PROCESS PARAMETER OPTIMIZATION OF THE DIAMOND BURNISHING OPERATION UNDER HYBRID COOLING-LUBRICATION SYSTEM

TỐI ƯU HÓA THÔNG SỐ CÔNG NGHỆ CỦA QUÁ TRÌNH LĂN ÉP KIM CƯƠNG VỚI HỆ THỐNG BÔI TRƠN LÀM NGUỘI TÍCH HỢP

Nguyen Trung Thanh[1,*], Pham Long Hai[2], Le Xuan Ba[2]

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ABSTRACT

Diamond burnishing is an effective finishing process to enhance the surface quality and production rate of machined components. The purpose of this investigation is to select the optimal process parameters, including the spindle speed (S), feed rate (f), and burnishing depth (D) of the hybrid cooling-lubrication system-based diamond burnishing process for decreasing the average roughness (AR) and improving Vickers hardness (VH). The design of experiment entitled Taguchi L_{16} is applied to perform trials. The principal component analysis (PCA) is employed to compute the weight values of all responses. The combined compromise solution (CCS) is utilized to select the best optimal solution. The results indicated that optimal outcomes of the S, D, and f were 630RPM, 0.10mm, and 0.04mm/rev., respectively. The AR was decreased by 56.0%, while the VH was increased by 16.8% at the optimal solution. The proposed approach comprising the Taguchi, PCA, and CCS could be considered as a powerful technique to solve complex optimizing problems for the diamond burnishing process.

Keywords: *Diamond burnishing process; average roughness; vickers hardness; Taguchi; PCA; CCS.*

TÓM TẮT

Lăn ép kim cương là một quá trình gia công tinh hiệu quả để nâng cao chất lượng bề mặt và năng suất gia công. Mục đích của nghiên cứu này là để chọn các thông số công nghệ tối ưu, bao gồm tốc độ trục chính (S), tốc độ tiến dao (f) và chiều sâu lăn (D) của quá trình lăn ép kim cương dựa trên hệ thống bôi trơn-làm nguội tích hợp để giảm độ nhám trung bình (AR) và cải thiện độ cứng Vickers (VH). Quá trình thực nghiệm được tiến hành dựa trên quy hoạch Taguchi L_{16}. Phương pháp phân tích thành phần (PCA) được sử dụng để tính toán các giá trị trọng số của các hàm mục tiêu. Giải pháp thỏa hiệp kết hợp (CCS) được sử dụng để chọn giải pháp tối ưu tốt nhất. Kết quả tối ưu của S, D và f lần lượt là 630RPM, 0,10mm và 0,04mm/vòng. Độ nhám trung bình đã giảm 56,0%, trong khi độ cứng Vickers được tăng lên 16,8% tại giá trị tối ưu. Cách tiếp cận được đề xuất bao gồm Taguchi, PCA và CCS có thể được coi là một phương pháp hiệu quả để giải quyết vấn đề tối ưu hóa phức tạp cho quá trình đánh bóng kim cương.

Từ khóa: *Lăn ép kim cương; độ nhám trung bình; độ cứng Vickers; Taguchi; PCA; CCS.*

[1]Faculty of Mechanical Engineering, Le Quy Don Technical University
[2]25 Mechanical Co., LTD, Hanoi
[*]Email: trungthanhk21@mta.edu.vn; trungthanhnguyen@lqdtu.edu.vn
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1. INTRODUCTION

The surface roughness and hardness were significantly improved with the aid of the diamond burnishing process, in which the plastic deformation is produced using the sliding friction between the tool tip and the surface to be machined. This operation is easily implemented on the conventional and CNC turning machines due to similar characteristics to the turning process. This process provides various benefits, including easy implementation, longer tool life, and flexible functions.

The technical parameters of different diamond burnishing operations have been improved by means of optimal factors. The optimal data of the burnishing speed (V), feed rate (f), and burnishing force (F) were applied to decrease the surface roughness (SR) and enhance the surface hardness (SH) of the diamond burnishing stainless steel under the cryogenic condition [1]. For the diamond burnishing 17-4 stainless steel, the optimal outcomes of the SR and SH were 0.2µm and 398HV, respectively [2]. The minimum quantity lubrication (MQL) was employed to improve the SR and SH for the diamond burnishing process, in which the SR and SH were decreased by 36.8% and 42.7%, as compared to un-optimal case [3]. The small value of the tool tip could be applied to increase the SH and compressive residual stress of the burnished surface [4]. The fatigue limit (FL) of the burnished carbon steel was enhanced by 28.6% with the support of the diamond burnishing, as compared to the pre-machined surface [5]. Similarly, the FL of the burnished 41 Cr4 steel was increased by 23.0% with the aid of slide diamond burnishing process [6]. Moreover, the wear resistance of the burnished surface was increased by 1.75 times, as compared to the turning operation [7].

In the current investigation, the Hilsch Vortex Tube-minimum quantity lubrication-based diamond burnishing operation has been proposed and optimized to enhance Vickers hardness (VH) and decrease the average roughness (AR). The process parameters, including the spindle speed (S), burnishing depth (D), and feed rate (f) are selected as optimizing inputs. The hardened steel namely 40XC is selected as the experimental specimen due to wide applications for fabricating motor shafts and sliver bearings. The principal component analysis (PCA) and combined compromise solution (CCS) are employed to calculate the weight value of each response and select the best optimal solution.

2. OPTIMIZATION APPROACH

2.1. Process parameters and burnishing responses

In this investigation, two primary indicators of the burnishing quality, including the average roughness (AR) and Vickers hardness (VH) are addressed and optimized.

The AR value is computed as:

$$AR = \frac{\sum_{i=1}^{n} R_{ai}}{5} \quad (1)$$

where R_{ai} presents the average roughness at the i_{th} measured location.

The VH value is calculated as:

$$VH = \frac{\sum_{i=1}^{5} VH_i}{5} \quad (2)$$

where VH_i denotes the Vickers hardness at the i_{th} measured position.

In this work, process parameters, including the spindle speed, feed rate, and depth of penetration are selected as optimizing inputs, as shown in Table 1. The ranges of each factor are determined based on the characteristics of the machine tool and the recommendations of the manufacturer of the diamond burnishing tool.

Table 1. Process parameters for the diamond burnishing process

Symbol	Parameters	Level 1	Level 2	Level 3	Level 4
S	Spindle speed (RPM)	105	185	370	630
D	Burnishing depth (mm)	0.04	0.06	0.08	0.10
f	Feed rate (mm/rev.)	0.04	0.05	0.06	0.07

2.2. Systematic approach

The systematic approach for the diamond burnishing process is presented in Fig. 1, which includes the following steps:

Step 1: The diamond burnishing trials are conducted to obtain the necessary data. In this study, the using Taguchi design L_{16} is applied to save the experimental costs and human efforts.

Step 2: The principal components analysis (PCA) is used to compute the weight value of each response.

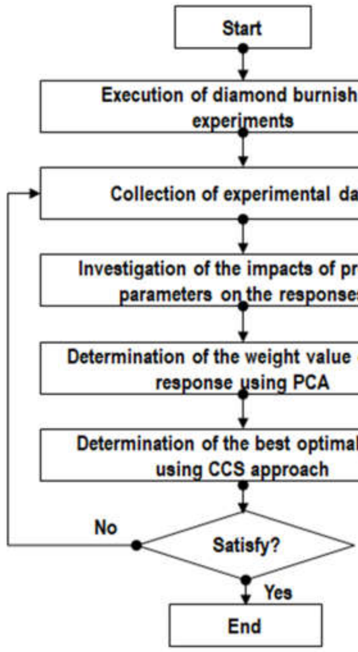

Fig. 1. Optimization approach for the diamond burnishing process

The normalized response (r_{ij}) for the 'lower the better' criterion is computed as:

$$r_{ij} = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (3)$$

The normalized response (r_{ij}) for the 'higher the better' criterion is computed as:

$$r_{ij} = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (4)$$

The correlation coefficient is calculated as:

$$S_{jl} = \left[\frac{Cov(I_i(j), I_i(l))}{\sigma_{li}(j) \times \sigma_{li}(l)}\right] \quad (5)$$

where $Cov(I_i(j)$ and $I_i(l))$ presents the covariance of sequences $I_i(j)$ and $I_i(l)$, respectively. $\sigma_{li}(j)$ and $\sigma_{li}(l)$ denotes standard deviations of sequences $I_i(j)$ and $I_i(l)$, respectively.

The eigenvalues and consequent eigenvectors are calculated as:

$$(S - \lambda_k J_m)V_{ik} = 0 \quad (6)$$

where λ_k, V_{ik}, and J_m presents the eigenvalues, eigenvectors, and the identity matrix, respectively.

The major principal coefficient is calculated as:

$$PC_m = \sum_{i=1}^{n} I_m(i) \times V_{ik} \quad (7)$$

Step 3: The combined compromise solution (CCS) is applied to select the best optimality.

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The total weighted comparability sequence (S_i) is computed as:

$$S_i = \sum_{j=1}^{n} (\omega_j r_{ij}) \tag{8}$$

where ω_i presents the weight value of each response.

The complete comparability weight (P_i) is computed as:

$$P_i = \sum_{j=1}^{n} (r_{ij})^{\omega_j} \tag{9}$$

The relative weights of the alternatives (k_{ia}, k_{ib}, and k_{ic}) are computed as:

$$k_{ia} = \frac{S_i + P_i}{\sum_{i=1}^{m} S_i + P_i} \tag{10}$$

$$k_{ib} = \frac{S_i}{\min S_i} + \frac{P_i}{\min P_i} \tag{11}$$

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)P_i}{(\lambda \min S_i + (1-\lambda)\max P_i)} \tag{12}$$

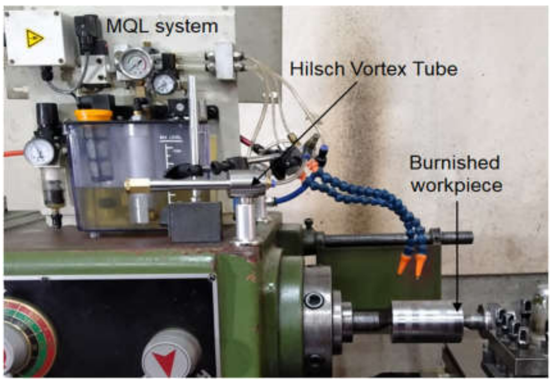
where λ present the decisive coefficient. In this investigation, the λ of 0.5 is applied.

The solution having the highest compromise score (k_i) is selected as the best optimality. The compromise score is computed as:

$$k_i = (k_{ia}k_{ib}k_{ic})^{1/3} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \tag{13}$$

3. EXPERIMENTAL SETTING FOR THE DIAMOND BURNISHING OPERATION

The hybrid cooling-lubrication system is proposed based on the combination of the Hilsch Vortex Tube and minimum quantity lubrication (MQL) devices. In the MQL system, the regulator is utilized to receive as well as control the compressed air, while the lubricant is stored in the tank and transferred with the aid of the electrical pump. The compressed air is transferred through the Hilsch Vortex Tube to decrease the working temperature. The cold air is mixed with the minute amount of the soybean oil in the chamber and then delivered into the burnishing region using the nozzles.



(a) Experimental setting

(b) Burnishing tool and diamond tip

Fig. 2. The diamond burnishing experiments

The conventional turning machine is used to perform the experiments (Fig. 2a). The friction between the dead center and workpiece is used to perform the rotational movement of the machining specimen. The length and outer diameter of each workpiece are 110.0mm and 70.0mm, respectively. The average roughness and Vickers hardness of the pre-machined surface are approximately 1.86µm and 418.4HV, respectively. The structure of the diamond burnishing tool is depicted in Fig. 2b.

The tester namely Mitutoyo Surftest-301 is used to capture roughness values in three different positions. The Vickers hardness is measured in three different points on the burnished surface using a tester namely Wilson Wolpert, in which the pressed load of 29.42N and the dwell time of 10 seconds are used for each hardness testing.

4. RESULTS AND DISCUSSIONS

4.1. Parametric impacts on the burnishing responses

The experimental data of the diamond burnishing operation are presented in Table 2, in which the Taguchi method having 16 trials is presented.

Table 2. Experimental data for the diamond burnishing process

No.	S (RPM)	D (mm)	f (mm/min)	AR (µm)	VH (HV)
1	105	0.04	0.04	0.48	569.7
2	105	0.06	0.05	0.43	543.8
3	105	0.08	0.06	0.38	547.6
4	105	0.10	0.07	0.34	571.2
5	185	0.04	0.05	0.46	535.1
6	185	0.06	0.04	0.35	540.5
7	185	0.08	0.07	0.36	519.6
8	185	0.10	0.06	0.26	579.5
9	370	0.04	0.06	0.41	495.3
10	370	0.06	0.07	0.34	475.4
11	370	0.08	0.04	0.19	512.1
12	370	0.10	0.05	0.15	536.7
13	630	0.04	0.07	0.39	467.1
14	630	0.06	0.06	0.25	465.5
15	630	0.08	0.05	0.14	497.6
16	630	0.10	0.04	0.11	543.5

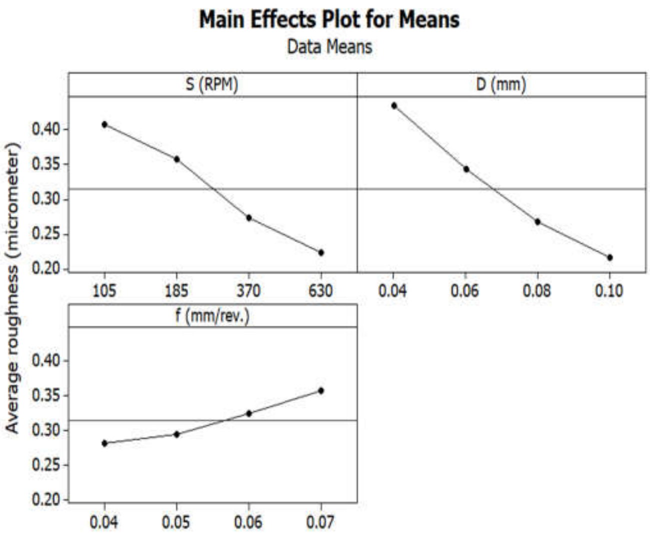


Fig. 3. Parametric influences on the average roughness

The impacts of process parameters on the average roughness are presented in Fig. 3. It can be stated that the average roughness decreases (relatively around 45.2%) with an increment in the spindle speed (from 105 to 630RPM). Higher spindle speed increases the engagement frequency between the diamond tip and the surface to be machined, which increases the number of burnishing traces. The irregularities of the pre-machined surface are easily deformed; hence the average roughness decreases. Additionally, the machining temperature at the interface increases with an increased spindle speed, which reduces the hardness and strength of the workpiece; hence, the surface is smoothly compressed. Therefore, a reduction in the average roughness is obtained.

As shown in Fig. 3, an increment in the burnishing depth (from 0.04 to 0.10mm) leads to a reduction in the average roughness (relatively around 51.2%). Higher burnishing depth increases the machining pressure on the surface to be machined and the material is hardly compressed. The peaks are flatted and the valleys are filled up. Therefore, the average roughness significantly reduces.

As shown in Fig. 3, higher feed rate (from 0.04 to 0.07mm/rev.) increases the average roughness (relatively around 28.6%). An increased burnishing feed causes higher distance between the consecutive burnishing paths, which decreases the the engagement frequency. The machining time available to process material decreases with the an increased feed rate; hence, the average roughness decreases.

The SEM image of the diamond burnished surface at the experimental No. 8 is depicted in Fig. 4. It can be stated that the irregularities (peaks and valleys) have been smoothly compressed with the aid of the diamond tip.

The contribution of each factor on the average roughness is shown in Table 3. As a result, the computed contributions of the burnishing depth, spindle speed, and feed rate are 53.23%, 40.24%, and 6.53%, respectively.

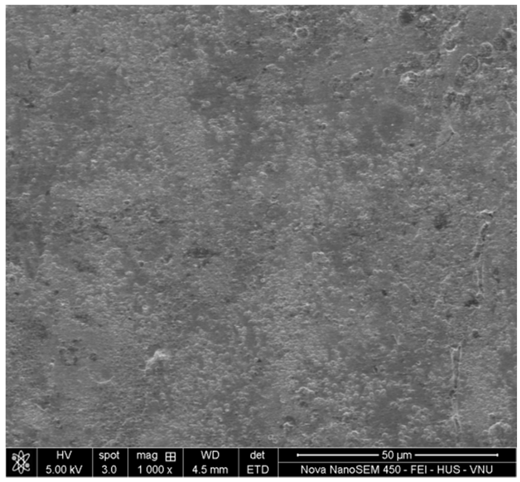


Fig. 4. The SEM image at the experimental No. 8

Table 3. ANOVA results for the average roughness

Source	Sum of Squares	Mean Square	F-Value	P value	Contribution (%)
S	0.082900	0.027633	103.63	<0.0001	40.24
D	0.109650	0.036550	137.06	<0.0001	53.23
f	0.013450	0.004483	16.81	0.003	6.53
Error	0.001600	0.000267			
Total	0.207600				

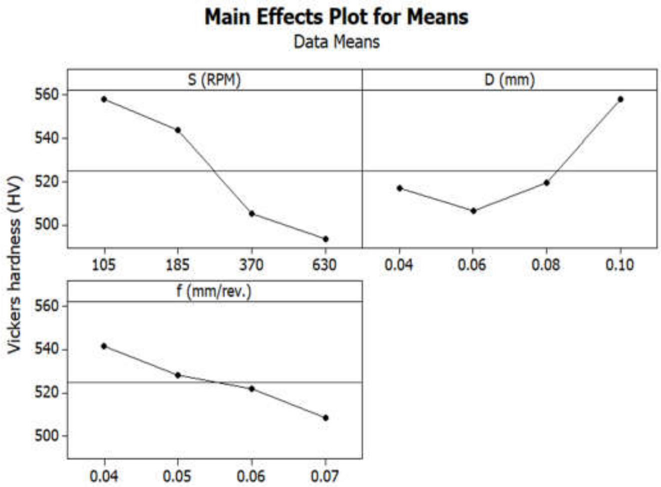


Fig. 5. Parametric influences on the Vickers hardness

The impacts of process parameters on the Vickers hardness are presented in Fig. 5. It can be stated that the Vickers hardness decreases (relatively around 11.6%) with an increased spindle speed (from 105 to 630RPM). An increment in the spindle speed causes higher machining temperature at the burnishing area; hence, the obtained hardness decreases.

As depicted in Fig. 5, an increased burnishing depth (from 0.04mm to 0.10mm) leads to a higher Vickers hardness (relatively around 8.1%). A higher depth of penetration causes excessive machining pressure on the surface to be machined. The material is hardly compressed and increased Vickers hardness is obtained.

As depicted in Fig. 5, a higher feed rate (from 0.04 to 0.07mm/rev.) decreases the Vickers hardness (relatively around 6.1%). An increased burnishing feed causes a low degree of the plastic deformation due to higher distance among the consecutive traces; hence, the Vickers hardness decreases.

The contribution of each factor on the Vickers hardness is shown in Table 4. As a result, the computed contributions of the spindle speed, burnishing depth, and feed rate are 57.65%, 30.83%, and 11.52%, respectively.

Table 4. ANOVA results for the Vickers hardness

Source	Sum of Squares	Mean Square	F-Value	P value	Contribution (%)
S	11378.8	3792.9	98.44	<0.0001	57.65
D	6084.8	2028.3	52.64	<0.0001	30.83
f	2274.8	758.3	19.68	0.002	11.52
Error	231.2	38.5			
Total	19969.6				

4.2. Optimization results

The normalized values of burnishing responses are shown in Table 5. The eigenvalues and proportions of the responses are presented in Table 6. As a result, the proportion of the first principal component is 55.5%, followed by the second component (44.5%). The weight values are calculated using the squares of subsequent eigenvectors of the first and second components. Table 7 revealed that the weight values of the AR and VH are 0.5 and 0.5, respectively.

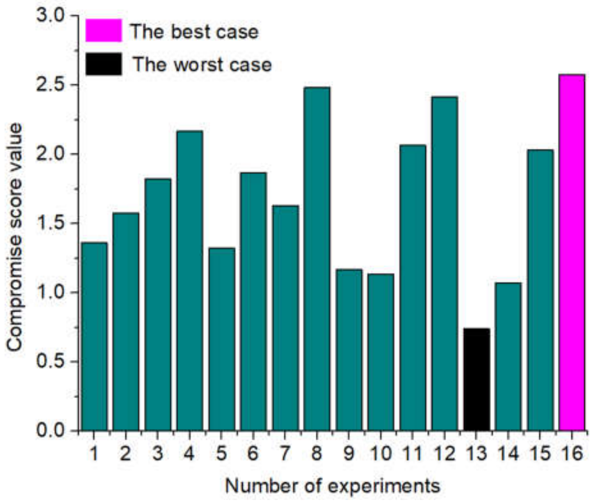


Fig. 6. The variations of the compromise score value

Table 8 presents the values of the S_i, P_i, and k_i. It can be stated that the highest value ki can be obtained at the experimental No. 16, as shown in Fig. 6. The optimal values of the S, D, and f are 630RPM, 0.10mm, and 0.04mm/rev., respectively. The optimal values of the AR and VH are 0.11µm and 543.5µm, respectively (Table 9). The improvements in the AR and VH are 56.0% and 16.8%, respectively, as compared to the worst-case (No. 13). The AR is decreased by 94.1%, while the VH is enhanced by 29.9%, as compared to the pre-machined properties (Table 10).

Table 5. Normalized response for diamond burnishing responses

No.	*AR*	*VH*	No.	*AR*	*VH*
1	0.00000	0.91404	9	0.18919	0.26140
2	0.13514	0.68684	10	0.37838	0.08684
3	0.27027	0.72018	11	0.78378	0.40877
4	0.37838	0.92719	12	0.89189	0.62456
5	0.05405	0.61053	13	0.24324	0.01404
6	0.35135	0.65789	14	0.62162	0.00000
7	0.32432	0.47456	15	0.91892	0.28158
8	0.59459	1.00000	16	1.00000	0.68421

Table 6. Eigenvalues and proportions of principal components

Eigenvalue	1.1099	0.8901
Proportion	0.555	0.445
Cumulative	0.555	1.000

Table 7. The weight values of the responses

Responses	PC1	PC2	Weights
AR	-0.707	-0.707	0.5
VH	0.707	0.707	0.5

Table 8. The compromise score values and ranking

No.	S_i	P_i	k_{ia}	k_{ib}	k_{ic}	k_i	Rank
1	0.45702	0.95605	0.08424	2.10572	0.52938	1.36099	11
2	0.41099	1.19637	0.09970	2.44395	0.60217	1.57604	10
3	0.49522	1.36851	0.11494	2.82540	0.69821	1.82263	8
4	0.65279	1.57803	0.13544	3.35506	0.83574	2.16625	4
5	0.33229	1.01386	0.08392	2.05212	0.50431	1.32296	12
6	0.50462	1.40386	0.11778	2.89436	0.71498	1.86703	7
7	0.39944	1.25838	0.10370	2.53162	0.62107	1.63177	9
8	0.79730	1.77110	0.15431	3.84230	0.96221	2.48231	2
9	0.22530	0.94624	0.07531	1.81451	0.43889	1.16766	13
10	0.23261	0.90981	0.07298	1.76365	0.42799	1.13536	14
11	0.59628	1.52467	0.12964	3.20071	0.79458	2.06580	5
12	0.75823	1.73469	0.15033	3.73638	0.93393	2.41338	3
13	0.12864	0.61167	0.04808	1.15275	0.27734	0.74136	16
14	0.31081	0.78843	0.06712	1.65806	0.41181	1.07021	15
15	0.60025	1.48924	0.12726	3.14751	0.78279	2.03188	6
16	0.84211	1.82717	0.15989	3.98718	1.00000	2.57634	1

Table 9. Optimization results produced by the CCS

Method	S (RPM)	D (mm)	f (mm/min)	AR (µm)	VH (HV)
The worst case	630	0.06	0.06	0.25	465.5
The best case	630	0.1	0.04	0.11	543.5
Improvements (%)				-56.0	16.8

Table 10. Comparisons between the pre-machined and diamond burnished surface

Method	Characteristics	
	AR (μm)	*VH* (HV)
Pre-machining surface	1.86	418.4
Diamond burnishing surface	0.11	543.5
Improvements (%)	94.1	29.9

5. CONCLUSION

In this investigation, a hybrid cooling-lubrication system-assisted diamond burnishing operation has been developed and optimized to decrease the average roughness (AR) and improve the Vickers hardness (VH) of the burnished surface. The optimizing process parameters are the spindle speed (S), burnishing depth (D), and feed rate (f). The principal component analysis (PCA) was utilized to compute the weight value of each response. The combined compromise solution (CCS) was applied to select the best optimal point. The obtained findings can be listed as follows:

1. It can be stated that process parameters have significant impacts on the burnishing responses. To decrease the average roughness, the highest levels of spindle speed and burnishing depth could be applied, while a low feed rate was recommended. To boost the Vickers hardness, the lowest levels of the spindle speed and feed rate could be employed, while the highest burnishing depth was applied.

2. For the average roughness, the burnishing depth was the dominant factor, followed by the spindle speed and feed rate, respectively. For the Vickers hardness, the spindle speed was named as the most contributing parameter, followed by the burnishing depth and the feed rate, respectively.

3. The optimal parameters the S, D, and f were 630RPM, 0.10mm, and 0.04mm/rev., respectively. The AR was decreased by 56.0%, while the VH was increased by 16.8% at the optimal solution in comparison with the worst case. The improvements in the AR and VH were 94.1% and 29.9%, respectively, as compared to the pre-burnished surface.

4. The proposed cooling-lubrication system can be effectively employed as a significant reference to develop new cooling-lubrication systems. The obtained results can be applied to industrial applications to enhance the burnishing quality, save experimental costs, and decrease human efforts.

5. The proposed optimizing approach comprising the Taguchi L16, PCA, and CCS could be effectively and efficiently utilized to determine the optimal process parameters of not only the diamond burnishing process but also other machining operations.

6. The impacts of operating parameters of the developed cooling-lubrication system, such as the air pressure, flow rate of lubricant, and spraying angle on the burnishing quality will be considered in future investigations.

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THÔNG TIN TÁC GIẢ

Nguyễn Trung Thành[1], Phạm Long Hải[2], Lê Xuân Ba[2]

[1]Khoa Cơ khí, Học viện Kỹ thuật Quân sự

[2]Công ty TNHH MTV Cơ khí 25