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Cost Optimization of Internal Grinding

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Abstract: This paper presents a study on cost optimization of internal grinding. In this study, the influences of grinding process parameters including the wheel life, the total dressing depth, the radial grinding wheel wear per dress and the initial grinding wheel diameter on the exchanged grinding wheel diameter were investigated. Also, the effect of cost components including the machine tool hourly rate and the grinding wheel cost were taken into account. For finding the optimum exchanged grinding wheel diameter, a cost optimization problem was built. Based on the results of the optimization problem, a formula for calculating the optimum exchanged grinding wheel diameter was proposed. With the optimum diameter, a new and effective way of using the grinding wheel was proposed and both the grinding cost and grinding time can be reduced considerably.

Key words: Grinding process, internal grinding, grinding, cost optimization.

1. Introduction

The history of the use of abrasives for shaping materials goes back to more than 2,000 years. Abrasive stones were used for sharpening early tools, knives, and weapons [1]. Nowadays, grinding process as well as internal grinding process is a common machining which used for precision sharped, high-quality surface productions. Therefore, optimization of grinding process has been subjected to many studies. Until now, most of studies are focusing on optimization for external cylindrical grinding [2-6] or for surface grinding [7-9]. For internal grinding process, studies on this topic have been done on off-line optimization for effective determination of the wheel life [10], on online-optimization for optimizing process and dressing parameters to reduce the grinding time [11], on adaptive process control to increase the efficiency in internal grinding [12] or on multi-criteria methodology for the effectiveness of grinding process [13].

This paper introduces a cost optimization study for internal grinding. The effects of many grinding process parameters as well as the effect of cost components were taken into account of a cost optimization problem. From the results of the optimum problem, a new and effective way of using the internal grinding wheel was proposed. Using this way, both the grinding cost and grinding time can be reduced considerably.

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2. Cost Analysis

In internal grinding process, the manufacturing single cost per piece $C_{\sin}$ can be determined as follows:

$$C_{\sin} = t_s \cdot C_{mt,h} + C_{gw,p} \quad (1)$$

where, $C_{mt,h}$ is the machine tool hourly rate (USD/h) including wages, overhead and cost of maintenance, etc., the value of $C_{mt,h}$ is different from companies $C_{gw,p}$ is the grinding wheel cost per workpiece (USD/workpiece), $C_{gw,p}$ can be calculated by:

$$C_{gw,p} = C_{gw} / n_{p,w} \quad (2)$$

where, C_{gw} is the cost of an internal grinding wheel (USD/piece), $n_{p,w}$ is the total number of workpieces ground by a grinding wheel and it can be written [14]:

$$n_{p,w} = \left(d_{s,0} - d_{s,e}\right) \cdot n_{p,d} / \left[2\left(\delta_{rs} + a_{ed,ges}\right)\right] \quad (3)$$

where, $d_{s,0}$ is the initial grinding wheel diameter (mm), $d_{s,e}$ is exchanged grinding wheel diameter (mm), δ_{rs} is the radial grinding wheel wear per dress (mm/dress), $a_{ed,ges}$ is total depth of dressing cut (mm), $n_{p,d}$ is number of workpieces per dress and is given by:

$$n_{p,d} = t_w / t_c \quad (4)$$

where, t_W is wheel life (h) and t_c is grinding time (h). In internal grinding, the grinding time can be expressed as:

$$t_c = l_w \cdot a_{e,tot} / \left(v_{fa} \cdot f_r\right) \quad (5)$$

where, $a_{e,tot}$ is total depth of cut (mm), l_w is length of workpiece (mm), v_{fa} is axial feed speed (mm/min), and f_r is radial wheel feed (mm/double stroke).

The axial feed speed v_{fa} is calculated as [15]:

- When grinding cast iron, brass and steel with the Rockwell hardness HRC < 30:

$$v_{fa} = 208.94 \cdot B_{gw}^{0.9976} \cdot d_w^{-0.0156} \cdot tg^{-3.0447} \cdot n_w^{0.9437} \quad (6)$$

- When grinding steel with the Rockwell hardness $HRC = 30 \div 50$:

$$v_{fa} = 127.29 \cdot B_{gw}^{1.0066} \cdot d_w^{-0.046} \cdot tg^{-2.9871} \cdot n_w^{1.0012} \quad (7)$$

- When grinding stainless steel, carbon steel, alloy steel, steel with the Rockwell hardness HRC > 50 and tool steels:

$$v_{fa} = 22.88 \cdot B_{gw}^{0.9865} \cdot d_w^{0.0821} \cdot tg^{-2.9833} \cdot n_w^{1.2471} \quad (8)$$

In the above formulas, B_{gw} is grinding wheel diameter; d_w is workpiece diameter; tg is tolerance grade; n_w is workpiece speed; n_w can be determined as follows [15]:

- When grinding cast iron, brass and steel with the Rockwell hardness HRC < 30:

$$n_w = 1114.6 \cdot d_w^{-0.4203} \quad (9)$$

- When grinding steel with the Rockwell hardness $HRC = 30 \ldots 50$:

$$n_w = 1046.5 \cdot d_w^{-0.3491} \quad (10)$$

- When grinding stainless steel, carbon steel, alloy steel, steel with the Rockwell hardness HRC > 50 and tool steels:

$$n_w = 1255.8 \cdot d_w^{-0.3491} \quad (11)$$

f_r is radial wheel feed (mm/double stroke); f_r is calculated by following equation [15]:

$$f_r = f_{r,tab} \cdot c_1 \cdot c_2 \cdot c_3 \cdot c_4 \quad (12)$$

where, $f_{r,tab}$ is tabled radial wheel feed (mm/double stroke); $f_{r,tab}$ is determined as follows [15]:

$$f_{r,tab} = 30.2944 \cdot a_{e,tot}^{0.567} \cdot v_{fa}^{-0.9693} \cdot d_w^{-0.1269} \quad (13)$$

In which, $a_{e,tot}$ is the total depth of cut (mm).

c_1 is the coefficient which depends on workpiece material and tolerance grade tg; it can be calculated by the following formulas [15]:

- When grinding structural carbon steel, chromium steel and tool steels:

$$c_1 = 0.0857 \cdot tg^{1.2767} \quad (14)$$

- When grinding molybdenum and tungsten steels:

$$c_1 = 0.0904 \cdot tg^{1.1531} \quad (15)$$

- When grinding high-temperature steels and stainless steels:

$$c_1 = 0.0288 \cdot tg^{1.4153} \quad (16)$$

$$K_1 = 0,0288 \cdot ccx^{1,4153}$$

When grinding high-speed steels and tungsten alloy steels:

$$c_1 = 0.0196 \cdot tg^{1.0431} \quad (17)$$

When grinding cast iron and copper alloys:

$$c_1 = 0.0862 \cdot tg^{1.4965} \quad (18)$$

c_2 is a coefficient which depends on grinding wheel diameter d_s. Based on data in [16], c_2 can be calculated by the following regression equation (with $R^2 = 0.9977$):

$$c_2 = 0.5657 \cdot d_s^{0.153} \quad (19)$$

c_3 is a coefficient which depends on measurement type; $c_3 = 1$ if a micrometer is used for measurement and $c_3 = 1.4$ if a snap gauge is used [16];

c_4 is a coefficient which depends on the character of workpiece's hole and the ratio of the length of workpiece (l_w) to its diameter (d_w). Based on the data in [16], the following formulas were found for determination of coefficient c_4:

When grinding continuous cylindrical hole, c_4 can be calculated by ($R^2 = 0.9637$):

$$K_4 = 1.0642 \cdot \left(l_w / d_w\right)^{-0.5079} \quad (20)$$

When grinding non-continuous cylindrical hole, c_4 can be calculated by ($R^2 = 0.955$):

$$K_4 = 1.375 \cdot \left(l_w / d_w\right)^{-0.5058} \quad (21)$$

When grinding cylindrical hole with a curved shoulder, c_4 can be calculated by ($R^2 = 0.9637$):

$$K_4 = 0.8514 \cdot \left(l_w / d_w\right)^{-0.5079} \quad (22)$$

t_s is manufacturing time includes auxiliary time (h); in internal grinding process, the manufacturing time can be express as:

$$t_s = t_c + t_{lu} + t_{sp} + t_{d,p} + t_{cw,p} \quad (23)$$

where, t_{lu} is time for loading and unloading workpiece (h), t_{sp} is spark-out time (h); $t_{d,p}$ is dressing time per piece (h):

$$t_{d,p} = t_d / n_{p,d} \quad (24)$$

where, t_d is dressing time (h); Substituting Eq. (4) into Eq. (24) we have:

$$t_{d,p} = t_d \cdot t_g / t_w \quad (25)$$

$t_{cw,p}$ is time for changing a grinding wheel per workpiece (h); $t_{cw,p}$ can be calculated as:

$$t_{cw,p} = t_{cw} / n_{p,w} \quad (26)$$

With t_{cw} is time for changing a grinding wheel (h); substituting Eq. (3) into Eq. (26) we have

$$t_{cw,p} = 2t_{cw}\left(\delta_{rs} + a_{ed,ges}\right) / \left[n_{p,d}\left(d_{s,0} - d_{s,e}\right)\right] \quad (27)$$

t_c is the grinding time (h); in internal cylindrical grinding, the grinding time can be calculated as [16]:

$$t_c = \frac{l_w \cdot a_{e,tot}}{v_{fa} \cdot v_{fr}} \quad (28)$$

3. Optimization Problem

For internal grinding process, the cost optimum problem can be expressed as an objective function:

$$C_{\sin\min} = f(d_{s,e}) \quad (29)$$

With the following constraints:

$$\begin{aligned}
&C_{mt,h\min} \le C_{mt,h} \le C_{mt,h\max};\\
&C_{gw\min} \le C_{gw} \le C_{gw\max};\\
&d_{s,0\min} \le d_{s,0} \le d_{s,0\max}\\
&a_{ed,ges\min} \le a_{ed,ges} \le a_{ed,ges\max}\\
&\delta_{rs\min} \le \delta_{rs} \le \delta_{rs\max};\\
&T_{w\min} < T_w \le T_{w\max};\\
&a_{e,tot\min} \le a_{e,tot} \le a_{e,tot\max};
\end{aligned} \quad (30)$$

From Eqs. (1), (29) and (30), a computer program was built for determining the optimum of the exchanged grinding wheel diameter for getting the minimum grinding cost. The data of the constraints used in the program was chosen: $C_{mt,h}$ = 1.5 ÷ 10 (USD/h); C_{gw} = 0.2 ÷ 2 (USD/piece); $d_{s,0}$ =5 ÷ 30 (mm); $a_{ed,ges}$ =0.01 ÷ 0.03; δ_{rs} = 0.01 ÷ 0.03 (mm/dress); T_w =10 ÷ 30 (min); $a_{e,tot}$ =0.05 ÷ 0.15 (mm).

4. Results and Discussion

Fig. 1 shows the relation between the exchanged grinding wheel diameter and the manufacturing single cost per part. The data used in this case was: $C_{mt,h}$ = 4 (USD/h); C_{wp} = 1 (USD/piece); $d_{s,0}$ =16 (mm); $a_{ed,ges}$ = 0.03 (mm); δ_{rs} = 0.02 (mm/dress); $a_{e,tot}$ = 0.1 (mm); t_d = 6 (min); t_w = 20 (min); t_{cw} = 2 (min). It was noted that the grinding cost depends strongly on the exchanged grinding wheel diameter and it gets the minimum value when the exchanged diameter equals a

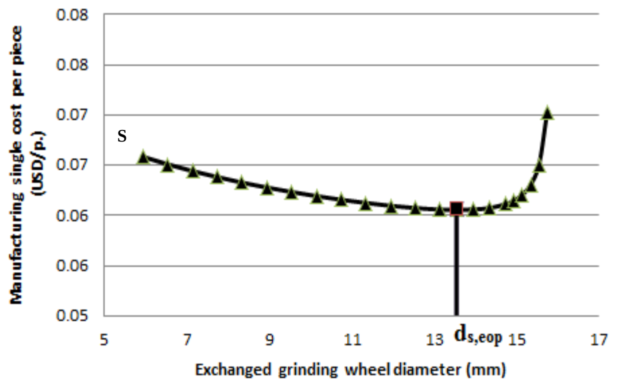

Fig. 1 Manufacturing single cost versus exchanged grinding wheel diameter.

value $d_{s,eop}$ (Fig. 1). This exchanged diameter is called "optimum diameter". It was found that the optimum diameter is much larger than the traditional exchanged diameter. In this case, the optimum diameter was 13.55 mm (Fig. 1) while the traditional exchanged diameter was about 7.2 mm. Also, with the optimum diameter the manufacturing cost per piece was 0.061 (USD/p.) when with traditional exchanged diameter (7.15 mm) it was 0.064 (USD/p.). Calculating for the manufacturing time, with optimum diameter the grinding time was 0.91 (min.) and with the traditional

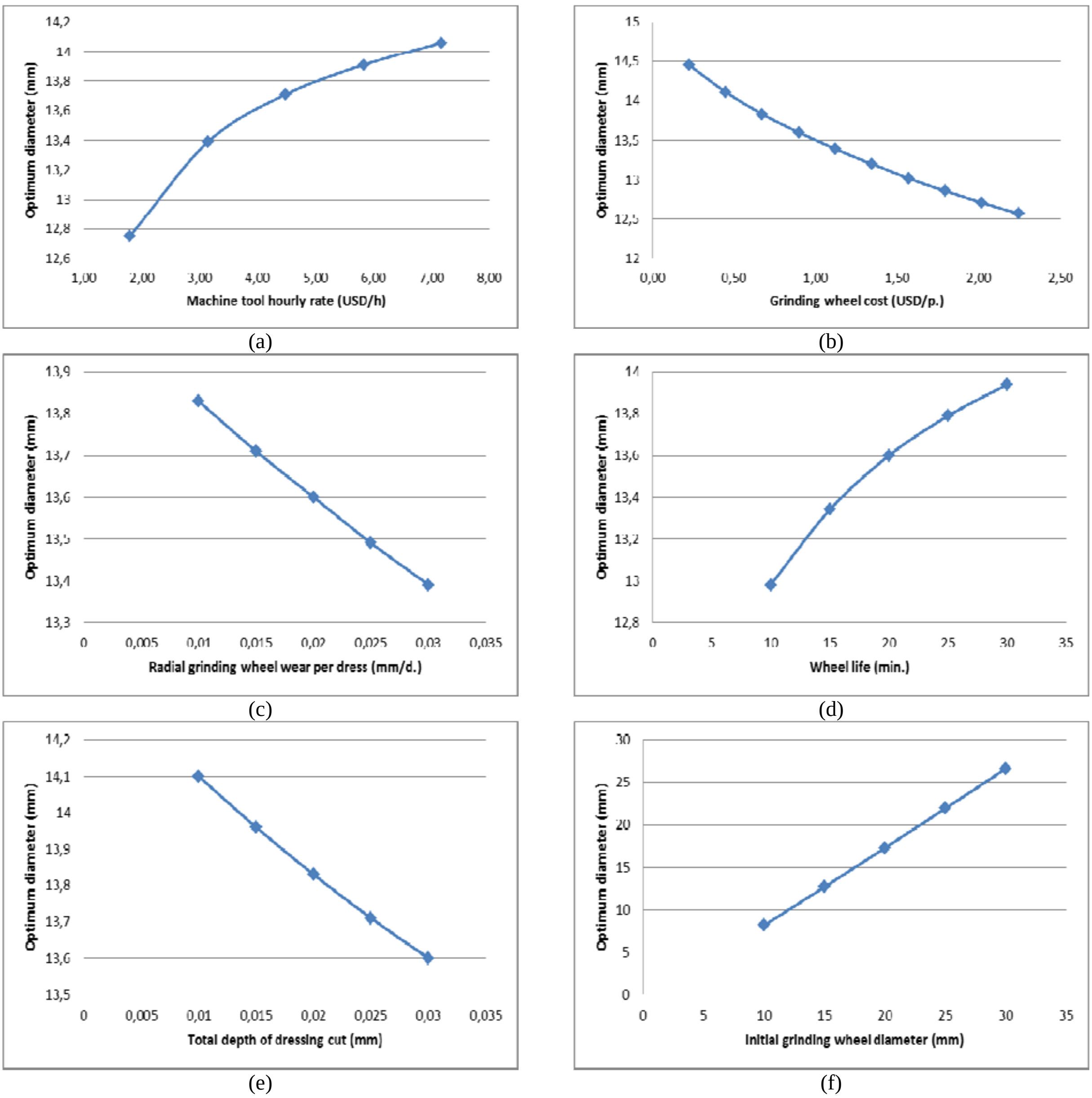

Fig. 2 Cost and process factors versus optimum diameter.

exchanged diameter it was 0.78 (min.). Therefore, in this case, grinding with optimum diameter can reduce the manufacturing cost 5.11% and the manufacturing time 6.83%.

From the results of the optimum problem, it was found that the optimum diameter depends on several factors, including the machine tool hourly rate (Fig. 2a), the grinding wheel cost C_{gw} (Fig. 2b), the radial grinding wheel wear per dress (Fig. 2c), the wheel life (Fig. 2d), the total depth of dressing cut (Fig. 2e) and the initial grinding wheel diameter (Fig. 2f). Among them, the initial grinding wheel diameter is the main effect factor of the optimum diameter. It was also recognized that the optimum diameter do not depend on the tolerance grade required. The reason of that is the axial feed speed v_{fa}, which is much affected by the required tolerance grade, does not depend on the grinding wheel diameter (see Eqs. (6)-(8)).

From the results of the cost optimization program, the following regression model (R^2 = 0.9964) was proposed for determination of the optimum diameter:

$$d_{s,eop} = 0.3818 \cdot C_{mt,h}^{0.0677} \cdot C_{gw}^{-0.0493} \cdot T_{w}^{0.0588} \cdot a_{ed,ges}^{-0.0349} \cdot \delta_{rs}^{-0.0349} \cdot d_{s,0}^{1.0871} \quad (31)$$

5. Conclusions

A study on cost optimization of internal cylindrical grinding was investigated. In this study, the cost analysis for the grinding process was carried out. Besides, the effects of cost components and grinding process parameters on the optimum exchanged grinding wheel diameter were investigated. For determination of the optimum exchanged diameter for getting the minimum grinding cost, a computer program was built. Based on the results of the program, a regression formula for calculating the optimum diameter was proposed. Grinding with optimum diameter can save a lot of both the grinding cost and the grinding time. Also, by giving an explicit equation, the optimum diameter for internal grinding process can be determined very simple.

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