High-speed dry hobbing geometry parameterization and hobbing simulation

Shufeng Jiang[*a,b], Hezeng Tang[a]
[a]School of Mechanical and Electrical Engineering, Qiqihar University, Qiqihar 161006, Heilongjiang, China; [b]The Engineering Technology Research Center for Precision Manufacturing Equipmentand Industrial Perception of Heilongjiang Province, Qiqihar 161006, Heilongjiang, China

ABSTRACT

In order to explore the cutting force, cutting temperature and cutting parameters and other key factors in the high-speed dry hobbing process between the influence of the relationship and change rule. In this paper, based on the principle of hobbing combined with cutting mechanics and heat transfer theory, the cutting force and cutting temperature during high-speed dry hobbing are modeled, and the relationship between the average cutting force and the feed, cutting speed and back-eating amount is derived from the results of finite-element simulation, and the parametric equations of the tangential force and the radial force empirically are derived from the coordinate transformation and input empirical values, and the empirical parametric regression equations of the axial force are derived, respectively. The method of calculating cutting force and cutting temperature under high-speed dry hobbing conditions is derived, respectively. This research provides a theoretical basis and experimental basis for further exploring the intrinsic mechanism of high-speed dry hobbing, including cutting force, cutting temperature and machining dynamics, etc., so that the traditional hobbing cutting method can be developed in the direction of more energy-saving, high-efficiency and precision.

Keywords: Cutting parameters, cutting force, cutting temperature, high speed dry hobbing

1. INTRODUCTION

In the competitive environment of globalization of equipment manufacturing production, manufacturing enterprises need to have the ability to respond quickly to market demand and provide superior performance, reasonable price, and timely delivery of products, which will promote the manufacturing and processing of a variety of spare parts technology toward a faster, more energy efficient, higher quality, more precise direction. Among them, hobbing technology, as an efficient gear-cutting process, is widely used in the manufacturing industry to produce high-quality straight and helical external gears[1]. Hobbing actual processing conditions is complex, in the actual production before the sample processing and then do the physical properties of the experiment, and then compare and optimize the design of the high cost. Therefore, modeling and machining simulation based on physical properties becomes a crucial tool. Virtual experiments conducted after modeling can reduce the number of actual tests and enable accurate process simulation, analysis and optimization, thus reducing development and production costs and helping to meet the challenges of higher productivity as well as part quality.

Gears are important basic transmission parts in the traditional manufacturing industry, assuming important functions. Therefore, this leads to the gear processing industry on the precision of the product, as well as product productivity, quality and environmental protection aspects of the control more stringent. Gear processing is divided into wet processing and dry processing different processing technologies, as one of the advanced manufacturing technologies of recent years of rapid development, high-speed dry hobbing technology has a higher efficiency and higher precision, this technology will play an important role in the field of gear processing[2].

Because keeping the tool and workpiece cool reduces mutual wear during cutting friction contact, uneven cooling and different cutting conditions on the gear meshing and disengaging sides can cause strong wear on the teeth of the worm gear hob, which reduces the life of the worm gear hob and increases tool consumption. Cutting fluids are widely used as coolants in hobbing and help flush chips away from the work area. Cutting fluids are generally expensive mineral and synthetic oils being applied, but oil evaporation is environmentally hazardous due to chlorine, heavy metals and aromatic hydrocarbons in their vapors. In addition, coolant disposal costs have risen recently, and in some cases, it can account for

[*]474118867@qq.com

International Conference on Optics, Electronics, and Communication Engineering (OECE 2024), edited by Yang Yue, Proc. of SPIE Vol. 13395, 133952T · © 2024 SPIE · 0277-786X · Published under a Creative Commons Attribution CC-BY 3.0 License · doi: 10.1117/12.3049803

15-20% of the cost. Against this background, some companies manufacturing cylindrical gears are considering dry hobbing. The development of this technology offers new solutions for the gear processing industry and helps to meet the market's increasing demand for precision and productivity in gear manufacturing[3].

In dry hobbing cutting simulation, the study of cutting temperature and cutting force has multiple important roles and significance[4]. First, by simulating the cutting temperature and cutting force, machining parameters such as cutting speed, feed rate, and depth of cut can be optimized to achieve the best machining efficiency and machining quality[5]. Second, accurate cutting force and temperature simulation can effectively reduce energy consumption and tool wear during machining, reducing overall machining costs. Once again, the simulation of cutting temperatures and forces helps to predict thermal deformation and surface quality problems that may occur during machining, allowing engineers to take appropriate measures to improve the machining quality of the final product. Simulation can also identify potential machining problems and risks, reduce the probability of accidents and improve machining safety.

2. MODEL OF CUTTING FORCES AND CUTTING TEMPERATURES

When machining gears with a hob, three basic unit motions are usually involved. The first is the rotary cutting motion of the tool, which is achieved by the rotation of the tool itself to realize the cutting process. Secondly, there is the rotary motion between the workpiece and the hob, i.e. the parting motion, which rotates relative to each other at an angle. Finally, the tool feeds in a direction parallel to the workpiece axis. Through the coordination of these three motions, the hob can efficiently complete the gear machining process[6].

When the tool comes into contact with the workpiece during the cutting process, a certain cutting force is generated. This cutting force includes radial and tangential forces, depending on parameters such as material properties, cutting speed, feed and depth of cut. In terms of process improvement, cutting parameters can be optimized to reduce the size and variation of the cutting force, thereby reducing the load on the machine tool and cutting tool and improving productivity. The friction between the tool and the workpiece causes localized heating, which leads to an increase in cutting temperature, and the high temperature for a long time will cause problems such as deformation of the tool surface, and severe wear and cracks on the workpiece surface. By simulating the machining process, the best combination of process parameters can be found to improve machining efficiency and product quality.

2.1 Coordinate transformation and cutting force calculation models

First, a gear coordinate system connected by $\sigma d=[Od: Xd, Yd, Zd]$ is established, as shown in Figure 1, which is a schematic diagram of the relative coordinates of the hob and gear.

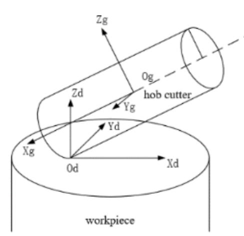


Figure 1. Schematic diagram of the relative coordinates of the hobs and gears.

The coordinates of the workpiece and tool can be transformed as follows:

$$\begin{bmatrix} Xd \\ Yd \\ Zd \\ 1 \end{bmatrix} = \begin{bmatrix} -\cos\Sigma & 0 & -\sin\Sigma & 0 \\ 0 & -1 & 0 & a \\ -\sin\Sigma & 0 & \cos\Sigma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Xd \\ Yd \\ Zd \\ 1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} Xg \\ Yg \\ Zg \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & f(Zk) \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Xg \\ Yg \\ Zg \\ 1 \end{bmatrix} \tag{2}$$

Combined with the cut-off theory, the cut-off shear force Fs can be set as[7]:

$$F_s = \tau_s \cdot \frac{S_n}{\sin\phi} \tag{3}$$

The tangential force Ft and radial force Fn can be expressed as:

$$\begin{cases} F_t = F_r\cos(\beta-\gamma) = \dfrac{\tau_s f_z(\cos\theta - a_{sp}\sin\theta)\cdot(a_{sp}\cos\theta + f_z\sin\theta)\cdot\cos(\beta-\lambda)}{\sin\phi\cos(\phi+\beta-\gamma)} \\ F_n = F_r\sin(\beta-\gamma) = \dfrac{\tau_s f_z(\cos\theta - a_{sp}\sin\theta)\cdot(a_{sp}\cos\theta + f_z\sin\theta)\cdot\sin(\beta-\lambda)}{\sin\phi\cos(\phi+\beta-\gamma)} \end{cases} \tag{4}$$

$$\begin{cases} a_{sp} = Ym\cos\theta - Zm\sin\theta \\ f_z = Zm\sin\theta + Xm\cos\theta \end{cases} \tag{5}$$

The cutting force of a hob can be calculated by calculating the cutting area of a single tooth and adding up the cutting forces of the teeth involved in cutting at the same time.

2.2 Cutting temperature calculation model

The process of hobbing a gear can be viewed as a meshing motion between worm gears. In order to effectively cut the workpiece, the hob also needs to carry out the traveling motion. Therefore, hobbing is actually a complex spatial three-dimensional meshing motion process. The coordination and cooperation of this three-dimensional motion is the key to ensuring high-precision machining of gears. In order to study this process in depth, a hob is cutting a tooth as the object of study, the hob cutting temperature simplified model is shown in Figure 2. The model will help to analyze the hobbing cutting process temperature distribution of influencing factors and its changing law, so as to improve machining accuracy to provide theoretical support.

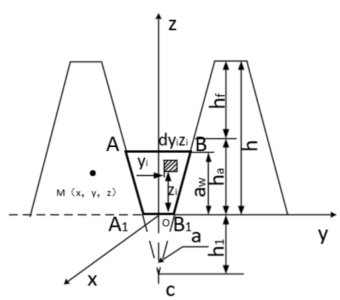


Figure 2. Simplified model of hobbing cutting temperature.

Assuming that the heat loss through the boundary is negligible, we take a distance *y*-axis is z_i, z-axis is y_i microelement $dy_i dz_i$ in the trapezoidal surface heat source, according to the instantaneous cutting temperature field calculation model of the surface heat source method, then the finite and large trapezoidal surface heat source which generates heat as Q_t has the following temperatures for the hob teeth of any point $M(x, y, z)$ at any time t:

$$dT = \frac{Q_t}{c\rho(4\pi at)^{3/2}}\exp\left[-\frac{x^2 + (y-y_i)^2 + (z-z_i)^2}{4at}\right] \tag{6}$$

Integrating equation (6) yields:

$$T_{\Delta ABC} = \frac{Q_t}{c\rho(4\pi at)^{3/2}}\exp\left[-\frac{x^2}{4at}\right]\int_{-\frac{1}{2}AB}^{\frac{1}{2}AB}\int_{ctg(a)y_i - h_1}^{a_w}\exp\left[-\frac{(y-y_i)^2 + (z-z_i)^2}{4at}\right]dy_i dz_i \tag{7}$$

$$T_{\Delta A_1B_1C} = \frac{Q_t}{c\rho(4\pi at)^{3/2}}\exp\left[-\frac{x^2}{4at}\right]\int_{-\frac{1}{2}A_1B_1}^{\frac{1}{2}A_1B_1}\int_{ctg(a)y_i-h_1}^{0}\exp\left[-\frac{(y-y_i)^2+(z-z_i)^2}{4at}\right]dy_i dz_i \tag{8}$$

Then the temperature of the trapezoidal surface heat source on the hob tooth for any point $M(x, y, z)$ is:

$$T = T_{\Delta ABC} - T_{\Delta A_1B_1C} \tag{9}$$

where, Q_t—Heat generation from surface heat sources, cal; ρ—Density of hobbing media material, $\mathrm{g/cm^3}$; c—Specific heat capacity of the hobbing media material, $\mathrm{cal/g\cdot ℃}$; a—Thermal conductivity of the hobbing media material, cm^2/s.

3. FINITE ELEMENT SIMULATION OF HIGH SPEED DRY HOBBING CUTTING FORCE AND CUTTING TEMPERATURE

The cutting model realizes the transition from process description to prediction development and from static prediction to dynamic prediction through the interrelationships of physical parameters such as cutting deformation, stress, temperature, and strain rate. With the development of computer technology, numerical simulation methods have emerged, of which the finite element method is the most widely used. It analyzes elastoplastic deformation, temperature-dependent material property parameters and strain rate problems. The finite element method simulation of metal cutting takes into account factors such as workpiece material, tool geometry parameters, and cutting dosage. Physical simulation can therefore be used to study the stress, strain and temperature distribution between chips, tools and workpieces, thus speeding up process design and improving the reliability of the design of machine tools, cutting tools and fixture systems[8].

3.1 Setting and modeling of geometric parameters of high-speed dry hobbing cutter

Based on the principle of hobbing and hobbing actual working conditions for digital simulation requirements, and combined with the specific geometric parameters shown in Table 1, designed in SOLIDWORKS hob model shown in Figure 3. Subsequently, the hob model was meshed in Abaqus software to generate the mesh shown in Figure 4.

Table 1. Hob geometry parameters.

Hob diameter	Headcount	Number of grooves	Coating material	Anterior horn	Back angle	Pressure angle
240 mm	1	10	TiAIN	5°	15°	30°

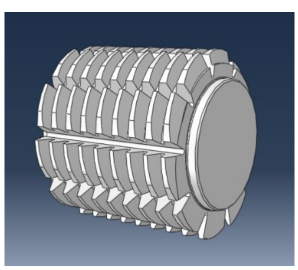


Figure 3. Hob solid mode.

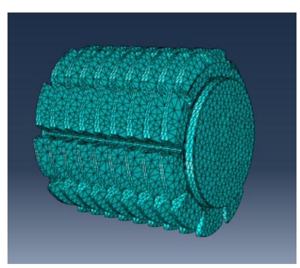


Figure 4. Mesh diagram of the hob.

3.2 One-way simulation test and result analysis

In order to obtain the law of influence of cutting speed, feed and back draft on cutting force as well as cutting temperature, a one-factor test program will be used. Analyze the pattern of influence of each experimental variable on cutting force and cutting temperature. The simulation experiments were arranged with 3 variables and 3 levels for each variable, totaling 9 groups of experiments[9]. The parameters of the simulation experiment are shown in Table 2.

Table 2. Simulation test parameter design.

	Cutting speed (m/min)	Feed (mm/r)	Back draft (mm)
1	200	1	0.2
2	200	2	0.4
3	200	3	0.6
4	250	1	0.4
5	250	2	0.6
6	250	3	0.2
7	300	1	0.6
8	300	2	0.2
9	300	3	0.4

Each test scenario was brought into Abaqus finite element numerical simulation software to simulate the tool-workpiece machining to obtain the cutting forces under different cutting parameters, and in addition to the cutting force data, the average cutting temperature data of the hob face was also obtained. According to the orthogonal scheme to simulate the cutting temperature field under nine sets of cutting conditions, the average cutting temperature regression equation of hobbing was solved by finite element simulation based on the regression of the average cutting temperature of the front blade surface. As shown in Figure 5, when $v = 300m/\min, a_p = 1mm$ is the stress cloud and temperature cloud obtained after Abaqus simulation.

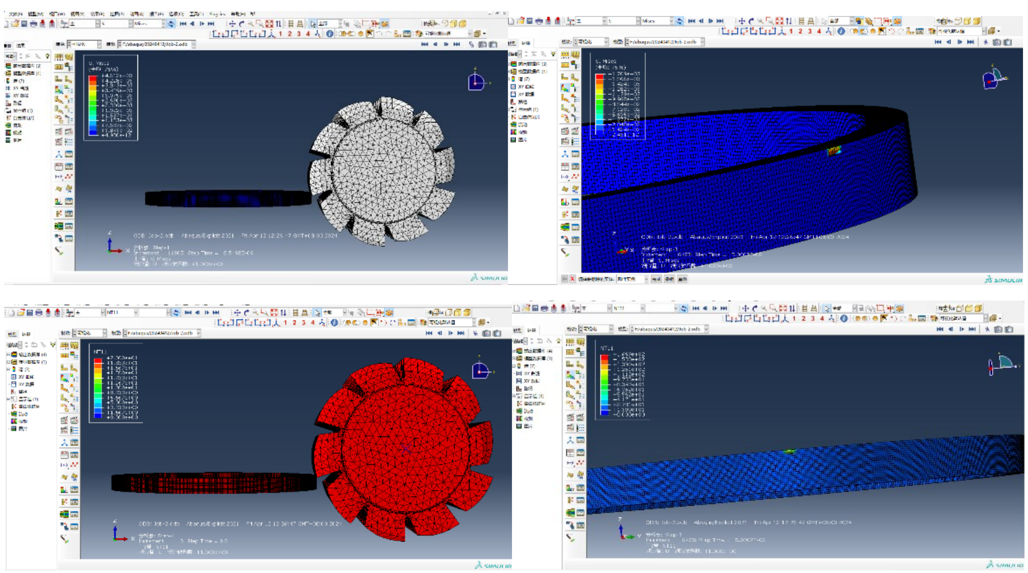
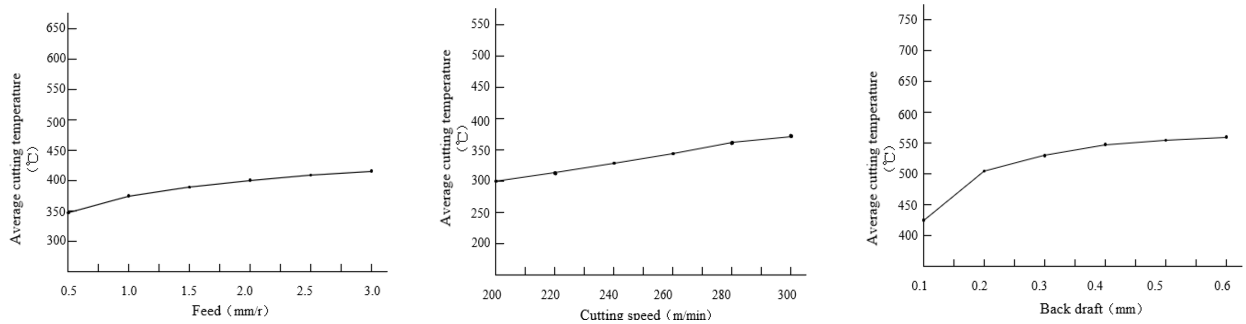


Figure 5. Stress cloud map and temperature cloud map.

Finite element simulations were performed to derive the regression equation (10) for the average cutting temperature in relation to feed, cutting speed, and backdraft:

$$T(\mathrm{v}, \mathrm{a_p}, f_z) = 28.3314 v^{0.5354} a_p^{\ 0.1024} f_z^{\ 0.5184} \tag{10}$$

The analytical results obtained after inputting the empirical values, i.e., the average cutting temperature of hobbing in relation to cutting speed, feed, and depth of cut on the back draft are shown in Figure 6.



$v=300m/\min, \mathrm{ap}=0.4mm$ $a_p=1mm, f_z=0.4mm/\mathrm{r}$ $v=300m/\min, f_z=1mm/\mathrm{r}$

Figure 6. Relationship between the average cutting temperature of hobbing teeth and feed, cutting speed and back draft.

The study shows that the average cutting temperature of hobbing increases from 347.86°C to 417.91°C with the change of feed, from 300.57°C to 373.45°C with the change of cutting speed, and from 424.37°C to 569.91°C with the change of backdraft, and there is a certain gap between the results of the finite element numerical simulation and the theoretical analysis, but the trend of the average cutting temperature change with cutting factors is consistent with the theoretical analysis. temperature with cutting factors is consistent with the theoretical analysis.

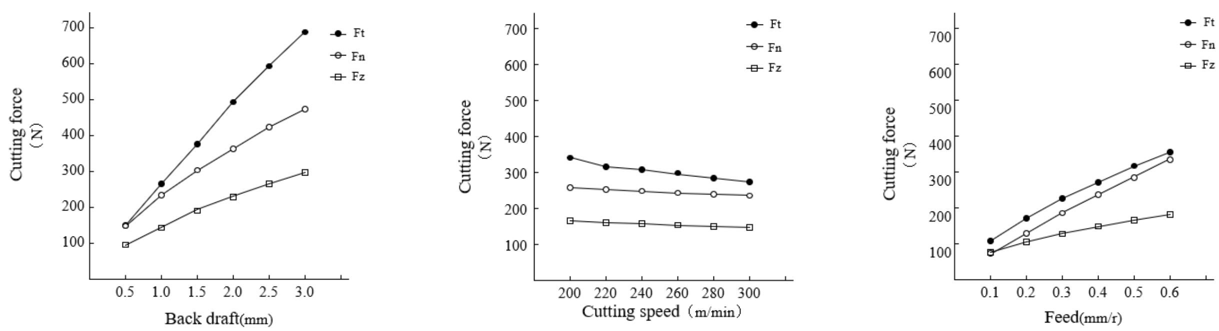
Finite element simulation was carried out to derive the regression equations for the average cutting force in relation to feed, cutting speed and back draft for tangential force equation (11), radial force equation (12) and axial force equation (13) respectively:

$$F_{\mathrm{t}}=11492.85v^{-0.5481}ap^{0.8387}f^{0.67} \tag{11}$$

$$F_{\mathrm{n}}=1881.935v^{-0.2233}ap^{0.6354}f^{0.8744} \tag{12}$$

$$F_{\mathrm{z}}=1063.552v^{-0.2667}ap^{0.6361}f^{0.4926} \tag{13}$$

According to the analytical results obtained after the input of empirical values, the relationship between feed, cutting speed and back draft on the average cutting force of hobbing is shown in Figure 7.



$v=300m/\min, f_z=0.4mm/r$ $a_p=1mm, f_z=0.4mm/r$ $v=300m/\min, a_p=1mm$

Figure 7. Relationship between hobbing cutting force and feed, cutting speed and back draft.

Research shows that when the feed increases, the cutting force also increases, and the two have a linear relationship. An increase in feed makes the cutting volume per tooth increase, milling force becomes larger. If the spindle speed is fixed, increasing the feed rate increases the amount of feed per tooth, resulting in an increase in cutting force. In order to reduce the cutting force, a small feed rate and high spindle speed should be selected. In high-speed dry cutting, an increase in cutting speed results in a reduction in cutting force, especially for hobbing cutters with a negative rake angle. When the back draft increases, the cutting area also increases and the cutting force increases.

4. CONCLUSION

This paper proposes and verifies the cutting force and cutting temperature model of high-speed dry hobbing, studies the relationship between the main cutting parameters and cutting force and temperature, and finds that the cutting temperature increases with the increase of feed, back draft and cutting speed, and the cutting force increases with the increase of feed and back draft and decreases with the increase of cutting speed. This study lays a foundation for in-depth exploration of the cutting mechanism of high-speed dry hobbing and large-scale promotion of dry machining, and provides new ideas for optimizing the machining conditions and developing experimental methods.

ACKNOWLEDGEMENT

The Fundamental Research Funds in Heilongjiang Provincial Universities (No: 145109406).

REFERENCES

[1] Li, C. B., Cao, H. J. and Liu, F., [Green manufacturing key technologies and applications of machine tools]. Mechanical Industry Press: National Publication Fund Project—Green Manufacturing Series, 202205.326. (2022).

[2] Ni, H. X., [Research on Energy Consumption Prediction and Process Parameter Optimization Method of High-Speed Dry Cutting Hobbing Machine Tool], Chongqing: Chongqing University, (2022).

[3] Kalashnikov, A. S., Morgunov, Y. A. and Kalashnikov, P. A., "Hobbing of cylindrical wheels without coolants", Materials Science Forum, (2019).

[4] Ghafarizadeh, S., Jean-François, C. and Gilbert, L., "Experimental investigation to study cutting temperature during milling of unidirectional carbon fiber reinforced plastic", Advances in Aerospace Technology, (2014).

[5] Shi, L. and Meng, Y. X., "Optimization analysis of machining parameter selection by fuzzy neural network algorithm," Internal Combustion Engines and Accessories, (11), 75-77 (2023).

[6] Zhou, P. J., Lin, C., Lu, D. C., et al., "Theoretical and experimental study on cutting temperature of high-speed dry hobbing," Mechanical Transmission, 34(12), 10-14 (2010).

[7] Chen, S. P., Liu, S., Yan, W., et al., "Research on thermal deformation error model of dry cutting hobbing machine and its error compensation technology," Manufacturing Technology and Machine Tools, 2019(11), 119-124 (2019).

[8] Guo, X., [Theoretical and Experimental Research on Cutting Force of High-Speed Dry Hobbing], Chongqing: Chongqing University, Master's Thesis, (2006).

[9] Yang, X. L., Yang, Y., Chen, B., et al., "Simulation and analysis of inconel 718 turning based on deform," Mechanical Design and Manufacturing Engineering, 51(05), 13-18 (2022).