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MULTI-COMPONENT MEASUREMENT OF GRINDING FORCE DURING HIGH SPEED INTERNAL THREAD GRINDING

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Abstract:
Experiments of internal thread grinding and flat groove grinding show that grinding efficiency and quality can be significantly improved by increasing the wheel speed. According to the characteristics of internal thread grinding and flat groove grinding, the grinding force measurement experiment is designed. The equivalent substitution method is used to compare with the Grinding Force per Unit Area in surface grinding test under the same conditions. The experimental results show that the measurement error of Grinding Force per Unit Area is less than 25 %.

Keywords: High speed internal thread grinding; grinding force; multi-component force measurement; machining detection; online measurement

1. INTRODUCTION

The results show that the surface quality of a workpiece can be effectively improved by increasing the linear speed of the grinding wheel. When the linear speed of the grinding wheel reaches 80 m/s, the surface quality of workpiece can reach a roughness of $Ra = 0.4$ µm. In a certain range of grinding force, the surface quality will not be reduced while the feed speed of workpiece is increased, that is to say, the machining time is shortened and the work efficiency is improved. The existing literature mainly focus on high-speed grinding experiments of the plane and the outer circle, and the grinding force is taken as the index to verify the correctness of the high-speed grinding mechanism [1-2]. However, the experimental data of other types of high-speed grinding, such as internal thread and flat groove grinding, are less, so it is difficult to provide more comprehensive data support for studying the mechanism and theory of high-speed grinding and the calculation of Grinding Force per Unit Area.

The general method for measuring grinding force is to select a three-component measuring instrument as a sensor and to connect the workpiece, the three-component measuring instrument and the machine tool. The grinding force generated by the grinding wheel and the workpiece is decomposed into axial force, tangential force and normal force through the three-component dynamometer [3]. The difficulty of measuring the grinding force of internal threads is that after the lead of the internal thread is determined, the workpiece needs to keep rotating with respect to the machine tool at a certain angular speed, which will greatly interfere with the normal force and tangential force. The linear speed of the grinding wheel is limited by the inner diameter of the nut, so it is difficult to enlarge the diameter of the grinding wheel. It is difficult to keep the relative stability between the grinding wheel and the workpiece because of the vibration of the supporting rod caused by the increase of the rotating speed. Moreover, the contact area between the grinding wheel and the workpiece is very small in internal thread grinding and flat groove grinding, which leads to the decrease of grinding force amplitude, which makes it difficult to distinguish the interference amplitude caused by machine tool vibration, grinding fluid impact and other factors, and reduces the signal-to-noise ratio. All these factors reduce the accuracy of the grinding force measurement.

In order to measure the internal thread grinding force as accurately as possible, the grinding force of internal thread grinding is measured by a six-dimensional torque sensor and a torque sensor respectively, and the grinding force of flat groove grinding is measured by a three-component dynamometer. By using the equivalent substitution method, the contact models of instantaneous grinding wheels for surface grinding, internal thread grinding, external thread grinding, and flat groove grinding are established respectively. The instantaneous contact area and the equivalent radius of grinding wheel for surface grinding by internal thread grinding, external thread grinding, and flat groove grinding are calculated respectively, and the Grinding Force per Unit Area is calculated on the basis of these models.

2. DESCRIPTION OF THE WORK

2.1. Measuring Method

The grinding force in internal thread grinding is measured by a six-dimensional torque sensor and a standard torque sensor respectively (we just used one axis of the six-dimensional torque sensor so that is able to compared with the standard torque sensor), and the grinding force in flat groove grinding is measured by a three-component dynamometer. In the measurement test of each sensor, the cutting line speed of the grinding wheel is 80 m/s, the wheel speed is 40 000 rpm, the grinding wheel r_1 is 20 mm, and the tooth profile half angle θ is 45°; two kinds of head frame speeds are selected, which are 1 rpm and 2 rpm respectively, and the inner radius r_2 of the workpiece is 50 mm; the feed p is 0.02 mm and this is performed five times until the grinding depth reaches 0.1 mm, and ten groups of data are obtained. A total of thirty groups of data were obtained from the three kinds of sensors.

Grinding Force Measurement Method Based on Six-Axis Torque Sensors

The experimental arrangement for the grinding force measurement using a six-axis torque sensor is shown in Figure 1. The maximum outer diameter of the grinding wheel is d_1 ($d_1 = 2r_1$), and the half angle of tooth profile is θ; the workpiece to be ground is a cup-shaped wheel with an inner diameter of d_2 ($d_2 = 2r_2$) and the workpiece is fixed to the sensor by a screw; after the sensor is fixed to the tooling through the screw, it is installed in the chuck of the machine tool (ensuring that the radial runout of the workpiece is not greater than 0.002 mm). The sensor is sensitive to the grinding torque M_1 generated in the high-speed grinding process of the internal thread, and enters the data acquisition system through the data line as the original data of the test. The n is number of data points in a cycle. By calculating the average grinding torque $\overline{M_1}$ and dividing by r_2, the tangential grinding force F_1 measured by six-axis torque sensor can be obtained:

$$\overline{M_1} = \sum_{i=1}^{n} M_i/n, \quad F_1 = \overline{M_1}/r_2 \tag{1}$$

Grinding Force Measurement Method Based on Standard Torque Sensor

The experimental arrangement for the grinding force measurement using a standard torque sensor is shown in Figure 2. The grinding wheel with the maximum outer diameter of d_1 ($d_1 = 2r_1$) and half angle of tooth profile of θ and cup-shaped wheel shaped workpiece with inner diameter of d_2 ($d_2 = 2r_2$) are connected to the torque sensor by a flat key, and the axial displacement is limited by bolts; the sensor is installed in the chuck of the machine tool through the flat key (ensuring that the radial runout of the workpiece is not greater than 0.002 mm), and the bottom is fixed to the base using screws. The axial elastic strain cell of the sensor collects the grinding torque M_2 generated during the high-speed grinding of the internal thread, which enters the data acquisition system through the data line as the original data of the test. By calculating the average grinding torque $\overline{M_2}$ and dividing by r_2, the tangential grinding force F_2 measured by the standard torque sensor can be obtained:

$$\overline{M_2} = \sum_{i=1}^{n} M_i/n, \quad F_2 = \overline{M_2}/r_2 \tag{2}$$

Figure 1: Experimental assembly for measurement based on six-axis torque sensors

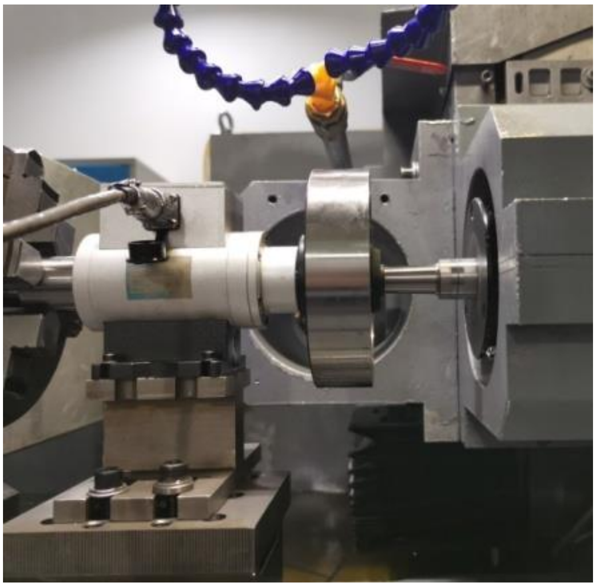

Figure 2: Experimental assembly for measurement based on standard torque sensor

Grinding Force Measurement Method Based on Three Component Dynamometers

The experimental arrangement for the grinding force measurement using a three-component dynamometer is shown in Figure 3. The maximum outer diameter of the grinding wheel is d_1

($d_1 = 2r_1$), and the half angle of the tooth profile is θ . The force sensor is a three-component dynamometer (9256C2, Kistler). The workpiece to be ground is a circular flat plate. The three-component dynamometer is fixed between the base and the workpiece by screws (the parallelism between the workpiece and the plane datum of the machine tool is not greater than 0.003 mm). When the grinding wheel moves parallel to the surface of the workpiece, its moving speed is equivalent to the relative speed between the workpiece and the grinding wheel during internal thread grinding. The forces F_x and F_y on the surface of the parallel workpiece are collected by the three-component dynamometer, and the resultant force F_{he} is obtained by point-by-point geometric addition. By calculating the average grinding force $\overline{F_{\mathrm{he}}}$ in the grinding process, the tangential grinding force F_3 measured by the dynamometer can be obtained:

$$F_{\mathrm{he}} = \sqrt{F_x^2 + F_y^2},\ \ F_3 = \overline{F_{\mathrm{he}}} = \textstyle\sum_{i=1}^{n} F_{\mathrm{he}_i}/n \qquad (3)$$

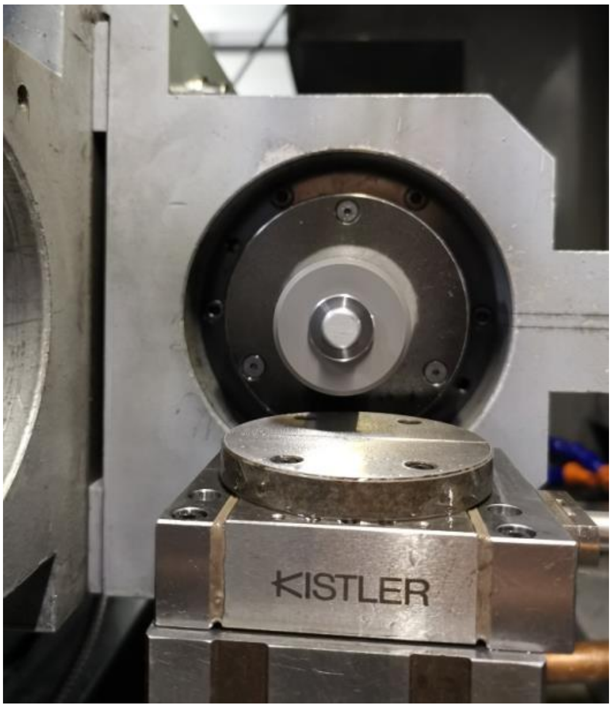

Figure 3: Experimental assembly for measurement based on three component dynamometers

2.2. Grinding Contact Model and Grinding Force per Unit Area Calculation

Grinding Contact Model

The instantaneous contact models of flat grinding, flat groove grinding, and internal thread grinding are shown in Figure 4. Among them, the workpiece surface of flat grinding and groove grinding is plane, and the workpiece surface of internal thread grinding is cylindrical; the grinding wheel of flat groove grinding and internal thread grinding is a disc wheel with tooth half angle of θ, and flat grinding wheel is a cylindrical wheel.

For the flat grinding process, the contact between the grinding wheel and the workpiece is shown in Figure 5. It can be seen that the contact area is related to the wheel width k, feed rate p and grinding wheel radius r_1. If the contact area is S_{p}, then:

$$l_1 = \sqrt{r_1^2 - (r_1 - ap)^2} \qquad (4)$$

$$S_{\mathrm{p}} = 2kr_1 \sin^{-1}(l_1/r_1)\,. \qquad (5)$$

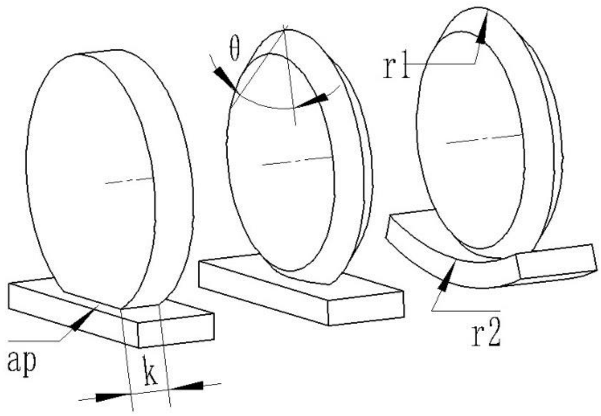

Figure 4: The instantaneous contact models of flat grinding, flat groove grinding and internal thread grinding

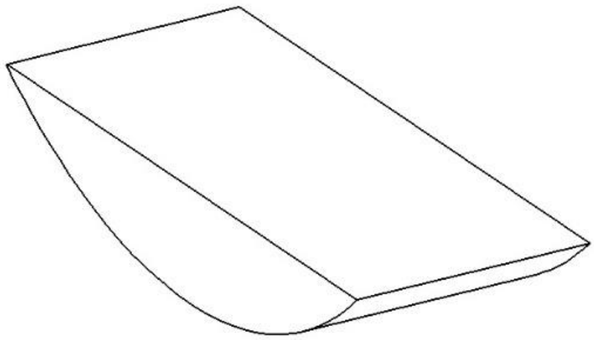

Figure 5: Shape of contact area in flat grinding process

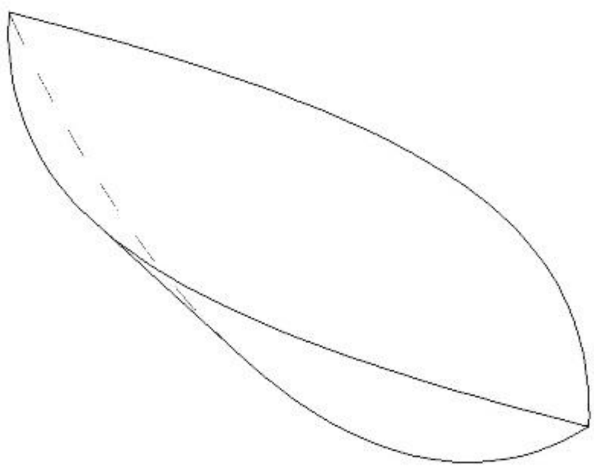

Figure 6: Shape of contact area in flat groove grinding process

For the flat groove grinding process, the instantaneous contact between the grinding wheel and the workpiece is shown in Figure 6.

As opposed to flat grinding, the grinding wheel used in flat groove grinding is no longer a cylinder, but a symmetrical cone. Therefore, the relationship between the wheel width k and the feed rate p and the tooth profile half angle θ of the grinding wheel is as follows:

$$k = p \tan\theta \, . \tag{6}$$

If the contact area is S_c, then:

$$S_\mathrm{c} = r_1^2 \, (\alpha - \cos\alpha \sin\alpha)/\cos\theta \, , \tag{7}$$

where α is the angle corresponding to the arc length of the grinding wheel contacting the workpiece in the flat groove grinding. The relationship between the angle and the feed rate p and the grinding wheel radius r_1 is as follows:

$$\alpha = \cos^{-1}[(r_1 - ap)/r_1] \, . \tag{8}$$

For the internal thread grinding process, the contact between the grinding wheel and the workpiece is shown in Figure 7.

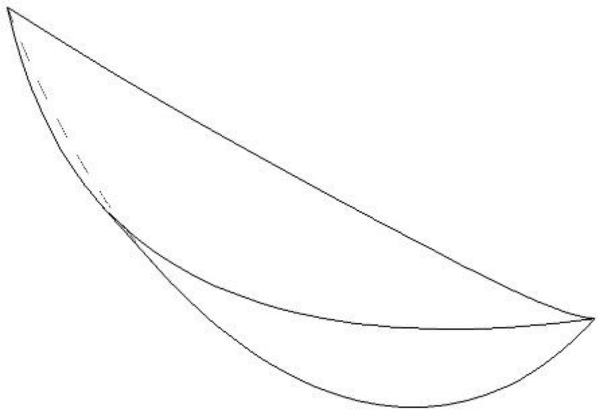

Figure 7: Shape of contact area in internal thread grinding process

Compared with the flat groove grinding, the grinding wheel profile used in internal thread grinding is the same, but the shape of the workpiece is changed from a plane to a circular arc surface, so the contact area is related to the inner radius r_2 of the workpiece. When the contact area of internal thread grinding is S_n, then:

$$S_n = \frac{\left[ac - r_2^2 \sin^{-1}\left(\frac{c}{r_2}\right) + r_1^2 \sin^{-1}\left(\frac{c}{r_1}\right)\right]}{\cos\theta} \, , \tag{9}$$

where a is the distance between grinding wheel axis and workpiece axis:

$$a = r_2 - r_1 + p \, , \tag{10}$$

b is the tangential distance from the contact arc of grinding wheel to the plane of grinding wheel and workpiece axis:

$$b = (a^2 + r_1^2 - r_2^2)/2a \tag{11}$$

and c is the normal distance from the contact arc of grinding wheel to the plane of grinding wheel and workpiece axis:

$$c = \sqrt{r_1^2 - b^2} \, . \tag{12}$$

Calculation of Grinding Force per Unit Area

Given the radius of the grinding wheel r_1, the inner radius of the workpiece r_2, the half angle of tooth profile θ, and the feed p, the unit grinding force $\overline{F_i}$ (i =1 to 3) can be obtained by dividing the tangential grinding force $\overline{F_i}$ ($i = 1$ to 3) by the surface area formula of the corresponding contact model:

$$\overline{F_1} = \frac{F_1}{S_\mathrm{n}}, \;\; \overline{F_2} = \frac{F_2}{S_\mathrm{n}}, \;\; \overline{F_3} = \frac{F_3}{S_\mathrm{c}} \, . \tag{13}$$

2.3. Test Data and Results

Measurement Environment and Processing Parameters

Measurement environment: temperature is 22 °C ± 1 °C, relative humidity is 56 % ± 10 %, atmospheric pressure is local atmospheric pressure.

Processing parameters: grinding wheel speed is 40 000 rpm, two kinds of head frame motor speed are selected, which are 1 rpm and 2 rpm respectively; each thread line is fed five times, each feed p is 0.02 mm, grinding depth is 0.1 mm; grinding wheel radius r_1 is 20 mm, profile half angle θ is 45°, thread lead is 3 mm; workpiece inner radius r_2 is 50 mm, material is GCr15, inner diameter is 100 mm, length is 50 mm. The cylindricity of the outer circle is 0.001 mm. The coaxiality of the inner hole is 0.002 mm.

Main Parameters of Sensors

Table 1: Parameters of sensors

Sensor type	Range	Resolution	Sensitivity	Linearity / % fso
Six-axis torque	1.5 N·m	7.5 mN·m	0.1 pC/N	0.5
Torque sensor	1.5 N·m	50 mN·m	0.1 pC/N	0.5
Kistler 9256C2	25 N	0.1 N	-24.79 pC/N	0.04

Statistical Tables of Results

By comparing Table 2 and Table 3, it can be seen that the Grinding Force per Unit Area based on six-dimensional torque sensor and torque sensor has little difference, and the maximum relative difference is 17.4 %; the maximum relative difference between the results from the torque sensors detailed in Table 2 and Table 3 and the three-component sensor detailed in Table 4 are 21.3 % and 21.7 % respectively. At the same time, it can be seen that with the increase of cutting depth, the grinding force increases, while the Grinding Force per Unit Area decreases gradually; when the head frame speed increases, both the grinding force and the Grinding Force per Unit Area increase.

Table 2: Grinding force test results using six-axis torque sensor

Head frame speed / rpm	**Cut number**	**Cut depth / µm**	**Measured grinding force / N**	**Grinding Force per Unit Area / N/mm²**
1	1	20	0.0248	0.57
	2	40	0.0259	0.21
	3	60	0.0356	0.16
	4	80	0.0481	0.14
	5	100	0.0565	0.12
2	1	20	0.053	1.21
	2	40	0.0742	0.60
	3	60	0.0876	0.39
	4	80	0.1212	0.35
	5	100	0.1224	0.25

Table 3: Grinding force test results using standard torque sensor

Head frame speed / rpm	**Cut number**	**Cut depth / µm**	**Measured grinding force / N**	**Grinding Force per Unit Area / N/mm²**
1	1	20	0.0264	0.60
	2	40	0.0272	0.22
	3	60	0.0392	0.17
	4	80	0.0429	0.12
	5	100	0.052	0.10
2	1	20	0.057	1.30
	2	40	0.072	0.58
	3	60	0.093	0.41
	4	80	0.1203	0.34
	5	100	0.1411	0.29

Table 4: Grinding force test results using three-component force sensor

Head frame speed / rpm	**Cut number**	**Cut depth / µm**	**Measured grinding force / N**	**Grinding Force per Unit Area / N/mm²**
1	1	20	0.035	0.63
	2	40	0.041	0.26
	3	60	0.052	0.24
	4	80	0.061	0.21
	5	100	0.071	0.18
2	1	20	0.061	0.80
	2	40	0.096	0.55
	3	60	0.105	0.39
	4	80	0.151	0.35
	5	100	0.150	0.24

3. SUMMARY

Through three kinds of grinding force measurement experiment, the Grinding Force per Unit Area under the same working conditions was measured. The results show relative agreement to within 25 %. With an increase of grinding depth, the grinding force increases while the Grinding Force per Unit Area decreases.

4. REFERENCES

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