Determination of Optimal Exchanged Grinding Wheel Diameter when Internally Grinding Alloy Tool Steel 9CrSi

Le Xuan Hung[1], Vu Ngoc Pi[1]*, Luu Anh Tung[1], Hoang Xuan Tu[1], Gong Jun[2] and BanhTien Long[3]

[1.] Thai Nguyen University of Technology,Thai Nguyen 23000, Vietnam
[2.] Lanzhou University of Technology, Lanzhou, 730050, China
[3.] Ha Noi University of Science and Technology, Ha Noi 100000, Vietnam

Corresponding author's email: vungocpi@tnut.edu.vn

Abstract. This paper introduces a study on optimal determination of exchanged grinding wheel diameter in internal grinding. In the 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. In addition, the influence of cost components including the machine tool hourly rate and the grinding wheel cost were taken into account. For evaluating the effects of these factors on the optimal 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 model for calculating the optimal exchanged grinding wheel diameter was proposed

1. Introduction

Grinding is a machining process which uses high-speed abrasive wheels, pads, and belts [1]. It is mentioned that this type of machining accounts for about 20-25% of the total expenditures on machining operations in industries [2]. Consequently, optimization of grinding process as well as of internal grinding process have been subjected to many studies.

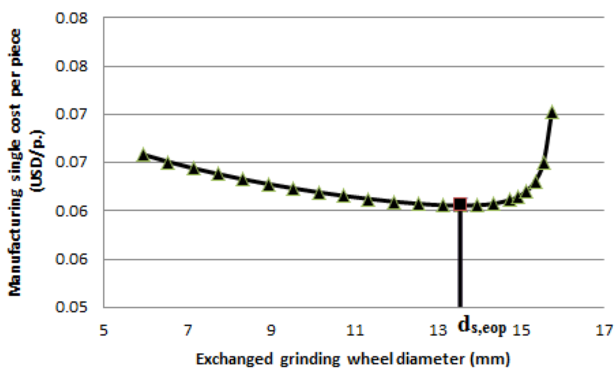

Figure 1. Manufacturing single cost versus exchanged grinding wheel diameter

*Corresponding author: Vu Ngoc Pi, Ass. Prof., Ph.D., E-mail: vungocpi@tnut.edu.vn.

IOP Conf. Series: Materials Science and Engineering **417** (2018) 012026 doi:10.1088/1757-899X/417/1/012026

So far, numerous studies have been focusing on optimization for external cylindrical grinding [3, 4, 5, and 6] or for surface grinding [7, 8 and 9]. For internal grinding process, there have been done several studies on determination of the wheel life [10], on online-optimization of grinding process and dressing parameters in order to reduce the grinding time [11], and on adaptive process control for increasing the efficiency of the grinding process [12]. Recently, there has been a cost optimization study on internal grinding process [13] for finding optimum exchanged grinding wheel diameter. It was found that there is an optimum exchanged grinding wheel diameter at which the grinding cost is minimal (Figure 1). Also, it was presented that grinding with optimal exchanged diameter significantly reduce not only the grinding cost but also the grinding time. However, in this study, the influences of grinding process parameters on optimal exchanged diameter still not evaluated in scientific way.
Hence, this paper presents a study on calculation of optimal exchanged grinding wheel diameter when internally grinding alloy tool steel 9CrSi. In the study, the effects of grinding process parameters as well as the effect of cost components on the optimum exchanged diameter were analyzed in detail. To evaluate the effects of these factors on the optimal exchanged grinding wheel diameter, an “experiment” was designed and a computer program was built for achievement the “experiment”. From the results of the “experiment”, the influences of process parameters and cost elements on the optimal exchanged grinding wheel diameter were analyzed scientifically. Moreover, a model for determining the optimal exchanged diameter was presented.

2. Cost analysis

In internal grinding process, the manufacturing single cost per piece $C_{\sin}$ can be determined as follows [13]:

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

Wherein,

$C_{mt,h}$ - 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 calculated by:

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

Where, C_{gw} is the cost of an internal grinding wheel (USD/piece); $n_{p,w}$ is total number of parts ground by a grinding wheel and it can be written [1]:

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

In which, $d_{s,0}$ 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 parts per dress and is given by:

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

Where, t_w is wheel life (h) and t_c is grinding time (h);The grinding time can be determined as:

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

In which, $a_{e,tot}$ is total depth of cut (mm), l_w is length of part (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 by [14]: $v_{fa} = 22.88 \cdot D_{gw}^{0.9865} \cdot d_w^{0.0821} \cdot tg^{-2.9833} \cdot n_w^{1.2471}$ (when grinding alloy tool steel 9CrSi).

In the above formulas, D_{gw} is grinding wheel diameter; d_w is workpiece diameter; tg is tolerance grade; n_w is workpiece speed; As the workpiece is alloy tool steel 9CrSi , from the tabulated data in [15], n_w can be determined by the following regression model [14]: $n_w = 1255.8 \cdot d_w^{-0.3491}$.

f_r –radial wheel feed (mm/double stroke); f_r is determined by [14]:

$$f_r = f_{r,tab} \cdot c_1 \cdot c_2 \cdot c_3 \cdot c_4 \tag{6}$$

In which, $f_{r,tab}$ is tabled radial wheel feed (mm/double stroke); From the tabulated data in [15], the following regression equation was found for determining $f_{r,tab}$ [14]:

$$f_{r,tab} = 30.2944 \cdot a_{e,tot}^{0.567} \cdot v_{fa}^{-0.9693} \cdot d_w^{-0.1269} \tag{7}$$

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

c_1 - coefficient which depends on workpiece material and tolerance grade tg ; As the workpiece material is alloy tool steel 9CrSi , c_1 is calculated by [14]: $c_1 = 0.0857 \cdot tg^{1.2767}$;

c_2 - coefficient which depends on grinding wheel diameter d_s. Based on data in [15], c_2 can be calculated by the following regression equation (with $R^2 = 0.9977$):

$$c_2 = 0.5657 \cdot d_s^{0.153} \tag{8}$$

c_3 - 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 [15];

c_4 - 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 [15], the following formulas were found for determination of coefficient c_4: $c_4 = 1.0642 \cdot (l_w / d_w)^{-0.5079}$ when grinding continuous cylindrical hole (with $R^2 = 0.9637$); $c_4 = 1.375 \cdot (l_w / d_w)^{-0.5058}$ when grinding non-continuous cylindrical hole (with $R^2 = 0.955$); $c_4 = 0.8514 \cdot (l_w / d_w)^{-0.5079}$ when grinding cylindrical hole with a curved shoulder (with $R^2 = 0.9637$);

t_s - Manufacturing time includes auxiliary time (h); in internal grinding process, the manufacturing time can be expressed as:

$$t_s = t_c + t_{lu} + t_{sp} + t_{d,p} + t_{cw,p} \tag{9}$$

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

$$t_{d,p} = t_d / n_{p,d} \tag{10}$$

In which t_d is dressing time (h). Substituting (4) into (10) we have:

$$t_{d,p} = t_d \cdot t_g / t_w \tag{11}$$

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

$$t_{cw,p} = t_{cw} / n_{p,w} \tag{12}$$

Where, t_{cw} is time for changing a grinding wheel (h).

Substituting (3) into (12) we have:

$$t_{cw,p} = 2t_{cw}\left(\delta_{rs} + a_{ed,ges}\right) / \left[n_{p,d}\left(d_{s,0} - d_{s,e}\right)\right] \tag{13}$$

t_c - grinding time (h); it can be calculated as [15]:

$$t_c = \frac{l_w \cdot a_{e,tot}}{v_{fa} \cdot v_{fr}} \quad (14)$$

3. Experiment work

Table 1. Grinding parameters for "the experiment"

Factor	Code	Unit	Low	High
Op. exchanged grinding wheel diameter	D_0	mm	5	30
Total depth of dressing cut	t_{sd}	Mm	0.01	0.03
Wheel life	T_d	min.	10	30
Radial grinding wheel per dress	D_{max}	Mm	0.01	0.03
Machine tool hourly rate	C_m	USD/h	1.5	10
Grinding wheel cost	C_d	USD/p.	0.2	2

To explore the influence of factors on the optimum exchanged grinding wheel diameter an "experiment" was designed and performed by a computer program. In this "experiment", 6 process parameters were selected as the input factors for the exploring. They are the initial grinding wheel diameter D_0, the total depth of dressing cut t_{sd}, the wheel life T_d, the radial grinding wheel per dress $D_{\max}$ and the machine tool hourly rate C_m. Also, a 2-level full factorial design was chosen for the design of the "experiment". Therefore, the design was prepared with $2^6 = 64$ numbers of experiments. Fig. 2 shows the creation of factorial design with the factors were described in the Table 1. To accomplish the experiment, a computer program was built. Table 2 shows the input parameters and the output results of the computer program (the optimum exchanged grinding wheel diameter D_{op}) with many levels.

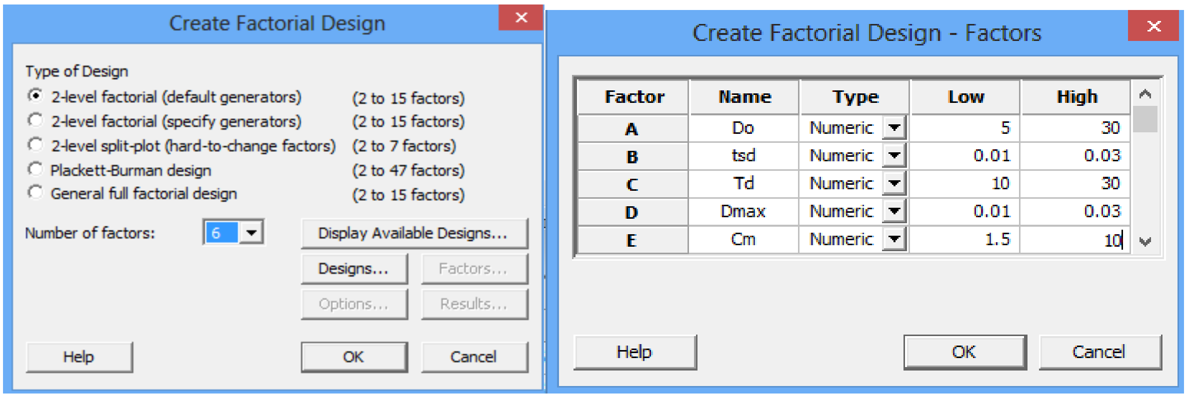

Figure 2. Creation of factorial design

4. Results and discussions

Figure 3 presents the graph of the main effect of each factor. The graph is used for evaluating the influences of factors on the response and for comparing the relative strength of the influence. From this graph, it is clear that the optimum exchanged grinding wheel diameter D_{op} depends strongly on the initial grinding wheel diameter. Furthermore, it is affected by the machine hourly rate C_m and the grinding wheel cost C_d. Besides, the other factors including the total depth of dressing cut t_{sd}, the wheel life T_d and the radial grinding wheel per dress $D_{\max}$ do not affect the optimum diameter D_{op} because the line is nearly parallel to the mean value of all responses.

Fig. 4 shows the Pareto chart of the standardized effects from the largest effect to the smallest effect. From the chart, the bars that represent factors A (the initial grinding wheel diameter), F (grinding wheel cost), E (the machine hourly rate), AF, AE, and EF cross the reference line. Consequently, these factors are statistically significant at the 0.05 level with the response model.

Figure 5 reports the Normal Plot of the standardized effects. From this Figure, it is seen that, the initial grinding wheel diameter (factor A) and the grinding wheel cost (factor F) are the significant effects factors. Also, all the effects which lie along the line (including B, C, D and their interactions) are negligible. In addition, the initial grinding wheel diameter (factor A) has a positive standardized effect. When it changes from the low level to the high level of the factor, the optimum exchanged diameter increases. Besides, the grinding cost has a negative standardized effect. When it grows the optimum exchanged diameter decreases.

Figure 6 describes the estimated effects and coefficients for D_{op} after ignoring insignificant effects. It was found that factors which have a significant effect on a response have P-values lower than 0.05 are initial grinding wheel diameter D_0, machine hourly rate C_m, grinding wheel cost C_d and the interactions between D_0 and C_m, D_0 and C_d, C_m and C_d (Figure 6). Therefore, the following equation can be used for describing the relation between the optimum diameter and significant effect factors:

$D_{op} = 13.264 + 10.24D_0 + 1.214C_{m,h} – 1..437C_d + 0.803D_0C_{m,h} – 0.949D_0C_d + 0.534C_{m,h}C_d$ (15)

Table 2. 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)**
12	1	1	1	30	0.03	10	0.03	1.5	0.2	**24.7**
51	2	1	1	5	0.03	10	0.01	10	2	**2.94**
36	3	1	1	30	0.03	10	0.01	1.5	2	**17.74**
61	4	1	1	5	0.01	30	0.03	10	2	**3.06**
19	5	1	1	5	0.03	10	0.01	10	0.2	**3.83**
7	6	1	1	5	0.03	30	0.01	1.5	0.2	**3.17**
26	7	1	1	30	0.01	10	0.03	10	0.2	**27.08**
46	8	1	1	30	0.01	30	0.03	1.5	2	**18.43**
45	9	1	1	5	0.01	30	0.03	1.5	2	**2**
47	10	1	1	5	0.03	30	0.03	1.5	2	**2**
63	11	1	1	5	0.03	30	0.03	10	2	**2.94**
18	12	1	1	30	0.01	10	0.01	10	0.2	**27.08**
9	13	1	1	5	0.01	10	0.03	1.5	0.2	**3.28**
43	14	1	1	5	0.03	10	0.03	1.5	2	**2**
14	15	1	1	30	0.01	30	0.03	1.5	0.2	**25.08**
11	16	1	1	5	0.03	10	0.03	1.5	0.2	**3.17**
21	17	1	1	5	0.01	30	0.01	10	0.2	**3.91**
…										
40	61	1	1	30	0.03	30	0.01	1.5	2	**17.74**
25	62	1	1	5	0.01	10	0.03	10	0.2	**3.91**
32	63	1	1	30	0.03	30	0.03	10	0.2	**26.85**
55	64	1	1	5	0.03	30	0.01	10	2	**2.94**

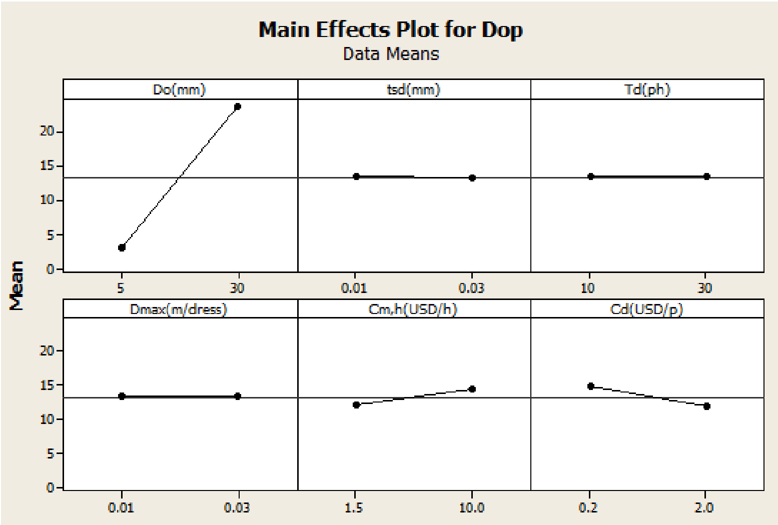

Figure 3. Main effects plot for optimum exchanged grinding wheel diameter

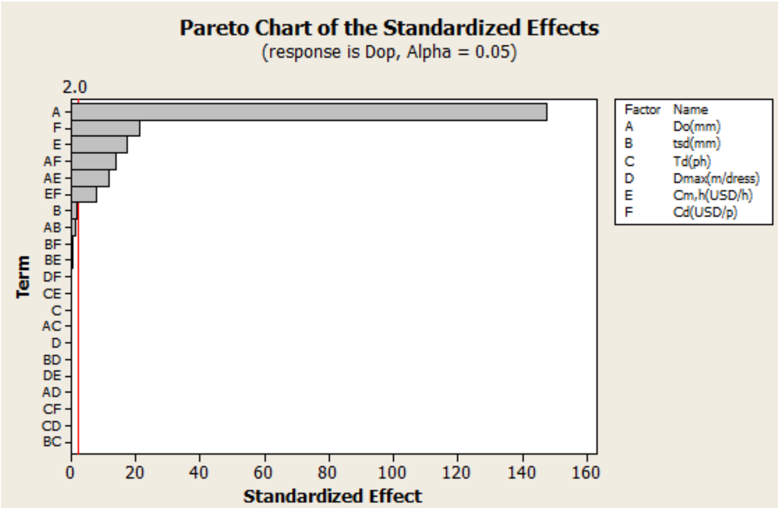

Figure 4. Pareto Chart of the Standardized Effects

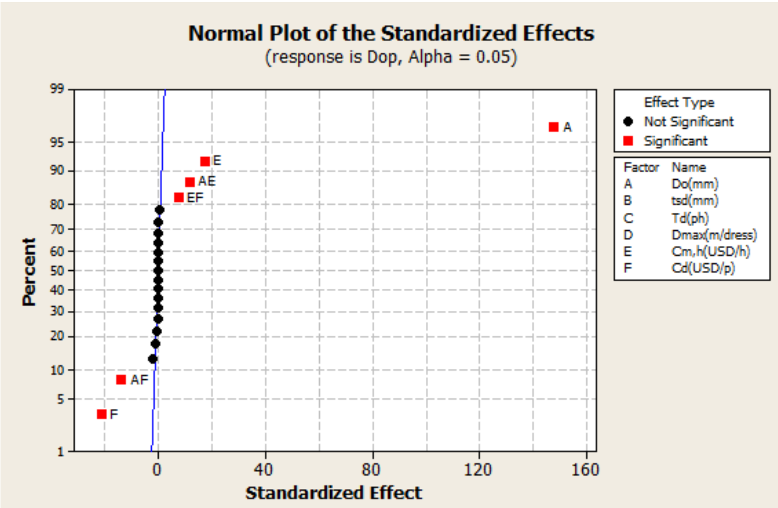

Figure 5. Normal Plot for D_{op}

Estimated Effects and Coefficients for Dop (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		13.264	0.06299	210.58	0.000
Do(mm)	20.481	10.241	0.06299	162.57	0.000
Cm,h(USD/h)	2.429	1.214	0.06299	19.28	0.000
Cd(USD/p)	-2.946	-1.473	0.06299	-23.39	0.000
Do(mm)*Cm,h(USD/h)	1.606	0.803	0.06299	12.75	0.000
Do(mm)*Cd(USD/p)	-1.899	-0.949	0.06299	-15.07	0.000
Cm,h(USD/h)*Cd(USD/p)	1.069	0.534	0.06299	8.48	0.000

S = 0.503925 PRESS = 18.2481
R-Sq = 99.80% R-Sq(pred) = 99.74% R-Sq(adj) = 99.77%

Figure 6. Estimated Effects and Coefficients for D_{op}

5. Conclusions

A study on optimal determination of exchanged grinding wheel diameter when internally grinding alloy tool steel 9CrSi was carried out. In the study, the cost analysis for the grinding process was analyzed. In addition, the effects of grinding process parameters and cost components on the optimal exchanged diameter were investigated scientifically based on an “experiment” designed and performed by a computer program. From the results of the “experiment”, a model for determining the optimal exchanged diameter was proposed. As the model is an explicit equation, the optimal exchanged diameter for internal grinding process can be calculated in a simple way.

Acknowledgements

The work described in this paper was supported by Thai Nguyen University of Technology for the project N_0 T2017-B05.

References

[1] W. Brian Rowe, *Principle of Modern Grinding Technology,* William Andrew, 2009.

[2] Malkin S., Guo C., *Grinding Technology: Theory and Applications of Machining with Abrasives*, Industrial Press, 2008.

[3] G. F. Li, L. S. Wang, L. B. Yang, *Multi-parameter optimization and control of the cylindrical grinding process*,Journal of Materials Processing Technology, Volume 129, Issues 1-3, 11 October 2002, Pages 232-236.

[4] R. Gupta, K. S. Shishodia, G. S. Sekhon, *Optimization of grinding process parameters using enumeration method,* Journal of Materials Processing Technology, Volume 112, Issue 1, 3 May 2001, P. 63-67.

[5] Y. C. Fu, H. J. Xu, J. H. Xu, *Optimization design of grinding wheel topography for high efficiency grinding,* Journal of Materials Processing Technology, Volume 129, Issues 1-3, 11 October 2002, Pages 118-122.

[6] Vu Ngoc Pi, Phan Quang The, Vu Hong Khiem, Nguyen Ngoc Huong, *Cost optimization of external cylindrical grinding,* Applied Mechanics and Materials, Vols. 312 (2013), pp. 982-989.

[7] X.M. Wen, A.A.O. Tay, A.Y.C. Nee,*Micro-computer-based optimization of the surface grinding process*, Journal of Materials Processing Technology, Volume 29, Issues 1-3, January 1992, P. 75-90

[8] G. Warnecke, C. Barth, *Optimization of the Dynamic Behavior of Grinding Wheels for Grinding of Hard and Brittle Materials Using the Finite Element Method,* CIRP Annals - Manufacturing Technology, Volume 48, Issue 1, 1999, Pages 261-264.

[9] Vu Ngoc Pi, Luu Anh Tung, Le Xuan Hung, Nguyen Van Ngoc, *Experimental Determination of Optimum Exchanged Diameter in Surface Grinding Process,* Journal of Environmental Science and Engineering A (2017), pp. 85-89.

[10] I. Inasaki, *Monitoring and Optimization of Internal Grinding Process*, CIRP Annals - Manufacturing Technology, Volume 40, Issue 1, 1991, Pages 359-362.

[11] G. Xiao, S. Malkin, *On-Line Optimization for Internal Plunge Grinding*, CIRP Annals – Manufacturing Technology, Volume 45, Issue 1, 1996, Pages 287-292

[12] H.K. Tönshoff, A. Walter, *Self-tuning fuzzy-controller for process control in internal grinding,*Fuzzy Sets and Systems, Volume 63, Issue 3, 10 May 1994, Pages 359-373.

[13] Vu Ngoc Pi, Le Xuan Hung, Luu Anh Tung, Banh Tien Long, *Cost Optimization of Internal Grinding*, Journal of Material Science and Engineering B 6 (11-12) (2016), pp. 291-296.

[14] Banh Tien Long, Vu Ngoc Pi, Le Xuan Hung, Luu Anh Tung, *Building cutting regime formulas for internal grinding (In Vietnamese)*, Journal of Science and Technology, Thai Nguyen University, No. 9 (2016), Pages15-18.

[15] L.M. Kozuro, A.A. Panov, E.I. Remizovski, P.S. Tristosepdov, *Handbook of Grinding (in Russian)*, Publish Housing of High-education, Minsk, 1981.