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Minimization of Cleaning Cost in Sandblasting Using Silicon Carbide Composite Nozzle: A Case study

Nguyen Thanh Tu[1], Bui Thanh Danh[2], Bui Khac Khanh[3], Tran Thi Hong[4], Nguyen Hong Linh[5], Do The Vinh[1], Tran Ngoc Giang[1], and Vu Ngoc Pi[1,*]

[1]*Mechanical Engineering Faculty, Thai Nguyen University of Technology, Vietnam.*

[2]*Mechanical Engineering Faculty, University of Transport and Communications, Vietnam.*

[3]*Department of Mechanical Engineering, Hung Yen University of Technology and Education, Vietnam.*

[4]*Center of Excellence for Automation and Precision Mechanical Engineering, Nguyen Tat Thanh University, Vietnam.*

[5]*Hanoi Electric Power University, Vietnam.*

Correspondence: vungocpi@tnut.edu.vn

Abstract:

In this study, a minimization of cleaning cost in abrasive blasting with quartz sand was conducted by optimizing the replaced nozzle diameter. A cleaning cost analysis was conducted to find the minimum cost. For each specific sandblasting condition, the cost analysis indicated that there exists an optimal replaced nozzle diameter at which the cleaning cost is minimum. Further, the effects of the parameters including initial nozzle diameter, nozzle wear rate per hour, time for changing a nozzle, compressor power, machine cost per hour, nozzle cost per piece, and cost of sand on the optimum replaced nozzle diameter were investigated by applying a screening experiment. According to the research results, the initial nozzle diameter is the most influential factor in the optimum replaced nozzle diameter. To calculating the optimum replaced nozzle diameter, a mathematical model has been proposed.

Keywords: Abrasive Blasting, Sand Blasting, Replaced Nozzle Diameter, Silicon Carbide Composite Nozzle, Quartz Sand.

I. INTRODUCTION

Since its inception, sandblasting has played an important role in the automobile and shipbuilding industries. Sandblasting is used a lot in smoothing, shaping, rust removal, and especially surface preparation for the painting process [1]. The first model of sandblasting was invented in 1870 by Benjamin C. Tilghman [2]. In this model, compressed air is used to create a partial vacuum area that pushes and accelerates the abrasive particles into the surface to be cleaned [3]. The market for blast cleaning is huge. According to a report [4], the total demand for blast cleaning and related abrasive material in the EU is over 850,000 tonnes, with approximately €285 million. Reducing the cost and increasing the profitability of the abrasive cleaning process have attracted many researchers as well as manufacturers. In a study of Vu Ngoc Pi and A.M. Hoogstrate [5], A cost optimization of the abrasive blasting system was performed to find the minimum cost. The effect of the abrasive blasting process parameters, including the air pressure, the initial nozzle diameter, the nozzle wear on the cleaning cost was investigated. An empirical model was proposed for calculating the optimum replaced nozzle diameter. The application of the nozzle diameter optimization model has greatly reduced the cost and time of the blasting process. Several other studies have shown similar results, such as researches [6] and [7]. These studies all conclude that applying the right nozzle diameter will reduce costs, reduce machining time, and increase profits of the blasting process. In a study by James D. Hansink [8], a comparison between the cost of blasting with garnet and coal slag and between the cost of new and recycled garnet was conducted. The research results have shown that after blasting the garnet can be recycled three times and the first recycled garnet will be the cheapest. In [9], W. Momber proposed a general cost structure for a typical water blast-cleaning system. In this cost structure, the cost of labor is 46.6%, a high-pressure unit cost is 18.6%, the fuel cost is 15%, the cost of nozzle wear is 13.4%, the high-pressure gun cost is 3.3%, and the water treatment system cost is 3.1%. M.J. Woodward and R.S. Judson conducted a comparative study between the cost of wet abrasive blasting and the cost of dry blasting[10]. In this study, the authors analyzed the effects 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. They concluded that wet abrasive blasting cost had a great advantage over dry blasting.

From the above analysis, it was found that although there have been several studies on the influences of sandblasting input factors on the optimum responses, there is still a lack of using the Design of Experiment technique in these researches. In practice, this technique can be used effectively to investigate the influence of input process factors as well as determine the optimum responses in any machining process such as in electrical discharge machining [11-13], in wire discharge machining [14-16], in grinding [17-20], or in drilling [21-23]. In addition, there has not been a study on the cost optimization of the blasting process with silicon carbide composite nozzle.

In the current work, a cost analysis of the sandblasting process with silicon carbide composite nozzle was conducted to find the minimum cleaning cost. Furthermore, a screening experiment was carried out to determine the effects of factors such as 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. Besides, a mathematical model for calculating the optimum replaced nozzle diameter is also proposed.

II. COST ANALYSIS AND OPTIMIZATION

The cost of cleaning one square meter of the abrasive blasting process C_{cl} (USD/m^2) can be calculated by the Equation (1):

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

Where, $C_{m,h}$ is cleaning system cost, $C_{s,h}$ is sand cost, $C_{n,h}$ is nozzle cost per hour (USD/h), and v_{cl} is the cleaning rate (m^2/h).

The sand cost $C_{s,h}$ can be calculated by Equation (2):

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

Where C_s is the sand cost per kilogram (USD/kg); $\dot{m}_a$ is the abrasive mass flow rate (kg/h) that can be determined by Equation (3) with the determination coefficient R2=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 Equation (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).

The lifetime of a silicon carbide composite nozzle is from 300 to 400 (h) [24]. A silicon carbide composite nozzle will be replaced when it wears 1/16 inch (or 1.59 mm) beyond its original size [25]. Therefore, the wear rate WR can be determined by the following equation:

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

Based on the data in [24], the cleaning rate v_{cl} was found by the following regression equation with R^2=0.9984:

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

Where p is the air pressure (kPa); Based on the data in [24], the air pressure was determined by the regression equation (7) with $R^2 = 0.9774$:

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

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

As shown in Figure 1, the air pressure depends strongly on the nozzle diameter. The air pressure decreased with the increase of the nozzle diameter or increase of the nozzle lifetime growths. The cleaning rate depends on nozzle diameter and air pressure, according to Equation 6. Also shown in Figure 2, the cleaning rate growths significantly with the increase in the nozzle diameter.

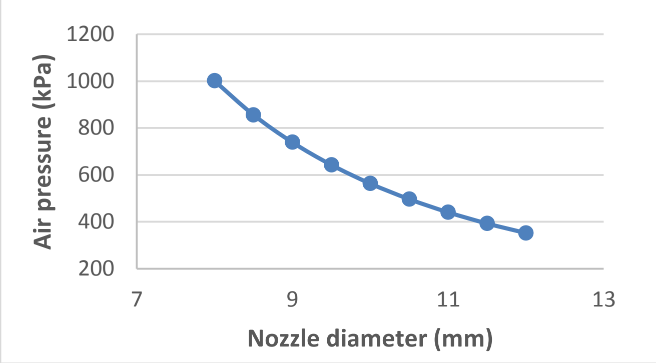

Fig. 1. Air pressure versus nozzle diameter

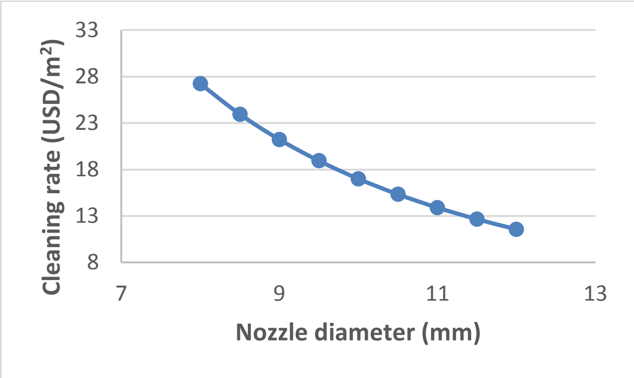

Fig. 2. Cleaning rate versus nozzle diameter

With $C_{m,h}$ = 8USD/h; C_s = 1USD/kg; $C_{n,p}$ = 50USD/piece; WR= 0.005 mm/h; P= 30kW, the relationship between the cost of cleaning for one square meter and nozzle diameter are shown in Figure 3. Figure 3 shows that the cleaning cost depends greatly on the replaced nozzle diameter. Besides, there is an optimum replaced nozzle diameter (d_{op}) on the chart at which the cleaning cost is minimal. If applying the optimum replaced nozzle diameter (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).

A computer program was used for solving the cost optimization problem. To solve this cost optimization problem, seven input parameters such as initial nozzle diameter, nozzle wear rate, time for changing a nozzle, compressor power, machine cost, nozzle cost, and cost of sand were investigated to find the optimum replaced nozzle diameter. The optimal problem can be described by following objective function and constraints:

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

The constraints were shown as follow:

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

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

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

$$1 \le t_{cn} \le 15 \tag{12}$$

$$5 \le C_{m,h} \le 100 \tag{13}$$

$$4 \le C_{n,p} \le 150 \tag{14}$$

$$0.4 \le C_s \le 4.5 \tag{15}$$

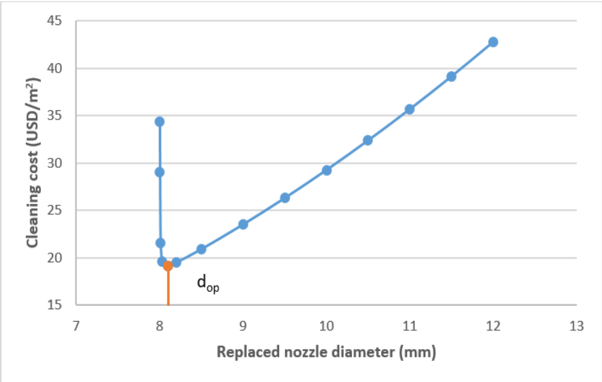

Fig. 3. Cleaning cost versus replaced nozzle diameter

Also, the optimum replaced nozzle diameter (d_{op}), depends on parameters of sandblasting process including initial nozzle diameter (d_{N0}), nozzle wear rate per hour (WR), time for changing a nozzle(tcn), compressor power (Pc), machine cost per hour ($C_{m,h}$), nozzle cost per piece ($C_{n,p}$), and cost of sand (Cs). Thus, the optimum replaced nozzle diameter can be expressed by the following Equation:

$$d_{op} = f\,(dN0,\ WR,\ tcn,\ Pc,\ Cm{,}h,\ Cn{,}p,\ Cs) \tag{16}$$

III. EXPERIMENTAL WORK

In this work, experimental processes of the sandblasting with the tungsten carbide nozzle were conducted to find out the effects of parameters such as initial nozzle diameter, nozzle wear rate per hour, time for changing a nozzle, compressor power, machine cost per hour, nozzle cost per piece, and cost of sand on the optimum replaced nozzle diameter. For this purpose, a screening experiment was applied. The parameters with levels are shown in Table 1. The parameters of sandblasting were selected within the recommended settings of the experimental equipment.

Table 1. Factors and levels

Levels	Sandblasting parameters						
	d_{N0} (mm)	WR (10^{-3} mm/h)	t_{cn} (min)	P_c (kW)	$C_{m,h}$ (USD/h)	$C_{n,p}$ (USD/piece)	C_s (USD/kg)
1	5	4	1	5	7	30	0.4
2	10	4.6	7	42.5	53.5	49.5	2.35
3	15	5.2	13	80	100	69	4.3

Minitab 18 software was used for experimental design and data analysis with the design of the experiment of RSM. The settings on the Minitab 18 software are shown in Figure 4. The parameters including initial nozzle diameter (d_{N0}), nozzle wear rate per hour (WR), time for changing a nozzle(tcn), compressor power (P_c), machine cost per hour ($C_{m,h}$), nozzle cost per piece ($C_{n,p}$), and cost of sand (C_s) were represented by A, B, C, D, E, F, and G, respectively.

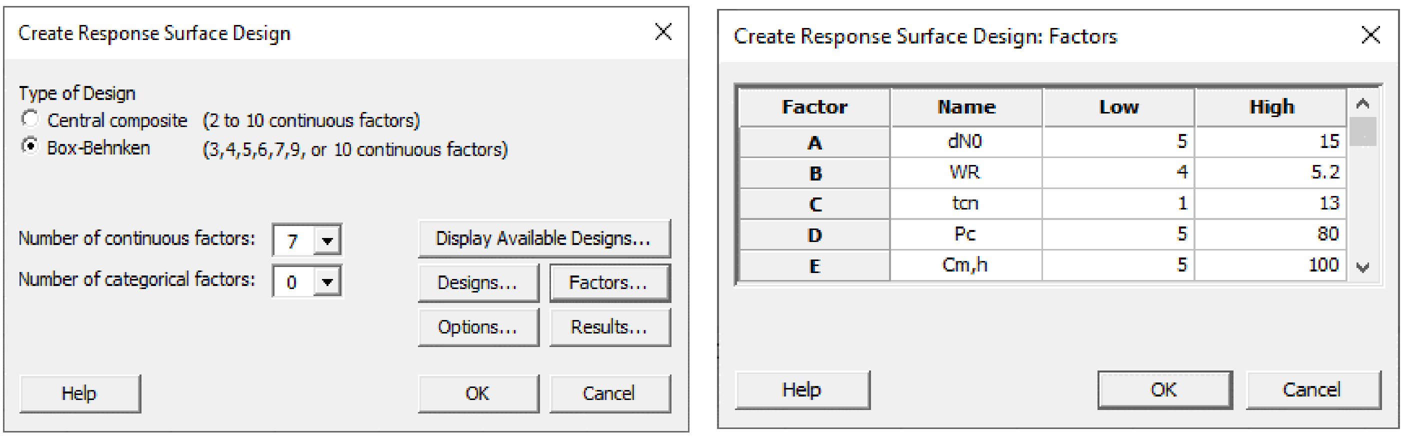

Fig.4. The settings on the Minitab 18 software

IV. RESULTS AND DISCUSSIONS

The result of the screening experiment with the input factors and the output response (the optimum replaced nozzle diameter) is shown in Table 2

Table 2. The result of the screening experiment

Input factors								Output response
No.	d_{N0} (mm)	WR (10^{-3} mm/h)	t_{cn} (min)	P_c (kW)	$C_{m,h}$ (USD/h)	$C_{n,p}$ (USD/piece)	C_s (USD/kg)	d_{op} (mm)
1	10	4.6	7	80	100	69	2.35	10.06
2	5	4	7	5	53.5	49.5	2.35	5.06
3	15	4.6	7	42.5	53.5	69	4.3	15.07
4	10	4	13	42.5	53.5	69	2.35	10.07
5	5	4.6	13	42.5	7	49.5	2.35	5.05
6	10	4.6	13	5	53.5	49.5	0.4	10.13
	…							
61	10	4.6	7	80	100	30	2.35	10.05
62	5	4.6	7	42.5	53.5	69	0.4	5.06

Figure 5 depicts the Normal Plot of the standardized effects. As shown in Figure 5, the initial nozzle diameter (d_{N0}) has a remarkable influence on the optimum replaced nozzle diameter compared to other factors. It has positive standardized effects. Also, other factors and the interactions have almost no significant influence on the optimum replaced nozzle diameter.

This can also be observed on the Pareto chart as shown in Figure 6. The Pareto chart illustrates the order of influence of the factors from the high to the low: A (the initial nozzle diameter), C (the time for changing a nozzle), D (the compressor power), G (the cost of sand), DD (the interaction), GG (the interaction), F (the nozzle cost per piece), B (the nozzle wear rate per hour), DG (the interaction), AC (the interaction), AD (the interaction), CC (the interaction), and finally AA (the interaction). In particular, A is the factor that has a dominant influence.

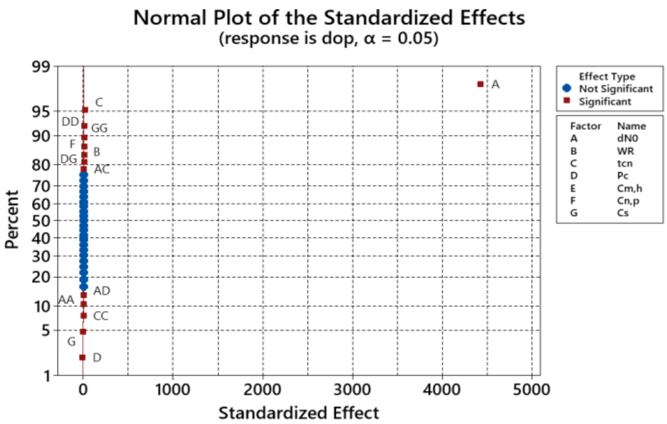

Fig.5. Normal Plot for d_{op}

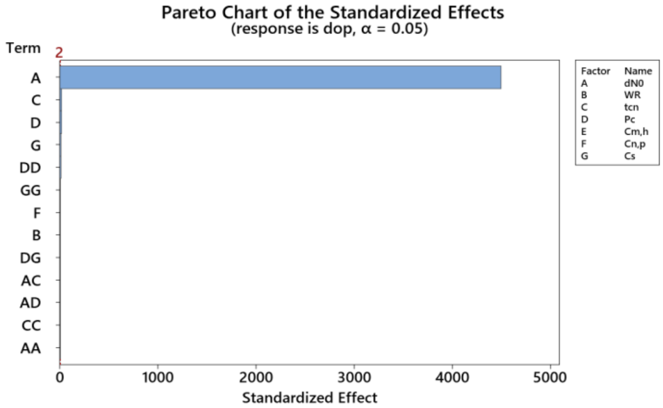

Fig.6. Pareto chart of the input factors affecting d_{op}

Besides, an equation was proposed to calculate the optimum replaced nozzle diameter as the following:

$$d_{op} = 0.0150 + 1.00611\, d_{N0} + 0.00625\, WR + 0.002975\, t_{cn} - 0.001185\, P_c + 0.000235\, C_{n,p} - 0.01991\, C_s - 0.000149\, d_{N0}{*}d_{N0} - 0.000103\, t_{cn}{*}t_{cn} + 0.000009\, P_c{*}P_c + 0.002145\, C_s{*}C_s + 0.000167\, d_{N0}{*}t_{cn} - 0.000027\, d_{N0}{*}P_c + 0.000085\, P_c{*}C_s \quad (17)$$

The analysis of variance is expressed in Table 3. As shown in the ANOVA table, the initial nozzle diameter is the dominant factor with over 99,99% of the total influence of the factors on the optimum replaced nozzle diameter. The influence of other factors as well as the interactions is very small. Their influence is less than 1% of the total effect. With the P index < 0.05, it indicates that the effect of all factors has statistical significance. Also, the determination coefficient R-squared is 100%. It means that the model of the optimum replaced nozzle diameter perfectly fit with data. The model is good for determining the optimum replaced nozzle diameter.

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Table 3. Analysis of variance for the optimum replaced nozzle diameter

Source	DF	Adj SS	Adj MS	F-Value	P-Value	PC %
Model	13	603.831	46.449	1557426.06	0.000[a]	99.9998
Linear	6	603.826	100.638	3374396.63	0.000[a]	99.9990
d_{N0}	1	603.806	603.806	20245703.61	0.000[a]	99.9957
WR	1	0.000	0.000	11.32	0.002[a]	0.0000
t_{cn}	1	0.009	0.009	295.62	0.000[a]	0.0015
P_c	1	0.007	0.007	234.85	0.000[a]	0.0012
$C_{n,p}$	1	0.001	0.001	16.90	0.000[a]	0.0002
C_s	1	0.004	0.004	117.50	0.000[a]	0.0007
Square	4	0.004	0.001	33.76	0.000[a]	0.0007
$d_{N0}*d_{N0}$	1	0.000	0.000	6.64	0.013[a]	0.0000
$t_{cn}*t_{cn}$	1	0.000	0.000	6.64	0.013[a]	0.0000
P_c*P_c	1	0.002	0.002	82.96	0.000[a]	0.0003
C_s*C_s	1	0.001	0.001	31.88	0.000[a]	0.0002
2-Way Interaction	3	0.001	0.000	7.96	0.000[a]	0.0002
$d_{N0}*t_{cn}$	1	0.000	0.000	6.71	0.013[a]	0.0000
$d_{N0}*P_c$	1	0.000	0.000	6.71	0.013[a]	0.0000
P_c*C_s	1	0.000	0.000	10.48	0.002[a]	0.0000
Error	48	0.001	0.000			0.0002
Total	61	603.832				100.0000
R-sq = 100%, R-sq (adj) = 100%, R-sq(pred) = 100%						
[a] significant						

Figure 7 shows the normal probability plot for the optimum replaced nozzle diameter. As shown in the figure, the points on this normal probability plot of Dop form a nearly linear pattern. It means that the normal distribution is a proper model for this data set. In other words, the model can be used perfectly for calculating the optimum replaced nozzle diameter.

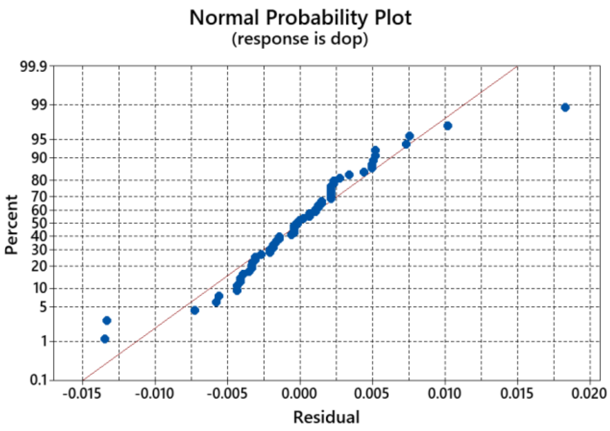

Fig.7. Normal Probability plot for d_{op}

V. CONCLUSION

In the current work, a cost analysis of the sandblasting process with silicon carbide composite nozzle was conducted to find the minimum cleaning cost. In addition, a screening experiment was carried out to determine the effects of process parameters on the optimum replaced nozzle diameter. The results of the study are as follows:

- For each specific sandblasting process, applying the optimum replaced nozzle diameter is a useful way to minimize cleaning costs.
- The initial nozzle diameter has a remarkable influence on the optimum replaced nozzle diameter compared to other factors. It contributes over 99.99 % of the total effect. The influence of other factors as well as the interactions is very small.
- A good mathematical model for calculating the optimum replaced nozzle diameter is proposed with the reliability level of 100%.

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