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Calculation of Optimum Exchanged Grinding Wheel Diameter When External Grinding Tool Steel 9CrSi

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Abstract—This paper presents a study on the optimum calculation of exchanged grinding wheel diameter when external grinding alloy tool steel 9CrSi. In this study, the effects of the grinding process parameters including the initial grinding wheel diameter, the total dressing depth, the radial grinding wheel wear per dress, and the wheel life on the exchanged grinding wheel diameter were considered. Furthermore, the impact of cost elements including the machine tool hourly rate and the grinding wheel cost were investigated. To evaluate the effect of these factors on the optimum exchanged grinding wheel diameter, an "experiment" was designed, and a computer program was built for performing the "experiment". Based on the results of the "experiment", a formula for determining the optimum exchanged grinding wheel diameter was proposed.

Index Terms—**external grinding, grinding, grinding process, cost optimization.**

I. Introduction

Grinding is a major machining process which accounts for about 20%–25% of the total expenditures on machining operations in industries [1]. This technology is used for precision sharped, high-quality surface productions. Subsequently, optimization of the grinding process as well as of external grinding process has been subjected to many studies.

So far, research for external cylindrical grinding have focused on minimizing the total grinding time [2], [3], the optimum grinding, and dressing conditions for maximizing the volumetric removal rate [1], the optimum selection of grinding parameters [4], [5], or optimum design of grinding wheel topography [6]. Recently, a cost optimization study on external cylindrical traverse grinding has been carried out [7] in order to find the optimum exchanged grinding wheel diameter was introduced. From the study, the grinding cost was at the minimum when the exchanged diameter equals a value $d_{s,eop}$ (optimum diameter) (Fig. 1). In addition, a formula for calculating the optimum exchanged grinding wheel diameter was introduced. Also, it was noted that grinding with the optimum exchanged diameter can save a lot of the grinding cost and the time of grinding. However, in this study, the effects of the grinding process parameters were still not carefully evaluated.

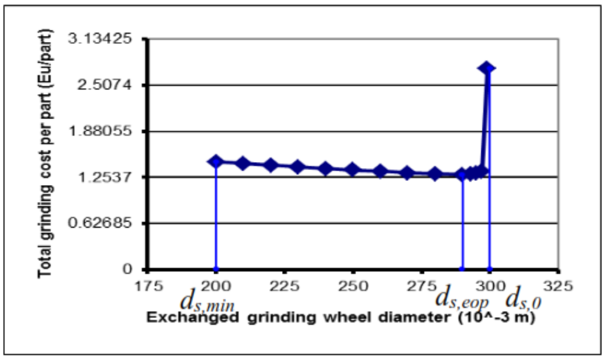

Figure 1. Grinding cost versus exchanged grinding wheel diameter [7].

This paper introduces a study on the optimum determination of exchanged grinding wheel diameter when external grinding tool steel 9CrSi. In this study, the effects of the grinding process parameters including the initial grinding wheel diameter, the total dressing depth, the radial grinding wheel wear per dress, and the wheel life on the exchanged grinding wheel diameter were considered. Furthermore, the impact of cost elements including the machine tool hourly rate and the grinding wheel cost were investigated. In order to evaluate the influence of these factors on the optimum exchanged grinding wheel diameter, an "experiment" was designed

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and a computer program was built to accomplish the "experiment". From the results of the "experiment", a model for calculating the optimum exchanged grinding wheel diameter was proposed.

Cost Analysis

In the external grinding process, the manufacturing single cost per piece $C_{\sin}$ can be calculated by following equation:

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

where,

$C_{mt,h}$ - Machine tool hourly rate (USD/h) including wages, overhead, and cost of maintenance etc.

$C_{gw,p}$ - Grinding wheel cost per part (USD/part);

$C_{gw,p}$ is determined by the following equation:

$$C_{gw,p} = C_{gw} / n_{p,w} \tag{2}$$

In which, C_{gw} is the cost of a grinding wheel (USD/piece); $n_{p,w}$ is the total number of parts ground by a grinding wheel and it can be written; $n_{p,w}$ can be calculated by [8]:

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

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

$$n_{p,d} = t_w / t_c \tag{4}$$

With t_w as the wheel life (h); t_c - grinding time (h); t_c is determined by the following equation:

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

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

For getting the tolerance grade 6, the axial feed speed v_{fa} is calculated as [9]:

$$v_{fa} = 0.2557 \cdot d_w^{\ 0.0749} \cdot n_w^{\ 1.1093} \cdot b_s^{0.9841} \tag{6}$$

In the above formula, d_w is the workpiece diameter; n_w is the workpiece speed. As the workpiece is the alloy tool steel 9CrSi, n_w can be determined as follows [9]:

$$n_w = 6292.1 \cdot d_w^{-0,861} \tag{7}$$

f_r is the radial wheel feed (mm/double stroke); f_r is calculated by following equation [9]:

$$f_r = f_{r,tab} \cdot c_1 \cdot c_2 \cdot c_3 \cdot c_4 \tag{8}$$

where, $f_{r,tab}$ is the tabled radial wheel feed (mm/double stroke); $f_{r,tab}$ is determined as follows [9]:

$$f_{r,tab} = 150.3605 \cdot d_w^{-0.9331} \cdot v_{fa}^{\ -0.4922} \cdot \left(2 \cdot a_e\right)^{0.2194} \tag{9}$$

c_1 - Coefficient which depends on the workpiece material and tolerance grade tg ; As the workpiece material is the alloy tool steel 9CrSi, c_1 can be calculated by the following formulas [9]:

$$c_1 = 0,0232 \cdot tg^{2,1826} \tag{10}$$

c_2 - Coefficient which depends on the grinding wheel diameter d_s and grinding wheel peripheral speed v_s; c_2 is calculated as [9]:

$$c_2 = 0.0032 \cdot v_s^{0.7147} d_s^{0.4984} \tag{11}$$

c_3 - Coefficient which depends on the measurement type; $c_3 = 0.8$ if a micrometer is used for measurement and $c_3 = 1$ if a snap gage is used [10];

c_4 - Coefficient which depends on the ratio of the length of workpiece to its diameter; $c_4 = 1$ if the ratio ≤ 10 and $c_4 = 0.8$ if the ratio >10 [10];

t_s - Manufacturing time includes auxiliary time (h); it can be calculated by the following formula:

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

where, t_{lu} -time for loading and unloading workpiece (h); t_{sp} - spark-out time (h);

$t_{d,p}$ -dressing time per part (h):

$$t_{d,p} = t_d / n_{p,d} \tag{13}$$

With t_d as the dressing time (h); Substituting (4) into (13) we have:

$$t_{d,p} = t_d \cdot t_g / t_w \tag{14}$$

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

$$t_{cw,p} = t_{cw} / n_{p,w} \tag{15}$$

With t_{cw} as the time for changing a grinding wheel (h).

Substituting (3) into (15) we have

$$t_{cw,p} = 2t_{cw}\left(\delta_{rs} + a_{ed,ges}\right) / \left[n_{p,d}\left(d_{s,0} - d_{s,e}\right)\right] \tag{16}$$

t_c - grinding time (h); in external cylindrical grinding, the grinding time can be calculated by the following equation:

$$t_c = \frac{l_w \cdot a_{e,tot}}{v_{fa} \cdot v_{fr}} \tag{17}$$

II. Experiment Work

To discover the effect of the factors on the optimum exchanged grinding wheel diameter an "experiment" was designed and performed by a computer program. For the design of the experiment, a 2-level full factorial design was chosen. Table I shows 6 process parameters which were selected as the input factors for exploring. Consequently, the design was arranged with $2^6 = 64$ number of experiments. To perform the experiment, a computer program was built. The various levels of input parameters and the results of the output of the computer program (the optimum exchanged grinding wheel diameter D_{op}) are given in Table II.

TABLE I. Grinding Parameters of "Experiment"

Factor	Code	Unit	Low	High
Initial grinding wheel diameter	D_0	mm	250	550
Total depth of dressing cut	t_{sd}	mm	0.01	0.03
Wheel life	T_d	min.	10	30
Radial grinding wheel wear per dress	D_{max}	mm	0.01	0.03
Machine tool hourly rate	C_m	USD/h	3	10
Grinding wheel cost	C_d	USD/p.	8	50

III. Results and Discussions

For visualizing the effect of the factors on the response and for evaluating the relative strength of the effect, a graph of the main effect of each factor is plotted in Fig. 2. As in Fig. 1, the value of the optimum exchanged grinding wheel diameter D_{op} increases significantly with the initial grinding wheel diameter, and it also effected by the total depth of the dressing cut t_{sd}, the wheel life T_d, the radial grinding wheel wear per dress $D_{\max}$, the machine hourly rate C_m, and the grinding wheel cost C_d.

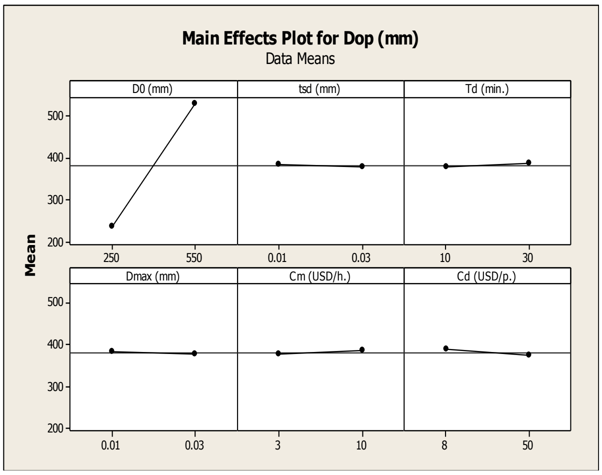

Figure 2. Main effects plot for optimum exchanged grinding wheel diameter.

Fig. 3 shows the Pareto chart of the standardized effects from the largest to the smallest effect. According to this chart, the bars that represent all factors including the initial grinding wheel diameter, the grinding wheel cost, the machine hourly rate, the wheel life, the radial grinding wheel wear per dress, and the total depth of the dressing cut crossed the reference line. Therefore, these factors are statistically significant at the 0.05 level with the response model.

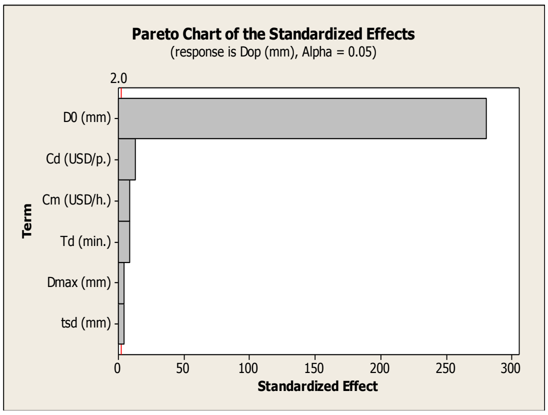

Figure 3. Pareto chart of the standardized effects.

As the Pareto chart cannot show which effects increased or decreased the response, the Normal Plot of the standardized effects is used for that (Fig. 4). It can be learned from Fig. 4 that the initial grinding wheel diameter is the most significant factor for the optimum exchanged grinding wheel diameter and the grinding wheel cost. In addition, the initial grinding wheel diameter, the wheel life, and the machine hourly rate have a positive standardized effect. When they changed from the low level to the high level of the factors, the optimum exchanged diameter increased. Also, the total depth of the dressing cut, the radial grinding wheel wear per dress, and the grinding cost have a negative standardized effect. When they increased the optimum exchanged diameter decreased.

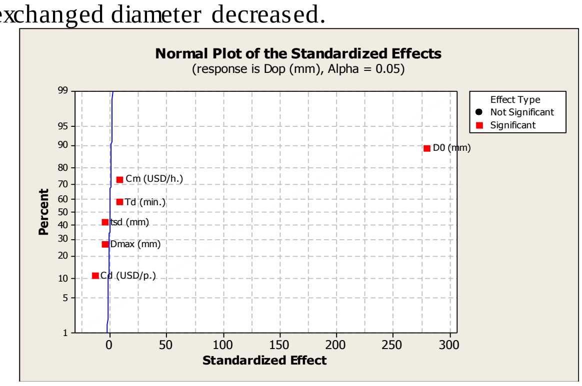

Figure 4. Normal Plot for D_{op}.

TABLE II. EXPERIMENTAL PLANS AND OUTPUT RESPONSE

StdOrder	RunOrder	CenterPt	Blocks	Do (mm)	tsd (mm)	Td (min)	Dmax (mm/dress)	Cm,h (USD/h)	Cd (USD/p)	**Dop (mm)**
30	1	1	1	550	0.01	30	0.03	10	8	540.77
44	2	1	1	550	0.03	10	0.03	3	50	490.42
52	3	1	1	550	0.03	10	0.01	10	50	520.36
60	4	1	1	550	0.03	10	0.03	10	50	514.21
35	5	1	1	250	0.03	10	0.01	3	50	218.13
50	6	1	1	550	0.01	10	0.01	10	50	528.65
1	7	1	1	250	0.01	10	0.01	3	8	239.14
41	8	1	1	250	0.01	10	0.03	3	50	218.13
20	9	1	1	550	0.03	10	0.01	10	8	535.11
56	10	1	1	550	0.03	30	0.01	10	50	531.4
24	11	1	1	550	0.03	30	0.01	10	8	540.77
17	12	1	1	250	0.01	10	0.01	10	8	242.91
25	13	1	1	250	0.01	10	0.03	10	8	240.11
62	14	1	1	550	0.01	30	0.03	10	50	531.4
37	15	1	1	250	0.01	30	0.01	3	50	234.84
61	16	1	1	250	0.01	30	0.03	10	50	237.69
15	17	1	1	250	0.03	30	0.03	3	8	238.51
19	18	1	1	250	0.03	10	0.01	10	8	240.11
64	19	1	1	550	0.03	30	0.03	10	50	527.42
11	20	1	1	250	0.03	10	0.03	3	8	231.87
54	21	1	1	550	0.01	30	0.01	10	50	536.7
13	22	1	1	250	0.01	30	0.03	3	8	240.53
53	23	1	1	250	0.01	30	0.01	10	50	241.15
48	24	1	1	550	0.03	30	0.03	3	50	511.53
59	25	1	1	250	0.03	10	0.03	10	50	226.76
47	26	1	1	250	0.03	30	0.03	3	50	225.09
14	27	1	1	550	0.01	30	0.03	3	8	535.75
27	28	1	1	250	0.03	10	0.03	10	8	238.01
38	29	1	1	550	0.01	30	0.01	3	50	526.99
23	30	1	1	250	0.03	30	0.01	10	8	243.84
46	31	1	1	550	0.01	30	0.03	3	50	518.1
8	32	1	1	550	0.03	30	0.01	3	8	535.75
32	33	1	1	550	0.03	30	0.03	10	8	538.75
39	34	1	1	250	0.03	30	0.01	3	50	229.19
58	35	1	1	550	0.01	10	0.03	10	50	520.36
45	36	1	1	250	0.01	30	0.03	3	50	229.19
63	37	1	1	250	0.03	30	0.03	10	50	235.12
18	38	1	1	550	0.01	10	0.01	10	8	539.38
6	39	1	1	550	0.01	30	0.01	3	8	539.84
10	40	1	1	550	0.01	10	0.03	3	8	527.16
34	41	1	1	550	0.01	10	0.01	3	50	513.55
49	42	1	1	250	0.01	10	0.01	10	50	235.91
28	43	1	1	550	0.03	10	0.03	10	8	531.89

22	44	1	1	550	0.01	30	0.01	10	8	543.44
26	45	1	1	550	0.01	10	0.03	10	8	535.11
9	46	1	1	250	0.01	10	0.03	3	8	234.96
51	47	1	1	250	0.03	10	0.01	10	50	230.62
4	48	1	1	550	0.03	10	0.01	3	8	527.16
55	49	1	1	250	0.03	30	0.01	10	50	237.69
42	50	1	1	550	0.01	10	0.03	3	50	500.12
2	51	1	1	550	0.01	10	0.01	3	8	533.62
33	52	1	1	250	0.01	10	0.01	3	50	226.35
57	53	1	1	250	0.01	10	0.03	10	50	230.62
16	54	1	1	550	0.03	30	0.03	3	8	532.66
43	55	1	1	250	0.03	10	0.03	3	50	212.37
21	56	1	1	250	0.01	30	0.01	10	8	245.61
31	57	1	1	250	0.03	30	0.03	10	8	242.5
12	58	1	1	550	0.03	10	0.03	3	8	522.33
40	59	1	1	550	0.03	30	0.01	3	50	518.1
29	60	1	1	250	0.01	30	0.03	10	8	243.84
5	61	1	1	250	0.01	30	0.01	3	8	243.22
36	62	1	1	550	0.03	10	0.01	3	50	500.12
7	63	1	1	250	0.03	30	0.01	3	8	240.53
3	64	1	1	250	0.03	10	0.01	3	8	234.96

Estimated Effects and Coefficients for Dop (mm) (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		380.600	0.5203	731.43	0.000
D0 (mm)	291.857	145.928	0.5203	280.44	0.000
tsd (mm)	-4.746	-2.373	0.5203	-4.56	0.000
Td (min.)	8.669	4.334	0.5203	8.33	0.000
Dmax (mm)	-4.746	-2.373	0.5203	-4.56	0.000
Cm (USD/h.)	9.313	4.656	0.5203	8.95	0.000
Cd (USD/p.)	-13.808	-6.904	0.5203	-13.27	0.000

S = 4.16279 PRESS = 1245.24

R-Sq = 99.93% R-Sq(pred) = 99.91% R-Sq(adj) = 99.92%

Figure 5. Estimated effects and coefficients for D_{op} .

IV. Conclusions

A study on the optimum determination of exchanged grinding wheel diameter when external grinding alloy tool steel 9CrSi was explored. In this study, the cost analysis for the external grinding process was investigated. Furthermore, the influences of the grinding process parameters as well as cost elements on the optimum exchanged grinding wheel diameter were investigated in detail based on an "experiment" which was designed and performed by a computer program. From the results of the "experiment", a formula for the calculation of the optimum exchanged diameter was suggested. As the formula is an explicit equation, the optimum exchanged diameter for external grinding process can be determined very simply.

Fig. 5 shows the estimated effects and coefficients for D_{op}. As in Fig. 5, factors which have a significant effect on a response and have P-values lower than 0.05 are initial grinding wheel diameter D_0 , the total depth of the dressing cut t_{sd} , the wheel life T_d , the radial grinding wheel wear per dress $D_{\max}$, the machine hourly rate C_m , and the grinding wheel cost C_d . As a result, the relation between the optimum diameter and significant effect factors can be described by the following equation:

$$D_{op} = 380.6 + 145.928 D_0 - 2.373 t_{sd} + 4.334 T_d - 2.373 D_{max} + 4.656 C_{m,h} - 6.904 C_d \tag{18}$$

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