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Effect of Roller Burnishing on the Surface Roughness and Hardness of 6061-T6 Aluminum Alloy Using ANOVA

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***Abstract*—Roller burnishing is an important finishing operation that is widely used to improve metals' tribological properties such as surface finish and hardness. Burnishing speed and depth of interference are key process conditions when it comes to maximizing the benefits gained from this operation. This study aims to optimize these two parameters in the case of roller burnishing of 6061-T6 aluminum rods in terms of their impact on surface roughness and hardness. To achieve results that are sound statistically, data collected from carefully designed factorial experiments were analyzed using the analysis of variance (ANOVA) approach. Mintab® was the statistical software of choice used to conduct actual computations and analysis of the data. Results showed that both surface roughness and hardness were improved. Surface roughness was reduced on average by 87.6% while hardness was increased on average by 14.5%.**

***Index Terms*—ANOVA, roller burnishing, surface roughness, hardness**

I. INTRODUCTION

Burnishing is a low cost process that applies a cylindrical or ball roller against a metal workpiece to smooth or level its surface irregularities. Burnishing leads to residual stresses up to a depth of 0.6 mm beneath the surface [1], which tend to improve surface properties such as microhardness [2], wear resistance [3], fatigue strength [4] and surface finish [5]–[8]. Due to these gains, burnishing is widely used in important applications in the aerospace, nuclear, and medical industries [9]. Despite the apparent simplicity of the process, it has received a wide interest in the literature trying to understand its mechanics [10], evaluate its impact on surface characteristics [11], or optimize process conditions [7].

Analytical models that take into consideration the geometries of the burnishing tool and the workpiece, and the microscopic topography of the machined surface have been proposed in the literature [12], [13]. The model in [12] indicated that the decrease of surface roughness is proportional to burnishing force to the 2/3 power in roller burnishing and to the ½ power in ball burnishing. A 3D finite element model for the ball burnishing operation was proposed in [14]. In their model, the mechanism of formation and flow of the ridge seemed to have a pivotal role in shaping surface characteristics by burnishing.

The effect of contact width and orientation in roller burnishing on surface quality and tribological behaviour of Aluminium 6061 was investigated by [15]. Based on their findings, the smaller the rollers were, the lower the friction coefficient was produced. This was noticed under dry conditions and when sliding was in the direction parallel to burnishing orientation. Reference [16] studied the effect of the burnishing force and the number of passes in the case of ball- and roller-burnishing tools, on the surface roughness and surface hardness of commercially available aluminum and brass. His results showed that improvements in the surface roughness and hardness were achieved by the application of both ball and roller burnishing tools. Both ball and roller burnishing of Rb40 steel was studied in terms of associated roughness, hardness and wear resistance [11]. It was found that roller burnishing provides the best roughness results, but in terms of hardness and wear resistance, ball burnishing was better.

In the search for optimal conditions in roller burnishing of 6061-T6 aluminum alloy, various burnishing speeds, burnishing depths of penetration and number of passes were considered in the study by [17]. They showed that low speeds and high penetration depths produce much smoother surfaces, whereas a combination of high speed with high penetration depth leads to rougher surfaces. The best surface finish was achieved at number of passes of 3 and 4. An optimization approach based on desirability functions together with response surface methodology to optimize ball burnishing process of 7178 aluminium alloy was introduced by [18]. The burnishing force, number of passes, feed rate and burnishing speed were the model variables under investigation. The results indicated that burnishing force and number of passes were the significant factors on the surface roughness. The effect of roller burnishing on high cycle fatigue properties of the hot-rolled Mg–12Gd–3Y magnesium alloy was examined in [4]. In the as-rolled and aging heat-treated specimens, their results showed an increase from 150 and 155 MPa, to 225 and 210 MPa, respectively, in fatigue strength.

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More recent studies aim to optimize the process conditions in burnishing by employing advanced techniques such as response surface methodology (RSM) [18] and Taguchi method [7]. In this study, the aim is to apply ANOVA technique to assess the significance of the burnishing effect and some of its process conditions on surface roughness and hardness of the widely used 6061-T6 aluminum alloy. This study is motivated by the large variability in the results presented in related research studies [12]–[18]. Accordingly, the use of a powerful statistical technique such as ANOVA will be highly valuable in reaching sound conclusions with acceptable levels of confidence.

II. DESCRIPTION OF EXPERIMENTS

Specimens used in this study were 23 mm circular rods made of 6061-T6 aluminum alloy. The rods were then cut into an approximate length of 100 mm and turned on a lathe machine to a diameter of 22 mm. Cutting speed during turning was 550 rpm, feed rate was 0.5 mm/rev, and depth of cut was 0.1 mm. After turning, rods were burnished using a 13 mm diameter steel roller of 5 mm width, as shown in Fig. 1. A water-based lubricant was also used in these experiments to prevent the formation of built-up material on the burnishing roller. Different levels of burnishing speed and depth of interference were tried and studied in the burnishing experiments. Four levels of burnishing speed were used: 0.123, 0.1435, 0.164 and 0.205 mm/min. Also, four levels of depth of interference were used: 0.02, 0.04, 0.06 and 0.08 mm. At every combination of levels of burnishing speed and depth of interference, four replicates of average surface roughness measurements and four replicates of hardness measurements were taken. In each replicate, measurements were taken before and after. Then the absolute difference or change in the two readings was calculated.

Surface roughness was measured using a stylus-type surface profilometer. Hardness was measured on a universal hardness tester according to ASTM E18 standard. An E-scale, with 1/8 inch steel ball, 90 kgf of major load, and 10 kgf minor load was used. Four hardness readings at 90o intervals were collected over the surface of the mid cross section of the specimen. The average value was then registered as one hardness reading.

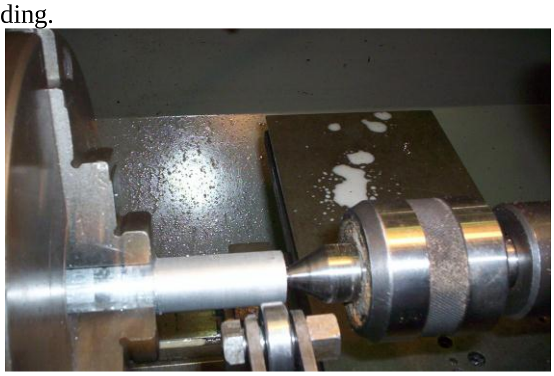


Figure 1. Setup of burnishing experiments as conducted on a lathe machine

III. EXPERIMENTAL RESULTS

Results of average surface roughness and hardness measurements are summarized in Tables I and II, respectively. As mentioned above, these tables show readings of average surface roughness and hardness before and after roller burnishing, as well as the calculated absolute change between the two readings. It should be noted that all burnishing experiments and associated measurements were conducted in a random order to minimize the effects of time-related nuisance factors.

Considering average surface roughness readings of Table I at before and after conditions, it can be shown that the average surface roughness is reduced on average by 87.6% following burnishing. Similarly, it can be shown that surface hardness is increased on average by 14.5% following burnishing. These two results suggest that burnishing has a significant and positive effect on both surface roughness and hardness of the 6061-T6 aluminum alloy.

IV. ANALYSIS OF VARIANCE AND RESULTS DISCUSSION

Data of Tables I and II for the average surface roughness and hardness measurements can be analyzed using the ANOVA statistical technique. This technique is based on partitioning the variability present in the data guided by an assumed, but suitable, statistical model. Considering the absolute change between the two 'before and after' readings as the response variable, the following linear statistical model is used to describe the data for both average surface roughness and hardness measurements:

$$Y_{ijk} = \mu + S_i + D_j + (SD)_{ij} + \in_{ijk} \ , \quad \begin{cases} i = 1,2,3,4 \\ j = 1,2,3,4 \\ k = 1,2,3,4 \end{cases} \tag{1}$$

where Y_{ijk} is a random variable denoting the $(ijk)^{th}$ average surface roughness or hardness reading, μ is the overall mean, S_i is the effect of the i^{th} level of the burnishing speed, D_j is the effect of the j^{th} level of the depth of interference, $(SD)_{ij}$ is the effect of the interaction between the burnishing speed and depth of interference, and ϵ_{ijk} is a random error term, which is assumed normally distributed with zero mean and constant variance [10]. Since the errors are assumed normally distributed, and the results by the ANOVA technique are somewhat sensitive to this assumption, such assumption needs to be tested first. A histogram plot of the residuals can be used for this reason as one of the approaches used. The residuals histogram is established for the case of average surface roughness data, as shown in Fig. 2. It can be noted from this figure that the data are adequately described by the bell-shaped normal distribution, as needed by the ANOVA technique.

TABLE I. EXPERIMENTAL RESULTS FOR ROUGHNESS VERSUS BURNISHING SPEED AND DEPTH OF INTERFERENCE

Roughness (µm)		Burnishing speed (mm/min)											
		0.123			0.1435			0.164			0.205		
		Before	After	Change	Before	After	Change	Before	After	Change	Before	After	Change
Depth of interference (mm)	0.02	3.58	0.46	3.12	4.24	0.97	3.27	3.14	0.52	2.62	4.72	0.49	4.23
		2.85	0.3	2.55	2.86	0.46	2.4	3.42	0.2	3.22	4.68	0.44	4.24
		2.52	0.21	2.31	3.61	0.66	2.95	4.46	0.45	4.01	3.97	0.59	3.38
		2.63	0.36	2.27	2.8	0.23	2.57	3.71	0.3	3.41	3.27	0.66	2.61
	0.04	3.5	0.57	2.93	2.63	0.41	2.22	3.02	0.26	2.76	4.28	0.41	3.87
		4.24	0.32	3.92	3.16	0.26	2.9	3.26	0.58	2.68	3.3	0.2	3.1
		3.81	0.22	3.59	2.81	0.29	2.52	3.24	0.18	3.06	2.14	0.27	1.87
		3.48	0.84	2.64	3.29	0.33	2.96	2.58	0.34	2.24	1.92	0.28	1.64
	0.06	4.56	0.3	4.26	3.24	0.33	2.91	3.7	0.3	3.4	3.19	0.37	2.82
		4.59	0.67	3.92	2.59	0.37	2.22	2.99	0.71	2.28	3.07	0.44	2.63
		2.52	0.27	2.25	3.08	0.35	2.73	2.61	0.32	2.29	5.15	0.75	4.4
		2.76	0.31	2.45	2.62	0.21	2.41	3.29	0.27	3.02	3.18	0.21	2.97
	0.08	2.84	0.48	2.36	3.08	0.55	2.53	2.66	0.25	2.41	2.21	0.57	1.64
		3.11	0.46	2.65	3.72	0.6	3.12	3.49	0.44	3.05	3.3	0.57	2.73
		2.73	0.37	2.36	3.06	0.4	2.66	2.72	0.34	2.38	3.29	0.35	2.94
		3.45	0.26	3.19	3.05	0.27	2.78	3.15	0.26	2.89	2.42	0.43	1.99

TABLE II. EXPERIMENTAL RESULTS FOR HARDNESS VERSUS BURNISHING SPEED AND DEPTH OF INTERFERENCE

Hardness (HRE)		Burnishing speed (mm/min)											
		0.123			0.1435			0.164			0.205		
		Before	After	Change	Before	After	Change	Before	After	Change	Before	After	Change
Depth of interference (mm)	0.02	63	70	7	61	68	7	63	68	5	63	66	3
		59	67	8	66	72	6	64	68	4	67	71	4
		67	74	7	63	69	6	65	70	5	63	66	3
		65	74	9	67	73	6	59	65	6	62	65	3
	0.04	64	75	11	60	67	7	55	60	5	66	70	4
		61	70	9	64	70	6	68	73	5	69	74	5
		68	78	10	57	66	9	62	69	7	63	69	6
		59	69	10	66	73	7	64	70	6	61	66	5
	0.06	63	78	15	65	78	13	63	74	11	70	78	8
		66	80	14	63	74	11	67	77	10	61	70	9
		65	78	13	59	68	9	63	72	9	67	74	7
		65	78	13	71	84	13	63	73	10	65	73	8
	0.08	68	84	16	58	73	15	56	68	12	58	69	11
		61	78	17	64	76	12	59	72	13	65	75	10
		57	73	16	67	81	14	64	76	12	67	76	9
		63	78	15	62	75	13	63	77	14	61	73	12

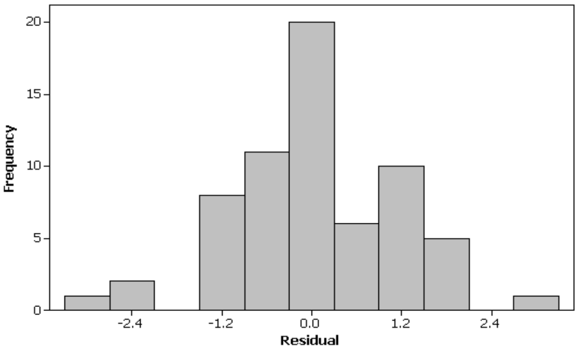
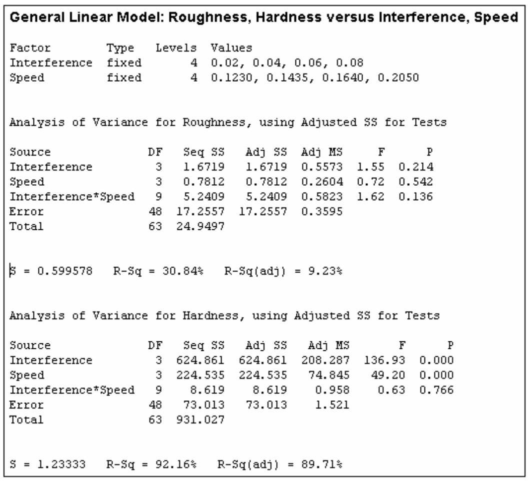


Figure 2. Histogram of residuals showing a normal distribution for roughness data

Applying ANOVA to the average surface roughness and hardness data using Minitab® software, the output shown in Fig. 3 is obtained. It can be seen in this figure that the R2 (reads R-Sq) value is 30.84% for average surface roughness and 92.16% for hardness. The R2 value represents the percentage of data variability accounted for by the model [19], [20], as written in Eq. (1). The low R2 value for average surface roughness can be explained by the effect of other nuisance factors, e.g. specimen-to-specimen variations in micro-features. The high R2 value for hardness indicates that the linear statistical model adequately describes the variability in the data.

Fig. 3 also shows the p-values, reads P, for the burnishing speed, depth of interference, and the interaction between the burnishing speed and depth of interference factors. Assuming a 95% level of statistical significance, i.e. $\alpha = 0.05$, then any p-value $< \alpha = 0.05$ would indicate that the effect of the corresponding factor is significant. Accordingly, it can be concluded that the effects of burnishing speed, depth of interference, and the interaction between the burnishing speed and depth of interference factors on average surface roughness are not significant. In addition, it can be concluded that the effects of burnishing speed and depth of interference factors on surface hardness are significant, where as the effect of interaction between the burnishing speed and depth of interference factors on surface hardness is not significant.



General Linear Model: Roughness, Hardness versus Interference, Speed

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Factor        Type   Levels  Values
Interference  fixed       4  0.02, 0.04, 0.06, 0.08
Speed         fixed       4  0.1230, 0.1435, 0.1640, 0.2050


Analysis of Variance for Roughness, using Adjusted SS for Tests

Source             DF   Seq SS   Adj SS  Adj MS     F      P
Interference        3   1.6719   1.6719  0.5573  1.55  0.214
Speed               3   0.7812   0.7812  0.2604  0.72  0.542
Interference*Speed  9   5.2409   5.2409  0.5823  1.62  0.136
Error              48  17.2557  17.2557  0.3595
Total              63  24.9497


S = 0.599578   R-Sq = 30.84%   R-Sq(adj) = 9.23%


Analysis of Variance for Hardness, using Adjusted SS for Tests

Source             DF   Seq SS   Adj SS   Adj MS       F      P
Interference        3  624.861  624.861  208.287  136.93  0.000
Speed               3  224.535  224.535   74.845   49.20  0.000
Interference*Speed  9    8.619    8.619    0.958    0.63  0.766
Error              48   73.013   73.013    1.521
Total              63  931.027


S = 1.23333   R-Sq = 92.16%   R-Sq(adj) = 89.71%
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Figure 3. ANOVA results generated using Minitab for the roughness and hardness data

The ANOVA technique is sometimes supplemented by the main effect plots of the individual factors, as another way of confirmation. The main effect plot for a factor is a graphical representation of the average responses for the different levels of that factor. Thus, the main effect plots for the depth of interference and burnishing speed are presented in the case of average surface roughness and hardness data, respectively, in Fig. 4 and Fig. 5. It can be seen from Fig. 4 that a constant mean response is evident in the main effect plot for the depth of interference. This indicates that the effect of the depth of interference on the average surface roughness is not significant, which agrees with the conclusion that was reached based on the ANOVA technique. The main effect plot for the burnishing speed in Fig. 4 shows a weak increasing trend in the mean response, which varies between 2.9 and 3.1 μm only. Therefore, as was concluded based on the ANOVA technique, the effect of the burnishing speed on the average surface roughness seem to be negligible.

It can be seen in Fig. 5 that as the depth of interference increases the mean hardness increases. This figure also shows that as the burnishing speed increases the mean hardness decreases. This indicates that the effects of the depth of interference and burnishing speed on the surface hardness are significant, in agreement with our previous conclusion that was based on the ANOVA technique. It can be shown also from the data in Table 2 that maximum surface hardness is achieved when the depth of interference is set at 0.08 mm and the burnishing speed is set at 0.123 mm/min. This corresponds to an average surface hardness of 78.25 HRE.

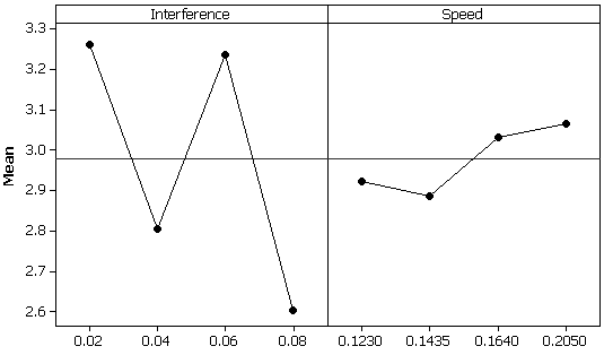

Figure 4. Main effect plots for depth of interference and burnishing speed in the case of roughness data

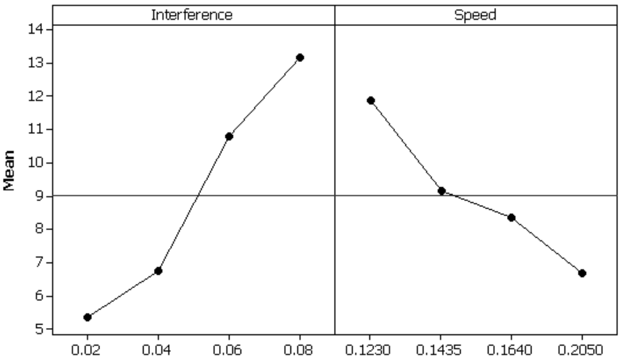

Figure 5. Main effect plots for depth of interference and burnishing speed in the case of hardness data

V. CONCLUSIONS

In this work, the effect of roller burnishing and relevant process conditions such as burnishing speed and depth of interference were examined in the case of 6061-T6 aluminum alloy. The following conclusions can be made in light of the experimental results and analysis using ANOVA technique presented in this study:

1. Roller burnishing leads to significant improvements in surface roughness and hardness of the 6061-T6 aluminum alloy. This is evident as the average surface roughness was reduced on average by 87.6% following burnishing, surface hardness was increased on average by 14.5% after burnishing.
2. Variations in burnishing speed and depth of interference have negligible effects on average surface roughness.
3. Burnishing speed and depth of interference have independent and significant effects on surface hardness.
4. Maximum surface hardness was achieved when the depth of interference was set at 0.08 mm and the burnishing speed was set at 0.123 mm/min. This corresponds to an average surface hardness of 78.25 HRE.

REFERENCES

[1] A. A. García-granada, G. Gomez-gras, R. Jerez-mesa, A. Travieso-rodriguez, and G. Reyes, “Ball-burnishing effect on deep residual stress on AISI 1038 and AA2017-T4,” Mater. Manuf. Process., vol. 32, no. 11, pp. 1279–1289, 2017.

[2] X. L. Yuan, Y. W. Sun, L. S. Gao, and S. L. Jiang, “Effect of roller burnishing process parameters on the surface roughness and microhardness for TA2 alloy,” *Int. J. Adv. Manuf. Technol*., vol. 85, pp. 1373–1383, 2016.

[3] G. Devaraya, R. Shetty, S. Srinivas, and V. Neelakanth, “Wear resistance enhancement of titanium alloy (Ti – 6Al – 4V) by ball burnishing process,” *Integr. Med. Res*., vol. 6, no. 1, pp. 13–32, 2016.

[4] P. Zhang, J. Lindemann, W. J. Ding, and C. Leyens, “Effect of roller burnishing on fatigue properties of the hot-rolled Mg–12Gd–3Y magnesium alloy,” *Mater. Chem. Phys*., vol. 124, no. 1, pp. 835–840, 2010.

[5] H. Amdouni, H. Bouzaiene, A. Montagne, and A. Van Gorp, “Experimental study of a six new ball-burnishing strategies effects on the Al-alloy flat surfaces integrity enhancement,” *Int J Adv Manuf Technol*, vol. 90, pp. 2271–2282, 2017.

[6] V. Kurkute and S. T. Chavan, “Modeling and optimization of surface roughness and microhardness for roller burnishing process using response surface methodology for Aluminum 63400 alloy,” in *Procedia Manufacturing*, 2018, vol. 20, pp. 542–547.

[7] S. R. Thorat and A. G. Thakur, “Optimization of Burnishing Parameters by Taguchi Based GRA Method of AA 6061 Aluminum Alloy,” *Mater. Today Proc*., vol. 5, no. 2, pp. 7394–7403, 2018.

[8] V. Franzen, M. Trompeter, A. Brosius, and A. E. Tekkaya, “Finishing of thermally sprayed tool coatings for sheet metal forming operations by roller burnishing,” *Int J Mater Form*, vol. 3, no. 1, pp. 147–150, 2010.

[9] T. Zhang, N. Bugtai, and I. D. Marinescu, “Burnishing of aerospace alloy: A theoretical – experimental approach,” *J. Manuf. Syst*., vol. 37, pp. 472–478, 2015.

[10] P. Balland, L. Tabourot, F. Degre, and V. Moreau, “Mechanics of the burnishing process,” *Precis. Eng*., vol. 37, no. 1, pp. 129–134, 2013.

[11] H. Hamadache, L. Laouar, N. E. Zeghib, and K. Chaoui, “Characteristics of Rb40 steel superficial layer under ball and roller burnishing,” *J. Mater. Process. Technol*., vol. 180, no. 1, pp. 130–136, 2006.

[12] F. L. Li, W. Xia, Z. Y. Zhou, J. Zhao, and Z. Q. Tang, “Analytical prediction and experimental verification of surface roughness during the burnishing process,” *Int. J. Mach. Tools Manuf*., vol. 62, pp. 67–75, 2012.

[13] L. Hiegemann, C. Weddeling, N. Ben Khalifa, and A. E. Tekkaya, “Analytical prediction of roughness after ball burnishing of thermally coated surfaces,” *Procedia Eng*., vol. 81, no. October, pp. 1921–1926, 2014.

[14] P. Balland, L. Tabourot, F. Degre, and V. Moreau, “An investigation of the mechanics of roller burnishing through finite element simulation and experiments,” *Int. J. Mach. Tools Manuf*., vol. 65, pp. 29–36, 2013.

[15] N. s. M. El-Tayeb, K. O. Low, and P. V. Brevern, “Influence of roller burnishing contact width and burnishing orientation on surface quality and tribological behaviour of Aluminium 6061,” *J. Mater. Process. Technol*., vol. 186, pp. 272–278, May 2007.

[16] A. M. Hassan, “The effects of ball- and roller-burnishing on the surface roughness and hardness of some non-ferrous metals,” *J. Mater. Process. Technol*., vol. 72, no. 3, pp. 385–391, 1997.

[17] M. M. El-Khabeery and M. H. El-Axir, “Experimental techniques for studying the effects of milling roller-burnishing parameters on surface integrity,” *Int. J. Mach. Tools Manuf*., vol. 41, no. 12, pp. 1705–1719, 2001.

[18] A. Sagbas, “Analysis and optimization of surface roughness in the ball burnishing process using response surface methodology and desirabilty function,” *Adv. Eng. Softw*., vol. 42, no. 11, pp. 992–998, 2011.

[19] O. Bataineh and D. Dalalah, “Strategy for optimising cutting parameters in the dry turning of 6061-T6 aluminium alloy based on design of experiments and the generalised pattern search algorithm,” *Int. J. Mach. Mach. Mater*., vol. 7, no. 1/2, pp. 39–57, 2010.

[20] A. M. Hassan, O. M. Bataineh, and K. M. Abed, “The effect of time and temperature on the precipitation behavior and hardness of Al-4 wt%Cu alloy using design of experiments,” *J. Mater. Process. Technol*., vol. 204, no. 1–3, pp. 343–349, 2008.

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