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Online dressing of profile grinding wheels

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Abstract Improving the dressing accuracy and efficiency of profile grinding wheels has been increasingly demanded. The significance is addressed in the practical application of precision engineering. In this study, an online dressing system of profile grinding wheels is introduced. A special feature of the system is the application of the non-contact image measuring method used to evaluate deviation of the grinding wheel's edge in determining the timing and amount of dressing. Diamond form rollers were selected to generate the profile grinding wheels with steep profile flanks by taking advantage of their high flexibility, short dressing times, and low wear rate. A series of grinding and dressing tests were carried out to investigate the dressing accuracy and surface quality for the profile grinding wheels with the proposed system. Through repeated experimental investigations, it was found that the dressing force is a key parameter in determining the number of passes needed in achieving high efficiency dressing. This is to assure that the length of the dressing time, and waste of the dresser and grinding wheel can be minimized. Other main dressing conditions that influence the grinding wheel and workpiece roughness include speed ratio, cross feed and roller profile radius.

Keywords Dressing · Grinding wheels · Weir · Form roller

1 Introduction

The grinding wheel plays a key role in the grinding process for obtaining high machining accuracy and good surface roughness of the workpiece [3]. It is, however, not always easy to obtain satisfactory results because of the progressive wear and sharpness loss of the grinding wheel, and the situation is worsened with the grinding time. This is especially critical when using

profile grinding wheels to machine a form part that has a complicated outline. Therefore, an online dressing system becomes essential for the grinding wheels to acquire the required accuracy and efficiency.

In previous research works, an anemometer was used to detect the position of the grinding wheel surface by measuring the air flow that surrounds the grinding wheel [4]. This method, however, does not give the necessary accuracy required by the standard of precision grinding machines. Recently, acoustic emission (AE) has been used in detecting grinding wheel sharpness while applying touch probe in measuring the grinding wheel position [5–7]. The results show that AE frequency rises faster for a hard grinding wheel and a worn dresser. Although the AE method is good enough for a certain feedback control system, the in-process measurement of the profile grinding wheel in precision grinding operations is not adequate due to the adverse influences of the grinding fluid, cutting force, eccentricity, machine or thermal deformations, etc.

To avoid the above problems, a non-contact optical measuring method with image digital techniques was devised in this study to evaluate the grinding wheel position [8]. The “mapping function method” was then used to transfer the image pixel coordinate to the space coordinate directly without considering the calibration of distortion parameters. After proper manipulation, the captured images, before and after the grinding process, were compared. The measurement of profile grinding wheel images show that dimensional accuracy is achievable to a degree of 1 μm . Using this method, the dressing timing was determined by comparing the measuring point after grinding with the ideal profile for geometry matching. The maximum position deviation was then evaluated to check if it is greater than a critical value based on the required accuracy of the parts to be produced. The wear compensation of dressing tools was also managed under this methodology by evaluating the profile radius deviation of dressers, and the compensation was taken into account in planning each of the dressing paths.

The minimization (optimization) of the dressing pass is another research focus in the present study as higher tool cost, wheel loss and higher process time are accompanied under an

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inappropriate dressing operation. Through the experimental investigations, the dressing force was found useful in determining the number of passes needed in dressing. This step is critical to ensure that the grinding wheel has regained its machining capability while keeping its dressing time a minimum. The main objective of this study is to present an effective online dressing system for profile grinding wheels. The system demonstrated its capability of extracting information about the grinding wheel surface position and verifying the state of its sharpness.

2 Truing and dressing

Truing is, in normal terms, defined as the operation of shaping a wheel face, while dressing is the operation of sharpening a wheel face. In general practice, these two operations are treated separately. In the following study, “dressing” is given to mean that both of the two operations are carried out simultaneously for the conventional aluminum oxide profile grinding wheels. The dressing method for the profile grinding wheel, as shown in Fig. 1, is using a diamond form roller as the dresser to contour the profile through the prescribed locus. The dresser is placed on the machine table with its rotating axis perpendicular to the machine spindle mounted with a grinding wheel. After the initial contact between the grinding wheel and form roller is made, the dresser can generate and shape the required profile by a three-axis control system in the radial, axial and rotating directions (ϕ in Fig. 1). In general application, a new conventional grinding wheel always requires a rough shaping process to remove the major part of material from the blank and carve the pre-form into a rugged profile. It is clear that roughing operations need more time, and consequently a higher cost to complete the whole process including shaping and preparation. In the present arrangement, a single-point diamond is selected as the dresser

Fig. 1. Dressing process of profile grinding wheel with diamond form roller

Fig. 2. Rough shaping operation

on rough shaping as, within the required accuracy, it has the advantages of being easier to setup than a diamond form roller. In addition, the importance of developing rough shaping is its usefulness in getting a much higher material removal rate with a relatively short cycle time and low wear. Figure 2 shows an instance of rough shaping in which the operation has been divided into two parts and the feed directions are opposite to each other. The planning is found to significantly reduce the influence of backlash in gears during the dressing process. This leads to the production of higher quality parts in terms of accuracy and surface roughness.

3 Experimental setup and procedures

A surface grinding machine with a dresser was used for a series of dressing and grinding tests. The profiles of dressing tools as well as those of the grinding wheel were measured with a non-contact optical measuring system. The dressing force was measured with a dynamometer. At the first stage conventional aluminum oxide grinding wheels (WA120K8V, GC90U9V, 180 mm $\times$ 13 mm) were used to shape a 4 mm radius half circle profile. Diamond form rollers (SD170, 75 mm $\times$ 3 mm) and single point diamonds with tip radius 0.5 mm were used for dressing. The coolant or water miscible grinding fluid was not applied during the dressing and grinding processes. The effect of dressing was evaluated through the grinding of an advanced carbide steel (S45C, HRB105) workpiece. After grinding, roughness of the workpiece was immediately measured to find its correspondence with the roughness of respective profile grinding wheels. Figure 3 shows the experimental setup for the dressing force measurement. Because of the small average cross-sectional area of active cutting edges, the cutting force which acts on each grain is quite small. An example of selected dressing parameters for the profile grinding wheel is shown in detail in Table 1.

Table 1. Dressing parameters for profile grinding wheel

Dressing parameter	Condition	
Grinding wheel	WA120K8V	GC90U9V
Dresser	D. form roller (SD170)	Single point diamond
Cutting depth per pass (<i>frd</i>)	20 μm	
Dressing cross feed (<i>fad</i>)	4 ~ 30 mm/min	
Surface speed of grinding wheel (<i>Vsd</i>)	$\sim \pm 16$ m/s	
Surface speed of dresser (<i>Vnd</i>)	16 m/s	0 m/s
Speed ratio ($qd = Vsd/Vnd$)	+1 ~ -1	± 1
Passes of dressing	~ 10

Fig. 3. Experimental setup of the dressing force measurement

4 Measurement of dresser and grinding wheel wear

The wear of profile grinding wheels is detected by a non-contact image process system as shown in Fig. 4. By using the CCD camera and image card, the captured profile image of the grinding wheel was converted to a set of analog signals corresponding to the digital gray level values. Then the technique of binarization [9] was used to segregate the background and the grinding wheel for an identification of grinding wheel's edge. Then the transformation of the edge pixel coordinates to space coordinates were proceeded by using the mapping function method, which is directly related to the grid points of the standard mask in space to the mapping points on the image plane. This cuts

Fig. 4. The optical measuring system**Fig. 5.** The flowchart of profile grinding wheel measurement and a captured image

down the process of considering the compensation of various coordinate systems. The flowchart of the profile grinding wheel measurements and a captured image are shown in Fig. 5. The above system is applied to evaluate the wear of dressers as well as grinding wheels.

The results are obtained through the process of analyzing the position deviation captured from the images before and after the grinding process. In this study, an auto-focus technique was also combined in the system to control the lens movement. The focused plane was quickly in place by image processing through the control card to drive the DC motor.

5 Profile accuracy of grinding wheel

Table 2 gives the measured dimensions in radius, angle, and width, respectively of the grinding wheel profile after dressing. The experimental parameters applied include dressing cross feed (*fad*) = 25 mm/min and cutting depth per pass (*frd*) = 20 μm . As these tables indicate the profile accuracy is quite satisfactory. In a total of 30 dressing experiments, the profile accuracies are within 15 μm and 0.05 degrees. The results obtained by optical means are almost the same as those by 3-D coordinate measurement. The measured results also show that the same accuracies can be obtained by dressing with a single point diamond attached on the rotary dressing device as the diamond form roller.

Table 2. The measured results of profile grinding wheel dimensions

	Diamond form roller		Single-point diamond	
	Optical measurement	3-D coor. measurement	Optical measurement	3-D coor. measurement
(a) radius ($r = 4$ mm) measurement				
4.013		4.001	4.000	4.003
4.015		3.995	4.002	4.012
4.010		4.001	4.011	3.974
4.021		4.011	4.016	4.007
4.015		4.012	4.013	3.982
(b) angle ($\alpha = 30$ degrees) measurement				
29.922		29.941	29.663	29.733
29.940		30.002	29.728	29.914
(c) width ($w = 13$ mm) measurement				
12.999		12.986	13.010	12.997
13.001		13.000	12.983	12.981

6 Dressing result of diamond form roller

Figure 6 shows the roughness of the workpiece as a function of the speed ratio (qd) and dressing cross feeds (fad), respectively

Fig. 6. Qualitative relation between dressing cross feed (fad) – speed ratio (qd) and roughness (Ra) **Fig. 7.** Three-dimensional surface roughness topography of workpiece (Zygo)

with the dressing removal rate Qd for dressing with diamond form rollers. The worst situation appears when $qd = +1$ and can clearly be seen [10]. It is also seen that the roughness increases with dressing cross feed (fad). Let plane $Ra = 3.0 \mu\text{m}$, as an example, be given by the requirement of a machining task. Cross sectioning of this plane with the surface corresponding to $rp = 0.5$ mm gives the shaded region. The bounded region represents obtainable results in various combinations of set dressing conditions which lead to the required roughness for the ground workpiece. An example of 3-D surface roughness topography of a small area on the surface of the workpiece near the center is given in Fig. 7.

7 Influence of dressing conditions

The dressing normal force is a key parameter in ending the finishing operation of a grinding wheel. The influence of individual dressing conditions and the roller profile radius (rp) on the dressing normal force is shown in Fig. 8. Small dressing cross feeds

Fig. 8. Qualitative relation between dressing cross feed (fad) – speed ratio (qd) and normal dressing force (F_n)

Fig. 9. Dressing pass and dressing force ratio

(*fad*) lead to the result that the dressing normal force (F_n) is nearly independent of the speed ratio (q_d). On the other hand, the dressing normal force increases with the speed ratio for high dressing cross feeds. The effect of the roller profile radius (r_p) on the dressing normal force (F_n) can be further investigated on Fig. 9.

8 Passes required for dressing

A crucial step with respect to dressing is to find a criterion in concluding the finishing operation. An excessive dressing causes unnecessary material wastes in the dresser, the grinding wheel, and the process time. On the other hand, under dressing results in insufficient cutting capability for the grinding wheel. The normal dressing force and the force ratio were tested and plotted against the dressing pass in Fig. 9 for initial investigation. The dressing parameters are: width of grinding wheel (b) = 13 mm, depth of cut (frd) = 20 μ m, roller profile radius (r_p) = 0.5 mm, roller surface speed (V_{nd}) = 16 m/sec, and grinding wheel surface speed (V_{sd}) = -16 m/sec. As is evident from the figure, the normal dressing force decreases rapidly against dressing time and finally becomes nearly constant after a dressing pass of about 3–4. In the mean time, it is seen that the dressing force ratio

Fig. 10. Dressing pass and roughness (R_a)

increases in the initial dressing and then settles to a constant after 3–4 passes. A close correspondence was found between the machined surface quality and the applied dressing pass. Figure 10 shows the roughness (R_a) of the workpiece decreases with the dressing pass to about 3–5 and then comes to a constant value. Obviously the dressing forces can be taken as an indicator in the online dressing system for assured final product quality. The changes in the dressing forces gives a plausible indication that the profile surface has been modified and grain cutting edges were protruding and consequently, the cutting action of the grinding wheel was restored. The system makes use of the above observation to indicate that the threshold is reached for the finished dressing when the dressing force or the force ratio comes to steady state.

9 Conclusions

An innovative online dressing system of profile grinding wheels that applies non-contact image measuring method was introduced. By using diamond form rollers as the dressing tools, a series of fundamental experiments were carried out to refine the dressing accuracy for the profile grinding wheels. The grinding results obtained have proved its usefulness, and its potential in industrial applications. Figure 11a,b and Fig. 12 show respectively the actual dressing machining and the final images of different profiles after dressing. The results obtained through the

Fig. 11. a Dressing experiment of profile grinding wheel b Dressing experiment of profile grinding wheel

(a)

(b)

Fig. 12. Different profile images of grinding wheels

dressing experiments as well as grinding tests are summarized as follows:

- The online dressing system introduced has shown the capability to generate highly satisfactory and consistent dressing results for profile grinding wheels.
- The minimum dressing pass which is needed to restore the sharpness of the grinding wheel can be determined by the ratio of the dressing force. The dressing cycle is completed when the dressing force ratio settles to a constant.
- The proposed system is cable of handling the timing of dressing and its optimum amount of dressing. These features add extra value to the present system in terms of working efficiency.

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