Finite element analysis of a precision machine tool spindle
40GrMo turning process based on DEFORM

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Abstract: Turning as a common forming method of parts, its typical processing characteristics are: in the process of turning there is a lot of turning heat, turning temperature concentration, stress concentration, etc; these phenomena in addition to affecting the tool life, but also to a large extent affect the quality of turning. In this paper, the temperature and stress concentration phenomenon in the turning process of 40GrMo is studied by using orthogonal parameters in combination with experiment and simulation, and the influence rule and correlation are analyzed. In order to improve the surface quality and tool life after machining, the combination of cutting parameters of the above two processes is optimized.

1. Introduction
Shaft parts are common parts in machining. Although the shape of shaft parts is simple, the machining errors are relatively large in the cutting process, so the turning of shaft parts has always been a difficult point in machining. As people have higher and higher requirements for the accuracy of shaft products, how to improve the processing accuracy of slender shaft products while saving manpower and material resources is an urgent problem to be solved. Finite element simulation technology can solve this problem. Its application in turning shaft parts is mainly manifested in the following aspects:

(1) Analysis of cutting force: Radial cutting force is the main factor affecting the machining of slender shafts. Through simulation, the cutting force changes during turning can be predicted, and corresponding measures can be taken to reduce the impact of cutting force on machining accuracy.

(2) Analysis of tool wear: Due to the increased requirements for shaft turning accuracy, tool wear in the turning process has attracted people's attention. The finite element simulation technology can be used to predict the change of tool wear in the turning process, and the turning accuracy can be improved by tool compensation.

(3) Thermal deformation analysis: In the process of turning a slender shaft, due to the sharp increase in temperature, the shaft will inevitably deform due to temperature, which will lead to dimensional errors. This problem can be solved well through simulation.

DEFORM-3D is a set of finite element simulation system based on process simulation, specially
used to analyze the three-dimensional flow in the metal forming process and the flow of material and temperature during the forming process. The simulation function of DEFORM is very powerful. With multiple correlations and multiple couplings, it can analyze the large deformation, large displacement and thermal characteristics of the metal forming process. The division of the mesh is very important in the finite element analysis software. Sometimes the destruction of the grid during the solution process is the termination of the solution process, but the DEFORM software has a generator that can trigger the grid redrawing on its own. If the solution is difficult to solve due to the grid, it can automatically restart Divide the grid and optimize the online shopping to make the solution calculation better continue. The establishment of forming process simulation in DEFORM is a process of organically combining elastic-plastic finite element theory, computer image processing technology, and rigid-plastic forming technology. Its finite element analysis process is shown in Figure 1 below, and the specific functions of each module are as follows:

1. Pre-processor module: used for interactive input of data, such as: temperature field, initial velocity field, punch stroke, boundary conditions and friction coefficient. It is used for the transmission of initial conditions, velocity fields, boundary conditions and other data.

2. Analog processor module: This module is mainly used to perform huge calculation simulations in the background. At the same time, it can monitor the simulation status in real time through simulation monitoring. This module can help the operator monitor the simulation progress and discover simulation failures in time.

3. Post-processor module: through the post-processor, the simulation results can be output in graphics, data or mixed. It can output a variety of physical parameters such as force, stress, strain, speed, density, temperature, hardness, etc, and can output data of wear rate, wear depth, and life after wear of the tools in the cutting model. Various complicated processing such as multi-point tracking.

![Figure1. Process of deform processing](image)

This paper studies the problems of tool wear, cutting heat, and cutting force in the cutting process of a precision spindle. The spindle adopts 40GrMo alloy steel. Its main mechanical properties are shown in Table 1. Its hot rolling hardness is 241HBS and annealing hardness is 198HBS. With better performance and lower cost, it is widely used in manufacturing shafts, gears, molds and other important mechanical parts. The forming method of 40GrMo alloy steel spindle is still mainly machining, and the most common machining method is turning. Because of its high mechanical strength, the cutting force required in the cutting process is relatively large, and the resulting problems such as cutting heat, tool wear, and processed surface quality are more prominent. This article mainly simulates the 40GrMo turning process of a precision machine tool spindle and verifies it through experiments, establishes the orthogonal parameters of cutting parameters, and analyzes the influence of cutting parameters on cutting heat, tool wear and cutting force.

| σb (Mpa) | σs (Mpa) | ψ | HB  | C%   | Mo%   | Gr%   | Mn%  |
|----------|----------|----|-----|------|-------|-------|------|
| ≥520     | ≥280     | ≥38%| ≤217| 0.35–0.45| 0.15–0.25| 1–1.50 | 0.4–0.7 |
2. Establishment of finite element model

2.1 Prefabricated parameters and calculation model
According to the degree of influence of the main angle of the tool on the turning quality, and according to the specific situation, turning shaft parts, the typical problem is that the workpiece is too long, resulting in poor rigidity and easy bending. Therefore, when choosing a tool, it should be based on the premise of taking into account the use requirements. Reduce the deformation of the workpiece first. The maximum temperature of this experiment can reach 1000 ℃, so the modeling simulation and experiment process adopt WC material, and the WC tool is made by powder metallurgy, and the working condition is good at high temperature and high temperature[2]. The tool model is DNMA432, and the WC tool is assigned the corresponding material properties in the modeling. The specific parameters are shown in Table 2.

Table 2. Part of tool working parameters

| Materials | Rate angle | Relief angle | Entering angle | Tool nose arc radius/mm |
|-----------|------------|--------------|----------------|------------------------|
| wc        | 10°        | 5°           | 90°            | 0.8                    |

The simulation process uses a typical tool model Usui, and the calculation formula of Usui wear depth is:

\[ W = \int apVe^{-b/T}dt \]

In the formula, \( W \): the wear depth; \( p \): the contact pressure; \( Ve \): the slip speed; \( T \): the contact surface temperature; \( dt \): the time increment; \( a \) and \( b \) are the constants determined through experiments. This experiment takes \( a = 10^{-7} \), \( b = 885 \).

2.2 Modeling process
Under the operating environment of the Deform-3D Turning module, import the tool model DNMA432, import the alloy workpiece model 40GrMo and the corresponding parameters and store them to fill the material library. Set the ambient temperature 20℃, sufficient cooling and lubrication, a coefficient of heat exchange with the environment 0.05, a coefficient of friction between the workpiece and the tool 0.4, and a coefficient of thermal conductivity between the two 40. The coefficient of friction selects the tool and gives the material properties of tungsten carbide. Absolute meshing is performed on the tool to 30, 000, and the workpiece is relatively meshed to control the minimum unit size 20% of the feed. After checking the data, the turning data DB file is generated and the simulation calculation is started[3].

3. Acquisition and Analysis of Parameters of Orthogonal Simulation Experiment

3.1 Orthogonal simulation experiment
Orthogonal experiment is a common method to explore the influencing factors of multiple factors[4],
by designing an orthogonal data table to obtain a set of optimal combination parameters, and use the parameters to conduct experiments. Establish two-dimensional and three-dimensional models, use a large number of orthogonal cutting data combinations to explore the reasonable three-element selection principle for 40GrMo alloy steel in the turning process, and then test the reliability of the simulation test through the actual vehicle. Table 3 shows part of the orthogonal test data orthogonal test factor level, the spindle speed range is 400-2500rpm, the feed range is 0.1-0.3mmrev-1, and the cutting depth range is 0.5-1.5mm. After a large amount of simulation data, it is found that when the feed is 0.1-0.3mmrev-1 and the cutting depth is orthogonally changed between 0.5-1.5mm, the effect on the cutting force, cutting heat and tool wear studied in this paper is not significant. Therefore, this article mainly analyzes the influence of cutting speed changes.

Figure 3-Figure 5 are the simulation effect diagrams under a specific cutting element. Figure 3 is a cloud diagram of the cutting temperature distribution of the simulation experiment. Figure (a) is the overall cutting heat distribution. It can be seen that the chip temperature is significantly higher than that of other parts. It can be seen from the partial enlarged figure b and the temperature d distribution of the tool tip that the cutting process The highest temperature in the medium is not at the tip of the tool, but above the rake face. The reason may be caused by friction when the chips flow out along the rake face. Therefore, the chip should be removed and broken in time during the cutting process, and cooling should be strengthened. Reasonable lubrication Reduce the cutting temperature. Figure 4 is a cloud diagram of the distribution of the wear rate of the cutter head. It can be seen that the part with the largest wear rate during the cutting process is above the rake face and basically coincides with the highest temperature. It is not at the main cutting edge with the greatest force. The main factor of tool life is temperature. Figure 5 shows the law of cutting force change. It can be seen from multiple simulations that the feed resistance is about 1/5 of the main cutting force. The machine tool consumes more power in the feed motion transmission chain, which is different from the alloy steel. Relatively high mechanical strength.

Table 3. Partial orthogonal experimental data

| Spindle speed n/rpm | Feed rate f/(mm·r⁻¹) | Depth of cut ap/mm | Main cutting force Fy/N | Feed force Fz/N | Temperature /°C | Wear depth /µm | Residual stress/Mpa |
|---------------------|-----------------------|-------------------|------------------------|----------------|-----------------|----------------|-------------------|
| 1 1000              | 0.1                   | 1.5               | 790                    | 170            | 810             | 0.135          | 714               |
| 2 1000              | 0.2                   | 0.5               | 530                    | 130            | 882             | 0.141          | 804               |
| 3 1000              | 0.3                   | 1                 | 1280                   | 210            | 985             | 0.149          | 758               |
| 4 1500              | 0.1                   | 1.5               | 827                    | 123            | 893             | 0.123          | 772               |
| 5 1500              | 0.2                   | 0.5               | 400                    | 110            | 953             | 0.107          | 759               |
| 6 1500              | 0.3                   | 1                 | 1158                   | 230            | 965             | 0.154          | 739               |
| 7 2000              | 0.1                   | 1.5               | 840                    | 130            | 1002            | 0.118          | 763               |

(a) Overall distribution cloud image  (b) Local enlarged view
3.2 Experimental results

Figure 6–Figure 9 are the results of the orthogonal experiment. Figure 6 (a) is the law of the cutting force changing with the spindle. It can be seen that the law of the main cutting force is to increase the speed in the low speed range, and the cutting effort is saved. After entering the medium and high speed, the speed The higher the cutting force, the cutting force will rise again. The most labor-saving point in cutting is at the speed of 1500 rpm. When the speed is exceeded, the cutting force will rise rapidly. Figure 6(b) shows the law of the feed resistance changing with the speed. The feed resistance increases slowly with the spindle speed, and its value is on average 1/7 to 1/5 of the dominant and must. Figure 7 shows the law of the cutting temperature changing with the spindle speed. The simulation curve and the experimental curve are in good agreement. The overall trend rises. The higher the speed, the higher the temperature, which shows a one-way trend. Simulation and experiment found that when the spindle speed is above 2000rpm, local high temperature Above 1000°C, the chips may melt locally, the cutting state is bad, and the adhesion with the rake face is serious, which will increase tool wear.
Therefore, during high-speed cutting, it is necessary to strengthen cooling, use coolant with high cooling coefficient and remove chips in time. Figure 8 shows the tool wear depth curve. The wear is relatively gentle at medium and low speeds. When the spindle speed exceeds 2000 rpm, the tool enters a period of sharp wear. Figure 9 is the curve of residual stress variation. From the figure, it can be seen that the residual stress level is lower when the spindle speed is 1500 rpm, the surface quality is better, and the surface residual stress is larger at low speed and high speed.

![main cutting force](image1)

(a)  
(b)  
Fig 6. Variation law of cutting force

![main cutting force](image2)

Fig 7. Variation law of cutting temperature

![Variation law of tool wear](image3)

![Variation law of residual stress](image4)

Fig 8. Variation law of tool wear  
Fig 9. Variation law of residual stress

4. Summary
On the basis of a large number of orthogonal simulation experiments, this paper analyzes the influence of the spindle speed change on the cutting force, cutting temperature and tool wear during the cutting of 40GrMo shaft during turning. It is recommended that 40GrMo shafts are cut under conventional turning conditions. When the feed is 0.1-0.3mm rev⁻¹ and the cutting depth is orthogonally changed
between 0.5-1.5mm, in order to ensure tool life and ensure surface residual stress, the optimum range of spindle speed is 1500rpm. Through the simulation of temperature, it can be seen that when the speed exceeds 2000rpm, the local temperature exceeds 1000℃, and the cutting state is bad. It is recommended to choose high temperature resistant tools and strengthen lubrication.

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