first order variational of the functional is as follows:

$$\delta \Pi = \int_v \bar{\sigma} \delta \dot{\bar{\varepsilon}} dV + K \int_V \dot{\varepsilon} \delta \dot{\varepsilon} dV - \int_{sp} p \delta \upsilon dS + \int_{S_D} \tau_f \Delta \upsilon dS \tag{3}$$

where, $\delta\bar{\varepsilon}$ is the increment of equivalent strain rate, ε is strain rate, δv is velocity increment, $\delta\epsilon$ is strain rate increment, S_D is velocity discontinuities, K is penalty factor, usually take 105-107.

Thermal coupling model: In the process of metal cutting, the plastic deformation energy of workpiece is mostly transformed into heat. Therefore, the problem of heat transfer in metal cutting process belongs to non steady state heat conduction problem with inner heat source. The inner heat source is transformed from a plastic deformation energy of the workpiece. Coupling energy in metal milling process can be expressed as follows (Sasahara *et al.*, 1996):

$$\dot{E} = \dot{\sigma}_{ij} \varepsilon_{ij} + q_{ij} + \omega i \tag{4}$$

where, ε_{ij} is strain rate tensor, q_{ij} is heat flux deformable body heat exchange with the outside world, ω_i is heat flux of heat sources in deformation body.

Milling friction formula: Shen *et al.* (2005) stated that friction between the tool rake face and chip underside is generated when the tool enters the workpiece and the chip separates from the workpiece. The friction zone is divided into two regions. They are stick area and slip zone. In Deform-3D, the friction model available is Coulomb Friction Model and Shear Friction Model. The coefficient of friction can be defined as a constant or a function of the contact surface pressure:

$$\frac{\tau_t}{\tau_e} = 1 - \exp\left(-\lambda \frac{\sigma_t}{\tau_e}\right) \tag{5}$$

where, σ_t and τ_t are normal stress and shear stress of contact surface between work piece and tool, λ is material constants, τ_e is shear yield stress of cutting material.

Chip separation criterion: Cutting is a continuous process of producing chip separation. A separate guideline must truly reflect the mechanical and physical properties of the cutting material. In the finite element simulations, all kinds of chip separation criteria have been proposed. These criteria can be divided into two types: Geometric criteria and physical criteria. Geometric physical chip separation criteria based on fracture mechanics is used in the software Deform (Yang *et al.*, 2006).

$$f = \sqrt{(\sigma_n / \sigma_f)^2 + (\tau_n / \tau_f)^2} \tag{6}$$

where, f is the fracture stress index, σ_n and τ_n are normal stress and shear stress before tip, respectively; σ_f and τ_f are failure stress of work piece material under the load of pure tension and shear, respectively.

MATERIALS AND METHODS

Establishment of workpiece material constitutive model is the key technology of three-dimensional finite element simulation of milling. The workpiece material is bearing steel 20CrMnTi. The flow stress is affected by temperature, strain and strain rate. Construction of material constitutive model that can accurately eflect the high temperature, high strain and high strain rate of the cutting process is the key to simulation analysis. The material constitutive equations established according to power hardening law are as follows.

When:

$$\dot{\varepsilon}^p \le \dot{\varepsilon}_t$$

there is following equation:

$$(1+\dot{\varepsilon}^p/\dot{\varepsilon}_0^p) = (\sigma/(g(\varepsilon^p)))^{m_1} \tag{7}$$

When:

$$\dot{\varepsilon}^p > \dot{\varepsilon}_t$$

there is following equation:

$$(1+\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0^p})(1+\frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_0^p})^{\frac{m_1}{m_2}-1} = (\frac{\sigma}{g(\varepsilon^p)})^{m_2} \tag{8}$$

where, σ is Mises equivalent stress, ε^p is Cumulative plastic strain, $\dot{\varepsilon}^p$, is cumulative plastic strain rate, $\dot{\varepsilon}_0^p$ is plastic strain rate as a benchmark; m_1 is low strain rate sensitivity index, m_2 is high strain rate sensitivity index, cut-off point for the plastic strain rate, $\dot{\varepsilon}^p$ is calculated according to the Eq. 1 and 2. Softening temperature equation is as follows:

$$g = [1-\alpha(T-T_0)]\sigma_0(1+\frac{\varepsilon^p}{\varepsilon_0^p})^{\frac{1}{n}} \tag{9}$$

where, n is the hardening exponent; T is the surface temperature of the material; T_0 is the reference temperature; α is softening coefficient; σ_0 is yield stress of reference temperature T_0.

Physical model of finite element simulation: Deform-3D software is a finite element software based on process simulation system. It is used to analyze the three-dimensional flow in various metal forming process in order to provide valuable process analysis data. The software has a

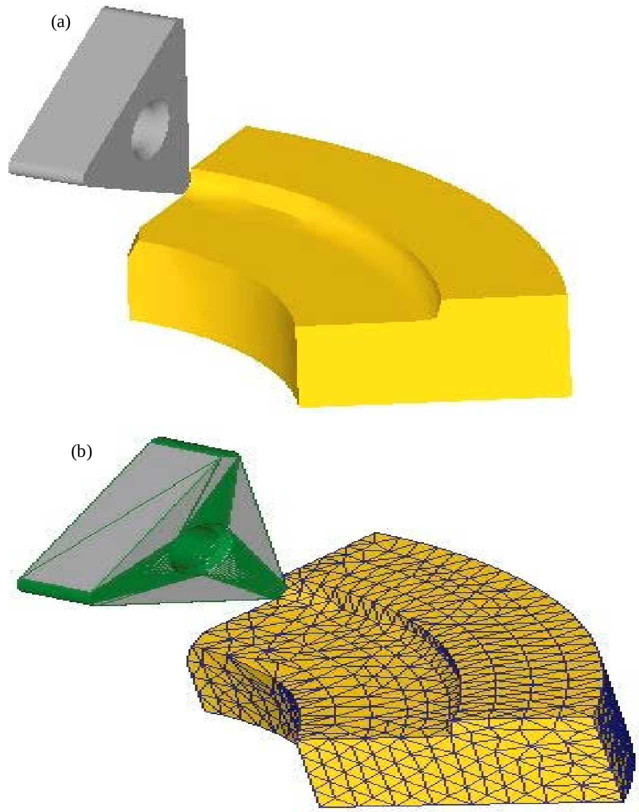

Fig. 1(a-b): (a) Geometry model and (b) Finite element model of metal milling

powerful nonlinear solution capability. It is suitable for strongly nonlinear case of metal cutting spatial and temporal domain. The three-dimensional finite element simulation of milling cycloidal gear material 20CrMnTi is conducted and the material is set to the plastic body. Tool material is tungsten carbide and it is set to the rigid body. Ambient temperature and the initial temperature was set to 20°C. Adaptive meshing technique is applied by the software Deform. The grid number of tool and work piece is 2000, respectively. The geometry model and finite element model of metal milling are shown in Fig. 1a and b, respectively.

RESULTS

Three-dimensional simulation results and analysis

Chip formation process: In the process of milling metal, the work piece material is divided into two parts by milling cutter. Part of the material is turned into cutting chips, another part of the material is subjected to extrusion and friction of milling cutter. The chip formation process with the milling speed of 110 m min^{-1}, milling depth of 1.8 mm and the feed rate of 1.2 mm r^{-1} is shown in Fig. 2. Figure 2 shows, in the milling process, curled chip is gradually formed. The chip and the workpiece are close to separation at the calculation of step 605. Chip formation process is deformation process of cutting metal. The cutting chip is separated from the work piece under the action of the tool. As can be seen from the Fig. 2 that the mesh density of workpiece becomes large with the movement position of the tool. The software Deform has the function of adaptive meshing. Continuous chip with curl shape is gradually formed in the process of milling.

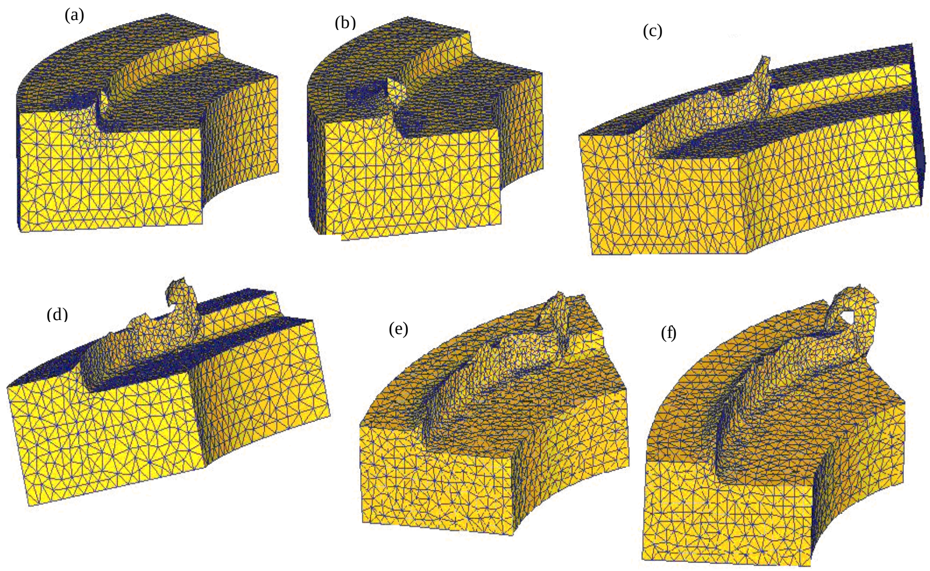

Fig. 2(a-f): Formation of the cutting chip in the process of milling 5.2 in step (a) 100, (b) 200, (c) 300, (d) 400, (e) 500 and (f) 605

Distribution of milling mises stress: Metal cutting process has three deformation zones:the first deformation zone where the cutting chip is formed; the second deformation zone where the friction of chip and the rake face is produced; the third deformation zone where the flank contacts with the newly formed surface. Figure 3 shows the equivalent stress contours of cutting chip in the milling process. As can be seen from the Fig. 3 that the maximum stress zone of workpiece and chips is located near the cutting edge. The maximum stress of the region reaches 1700 MPa. The equivalent stress that is far away from the cutting edge region decreases faster.

Variation of milling force: The cutting force curve in X, Y and Z direction with milling time in milling process is shown in Fig. 4a-c, respectively. Cutting force is divided into the main cutting force (tangential force), radial force and feed force (axial force). Figure 4 shows that the radial force is greater than main cutting force and feed force. The maximum cutting force of the direction X, Y and Z is, respectively 9100, 18720 and 17550 N. Fluctuations of the main cutting force is relatively large. In the milling process, the variety of milling thickness leads to the dramatic changes in the main cutting force. The variation curve of radial force and feed resistance force can be divided into the initial stage and the stable stage of milling. As can be seen from the Fig. 4 that the cutting force is gradually increased from zero and then fluctuates within a steady range. Because the plastic deformation of the material becomes large and the the friction increases in the initial cutting process, cutting force also increases. Cutting force is relatively stable in the steady-state of cutting process because the contact length of the cutting chip does not change when the chip has been produced. The old units are removed and the new units continue to enter the calculation with the removing of cutting chip. Cutting force fluctuations are caused by the difference of unit. The fluctuations of cutting force are smaller when the grid number of simulation model is increased.

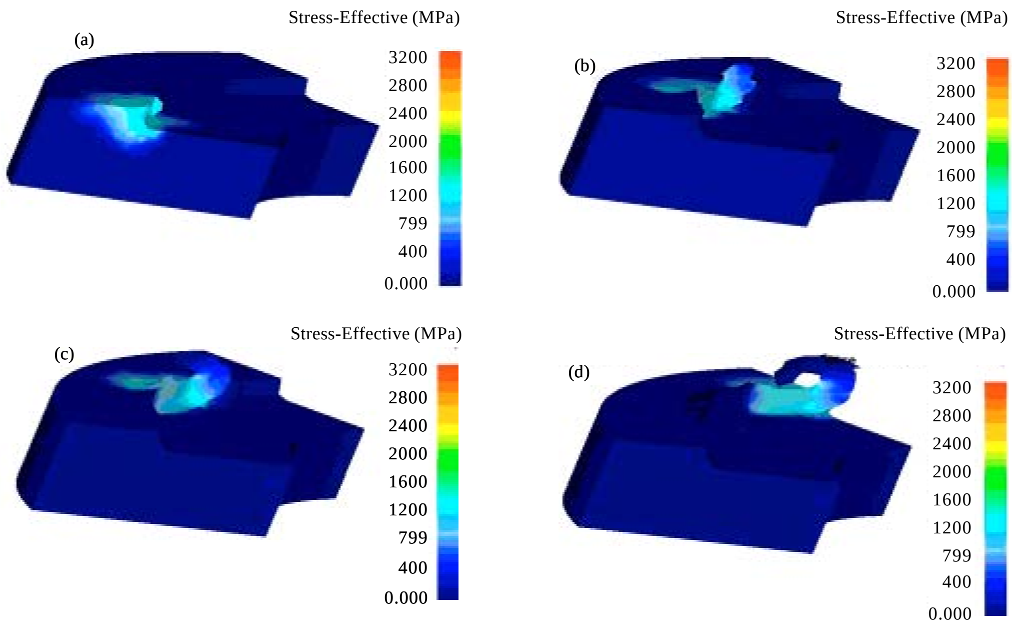

Fig. 3(a-d): Equivalent stress contours of cutting chip in the milling process at step (a) 100, (b) 300, (c) 400 and (d) 605

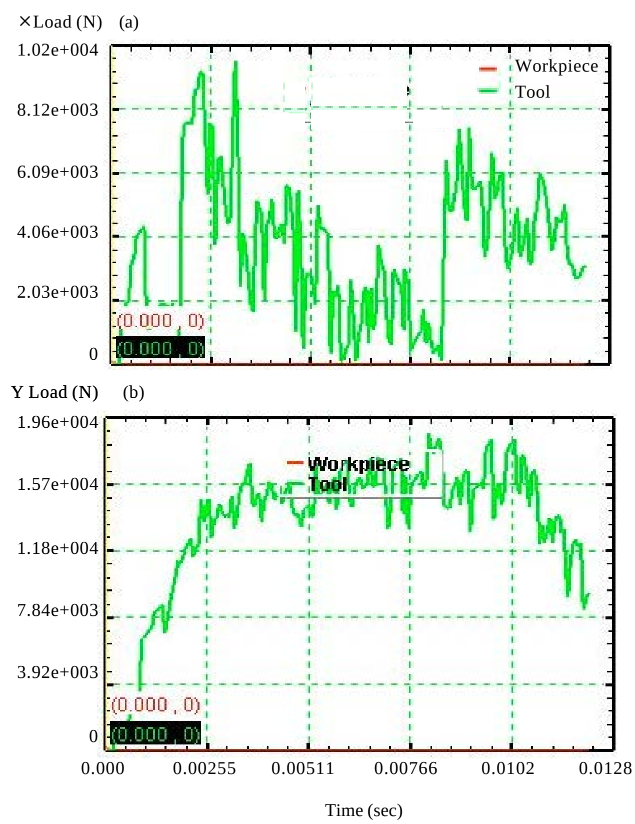

Fig. 4(a-c): Continue

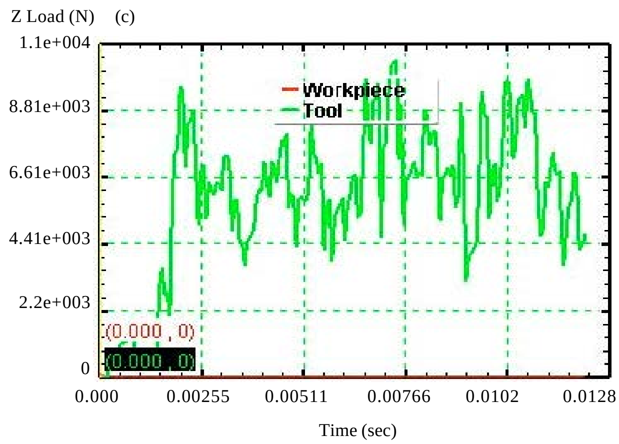

Fig. 4(a-c): Variation curve of milling force in the (a) X, (b) Y and (c) Z direction

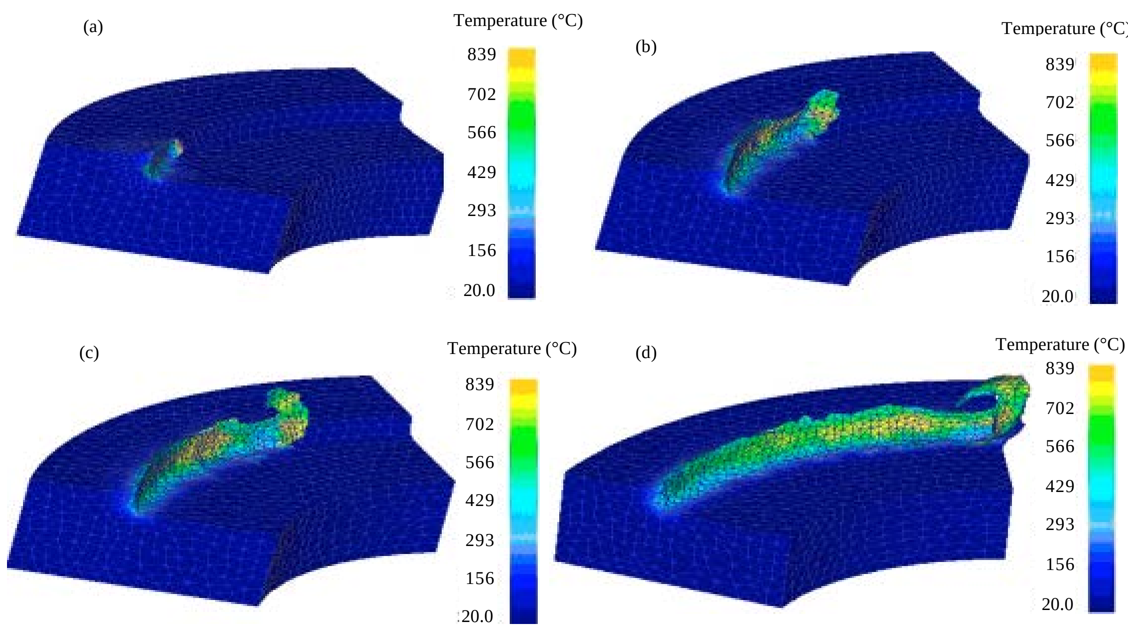

Fig. 5(a-d): Distribution of cutting chip temperature in step (a) 100, (b) 300, (c) 400 and (d) 605

Distribution of temperature field of milling: In the milling process, most mechanical energy is transformed into heat energy. In the chip formation process, the heat generated by plastic deformation in the first deformation zone accounts for 80%. Heat generated in tool-chip contact area accounts for 20%. Approximately 75% of the heat is taken away by the cutting chip. The temperature field contours of cutting chip in milling process are shown in Fig. 5. Figure 5 shows that the temperature of the cutting chip is large and the the maximum temperature of cutting chip reaches 1180°C. The high-temperature region of cutting chip is mainly concentrated in contact site of cutting edge and chip because in this area the friction between the tool and the chip is relatively large and much heat is generated. At the same time, plastic deformation of metal near the cutting roots generates a lot of heat.

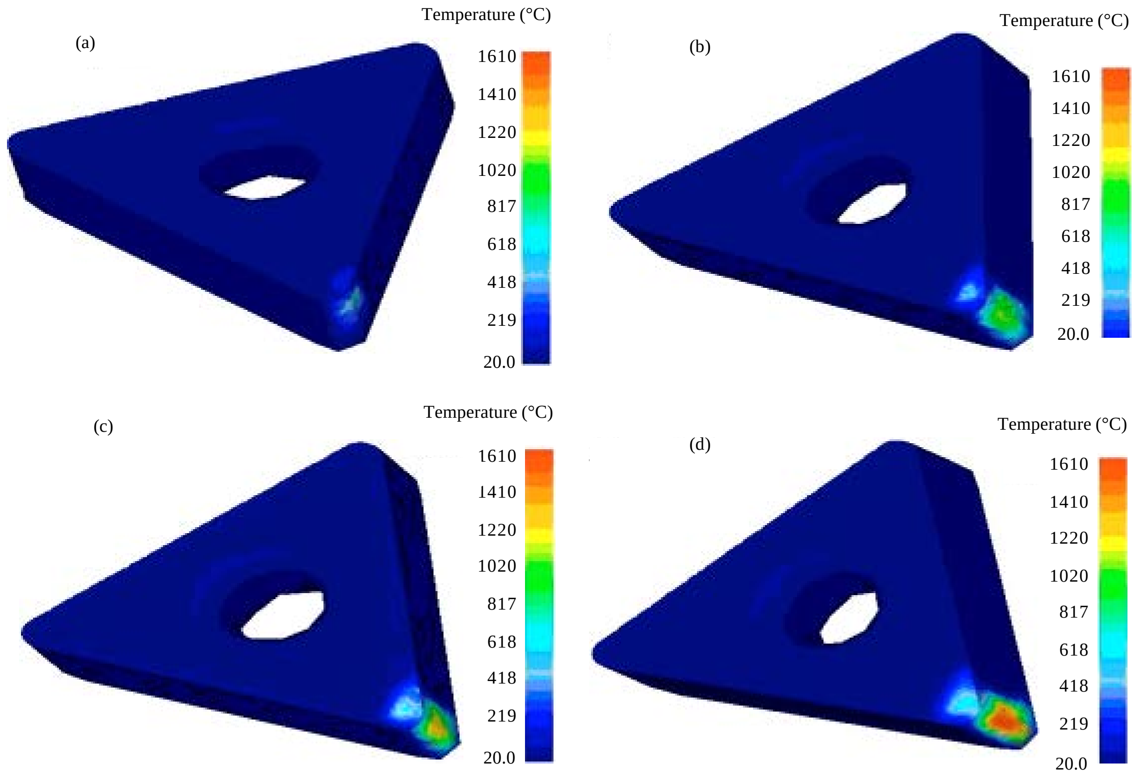

Fig. 6(a-d): Temperature field contours of tool in step (a) 100, (b) 300, (c) 400 and (d) 605

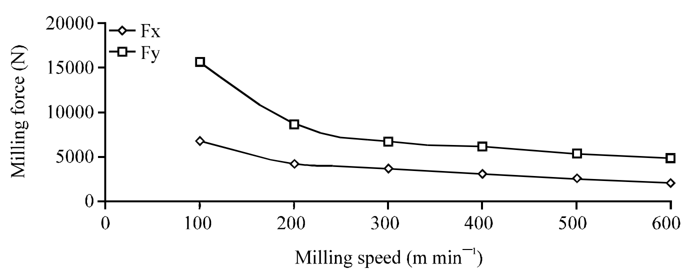

Fig. 7: Impact curve of milling speed on milling force

The temperature distribution of tool is shown in Fig. 6. Figure 6 shows that the maximum temperature of the tool is located in the contact area of the tool flank and transition surface. The region is the relatively concentrated area that has the plastic deformation and knife-crumb friction. The tool temperature is higher than that of the workpiece and the cutting chip.

Impact of milling speed on milling force: Impact of milling speed on milling force is researched. The feed rate is set to 1.8 mm h^{-1} and the milling depth is set to 1.2 mm. Figure 7 shows the impact curve of milling speed on milling force. Tangential and radial forces of milling are all gradually decrease with the increase of the cutting speed. This is because with the increase of milling speed, the milling temperature is gradually increased and built-up edge gradually disappear. When the milling speed is from 100-200 m min^{-1}, the decrease of the milling force is relatively large. The contact deformation zone temperature of tool crumbs increase with the increase of milling speed in the milling process. The friction force between the blade and crumbs decreases because of the decrease of sliding friction coefficient.

DISCUSSION

The simulation results obtained in this study the chip is curled shape. The findings of this study is consistent with the literature "Finite element simulation and analysis of aluminum alloy three-dimensional milling" (Dong *et al.*, 2006). But the material bearing steel 20CrMnTi is a kind of materials that is difficult to machine, so the chip did not form a plurality of helical. This is because the hardness of bearing steel 20CrMnTi is bigger than that of aluminum alloy. In this study, the milling force and milling temperatures were bigger than the findings of the literature "3D Milling Process Simulation of Aero-aluminum Alloy 7075-T7451". This is because this study did not fully consider the effect of cooling fluid. The milling force variation of this simulation is consistent with the test results of the literature "Three Dimensional Numerical Simulation of Cutting Force During Milling of Titanium Alloy Ti6Al4V". The difference lies in the greater volatility of milling force in this article. This is due to the grid number of finite element model is less than normal. Influences of milling speed on milling force in this paper are consistent with the research results of the literature "The Simulation Analysis for the Milling Process of Ball End Mill Using the Deform 3D". The finite element simulation result is scientific and rational by comparison though the numerical simulation results are not verified by experiments.

CONCLUSION

- The thermal coupling model of milling material 20CrMnTi used in cycloidal gear is established based on rigid viscoplastic finite element theory. Three-dimensional numerical simulation of milling bearing steel 20CrMnTi is conducted using the finite element method based on rigid viscoelastic variational principle. The milling force curve of single tooth milling process is obtained. In the initial milling stage, the milling force in three directions increases dramatically. With the advance of milling, the milling force is gradually in steady state
- The temperature distribution of tool, the work piece and the chip in the milling process is analyzed. The tool temperature is higher than that of the work piece. Chip temperature is greater than that of the work piece and it shows that the chip takes away most of the milling heat in the milling process. High-temperature region is mainly concentrated in the contact area of the chip and the cutting edge, the maximum temperature is 839°C
- In the milling process, the radial milling force F_y is greater than the tangential milling force F_x. The milling force decreases with the increase of the milling speed. The decrease of milling force is relatively large when the milling speed is from 100-200 m min^{-1}
- The finite element numerical simulation can provide a theoretical basis for optimization of process parameters in millling material 20CrMnTi. In future studies, milling tests should be conducted on a cnc milling machine to validate and improve the accuracy of the finite element model. The milling parameters, tool geometry and size will be optimized based on the the finite element model

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