OPTIMIZATION OF COMPRESSED AIR-ASSISTED TURNING-BURNISHING PROCESS FOR IMPROVING ROUGHNESS AND HARDNESS

TỐI ƯU HÓA QUÁ TRÌNH TÍCH HỢP TIỆN-LĂN ÉP VỚI SỰ HỖ TRỢ CỦA KHÍ NÉN ĐỂ CẢI THIỆN ĐỘ NHÁM VÀ ĐỘ CỨNG

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ABSTRACT

A hybrid process combining the turning-burnishing operation is a prominent solution to improve productivity due to the reduction in the auxiliary time. The objective presents a parameter-based optimization of the compressed air-assisted turning-burnishing (CATB) process to enhance the Vickers hardness (HN) and decrease the roughness (SR). The inputs are the cutting speed (V), depth of cut (a), feed rate (f), and ball diameter (D). A turning machine was used in conjunction with the turning-burnishing device to perform the experimental runs for aluminum 6061. The response surface method (RSM) was applied to render the correlations between the inputs and performances measured. The multi-objective particle swarm optimization (MOPSO) is used to select the optimal factors. The results revealed that machining targets are primarily affected by feed, speed, and depth. The roughness is reduced by 36.84% and the Vickers hardness is improved by 17.51% at the optimal solution, as compared to the general process. The obtained outcome is expected as a technical solution to make the CATB process become more efficient.

Keywords: *Turning-burnishing operation, Roughness, Vickers hardness, Aluminum 6061, RSM, MOPSO.*

TÓM TẮT

Quá trình tích hợp tiện - lăn ép là một giải pháp nổi bật để cải thiện năng suất do giảm thời gian phụ. Mục tiêu của nghiên cứu này là tối ưu hóa các thông số của quá trình tích hợp tiện - lăn ép với sự hỗ trợ của khí nén (CATB) để tăng cường độ cứng (HN) và giảm độ nhám (SR). Các thông số được cân nhắc là tốc độ cắt (V), chiều sâu cắt (a), lượng tiến dao (f) và đường kính bi lăn (D). Máy tiện được sử dụng cùng với dụng cụ tích hợp tiện-lăn ép để thực hiện các thí nghiệm cho vật liệu nhôm 6061. Phương pháp bề mặt đáp ứng (RSM) được sử dụng để thể hiện mối tương quan giữa các yếu tố đầu vào và hàm mục tiêu. Phương pháp tối ưu hóa bầy đàn đa mục tiêu (MOPSO) được sử dụng để xác định các giá trị tối ưu. Kết quả cho thấy các hàm mục tiêu chủ yếu bị ảnh hưởng bởi lượng tiến dao, tốc độ cắt, và chiều sâu cắt. Độ nhám có thể giảm 42,10% và độ cứng được cải thiện 17,51% ở giải pháp tối ưu khi so sánh với các giá trị trung gian. Kết quả thu được kỳ vọng như một giải pháp kỹ thuật để quá trình tích hợp tiện - lăn ép với sự hỗ trợ của khí nén trở nên hiệu quả hơn.

Từ khóa: *Tích hợp tiện - lăn ép, độ nhám, độ cứng Vicker, nhôm 6061, bề mặt đáp ứng, tối ưu hóa bầy đàn đa mục tiêu.*

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1. INTRODUCTION

The surface treatment can be classified into three primary operations, including the thermal impact (quenching and tempering), mechanical influence (turning, burnishing, and rolling), and chemical processes (carburizing, nitriding, etc.). Burnishing is a prominent solution to improve the surface properties, in which the profile irregularities generated by the former operation will be flattened under the effects of ball or roller pressure. The compressive residual stress, one of the effective residual stresses is then obtained. This method effectively enhances the mechanical properties as well as surface quality and can be considered as a potential solution to replace the traditional approaches, such as reaming, grinding, honing, lapping, supper-finishing and polishing [1].

The burnishing process brings some attractive advantages, including decreased roughness, increased hardness as well as the depth of the affected layer and generated compressive stress. Additionally, its productivity is higher 2-3 times than the honing process [2]. The surface properties and the component's functionality have been greatly improved, contributing significantly to increased strength behavior and abrasion as well as chemical corrosion resistances. Moreover, this process can be considered as a greener manufacturing due to eliminating chips and saving raw materials in the processing time.

To improve the production rate, a hybrid process combining turning and burnishing operations has been considered. Mezlini *et al.* emphasized that the manufacturing costs could be decreased up to 4 times using this approach for treated C45 steel [3]. Moreover, the roughness was reduced by 58%, as compared to the turning process. Similarly, the roughness could be decreased by 85.33% for the aluminum material. Axinte and Gindy revealed that a smooth surface was obtained and the hardness depth could be reached to 300 µm for treated Inconel 718 [4]. Rami *et al.* stated that the improvements in the roughness, residual stress, and micro hardness of the AISI 4140 steel were achieved [5]. However, the parameter-based optimization of the turning-burnishing process of aluminum 6061 has been not considered in the aforementioned works.

In this work, a multiple-response optimization of process parameters for the turning-burnishing process of aluminum 6061 has performed to improve the hardness and decrease the roughness. In practice, the variety of process inputs may lead to the contradictory results of the machining performances. Moreover, the selection of optimal factors for improvements of the roughness and hardness has a significant contribution to the applicability of the turning-burnishing process.

2. OPTIMIZATION ISSUE

The optimizing approach shown in Fig. 1 includes the following steps:

Step 1: The experimental runs are performed based on the Box-Behnken matrix [6].

Step 2: The predictive models of the SR and HN are then proposed regarding the inputs using the RSM method [7].

Step 3: The soundness of the correlations is assessed by ANOVA analysis.

Step 4: The optimal parameters are determined using the MOPSO.

Multi-Objective Particle swarm optimization (MOPSO) mimics the social behavior of animal groups such as flocks of birds or fish shoals. The process of finding an optimal design point is likened to the food-foraging activity of these organisms. Particle swarm optimization is a population-based search procedure where individuals (called particles) continuously change position (called state) within the search area. In other words, these particles 'fly' around in the design space looking for the best position. The best position encountered by a particle and its neighbors along with the current velocity and inertia are used to decide the next position of the particle [8].

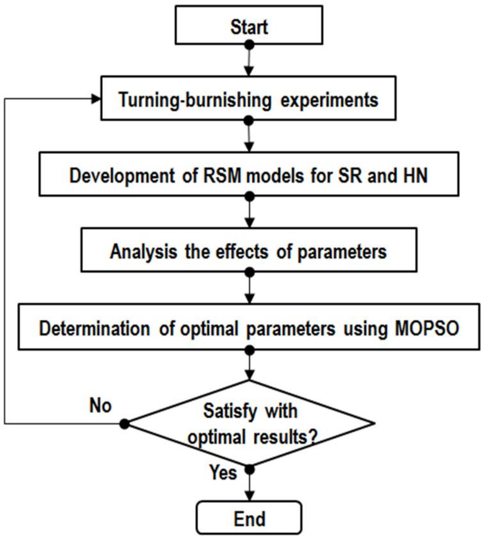


Figure 1. Optimization approach

Table 1. Process inputs

Symbol	Parameters	level-1	level 0	level +1
V	Cutting speed (m/min)	60	90	120
a	Depth of cut (mm)	0.50	1.00	1.50
f	Feed rate (mm/rev.)	0.056	0.112	0.168
D	Ball diameter (mm)	8	10	12

Table 2. Chemical compositions of Aluminium 6061

Si	Fe	Cu	Mn	Mg	Zn	Cr	Ni	Ti	Al
1.00	0.290	0.030	0.530	0.570	0.009	0.011	0.019	0.020	97.400

For the CATB process, three kinds of parameters are considered, including the turning factors (cutting speed, depth of cut, and feed rate), the burnishing factors (pressure and ball diameter), and general inputs (cutting speed and feed rate). In this paper, the burnishing pressure is kept as a constant. Process parameters, including the V, a, f, and D as well as three levels (-1; 0; +1) were shown in Table 1. The values of the process inputs are selected based on the recommendations of the manufacturers for the turning tool, pneumatic cylinder, and workpiece properties.

Consequently, the optimizing problem can be defined as follows:

Find X = [V, a, f, and D]

Minimize surface roughness and maximize the Vickers hardness.

Constraints: $60 \le V \le 90$ (m/min), $0.5 \le a \le 1.50$ (mm), $0.056 \le f \le 0.168$ (mm/rev.),

$8 \le D \le 12$ (mm).

3. EXPERIMENTS AND MEASUREMENTS

The experimental runs were performed on a turning machine, namely EMCOMAT-20D. The turning tool and burnishing tool are integrated in one device, which can be installed in the tool-turret of the lathe machine (Fig. 2). The finished surface is simultaneously treated by turning and burnishing processes. The hardness and roughness of the ball are 63 HRC and 0.05µm. The pneumatic cylinder is used to generate the burnishing pressure. The aluminum bar of 40mm diameter is used for all machining runs. The chemical compositions of aluminum 6061 are shown in table 2. The chosen workpiece is applied due to the wide applications in the automotive and aerospace components.

The roughness and Vickers hardness are measured by Mitutoyo SJ-301 (Fig. 2b) and HV-112 (Fig. 2c), respectively. The average values of the outputs are identified from 5 investigated points.

The average value of the surface roughness is calculated using Eq. 1:

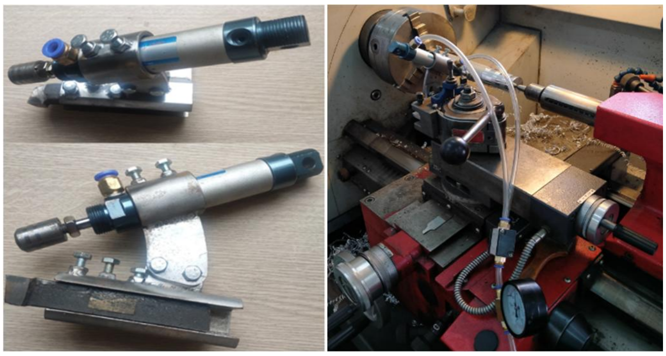
$$SR = \frac{R_{a1} + R_{a2} + R_{a3} + R_{a4} + R_{a5}}{5} \quad (1)$$

where R_{ai} is the arithmetic roughness at the i_{th} position.

The average value of the Vickers hardness is calculated using Eq. 2:

$$HN = \frac{HN_1 + HN_2 + HN_3 + HN_4 + HN_5}{5} \quad (2)$$

where HN_i is the Vickers hardness at the i_{th} position.



(a) Turning-burnishing tool (b) Experimental trials

(c) Measuring roughness (d) Measuring Vickers hardness

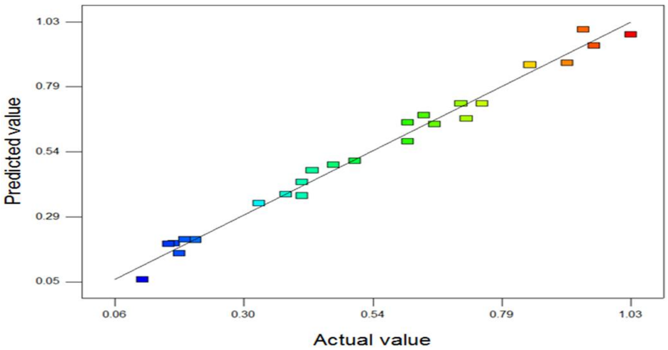
Figure 2. Experiments and measurements

4. RESULTS AND DISCUSSIONS

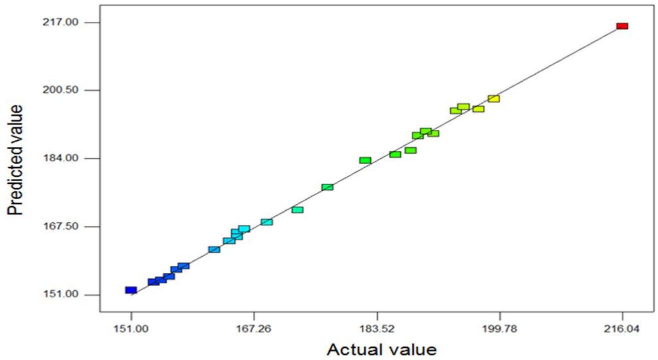
4.1. Development of RSM models

The experimental matrix and results of the CATB process are given in table 3.

The adequacy of the RSM models can be evaluated using the R^2-values and adjusted R^2. The R^2 value is defined as the ratio of explained variety to total variety. This indicator is used to explore the fitness of the model. The adjusted R^2 denotes the total variability of the model using the significant factors. The R^2-values of SR and HN are 0.9865 and 0.9892, respectively, indicating an acceptable fitness between predicted and actual values. The adjusted R^2-values of SR and HN are 0.9676 and 0.9686, respectively, proving the soundness of the proposed models. Moreover, Fig. 3 depicts that the measured data evenly distributes on the straight line and the unique behavior does not show.



(a) For the surface roughness



(b) For the Vickers hardness

Figure 3. Investigations of the fitness for the RSM models

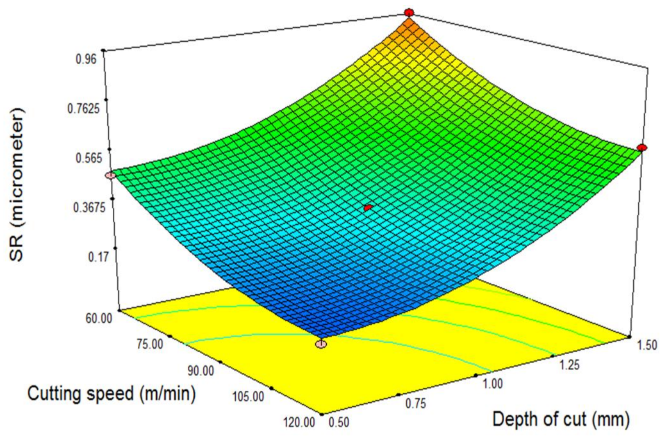
4.2. The effects of process parameters on the technical responses

The effects of processing factors on the roughness are shown in Fig. 4. When the cutting speed or spindle speed increases, higher ball pressure is obtained, which causes more plastic deformation of the burnished material; hence, the roughness is decreased. Moreover, as the cutting speed increases, the temperature of the machining region enhances, which leads to a decrease in the strength of the workpiece. The chip produced is easily detached from the workpiece and the turned material is more pressed, resulting in a reduction in surface roughness (Fig. 4a). When the depth of cut increases, the material removal volume increases, resulting in an increment in the cutting forces and instability. This may lead to more chattering in machine tool which eventually causes a coarse surface. Moreover, an increment in the removal volume causes an increased thickness of the chip. The material is difficult removed out from the workpiece and a coarse surface is produced.

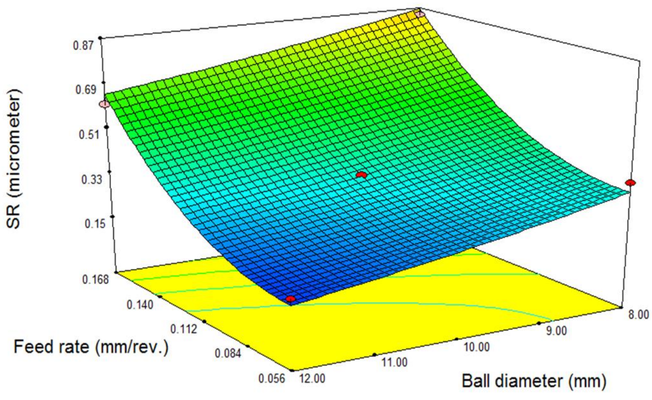
As the burnishing feed increases, higher burnishing forces and instability are produced; hence, a higher roughness is obtained. Moreover, a higher burnishing trace is obtained at a high value of the feed and roughness is increased (Fig. 4b). A higher burnishing pressure generated at an increased ball diameter causes a reduction in the peak and a smoother surface is obtained. When ball diameter increases, a high contact length between the turned surface and the burning ball is produced, leading to smaller peaks on the trail. The roughness is decreased with high diameter, resulting in a smoother surface.

Table 3. Experimental results

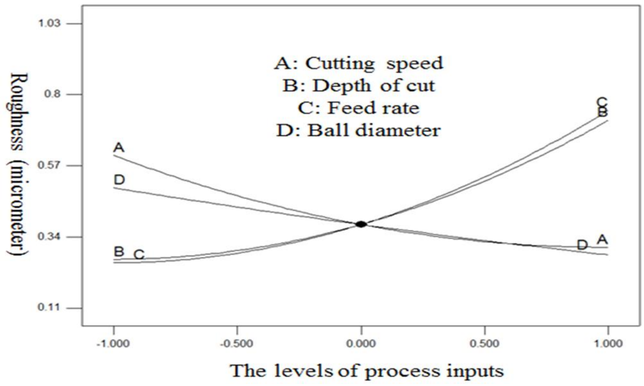
No.	V (m/min)	a (mm)	f (mm/rev.)	D (mm)	SR (μm)	HN (HV)
1	60	1.5	0.112	10	0.96	165
2	120	1.5	0.112	10	0.66	194
3	120	0.5	0.112	10	0.17	189
4	90	1.5	0.112	8	0.91	197
5	120	1.0	0.112	12	0.21	190
6	90	1.0	0.056	12	0.18	154
7	90	1.0	0.168	12	0.61	165
8	90	0.5	0.056	10	0.11	151
9	120	1.0	0.056	10	0.16	188
10	90	0.5	0.168	10	0.75	169
11	90	1.5	0.056	10	0.64	164
12	60	1.0	0.112	8	0.71	191
13	90	1.0	0.112	10	0.38	177
14	60	1.0	0.168	10	1.03	166
15	60	1.0	0.112	12	0.51	155
16	90	1.0	0.056	8	0.41	182
17	90	0.5	0.112	8	0.33	186
18	60	1.0	0.056	10	0.43	156
19	90	1.5	0.112	12	0.61	162
20	60	0.5	0.112	10	0.47	157
21	90	0.5	0.112	12	0.19	158
22	90	1.5	0.168	10	0.94	173
23	120	1.0	0.168	10	0.72	199
24	120	1.0	0.112	8	0.41	216
25	90	1.0	0.168	8	0.84	195



(a) Roughness versus speed and depth of cut



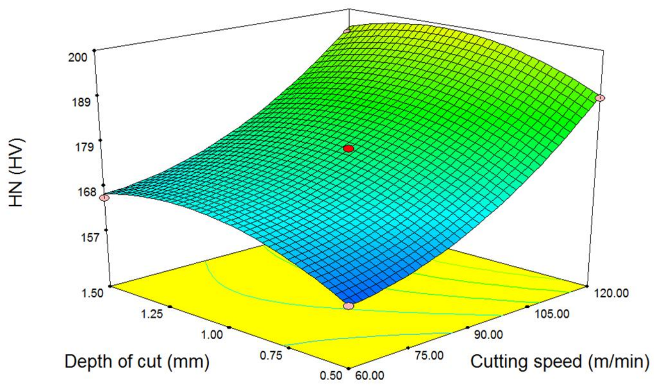
(b) Roughness versus feed and ball diameter



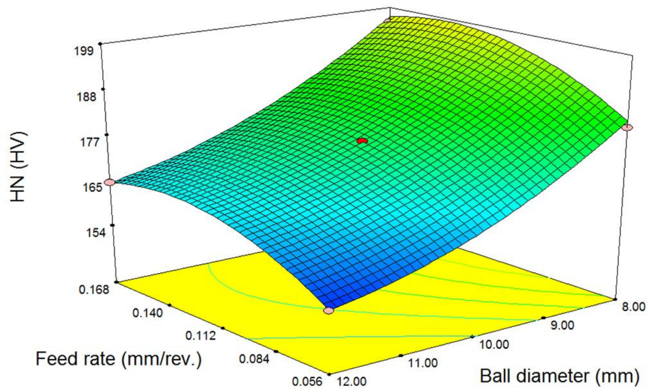
(c) Single impact of the inputs

Figure 4. The effects of the process inputs on the roughness

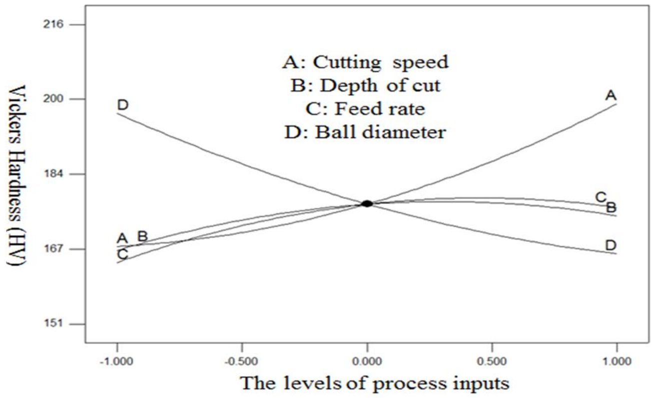
The effects of processing factors on the Vicker hardness are shown in Fig. 5. When the cutting speed increases, larger plastic deformation is obtained, leading to work-hardening behavior; hence, the hardness enhances (Fig. 5b). Similarly, an increased depth of cut or feed causes a larger degree of work-hardening, resulting in an improved hardness. However, a further increment in the depth of cut or feed leads to high material volume is obtained and the machining heat enhances. The increased amount of heat would have relieved the residual stress consequently causing hardness to drop with may lead to a slight reduction of the hardness. At a lowe value of the ball diameter, a higher burnishing pressure is generated, which causes more pressed material and enhanced hardness (Fig. 5b).



(a) Hardness versus speed and depth of cut



(b) Hardness versus feed and ball diameter



(c) Single impact of the inputs

Figure 5. The effects of the process inputs on the Vickers hardness

The ANOVA results for the roughness model are shown in table 4. The feed is found to the most effective factor with a contribution of 38.99%, followed by the depth of cut (32.44%), cutting speed (14.10%), and ball diameter (7.52%), respectively. The contribution of the f^2, a^2, and V^2 are 2.26%, 1.91%, and 0.85%, respectively.

Table 4. ANOVA results for surface roughness model

Source	Sum of squares	Mean square	F-value	p-value	Remark	Contribution (%)
Model	1.8651	0.1332	52.2430	< 0.0001	Significant	
V	0.2640	0.2640	103.5425	< 0.0001	Significant	14.10
a	0.6075	0.6075	238.2353	< 0.0001	Significant	32.44
f	0.7301	0.7301	286.3268	< 0.0001	Significant	38.99
D	0.1408	0.1408	55.2288	< 0.0001	Significant	7.52
Va	0.0000	0.0000	0.0000	1.0000	Significant	0.00
Vf	0.0004	0.0004	0.1569	0.7004	Significant	0.02
VD	0.0000	0.0000	0.0000	1.0000	Significant	0.00
af	0.0289	0.0289	11.3333	0.0072	Significant	1.54
aD	0.0064	0.0064	2.5098	0.1442	In significant	0.34
fD	0.0000	0.0000	0.0000	1.0000	In significant	0.00
V2	0.0159	0.0159	6.2284	0.0317	Significant	0.85
a2	0.0357	0.0357	14.0138	0.0038	Significant	1.91
f2	0.0424	0.0424	16.6159	0.0022	Significant	2.26
D2	0.0003	0.0003	0.1107	0.7462	In significant	0.02
Residual	0.0255	0.0026				
Total	1.8906					

The ANOVA results for the Vickers hardness model are shown in table 5. As a result, the percentage contributions of V, D, f, and a are 39.62%, 38.35%, 5.94%, and 2.32%, respectively. The f^2 account for the highest percentage contribution with respect to quadratic terms (1.72%); this followed by V^2 (1.56%), f^2 (1.72%), and D^2 (0.77%), respectively.

Table 5. ANOVA results for Vickers hardness model

Source	Sum of squares	Mean square	F-value	p-value	Remark	Contribution (%)
Model	7419.94	534.24	247.52	< 0.0001	Significant	
V	2883.00	2883.00	1335.75	< 0.0001	Significant	39.62
a	168.75	168.75	78.19	< 0.0001	Significant	2.32
f	432.00	432.00	200.15	< 0.0001	Significant	5.94
D	2790.75	2790.75	1293.01	< 0.0001	Significant	38.35
Va	2.25	2.25	1.04	0.3313	In significant	0.03
Vf	0.25	0.25	0.12	0.7406	In significant	0.00
VD	25.00	25.00	11.58	0.0067	Significant	0.34
af	20.25	20.25	9.38	0.0120	Significant	0.28
aD	12.25	12.25	5.68	0.0385	Significant	0.17
fD	1.00	1.00	0.46	0.5115	In significant	0.01
V2	113.25	113.25	52.47	< 0.0001	Significant	1.56
a2	111.77	111.77	51.79	< 0.0001	Significant	1.54
f2	125.49	125.49	58.14	< 0.0001	Significant	1.72
D2	56.12	56.12	26.00	0.0005	Significant	0.77
Residual	81.02	2.16				
Total	7500.96					

5. OPTIMIZATION RESULTS

The predictive models of roughness and Vickers hardness are expressed as follows:

$$\begin{aligned} SR &= 1.48833 - 0.019278V + 0.29000a \\ &- 0.77381f - 0.064167D - 3.03571af \\ &+ 0.0000833V^2 + 0.45000a^2 + 39.06250f^2 \end{aligned} \quad (3)$$

$$\begin{aligned} HN &= 306.87500 - 1.13333V + 88.83333a \\ &+ 694.94048f - 31.41667D + 0.041667VD \\ &- 80.35714af - 1.75000aD + 0.007037V^2 \\ &- 25.16667a^2 - 2125.85034f^2 + 1.11458D^2 \end{aligned} \quad (4)$$

The mathematical models of the responses were used to select the optimal values of the inputs with the support of the MOPSO. The values of the maximum iterations, number of particles, global increment, and particle increment are 50, 10, 1.2, and 1.8, respectively. The Pareto front was exhibited in Fig. 6, in which the pink points are feasible solutions. The optimization results are listed in Table 6. As a result, the roughness is decreased around 42.10% and the Vickers hardness is approximately increased 17.51%.

Table 6. Optimization results

Method	Optimization parameters				Responses	
	V (m/min)	a (mm)	f (mm/rev.)	D (mm)	SR (µm)	HN (HV)
MOPSO	120	0.70	0.09	8	0.22	208
Common values used	90	1.00	0.112	10	0.38	177
Improvement (%)					- 42.10	17.51

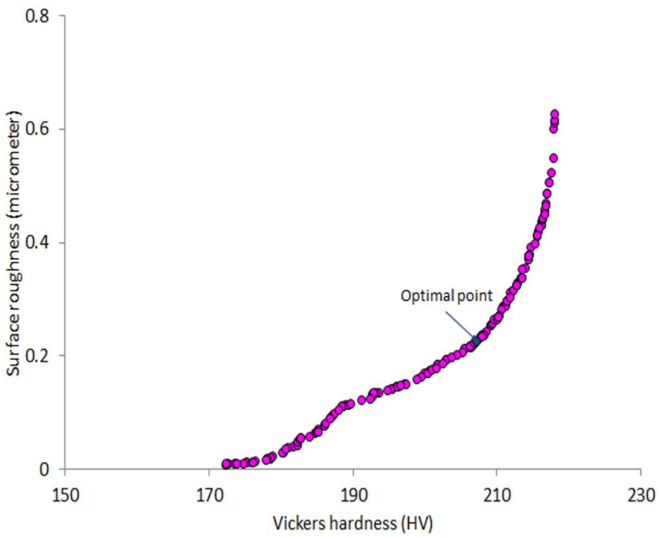


Figure 6. Pareto fonts generated by MOPSO

6. CONCLUSION

This work addressed a multi-objective optimization of the CATB process of the aluminum 6061 to reduce the roughness and enhance the Vicker hardness. The predictive correlations of the machining responses were proposed using the RSM approach. The MOPSO was adopted to select the optimal inputs. The following conclusions are listed as:

1. The process inputs have contradictory impacts on the machining outputs. The highest levels of the speed and ball diameter could be used to minimize the roughness. The minimal values of the depth and feed are recommended to use for minimizing roughness. Higher values of the speed, depth, and feed could be applied to achieve maximizing hardness. The lowest diameter is used to improve the Vickers hardness.

2. The predictive formulas of the roughness and Vickers hardness could be used to predict the response values of the machining performances in the CATB process of the aluminum 6061.

3. The optimal values of the speed, depth, feed, and diameter are 120 m/min, 0.7 mm, 0.09mm/rev., and 8mm, respectively. The improvements in the roughness and Vickers hardness are 42.10% and 17.51%, as compared to the initial values.

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