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Experimental techniques to investigate the effects of roller burnishing on the surface roughness and hardness of high strength thermoplastic-Polyoxymethylene

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ABSTRACT

Background: Burnishing is used progressively more as a finishing operation that offers added advantages, such as increased hardness, fatigue strength and wear resistance. **Objective:** This study aim to investigate the effects of roller burnishing process on the polymeric materials. **Results:** Measured results were analyzed for surface roughness R_a and surface hardness H_v were conducted using signal-to-noise (S/N) response analysis and analysis of variance (Pareto ANOVA) to determine which process parameters are statistically significant**. Conclusion:** The burnishing process leads to a smoother surface on which significant effects of process parameters that include burnishing depth, speed, feed, roller width and lubrication.

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INTRODUCTION

Polymers are recently utilized in many tribological applications. They perform better than metals in terms of bending, misalignment and shock loading (Hooke, C., *et al*., 1996). The polymers addressed in this article are polyoxymethylene (POM). These materials are type of engineering thermoplastics with good performance, higher abrasion resistance and excellent fatigue life. Besides, POM is recognized for having low wear and friction characteristics, which are required in some engineering applications such as bearings, couplings, cams and gears. Roller burnishing is a machining process that influences certain material properties. This process was traditionally used on non ferrous materials (Hassan, A.M. and A.S. Al-Bsharat, 1996; Hassan, A.M. and A.M. Maqableh, 2000; Thamizhmanii, S., *et al*., 2007; Dweiri, F., *et al*., 2003) and gradually expanded to polymers (Low, K. and K.J. Wong, 2011; Low, K., *et al*., 2009) and other materials (Thamizhmnaii, S., *et al*., 2008). The burnishing principle entails applying a polished ball or roller with pressure into the workpiece surface and getting feed motion into the same direction (Tian, Y. and Y.C. Shin, 2007). A schematic diagram of a ball and roller burnishing process is shown in Fig. 1.Engineering components are usually left with various, irregularly shaped machining marks. Therefore, when the ball or roller tool applies pressure the asperities get plastically compressed into the valleys, resulting in uniform and smooth surface finish (Hassan, A.M., 1997; Ovali, İ. and A. Akkurt, 2011). There are a number of important parameters affecting the burnishing process, e.g. burnishing force, burnishing feed rate, burnishing speed, number of tool pass, ball diameter and roller width. These parameters should be selected carefully to ensure optimal outcome (El-Axir, M. and M. El-Khabeery, 2003; Luca, L., *et al*., 2005; Rao, D.S., *et al*., 2008). In early 1975, Rajasekariah and Vaidyanathan pointed out that burnishing has been known for a long time but has encountered a few problems, for instance a lack of understanding controlling parameters (Rajasekariah, R. and S. Vaidyanathan, 1975). Besides good surface finish produced by burnishing (Travieso-Rodríguez, J.A., *et al*., 2011; López de Lacalle, L.N., *et al*., 2011), this technique can induce compressive residual stress that increases tensile strength and surface hardness (Fattough, M. and M. El-Khabeery, 1989; Rao, D.S., *et al*., 2007; Zamashchikov, Y.I., 2006). According to the current study, the utmost residual stress appeared on the surface and gradually decreased at greater depths.

Following a literature review, this study was conducted to anticipate burnishing depth, burnishing speed, burnishing feed rate, roller width and lubrication as control variables to investigate the effects of the roller burnishing parameters to enhance polyoxymethylene surface quality and hardness. The conventional method of attaining these is via "trial and error," an approach that is very time consuming

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due to the large number of experiments required. Hence, a reliable systematic approach for machining parameter optimization is necessary.The experimental process applied is the Taguchi optimization method, which was developed by Dr. Genichi Taguchi. It is a set of methodologies in which the inherent variability of materials and manufacturing processes are taken into account in the design stage (Ab Karim, M.S., *et al*., 2011; Zhang, J.Z., J.C. Chen and E.D. Kirby, 2007). In Taguchi optimization, multiple factors can be considered at once/at the same time. Moreover, nominal design points that are insensitive to variations in production and user environments are sought out to improve manufacturing yield and product performance reliability. By using Taguchi optimization techniques, industries are able to greatly reduce product development cycle time for design and production, therefore economizing and increasing profit (Ghani, J., I. Choudhury, and H. Hassan, 2004; Hamdan, A., A.A. Sarhan and M. Hamdi, 2012).In the present study, the Taguchi method is implemented to the burnishing parameters to achieve the lowest surface roughness and highest surface hardness in burnishing polymer materials. For this purpose to be achieved, the relationships between parameters (i.e., burnishing depth, burnishing speed, burnishing feed rate, roller width and type of lubrication) and response factors (i.e., surface roughness and surface hardness) are investigated to distinguish the significant factors affecting machined surface profile. The Taguchi optimization steps comprise selecting the orthogonal array (OA) according to the number of controllable factors, running experiments based on the OA, analyzing data, identifying the optimum parameters and conducting confirmation runs with the optimal levels of all parameters (Ab Karim, M.S., *et al*., 2011; Hsiao, Y., Y. Tarng, and W. Huang, 2007; Sayuti, M., *et al*., 2012).

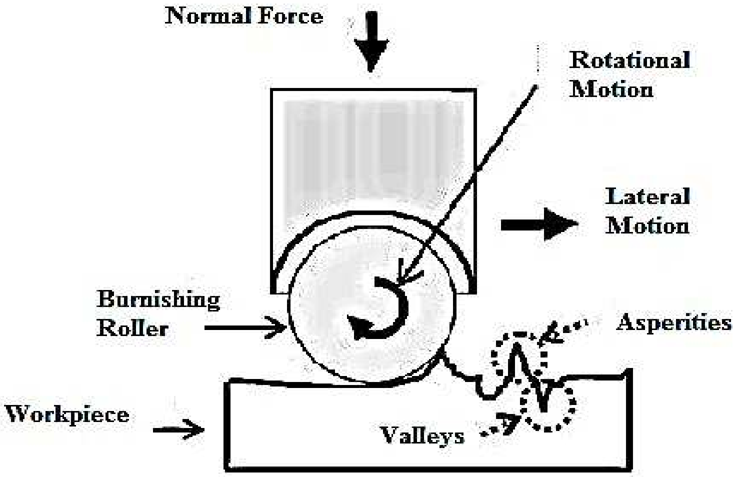


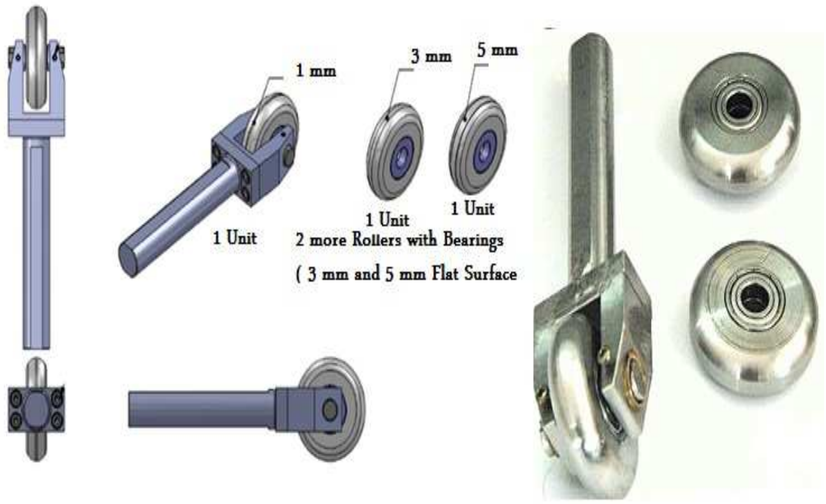
Fig. 1: Schematic of the burnishing process

MATERIALS AND METHODS

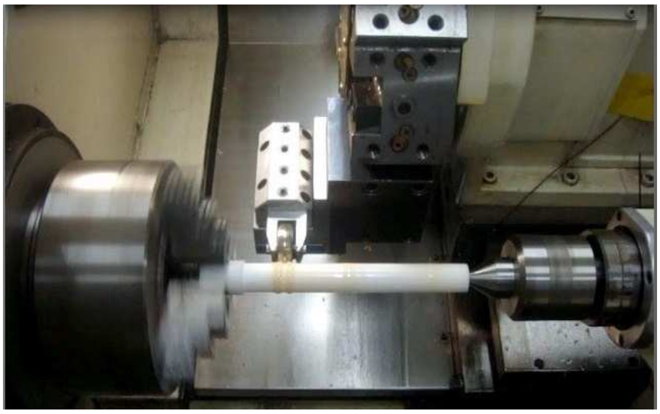
In this research polyoxymethylene (POM) material is used. Typical applications for POM include high performance engineering components, such as small gear wheels, ball bearings, ski bindings, fasteners, knife handles, lock systems, and model rocket launch buttons. This material is widely utilized in the automotive and consumer electronics industries. The workpiece materials were received in the form cylindrical bars with 30mm diameter. The bars were cut to be appropriately 200 mm long and then turned to 26mm diameter. Each specimen was burnished and one region was left for measuring initial surface roughness. The mechanical properties of the polymer bars are tensile strength 70 Mpa, yield strength 67 Mpa , and modulus of elasticity 3.3 Gpa. Table 1 indicate burnishing parameters used throughout the experimental work.

Table 1: Control factors and experimental conditions levels

	Burnishing Parameters	Levels (*i*)		
A	Burnishing Depth, mm	0.1	0.15	0.2
B	Burnishing Speed, n (rpm)	110	245	490
C	Burnishing Feed rate, f (mm/rev)	0.035	0.105	0.210
D	Roller width, (mm)	1	3	5
E	Lubrication mode	Dry	Fluid	MQL



a) Roller burnishing tool



b) Schematic of the burnishing process

Fig. 2: Experimental setup

Machines And Equipment:

The multi-roller type burnishing tool is made of stainless steel and a detailed drawing of the 3 rollers with bearings and flat surfaces is shown in Fig. 2(a), while the experimental setup is shown in Fig. 2(b). The roller is attached on the tool turret and pressed against the material's surface.

This study was performed on a CNC turning machine (OKUMA LB15, 7.5Kw) with maximum spindle speed of 4200 rpm. A roughness tester (mitutoyo SJ.201, 350µm wide measurement range, ISO) took 5 surface roughness readings after burnishing. Hardness was also measured by taking 5 readings with the Vickers indenter michrohardness tester (Model HMV Shimadzu, 98.07mN test force).

Design of Experiments:

In full factorial design, the number of experimental runs exponentially increases with the increasing number of factors as well as levels (Procesu, U.G.-T.M.P., 2010). This requires more extensive experimental cost and time. Therefore, to compromise between these factors and identify optimal process conditions within a limited number of experimental runs, the Taguchi L_{27} (3^5) orthogonal array consisting of 27 data sets was selected to optimize the multiple performance characteristics of surface roughness and hardness. The standard orthogonal array comprises 27 experiments with 5 control factors and 3 different experimental condition levels for each factor. The 27 experiments were carried out in random sequence to eliminate any other invisible factors potentially contributing to the result.

RESULTS AND DISCUSSION

The measured roughness and hardness values are shown in Table 3. An example of measured surface roughness is shown in Figure 3. The next step in Taguchi optimization is data analysis, parameter optimization and identifying the best significant parameters. Data analysis was done by using two techniques: signal-to-noise (S/N) response and Pareto analysis of variance (ANOVA).

Table 3: The Measured values of surface roughness and hardness

Exp.no	Control Factors and levels (*i*)					Measured values											
	A	B	C	D	E	Surface roughness, *R*a (µm)						Surface hardness (*H*v)					
						1	2	3	4	5	Avg	1	2	3	4	5	Avg
1	*i*=1	1	1	1	1	3.76	3.73	3.05	3.46	3.36	3.472	15.1	16	14.7	15.6	16.5	15.58
2	*i* =1	1	1	1	2	2.82	2.82	2.91	2.78	2.91	2.848	15.9	15.5	16	15.7	15.9	15.8
3	*i* =1	1	1	1	3	2.12	2.11	2.14	2.04	2.08	2.098	26	24.8	25	26.5	25.3	25.52
4	*i* =1	2	2	2	1	3.73	3.64	3.6	3.77	3.7	3.688	17.6	17.3	16.7	17.1	17.01	17.142
5	*i* =1	2	2	2	2	3.63	3.68	3.63	3.61	3.67	3.644	20.9	20.1	21.5	19	17.7	19.84
6	*i* =1	2	2	2	3	1.21	1.14	1.17	1.18	1.2	1.18	10.6	11.5	10.2	11.8	10.9	11
7	*i* =1	3	3	3	1	2.69	3.04	2.88	2.83	2.76	2.84	11.4	11.7	12.3	11.1	9.5	11.2
8	*i* =1	3	3	3	2	2.44	2.51	2.52	2.53	2.53	2.506	19.95	12.5	11.5	11.75	10	13.14
9	*i* =1	3	3	3	3	3.37	3.39	3.37	3.13	3.09	3.27	15.2	15	14.4	14.6	16.65	15.17
10	*i* =2	1	2	3	1	3.64	3.69	3.62	3.63	3.67	3.65	14.4	13.7	13.5	15	14.65	14.25
11	*i* =2	1	2	3	2	2.13	2.43	2.39	2.44	2.44	2.366	13.3	13.81	13.7	13.6	13.7	13.622
12	*i* =2	1	2	3	3	0.93	0.96	1	0.86	0.9	0.93	18	18.1	17.78	17.9	17.9	17.936
13	*i* =2	2	3	1	1	3.5	3.56	3.55	3.5	3.48	3.518	17.5	17.2	16.8	16.2	17.3	17
14	*i* =2	2	3	1	2	3.37	3.56	3.3	3.62	2.61	3.292	8.91	9.5	8.4	10	8.6	9.082
15	*i* =2	2	3	1	3	0.9	0.86	0.94	0.84	0.9	0.888	16.85	16.57	16.28	16.35	16.68	16.546
16	*i* =2	3	1	2	1	2.67	2.61	2.7	2.53	2.58	2.618	17	17.05	16.25	16.85	17.1	16.85
17	*i* =2	3	1	2	2	1.14	1.17	1.13	1.15	1.12	1.142	17.7	16.9	18.3	18.2	17.6	17.74
18	*i* =2	3	1	2	3	0.92	0.83	0.92	0.86	0.89	0.884	14.1	14.4	15.1	13.6	15.7	14.58
19	*i* =3	1	3	2	1	3.62	3.64	3.59	3.51	3.6	3.592	19.36	20.3	18.4	19.2	21	19.652
20	*i* =3	1	3	2	2	3.71	3.66	3.65	3.67	3.71	3.68	12.44	12.71	12.21	12.2	12.8	12.472
21	*i* =3	1	3	2	3	0.94	0.87	0.92	0.89	0.88	0.9	10.6	10.7	11.5	10.2	9.87	10.574
22	*i* =3	2	1	3	1	2.04	2.03	1.99	2.12	2.08	2.052	11.7	13.5	13.6	12.9	13.2	12.98
23	*i* =3	2	1	3	2	1.98	1.91	1.96	1.9	1.97	1.944	13.8	13.2	12.9	13.21	12.8	13.182
24	*i* =3	2	1	3	3	2.02	1.94	1.99	2.1	1.92	1.994	17.6	16.3	18.54	17.3	17.6	17.468
25	*i* =3	3	2	1	1	3.55	3.52	3.33	3.24	3.56	3.44	18.6	17.89	18.6	19	16.51	18.12
26	*i* =3	3	2	1	2	3.74	3.91	3.76	3.9	3.73	3.808	16.8	17.4	18.2	16.3	16.7	17.08
27	*i* =3	3	2	1	3	1.2	1.12	1.47	1.18	1.2	1.234	19.56	18.93	19.77	19.86	19.5	19.524

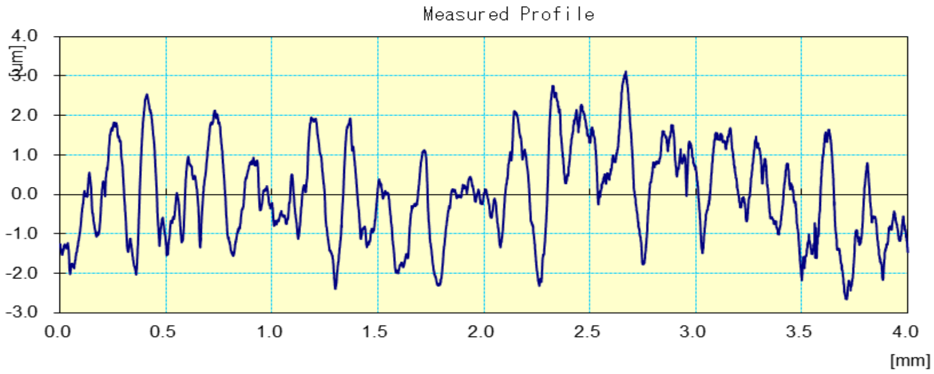


Fig. 3: An example of measured surface roughness

S/N response analysis:

To calculate the S/N ratio, three methods classified into the following main categories can be used, depending on whether the desired quality characteristics are smaller-the-better, larger-the-better or nominal-the-better. In this study, the smaller values are always ideal for surface roughness and higher values for surface hardness. The equations for calculating the S/N ratio of surface roughness and hardness, respectively, are as follows:

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum y_i^2\right)_j \qquad (1)$$

$$\frac{S}{N} = -10\log\left(\frac{1}{N}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (2)$$

where (j) is the test number from 1 to 27; y_i is the individual measured surface roughness and hardness in Table 3; and n is the number of the individual measured responses, in this case n=5. The S/N value function is a performance measurement parameter to develop processes insensitive to noise factors. The higher the S/N ratio, the better the result for surface roughness and hardness is.

Furthermore, the TPM and S/N response data are calculated and summarized in Table 5 for surface roughness and hardness. As an example of TPM and S/N response calculation, A_i is the average of all TPM and S/N values corresponding to the same level of input parameter (i) under A in Table 3. In this case, (i) equal 1, 2 or 3. Similarly, the S/N and TPM response values are calculated for B_i, C_i, D_i and E_i. The TPM and S/N response values are plotted as shown in Figs. 4 and 5. The desired “smaller-the-better” criterion implies that smaller surface roughness for TPM would be the ideal result, while the largest S/N response would reflect the best response, resulting in the least noise (Fig. 4). The preferred “larger-the-better” criterion implies that greater surface hardness for TPM would be the ideal result while the largest S/N would reflect the best response for surface hardness (Fig. 5).Based upon the smaller TPM and larger S/N ratio criteria (Fig. 4), the burnishing speed (B_3, 490rpm), burnishing depth (A_2, 0.15mm), lowest burnishing feed rate (C_1, 0.035mm/rev), roller width (D_2, 3mm) and (E_3, MQL) type of lubrication are determined to be the best choices for obtaining the lowest surface roughness. While from Fig. 5 and based on the criteria of higher TPM and higher S/N ratio with burnishing speed (B_1, 110rpm), burnishing depth (A_1, 0.1mm), lowest burnishing feed rate (C_1, 0.035mm/rev), roller width (D_1, 1mm) and (E_1, MQL) are deemed the best choice for obtaining the greatest surface hardness.

Table 5: TPM and SN response data

	TPM response data									
	Surface roughness					Surface hardness				
Level of input Parameters (*i*)	A*i*	B*i*	C*i*	D*i*	E*i*	A*i*	B*i*	C*i*	D*i*	E*i*
Level 1	2.84	2.62	2.12	2.73	3.21	16	16.2	16.6	17.1	15.9
Level 2	2.14	2.47	2.66	2.37	2.54	15.3	14.9	16.5	15.5	13.1
Level 3	2.52	2.42	2.72	2.39	1.49	15.7	15.9	13.9	14.3	16.5
	SN response data									
	Surface roughness					Surface hardness				
Level of input Parameters (*i*)	A*i*	B*i*	C*i*	D*i*	E*i*	A*i*	B*i*	C*i*	D*i*	E*i*
Level 1	-8.64	-7.33	-5.87	-7.88	-9.99	23.72	23.88	24.23	24.4	23.9
Level 2	-5.21	-6.93	-7.37	-6	-7.62	23.52	23.21	24.19	23.59	20.5
Level 3	-7.09	-6.67	-7.69	-7.06	-2.49	23.69	23.83	22.5	22.94	24

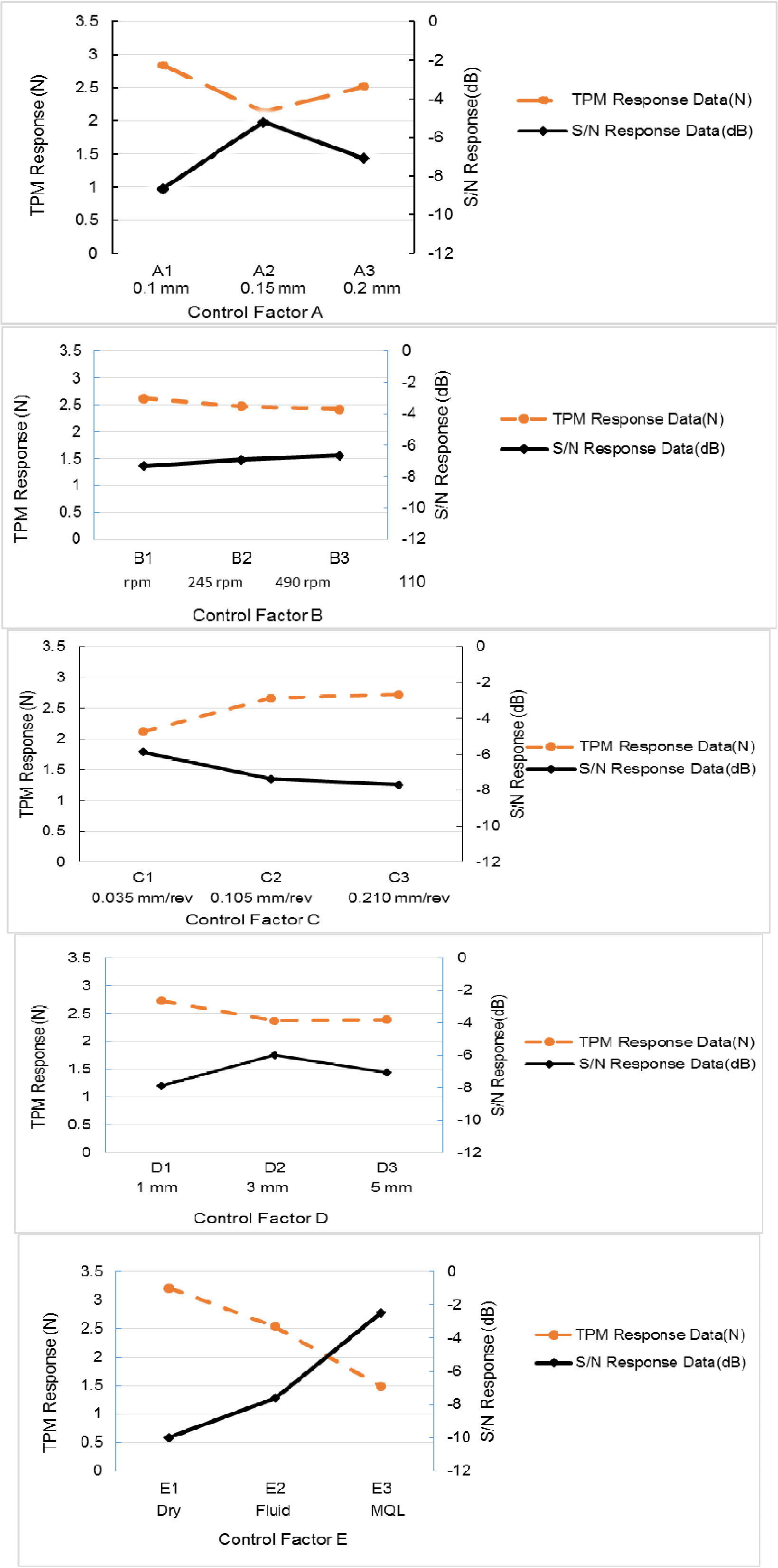


Fig. 4: TPM and S/N response graphs for surface roughness at different control factors

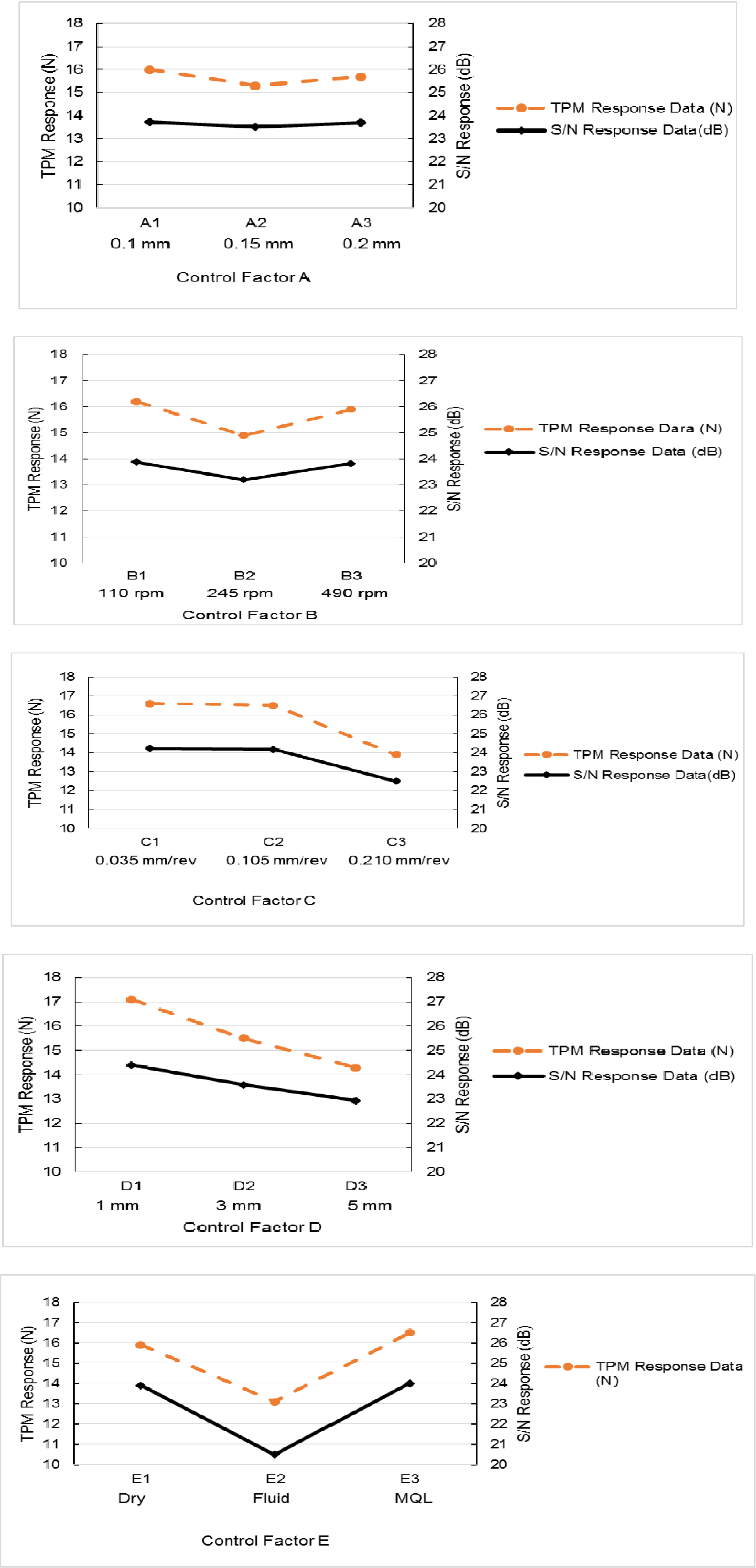


Fig. 5: TPM and S/N response graphs for surface hardness at different control factors

Analysis of variance (Pareto ANOVA):

The analysis of variance using ANOVA is another means of analyzing data for the optimization process. It is used to investigate which burnishing parameters significantly affect the performance characteristics. Pareto ANOVA for surface roughness is presented in Table 6 and for surface hardness in Table 7. Using the S/N response data from Table 5, the summation of squares of differences (S) for each control factor is calculated with the following equation:

$$S_A = (A_1 - A_2)^2 + (A_1 - A_3)^2 + (A_2 - A_3)^2 \qquad (3)$$

In the same way, S_B, S_C, S_D and S_E are calculated. For each factor, the contribution factor is calculated as the percentage of summation of squares of differences to the total summation of the squares of differences.ANOVA analysis additionally suggests that $A_2 B_3 C_1 D_2 E_3$ is the best parameter combination to obtain the lowest surface roughness and $A_1 B_1 C_1 D_1 E_3$ is ideal to obtain maximum surface hardness. It should be noted that these results are similar to the ones obtained using S/N and TPM analysis.

Table 6: Pareto ANOVA for surface roughness

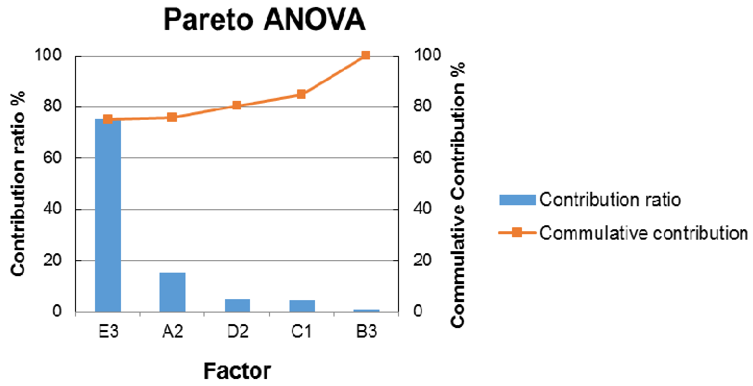
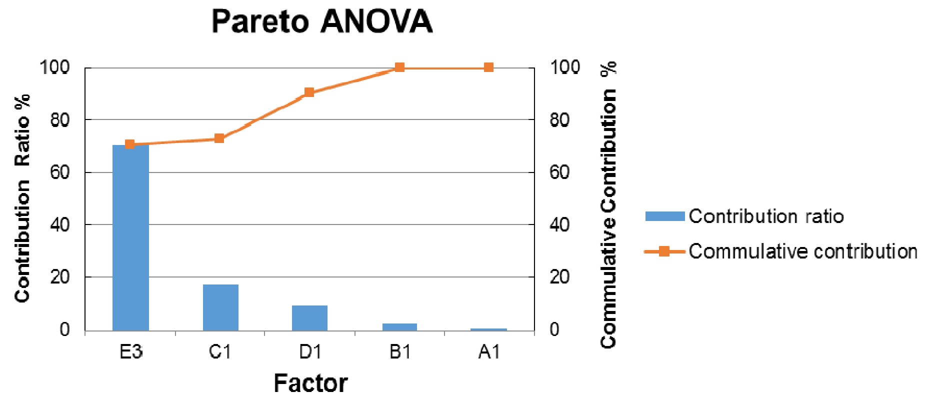
S/N	S/N response data (dB)				
Control Factors (*i*)	A*i* Burnishing depth	B*i* Burnishing Speed	C*i* Burnishing feed rate	D*i* Roller width	E*i* Lubrication
Level 1	-8.64	-7.33	-5.87	-7.88	-9.99
Level 2	-5.21	-6.93	-7.37	-6	-7.62
Level 3	-7.09	-6.67	-7.69	-7.06	-2.49
Total summation	-20.94	-20.9	-20.93	-20.9	-20.1
Square of differences (S)	17.7018	0.66	5.6648	5.33	88.1838
Total summation of squares of differences $St = SA + SB + SC$	117.544				
Contribution ratio (%)	15.05972	0.56	4.819302	4.53	75.02195
Cumulative contribution	75	75.5	80.34	84.9	100
Optimum combination	A2	B3	C1	D2	E3
					
Overall optimum conditions for all factors	A2B3C1D2E3				

Table 7: Pareto ANOVA for surface hardness

S/N	S/N response data (dB)				
Control Factors (*i*)	A*i* Burnishing depth	B*i* Burnishing Speed	C*i* Burnishing feed rate	D*i* Roller width	E*i* Lubrication
Level 1	23.72	23.88	24.23	24.4	23.9
Level 2	23.52	23.21	24.19	23.59	20.5
Level 3	23.69	23.83	22.5	22.94	24
Total summation	70.93	70.92	70.92	70.93	68.4
Square of differences (S)	0.07	0.836	5.851	3.2102	23.82
Total summation of squares of differences $St = SA + SB + SC$	33.7864				
Contribution ratio (%)	0.207	2.474	17.32	9.5015	70.5
Cumulative contribution	70.5	72.97	90.29	99.792	100
Optimum combination	A1	B1	C1	D1	E3



Overall optimum conditions for all factors	A1B1C1D1E3

Discussion:

It is noted that burnishing improves the material's surface quality due to the action of plastic deformation on the material.

In this work, both S/N ratio and ANOVA techniques delivered similar results. An investigation of surface roughness results indicated that lower surface roughness is achieved with medium burnishing depth, maximum burnishing speed, lower feed rate, 3mm roller width and MQL lubrication mode. This is on account of the fact that a higher feed rate causes the surface to deteriorate, so a low feed rate is recommended for roller burnishing polymers because the small gap between consecutive burnishing roller tracks will help compress the preceding roller track. This outcome is also attributed to the combined effect of both roller width and burnishing depth, as these lead to optimum penetration of the roller, resulting in enhanced plastic deformation.

According to the results, the best hardness is achieved with lower burnishing depth, lower speed, lower feed rate, small roller width and MQL lubrication mode. This is due to the small roller width that causes deeper penetration on the workpiece surface, which will increase hardness. This could also be explained in terms of lower burnishing speed that provides more adequate time for work hardening and increased surface hardness. The increase in hardness with a decrease in feed rate is attributed to the diminishing distances between successive burnishing traces. This results in increased deformation action on the material's surface, which consequently results in increased hardness.

Conclusion:

Based on the results, it can be concluded that the best surface roughness is obtained with medium burnishing depth, higher burnishing speed, lower burnishing feed rate, 3mm roller width and MQL lubrication mode while the best surface hardness can be obtained with lower burnishing depth, lower burnishing speed, lower burnishing feed, smaller roller width and MQL lubrication.

In the method of Taguchi optimization, the final step is to conduct a verification test for the validation of the suggestions using the optimal parameter combinations. The optimal combination of parameters for surface roughness and hardness corresponds to the orthogonal array of the experiment. It may be mentioned that, if the optimal combination of parameters as well as their levels match with one of the experiments in the OA coincidently, in that case no confirmation test will be required (Kamaruddin1, S., *et al*., 2004).

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