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Research paper

An optimization study on surface grinding stainless steel

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Abstract

This paper presents a study on optimization of the exchanged grinding wheel diameter based on the analysis cost for surface grind-ing stainless steel. The optimum exchanged grinding wheel diameter is determined by minimizing the cost function. An experi-mental design was conducted to describe the influence of the input technological parameters i.e., the initial grinding wheel diameter, the grinding wheel width, the total depth of dressing cut, the Rockwell hardness of workpiece, the wheel life, and the radial grind-ing wheel wear per dress and the cost components i.e., the machine tool hourly rate and the grinding wheel cost on the optimum diameter. Based on the regression analysis, a mathematical model to compute the optimum diameter was resulted as an explicit equation. The reliability of the mathematical model is verified by the result of the experiment. The difference of optimum diameter between the model and the experiment was 1.7%. For these results, the proposed model can be used for calculating the optimum exchanged grinding wheel for surface grinding; therefore, this can increase the economic and technical effectiveness of the grinding process.

Keywords: *Grinding, Surface Grinding; Cost Optimization; the Exchanged Grinding Wheel Diameter.*

1. Introduction

Grinding is an operation applied in almost every type of manufacturing process. In industries, it can be accounted about 20-25% of the amount of expenditures on machining operations [1]. Therefore, grinding is one of the important technologies to obtain the quality of the surface finish of components and tight tolerances [2].
Numerous researches have been focused on optimization problems of a grinding process. Optimum grinding process parameters including wheel and machine parameters were proposed on the basis of minimizing grinding time and maximizing the volume of material removed rate [3], [4]. The optimization to reduce the high temperature in the cutting area for grinding process has been proposed for optimization of parameters for lubrication [5], coolant parameters on surface roughness [6]. The relevance to the optimization of grinding and dressing parameters was presented for maximizing the material removal rate [7], minimizing the grinding time [8, 9], as well as minimizing the dressing and grinding costs [10]. Regarding the optimization of cost for internal and external grinding processes, several previous researches presented the cost function based on the grinding parameters [11-15]. Since then, this field has been continuously studied for surface grinding process. Vu et al. [16] proposed a study on cost optimization based on the dressing regime parameters. Based on the cost optimization, the replaced grinding wheel diameter was determined for surface grinding operation for 9CrSi steel material [17].
This paper is studied on optimization of the exchanged grinding wheel diameter for surface grinding stainless steel. This work is continuously developed by the proposed formula [16], which has not yet carefully evaluated grinding process parameters and cost components. In this paper, the analysis of the cost for surface grinding based on the grinding technological parameters is investigated, and the optimum exchanged grinding wheel diameter is determined by minimizing the cost function. In addition, the influence of the grinding parameters such as the initial grinding wheel diameter D_0, the grinding wheel width W_{gw}, the total depth of dressing cut a_{ed}, the Rockwell hardness of workpiece HRC, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, and the grinding wheel cost C_{gw} on the optimum diameter on the optimum exchanged grinding was considered. In order to investigate the effect of these parameters on the optimum diameter, the design of experiment was carried out. By using regression analysis, a mathematical model was established.

2. Methodology

This section presents the cost analysis of the surface grinding process. The schema of surface grinding is shown in Fig. 1. The cost of the surface grinding process depends on the exchanged grinding wheel diameter. The procedure for computing the cost function is described as follows.

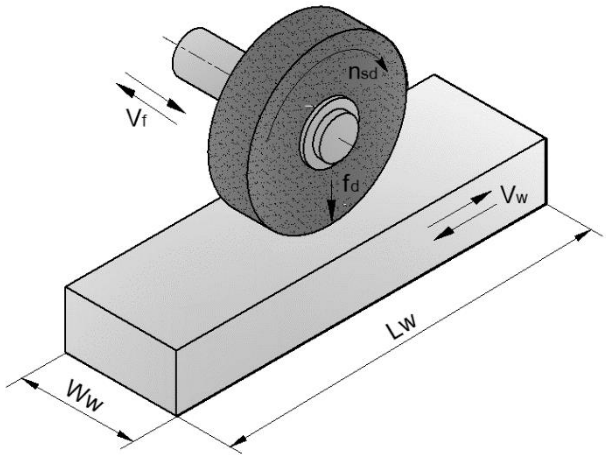

Fig. 1: Schema of Surface Grinding.

The surface grinding cost is based on the manufacturing time t_s(h), the machine tool hourly rate C_{mh} (USD/h), and the grinding wheel cost per workpiece C_{gw}(USD/workpiece). Thus, the manufacturing single cost per piece, denoted by C_{sin} is computed as

$$C_{sin} = t_s . C_{mh} + C_{gw} . \quad (1)$$

Here, C_{gw} can be expressed as

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

where $C_{gw,p}$ is the grinding wheel cost per piece (USD/piece), and $n_{p,w}$ is the total number of workpieces ground by a grinding wheel; $n_{p,w}$ can be written as follows [2]

$$n_{p,w} = \frac{(D_0 - D_e)\, n_{p,d}}{2(W_{pd} + a_{ed})} . \quad (3)$$

In which, D_0, D_e, W_{pd}, and a_{ed} are the initial grinding wheel diameter (mm), the exchanged grinding wheel diameter (mm), the radial grinding wheel wear per dress (mm/dress), and the total depth of dressing cut (mm) respectively; $n_{p,d}$ is the number of workpieces per dress and is calculated by

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

in which T_w and t_c are the wheel life (h) and the grinding time (h), respectively. For surface grinding, t_c can be computed as

$$t_c = l_c\, w_c\, a_{e,tot}/(1000\, v_w\, v_f\, v_d\, N_t) . \quad (5)$$

Where, l_c, w_c, $a_{e,tot}$, and N_t are the calculated grinding length (mm), the calculated grinding width (mm), the total depth of cut (mm), and the number of workpieces per grinding time, respectively. The grinding length and grinding width can be computed as follows: $l_c = l_w + (20 \ldots 30)$ and $w_c = w_w + w_{gw} + 5$, in which, l_w and w_w are respectively the length and width of the workpieces (mm) (see Fig. 1). The other parameters in Eq. (5), v_w , v_f and v_d , are the work speed (m/s), the work feed rate (mm/min), and the downfeed (mm/pass) as shown in Fig. 1. They can be respectively calculated as the following regression equations [16], [18], [19]

$$v_w = 0.0598\, HRC^{1.4} \quad (6)$$

$$v_f = (46\, w_{gw}^{0.983})/N_{Ra}^{2.44} \quad (7)$$

$$v = f_{d,t}\, c_1\, c_2\, c_3 \quad (8)$$

In Eqs. (6) and (7), $HRC^{1.4}$, w_{gw}, and N_{Ra} are the Rockwell hardness of workpiece, the grinding wheel width, and the required roughness grade number, respectively.
In Eq. (8), $f_{d,t}$ is the tabulated downfeed (mm/pass); c_1, c_2, and c_3 are coefficients. For grinding stainless steel, $f_{d,t}$ can be expressed in Eq. (9) as found in [2]. The coefficients, c_1 and c_2, can be determined in [19]

$$f_{d,t} = 0.649\, a_{e,tot}^{0.651}\, v_f^{-0.985} \quad (9)$$

$$c_1 = 0.61\, tg^{0.466} \quad (10)$$

$$c_2 = (0.0292\, d_s^{0.5151})/D_w^{0.4949} \quad (11)$$

Where, tg, d_s, and D_w are the required tolerance grade, the grinding wheel diameter, and the density of the workpiece loaded on the machine table, respectively.
The coefficient c_3 is selected by the grinding machine age as follows: $c_3 = 1$ when the grinding machine age is less than 10 years; $c_3 = 0.85$ when the age is in the interval [10, 20] years, and $c_3 = 0.7$ when the age is more than 20 years [18].
The manufacturing time including auxiliary time, t_s in Eq. (1), is determined by

$$t_s = t_c + t_{lu} + t_{sp} + t_{d,p} + t_{cw,p} \quad (12)$$

In which, t_c as known above is the grinding time; t_{lu} is the time for loading and unloading workpiece; $t_{sp}, t_{d,p}$, and $t_{cw,p}$ are respectively the spark-out time, the dressing time per piece, and the time for changing a grinding wheel per workpiece. The calculation of these time parameters is described in Table. 1

Table.1: Time Parameters

Time parameters	Symbol	Equation
Spark-out time	t_{sp}	$t_{sp} = (l_c\, w_c)/(1000\, v_w\, v_f\, N_t)$
Dressing time per piece	$t_{d,p}$	$t_{d,p} = t_d/n_{p,d}$
Time for changing a grinding wheel per workpiece	$t_{cw,p}$	$t_{cw,p} = t_{cw}/n_{p,w}$

As analyzed above, with a given value of the input grinding parameters i.e., $D_0 = 500\ (mm)$; $W_{gw} = 40\ (mm)$; $z = 0.1\ (mm)$; $C_{mh} = 10\ (USD/h)$; $C_{gw} = 30\ (USD/piece)$; $n_s = 1450\ (rpm)$; $n_{pd} = 35$; $a_{ed} = 0.1\ (mm)$; $T_w = 20\ (mim)$; $W_{pd} = 0.02\ (mm/dress)$, the grinding cost in Eq. (1) depends on the exchange grinding wheel diameter D_e . Fig 2 shows the relationship between the grinding cost and the diameter of exchange grinding wheel. It is clearly seen that the grinding cost obtains the minimum value at $D_{e,op} = 475\ (mm)$ (see Fig. 2). For the comparison between the optimum diameter $D_{e,op}$ and the conventional exchanged grinding wheel diameter, the value of conventional diameter, which can be from 200 to 250mm, is much smaller than the optimum value. Therefore, the objective function for the grinding cost depending on the exchanged grinding wheel diameter D_e can be written as

$$Minimize\ C_{sin} = f(D_e) \quad (13)$$

$$D_{e,min} \le D_e \le D_{e,max} . \quad (14)$$

subject to

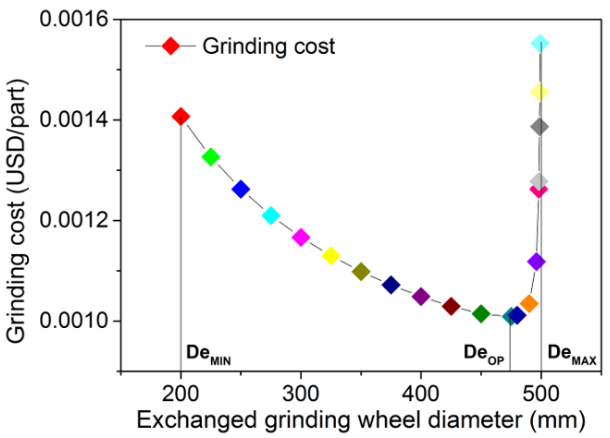

Fig. 2: Grinding Cost Versus Exchanged Grinding Wheel Diameter.

In addition, with the surface grinding process, the value of the optimum exchanged grinding wheel is also affected by various grinding parameters such as the initial grinding wheel diameter D_0, the grinding wheel width W_{gw}, the total depth of dressing cut a_{ed}, the Rockwell hardness of workpiece HRC, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, and the grinding wheel cost C_{gw} . Thus, the optimum exchanged grinding wheel diameter can be expressed as

$$D_{e,op} = f\left(D_0, W_{gw}, a_{ed}, HRC, T_w, W_{pd}, C_{mh}, C_{gw}\right). \quad (15)$$

3. Experimental work

In this section, the experimental work is presented to describe the influence of the input parameters i.e., the initial grinding wheel diameter D_0, the grinding wheel width W_{gw}, the total depth of dressing cut a_{ed}, the Rockwell hardness of workpiece HRC, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, and the grinding wheel cost C_{gw} on the optimum diameter. In order to investigate the effect of these parameters on the exchanged grinding wheel, the value of the grinding parameters is chosen in Table. 2.

Table 2: Grinding Parameters for Experiment

Factor	Code	Unit	Low	High
Initial grinding wheel diameter	D_0	mm	250	500
Grinding wheel width	W_{gw}	mm	20	50
Total depth of dressing cut	a_{ed}	mm	0.1	0.2
Rockwell hardness of workpiece	HRC	-	20	65
Wheel life	T_w	min	10	30
Radial grinding wheel wear per dress	W_{pd}	mm	0.01	0.03
Machine tool hourly rate	C_{mh}	USD/h	5	15
Grinding wheel cost	C_{gw}	USD/p	15	50

Minitab 18 was used to conduct the experiment and to analyze the experimental data. With the eight input parameters as shown in Table.2, the total of test runs is 128 ($2^{(8-1)}$) for this experimentation. As discussed in Sec. 2, the optimum exchanged grinding wheel is determined by minimizing the cost function in Eq. (1) and also depends on the eight input parameters. Therefore, the optimum diameter of the exchanged grinding at each test run is simply determined according to the value change of the parameters in the conducted experiments as shown in Table.3.

Table 3: Experimental Plans and Output Response

Std Order	Run Order	CenterPt	Blocks	D_0	W_{gw}	a_{ed}	HRC	T_w	W_{pd}	C_{mh}	C_{gm}	D_{op}
97	1	1	1	250	20	0.1	20	10	0.03	15	15	231.75
82	2	1	1	500	20	0.1	20	30	0.01	15	50	474.52
51	3	1	1	250	50	0.1	20	30	0.03	5	50	220.16
89	4	1	1	250	20	0.1	65	30	0.01	15	50	232.38
108	5	1	1	500	50	0.1	65	10	0.03	15	50	459.16
104	6	1	1	500	50	0.2	20	10	0.03	15	50	447.25
…												
54	127	1	1	500	20	0.2	20	30	0.03	5	15	465.51
9	128	1	1	250	20	0.1	65	10	0.01	5	50	210.3

4. Results and discussions

Based on the analysis of variance - ANOVA for the data reported in Table 3, Fig. 2 shows the effect of each factor on the optimum exchanged grinding wheel diameter D_{op}. It is clearly seen that the relation between the optimum diameter and each factor is described by the straight lines. From the observation of the slope angles of the straight lines in Fig. 3, the strong influence on the optimum diameter is the initial grinding wheel diameter D_0. The other parameters such as the total depth of dressing cut a_{ed}, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, and the grinding wheel cost C_{gw} have the less effect on the optimum diameter compared to the initial grinding wheel diameter D_0. It is also observed that the lines of the factor HRC and the grinding wheel width W_{gw} are parallel to the horizontal axis; therefore the Rockwell hardness of workpiece HRC and the grinding wheel width W_{gw} have insignificant effect on the D_{op}.

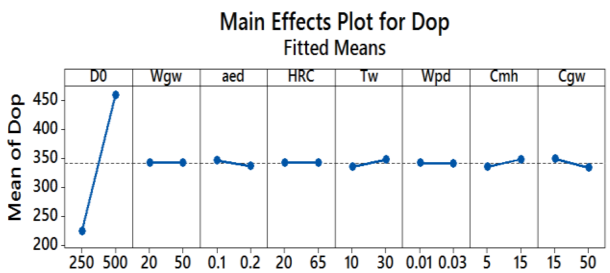

Fig. 3: Main Effects Plot for Optimum Exchanged Grinding Wheel Diameter.

Fig. 4 presents the Pareto chart of the standardized effects with statistical significance at the 0.5 level. In Fig. 4, the influence of the grinding parameters is more clearly evaluated by the magnitude of these parameters. As seen in Fig. 4, the absolute values of the factors and the interactions are distributed from the lowest to the highest values; therefore, influences of these parameters and interactions are arranged from the smallest to largest effects on the optimum diameter D_{op}. From the observation in this figure, the initial grinding wheel D_0 (factor A) has the strongest effect on the optimum diameter D_{op} because of its largest magnitude among the factors and interactions.

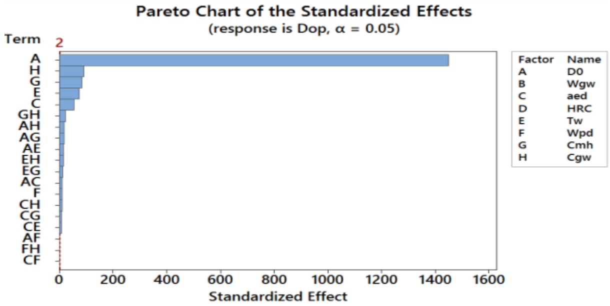

Fig. 4: Pareto Chart of the Standardized Effects.

The Pareto chart can determine which effects are large but cannot determine which effects increase or decrease the response. Therefore, the Normal Plot of the standardized effects presents the trend of the effect of the factors and the interactions of the parameters on the optimum exchanged grinding wheel diameter D_{op} as shown in Fig. 5. It is observed from Fig. 5 that the distribution of the standardized effects for most of the factors is close to the reference line (the red line). Positive effects of the factors and interactions (see the red squares in the right side of the reference line) increase the optimum diameter D_{op} when the settings change from the low value of the factors and interactions to the high value. Otherwise, negative effects located on the left side of the reference line decrease the optimum diameter D_{op} when the settings change from the low value of the factors and interactions to the high value. Effects further from the reference line are more statistically significant e.g., the initial grinding wheel diameter D_0 (factor A). It is clearly seen that the factors and interactions with the blue circles have insignificant effects on the optimum diameter D_{op}.

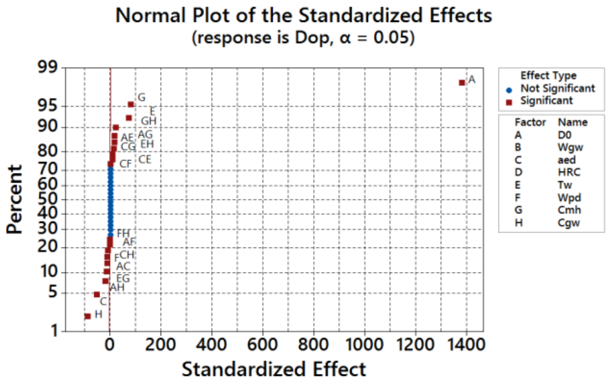

Fig. 5: Normal Plot for Dop.

After neglecting the insignificant effects on D_{op}, the estimated effects and coefficients for the optimum diameter are presented in Fig. 6. As seen that the parameters and the interactions have the p-values that are smaller than the significant level (α = 0.05). Therefore, they absolutely have significant effects on the respond.

From the results above, we have the six grinding parameters i.e., the initial grinding wheel diameter D_0, the machine tool hourly rate C_{mh}, the wheel life T_w, the grinding wheel cost C_{gw}, the total depth of dressing cut a_{ed}, and the radial grinding wheel wear per dress W_{pd} and thirteen interactions i.e., $C_{mh}*C_{gw}$, D_0*C_{mh}, D_0*T_w, T_w*C_{gw}, $a_{ed}*C_{mh}$, $a_{ed}*T_w$, $a_{ed}*W_{pd}$, D_0*C_{gw}, T_w*C_{mh}, D_0*a_{ed}, $a_{ed}*C_{gw}$, D_0*W_{pd}, and $W_{pd}*C_{gw}$ which affect the optimum diameter. Thus, the mathematical model can be built by using the analysis regression technique in order to compute the optimum exchanged grinding wheel diameter for surface grinding. This model depending on those grinding parameters and the their interactions can be expressed as

$$D_{op} = -1.29 + 0.95384\, D_0 - 67.02\, a_{ed} + 0.0045\, T_w - 51.1\, W_{pd} - 0.2469\, C_{mh} - 0.3436\, C_{gw} - 0.1522\, D_0 a_{ed} + 0.001055 D_0 T_w - 0.156\, D_0 W_{pd} + 0.0235\, D_0 C_{mh} - 0.000733\, D_0 C_{gw} + 1.436\, a_{ed} T_w + 344\, a_{ed} W_{pd} + 3.183\, a_{ed} C_{mh} - 0.9975\, a_{ed} C_{gw} - 0.02225\, T_w C_{mh} + 0.006973\, T_w\, C_{gw} - 1.032\, W_{pd} C_{pd} + 0021879\, C_{mh} C_{gw}\,. \quad (15)$$

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	19	1822884	95941	112062.50	0.000
Linear	6	1820865	303478	354471.61	0.000
D0	1	1799969	1799969	2102421.56	0.000
aed	1	2540	2540	2966.46	0.000
Tw	1	4912	4912	5737.83	0.000
Wpd	1	107	107	125.43	0.000
Cmh	1	6075	6075	7095.53	0.000
Cgw	1	7263	7263	8482.88	0.000
2-Way Interactions	13	2019	155	181.37	0.000
D0*aed	1	116	116	135.20	0.000
D0*Tw	1	222	222	259.89	0.000
D0*Wpd	1	5	5	5.69	0.019
D0*Cmh	1	276	276	322.52	0.000
D0*Cgw	1	329	329	384.09	0.000
aed*Tw	1	66	66	77.03	0.000
aed*Wpd	1	4	4	4.42	0.038
aed*Cmh	1	81	81	94.64	0.000
aed*Cgw	1	98	98	113.90	0.000
Tw*Cmh	1	158	158	185.04	0.000
Tw*Cgw	1	191	191	222.64	0.000
Wpd*Cgw	1	4	4	4.88	0.029
Cmh*Cgw	1	469	469	547.92	0.000
Error	108	92	1		

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.925279	99.99%	99.99%	99.99%

Fig. 6: Estimated Effects and Coefficients for Dop.

The reliability of the mathematical model as shown in Eq. (15) is verified by the result of the experiment as found in [18]. The input data of the grinding parameters was used for the experiment and the mathematical model as follows: $D_0 = 300\ (mm)$, $a_{ed} = 0.115\ (mm)$; $T_w = 22.5\ (min.)$; $W_{pd} = 0.02\ mm/dress$; $C_{mh} = 5\ USD/h$; $C_{gw} = 25\ (USD/piece)$. The optimum exchanged grinding wheel diameter obtained by the experiment and the model in Eq. (15) was 265 (mm) and 269.59 (mm), respectively. The difference between the mathematical model and the experiment can be expressed as

$$\delta_{D_{op}} = \frac{(269.59 - 265).100}{269.59}\% = 1.7\% \quad (16)$$

The result from Equation (16) shows that the optimum exchanged grinding wheel diameter is calculated by the formula (16) in accordance with the optimum value obtained from the experiment.

5. Conclusions

In this paper, the analysis of cost for surface grinding stainless steel was proposed in order to determine the optimum exchanged grinding wheel based on minimizing the cost function. Furthermore, the optimum diameter also depends on the eight grinding parameters i.e., the initial grinding wheel diameter D_0, the grinding wheel width W_{gw}, the total depth of dressing cut a_{ed}, the Rockwell hardness of workpiece HRC, the wheel life T_w, the radial grinding wheel wear per dress W_{pd}, the machine tool hourly rate C_{mh}, and the grinding wheel cost C_{gw}. By the design of experiment, the effects of the grinding parameters on the optimum diameter were investigated. In addition, determining the optimum exchanged grinding wheel diameter was concluded by a mathematical model. The results of this work are drawn as follows

- It was found that the initial grinding parameter D_0 has the strongest effect on the optimum exchanged grinding wheel diameter whereas the Rockwell hardness of workpiece HRC and the grinding wheel width W_{gw} have insignificant effect on the optimum diameter.
- The positive effects of the three parameters i.e., the initial grinding wheel diameter D_0, the wheel life T_w, the machine

tool hourly rate C_{mh} increase the optimum diameter D_{op}. Whereas negative effects of the three parameters i.e., the total depth of dressing cut a_{ed}, the grinding wheel cost C_{gw}, and the radial grinding wheel wear per dress W_{pd} decrease the optimum diameter D_{op}.

- The difference of the optimum diameter between the experiment and the mathematical model was 1.7%. Due to this, the model is reliable to apply for calculating the optimum exchanged grinding wheel diameter in surface grinding tool steel.

Acknowledgments

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