

Cost Optimization of Surface Grinding Process

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Abstract: This paper introduces a new study on cost optimization of surface grinding. In the study, the effects of grinding parameters including the dressing regime parameters, the wheel life and the initial grinding wheel diameter on the exchanged grinding wheel diameter which were investigated. In addition, the influence of cost parameters including the machine tool hourly rate and the grinding wheel cost were taken into account. In order to find the optimum exchanged grinding wheel diameter, a cost optimization problem was built. From the results of the optimization problem, a model for determination of the optimum exchanged grinding wheel diameter was found. By using the optimum diameter, both the grinding cost and grinding time can be reduced significantly.

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

1. Introduction

Grinding is a machining process which uses a grinding wheel as a cutting tool. It is a major machining process which accounts for about 20-25% of the total expenditures on machining operations in industries [1]. As a result, there have been many studies that have been subjected to optimization of grinding process such as for external cylindrical grinding [2-4], for surface grinding [5-7] and for internal grinding process [8-10].

In practice, grinding machines with fixed revolutions of grinding wheel are used widely, especially in developing countries because of their low cost. Also, in grinding process, during the wheel lifetime, the diameter of grinding wheel will reduce gradually because of the wheel wear and dressing. Therefore, with this kind of machines the grinding wheel peripheral speed will decrease and the grinding time as well as the grinding cost per part will increase. From that point of view, the effect of the exchanged grinding wheel diameter on the total grinding cost should be taken into account in the optimization problem of grinding process for optimum

using of this kind of machines.

From previous studies, it was learned that, until now, there is still lack of study on the optimization of surface grinding process which take into account the effect of the exchanged grinding wheel diameter. This paper introduces a cost optimization study for surface grinding. In the study, the influences of many grinding process parameters as well as cost components were taken into account. Also, a new and effective way of using the surface grinding wheel was proposed. Using this way, both the grinding cost and grinding time can be reduced significantly.

2. Cost Analysis for Surface Grinding Process

In surface grinding process, the manufacturing single cost per piece $C_{\sin}$ can be determined as Eq. (1):

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

in which,

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

$C_{gw,p}$ -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 a surface grinding wheel

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(USD/piece); $n_{p,w}$ is total number of workpieces ground by a grinding wheel and it can be written [11]:

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

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:

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

in which, t_w is wheel life (h); The optimum values of the wheel life are from 10 to 30 minutes [12]; t_c is grinding time (h). In surface grinding, the grinding time can be expressed as:

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

where, l_c is the calculated grinding length (mm); $l_c = l_w + (20 \dots 30)$ with l_w is the length of the workpieces (mm); w_c is the calculated grinding width (mm); $w_c = w_w + w_{gw} + 5$ with w_w is the width of the workpieces (mm) and w_{gw} is the grinding wheel width (mm) (Fig. 1); $a_{e,tot}$ is total depth of cut (mm); v_w is the work speed (m/s); v_f is work feed rate (mm/min); f_d is downfeed (mm/pass) and N_t is number of workpieces per grinding time.

The work speed v_w can be determined as [13]:

When grinding cast iron $v_w = 5$ (m/s); when grinding heat resistant steel, stainless steel and tool steel $v_w = 25$ (m/s);

When grinding carbon steel, alloy steel and brass v_w depends on the Rockwell hardness of workpiece HRC. From the tabulated data for finding v_w [13], v_w can be calculated by the Eq. (6) (with $R^2 = 0.9668$):

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

The work feed rate v_f depends on the required roughness grade number N_{Ra} and the grinding wheel width w_{gw} . From the tabulated data for

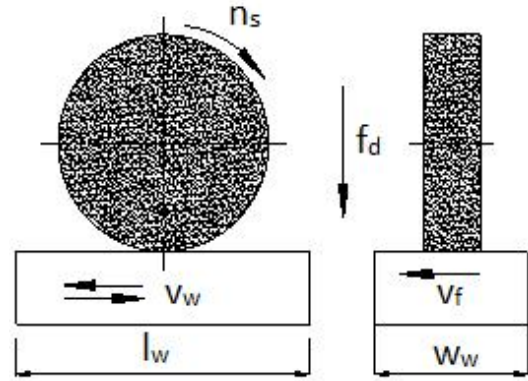


Fig. 1 Schema of surface grinding.

determining the work feed rate [13], the Eq. (7) for determination of N_{Ra} was found (with $R^2 = 0.984$):

$$v_f = 46.1 \cdot w_{gw}^{0.983} / N_{Ra}^{2.44} \quad (7)$$

The downfeed f_d is determined by the Eq. (8) [13]:

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

With $f_{d,t}$ is the tabulated downfeed (mm/pass); $f_{d,t}$ depends on workpiece materials, the total depth of cut $a_{e,tot}$ and the work feed rate v_f . It can be determined as follows [14]:

When grinding cast iron $f_{d,t}$ is calculated by the following regression equation (with $R^2 = 0.9995$):

$$f_{d,t} = 3.05 \cdot a_{e,tot}^{-0.584} \cdot v_f^{-0.993} \quad (9)$$

When grinding carbon steel and alloy steel $f_{d,t}$ can be determined as (with $R^2 = 0.9995$):

$$f_{d,t} = 226 \cdot HRC^{-1.34} \cdot a_{e,tot}^{0.604} \cdot v_f^{-1.01} \quad (10)$$

When grinding heat resistant steel, stainless steel and tool steel, $f_{d,t}$ is calculated by the following equation (with $R^2 = 0.998$):

$$f_{d,t} = 0.649 \cdot a_{e,tot}^{0.651} \cdot v_f^{-0.985} \quad (11)$$

c_1 -coefficient which depends on the workpiece material and the required tolerance grade tg ; it can be determined as follows [14]:

When grinding structural carbon steel, chromium steel and tool steels (with $R^2 = 0.9996$):

$$c_1 = 4.13 \cdot tg^{0.474} \quad (12)$$

When grinding molybdenum and tungsten steels (with $R^2 = 0.999$):

$$c_1 = 3.33 \cdot tg^{0.458} \quad (13)$$

When grinding high-temperature steels and stainless steels (with $R^2 = 0.9997$):

$$c_1 = 1.87 \cdot tg^{0.477} \quad (14)$$

When grinding high-speed steels and tungsten alloy steels (with $R^2 = 0.9969$):

$$c_1 = 0.61 \cdot tg^{0.466} \quad (15)$$

When grinding cast iron and copper alloys (with $R^2 = 0.9962$):

$$c_1 = 5.92 \cdot tg^{0.434} \quad (16)$$

c_2 -coefficient which depends on grinding wheel diameter d_s and on the density of the workpieces loaded on the machine table D_w ; c_2 can be calculated by the Eq. (17) (with $R^2 = 0.9985$) [14]:

$$c_2 = 0.0292 \cdot d_s^{0.5151} / D_w^{0.4949} \quad (17)$$

c_3 -Coefficient which depends on the grinding machine age; $c_3 = 1$ if the age is less than 10 years; $c_3 = 0.85$ if the age is from 10 to 20 years and $c_3 = 0.7$ if the age is more than 20 years [13];

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

$$t_s = t_c + t_{lu} + t_{sp} + t_{d,p} + t_{cw,p} \quad (18)$$

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

t_{sp} -spark-out time (h); t_{sp} is calculated by:

$$t_c = l_c \cdot w_c / (1000 \cdot v_w \cdot v_f \cdot N_t) \quad (19)$$

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

$$t_{d,p} = t_d / n_{p,d} \quad (20)$$

With t_d is dressing time (h); Substituting (4) into Eq.

(20) we have:

$$t_{d,p} = t_d \cdot t_g / t_w \quad (21)$$

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

$$t_{cw,p} = t_{cw} / n_{p,w} \quad (22)$$

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

The following equation is given by substituting Eqs. (3) into (22):

$$t_{cw,p} = 2t_{cw} (\delta_{rs} + a_{ed,ges}) / [n_{p,d} (d_{s,0} - d_{s,e})] \quad (23)$$

3. Optimization Problem

For surface grinding process, the cost optimum problem can be expressed as the Eq. (24):

$$\min C_{\sin} = f(d_{s,e}) \quad (24)$$

with the following constraints:

$$C_{mt,h \min} \leq C_{mt,h} \leq C_{mt,h \max};$$

$$C_{gw \min} \leq C_{gw} \leq C_{gw \max};$$

$$d_{s,0 \min} \leq d_{s,0} \leq d_{s,0 \max}$$

$$a_{ed,ges \min} \leq a_{ed,ges} \leq a_{ed,ges \max} \quad (25)$$

$$\delta_{rs \min} \leq \delta_{rs} \leq \delta_{rs \max};$$

$$t_{w \min} < t_w \leq t_{w \max};$$

$$a_{e,tot \min} \leq a_{e,tot} \leq a_{e,tot \max};$$

From Eqs. (1), (24) and (25), a computer program was built for determining the optimum of the exchanged grinding wheel diameter in order to get the minimum grinding cost. The data of the constraints used in the program were chosen: $C_{mt,h} = 10 \div 50$ (USD/h); $C_{gw} = 5 \div 25$ (USD/piece); $d_{s,0} = 250 \div 500$ (mm); $a_{ed,ges} = 0.08 \div 0.2$; $\delta_{rs} = 0.1 \div 0.3$ (mm/dress); $T_w = 10 \div 30$ (min); $a_{e,tot} = 0.05 \div 0.15$ (mm).

4. Results and Discussions

The relation between the exchanged grinding wheel diameter and the manufacturing single cost per part were shown in Fig. 2. The data used in this example were: $C_{mt,h} = 32$ (USD/h); $C_{wp} = 14$ (USD/piece); $d_{s,0} = 400$ (mm); $N_t = 35$; $l_c = 200$ (mm); $w_c = 150$ (mm); $D_w = 0.7$; $a_{ed,ges} = 0.12$ (mm); $\delta_{rs} = 0.1$ (mm/dress); $a_{e,tot} = 0.1$ (mm); HRC = 57; $t_w = 20$ (min); $t_{cw} = 20$ (min). It was found that the grinding cost strongly depends on the exchanged grinding wheel diameter. In addition, it gets the minimum value when the exchanged diameter equals a value $d_{s,eop}$ (Fig. 2). This value is called “optimum diameter”. It was noted that the optimum diameter was much larger than the traditional exchanged diameter. In this case, the optimum diameter was 335 mm (Fig. 2) while the traditional exchanged diameter was about 220 mm. Also, with the optimum diameter the grinding cost per piece was 0.072 (USD/p.) when it was 0.08 (USD/p.) with traditional exchanged diameter (220 mm). Calculating for the grinding time, with optimum diameter it was 1.03 (min/p.) and with the traditional exchanged diameter it was 1.20 (min/p.). Consequently, in this case, grinding with

optimum diameter can reduce the grinding cost for 10% and the grinding time for 14.17%.

The influences of grinding process parameters as well as cost parameters on the optimum diameter were investigated. It was found that the optimum diameter depends on the machine tool hourly rate (Fig. 3a), the grinding wheel cost C_{gw} (Fig. 3b), the radial grinding wheel wear per dress (Fig. 3c), the wheel life (Fig. 3d), the total depth of dressing cut (Fig. 3e) and the initial grinding wheel diameter (Fig. 3f). In addition, the optimum diameter depends strongly on the initial grinding wheel diameter. It was also found that the optimum diameter does not depend on the required tolerance grade. This is because the downfeed f_d , which is affected by the required tolerance grade, does not depend on the grinding wheel diameter (Eqs. (8-16)).

Based on the results of the optimization program, the following regression model (with $R^2 = 0.9999$) was proposed for determination of the optimum diameter:

$$d_{s,eop} = 0.5096 \cdot C_{mt,h}^{0.0299} \cdot C_{gw}^{-0.0239} \cdot T_w^{0.0469} \cdot a_{ed,ges}^{-0.0204} \cdot \delta_{rs}^{-0.028} \cdot d_{s,0}^{1.0519} \quad (26)$$

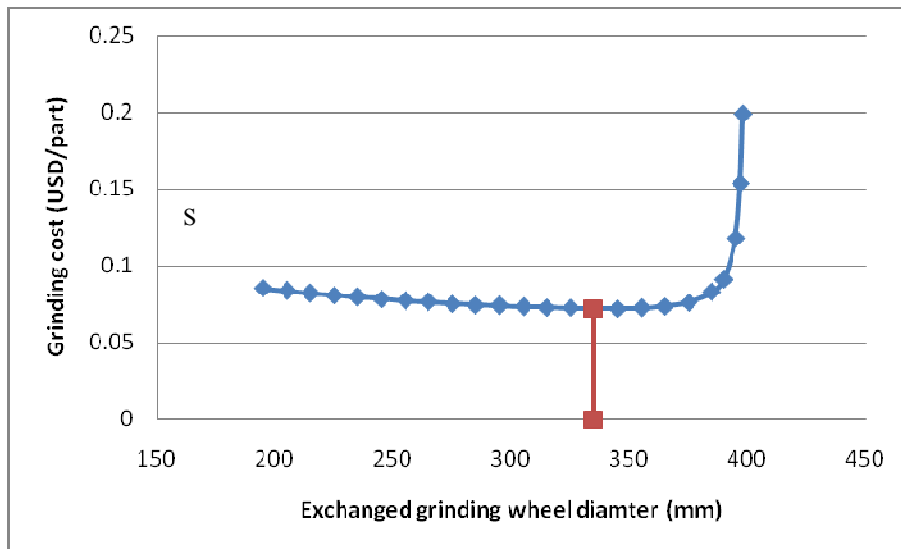


Fig. 2 Manufacturing single cost versus exchanged grinding wheel diameter.

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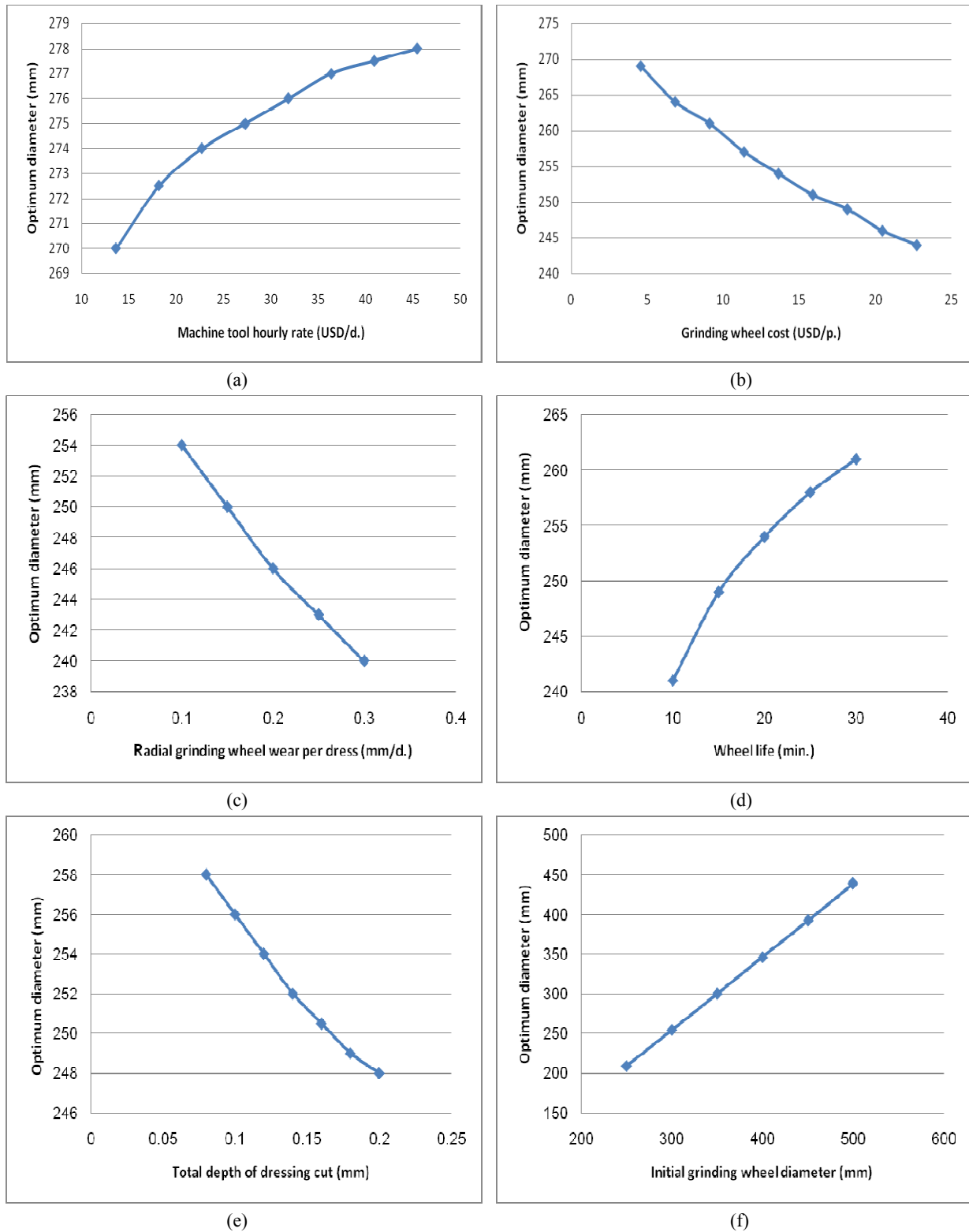


Fig. 3 Cost and process factors versus optimum diameter.

5. Conclusion

A study on cost optimization of surface grinding was carried out. The cost structures for surface grinding process were analyzed. Also, the influences of cost components as well as grinding process parameters on the optimum exchanged grinding wheel diameter were investigated. In order to determine of the optimum exchanged diameter for getting the minimum grinding cost, a computer program was built. From the results of the optimization program, a regression model for calculation of the optimum exchanged diameter was proposed. Grinding with optimum diameter can save a lot of both the grinding cost and the grinding time. Besides, by using an explicit model, the optimum diameter for surface grinding process can be determined very simply.

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References

- [1] Malkin, S., and Guo, C. S. 2008. "Grinding Technology: Theory and Applications of Machining with Abrasives." Industrial Press.
- [2] Li, G. S., Wang, L. S., and Yang, L. B. 2002. "Multi-Parameter Optimization and Control of the Cylindrical Grinding Process." *Journal of Materials Processing Technology* 129 (1): 232-36.
- [3] Gupta, R., Shishodia, K. S., and Sekhon, G. S. 2001. "Optimization of Grinding Process Parameters Using Enumeration Method." *Journal of Materials Processing Technology* 112 (1): 63-67.
- [4] Pi, V. N., The, P. Q., Khiem, V. H., and Huong, N. N. 2013. "Cost Optimization of External Cylindrical Grinding." *Applied Mechanics and Materials* 312: 982-89.
- [5] Wen, X. M., Tay, A. A. O., and Nee, A. Y. C. 1992. "Micro-Computer-Based Optimization of the Surface Grinding Process." *Journal of Materials Processing Technology* 29 (1-3): 75-90.
- [6] Warnecke, G., and Barth, C. 1999. "Optimization of the Dynamic Behavior of Grinding Wheels for Grinding of Hard and Brittle Materials Using the Finite Element Method." *CIRP Annals-Manufacturing Technology* 48 (1): 261-64.
- [7] Krishna, A. G., and Rao, K. M. 2006. "Multi-Objective Optimisation of Surface Grinding Operations Using Scatter Search Spproach." *International Journal of Advanced Manufacturing Technology* 29: 475-80.
- [8] Inasaki, I. 1991. "Monitoring and Optimization of Internal Grinding Process." *CIRP Annals-Manufacturing Technology* 40 (1): 359-62.
- [9] Xiao, G., and Malkin, S. 1996. "On-Line Optimization for Internal Plunge Grinding." *CIRP Annals-Manufacturing Technology* 45 (1): 287-92.
- [10] Tönshoff, H. K., and Walter, A. 1994. "Self-Tuning Fuzzy-Controller for Process Control in Internal Grinding." *Fuzzy Sets and Systems* 63 (3): 359-73.
- [11] Rowe, W. B. 2009. *Principle of Modern Grinding Technology*, William Andrew.
- [12] Karpuschewski, B. 2004. *Fundamentals of Machine Tools. Lecture Notes*. TU Delft.
- [13] Kozuro, L. M., Panov, A. A., Remizovski, E. I., and Tristosepdov, P. S. 1981. *Handbook of Grinding* (in Russian), Publish Housing of High-education, Minsk.
- [14] Long, B. T., Pi, V. N., Tung, L. A., and Hung, L. X. 2013. "A Study on Building Cutting Regime Formulas for Surface Grinding (In Vietnamese)." In *Proceedings of the 3rd National Conference on Mechanical Science and Technology*, Ha Noi.