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Thermal Analysis of Cutting Force and Optimization of Process Parameters for Curved Rake Face Skiving Tools

Jiawei Li, Yanan Gao

Tianjin University of Technology and Education, Tianjin, China

ABSTRACT

Power skiving is a highly efficient and high-precision gear machining method. During the power skiving process, the cutting force and cutting temperature exerted on the tool significantly influence its service life. Improper selection of process parameters can easily lead to rapid wear and failure of the skiving tool. Currently, the characteristics of cutting forces and thermal behavior in such machining processes remain unclear, lacking theoretical guidance for tool design and process parameter optimization. To address these issues, this study designed and developed a three-dimensional model of a curved rake face skiving tool. A finite element-based simulation model of the power skiving process was established to calculate the cutting force and cutting temperature data. The influence of key process parameters on the cutting performance was analyzed. A full factorial experimental approach was adopted to optimize the power skiving process parameters based on the mean and peak values of cutting force, as well as the mean value of cutting temperature. Through comprehensive analysis, the primary factors affecting the cutting force and cutting temperature in power skiving were identified.

KEYWORDS

Power Skiving; Cutting Force; Cutting Temperature; Finite Element Method.

1. INTRODUCTION

Power skiving is a kind of gear machining method first proposed by Wilhelm von Pittler in 1910 [1]· The advantages of power skiving result from combining the traditional machining processes of hobbing and shaping. However, due to its continuous chip removal capability, power skiving is faster than shaping, and more flexible than broaching; particularly in the machining of inter-nal gears. Power skiving has always presented a significant challenge to machines and tools due to their low stiffness and high wear characteristics, respectively. However, over the past few years, developments in manufacturing engineering have overcome these limitations, and power skiving technology now provides an efficient and flexible approach for the machining of gearcomponents. per-formed a numerical investigation into the tool design, cutting angles and cutting load in the skiving of periodic structures.Bouzakis et al. [2] investigated the efficiency of various types of gear cutting process for the manufacturing of cylindrical gears,including power skiving. Guo et al. [3] proposed a method for the design and analysis of skiving tools for internal gears Zheng Guo et al. [4] derived a mathematical model for power skiving based on gear meshing theory, analyzing the distribution characteristics of the tool's working rake angle and working clearance angle. They established a mathematical model for cutting forces in power skiving and conducted comparative studies on the mechanical behavior of tools under commonly used feed modes. Their research demonstrated that multi-directional feed technology offers better engineering applicability, providing important references for feed strategies with different working angles in practical engineering applications. Hideaki Onozuka [5] proposed an analytical model that considers the influence of cutting direction, chip thickness, and effective rake angle variations on cutting forces during the machining process. The model's validity was verified through experiments, providing theoretical support for optimizing power skiving tool design to reduce cutting forces. Pierce McCloskey et al. [6] developed a novel virtual model for predicting uncut chip geometry and cutting forces in power skiving, offering an advanced tool for machining process simulation and optimization.

2. SIMULATION MODELING OF POWER SKIVING PROCESS

2.1. Section Headings

The design parameters of the skiving tool and workpiece are presented in Table 1 and Table 2, respectively.

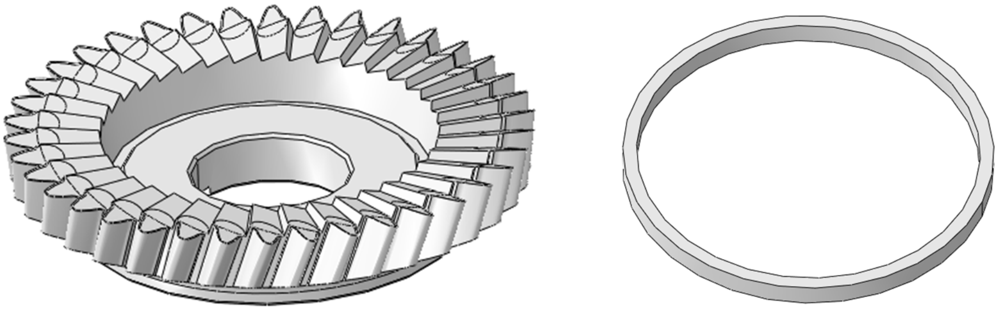
Table 1. Design Parameters of the Power Skiving Tool

Number of Teeth	Helix Angle	Helix Direction	Rake Angle	Clearance Angle
38	20	Right-handed	10°	6°

Table 2. Parameters of the Gear Workpiece

Number of Teeth	Module	Pressure Angle	Tip Diameter	Root Diameter
92	3.5	20°	314.073	329.823

Figure 1 illustrates the designed components of the power skiving tool and workpiece.



(a) Power skiving tool with curved rake fac (b) Workpiece blank

Figure 1. Component Design

2.2. Material Properties and Mesh Generation

As shown in Table 3, the skiving tool is made of WC (Tungsten Carbide), while the workpiece material is 25CrMo4 alloy steel.

Table 3. Basic Material Properties

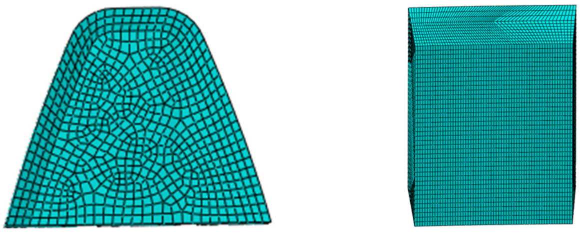
Component	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Thermal Conductivity (W/(m·K))	Specific Heat Capacity (J/(kg·K))
Tool	15700	6.5×10^{9}	0.25	59	470
Workpiece	7850	2.1×10^{5}	0.33	42	450

To address the issues of large strain and high strain rates generated during the power skiving process, the Johnson-Cook constitutive model was selected for its suitability in describing the strength limit and failure behavior of metallic materials under conditions of large strain, high strain rate, and elevated temperatures. This model is widely used in finite element simulation studies of cutting processes. The constitutive equation is as follows:

$$\overline{\sigma} = [A + B\varepsilon^n](1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})[1 - (\frac{T - T_{room}}{T_{melt} - T_{room}})^m] \tag{1}$$

Where: σ is the equivalent stress; ε is the equivalent plastic strain; A is the yield stress of the material; B and n are the strain hardening coefficients; C is the strain rate sensitivity coefficient; m is the thermal softening exponent; $\dot{f}$ is the plastic strain rate; $\dot{f}_0$ is the reference plastic strain rate; T is the deformation temperature; T_{room} is the room temperature; T_{melt} is the melting temperature of the material.

Figure 2 shows the meshed models of the simplified workpiece and two types of power skiving tools. Structured meshes, characterized by quadrilateral and hexahedral elements, were employed due to their advantages of simple structure, fast generation speed, and high mesh quality. Both the skiving tool and workpiece were discretized using hexahedral elements. The workpiece was meshed using a hexahedral structure with an advanced sweeping algorithm, while the skiving tool was meshed using a hexahedral sweeping technique. The element type adopted for both components was C3D8T, an 8-node coupled temperature-displacement hexahedral element with trilinear displacement and temperature degrees of freedom.



(a) Power skiving tool with curved rake face (b) Workpiece

Figure 2. Component Meshing

2.3. Kinematic Model of Power Skiving Process

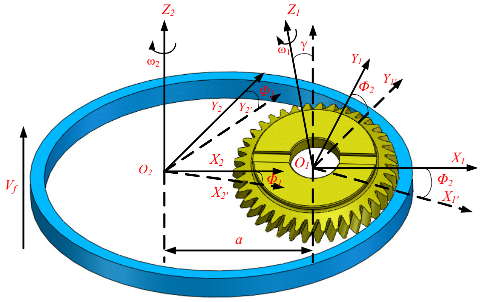


Figure 3. Kinematic Model of Power Skiving Process

Figure 3 illustrates the kinematic model of the power skiving process. The machining motion coordinate system was established based on the kinematic principles of power skiving. As shown in Figure 1, the initial coordinate systems of the skiving tool and workpiece are defined as $S_1(O_1\text{-}X_1Y_1Z_1)$ and $S_2(O_2\text{-}X_2Y_2Z_2)$, respectively. After rotational motion, the transformed coordinate systems become $S_1'(O_1\text{-}X_1'Y_1'Z_1')$ and $S_2'(O_2\text{-}X_2'Y_2'Z_2')$, achieved through rotations by angles α_1 and α_2, respectively. During the power skiving process, the tool rotates about the Z_1-axis with an angular velocity of ω_1, while the workpiece rotates about the Z_2-axis with an angular velocity of ω_2. Simultaneously, the workpiece undergoes an axial feed motion along the positive direction of the Z_2-axis at a velocity of V_f. The angle between the Z_1-axis and Z_2-axis is defined as the shaft intersection angle γ.

2.4. Experimental Design

The objectives of this experiment are to analyze the relationship between the cutting force, cutting temperature, and process parameters of the power skiving tool, and to determine the optimal combination of process parameters.

The main factors affecting the cutting force and cutting temperature of the power skiving tool are the rotational speeds of the tool and workpiece, and the cutting depth. Therefore, a two-factor three-level full factorial experimental design method was adopted. The two factors are denoted as A and B, with different levels under each factor labeled as A1, A2, A3 and B1, B2, B3, respectively. The factor level design is shown in Table 4, and the specific experimental design scheme is presented in Table5.

Table 4 Factor Level Design

Table 4. Economic Data Statistics

Level	A: Tool and Workpiece Rotational Speed (r/min)	B: Cutting Depth (mm)
1	1300, 537	1.0
2	1000, 413	0.8
3	800, 330	0.6

Table 5. Experimental Design Scheme

Experiment No.	Factors	Experimental Scheme
	A B	
1	1 1	A1B1
2	1 2	A1B2
3	1 3	A1B3
4	2 1	A2B1
5	2 2	A2B2
6	2 3	A2B3
7	3 1	A3B1
8	3 2	A3B2
9	3 3	A3B3

3. ANALYSIS OF CUTTING FORCES

Figure 4 shows the curves of mean and peak cutting forces obtained from the curved rake face power skiving tool under constant tool rotational speed with varying cutting depths. Initially, with the tool rotational speed of 1300 r/min and workpiece rotational speed of 537 r/min at a cutting depth of 1 mm, both the mean and peak cutting forces show a gradual increase with increasing cutting depth. Notably, when the cutting depth increases from 0.6 mm to 0.8 mm, the peak cutting force exhibits a substantial increase of 2643 N, representing approximately 30% growth. Further increasing the cutting depth from 0.8 mm to 1 mm results in an additional 400 N increase in peak cutting force. The mean cutting force increases by 1061 N and 286 N correspondingly.

At a tool rotational speed of 1000 r/min, increasing the cutting depth from 0.6 mm to 0.8 mm raises the peak and mean cutting forces by 1912 N and 662 N, respectively. Subsequent increase from 0.8 mm to 1 mm leads to additional increases of 1075 N in mean cutting force and 431 N in peak cutting force.

When the tool rotational speed is 800 r/min, the transition from 0.6 mm to 0.8 mm cutting depth causes increases of 687 N in peak cutting force and 634 N in mean cutting force. Further increasing to 1 mm cutting depth results in additional rises of 1927 N in mean cutting force and 629 N in peak cutting force.

The simulation results demonstrate that at constant tool rotational speed, both mean and peak cutting forces show significant reduction with decreasing cutting depth. The most effective reduction in both mean and peak cutting forces is achieved at a tool rotational speed of 1300 r/min with a cutting depth of 0.6 mm.

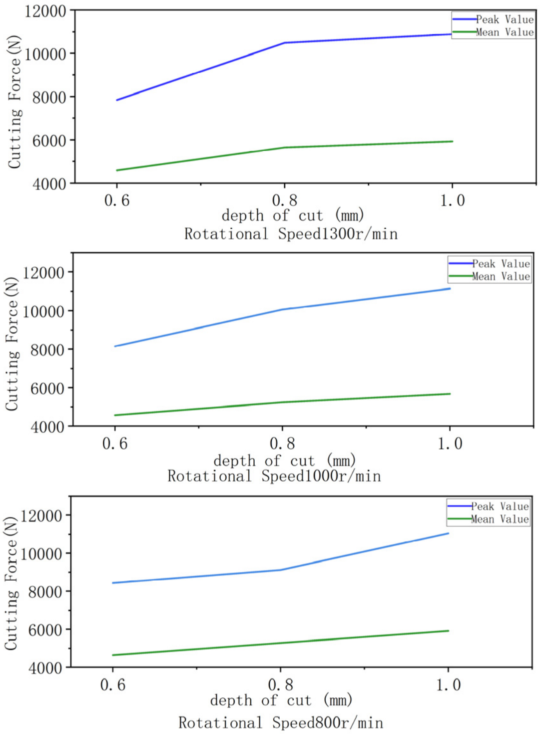


Figure 4. Comparison of Mean and Peak Cutting Forces under Constant Rotational Speed with Varying Cutting Depths

Figure 5 shows the comparison curves of mean and peak cutting forces for the curved rake face power skiving tool under different rotational speeds at constant cutting depths. At a cutting depth of 1 mm with tool rotational speeds of 800, 1000, and 1300 r/min, both the mean and peak cutting forces gradually decrease with increasing rotational speed. Specifically, when the rotational speed increases from 800 r/min to 1000 r/min, the peak and mean cutting forces decrease by 10 N and 239 N, respectively. A further increase from 1000 r/min to 1300 r/min results in reductions of 252 N in peak cutting force and 230 N in mean cutting force.

These results indicate that at 1 mm cutting depth, increasing the rotational speed from 800 r/min to 1000 r/min produces a slight reduction in peak cutting force but a significant reduction in mean cutting force. However, increasing from 1000 r/min to 1300 r/min demonstrates substantial reductions in both mean and peak cutting forces.

At 0.8 mm cutting depth, increasing the rotational speed from 800 r/min to 1000 r/min reduces the peak and mean cutting forces by 423 N and 312 N, respectively. Further increasing to 1300 r/min results in additional reductions of 942 N in peak force and 127 N in mean force.

For 0.6 mm cutting depth, the transition from 800 r/min to 1000 r/min reduces peak and mean cutting forces by 283 N and 102 N, respectively. Subsequent increase to 1300 r/min yields further reductions of 308 N in peak force and 139 N in mean force.

The results demonstrate that increasing tool rotational speed at constant cutting depth effectively reduces both mean and peak cutting forces. At 1 mm cutting depth, the increase from 800 r/min to 1000 r/min shows minimal effect on peak cutting force reduction, while increasing to 1300 r/min produces significantly greater reduction in peak cutting force.

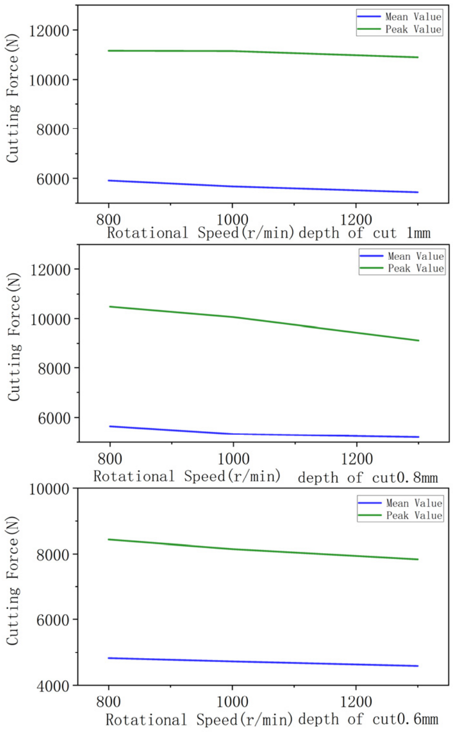


Figure 5. Comparison of Mean and Peak Cutting Forces under Different Rotational Speeds with Constant Cutting Depth

4. ANALYSIS OF CUTTING TEMPERATURE

Figure 6 shows the comparison of mean cutting temperatures for the curved rake face power skiving tool at different cutting depths with rotational speeds of 800, 1000, and 1300 r/min. At a tool rotational speed of 800 r/min, the mean cutting temperature is 375°C at 0.6 mm cutting depth. In comparison, when the cutting depth increases to 0.8 mm and 1.0 mm, the mean temperature rises by 25°C and 27°C, respectively. This indicates a continuous increase in mean cutting temperature with increasing cutting depth at 800 r/min.

At a tool rotational speed of 1000 r/min, the mean cutting temperature measures 379°C at 0.6 mm cutting depth. As the cutting depth increases to 0.8 mm and 1.0 mm, the mean temperature increases by 48°C and 58°C, respectively, showing a consistent rising trend of cutting temperature with cutting depth at this rotational speed.

When the tool rotational speed is 1300 r/min, the mean cutting temperature reaches 409°C at 0.6 mm cutting depth. Further increases in cutting depth to 0.8 mm and 1.0 mm result in temperature rises of 9°C and 33°C, respectively.

In summary, under constant tool rotational speed conditions, the mean cutting temperature demonstrates a gradual increasing trend with the augmentation of cutting depth.

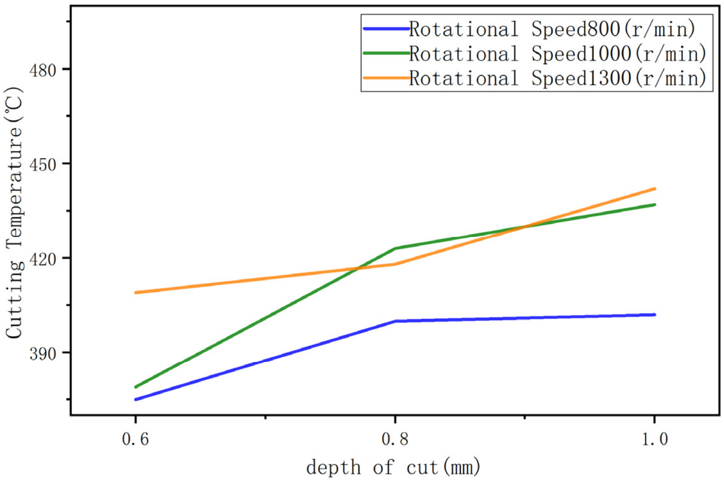


Figure 6. Comparison of Cutting Temperatures under Different Rotational Speeds with Constant Cutting Depth

Figure 7 shows the comparison of mean cutting tool temperatures for the curved rake face power skiving tool under different rotational speeds at cutting depths of 0.6, 0.8, and 1.0 mm. At a cutting depth of 0.6 mm with a tool speed of 800 r/min, the mean cutting temperature is 375°C. Maintaining the same cutting depth while increasing the tool speed to 1000 r/min and 1300 r/min results in temperature increases of 4°C and 34°C, respectively.

At a cutting depth of 0.8 mm with an initial speed of 800 r/min, the mean cutting temperature measures 400°C. When the tool speed is increased to 1000 r/min and 1300 r/min while maintaining this cutting depth, the temperature rises by 23°C and 18°C, respectively. Notably, when increasing the rotational speed from 1000 r/min to 1300 r/min at 0.8 mm cutting depth, the mean cutting temperature shows a decrease of approximately 5°C.

For a cutting depth of 1.0 mm at 800 r/min, the mean cutting temperature reaches 402°C. Increasing the tool speed to 1000 r/min and 1300 r/min while maintaining this depth results in temperature increases of 35°C and 40°C, respectively.

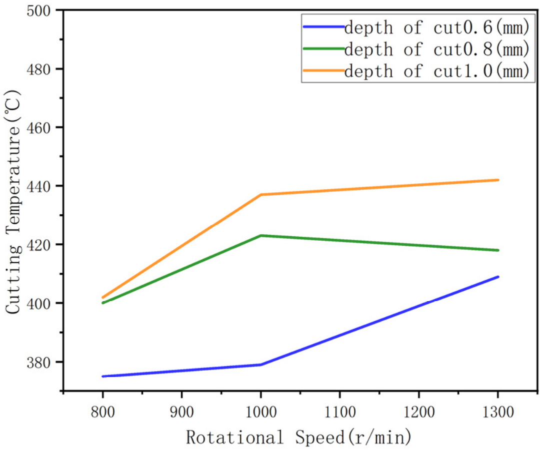


Figure 7. Comparison of Mean Cutting Temperatures under Constant Cutting Depth

5. SUMMARY

This study employed finite element simulation technology to simulate the cutting process of a curved rake face power skiving tool, systematically investigating the influence of two key process parameters - tool rotational speed and cutting depth - on cutting force and cutting temperature. Through a series of full factorial simulation experiments and comparative analysis of the results, the following main conclusions were drawn:

(1) Cutting depth is the primary factor affecting both cutting force and cutting temperature. At all rotational speed levels, both the mean and peak values of cutting force significantly increase with increasing cutting depth. Particularly when the cutting depth increases from 0.6 mm to 0.8 mm, the peak cutting force shows a substantial jump, with a maximum increase exceeding 30%. Simultaneously, the mean cutting temperature also demonstrates a clear upward trend with increasing cutting depth.

(2) The influence of tool rotational speed on cutting force and temperature exhibits complex characteristics. At constant cutting depth, increasing the tool rotational speed generally helps reduce cutting force. However, the increase in rotational speed also leads to elevated cutting temperatures. This indicates that the rotational speed parameter requires balanced optimization between reducing cutting force and controlling cutting temperature.

(3) Through comparison of full factorial experimental results, an optimal combination of process parameters was identified. Comprehensively considering the effects on both cutting force and cutting temperature, the recommended process employs a cutting depth of 0.6 mm with a tool rotational speed of 1300 r/min (workpiece rotational speed of 537 r/min). This combination effectively maintains both cutting force and temperature at relatively low levels, demonstrating positive significance for extending tool service life and ensuring machining accuracy.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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