OPTIMIZATION OF REPLACED NOZZLE DIAMETER FOR MINIMUM CLEANING COST DURING ABRASIVE BLASTING WITH QUARTZ SAND

DR. TRAN THI HONG¹, DR. DO THE VINH², DR. TRAN NGOC GIANG³ & DR. VU NGOC PI^{4*}

¹Associate Professor, Center of Excellence for Automation and Precision Mechanical Engineering, Nguyen Tat Thanh
University, Ho Chi Minh City, Vietnam

^{2,3,4}Assistant Professor, Mechanical Engineering Faculty, Thai Nguyen University of Technology, Thai Nguyen City, Vietnam

ABSTRACT

Sandblasting is a process of smoothing, shaping, and cleaning hard surfaces which is widely used in industry. In this research, the optimization of replaced nozzle diameter during abrasive blasting with quartz sand was carried out with the aim of reducing cleaning cost. For this purpose, an analysis was performed to find the minimum value of the cleaning cost obtained by determining the appropriate replaced nozzle diameter. Additionally, a series of meticulous experiments were conducted to investigate different factors including the initial diameter, the wear rate and the changing time for a nozzle, the compressor power, the cost of machine, nozzle and sand, and the effect of these factors on the optimum replaced nozzle diameter. As shown in the results, the initial nozzle diameter is the main factor affecting the optimum replaced nozzle diameter. Finally, an empirical model was developed for calculating the optimum replaced nozzle diameter.

KEYWORDS: Non-traditional machining, Sand blasting, Optimum nozzle diameter, Tungsten carbide nozzle, Cost optimization

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1. INTRODUCTION

Sandblasting is a cleaning method commonly used for cleaning hard surfaces to prepare for painting or rust removal in industries such as shipbuilding and automobile manufacturing etc. This cleaning method was invented in 1870 by Benjamin C. Tilghman. In his system, the abrasive particles are pushed away by a partial vacuum generated by the compressed air in the nozzle tube. Also, the stream of abrasive particles is accelerated by the aid of compressed air down on to a surface to clean it [1, 2]. In fact, the world's demand for abrasives increases every year. A recent report stated that, the world's demand for abrasives in 2014 was only \$8.6 billion while in 2019 was \$11.4 billion [3]. Therefore, it is necessary to reduce the abrasive cost in manufacturing processes as well as in sand blasting. Hence, this subject has attracted a number of scientists and manufacturers.

In a study of M.J. Woodward and R.S. Judson [4], a comparison of costs between wet abrasive blasting and dry blasting was conducted. The impacts of factors including water pressure, water flow rate, abrasive flow rate and nozzle stand-off distance on costs for each type of abrasive blasting system were analyzed. The results showed a distinct advantage of the cost of wet abrasive blasting over that of dry blasting. In a research of James D. Hansink [5], the author performed a cost comparison between blasting with garnet and coal slag and between new and recycled garnet. He concluded that the garnet could be recycled three times after blasting and the first recycled

garnet used was received the lowest cost. A typical cost structure of a water blast-cleaning system was presented by W. Momber [6]. The author reported the costs for different components, of which the labor costs the most with 46.6%. Besides, a high-pressure unit costs 18.6%, whereas the costs of the fuel, the nozzle wear, and the high-pressure guns are 15%, 13.4%, and 3.3% respectively. The water treatment system is invested at the lowest cost at 3.1%. A study on cost optimization of the abrasive blasting system was conducted by N.P Vu and A.M. Hoogstrate [7]. The influence of many parameters of the abrasive blasting process (the air pressure, the initial nozzle diameter, the nozzle wear, etc.) on the cleaning cost was investigated. The models for calculation of the optimal nozzle diameter to obtain the minimum cleaning cost were presented. Both the cost and time of the blasting process were greatly reduced when applying the nozzle diameter optimization model. Similar results were provided in [8]. Summary, optimized nozzle diameter is the key to cost reduction, increased profits, and reduced cleaning time.

From the above analysis, it can be noted that the Design of Experiment technique to study the effect of sandblasting process parameters on optimal responses has not been used in previous studies. The application of this technique can effectively figure out the effect of input process factors as well as determine the optimum responses in any machining process such as in electrical discharge machining process [9-11], in wire discharge machining processes [12-14], in grinding process [15-18], or in turning process [19, 20]. Therefore, it is essential to carry out regression analysis and analysis based on the main effect diagram in the machining processes.

This article introduces a study on optimization of replaced tungsten carbide nozzle diameter for minimum cleaning costs during abrasive blasting with quartz sand. Additionally, the effects of the factors including initial nozzle diameter, nozzle wear rate, time for changing a nozzle, compressor power, machine cost, nozzle cost, and cost of sand on the optimum replaced nozzle diameter were investigated. Further, an empirical model was developed to obtain the optimum replaced nozzle diameter.

2. METHODOLOGY

In abrasive blasting, the cost of cleaning one square meter C_{cl} (USD/m²) is determined by (1):

$$C_{cl} = (C_{m,h} + C_{a,h} + C_{n,h}) / v_{cl} \quad (1)$$

Where, $C_{m,h}$, $C_{a,h}$ and $C_{n,h}$ are the costs of the cleaning system, the abrasive and the nozzle per hour (USD/h), respectively; v_{cl} is the cleaning rate (m²/h).

The abrasive cost is calculated as:

$$C_{a,h} = 3600 \cdot \dot{m}_a \cdot C_{a,m} \quad (2)$$

Where, $C_{a,m}$ is the abrasive cost per kilogram (USD/kg); $\dot{m}_a$ is the abrasive mass flow rate (kg/h) that can be achieved by the regression equation (with $R^2 = 0.998$):

$$\dot{m}_a = 15.14 \cdot d_n^{-0.0214} \cdot p^{1.0359} \quad (3)$$

The nozzle cost per hour is calculated by (4):

$$C_{n,h} = C_{n,p} / L_n \quad (4)$$

Where, $C_{n,p}$ is the nozzle cost per piece (USD/piece); L_n is the nozzle lifetime (h).

For tungsten carbide, the nozzle lifetime lasts from 300 to 400 (h) [21]. With tungsten carbide nozzle, a nozzle will be replaced when it wears 1/16 inch (or 1.59 mm) beyond its original size [22]. Therefore, the wear rate WR is calculated by the following equation:

$$WR = 1.59/L_n = 1.59/(300 \div 400) \approx 0.004 \div 0.0053 \text{ (mm/h)} \quad (5)$$

As shown in the data of Norton Sandblasting Equipment[21], the regression equation (with $R^2 = 0.9984$) was used to calculate the cleaning rate v_{cl} :

$$v_{cl} = 6.6101 \cdot 10^{-6} \cdot d_n^{2.0121} \cdot p^{1.5988} \quad (6)$$

Where p is the air pressure (kPa); the regression equation (with $R^2 = 0.9774$) was applied to calculate the air pressure:

$$P = 3854.7 \cdot d_n^{-2.5783} \cdot p^{1.1801} \quad (7)$$

Where P is the power (kW); d_n is nozzle diameter (mm).

Figure 1 shows that air pressure depends heavily on the nozzle diameter. When the nozzle diameter increases (or the nozzle lifetime increases), the air pressure decreases. The cleaning rate is dependent on the nozzle diameter and air pressure according to Equation 3. Also shown in Figure 2, the cleaning rate grows significantly with an increase in the nozzle diameter.

Figure 1: Dependence of the air pressure on the nozzle diameter

Figure 2: Dependence of the cleaning rate on the nozzle diameter

Figure 3 depicts the relationship between the cost of cleaning for one square meter and nozzle diameter (With parameters fixed as $C_{m,h}=20$ USD/h; $C_{a,h}=0.5$ USD/kg; $C_{n,p}=50$ USD/piece; $WR=0.004$ mm/h; $P=20$ kW). As shown in Figure 3, the cleaning cost is dependent greatly on the replaced nozzle diameter. Besides, there is a replaced nozzle diameter (called the optimum replaced nozzle diameter d_{op}) on the chart at which the cleaning cost is minimum. If replacing the nozzle with this optimal value of diameter is applied (in this case $d_{op}=12.2$ mm), the cleaning cost is much smaller (22.56%) compared to replacing the nozzle in the normal way (conventional replaced nozzle diameter is 13.9 mm).

According to the analysis above, a program was built to optimize problems for cost. In the problem, seven input parameters including initial nozzle diameter, nozzle wear rate, time for changing a nozzle, compressor power, machine cost, nozzle cost, and cost of sand were investigated for determining the optimum replaced nozzle diameter. The optimal problem can be shown as in the equation (8):

$$\min C_{cl} = \min f(d_n) \quad (8)$$

With the following constraints:

$$5 \leq d_{n0} \leq 12.5 \quad (9)$$

$$0.004 \leq WR \leq 0.0053 \quad (10)$$

$$4 \leq P_c \leq 80 \quad (11)$$

$$1 \leq t_{cn} \leq 15 \quad (12)$$

$$5 \leq C_{m,h} \leq 100 \quad (13)$$

$$4 \leq C_{n,p} \leq 150 \quad (14)$$

$$0.4 \leq C_{a,h} \leq 4.5 \quad (15)$$

Additionally, as analyzed above, d_{op} depends on parameters such as d_{N0} , WR , t_{cn} , P_c , $C_{m,h}$, $C_{n,p}$, and C_s . Hence, the optimum replaced nozzle diameter is described as follows:

$$d_{op} = f(d_{N0}, WR, t_{cn}, P_c, C_{m,h}, C_{n,p}, C_s) \quad (16)$$

Figure 3: Cleaning cost versus nozzle diameter

3. EXPERIMENTAL DETAILS

In this work, a series of meticulous experiments were performed to investigate the effect of the above mentioned factors on the optimum replaced nozzle diameter. The factors with levels are shown in Table 1. Each experiment is carried out with fixed parameters selected within the allowable adjustment range of the equipment.

Table 1: Factors and levels

Factor	Code	Unit	Low	High
Initial nozzle diameter	d_{N0}	mm	5	12.5
Nozzle wear rate per hour	WR	10^{-3} mm/h	4	5.3
Time for changing a nozzle	t_{cn}	min.	1	15
Compressor power	P_c	kW	4	80
Machine cost per hour	$C_{m,h}$	USD/h	5	100
Nozzle cost per piece	$C_{n,p}$	USD/piece	4	150
Cost of sand	C_s	USD/kg	0.4	4.5

To find out the effects of sandblasting process parameters on the output factor, an experimental method called “screening experiment” was applied. The screening experiment method is conducted for purposes such as finding out the main influencing factors on the output factors, estimating the influence of the factors, determining the degree of interaction effects between factors; establishing the first-order relationship between input factors and output factors. Minitab 18 software was selected for the design of the experiment and data analysis.

4. RESULTS AND DISCUSSIONS

The influences of the input factors on the optimum replaced nozzle diameter are illustrated in Figure 4. As shown in Figure 4, the initial nozzle diameter is the factor with the most powerful influence on the optimum replaced nozzle diameter. Other factors including WR , t_{cn} , P_c , $C_{m,h}$, $C_{n,p}$, and C_s have insignificant influence.

Additionally, Figure 5 shows the Normal Plot of the standardized effects. The input factors including d_{N0} , WR , t_{cn} , P_c , $C_{m,h}$, $C_{n,p}$, and C_s were represented by A, B, C, D, E, F, and G, respectively. The factor A (initial nozzle diameter) is the most influential factor for the optimum replaced nozzle diameter. It has a positive standardized effect. The influence of other factors and the interactions are negligible.

Figure 4: The main effects plot for the optimum replaced nozzle diameter

Figure 5: Normal Plot for d_{op}

The results of d_{op} obtained from the experiments are shown in Table 2. Also, an empirical model was developed for calculating the optimum replaced nozzle diameter as the equation (17):

$$d_{op} = -0.0206 + 1.00607 d_{N0} + 0.00877 WR + 0.003278 t_{cn} - 0.000409 P_c - 0.000555 C_{m,h} + 0.001074 C_{n,p} - 0.00779 C_s - 0.000046 d_{N0} * P_c + 0.000030 d_{N0} * C_{n,p} - 0.000640 d_{N0} * C_s - 0.000010 t_{cn} * C_{n,p} + 0.000006 P_c * C_{m,h} - 0.000008 P_c * C_{n,p} + 0.000161 P_c * C_s - 0.000003 C_{m,h} * C_{n,p} + 0.000102 C_{m,h} * C_s - 0.000123 C_{n,p} * C_s \quad (17)$$

Table 3 indicates the analysis of variance. According to the table of ANOVA, the initial nozzle diameter is the most influential input factor on the optimum replaced nozzle diameter. It contributes 99.965 % to the total effect. The effects of other factors and the interactions are negligible (less than 1%). Otherwise, the effects of all factors and interactions on the optimum replaced nozzle diameter are statistically significant with P-value less than 0.05. With a determination coefficient R-sq of 100 %, it means that the model is a good model for calculating the optimum replaced nozzle diameter.

Table 2: Experimental results

RunOrder	Sandblasting process parameters							Optimum replaced nozzle diameter
	d_{N0}	WR	t_{cn}	P_c	$C_{m,h}$	$C_{n,p}$	C_s	d_{op}
1	5	4	15	80	100	4	0.4	5.05
2	12.5	4	15	4	100	150	4.5	12.62
3	5	4	15	4	5	4	4.5	5.05
4	5	5.3	1	4	5	150	0.4	5.25
5	5	4	15	4	100	150	0.4	5.12
6	12.5	4	15	4	5	150	0.4	12.85
...								
127	5	5.3	15	80	100	4	4.5	5.06
128	12.5	4	15	4	5	4	4.5	12.58

Table 3: The ANOVA

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
Model	17	1818.22	106.95	162995.69	0.000 ^a	99.996
Linear	7	1818.03	259.72	395804.67	0.000 ^a	99.985
d_{N0}	1	1817.67	1817.67	2770079.82	0.000 ^a	99.965
WR	1	0.00	0.00	6.34	0.013 ^a	0.000
t_{cn}	1	0.04	0.04	59.21	0.000 ^a	0.002
P_c	1	0.10	0.10	145.02	0.000 ^a	0.005
$C_{m,h}$	1	0.02	0.02	27.15	0.000 ^a	0.001
$C_{n,p}$	1	0.15	0.15	221.17	0.000 ^a	0.008
C_s	1	0.06	0.06	94.01	0.000 ^a	0.003
2-Way Interactions	10	0.19	0.02	29.40	0.000 ^a	0.010
$d_{N0} * P_c$	1	0.01	0.01	8.20	0.005 ^a	0.001
$d_{N0} * C_{n,p}$	1	0.01	0.01	13.13	0.000 ^a	0.001
$d_{N0} * C_s$	1	0.00	0.00	4.73	0.032 ^a	0.000
$t_{cn} * C_{n,p}$	1	0.00	0.00	5.34	0.023 ^a	0.000
$P_c * C_{m,h}$	1	0.02	0.02	25.73	0.000 ^a	0.001
$P_c * C_{n,p}$	1	0.07	0.07	103.61	0.000 ^a	0.004
$P_c * C_s$	1	0.02	0.02	30.86	0.000 ^a	0.001
$C_{m,h} * C_{n,p}$	1	0.01	0.01	17.43	0.000 ^a	0.001
$C_{m,h} * C_s$	1	0.01	0.01	19.20	0.000 ^a	0.001
$C_{n,p} * C_s$	1	0.04	0.04	65.75	0.000 ^a	0.002
Error	110	0.07	0.00	-	-	0.004
Total	127	1818.30	-	-	-	100.000
R-sq = 100%						
^a significant						

The normal probability plot of the optimum replaced nozzle diameter is indicated in Figure 6. It expressed that the points on this normal probability plot of d_{op} form a nearly linear pattern meaning that the normal distribution is a suitable model in this study. In other words, the model established is a good model for calculating the optimum replaced nozzle diameter.

Figure 6: Normal Probability plot of d_{op}

4. CONCLUSIONS

In the current study, a study on optimization of replaced tungsten carbide nozzle diameter for minimum cleaning costs during abrasive blasting with quartz sand was conducted. Additionally, the effects of process parameters on the optimum replaced nozzle diameter were investigated. These conclusions have been drawn:

- For certain process parameters, there exists an optimal replaced nozzle diameter at which the cleaning cost is minimum.
- The initial nozzle diameter is the most influential input factor on the optimum replaced nozzle diameter. It contributes 99.965 % to the total effect. The influences of other factors and the interactions are negligible.
- The empirical model used for determining the optimum replaced nozzle diameter is considered to be statistically significant in this study.

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