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Evaluation of grinding wheel wear in wet profile grinding for the groove of the ball bearing's inner ring by pneumatic probes[†]

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Abstract

Wear is one of the most influential factors in profile grinding. The measuring of grinding wheel wear is costly and time consuming. We introduce a new online wear measuring method in a wet profile grinding for the inner ring groove of ball bearing. The advantage of this method is the reduction of electromagnetic influence of workpiece as well as the impact of grinding debris and cutting lubricant. Two pneumatic gauging probes are positioned at two different locations with the biggest gap in the wear value on the curved edge surface of the grind stone. When the compressed air flow is blown onto the working surface of the grinding wheel, the back pressure in the measuring chamber corresponding to the gap between the probe and the working surface of the grinding wheel can be measured. Therefore, the radial wear value of grinding wheel can be determined. Based on theoretical calculations and the establishment of its dynamic characteristic curve, it is demonstrated that the first probe measuring wear at the top of the curved edge surface of the grinding wheel with the parameters of the probe d_1 = 0.85; d_2 = 1.5; P = 4 Bar has a measurement range of 200 µm, a maximum speed ratio of 0.01 Bar/µm. The second probe used to capture wear at the margin of the curved edge surface of the grinding stone with the parameters of the probe d_1 = 0.65; d_2 = 1.6; P = 4 Bar has a measurement range of 140 µm, a maximum speed ratio of 0.03 Bar/µm. The experimental results show that the grinding wheel wear value varies at different points of the curved edge surface of the grinding wheel. In profile grinding for the inner ring groove of the 6208 ball bearing, the wear value at the edge of the curved edge surface of the grinding wheel is usually bigger than that at the top of the curved edge surface of the grinding wheel.

Keywords: Pneumatic measuring probe; Profile grinding; Contactless measurement; Wear of grinding wheel

1. Introduction

Grinding is one of the most important methods for high-precision machining. However, the grinding process is inherently difficult to control because its typical parameters are influenced by many factors, including the wear of the grinding wheel [1]. This factor is especially important in profile grinding because of its direct influence on the cutting capacity of grinding stone, as well as on the productivity, quality, and effectiveness of the whole process [2]. Therefore, a suitable and accurate dressing of grinding wheel is required for successful profile grinding [3]. Measuring the wear value of grinding wheel is a crucial part of this process [3, 4].

A number of methods based on different principles have been studied to measure grinding wheel wear [1, 2, 4-7]. Some of them use capacitive sensor [5] or acoustic emission [6]. Another method is based on ultrasonic principle. Recently, a CCD camera has been used to monitor directly the changes of the wheel edge to determine the grinding wheel wear [1, 2, 4, 7]. All these methods are more suitable for measurement in the laboratory. However, they are not accurate enough for in-process measurement application of precision grinding because of negative influence of grinding lubricant, cutting force and machining debris as well as eccentricity in wet grinding. Another limit of these methods is high cost.

Some simple measurement techniques based on measuring dynamic pressure and air flow velocity around a rotating grinding wheel have also been presented [8, 9]. By using an air micrometer or a pitot tube, the average air velocity in the air belt around the wheel can be measured to determine wear value of grinding wheel. However, it is possible for these methods to be impacted by the negative effects of grinding lubricant and machining debris. Based on these principles, other measuring techniques have been developed [3, 10]. By using an air nozzle and a pressure sensor, the change of air rebound pressure from wheel surface can be captured [3, 10]. This method proves some advantages including simple design of the gauge, cost- effective maintenance as well as easy adjusting sensitivity and measuring range [8, 11, 12]. Another

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important feature of the method is that the measuring jet hole is not blocked by tiny particles from lubricant, by particles of chips or by broken grains in the air flow surrounding the grinding wheel [8, 13]. The layers of chips or coolants adhering to the grinding wheel surface would be blown away under the high pressure of this pneumatic probe. Therefore, it can self-clean the measured surface [12]. Thanks to these advantages the pneumatic probe is commonly used in many applications such as non-contact roughness assessment of a moving surface [13, 14], measurement of axial contour of grinding wheel active surface [15] or evaluation of in-process changes of the grinding wheel surface topography [8].

However, none of the previous researches has studied to measure grinding wheel wear in wet profile grinding for the inner ring groove of the ball bearing. In profile grinding, because of large contact area between grinding wheel and workpiece, the cutting force and the cutting heat arising from this process are much bigger than those generated by other normal grinding processes. Thus, a profile grinding wheel is worn continuously and unevenly at various points on its working surface, making its initial shape and accuracy change quickly, causing form errors of processing surface. Furthermore, grinding wheel wear also decreases its cutting capability and longevity. Therefore, grinding wheel wear, under the profile grinding, influences directly on the precision elements of grinding parts including groove surface roughness, groove dimensional accuracy, groove form accuracy. For these reasons, it is very important and necessary to determine grinding wheel wear right in wet profile grinding condition.

In this paper, we introduce a high-pressure pneumatic probe to measure the wear of profile grinding wheel. The goal was to develop an automatic on-line profile grinding wheel wear measuring system in a wet grinding condition with high accuracy. Since each pneumatic measuring probe can only capture the wear on a very small area, which can be considered as a point, we used two pneumatic probes simultaneously to measure wear value at two different points on the working surface of the grindstone. That can be used for evaluating the wear of contour of profile grinding wheel.

2. Principle of pneumatic measuring probe

Fig. 1 shows the measuring principle. Compressed air goes through the constant-pressure valve with source air pressure P to the probe. Two obstructions parts, one with diameter d_1 (Area F_1) and the other with diameter d_2 (Area F_2), are placed in the air flow perpendicular to the flow direction. The compressed air goes continuously onto the measuring surface in the normal direction. The measuring chamber is built between control orifice d_1 and measuring nozzle d_2. A pressure sensor is used to measure the change of pressure p inside the chamber. When the grinding wheel is worn, the distance z between the probe and the wheel surface increases, and therefore, the pressure of compressed air in the chamber p decreases. So that, based on the relationship between gap z and pressure p, the

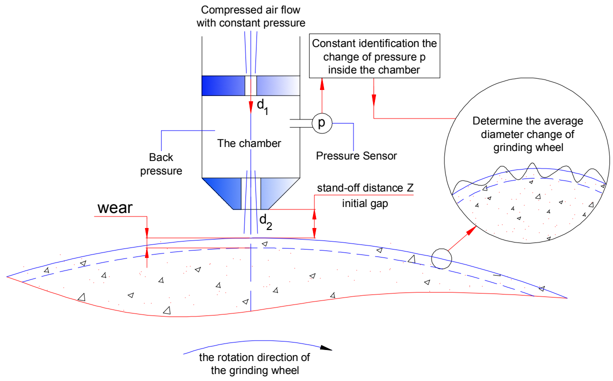


Fig. 1. Measured principle diagram.

wear value of grinding wheel can be determined. While P, d_1 and d_2 are constant, p is a function of z. Thus, measuring the change of pressure Δp by pressure sensor can identify the change of gap Δz, which leads to know the normal wear value of grinding wheel.

By calculating the air flow using air-electric equivalence method and considering the air flow and electric current to be equivalent, it is shown that:

(1) The pressure of air flow is characteristic of air flow's potential energy, which is equivalent to voltage being a characteristic of the potential energy of the electric current.

(2) Airflow obstruction is equivalent to current obstruction. The higher the airflow obstruction, the smaller the flow area.

(3) The intensity of airflow is equivalent to the intensity of electric current.

Thus, the back pressure p of the chamber can be determined by air source pressure P, parameters d_1, d_2 and gap z as follows:

$$p(z) = \frac{P}{1+\frac{R_1}{R_2}} \; with: R = \frac{\alpha}{F^2}$$

$$\rightarrow p(z) = \frac{P}{1+(\frac{F_2}{F_1})^2} \; with: F_1 = \frac{\pi d_1^2}{4}; F_2 = \pi d_2 z \tag{1}$$

$$\rightarrow p(z) = \frac{P}{\left(\frac{4d_2}{d_1^2}\right)^2 z^2 + 1} = \frac{P}{a^2 z^2 + 1}.$$

With:

$$a = \frac{4d_2}{d_1^2}; i_{\max} \approx 0.65Pa \approx \frac{2.6Pd_2}{d_1^2}$$

$$Z_1 = Z_{min} \approx \frac{0.4}{a}; Z_2 = Z_{max} \approx \frac{0.8}{a}. \tag{2}$$

Eq. (1) is the characteristic equation of compressed air conversion. Fig. 2 illustrates the characteristic curve of com-

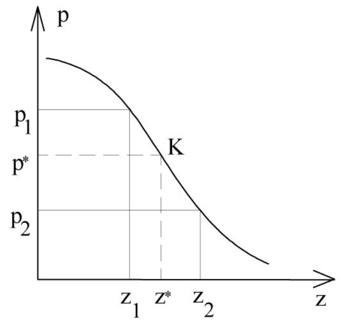


Fig. 2. Theoretical characteristic curve of the measuring probe system.

pressed air conversion. This curve has the inflection point at K. The curve's segment around the inflection point K can mostly be regarded as linear. The speed ratio or the sensitivity of the pneumatic probe system at the inflection point K is the greatest ($i_K = i_{max}$). Thus, it is usually chosen as the survey point to determine the measurement range of pneumatic probe system to minimize the non-linearity error.

In this research, the characteristic equation and curve of pneumatic probe system built on the basic of air-electric equivalence method are similar to the results shown in Ref. [13], which is based on the principle of conservation of mass in the variable pressure chamber. Therefore, the electrification method presented in this study is reliable and accurate.

3. Parameter calculation and design of pneumatic probe system

In profile grinding, it is necessary to increase the conversion ratio because the surface of grinding stone is uneven and the wear of grinding wheel is variable. The larger the measurement area, the easier the probe can be adjusted in the measurement range; however, the speed ratio and sensitivity decrease. For these reasons, parameters d_1, d_2, P should be reasonably calculated and chosen in order to have an appropriate measurement range. This study presents how to build a static characteristic curve with different combinations of parameters for the probe. Thereafter, the optimal parameter pairs are selected to design two probes with a resolution of 1 µm or less (When gap z changes by 1 µm, the indicated pressure will change 1 unit or more, which is equivalent to 0.01 Bar).

In Table 1 with P = 4 Bar, $d_1 = 0.85$, $d_2 = 1.5$, the following result can be obtained by Eq. (1):

$$p = \frac{P}{\left(\frac{4d_2}{d_1}\right)^2 z^2 + 1} = \frac{P}{a^2 z^2 + 1} = \frac{400}{1 + 8.3^2 z^2} \text{ (KPa)}$$

$$a = \frac{4d_2}{d_1^2} = \frac{4 * 1.5}{0.85^2} \approx 8.3\left(\frac{1}{mm}\right)$$

$$i_{max} \approx 0.65Pa \approx 0.65 * 4 * 0.0083 \approx 0.02 \text{ (Bar/µm)}.$$

From Table 1 and the characteristic equation of compressed air conversion, the theoretical characteristic curves of the probes are built as illustrated in Fig. 3.

Table 1. Parameters of the static characteristic line according to different parameter groups of the probe.

No	d_1 (mm)	d_2 (mm)	P (Bar)	a (1/mm)	Speed ratio i_{max} (Bar/µm)	Measurement range 0.4/a (µm)
1	0.5	1.2	4	19.2	0.05	20.83
2	0.72	1.2	4	9.259	0.024	43.2
3	0.85	1.2	4	6.643	0.017	60.21
4	0.5	1.5	4	24	0.062	16.67
5	**0.65**	**1.6**	**4**	**15.148**	**0.04**	**26.4**
6	0.72	1.5	4	11.574	0.03	34.56
7	**0.85**	**1.5**	**4**	**8.304**	**0.02**	**48.17**

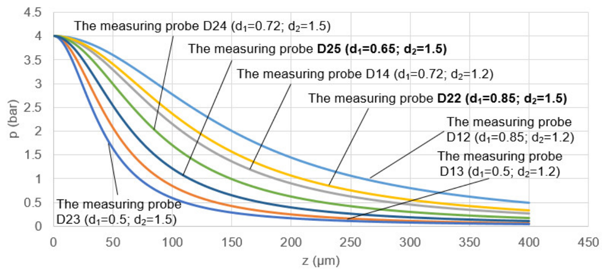
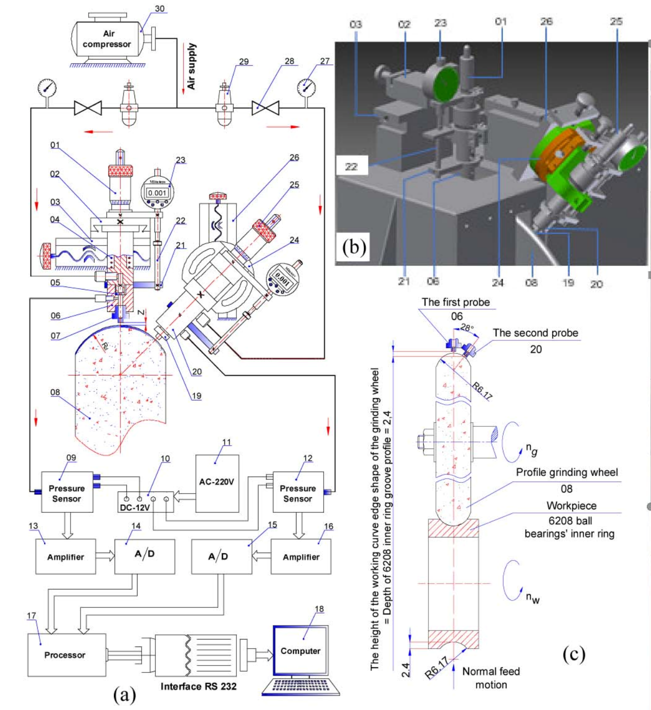
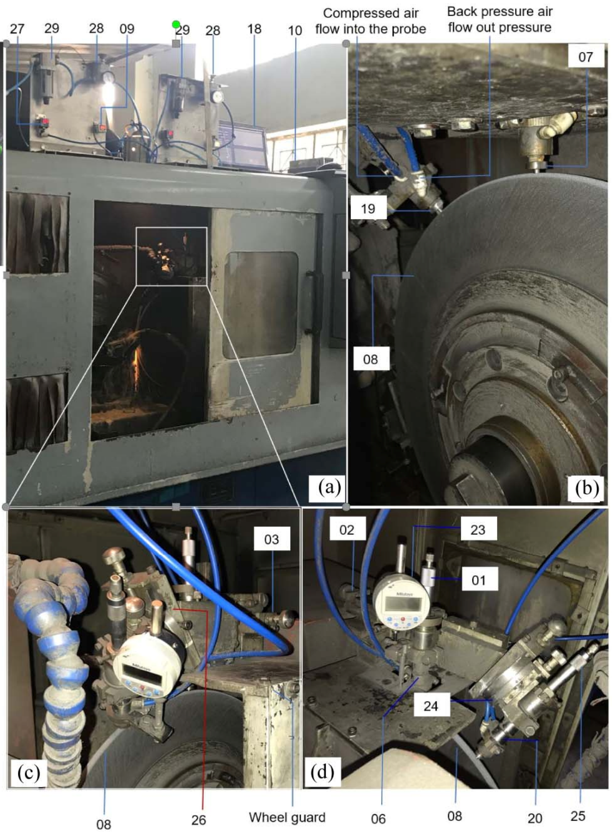


Fig. 3. Theoretical characteristic curves of the measuring probe systems.

Pneumatic measuring probe D_{22} with $d_1 = 0.85$ and $d_2 = 1.5$ has a linear working range of 48 µm and maximum speed ratio of 0.02 Bar/µm, which means that when gap z changes by 1 µm, the indicated pressure of the chamber will change by exactly 2 units: 0.02 Bar. Pneumatic measuring probe D_{25} with $d_1 = 0.65$ and $d_2 = 1.6$ has linear working range of 26.4 µm and maximum speed ratio of 0.04 Bar/µm, so when gap z changes by 1µm, the indicated pressure of the chamber will change by exactly 4 units, which is equivalent to 0.04 Bar. Therefore, the measuring probe systems have suitable speed ratios and measurement ranges, ensuring the ease for moving the probe into the measurement range and the required accuracy for measuring grinding wheel wear. These two measuring systems run simultaneously during the grinding process. A measuring probe system with a smaller sensitivity (D_{22}) is used to measure wear at the top of the curved edge surface of the grind stone because it is easier to fit, adjust and measure the wear at this point. While, the measuring probe system with a higher sensitivity (D_{25}) is employed to measure wear at the margin of the curved edge surface of the grind stone because it is more complicated to fit, adjust and measure the wear. However, there are always errors when processing control orifice d_1 and measuring nozzle d_2. Besides, the dynamic characteristic curve of the measuring probe system could be different from its theoretical characteristic curve when the pneumatic measuring probe is mounted on the grinding machine to measure the wear of grinding wheel, because of some factors which arise during the grinding process, such as the influence of





1. Micrometer head; 2. Measuring probe holder to adjust vertically; 3. Measuring probe holder to adjust horizontally; 4. Spring; 5. Control orifice; 6. The first probe (The top probe); 7. Measuring nozzle; 8. Grinding wheel; 9. Pressure sensor; 10. Adapter DC-12 V; 11. AC-220 V; 12. Pressure sensor; 13. Amplifier; 14. Analogue to digital converter; 15. Analogue to digital converter; 16. Amplifier; 17. Processor; 18. Computer; 19. Measuring nozzle; 20. The second probe (The margin probe); 21. Measuring rod holder; 22. Measuring rod; 23. Mitutoyo digit indicator; 24. Measuring probe holder to adjust the angle of rotation; 25. Micrometer head; 26. Measuring probe holder to adjust normal; 27. Pressure sensor; 28. Constant-pressure valve; 29. Air filter; 30. Air compressor

Fig. 4. The schematic and 3D render of our system setup: (a) The schematic of our system setup; (b) the 3D rendering of our system setup; (c) the diagram of probe fixing and principle of profile grinding for 6208 ball bearings' inner ring groove.

Fig. 5. The real probe system in measuring process: (a) General view; (b) close-up view of the two measuring nozzle; (c) close-up front view of the two measuring probe; (d) close-up back view of the two measuring probe.

chips, coolant, the uneven working surface of the grind stone, the curvature and rotation of working surface of the grind stone [16]. Therefore, finding the dynamic characteristic curve of the measuring probe system by experiment after mounting the measuring probe system on the grinding machine is an important step in designing and creating the pneumatic measuring probe: This step determines the accuracy of the wear measurement. In doing so, it is necessary to build a relationship between gap z and pressure p after the measuring probe system has been created and mounted on the machine, the coolant has been added, and the machine has been adjusted so that the grinding stone will rotate at the same speed with the rotating speed when grinding.

4. Experimental set up and procedures

A CNC profile grinding machine was used in the following experiments. Fig. 4 shows the schematic and 3D rendering of the applied system. Fig. 5 shows the actual probe system in measuring process.

Tables 2 and 3 show the specifications of the grinding conditions and grinding wheels. The specifications of pressure sensor and 6208 ball bearing's inner ring can be seen in Tables 4 and 5. The profile grinding wheel with white fused alumina grains is used to grind the groove of 6208 ball bearing's inner ring made from SUJ2 alloy steel.

5. Characteristics of generated pressure

Pressure is measured after mounting the probes on the grinding machine to calibrate pressure to gap distance. At first, by using a supporting system, one measuring probe system is mounted on the top of the curved edge surface and another at the margin of the curved edge surface of the grind stone on the profile grinder, that grinds the groove of the inner ring (As illustrated in Figs. 4 and 5), to adjust probe d_2 at each measur-

Table 2. Specifications of grinding conditions.

Grinding speed	60 m/s
Fine depth of cut	10 μm
Rough depth of cut	120 μm
Fine feed rate	6 μm/s
Rough feed rate	30 μm/s

Table 3. Specifications of grinding wheel.

JIS code	A100L5V
Grade	Soft
Grain	White fused alumina
Bond	Vitrifide
Wheel size (mm)	500 in outer diameter and 8 in width

Table 4. Specifications of SEU-31-N pressure sensor made Pisco.

Rated pressure range	0 ÷ 10 bar
Pressure resolution	0.01 bar

Table 5. Specifications of 6208 ball bearings' inner ring.

Depth of groove profile	2.4 mm
Radius of groove profile	6.17 mm

ing probe system so that the centerline of probe d_2 goes through the center of the curved edge surface of the grinding stone. Then, by using constant-pressure valve the compressed air source would be set at constant pressure P = 4 Bar while it is blowing continuously and perpendicularly to the working surface of the grinding stone. After that, the machine is adjusted so that the grinding stone rotates at 3000 rms. The coolant is also added (Similar conditions to those used for the grinding process). Next, the micrometer head is turned around in order to slowly move the probe step by step over the wheel surface. For more accuracy, because of the limited micrometer's resolution of 0.01 mm, a Mitutoyo digit indicator with resolution of 0.001 mm was mounted on each measuring system (Figs. 4 and 5) to ensure that the movement of the probe was accurate to each micrometer. Therefore, by turning micrometers and reading the numeric values showing on the digit indicator and sensor pressure of the chamber, the corresponding values of pressure p at every position of probe d_2 in each measuring probe can be captured. Thus, a table of experimental results for the relationship between pressure p of the chamber and gap z at each measuring probe system is available. By using the table of experimental results and applying the method of least square to the following general equation,

$$p = \frac{P_0}{1 + cz^2} .$$

A function representing the relationship between pressure p and gap z is determined. Based on this function, the dynamic characteristic curve of each measuring probe system is built as shown in Figs. 6 and 7.

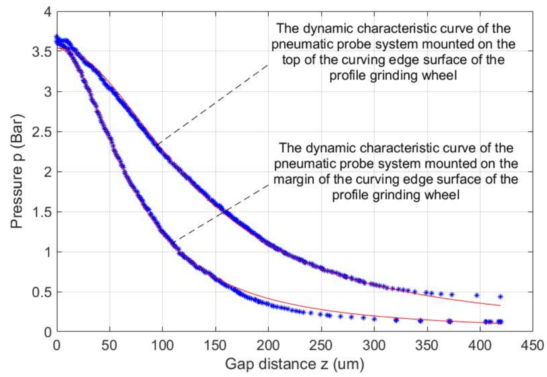


Fig. 6. The dynamic characteristic curves of the pneumatic probe systems mounted on two different points of the curved edge surface of profile grinding wheel - across the domain 0:4 bar.

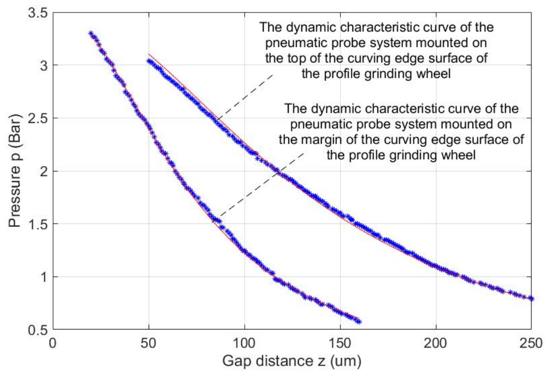


Fig. 7. The dynamic characteristic curves of the pneumatic probe systems mounted on two different points of the curved edge surface of profile grinding wheel - across the work domain.

The dynamic characteristic curve of the measuring probe system mounted on the machine is different from the theoretical characteristic curve, as mentioned in the previous section. This is due to errors during the creation of control orifice d_1 and measuring nozzle d_2. Other factors are influences of coolant, grind stone's surface, stability of the technological system when mounting the measuring probe system on the grinding machine, etc. [16].

The first probe measuring at the top of the curved edge surface of the grinding stone has a measurement range of 200 μm (between 50 μm ÷ 250 μm), a speed ratio of 0.01 Bar/μm and a transfer function of:

$$p = \frac{3.5}{1 + 5.4613e - 0.4 * z^2} .$$

The second probe, which was used for capture of the wear at the margin of the curved edge surface of the grinding stone, has a measurement range of 140 μm (Between 20 μm ÷ 160 μm), a speed ratio of 0.03 Bar/μm and a transfer function of:

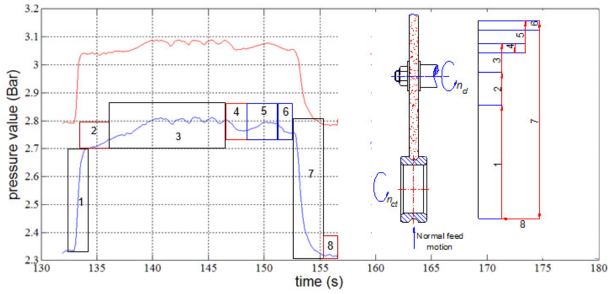


Fig. 8. The changes of back pressure during the grinding process of one part.

$$p = \frac{3.5}{1 + 1.8655e - 0.4 * z^2}.$$

This means the experimental speed ratio of the probe decreased by about 30-40 % compared to its theoretical calculation. The reason for this decrease in the speed ratio is the air loss in the air passages and at air connectors. Another reason is the increase of air resistance of the measuring probe system by fitting the air hoses together. Furthermore, the orifice long also increases air resistance of the measuring probe system. However, the probe with higher theoretical speed ratio has a higher experimental speed ratio. This proves that the measured experiment results are suitable for the calculation purposes.

Particularly, the pressure of the probe in the process of grinding a single part is not stable but changes constantly according to the radial motion of the workbench mounting the parts. This is evident by analyzing the pressure change in the chamber during the grinding process of one part as shown in Fig. 8.

In Fig. 8, the drawing on the right shows the operation principle of profile grinder 3MK136B that machines the inner ring groove of the ball bearing. The grinding wheel and workpiece rotate around their center while the workbench moves in the normal direction. Especially, the radial motion of the workbench is divided into the following stages: 1. The workbench jumps rapidly; 2. The workbench approaches forward; 3. The workbench performs a normal motion for the rough grinding; 4. The workbench moves back to rough bound; 5. The workbench performs a normal motion for the fine grinding; 6. The workbench runs back to fine bound; 7. The workbench turns back rapidly and returns its origin position; 8. Swing arm of grinder loads/unloads automatically.

The drawing on the left of Fig. 8 shows the pressure change in the chamber over time in a grinding process. Based on this graph and the actual time setting on the machine for each forward or backward motion of the workbench, the back pressure of the chamber increases rapidly when the worktable jumps rapidly (for stage 1). Then, the back pressure also increases but at a slower rate when the workbench runs at high speed approaching the working surface of grinding wheel (for stage 2). Next, when the worktable performs a normal motion to grind roughly and finely, the pressure also increases but at a

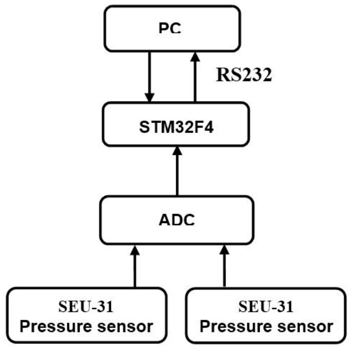


Fig. 9. Diagram of control circuit principle.

much slower rate (for stage 3 and 5). After that, the workbench runs back to grind without sparks (for stages 4 and 6), the pressure decreases but at a slower rate than the speed at which the workbench moves back to its original position (for stages 7 and 8). The reason for this is that the clearance gap from the stone surface to the part surface decreases when the workbench performs normal feed motion. Besides, the grinding wheel rotating at a high speed (3000 rpm) carries a layer of air on its surface [9]. These lead to increased pressure of air flow around the periphery of a rotating grinding wheel. Therefore, the amount of air blowing out from the measuring nozzle d_2 decreases, resulting in the back pressure increasing. On the contrary, the workbench performs backward movement; the gap distance from the grinding wheel surface to the part surface increases. This causes decreased pressure of air flow surrounding the periphery of a rotating grinding wheel. Consequently, the pressure in the chamber is reduced although the abrasive cannot be worn at this time. Therefore, it is necessary to determine the amount of back pressure difference Δp between the grinding times at the same grinding condition to calculate the wear value of the grinding wheel (The change of the clearance z) after each finished grinding of one part. In this paper, we selected the timing when the workbench is at its original position corresponding to the pressure p at the minimum value during the grinding process of a part. Since this is the time when the process of grinding a part has just finished and is preparing for the next grinding process, the pressure of air flow surrounding the periphery of a rotating grinding wheel is most stable and unaffected by the process of normal feed motion of worktable. Moreover, at the time under the impact of very high pressure of air flow impinging on the wheel surface, it is sufficient to avoid any interference from coolant or debris carried by the wheel [9].

6. System configuration and algorithm

Fig. 9 shows a diagram of the control circuit principle to process the data and save results on the computer. In the measurement system, two Pisco's SEU-31 pressure sensors are used to measure the pressure in the chamber of each pneumatic probe. Their signals are taken at the same time during

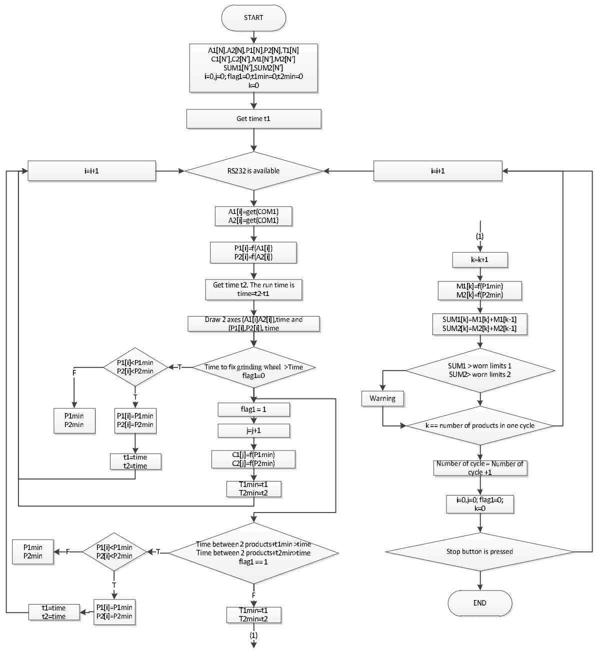


Fig. 10. Algorithm for interface software program to determine the normal wear value of grinding wheel.

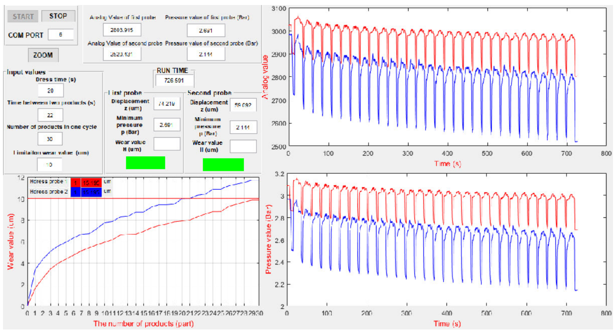


Fig. 11. The interface of the software system is designed and experimental results after grinding 30 parts in one cycle.

the measurement process. As required of continuous and synchronous signal transmission, the ADS1256 converter along with STM32F407 microcontroller are used and the software interface on Matlab guider is developed to handle data, store results and measure in-situ grinding wheel wear on the top of the curved edge surface and at the edge of the curved edge surface of the profile grinding wheel.

Fig. 10 shows an algorithm used to receive analog signals sent from microcontroller to process the data to determine the radial wear value of the grinding wheel.

7. Experimental result

Fig. 11 shows the interface of the software system designed for the study and experiment results after grinding 30 parts in one cycle.

In the software interface, there are three diagrams. The first one shows the change of the analog voltage values in each

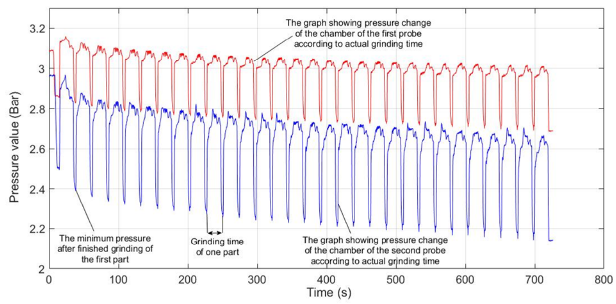


Fig. 12. The graphs showing pressure change according to actual grinding time.

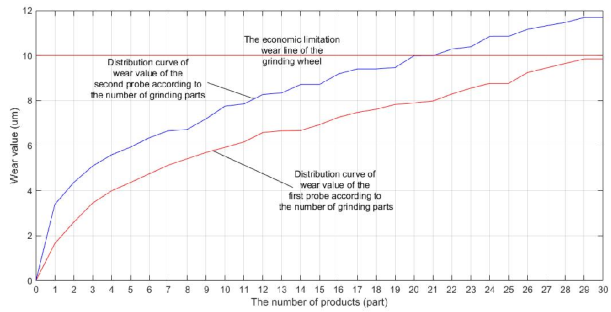


Fig. 13. Distribution curves of wear value according to the number of parts.

measuring system in actual time; the second one shows the pressure changes in each measuring system in actual time; the last diagram shows normal wear value of the grinding wheel in each measuring system according to the number of actual grinding parts.

The first and second graphs are quite similar. Because the value of pressure is determined by the analog voltage value, it is only necessary to analyze the graph showing pressure changes according to actual grinding time.

Fig. 12 shows pressure changes according to actual grinding time. From this diagram, the program determines the minimum pressure in each measuring system after each grinding of one part based on the actual grinding time of one part. Then, it determines the value of the clearance z in each measuring system based on the minimum pressure value and the equation of dynamic characteristic curve of the pneumatic probe built in the previous section. After that, the normal wear value of the grinding wheel in each measuring system is calculated after each finished grinding of one part, as shown in Fig. 13.

8. Conclusion

From the experimental results of the study, some findings can be presented as follows:

- In the same cycle, the wear value of grinding wheel tends to decrease from the first part to the last.

- The grinding wheel is more quickly worn at the first grinding parts of the cycle (The first part and the second part) at the time of new dressing.

- Wear speed slows according to time progress. However, in some special cases, the wear value increases due to minor and unexpected influence of self-dressing. Some small parts of the grinding wheel are removed, which improves the grinding effectiveness.

- Especially on the curved edge surface of the grinding stone, the grinding wheel is unevenly worn at various points. The wear value at the edge of the curved edge surface of the grinding wheel is usually bigger than that at the top of the curved edge surface of the grinding wheel. After grinding 30 parts in a cycle with the above grinding conditions, the total wear value at the top of the curved edge surface of the grinding wheel is equal to 9.85 μm. While the total wear value at the edge of the curved edge surface of the grinding wheel is equal to 11.69 μm. This is possibly caused by the unevenly distributed mechanical surplus. The mechanical surplus at the edge of the profile is bigger than that at the top of the profile. At the same time, the radius of inner-ring groove of 6208 ball bearing is very small compared to the diameter of the grinding wheel. Thus, the grinding force is mostly the same everywhere on the working surface of grinding wheel. This causes the uneven wear.

- The measurement results reflect well the wear rule of grinding wheel, which is divided into three phases including initial wear stage, steady wear rate phase and rapid wear towards end phase. In the initial wear phase, the wear time is small (Corresponding to wear at the first part and the second part), but the wear value is high. The reason is that after dressing, the grinding wheel has many abrasive grains with unfavorable locations and geometric parameters for the cutting process. These abrasive grains are easily emitted out of the bond. In the steady wear rate phase, the wear rate of the grinding wheel is slower (Corresponding to wear from the third part to the 30^{th} part). In the rapid wear towards end phase, the pores on the surface of the grinding stone are filled with chips; therefore, the grinding wheel loses its cutting ability. According to conventional grinding theory, this is the time to dress the grinding wheel. However, in the profile grinding for the inner-ring groove of the ball bearing, which each part is created with high precision, it is necessary to dress the grinding stone before the rapid wear towards end phase_to ensure the dimensional accuracy and surface roughness of the groove.

- With the above experimental results, it can be concluded that the top pneumatic probe used in the study has measurement range of 200 μm with accuracy of 1 μm, and the margin pneumatic probe has measurement range of 140 μm with an accuracy of 1 μm. The measurement system works stably in the simultaneous measurement process of the radius wear value at two different points of profile grinding wheel on the grinding machine 3MK136B after complete grinding of each part or after dressing. The measurement can be done at low cost (About $100). This is the basis to move towards automatic compensation for grinding wheel wear and determine the reasonable time of dressing the grinding wheel in order to ensure precision of the ground parts and increase grinding productivity.

References

[1] S. LaChance, A. Warkentin and R. Bauer, Development of an automated system for measuring grinding wheel wear flats, *J. of Manufacturing Systems,* 22 (2) (2003) 130-135.

[2] H.-T. Young and D.-J. Chen, Online dressing of profile grinding wheels, *Int. J. Adv. Manuf. Technol.*, 27 (2006) 883-888.

[3] T. M. A. Maksoud, A. A. Mokbel and J. E. Morgan, In-process detection of grinding wheel truing and dressing conditions using a flapper nozzle arrangement, *Proceedings of the Institution of Mechanical Engineering*, 211 (1997) 335-343.

[4] H. Yu, Y. Lu and J. Wang, Study on wear of the grinding wheel with an abrasive phyllotactic pattern, *Wear J.*, 358 (2016) 89-96.

[5] A. Paoletti and A. Di Ilio, A monitoring system for metal matrixcomposites gringding based on a nococtact capacitive sensor, *J. of Manufacturing Technology Research,* 3 (2011) 197-210.

[6] W. P. Dong, L. Annecchino and J. A. Webster, On-line measurement of grinding wheel wear using acoustic emission, *Proceedings of the 11th Annual Meeting of American Society for Precision Engineering*, USA, 11 (1996) 566-571.

[7] K. C. Fan, M. Z. Lee and J. I. Mou, On-line non-contact system for grinding wheel wear measurement, *The International J. of Advanced Manufacturing Technology,* 19 (2002) 14-22.

[8] J. Fazlurrahman and V. Radhakrishnan, Surface condition monitoring of grinding wheels by pneumatic back-pressure measurement, *Wear*, 70 (1981) 219-226.

[9] J. Shibata, T. Goto and M. Yamarnoto, Characteristics of air flow around a grinding wheel and their availability for assessing the wheel wear, *Annals of the ClRP,* 31 (1982) 233-238.

[10] N. V. Tiep, Obrobtitelnost Kovových materlálú brousením, *Dotoral Thesis,* Vysoká Skola Strojí a textliní Liberec, Czechoslovakia (1984).

[11] M. Rucki, B. Barisic and T. Szalay, Analysis of air gage inaccuracy caused by flow instability, *Measurement,* 41 (2008) 655-661.

[12] M. Rucki, B. Barisic and G. Varga, Air gauges as a part of the dimensional inspection systems, *Measurement,* 43 (2010) 83-91.

[13] P. Koshy, D. Grandy and F. Klocke, Pneumatic non-contact roughness assessment of moving surfaces, *Manufacturing Technology*, 58 (2009) 515-518.

[14] P. Koshy, D. Grandy and F. Klocke, Pneumatic non-contact topography characterization of finish-ground surfaces using multivariate projection methods, *Precision Engineering*, 35 (2011) 282-288.

[15] K. Nadolny, W. Kapłonek and Ján Valíček, Pneumatic method used for fast non-contact measurements of axial contour of grinding wheel active surface, *PAK,* 57 (2011) 1071-1074.

[16] J. G. Wager, *Surface effects in pneumatic gauging*, Pergamon Press, Great Britain, 7 (1967) 1-14.

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