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The influence of speed and cooling system setting on the thermal deformation of spindle temperature rise

WeiLi Zhong · WenHsin Hsieh

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Abstract In precision machining, thermal error has always been recognized as the most significant error, generally accounting for 40-70 % of all errors. In a typical machine tool, the components that generate thermal error usually include the spindle, spindle slide, column, bottom bed and feed system, while the heat source mainly comes from the rotation of spindle motor and feed system.The purpose of this paper is to observe the heat transfer phenomenon of the independent spindle system under different constant speed, variable speed and different environment temperature, and to analyze the correlation between temperature rise and thermal deformation by regression analysis.According to the previous paper and industrial experience, we selected 13 temperature points that are most relevant to the thermal deformation of the spindle system for measurement, including 4 points of the front bearing and 3 points of the rear bearing. The cooling liquid inlet and outlet from the outside will affect the spindle system, as well as the bracket temperature specially selected for more precise calculation of the deformation. Finally, there is a reference temperature.We conduct three steps(Fuzzy clustering, Pearson and Spearman correlation, Multiple regression)to know the relation between temperature rise and thermal deformation.After further testing, we can see that this method can predict the thermal deformation of the machine tool tip within the error of 7μm, which is quite good in the industry. It means that we can provide the machine tool controller with timely compensation to reduce the machining error.

WeiLi Zhong · WenHsin Hsieh
College of Engineering,Peking University
Tel.: +86-010-82524866
Fax: +86-010-82524866
E-mail: qq994478@pku.edu.cn

Keywords Machine tool spindle · Thermal error · Temperature-sensitive point · Fuzzy clustering · Correlation · Regression

1 Introduction

Let's start with a brief description of all the topics covered in this paper[3].We discuss why we pick spindle to analyze and spindle type in Section 1.Section 2 gives an overview of experimental set-up and design.Section 3 demonstrate experimental results.Section 4 present how we do data analysis and give discussion.Section 5 and Section 6 are acknowledgement and conclusion respectively.The contributions of this work are completely observing the temperature rise of spindle in different conditions, and provide a set of methods to analyze the relation between temperature rise and thermal deformation.Furthermore,it is helpful to industry that providing the machine tool controller with timely compensation to reduce the machining error.At the beginning,we need to know what the machine tool looks like as shown in Fig.1.

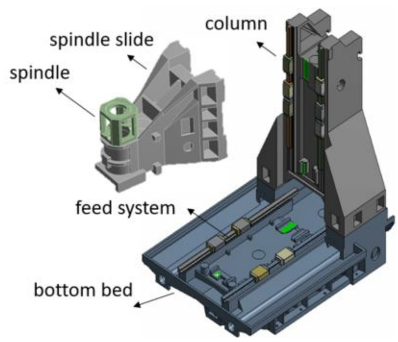


Fig. 1 Machine tool

1.1 Heat sources in machine

As before we have already talked about machining error 40-70 % coming from thermal error.The spindle is a component for holding the cutter and cutting. It needs to be operated for a long time[5]. During the operation, the internal bearing generates heat due to friction, which produces heat load and causes the thermal deformation of the spindle. In addition, the waste heat of the motor and the spindle will also be transferred to the spindle slide, column, bottom bed, etc. through heat conduction, resulting in the thermal deformation of these components. As we can see in Fig.2,

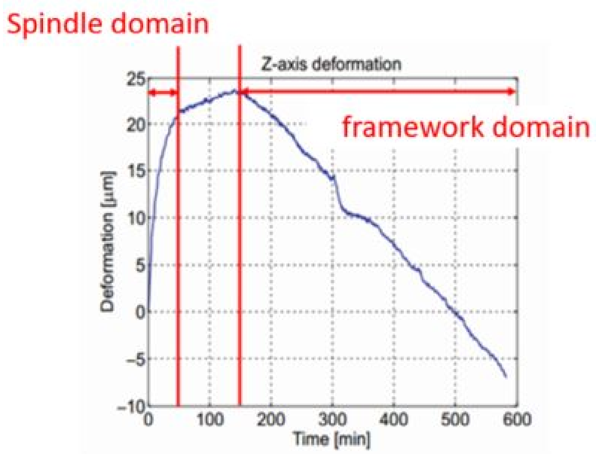


Fig. 2 Machine tool its tool tip Z-axis deformation

In the first 50 minutes, the thermal deformation rises rapidly. At this time, the thermal deformation is caused by the temperature rise of the spindle. Then, between 50 and 150 minutes, the heat of the spindle and the motor is gradually transferred to the spindle slide, column and other framework parts, so that these framework parts begin to produce negative thermal deformation. The thermal deformation of these framework parts and the thermal deformation of the spindle offset each other. After 150 Minutes, the thermal deformation of the spindle has reached a steady state, no longer changing. Other framework parts (such as spindle slide, column, bottom bed, etc.) are far away from the heat source and have a large thermal inertia, so they have not reached the thermal equilibrium, and the temperature continues to rise, resulting in the increase of the thermal deformation (negative value), so that the thermal deformation of the tool tip continues to decline, even to negative thermal deformation.It can be said that in order to correctly estimate the thermal deformation of the tool tip, the analyst of the spindle and framework parts must be clearly controlled.

In the past, the compensation of the machine tool was mostly analyzed by the whole machine. Although the results were obtained, they were often obtained by the superposition of several thermal deformation factors, not by the correct correlation between thermal deformation and temperature rise. Therefore, to solve the complex problem of the structure and heat transfer of the machine tool, we study and analyze separately. In this study, the spindle was selected, and the complete and accurate analysis was established through the measurement of various parameters.

1.2 Spindle type

Why do we need to spend time on the type of spindles? The reason is that we want to be closer to the needs of the industry. We need to know what kind of spindles are used by most machine tools in today's industry, and our experimental equipment is also built to be same as the industry as much as possible.The spindle as shown in Fig.3 Fig.4 can be divided into four types according to the driving mode, Belt type, Gear type, Built-in type, straight type.

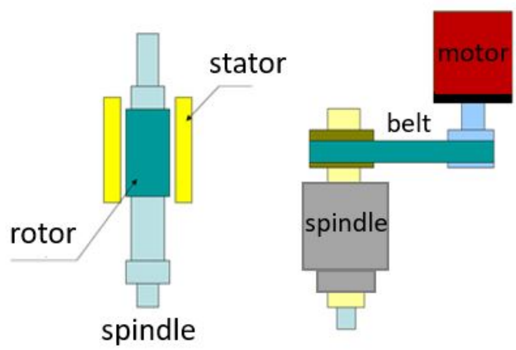


Fig. 3 Built-in type and Belt type

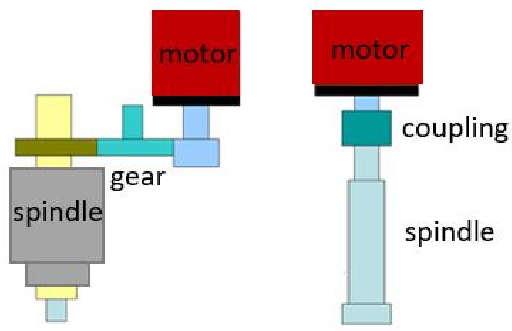


Fig. 4 Gear type and Straight type

The biggest advantage of gear type spindle is that it can transmit high torque and has good heavy cutting ability. Its disadvantage is that the speed is limited by the design of gear and it is not easy to improve.The belt type spindle transfers the movement of the spindle motor to the spindle by the belt. The advantages of the belt type spindle are that the vibration is smaller than that of the Gear type spindle, and it is easy to assemble. The disadvantages of the belt type spindle are that the noise is large at high speed, and the belt tension is not easy to control.The built-in spindle combines the motor and the spindle. The motor rotor is installed on the spindle axis with the stator outside. The operation principle is the same as that of the general spindle motor. It has low vibration characteristics and good dynamic rotation accuracy. However, we focus on the heat transfer so We do not select it. Because the motor is in the spindle, the temperature rise is too high. The straight type spindle its motor is located above the spindle. The motor and the spindle are connected by a high rigidity gapless coupling. The rotation of the motor is transmitted to the spindle through the coupling and its speed is higher than Gear type. Compared with belt type, the noise is much smaller.Also,it is good for controlling temperature rise.Nowadays,most of machine tools adopt straight type spindle except some special machining.

2 Experimental Set-up and Design

2.1 Experimental Set-up

The independent spindle system used in this study is the high-speed spindle model used in Secto: straight type 101A. As shown in Table 1, the specification is driven by asynchronous servo motor, with the speed of up to 12000rpm and the maximum power of 11kw. The two diagonal contact bearings are configured in the form of back-to-back (O-shape arrangement) and fixed-fixed way. The spindle will be supported on the base by the bracket, driven by the motor, cooled by the oil cooling system.

equipment	brand	model number
spindle	Setco	101a
coupling	SKF	SKF7014CE
cooling system	Harbor	HBO-250PTSBM4-409
dryer system	SMC	IDF8E-20
controller system	LNC	†
tool	†	BT40

Table 1 Equipment

The temperature measurement used in this study are data acquisition card NI9213 and E-type thermocouples. The thermal displacement of each axis and the height change of the base of the spindle are using the capacitance displacement sensor and data acquisition card NI9239, and to measure the temperature rise of the rotary tool by using the thermal imager.The model number and specification of measuring equipment are shown in Table 2. The accuracy of NI9213 is $0.25°C$, E-type $\pm1°C$, thermal imager $\pm2°C$, capacitance displacement sensor $96\mu m$, NI9239 is 0.014V.

variable	brand	model	accuracy
temperature	NI	DAQ9213	$0.25°C$
	OMEGA	E-type	$\pm1°C$
tool	CHCT	P384-20	$\pm2°C$
displacement	NI	DAQ9239	0.014V
	LION.P	CPL230	$96\mu m$

Table 2 Measuring Equipment

2.2 Experimental Design

In this study, according to ISO230-3, a set of spindle temperature rise thermal deformation experimental equipment will be established to understand the spindle heat transfer phenomenon. As shown in Fig.5 is the real independent spindle equipment. It can be divided into three parts: temperature measurement system, thermal deformation measurement system and experimental condition, which will be discussed in the following subsections.

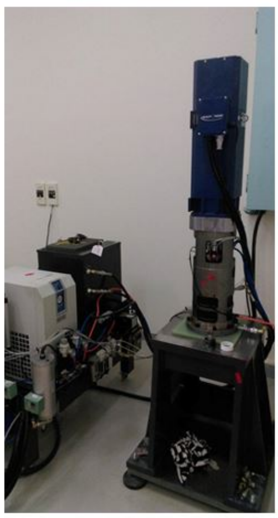


Fig. 5 Independent spindle equipment

2.2.1 Temperature measurement system

In terms of measuring equipment, this paper uses the thermal couple (TC) and two data acquisition cards NI9213 to measure the temperature. In order to see the overall situation of the spindle, 32 temperature points are measured in total. However, shown in Fig.6 Fig.7, 13 points have been selected most related to the thermal deformation for introduction. The other 19 points are deleted because of the low correlation with the thermal compensation equation.The TC1-TC4 are the inside of the front bearing and TC5-TC7 are the measuring points of the rear bearing. Tc8 and TC9 are the inlet and outlet temperature of the measured coolant, TC10-TC13 are the side of the measuring platform, the cylinder of the platform and the cylinder of the external displacement sensor, and T13 is room temperature.

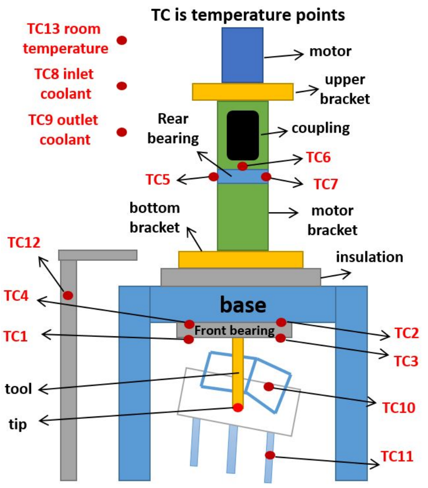


Fig. 6 Independent spindle system diagram

Fig. 7 Real independent spindle system

2.2.2 Thermal deformation measurement system

In the measurement of thermal deformation, we use capacitance displacement sensor.There are four terms to be defined for the spindle thermal deformation measurement system: (1) Deformation of the internal platform (2) deformation of outside cylinder (3)deformation measured by DS2 (4) deformation measured by DS1.

First, deformation of the internal platform refers to the deformation of the platform with DS1 placed in the experiment due to the temperature rise. Second, deformation of outside cylinder refers to the deformation of the cylinder with DS2 installed in the experiment due to the temperature rise. The deformation measured by DS2 is the measurement of the distance change relative to the Z-axis. If the value is positive, it means that the spindle goes up, i.e. we need to compensate the real machine tool tip deformation, so we put a minus sign in front of it. Deformation of the spindle system (3)(4) and the deformation of the platform (1) and cylinder (2) have an equation with machine tool tip as follow:

$$TCP = -(3) + (4) - (1) - (2)$$

The spindle is fixed on the bottom bracket and the downward expansion of its bottom bracket is defined as a negative value. From the physical phenomena, it is known that the deformation of the machine tool tip of the spindle should be calculated by (DS1) subtracting the base upward expansion amount (DS2). Furthermore, the expansion of outside cylinder and internal platform also need to be adjusted. We will demonstrate a series of calculation as follow:

$$(1) = \alpha_1 \cdot \Delta T_{10} \cdot L_1 + \alpha_2 \cdot \Delta T_{11} \cdot L_1$$

$$(2) = \alpha_3 \cdot \Delta T_{12} \cdot L_3$$

where α means coefficient of thermal expansion, ΔT is temperature rise of TC10-TC12 respectively, and (3) and (4) are the value measured by capacitance displacement sensor Fig.8.

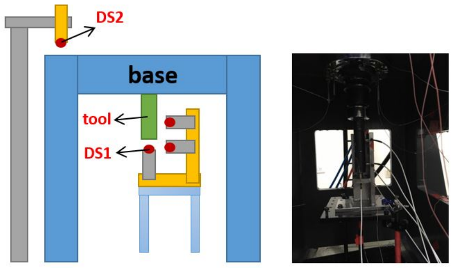


Fig. 8 Real independent spindle system

2.2.3 Experimental condition

In order to thoroughly understand the characteristics of the spindle, there are two experiments in total[2]. The first is fixed speed, three speeds are equipped with two kinds of ambient temperature (open air conditioner or not). In order to find the repeatability of each condition, we have done two times, total of 12 data, the second is variable speed, open air conditioner, total of 2 data, as shown in table 3.

The first one is on the fixed speed of the spindle. The maximum speed of the spindle is 30%, 60% and 90%, i.e. 3600, 7200 and 10800 rpm, respectively, for two hours of rotation. The purpose of this experiment is to to fully understand the performance of the spindle at constant rotating speed through a range from low to high. In addition, Whether there is open air conditioner or not as two kinds of ambient temperature. The purpose is to explore whether room temperature is controlled or not the deformation of machine tool tip error in the factory. Furthermore, the thermal deformation fitting equations of the training group are also established.

The second is variable speed of the spindle measurement. The spindle speed will change every 20 minutes, from 30%, 60%, 90% and no operation in sequence. The first is to see whether there is the same temperature rise trend with constant speed. The second is to test thermal deformation fitting equations, i.e. checking the equation constructed under the constant speed whether is correct or not. When the temperature rises under variable speed as input, we want to look how much the error between the actual and we predicted. If the error is under the industrial requirement, it represents our method is quite good. Note that here no operation does not mean shutdown the machine, and it is more likely standby. Specifically to say is that cooling system still operates but motor stops rotating.

constant speed			
speed	3600rpm	7200rpm	10800rpm
condition	Air × 2	Air × 2	Air × 2
	No × 2	No × 2	No × 2
totaltimes	12		
variable speed			
speed	3600rpm-7200rpm-10800rpm-standby		
condition	Air × 2		
totaltimes	22		

Table 3 Experimental condition

3 Experimental result

The experimental results here only show that 10800rpm constant speed no air-conditioner, 10800rpm constant speed air-conditioner and variable speed condition. Because under 10800rpm rotation speed, the performance of temperature rise is more dramatic that we can easily observe the spindle characteristic. Don't worry about other constant speed conditions, no matter do we open an air conditioner, we have double checked that the trend of temperature rise is familiar with 10800rpm.

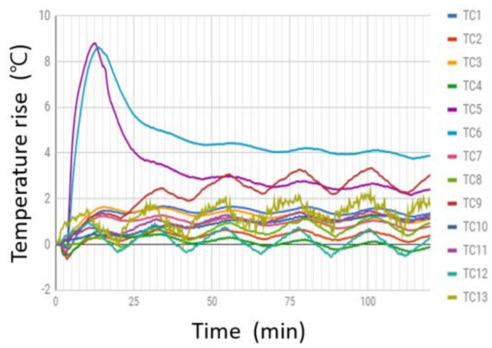


Fig. 9 Constant speed 10800rpm No air, To = 27.47°C

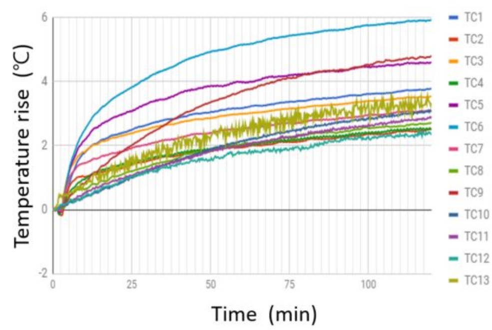


Fig. 10 Constant speed 10800rpm air, To = 22.03°C

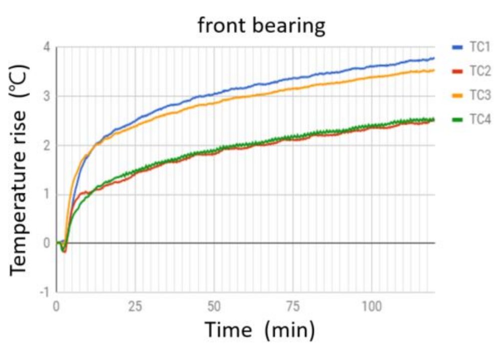


Fig. 11 Constant speed 10800rpm No air, To = 27.47°C

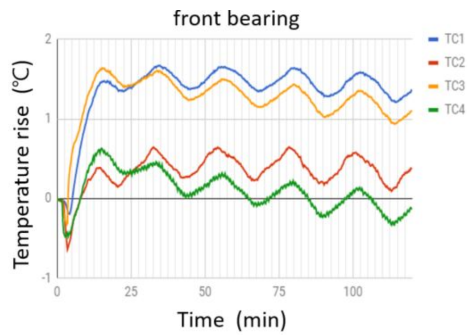


Fig. 12 Constant speed 10800rpm air, To = 22.03°C

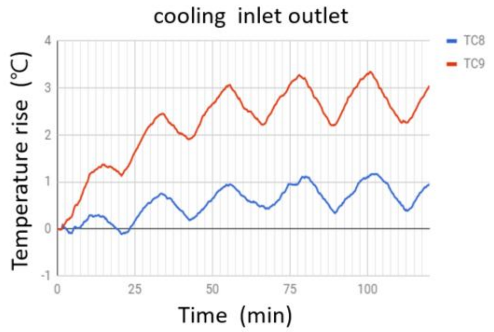


Fig. 16 Constant speed 10800rpm air, To = 22.03°C

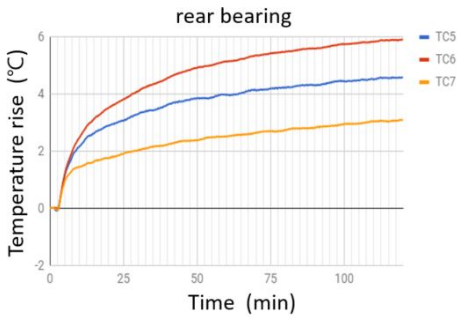


Fig. 13 Constant speed 10800rpm No air, To = 27.47°C

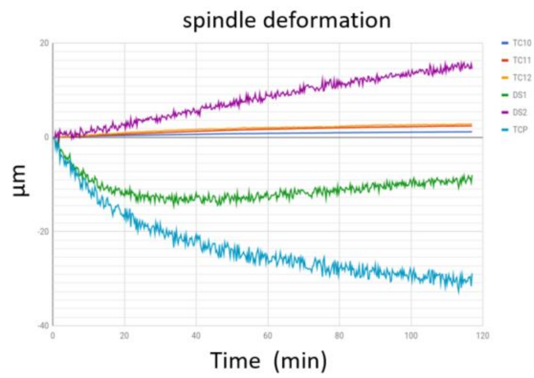


Fig. 17 Constant speed 10800rpm No air, To = 27.47°C

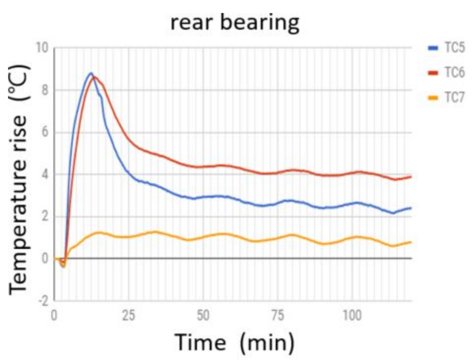


Fig. 14 Constant speed 10800rpm air, To = 22.03°C

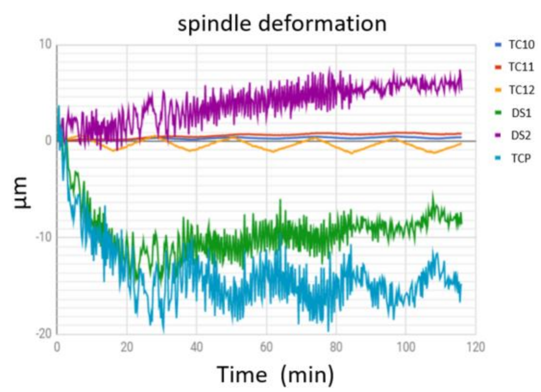


Fig. 18 Constant speed 10800rpm air, To = 22.03°C

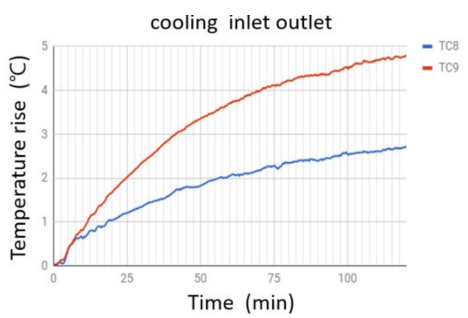


Fig. 15 Constant speed 10800rpm No air, To = 27.47°C

Let's explain more details what the experimental result meaning. In Section 3.1 gives constant speed 10800rpm No air, To = 27.47°C. Section 3.2 demonstrates constant speed 10800rpm air, To = 22.03°C. Section 3.3 compares constant speed 10800rpm No air and air. Section 3.4 shows the variable speed condition result.

3.1 Constant speed 10800rpm No air, To = $27.47°C$

As shown in Fig.9, this figure shows the temperature rise change of the measuring point under the non constant temperature environment. Therefore, the temperature rise of the measuring point is more significant, and then it reaches thermal equilibrium with the ambient temperature. Also, we can see the internal platform and outside cylinder TC10-TC12 was affected by increasing ambient temperature. Furthermore, ambient temperature TC13 rises due to the heat discharged by the spindle motor rotation. In Fig.11 shows the front bearing is under no air conditioner, the temperature of the measuring point decreases in the early stage due to oil gas omen, then rises rapidly, and it gradually reaches the balance with the ambient temperature in 12 minutes, and the temperature rise slope slows down. In Fig.13 shows the rear bearing temperature rise and it is the most significant measurement point. The maximum temperature rise is close to $6°C$, and the temperature rise trend is same as front bearing. In Fig.15, the cooling system is set to change with the ambient temperature, the ambient temperature will gradually rise due to the non constant temperature state under no air condition, so the coolant will also change. Outlet coolant temperature rise is bigger than inlet because coolant is used to bring out the heat of machine. Finally, in Fig.17 we calculate the machine tool tip deformation about 30μm goes down.

3.2 Constant speed 10800rpm air, To = $22.03°C$

As shown in Fig.10, this figure shows the temperature rise change of the measuring point under the constant temperature environment. Therefore, the temperature rise of the measuring point is not significant, and then it performs fluctuation to the ambient temperature. Also, we can see the internal platform and outside cylinder TC10-TC12 was fluctuated by ambient temperature. Furthermore, ambient temperature TC13 is due to the the air conditioner, the ambient temperature is controlled in a temperature range, so the temperature just rise slightly even if the heat emitted by the spindle. In Fig.12, the temperature of the measuring point decreases in the early stage due to oil gas omen, then rises rapidly, and it gradually reaches the balance in 12 minutes, and the temperature rise slope fluctuates. In Fig.14, the rear bearing temperature rise trend is same as front bearing, but TC6 and TC7 have problems in measurement, because the rear bearing has a water jacket to cover the point we measured and it is affected by waste heat, so the temperature rises rapidly at the beginning. In Fig.16, the cooling system is set to change with the ambient temperature, and air conditioner temperature is in a range, so the coolant will fluctuate instead of just rising. Finally, in Fig.18 we calculate the machine tool tip deformation about 15μm goes down which is smaller than no air conditioner.

3.3 Compare constant speed 10800rpm No air and air

As shown in Fig.9 Fig.10, The most obvious difference between the two is the final equilibrium temperature, no air condition temperature will reach 6 $°C$, air condition will be 2-4 $°C$. No air condition temperature will rise steadily while the air condition will rise with fluctuation. In Fig.11 Fig.12, the difference circumstance is as like we talked in Fig.9 Fig.10, the equilibrium temperature and fluctuation. In Fig.13 Fig.14, although we can explain as previous, the rear bearing is the closet to spindle motor, so under air condition, the temperature rise will be controlled i.e. the temperature rise dropped quickly after 25 minutes. In Fig.14 Fig.15, why the fluctuation is so obvious, it can be attributed to two reason. One is the measurement method and the other is air conditioner. We plunge the thermal couple into the coolant directly and temperature is in a range under air conditioner. In Fig.17 Fig.18, the most important is how much the machine tool tip deformation goes down. The reason why the deformation is so smaller than no air conditioner is that the air conditioner cool the machine at any time, reducing the thermal expansion, i.e. reducing the deformation of the machine tool tip. Therefore, people always say that they want to process machining under constant temperature, because it is the most efficiently to reduce thermal error.

3.4 Variable speed condition result

The reason why we only do the variable speed experiment under the air conditioner is that it is case-based. The case here is machining under constant temperature environment, and we hope to improve the machining accuracy by reducing the thermal error. However, my partner does the machining test under non constant temperature. I obtained the measurement data from my partner, and the result of this method is still quite good, but because of the obtaining data I get is not directly by myself, so I can't show it here.

In Fig.19, the figure shows the temperature rise change of the measuring point under the air conditioner. Therefore, the temperature rise of the total measuring point mainly follows with the change of the rotating speed, i.e. there will be a vibration phenomenon. Also, we can see the internal platform and outside cylinder TC10-TC12 temperature rise is affected by the ambient temperature, but the influence of the variable speed is not great at this place, which is similar to the result of the constant speed of the air conditioner, and has the same oscillation phenomenon in the temperature rise. Furthermore, ambient temperature TC13 is controlled by the air conditioner in a temperature range to vibrate. However, due to the influence of the rotating speed of the spindle and air conditioner, the room temperature will show periodic oscillation. In Fig.20, the temperature of the measuring point decreases at the early stage due to the oil gas omen, and then increases with the change of the speed respectively, and reaches the thermal equilibrium with the coolant at different temperatures. In Fig.21, the temperature rise of the rear bearing is the same as the front bearing. The temperature rises first, then slows down, and reaches the thermal equilibrium with the coolant, but the temperature rise slopes is bigger than front bearing because closer to the motor. In Fig.22, since the cooling system is set to change with ambient temperature, the ambient temperature is controlled in a range under the air conditioner. Therefore, the temperature of the cooling system changes with it, and it will appear period due to spindle speed and vibration due to air conditioner. In Fig.23, the emergency button is not used, so that the coolant is still cooling in standby state, so that the temperature returns to the original temperature, and the machine tool tip deformation will return to the original position. The whole process is presented periodically. In addition, there will be tool loading and unloading phenomenon from 10800rpm to the standby state and from standby state to 3600rpm, so the machine tool tip deformation of the Z-axis is very large. If we look more details, we can find the machine tool tip deformation is familiar with respective constant speed experimental result.

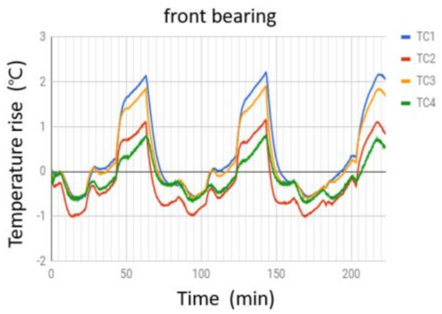


Fig. 20 3600rpm-7200rpm-10800rpm-standby, To=21.59°C

Fig. 21 3600rpm-7200rpm-10800rpm-standby, To=21.59°C

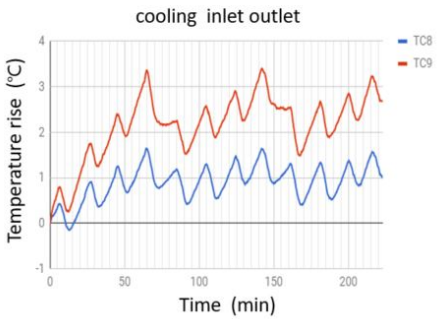


Fig. 22 3600rpm-7200rpm-10800rpm-standby, To=21.59°C

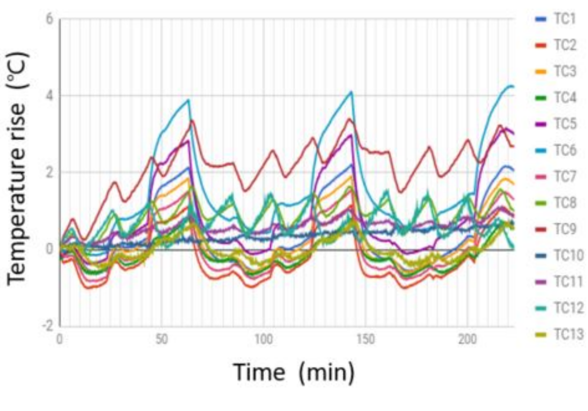


Fig. 19 3600rpm-7200rpm-10800rpm-standby, To=21.59°C

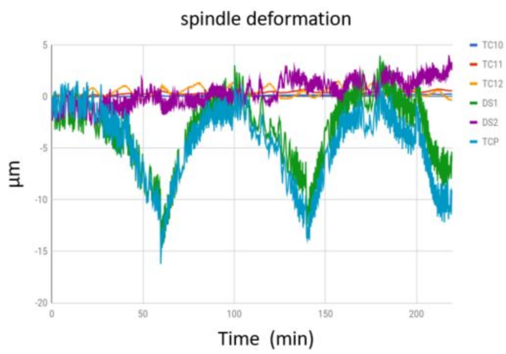


Fig. 23 3600rpm-7200rpm-10800rpm-standby, To=21.59°C

4 Data analysis and discussion

The most important thing here is to find out the relation between the deformation of the machine tool tip and the temperature rise, and then build the thermal compensation equation[1]. Furthermore,testing the thermal compensation equation by variable speed to know the error between prediction deformation and real deformation. Note that training group comes from constant speed and as shown in Fig.25, the X-axis, Y-axis cancel by its heat expansion, so we only consider the deformation of Z-axis[4]. But in the whole machine after 25 minutes in Fig.2, the X-axis, Y-axis need to be considered with framework expansion, i.e. it does not cancel by heat expansion.

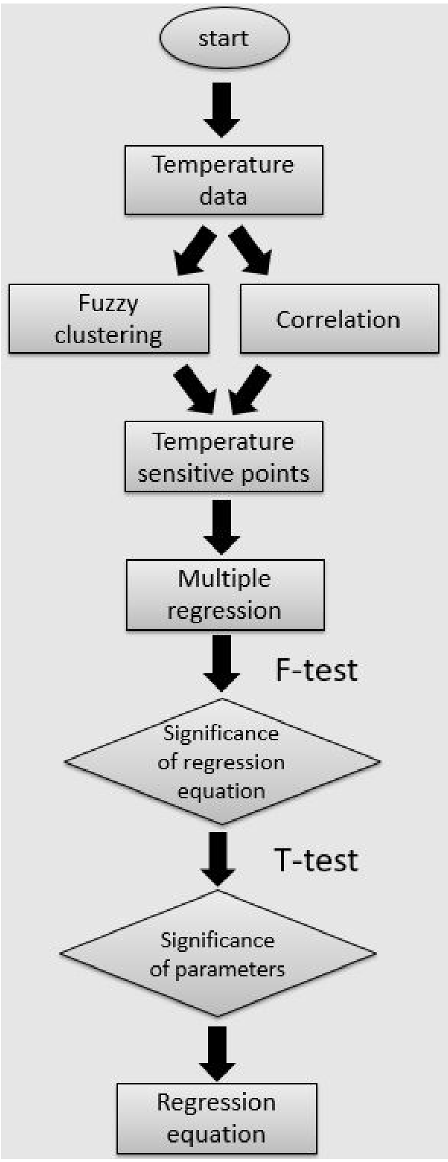


Fig. 24 The steps of data analysis

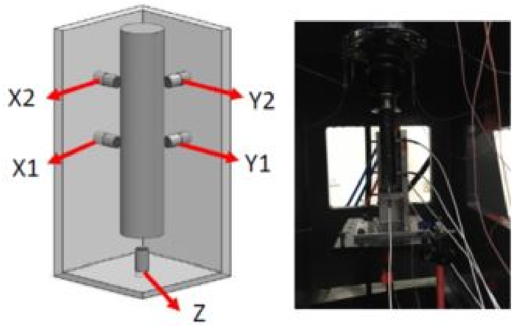


Fig. 25 X-Y-Z axis sensor

4.1 Fuzzy clustering

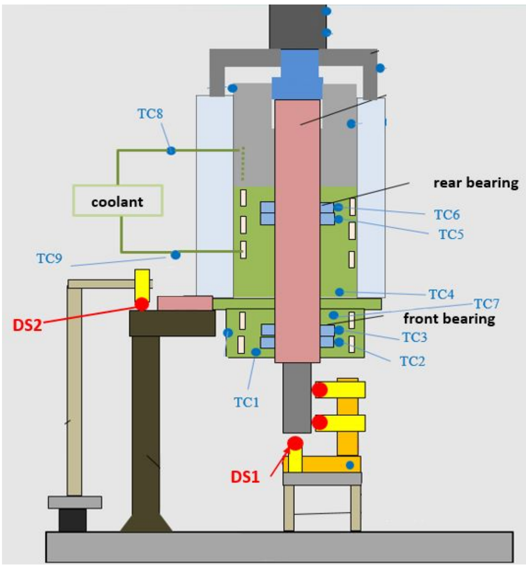


Fig. 26 Temperature points in fuzzy clustering

We process the data analysis according to the steps in Fig.24. First, we carry out the Fuzzy C-means clustering. The reason for this is that after the group divided, in the same group, we just only pick out a point to represent the group's temperature rise state. Physically, it is simplified to only one temperature point, and the temperature rise is only based on that point. Mathematically, the advantage is that it can reduce the parameters we need to consider in the thermal compensation equation. FCM algorithm follows:

$$\min_{C} \sum_{i=1}^{n} \sum_{j=1}^{c} w_{ij}^{m} \|x_i - c_j\| \tag{1}$$

$$w_{ij} = \frac{1}{\sum_{k=1}^{c} \left(\frac{\|x_i - c_j\|}{\|x_i - c_k\|} \right)^{\frac{2}{m-1}}} \tag{2}$$

where $X = \{x_1, ..., x_n\}$, it represents the nine temperature points in Fig.26. The algorithm returns a list of c cluster centres $C = \{c_1, ..., c_c\}$. It is divided into three groups. The first group is TC1-TC4 and TC7. The second group is TC5 and TC6. The third group is TC9. Among them, TC8 is not included in the group because it is dominated by the cooling system and has low correlation with the spindle. It can be found that the clustering result is highly correlated with the actual location of the point.

4.2 Temperature sensitive points and Correlation

In the second step, we make Pearson correlation between the machine tool tip deformation and eight temperature points,i.e.we can see which temperature points are more relative to spindle deformation. The result is shown in the Fig.27. Combined the first step and the second step, we pick out the temperature sensitive points. Specifically to say is that pick out the highest correlation coefficient among the same group, and the result is TC1 in first group, TC6 in second group, and TC9 in third group. Pearson correlation follows:

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2} \quad (3)$$

where r_{xy} is Pearson correlation coefficient between x and y, n is number of observations, x_i is value of temperature rise, y_i is value of machine tool tip deformation.

	TC1	TC2	TC3	TC4	TC5	TC6	TC7	~~TC8~~	TC9
r_{xy}	-0.96	-0.95	-0.93	-0.87	-0.7	-0.85	-0.93	-0.59	-0.71

Fig. 27 The result of correlation coefficient

4.3 Build the thermal compensation equation

In the third step, we conduct multiple regression analysis. After we pick out the three temperature sensitive points i.e. the variable in thermal compensation equation. We use F-test statistic to find out which thermal compensation equation we build has the best performance, mostly in two order to four order. Then, using t-statistic to leave out the variable which is bed in the best thermal compensation equation. But sometimes it needs to conduct cross validation to see the residual error, maybe it was not the best thermal compensation equation, after doing t-statistic might become the best fit equation. The independent variable parameters of multiple linear regression model based on the least squares estimation are: $b_0, b_1, ..., b_m$, so the multiple linear regression equation is : $\hat{y}_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + ... + b_m x_{im} + \varepsilon_i (i = 1, 2, ..., n)$ and calculating the F statistic:

$$F = \frac{ESS/m}{RSS/(n-m-1)}$$

$$TSS = RSS + ESS(\hat{y}_i - \bar{y})^2$$

$$ESS = \sum_{i=1}^{n}$$

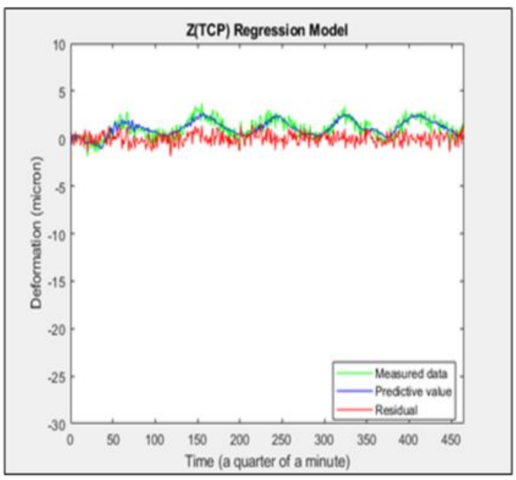
$$RSS = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2$$

where TSS is the overall square of regression equation, ESS is the regression square, RSS is the residual square, $b_i (i = 1, 2, ..., n)$ is the actual measurement values of dependent variable, $\bar{y}$ is the mean of $y_i (i = 1, 2, ..., n)$, $\hat{y}_i (i = 1, 2, ..., n)$ is the estimate values of the regression equation, m is the degree of freedom (DOF) of ESS, (n-m-1) is the DOF of RSS. Then, t statistic:

$$t_i = \frac{b_i}{\sigma\sqrt{q_{i+1}}}, (i = 1, 2..., m)$$

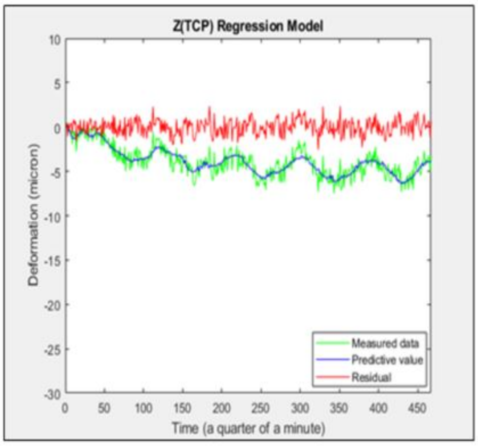
$$\sigma = \sqrt{\frac{RSS}{(n-m-1)}}$$

where b_i is parameters of equation, σ is residuals, q_{i+1} is the(i+1) th diagonal element of regression equation coefficient matrix A. Finally, we can get each training result i.e. the training thermal compensation equation as shown in Fig.28 Fig.29 Fig.30 Fig.31.



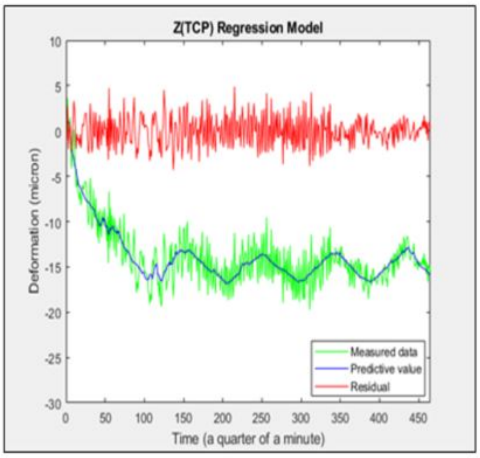
3600rpm

Fig. 28 3600rpm fit circumstance air conditioner



7200rpm

Fig. 29 7200rpm fit circumstance air conditioner



10800rpm

Fig. 30 10800rpm fit circumstance air conditioner

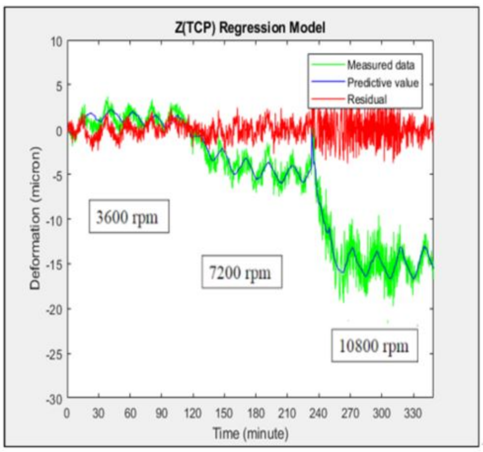


Fig. 31 total fit circumstance air conditioner

$$
\begin{aligned}
E =& b_0 + b_1T1 + b_2T6 + b_3T8 + b_4T1^2 + b_5T6^2 + \\
& b_6T9^2 + b_7T1T6 + b_8T1T9 + b_{10}T1^3 + b_{11}T6^3 + \\
& b_{12}T9^3 + b_{13}T1^2T6 + b_{14}T1^2T9 + b_{15}T6^2T1 + \\
& b_{16}T6^2T9 + b_{17}T9^2T1 + b_{18}T9^2T6 + b_{19}T1T6T9
\end{aligned} \tag{4}
$$

The training thermal compensation equation is above equation (4), Where E is the machine tool tip deformation, b_0 to b_{19} is coefficient, T1,T6,T9 is temperature rise data.

4.4 Testing compensation equation and discussion

How do we test compensation equation is that recalling the Fig.20 Fig.21 Fig.22, the figures give us not only the variable speed spindle characteristic , but also give as an overall testing data i.e. we can think testing data is that the real industry process machining. When process machining is variable speed, and when waiting for the next process, the machine is standby, and repeat like a period a period. So, we use the variable speed temperature rise as input to equation (4) and get output as prediction for machine tool tip deformation. Finally, compared with the real machine tool tip deformation (Fig.23), we can know the performance of our method. The compared result is shown in Fig.32, it is quite good because the error is under $7\mu m$ which is adopted in industry.

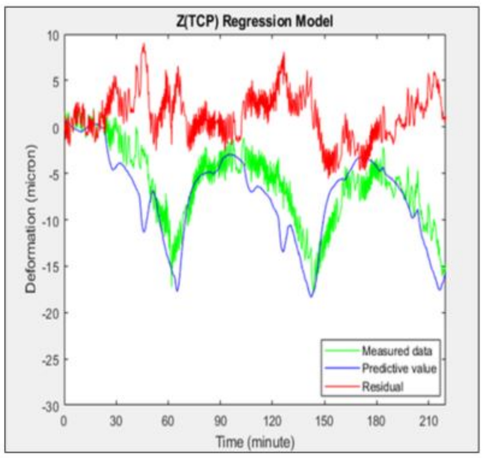


Fig. 32 Compared result air conditioner

Don't forget no matter the training data or testing data is under air conditioner, i.e. the constant temperature environment. Nothing to worry about if under no air conditioner, the performance is also adopted in industry i.e. under $15\mu m$. Okay,Let's go back the work we done and our contribution. We completely observe the temperature rise of independent spindle in different conditions, and provide a set of methods to analyze the relation between temperature rise and thermal deformation. Furthermore,it is helpful to industry that providing the machine tool controller with timely compensation to reduce the machining error. There has two things need to be noted. One, under no air conditioner machining is in mostly traditional industry, otherwise having air conditioner controlled is also existed, like machining chip enterprise. It is said that one more zero machining error after the decimal point, one more zero the value we get before the decimal point. Second, we do not consider the whole machine circumstance, as shown in Fig.2, the thermal deformation of whole machine is complicate. But don't worry about we can not figure out this problem, by decomposition of whole machine can deal with it, our study group team are going on that direction. Fortunately, we have solved the problem before 25 minutes process machining. And it is really helpful to the later study, because we have totally known the spindle characteristic which is one of main heat source.

5 Conclusion

The most efficient way to reduce machining error is by reducing thermal error. The thermal error comes form heat expansion, and causing the heat expansion is due to the heat source. i.e. the rotation of spindle motor and feed system. The whole machine analysis is too complicated, and too factors affect the result. By decomposition of whole machine, we focus on one heat source, i.e. the spindle. We selected 13 temperature points that are most relevant to the thermal deformation of the spindle system for measurement, including 4 points of the front bearing and 3 points of the rear bearing. The cooling liquid inlet and outlet, and the bracket temperature specially selected for more precise calculation of the deformation, and the last one ambient temperature. We provide a set of method to deal with our problem by taking Fuzzy clustering, Pearson and Spearman correlation, Multiple regression to find out the relation between temperature rise and thermal deformation, i.e. the thermal compensation equation. After further testing, the accuracy of thermal deformation of the machine tool tip between we predict and the real is lower than 7μm, which is quite good in the industry. It means that we can provide the machine tool controller with timely compensation to reduce the machining error and prove that our study is worthwhile.

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References

1. En-ming, Miao, et al. Temperature-sensitive point selection of thermal error model of CNC machining center. The International Journal of Advanced Manufacturing Technology 74.5-8 (2014): 681-691.
2. VYROUBAL, J. Using the spindle cooling temperature as a tool for compensating the thermal deformation of machines. Acta Polytechnica, 2010, 50.1.
3. VYROUBAL, Jiri. Compensation of machine tool thermal deformation in spindle axis direction based on decomposition method. Precision Engineering, 2012, 36.1: 121-127.
4. SARHAN, Ahmed AD. Investigate the spindle errors motions from thermal change for high-precision CNC machining capability. The International Journal of Advanced Manufacturing Technology, 2014, 70.5-8: 957-963.
5. Guo Hua Zhou, Application design of tool machine, Book, 2014