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ORIGINAL ARTICLE

Investigating effects of adhesion wear on cutting efficiency and energy cost in dry belt finishing

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Abstract Adhesion wear, an improper wear form on abrasive belt, is often found in dry belt finishing as a common phenomenon. Therefore, its effects on this machining process are important to be investigated. This paper gives a comprehensive understanding of its effects on cutting efficiency and energy cost. First, a series of finishing tests with different applied pressures and different belt feed rates are performed. Then, the material removal rate and specific energy are obtained and analyzed through an analytical approach to dissociate costed energy on sliding and cutting. It has been demonstrated that increasing belt feed rate can give a higher material removal rate with a lower energy cost in normal finishing. The adhesion wear can significantly worsen cutting ability and waste energy in sliding. Compared with belt finishing under minimal quantity lubrication (MQL), dry belt finishing is able to improve material removal but with an uneconomic energy consumption.

Keywords Dry belt finishing · Specific energy · Cutting efficiency · Adhesion wear

1 Introduction

Superfinishing process by using abrasive belt has already been widely introduced into the industry, and it has been successfully proved that it can significantly perfect the surface texture and generate compressive residual stresses for turned workpieces [1–4]. Compared with endless belt grinding process, its advantages including the long serving life of the belt and controllable wear state of grains give the priority to be used as a superfinishing method [4]. However, previous studies mainly focus on the improvement of surface integrity, so that cutting efficiency of this technology get a little attention, especially under a dry condition. Meanwhile, the lack of basic mechanisms study in dry condition has limited its application in some cases which pay more attention to material removal rather than surface quality, like rail way maintenance [5].

The work done by Rech et al. [6] mentioned that the material removal process in belt finishing is mainly due to the axial oscillation of the belt + roller system when finishing turned workpieces. Khellouki et al. [1] found that higher contact pressure gives better material removal rate. In addition, it has been demonstrated that cutting is more predominant than sliding in belt finishing process with MQL [7]. And the subsequent work made it clear that MQL with low belt feed is the best way to have the optimal roughness characteristics. However, dry belt finishing is not suitable to finish hard turned workpiece due to a rapid grains' destruction [8]. As for dry belt finishing, EI Mansori et al. [3] performed a study on the effect of the oscillation frequency and the belt duration on the specific energy. The results indicated that in the first second the process is dominated by the formation of microchips, but after that, the energy was dissipated and the removal rate became stable. However, there are a few published papers

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Table 1 Belt finishing conditions

Tangential speed of wprkpiece, V_s	160 m/min
Film feed rate, V_b	30, 50, and 70 mm/min
Oscillation frequency, f_{osc}	12 Hz
Oscillation amplitude, a_{osc}	±1.5 mm
Applied pressure, p_n	0.5 ~ 2.5 bar
Finishing time, t	36 s
Roller's hardness, *Hs*	90 Shores A
Belt grains' grade	50 μm
Abrasive grain material	Al_2O_3

discussing the blockage and adhesion wear during the finishing process, including its forming reason, its effects on material removal, and its surface integrity.

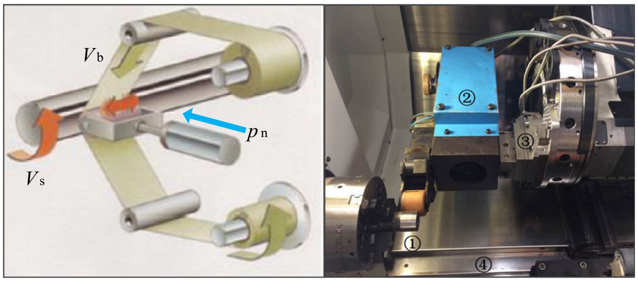
In this paper, we introduce an energetic analysis to help understand the change of cutting mechanisms brought by adhesion wear. The grinding forces and material removal will be measured and analyzed. The influences of applied pressure and belt feed rate on cutting efficiency and energy consumption will be discussed as well as compared with the previous research with MQL.

2 Experimental procedure

2.1 Experimental devices

Workpieces are made of 100Cr6 bearing steel (AISI 52100) with a hardness of 62 HRc. A pre-finishing was operated to obtain a constant surface with *Ra* between 0.23 and 0.28 μm. Belt finishing was applied after that. The belt finishing conditions of formal experiments are shown in Table 1.

To obtain the grinding forces during belt finishing, a dynamometer Kistler 9257B was chosen. The movement direction of the air cylinder on the belt finishing machine is parallel to the measuring direction *y* of the sensor. In order to measure the weight loss of the workpiece before and after each finishing procedure, a precision electronical scale with the accuracy of 0.01 g was selected. In addition, the workpiece has been carefully cleaned by using an ultrasound cleaner containing alcohol to ensure the precision of weight measurements (Fig. 1)



(a) (b)

Fig. 1 Belt finishing process. **a** Belt finishing working principle, **b** Belt finishing system, 1-workpiece, 2-belt finishing machine, 3-Kistler sensor, and 4-CNC

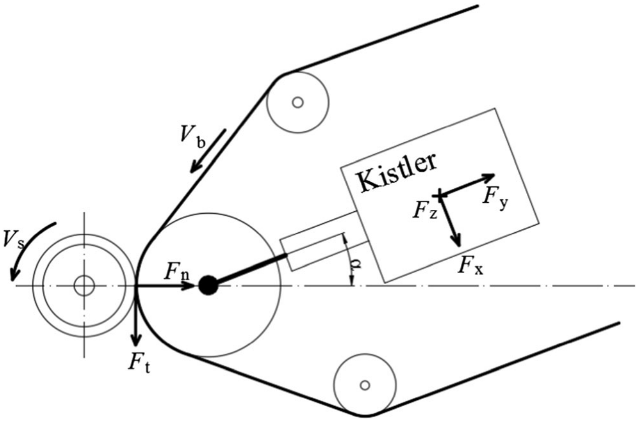


Fig. 2 Composition analysis of measured grinding forces

2.2 Data correction

Because of the limit of the installing position of Kistler on CNC as well as the deviation caused by manually position control, it is hard to perfectly keep the normal grinding force F_n parallel to the measuring direction F_y. There will be always a small angle α but controlled between 15° and 25°. But it has been checked before each test to revise the force's data based on following equations:

$$F_t = F_x \cdot \cos(\alpha) - F_y \cdot \sin(\alpha) \tag{1}$$

$$F_n = F_x \cdot \sin(\alpha) + F_y \cdot \cos(\alpha) \tag{2}$$

where F_t and F_n are tangential and normal grinding forces, respectively; F_x and F_y are forces measured by Kistler sensor in orthogonal directions.

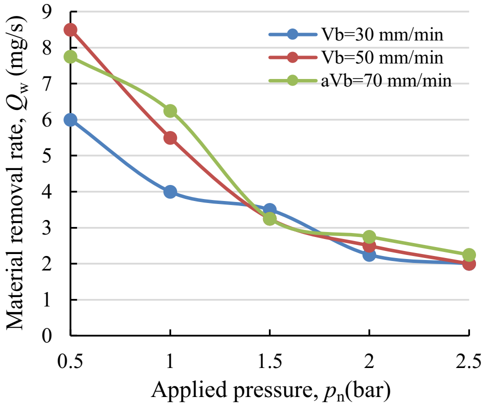


Fig. 3 Material removal rate versus applied pressure

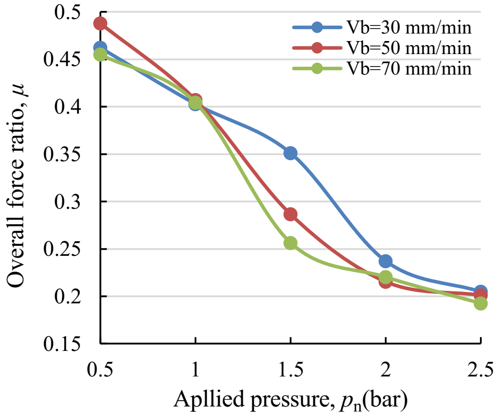


Fig. 4 Overall force ratio versus applied pressure

3 Analytical approach for belt finishing mechanisms

According to the work of Khellouki et al. [8], during the belt finishing, the tangential force F_t can be seen as the one including cutting component F_c and sliding component F_s due to dulled grains and metal chips against the workpiece, it means:

$$F_t = F_c + F_s \tag{3}$$

Then the overall force ratio μ can be calculated as:

$$\mu = \frac{F_t}{F_n} = \frac{F_c + F_s}{F_n} \tag{4}$$

The sliding friction coefficient μ_s can be defined as $\mu_s = F_s/F_n$. The Eq. (4) can be rewritten as:

$$\mu = \mu_s + \frac{F_c}{F_n} \tag{5}$$

Puthanangady TK and Malkin S [9] working on super finishing has concluded that the tangential grinding force is proportional to material removal rate Q_w, it means $F_c = k{\cdot}Q_w$, where k is a constant. According to this, Eq. (5) can be changed to

$$\mu = \mu_s + k{\cdot}\frac{Q_w}{F_n} \tag{6}$$

It reveals that the sliding coefficient μ_s can be determined through linear fitting by plotting material removal rate Q_w against the overall force ratio μ, and then finding the crossing point with y-axis ($Q_w = 0$).

Afterwards, it is able to continue on energetic analysis of belt finishing process with μ_s. The total specific energy E, the cutting and the sliding contributions E_c and E_s can be expressed as follows:

$$E = \frac{F_t{\cdot}V_s}{Q_w} \tag{7}$$

$$E_s = \frac{\mu_s{\cdot}F_n{\cdot}V_s}{Q_w} \tag{8}$$

$$E_c = E - E_s \tag{9}$$

4 Results

As shown in Fig. 3, material removal rate Q_w along with applied pressure p_n presents a very different varying pattern from belt finishing with MQL [1, 8, 10]. Figure 3 shows that Q_w declines continuously as p_n increasing. At the same time, the overall force ratio μ keeps falling from over 0.45 to about 0.2, as presented in Fig. 4. One possible reason for that is due to a more serious abrasive grains' wear made by a larger contact pressure, and more severe abrasion on grains brings both smaller penetration and friction coefficient [11]. Besides,

Fig. 5 Abrasive belts after finishing

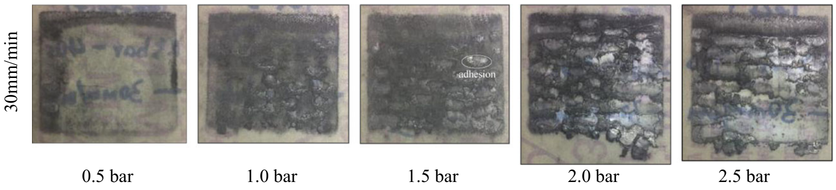
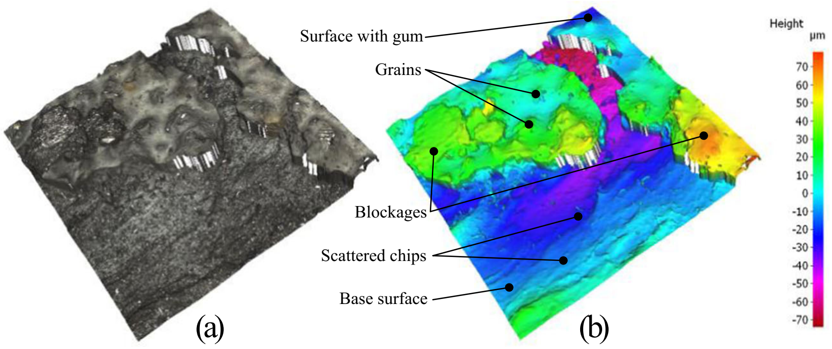


Fig. 6 The belt surface with adhesion. **a** Optical image; **b** Digital topography



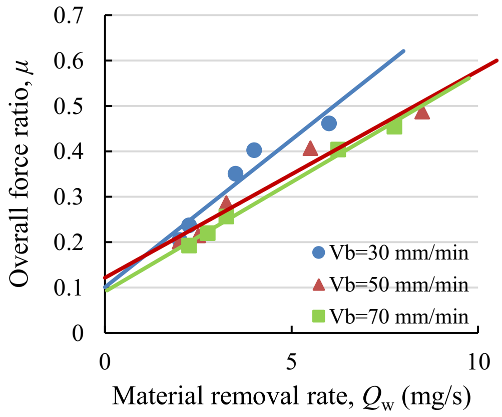


Fig. 7 Overall force ratio versus material removal rate

the phenomenon of adhesion wear on belt makes a great contribution for that, which will be discussed more in detail later. When $p_n = 1$ bar and no adhesion wear on the belt, $V_b = 50$ mm/min gives the highest Q_w, which indicates complicated effects of V_b on Q_w due to different grains sharpness and effective grains number. Generally speaking, higher V_b is helpful to induce greater Q_w due to more frequently renewed grains. However, Q_w becomes independent on belt feed rate since the applied pressure is beyond 1.5 bar when there is some severe adhesion wear happening.

Figure 5 shows the belt surfaces after finishing. It is clear that there is adhesion wear happening since the p_n is over 1 bar. Besides, larger applied pressure brings more severe adhesion. From Fig. 6, it can be found that the adhesion is caused by the loss of the gum, which leads to the loss of grains at the same time. After that, the combination of broken grains, chips, and gums covers on the new surface, which has significantly decreased the sharpness of grains and space between grains for escaping chips [12]. That is the reason why both Q_w and u decline with the growth of p_n.

Based on Eq. (6), sliding coefficient μ_s are estimated, as shown in Fig. 7. They are 0.1006, 0.122, and 0.094 for V_b = 30, 50, and 70 mm/min, respectively. It seems the sliding coefficients of different belt feed rates are pretty close. And here, the average value of μ_s is 0.105 with the standard deviation of 0.014.

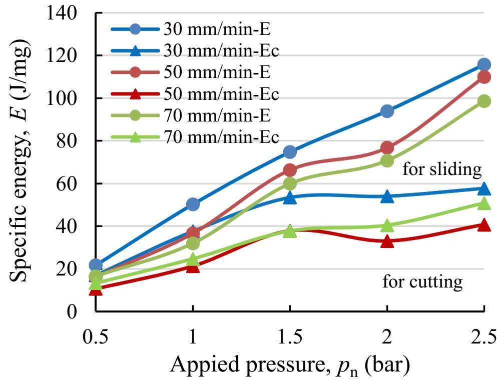


Fig. 8 Cutting and total specific energy versus applied pressure

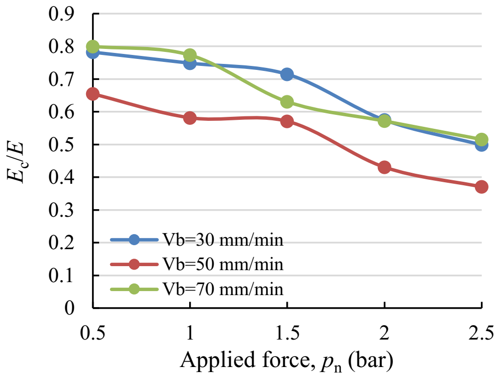


Fig. 9 Ratio between cutting and total specific energy

Figure 8 presents that total specific energy E and cutting specific energy E_c both grow up with the increasing of the applied pressure. The distinction area between those two curve groups corresponds to the energy cost on sliding, which change similarly with cutting specific energy. Figure 9 indicates the ratio between cutting specific energy and total specific energy versus the normal applied force. The E_c/E can arrive at 78~80% at p_n = 0.5 bar in a regular finishing (without adhesion). But finally, it declines dramatically to around 50%, which is an opposite tendency to the case with MQL lubrication [8]. It also reveals that more energy is spent on friction rather than on beneficial plastic deformation for chips formation under a higher applied pressure. The rest of energy that corresponds to sliding makes a contribution on generating friction heat, which may aggravate the melt of gum to form a vicious circle of adhesion wear. It can be said that cutting contribution is dominant in dry belt finishing; however, adhesion wear can dramatically decrease the cutting efficiency. The reason is that adhesion wear flats the belt surface, which results in an insufficient penetration of the grains, and more friction between adhesion and workpiece. Further studies to explain how this phenomenon happened and its effect on surface texture are needed.

Table 2 gives a general comparison between dry belt finishing and belt finishing with MQL. A several of

Table 2 Comparison between different lubrication conditions

Lubrication	Item compared				
	Q_w (mg/s)	u	u_s	E (J/mg)	E_c/E
Dry	6	0.462	0.101	21.65	0.79
MQL[8]	4.68	0.196	0.075	10.97	0.64

Working conditions: p_n = 0.5 bar (110 N), V_b = 30 mm/min, and V_s = 160 m/min.

parameters are compared under the working conditions $p_n = 0.5$ bar, $V_b = 30$ mm/min and $V_s = 160$ m/min. One thing should be mentioned is that the grain size is different in those two finishing way, 50 and 30 μm for dry and MQL, respectively. But it can still roughly evaluate the cutting efficiency of dry belt finishing. Compared with MQL finishing, dry belt finishing is not economy because of a double specific energy E. That is due to more energy spent on friction, which can be proved with a higher u of 0.462, more than two times than that of MQL. However, Q_w has been improved 28%. In addition, dry belt finishing has a pretty good E_c/E of 79%, which suggests most of energy is consumed on cutting. Although u_s of dry belt finishing is 34% higher than that of MQL, it just occupies 21% of μ, lower than 38% in MQL. Therefore, dry belt finishing can be an efficient machining method if the cutting conditions are well chosen, but it is still not economic.

5 Conclusion

Grinding forces and material removal rate for dry belt finishing were measured and analyzed. An analytical method was applied to give an observation on energy dispense. The material removal rate reveals an opposite tendency with the traditional lubricated belt finishing progress, which is mainly caused by adhesion wear. Higher applied force brings more severe adhesion wear and leads to worse cutting efficiency. Raising belt feed rate is helpful to improve the cutting ability in a regular finishing procedure, but no function when adhesion wear happens. A high E_c/E of 79% suggests that dry belt finishing can be an efficient process if the adhesion wear could be avoided through well-choosing working conditions. However, compared to MQL finishing it is still energy consumption.

In this paper, only the effect of adhesion wear on cutting efficiency and energy cost has been investigated. Additional studies about its effects on surface integrity and its formation mechanism will also be a great interest.

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