Simulation and Experimental Research on the Influence of Tool Geometries on the Cutting Force of High Temperature Alloy

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Abstract. For the difficult-to-process characteristics of the aero-engine turbine disk plank produced by Nickel-based superalloy GH4169 that appeared in the turning process, the numerical simulation and experimental research were conducted in this paper. The two-dimensional orthogonal cutting model of the Nickel-based superalloy GH4169 was established to conduct the single factor experiment, in which the rake angle and tip radius were as the single variable, and the influence of cutting force caused by the rake angle and tip radius was researched by the finite element analysis software ABAQUS. The correctness of the simulation modal was verified by the comparison of the cutting force data obtained in simulation and the experimental result. The study demonstrates the fact that the back force $F_y$ will decrease while the feed force $F_f$ and the main cutting force $F_c$ increase slowly with the increase of the rake angle. The back force $F_y$ will increase with the increase of the tip radius. In addition, the changing trend of cutting force obtained in the experiment was consistent with that of simulation. Under the experimental conditions, the rake angle of 10° and tip radius 0.4mm were suitable processing parameters for machining the Nickel-based superalloy GH4169.

1. Introduction
The high-temperature alloy, for its well high temperature plastic, high temperature oxidation resistance and mechanical properties at room temperature and high temperature, has been widely used in the area of aerospace. It is one of typical difficult machining materials. Domestic and foreign scholars have conducted in-depth research on the problems existing in the high speed cutting process of nickel-based superalloy GH4169[1-2], including two-dimensional and three-dimensional numerical simulation the cutting force influenced by cutting parameters when cutting the high temperature alloy GH4169 with the ceramic tools [3-4] and so on. By the cutting experiment and simulation of cutting iron-based superalloy with coated carbide tools [5], cutting the nickel-based superalloy with the PCBN tools [6], cutting the nickel-based superalloy in high-speed with the PCBN tools [7], the research was conducted for the high temperature alloy cutting performance influenced by such factors as rake angle, tip radius, negative chamfer parameters and PCBN material and so on.

In the paper, based on the result of the single factor experiment for the tool material, the single factor experiment, in which the rake angle and tip radius were as single factor various, was conducted. The cutting force obtained from the experiment was analyzed and the influence of turning high temperature alloy GH4169 was produced by the tools geometry parameters. In the single factor experiment, in which the tool geometry parameters were as single factors, the correctness of
simulation modal established by ABAQUS software was verified, and meanwhile, the influence of cutting force produced by rake angle and tip radius was researched, all of which provide the technical support for the machining of GH4169.

2. The establishment of simulation modal
The essential work, such as the arrangement of seeds grid of high temperature alloy GH4169, element shape set, element type set, meshing techniques and algorithms set, meshing and mesh quality inspection and so on, was finished with the Mesh functional module in ABAQUS/CAE. The ABAQUS grid cell type window is shown in figure 1. The two-dimensional orthogonal cutting model after meshing was shown in figure 2. The grid in the cutting zone was meshed intensively, but the grid far from the cutting zone was thin gradually. The element type of grid after meshing is four node plane strain reduced integral unit CPE4RT.

![Figure 1. Unit type setting window.](image1)

![Figure 2. Two-dimensional orthogonal cutting grid model.](image2)

3. The design for experiment

3.1 The establishment of experimental system
The work-piece size is Bar with Φ155×60;
The material of the tools is Coated Carbide KC5510;
In this paper, the experiment uses external turning superalloy GH4169 by ordinary horizontal lathe CA6140. Due to the outer surface of the purchase is not very smooth, using a dial indicator alignment clamping in the workpiece fixture and detecting workpiece center position. The central axis of the workpiece and machine tool spindle must be maintained a high coaxiality in order to enhance and ensure the machining accuracy of each test. Cutting force is measured by using Kistler 9257B dynamometer system which is shown in Figure 3.
3.2 The simulation and experiment condition

The cutting amount: cutting speed: $v_c = 50$ m/min.
- The feed rate: $f = 0.15$ mm/r;
- The back cutting depth: $a_p = 0.4$ mm;
- The tools geometry parameter: The tool relief angle: $\alpha = 3^\circ$.

4. The research for the experiment and simulation of cutting force

4.1 The influence of cutting force caused by rake angle

In the experimental condition mentioned above, the regular pattern of cutting force was studied when the rake angle respectively is $3^\circ$, $7^\circ$, $10^\circ$, $12^\circ$. The changing curve of cutting force influenced by the change of rake angle was shown in figure 4, was obtained after processing experimental data by extracting the average value of cutting force in each direction. When the cutting process is in the steady state, the comparison of the back force $F_y$ obtained from experiment and simulation, and was shown in figure 5–figure 8. The compared curve of cutting force was shown in figure 9.

As the figure 4 shown that: with the rake angle increasing, the feed force $F_x$ and the main cutting force $F_z$ performed decreasing slowly, when the rake angle increase to $10^\circ$, the feed force $F_x$ and the main cutting force $F_z$ decrease to the minimum value. Being the rake angle $10^\circ$ as the inflection point, the feed force $F_x$ and the main cutting force $F_z$ would perform the increasing trend slowly.

The back force $F_y$ will increase to 502 N when the rake angle is $3^\circ$. When the rake angle increase to $7^\circ$, the back force $F_y$ decreased to 486 N. When the rake angle increasing to $10^\circ$, the back force $F_y$ decreased to 423 N. When the rake angle increased to $12^\circ$, the back force continuously decreased to 254 N. By comprehensively analyzing, the preferred rake angle is $10^\circ$.

![Figure 4](image)

Figure 4. Cutting force is affected by cutting tool rake angle.
Figure 5. The dynamic cutting force changing curve obtained from experiment and simulation ($\gamma = 3^\circ$).

Figure 6. The dynamic cutting force changing curve obtained from experiment and simulation ($\gamma = 7^\circ$).
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4.2 The influence of cutting force caused by tools tip radius

In the experimental condition mentioned in the third part, the regular pattern of cutting force was studied when the tip radius respectively is 0.2 mm, 0.4 mm, 0.8 mm and 1.2 mm. The changing curve of cutting force influenced by the change of tip radius, shown as figure 10, was obtained after processing experimental data by extracting the average value of cutting force in each direction. When the cutting process is in the steady state, the changing curve of the back force $F_y$ obtained from experiment and simulation, were respectively shown in figure 11 ($r=0.2$ mm). The compared curve of cutting force was shown in figure 12.
As the figure 8 shown that: in the process of the tip radius increasing from 0.2 mm to 0.4 mm, the feed force $F_x$ and the main cutting force $F_z$ increase slowly, but the back force $F_y$ has little change. When the tip radius increases from 0.4 mm to 1.2 mm, the feed force $F_x$ and the main cutting force $F_z$ almost have little change, but the back force $F_y$ increases gradually. So the optimized tip radius is 0.4 mm.

![Figure 10. Influence of tip radius on cutting force.](image)

![Figure 11. The dynamic cutting force changing curve obtained from experiment and simulation($r=0.2$ mm).](image)

From the figure 10, we can see that: the changing trend obtained from simulation and experiment are consistent. With the tip radius increasing, the cutting force is increasing. Because the blunt edge radius will increase gradually, in the process of tip radius increasing gradually, which will directly lead to the weakening of cutting action in the edge of tool and the increasing of cutting force. However, in the process of tip radius decreasing gradually, the tip more sharp, the easier to cutting, which lead to the appearance of smaller cutting force. Always, the tip wear is very serious.

![Figure 12. Comparison of simulation and experiment of cutting force.](image)

5. Conclusions
In this paper, the influence of cutting force produced by rake angle and the tip radius was researched. From the study, It can be concluded that with the rake angle increasing, the back force $F_y$ decreased...
gradually but the feed force $F_f$ and the main cutting force $F_z$ increased slowly after the rake angle reflection angle 10°; With the tip radius increasing gradually, the back force increases gradually. 

By the simulation of the finite element analysis software ABAQUS, the law of the cutting force was changed with the changing of rake angle and tip radius was obtained. Meanwhile, by the comparison with the result obtained from experiment and simulation, we could find that the changing trend between them was consistent.

From the research above, the conclusion could be obtained: the rake angle suitable for cutting the high temperature alloy is 10° and the tip radius is 0.4 mm.

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