Thermal Reliability Analysis of Machining Center Spindle Based on Virtual Prototyping

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Abstract: Due to the complexity of structure and control on machining center, its reliability is usually difficult to ensure. In this paper, taking NBP1100 machining center spindle for example, the reliability virtual prototype model was built and the effects of thermal characteristics on reliability were analyzed. The spindle thermal reliability was analyzed by reliability simulation system in ANSYS. The distribution type and characteristic parameters of input variables were identified. The distributions of random sample variables were analyzed. The cumulative distribution function and failure probability of output variables were obtained. According to the sensitivity map, the main variables influencing spindle thermal characteristics were obtained. Methods and suggestions of improving spindle thermal reliability were also presented with the scatter diagrams.

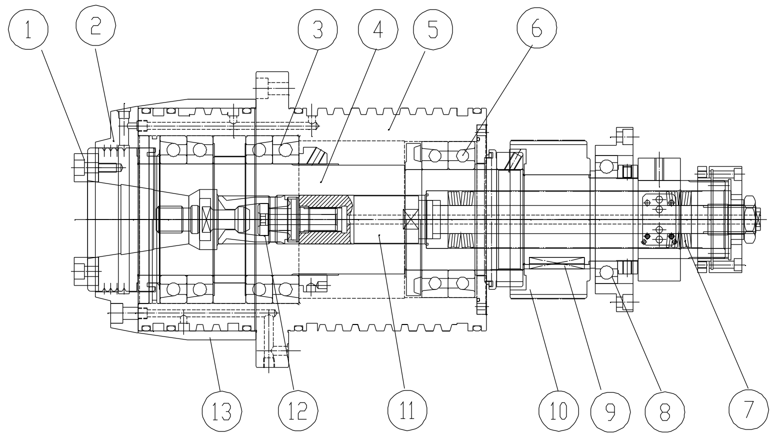
Introduction

The spindle is one of the core parts of the machining center. Many failure modes of machining center are caused by excessive temperature rise. The temperature rise of spindle system engenders thermal deformation and mangles the spindle during processing. Finally the spindle will unable to complete required function, which does not meet the requirement of reliability.

The basic parameters of material properties, initial temperature, thermal load and convective heat-transfer coefficient in traditional thermal analysis are determined. This is out of the actual situation, without taking into account the randomness of parameters. This makes the analysis results are not broadly representative, so it is necessary for the thermal characteristics of the spindle random reliability analysis. The random thermal reliability analysis is based on the randomness of the basic parameters of thermal characteristic. When the parameters are not determined, the impact of the calculation results is evaluated.

Thermal Characteristic Analysis Of Spindle

The research object is the spindle system of NBP1100 vertical machining center. The structure of spindle system is mainly composed of spindle, bearings, sleeve and end cap, is shown in Figure 1. The spindle adopts FAG precision spindle bearings, which can bear radial force and axial force at the same time. Spindle can realize automatically change the tools with automatic oil cylinder. The spindle cooling system is water cooling. The oil cylinder is a double-acting hydraulic cylinder, a signal ring for working position at the back of the cylinder rear spindle running signal output, to ensure the reliability while tightening or loosening the tool.



1.end bond 2.end cap 3.angular contact ball bearing 4.spindle 5.sleeve
6.angular contact ball bearing 7.disc spring 8.deep groove ball bearing
9.round key 10.pulley 11.pull rod 12.four disc claw 13.water lantern ring

Figure1 Structure of the spindle system

The parts and materials of spindle system: spindle material 45 steel, bearing material GCr15, sleeve and spacer ring is made of grey cast iron HT300. Their thermal conductivity coefficients are 48 $W/m{\cdot}℃$ 、44 $W/m{\cdot}℃$ and 47 $W/m{\cdot}℃$. When the temperature field of spindle system is analyzed, the parts that are no effect on the result are omitted. According to the structure and load of spindle system, the finite element model is further simplified to the 1/2 spindle system and imported into ANSYS. Considering the irregularity of the spindle system, the model adopts Solid7.0 unit to free meshing.

Referring to the spindle system processing idle without cooling liquid, analysis in temperature field of the spindle is under the following conditions: (1) the ambient temperature is 20˚C, (2) the viscosity of grease is 20 mm^2/s, (3) the spindle speed is $n = 4000 r/min$. In this case, heat quantity of the front bearing is 415 W , and the rear bearing is 165 W , and heat transfer coefficient is 163 $W/m^2 \cdot K$. The final temperature field of spindle system can be obtained, is shown in Figure 2. The maximum temperature of spindle system is 29.837˚C, located in the front bearing inner ring. The minimum temperature is 28.295˚C, located in the sleeve surface. In this work environment, the maximum temperature rise of the entire spindle system is 9.837˚C.

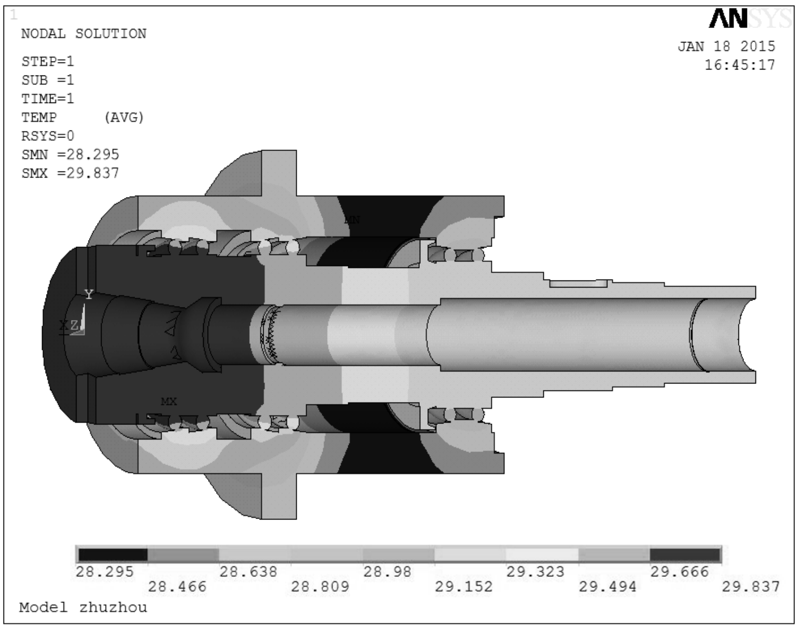


Figure2 Temperature field of the spindle system

Determination Of Major Parameters

After completing the analysis file that is used to loop simulation, the reliability analysis module in ANSYS is opened. The first step in the reliability analysis is to choose the random input and output variables. In this paper, the material properties, thermal loads and boundary conditions of the spindle system are used as the main parameters of the reliability analysis.

Experiments show that normal distribution applies to the random distribution of various parameters, and also can be used to random input parameters distribution of reliability analysis, such as the spindle material characteristic distribution, structure parameter distribution, thermal load distribution, ambient temperature distribution. The variation coefficient of steel thermal conductivity is 0.03. In this case, the variation coefficient of each parameter is 0.03, and is normally distributed. The standard deviation can be obtained, as shown in Table 1.

Table1 statistical properties of input variables

INPUT VARIABLE		MEAN	STANDARD DEVIATION
Thermal Conductivity(W/ m·℃)	KXX1	48	1.44
	KXX2	44	1.32
	KXX3	47	1.41
ambient temperature (˚C)	T	20	0.6
Heat Generation Rate(W/m^3)	HG1	4.4×10^5	13200
	HG2	4.4×10^5	11400
heat transfer coefficient(W/m^2·℃)	C	163	4.89

Thermal Reliability Analysis Results

Spindle system is simulated without coolant idling condition by the Monte Carlo method and Latin hypercube method. It will run 300 simulated steady-state temperature field distributions. First, verify whether cycle analysis times is enough. The output variable to maximum temperature and the minimum temperature difference value of TD is shown in Figure 3, as the figure can be seen a gradual convergence of the mean value of the output variables TD. The trend curve gradually tend to level indicates that the simulation analysis number is sufficient.

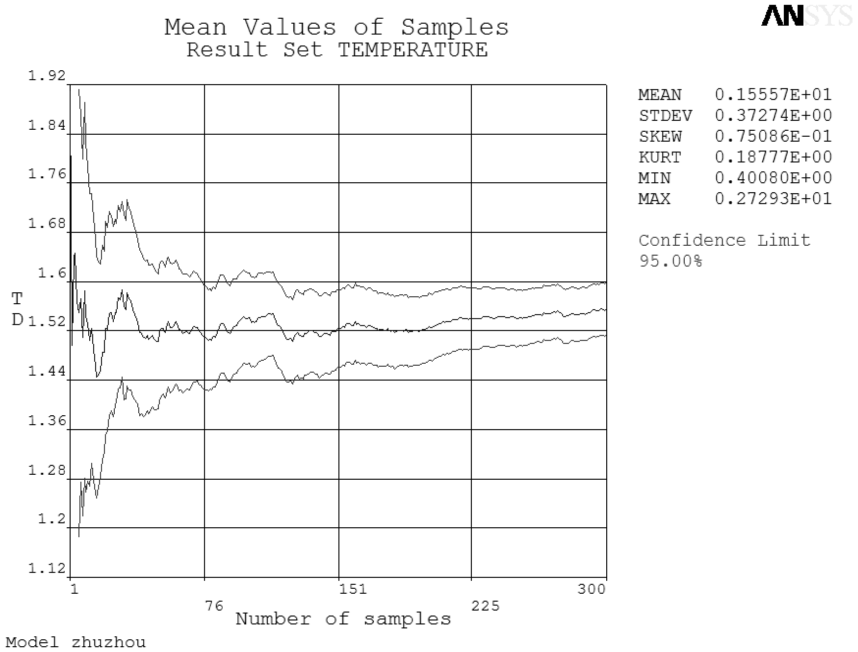


Figure 3 Mean value of temperature difference

Then, check the discrete case of the random output variable TD. Figure 4 is the cumulative distribution histogram of the random output variable TD. Through the cumulative distribution of the histogram can see that TD is clearly concentrated in a certain region. The concentration of TD is concentrated on 28.587~30.606. At the same time, the histogram is relatively smooth, and there is no large gap. The figure overall closes to normal distribution, also verify the number of sampling meets requirement.

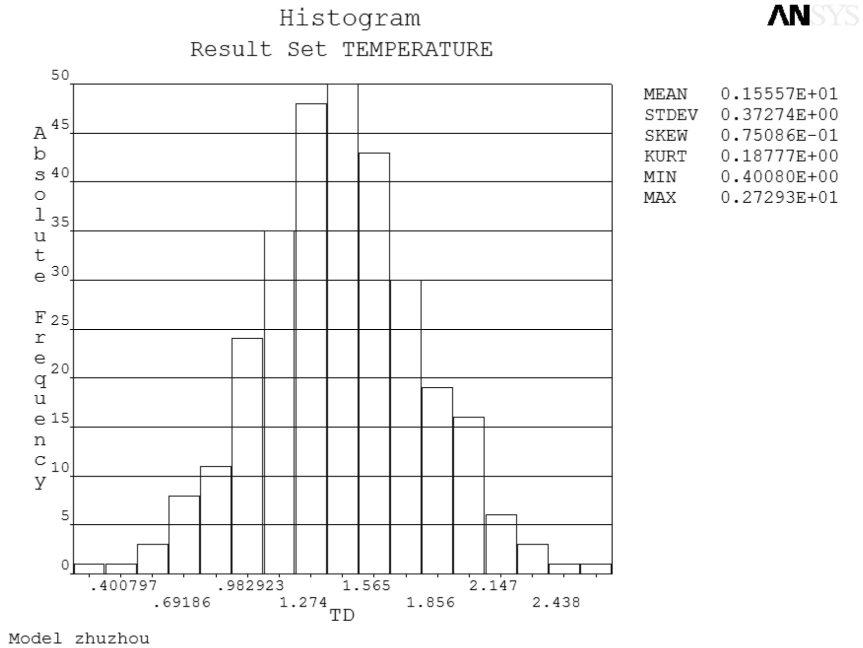


Figure 4 Histogram of temperature difference

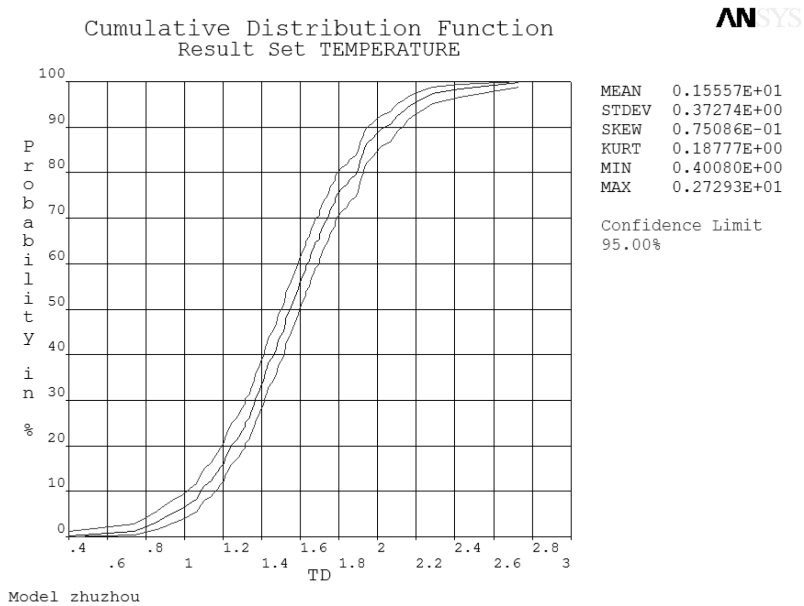


Figure 5 Cumulative distribution function of TD

The cumulative distribution function can completely describe the probability distribution of a random variable, which is the integral of probability density function. It is also called cumulative failure probability distribution, and can reflect the failure probability of the system. In the cumulative distribution function, the failure probability or reliability of the system is the probability of a random variable that is less than or equal to a certain value. In this paper, the failure probability of the thermal characteristics is defined as the probability that temperature difference is greater than the allowable value. Conversely, the reliability is the probability that temperature difference is less than the allowable value. The cumulative distribution function of TD is shown in Figure 5 when the confidence level is 95%. The maximum allowable temperature difference value W=2˚C for the spindle system thermal characteristic analysis, and the function value Z are expressed as the formula:

$$Z = W - (TMAX - TMIN) = W - TD \qquad (1)$$

When $Z \geq 0$, the thermal reliability of the spindle system can be obtained by the cumulative distribution function of the temperature difference TD shown in Figure 5, R=88.6925%, and the confidence interval is [0.847896, 0.919390].

It is necessary to analyze the probability sensitivity in reliability analysis, which reflects the influence of the input variables randomness on reliability analysis. In order to understand the system reliability, some variables that affect the thermal reliability clearly should be further analyzed. Figure 6 is the sensitivity of the input variables to the output variable temperature difference TD by 300 Monte Carlo simulations. The figure 6 shows that when the important degree is 0.025, the heat generation rate of front bearing group HG1 is most sensitive to temperature difference, followed by the thermal conductivity of sleeve KXX3.

From analysis can draw the main factor affecting the thermal characteristics of spindle system is heat generation rate of bearing group. In the actual processing reducing the heat generation rate of bearing is very important. Also in material selection of the spindle system, sleeve material should choose material with big thermal conductivity. It can enhance the convective heat transfer, and achieve the effect of decreasing the temperature difference. The failure probability can provide reliability reference for the enterprise, and it can provide the foundation for further improving reliability.

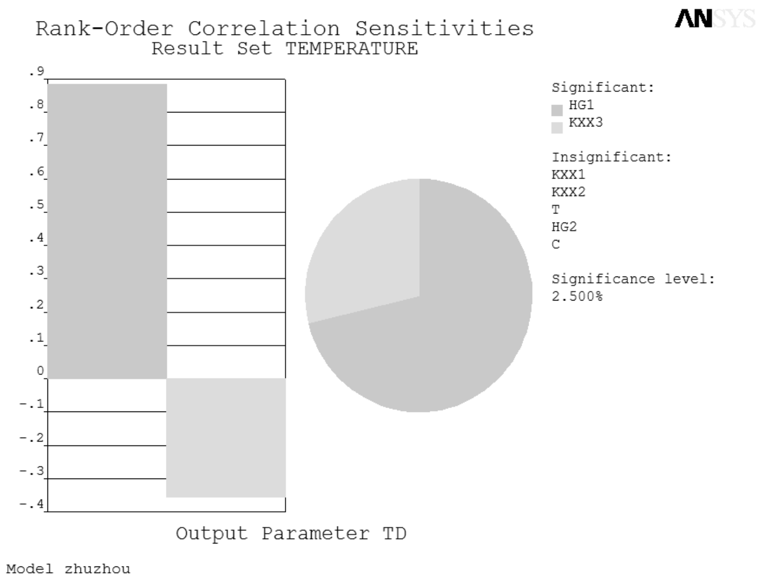


Figure 6 Sensitivity of the input variables to TD

CONCLUSIONS

As a result, the paper may acquire the following conclusions:

(1) The thermal reliability analysis is based on virtual prototype. For the purpose of failure probability calculation, considering the discretization of the input parameters, through the finite element model and the reliability method, using CAD / CAE software to complete the reliability analysis.

(2) The spindle temperature field result is obtained with certain parameters by ANSYS. Using reliability design module PDS, material properties, thermal loads and boundary conditions as the input

parameters, variable distribution, cumulative distribution function and failure probability are analyzed by Monte Carlo method,

(3) According to the sensitivity can be drawn that the main factors affecting the spindle thermal reliability are heat generation rate of front bearing group and thermal conductivity of sleeve. So in actual processing, it is necessary to reduce heat generation rate of front bearing group, and select sleeve material with big thermal conductivity.

Acknowledgements

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