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Geometric-angle Optimization of Milling Cutter for Processing Stainless Steel by the Finite Element Method

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In response to the developing trend of technology and the increasing number of difficult-to-machine materials, the geometric angle of the cutting tool is worthy of further study. In metal cutting, the geometric angle of the cutting edge is complicated, and it is difficult to compare different cutting tool geometric angles by mathematical model calculation. Therefore, in traditional tool geometry design, many experiments are required, which is time-consuming and laborious. Compared with traditional methods, simulated milling using the finite element method (FEM) not only saves time and labor, but also materials. Moreover, the repeatability of the experiment is high, and it can accurately obtain difficult-to-measure state variables in cutting experiments. Therefore, in this study, we configured the cutting conditions and tool geometric angles according to the control variates approach, then used the FEM to construct a model of tool geometric angles for the thread milling cutter machining of stainless steel and conducted simulated cutting analysis. The thread milling cutter cutting analysis model is constructed as orthogonal cutting in the simulation. However, milling involves oblique cutting, and the effective rake angle under oblique cutting performs the same function as the rake angle under orthogonal cutting. The effects of cutting conditions and tool geometry on the milling process are simulated and validated, and the accuracy of the milling simulation is confirmed. Finally, a Taguchi orthogonal array is employed to plan tool milling simulation experiments for further analysis and research. The Taguchi method's analysis of variance is then utilized to identify the optimal parameter combination; then, the second-stage optimization is performed with the back-propagation neural network (BPNN), followed by reversing the grinding angle and grinding the tool. After that, an actual processing experiment is conducted to verify the grinding angle. The experimental results show that the best parameters combination leads to an obvious

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improvement of the worst parameters combination. Therefore, it is proved that the FEM can be applied to the design and construction of the geometrical angle of the tool and is credible.

1. Introduction

The future development and research trends of cutting tools in various fields are worthy of in-depth discussion, as metal cutting tools serve as important indicators of industrial advancement.(1) Among the various fields, thread machining plays a significant role in mechanical manufacturing. Thread milling, an advanced machining method developed in recent years, offers the advantages of high efficiency and high precision compared with traditional thread machining methods. It is not restricted by the rotation direction or the thread structure, and its application has become increasingly widespread. During thread milling, the tool inclination angle directly affects the friction and deformation during milling, thus affecting the magnitude of cutting forces and the generation of cutting heat. Tool wear is particularly affected, and different tool geometries incur varying degrees of wear depending on the workpiece material. The level of tool wear directly impacts the milling efficiency of the workpiece. Therefore, selecting an appropriate tool inclination angle can effectively reduce tool wear, cutting forces, and cutting temperatures. It can also improve tool life and the surface roughness of the workpiece. Thus, our primary focus is to explore the functionality of tool geometry angles in order to deepen our understanding of these angles and determine the optimal cutting angles for different workpieces.

As technology advances and the number of difficult-to-machine materials increases, traditional tool materials must be changed and more suitable tool geometries must be designed by the tool industry to address the machining challenges faced by the manufacturing industry. Difficult-to-machine materials exhibit higher cutting forces and tend to cause tool wear and low machining efficiency. Therefore, selecting appropriate tool geometries and cutting conditions can effectively suppress cutting forces and control the increase in milling temperature. Traditional milling studies rely solely on experimental methods to investigate the milling process. Although experimental approaches provide data that closely reflect real milling conditions, they are time-consuming and labor-intensive, and increase production costs. Moreover, it is difficult to obtain accurate data on cutting forces and milling temperature during milling. Therefore, alternative methods with greater applicability must be explored. With the advancement of technology, the finite element method (FEM) has gradually been applied in various industries. Using the FEM for simulating milling not only saves materials but also ensures the high repeatability of the experiment. Therefore, this study is aimed at designing the geometry angles of thread milling cutters using the well-developed FEM and applying them to different workpiece materials.

Li(2) used a FEM to simulate the effects of cutting conditions and spindle speed on vibration and average stress. The results showed that higher spindle speeds led to increased vibration and average stress under suitable cutting conditions. Under appropriate cutting conditions and feed rates, the average stress and vibration did not differ significantly for different feed rates. Under suitable cutting conditions, a smaller helix angle resulted in higher average stress and vibration but lower stability. Furthermore, under suitable cutting conditions and for a given cutting depth and thickness, larger cutting volumes corresponded to higher vibration and average stress. Lin[3] employed the FEM software ANSYS/LS-DYNA to simulate and analyze the effects of cutting speed on various parameters in metal cutting. It was found that as the cutting speed increased, the maximum equivalent plastic strain, maximum equivalent stress, shear stress, shear angle, and maximum temperature of the chip increased. During metal cutting, an increase in tool rake angle resulted in decreases in unit cutting force and chip temperature. This, in turn, affected the equivalent plastic strain, shear stress, and equivalent stress. Therefore, it can be inferred that the cutting process is affected by the tool rake angle. The results analyzed using the model indicated that the change in cutting speed had minimal impact on the shear angle.

Wu[4] proposed the concept of transforming three-dimensional cutting into two-dimensional cutting and conducted a feasibility analysis focusing on the effective rake angle. Research findings revealed that when the same effective rake angle was combined with different helix angles, the calculated results showed various angles of radial cutting, but the trend of flank wear on the side edge was markedly similar. Therefore, the method of transforming three-dimensional cutting into orthogonal cutting is considered feasible. Azaath *et al.*[5] conducted a simulation of the carbide cutting tool milling process on AISI 4340 steel using the FEM software DEFORM-2D. They investigated the effects of tool geometry on contact length, tool wear rate, and cutting temperature. It was found that the contact length of a micro-groove tool could be neglected. When the rake angle was set to zero degrees, the cutting zone temperature increased. On the other hand, when a micro-groove tool was used, the cutting zone temperature decreased to its minimum. A comparison between the micro-groove tool and the zero-rake-angle tool showed a tool tip temperature reduction of 15% and a tool wear rate reduction of 71.6%. Therefore, the contact length plays a crucial role in the effects of tool wear and cutting temperature.

In the experiment conducted by Xiao,[6] the introduction of a variable rake angle design to the cutting tool was studied. Because of different helix angles, the time interval of each cutting edge entering the workpiece varied during milling. This approach suppressed tool vibration, thereby enhancing tool stability and surface quality, and prolonging tool life. In the study conducted by Chen,[7] the effects of changing the rake angle on machining characteristics were investigated using a dynamometer and a signal acquisition device. Different rake angles were applied to disposable end mills, and actual cutting experiments were performed. By observing the changes in cutting force, surface roughness, chip morphology, and tool wear associated with different tool rake angles, it was found that as the cutting depth increased, the tool wear, and cutting force also increased. However, at the same cutting depth, different tool rake angles resulted in different degrees of tool wear. Therefore, an appropriate rake angle can effectively suppress the increase in tool wear and prolong tool life. Faster feed per tooth leads to faster tool wear and higher cutting forces. However, at the same feed per tooth, different tool rake angles cause varying degrees of tool wear. Hence, suitable changes in tool rake angle can also reduce tool wear. The experimental study conducted by Li[8] showed that when negative-rake-angle end mills were used for the milling of hard alloy steel by the climb milling method, the surface roughness of the workpiece improved with increasing helix angle. On the other hand, when positive-rake-angle end mills were used for the climb milling of hard alloy steel, the surface roughness of the workpiece deteriorated with increasing helix angle. This can be attributed to the fact that the cutting edges of positive-rake-angle end mills are more fragile, making them prone to chipping that affects the surface roughness of the workpiece.

The experimental analysis conducted by Huang *et al.*(9) revealed that when milling thin-walled titanium alloy components, the vibration frequency of non-equal helix tools was lower than that of equal helix tools, indicating that non-equal helix tools exhibit stronger vibration damping characteristics. In terms of the tool displacement frequency spectrum, the vibration displacement distribution of equal helix tools was more scattered than that of non-equal helix tools. According to the theory of equivalent energy, under the same cutting conditions, the former had a larger cutting vibration displacement than the latter. When vibration occurs, the vibration energy of equal helix tools is more dispersed than that of non-equal helix tools. Therefore, the vibration energy of equal helix tools is greater than that of non-equal helix tools. In the study conducted by Shih,(10) the effects of end milling cutters on SK85 high-carbon steel were analyzed by the Taguchi method. The experimental results revealed that the optimal feed approach was the inclined downward milling method. The important control factors, in order, were milling depth, spindle speed, and feed per tooth. The signal-to-noise ratio of the optimized parameters in the experiment was 11.914 dB, which is significantly higher than the highest estimated value of 8.435 dB. The experimental results confirmed that the application of the Taguchi method helps reduce the number of experiments and facilitates experimental planning and analysis.

The research conducted by Huang(11) explains that among the mechanical material properties of NAK80, its toughness is relatively low. Therefore, in the design process, it is preferable to have smaller clearance angles that do not cause interference. However, when the clearance angle is very small, the rate of tool wear increases sharply once the cutting edge starts to wear. This not only leads to an early termination of the tool's lifespan but also affects the surface quality of the workpiece. The application of the Taguchi experimental method to investigate the optimization of process parameters under different machining conditions revealed that spindle speed is the factor with the highest effect. Variations in spindle speed and cutting depth were found to affect the change in surface roughness.(12,13) Youpeng and Mao(14) employed a neural network to predict the surface roughness of the workpiece. Stainless steel was chosen as the workpiece material, and various cutting experiments were conducted under different cutting speeds, feed rates, and cutting depths. By utilizing a neural network model, the surface roughness during milling was predicted for the variations in cutting conditions. The predicted results of the workpiece surface roughness indicated that this method had a small prediction error and high accuracy with a maximum error of less than 2%. Moreover, artificial neural network models can also be applied to predict other parameters, such as tool life and cutting forces.(15)

The aforementioned research indicates that the impact of the tool geometry on the milling process has mainly been studied through conventional experimental methods combined with the Taguchi approach. However, because of the complexity of tool edge geometry angles in metal cutting processes, it is challenging to compare different tool geometry angles using mathematical models. Therefore, traditional tool geometry design primarily relies on laborious and time-consuming large-scale cutting experiments. Moreover, force measurement instruments can be costly. Although conventional cutting experiments can provide numerical values that are closer to reality, obtaining accurate cutting forces and temperatures during cutting is difficult. In contrast to traditional methods, using the FEM for simulating milling can substitute conventional cutting experiments. This approach not only reduces the experimental time but also saves materials.

Additionally, it offers high experimental repeatability and enables the accurate acquisition of state variables that are difficult to measure in cutting experiments, such as cutting forces, heat transfer during cutting, material properties, and the process of chip formation. The use of the orthogonal array design of the Taguchi method for experimental planning can effectively reduce the number of experiments. However, the parameter combinations predicted by the Taguchi method are limited by the level of the factor experiments. On the other hand, the back-propagation neural network (BPNN) algorithm is currently the most widely used learning model in neural networks and is suitable for prediction models. Using BPNNs for prediction can shorten the overall output schedule of experiments. However, when the training sample size of the BPNN algorithm is insufficient, the prediction accuracy generally decreases as the training sample size decreases. In practical engineering problems, considering the cost and timeliness of experimental samples, only a limited number of experimental samples can be used as training data. As a result, the trained neural network model may have errors, which can be mitigated through manual inspection. Therefore, in this study, to improve the accuracy of predicting tool geometry angles, the advantages of three tools, namely, the FEM, the Taguchi method, and the BPNN algorithm, were combined. Specifically, the finite element analysis software DEFORM-2D was combined with the Taguchi method and BPNNs to construct a predictive model for tool geometry angles.

2. Construction of Geometric Angles for Milling Cutter

This study is focused on employing the FEM to design tool geometry angles for milling cutters used in the processing of stainless steel. The process begins with understanding the geometry angles of the tool and reviewing relevant literature. Next, DEFORM-2D is used to simulate and verify the effects of cutting conditions and tool geometry angles on the milling process, as well as to assess the feasibility of the simulations. Once the milling simulation is confirmed to be accurate, an orthogonal array design using the Taguchi method is employed to plan and analyze milling simulation experiments for the milling cutter. The control factors for the tool geometry angles in the simulation experiments are the effective rake and clearance angles, while the control factors for the cutting conditions are the cutting speed and feed rate. The cutting force is used as the target value in the cutting simulation. Subsequently, the Taguchi method's analysis of variance is used to determine the optimal parameter combination, followed by a second-stage optimization using BPNNs. The grinding angles are then deduced, and the tool is ground accordingly. Actual machining experiments are conducted to validate the results, followed by tool inspection and discussions to draw conclusions. The research process is illustrated in Fig. 1.

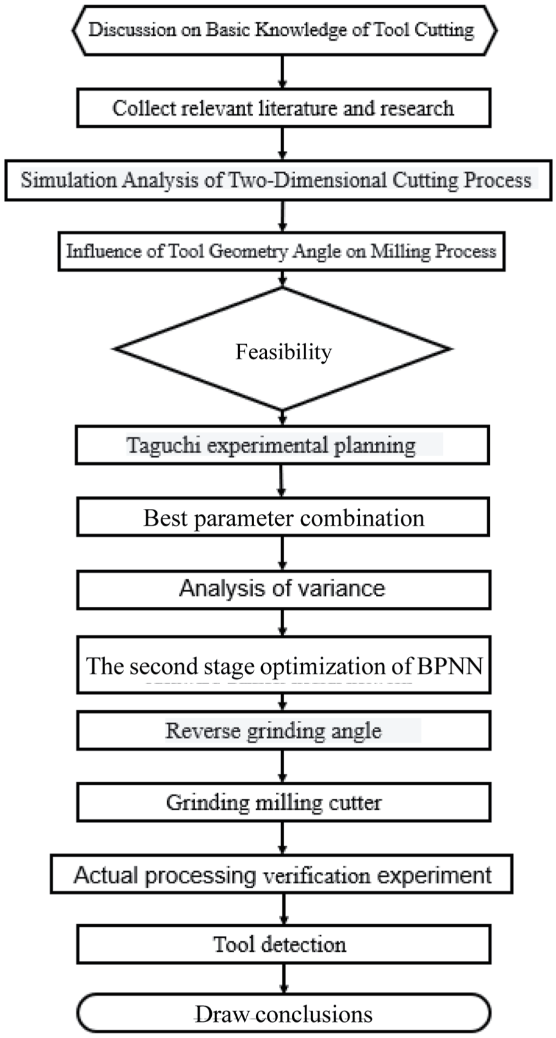

Fig. 1. Flowchart of research process.

3. Experimental Analysis

During metal cutting, when cutting forces and temperatures act on a specific area of the tool edge, the complex geometry angles of the tool make it difficult to compare different tool geometry angles using mathematical models. Therefore, traditional tool geometry design relies on time-consuming and labor-intensive large-scale experiments, in which it is also challenging to accurately measure cutting forces and temperatures. The FEM can be employed to construct orthogonal cutting models and obtain state variables that are difficult to measure in cutting experiments, such as cutting temperature, cutting forces, chip formation process, maximum equivalent stress, and other physical changes. The results can contribute to the design of tool geometry angles and reduce tool wear during machining. In this study, DEFORM-2D is used to construct a model of tool geometry angles for milling cutters employed in the processing of stainless steel. Simulated cutting analysis is performed using DEFORM-2D. After establishing the simulation model, the orthogonal cutting process between the tool and the workpiece will be observed, including chip formation, cutting forces, and temperature distribution. The obtained trends are compared with those in metal cutting theories. Then, the Taguchi method and neural networks are used for factor design and planning to obtain the optimal combination design.

We constructed the milling cutter cutting analysis model with orthogonal cutting. However, owing to the cutting behavior in milling, which is oblique cutting, in this study, the effective rake angle α_e of the milling cutter is adopted as the inclination angle α in orthogonal cutting. According to Refs. 4 and 16 during orthogonal cutting, when a chip passes through the surface of the oblique tool, it deviates at an angle of $90° - \alpha$. This phenomenon is similar to the situation where chips deviate in oblique cutting, indicating that in oblique cutting, the effective rake angle plays a role equivalent to that of the rake angle in orthogonal cutting. Therefore, the oblique cutting mode can be simplified as an orthogonal cutting mode. The effective rake angle is also an important angle indicator that affects the cutting performance. Tool geometry angles and cutting conditions are important factors affecting the tool life of milling cutters. Regarding tool geometry angles, when milling cutters are used in oblique cutting, it is necessary to consider the effective rake, radial inclination, radial clearance, and helix angles. In orthogonal cutting, only the rake and clearance angles must be considered. When selecting cutting conditions for milling cutters in oblique cutting, the cutting speed, feed per tooth, and radial cutting, and axial cutting depths must be considered. In orthogonal cutting, only the cutting speed and cutting depth must be considered. In terms of the corresponding relationship between oblique cutting and a milling cutter, the velocity inclination angle in oblique cutting corresponds to the radial inclination angle of the milling cutter, the inclination angle corresponds to the helix angle of the milling cutter, and the feed per tooth in oblique cutting corresponds to the cutting depth in the orthogonal cutting model.[4]

Before constructing geometric objects in DEFORM-2D, the pre-module requires the preparation of the tool geometry and workpiece material models using drawing software. These models can be imported into DEFORM-2D in DXF file format or directly defined using the built-in model definition in DEFORM-2D, as shown in Figs. 2 and 3. The tool geometry model consists of the rake and clearance angles, while the workpiece material model includes the workpiece length, workpiece height, and cutting depth. The geometric models of the tool and workpiece are depicted in Fig. 4.

The materials under investigation in our study are tungsten carbide for the tool and stainless steel 316L for the workpiece. In the simulation experiments, tungsten carbide is chosen as the tool material and set as a rigid body, while stainless steel 316L is selected as the workpiece material and set as a plastic material. DEFORM-2D provides a comprehensive material database that allows users to choose the desired materials or customize their own materials in accordance with their needs. The metric system is used in this study. The materials for the tool and workpiece are directly accessed from DEFORM's material library, and stainless steel 316L is chosen for the workpiece material in the analysis model. The physical properties of stainless steel 316L are presented in Table 1.

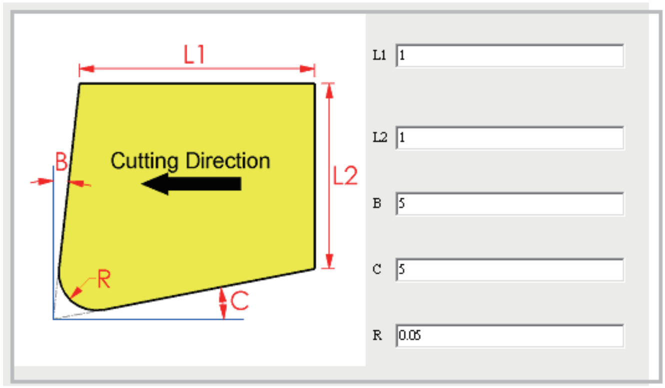

Fig. 2. (Color online) Definition of tool model.

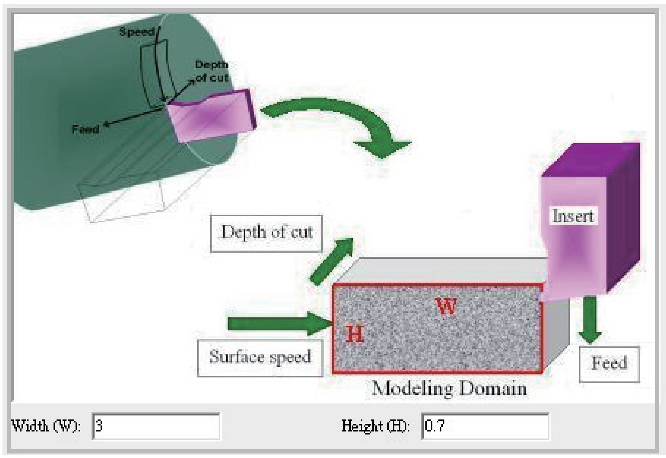

Fig. 3. (Color online) Definition of DEFORM-2D model.

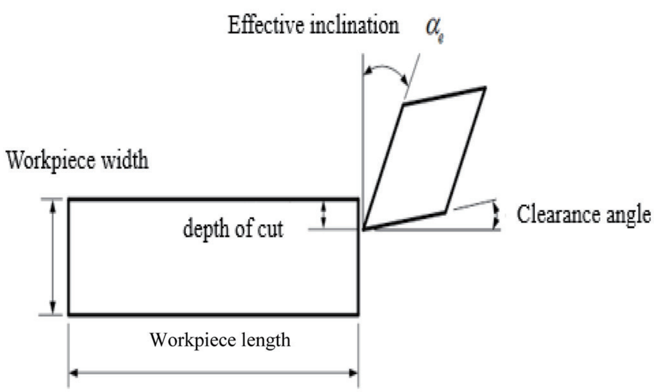

Fig. 4. Diagram of relative positions of tool and workpiece.(4)

Table 1
Physical properties of 316L stainless steel.[17]

Density (g/cm^3)	Specific heat capacity (J/kg·K)	Heat conduction (W/m·K)	Thermal expansion coefficient (°C^{-1})	Young's modulus (GPa)	Poisson's ratio
7.9	470	15	$1.6e^{-5}$	200	0.3

In the actual machining process, the workpiece is fixed on the fixture of the machine bed, and the tool undergoes relative motion with the workpiece by rotating around the center of the threaded hole. The cutting operation is performed by the milling cutter. Therefore, when setting the boundary conditions in the FEM, the workpiece model must be completely fixed to prevent any movement, while allowing the tool to have relative motion with the workpiece model. This is achieved by constraining the non-working surfaces of the workpiece model and setting their nodal velocities to zero. The surfaces of the workpiece model in contact with the tool are considered to be heat dissipation surfaces, and the tool itself is also set as a heat dissipation surface. During cutting, the heat generated in the workpiece material is primarily dissipated through convection and radiation to the surrounding environment. Therefore, the initial ambient temperature is set to 20°C. Because of built-up edge formation during stainless steel cutting, the friction coefficient is set to 0.8 and the thermal conductivity is set to 45. The constructed two-dimensional cutting model is shown in Fig. 5.

In DEFORM-2D, the analyzed tool geometric angles are the effective rake and clearance angles. However, in actual tool design and manufacturing, the milled tooth cutter has different geometric angles, namely, the radial rake angle α_v, radial clearance angle, and helix angle. According to the principles of oblique cutting, the effective rake angle must be converted into the radial rake angle. In this study, the helix angle is set to 15°. By combining the Taguchi method with the optimal parameter combination predicted by a BPNN, the optimal tool geometric angles are determined to be an effective rake angle of 17.504° and a radial clearance angle of 6°. Thus, on the basis of the literature,[16] the corresponding radial rake angles for the optimal and worst parameter combinations predicted by the Taguchi method are calculated as 15 and 4°, respectively. The radial clearance angle is directly selected as 6° for the optimal parameter combination and γ_v9° for the worst parameter combination predicted by the Taguchi method. The grinding angles for the verification experiments are presented in Table 2.

The tool material used for tool grinding is tungsten carbide with a diameter of 10 mm. Tool grinding was performed using the ToolRoom tool design software in conjunction with an ANCA MX7 five-axis CNC tool grinder. Two sets of tool geometric angles configured in accordance with Table 2 were used for the grinding experiments on the milling cutter. After the grinding process, the tool geometric angles were measured using the Zoller genius3s tool measuring device to minimize the error values of the experimental tools. The measurement results are presented in Table 3. From the experimental results, it can be seen that when the cutting length is 0.5 m, the average radial flank wear obtained using the optimal parameter combination after cutting is 0.048 mm. In contrast, the average radial flank wear obtained using the worst parameter combination after cutting is 0.050 mm. The difference between the two values is 0.002 mm. When the cutting length is 1.5 m, the average radial flank wear obtained using the

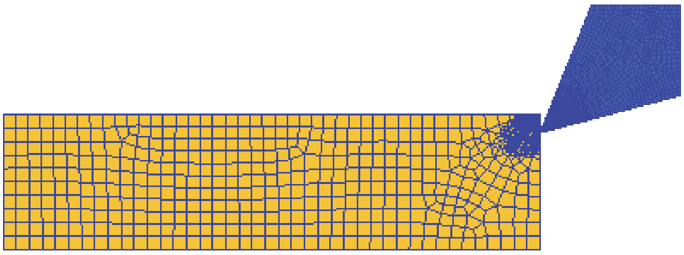

Fig. 5. (Color online) Grid diagram of tool and workpiece.

Table 2
Geometric angles of the tool in the verification.

	Radial rake angle (°)	Radial clearance angle (°)	Helix angle (°)
Optimal parameter combination	15	6	15
Worst parameter combination	4	9	15

Table 3
Test results of the geometric angle of the experimental tool.

Experimental combination	Optimal parameter combination		Worst parameter combination	
Setting/detection	Set value	Detected value	Set value	Detected value
Radial rake angle (°)	15	15.118	4	4.186
Radial clearance angle (°)	6	6.075	9	9.120
Helix angle (°)	15	15.13	15	15.028

optimal parameter combination after cutting is 0.085 mm, while the average radial flank wear obtained using the worst parameter combination is 0.116 mm. The difference between the two wear values is 0.032 mm. When the cutting length is 3 m, the average radial flank wear obtained using the optimal parameter combination after cutting is 0.126 mm. However, with the worst parameter combination at a position of 1.8 m, the flank wear becomes excessive and causes fracture, as shown in Table 4 and Fig. 6. It can be seen that the optimal parameter combination indeed shows significant improvement compared with the worst parameter combination. Therefore, This proves that the finite element analysis software DEFORM-2D can be used to construct the geometric angle model of the milling tool and simulate the effects of cutting conditions and tool geometry on the milling process, which is consistent with the actual cutting process. This also demonstrates the credibility of using the FEM for the design and construction of tool geometric angles.

Table 4
Optimal parameter and worst parameter combinations and corresponding results.

Parameter combination	Measurement	Optimal parameter combination A = 20 m/min, B = 0.03 mm/tooth, C = 17.504°, D = 6°	Worst parameter combination A = 40 m/min, B = 0.06 mm/tooth, C = 7.463°, D = 9°	Improvement amount
Cutting length (m)		0.5		
Flank wear (mm)	1	0.043	0.077	
	2	0.055	0.048	
	3	0.046	0.044	
	4	0.048	0.045	
	5	0.042	0.051	
	6	0.046	0.056	
	7	0.046	0.042	
	8	0.046	0.040	
	9	0.044	0.043	
	10	0.060	0.046	
	11	0.043	0.048	
	12	0.046	0.045	
	13	0.053	0.060	
	14	0.056	0.074	
	15	0.042	0.043	
	16	0.049	0.040	
	Mean	0.048	0.050	0.002
Cutting length (m)		1.5		
Frank wear (mm)	1	0.076	0.295	
	2	0.114	0.111	
	3	0.092	0.108	
	4	0.078	0.085	
	5	0.106	0.091	
	6	0.069	0.119	
	7	0.114	0.128	
	8	0.065	0.097	
	9	0.065	0.099	
	10	0.086	0.118	
	11	0.082	0.119	
	12	0.062	0.096	
	13	0.097	0.109	
	14	0.085	0.108	
	15	0.079	0.095	
	16	0.085	0.085	
	Mean	0.085	0.116	0.032
Cutting length (m)		3	1.8	
Frank wear (mm)	1	0.131	Tool break	
	2	0.128		
	3	0.135		
	4	0.095		
	5	0.116		
	6	0.185		
	7	0.129		
	8	0.097		
	9	0.136		
	10	0.160		

Table 4
(Continued) Optimal parameter and worst parameter combinations and corresponding results.

Parameter combination	Measurement	Optimal parameter combination A = 20 m/min, B = 0.03 mm/tooth, C = 17.504°, D = 6°	Worst parameter combination A = 40 m/min, B = 0.06 mm/tooth, C = 7.463°, D = 9°	Improvement amount
Cutting length (m)		3	1.8	
Frank wear (mm)	11	0.144	Tool break	
	12	0.100		
	13	0.084		
	14	0.141		
	15	0.137		
	16	0.105		
	Mean	0.126		

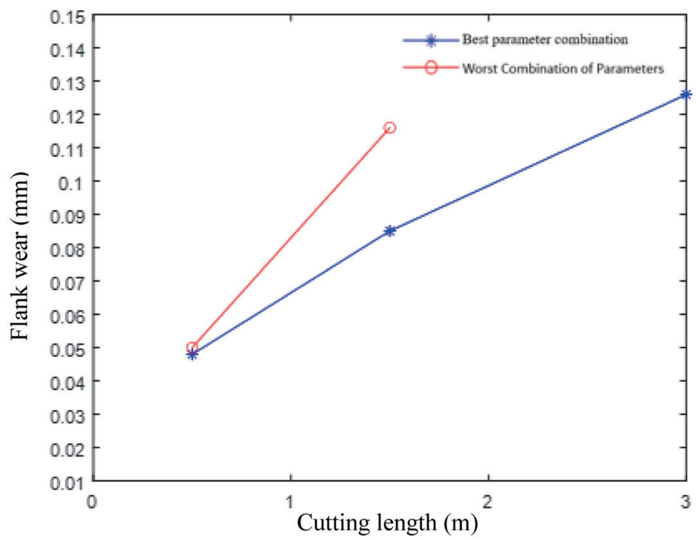

Fig. 6. (Color online) Relationship between cutting length and flank wear.

4. Conclusions

This study was aimed at investigating the impact of cutting conditions and tool geometry on the milling process using DEFORM-2D. By combining the Taguchi method with BPNN analysis, a predictive model for tool geometric angles in milling stainless steel was constructed. From the results of the simulated verification experiments, cutting force was observed to vary with the rake angle. When the rake angle increased, there was a notable decrease in cutting force. This was primarily due to the increase in rake angle, which led to an increase in shear angle and a reduction in chip resistance. Therefore, selecting an appropriate rake angle can effectively control cutting force and reduce tool wear. The cutting force did not exhibit significant variations upon changing the clearance angle. Increasing the clearance angle primarily was aimed at increasing the spacing between the cutting edge and the workpiece to avoid interference. However, when designing the clearance angle, it should not be excessively large, as it would reduce the wedge angle of the cutting edge, resulting in insufficient cutting-edge strength. This could lead to edge chipping and tool damage during cutting. As the inclination angle decreases, the temperature gradient on the inner side of the chip became larger. Conversely, as the inclination angle increased, the temperature gradient on the chip surface gradually decreased. The tool inclination angle significantly affected chip formation. When the tool inclination angle increased, chip deformation gradually decreased, and the chip thickness also decreased. According to the analysis of variance, the significant control factors affecting cutting force were ranked as follows: feed per tooth, effective inclination angle, cutting speed, and radial clearance angle. Among them, the most significant control factor was the feed per tooth, which contributed 93.39% of the variation in cutting force. Therefore, when designing and constructing tool geometry, the feed per tooth must be considered as an important design factor. The optimal parameter combination predicted by the Taguchi method combined with BPNNs revealed that the optimal tool geometry consists of a radial inclination angle of 15° and a radial clearance angle of 6°. The optimal cutting conditions included a cutting speed of 20 m/min and a feed per tooth of 0.03 mm/tooth. Through milling experiments and the analysis of actual experimental results, it was evident that the optimal parameter combination leads to significant improvements compared with the worst parameter combination. Finally, by utilizing DEFORM-2D to simulate the effects of cutting conditions and tool geometry on the milling process, the simulation results were demonstrated to align with the situation of actual cutting operations. This confirmed the credibility of converting the oblique cutting analysis model into a model of orthogonal cutting and subsequently applying DEFORM-2D simulation for the design of tool geometry.

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