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Optimization of Roller Burnishing Process for Improved Surface Finish, Electrical Conductivity and Grain Area for Al6061 Alloy

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Abstract: : Aluminum alloy Al6061 has wide range of applications in automobile, aircraft industries, production of parts used in medical purposes and in food processing industries. Due to high ductility of Aluminum alloys, it is difficult to get good surface finish after machining. In order to get good finish, the parts have to be burnished. The present work deals with manufacturing of burnishing tool in-house and studying the influence of different input parameters on burnishing responses. Burnishing tool is fabricated in house with chromium steel(6200z) as roller. Burnishing of Al6061alloy is performed considering input parameters as burnishing speed, feed, and burnishing force. Influence of these parameters on surface roughness, electrical conductivity and grain area is studied. Speed, feed and burnishing force with their 2-way interactions and 3-way interaction are found to have significant effect on surface roughness and electrical conductivity while only speed and feed has significant effect on grain area. Single response optimization is performed and optimum conditions which minimize surface roughness and grain area and maximize electrical conductivity separately are evaluated. Minimum surface roughness can be obtained at burnishing speed of 465rpm, feed of 0.223mm/rev and burnishing force of 125N with a percentage improvement of 51.57% with respect to the initial conditions. Maximum electrical conductivity can be obtained at burnishing speed of 290rpm, feed of 0.223mm/rev, and burnishing force of 54N with a percentage improvement of 37.09% with respect to the initial conditions. Minimum grain area can be obtained at burnishing speed of 290rpm, feed of 0.243mm/rev, and burnishing force of 125N with a percentage improvement of 37.26% with respect to the initial conditions. Initial conditions considered are burnishing speed of 100rpm, feed of 0.193mm/rev, and burnishing force of 54N. For industrial applications, optimizing single response is not desirable. Burnishing process has to be optimized considering priorities given to different responses based on applications. In the present work, multi response optimization is performed using Grey relational approach giving more and equal importance to surface roughness and electrical conductivity(0.4) and less importance to grain area(0.2). Grey relational grade showed highest improvement of 59.05% with respect to the initial design compared to single response optimization. Optimum parameters from multi response optimization are burnishing speed of 290rpm, feed of 0.243mm/rev, and burnishing force of 90N. Performing burnishing operation of Al6061 alloy at these parameters will yield best results.

Keywords: Single Optimization, Multi Response Optimization, Surface Finish, Electrical Conductivity, Grain Area.

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I. INTRODUCTION

Burnishing is a popular finishing process involving rotation of tool over cylindrical surface. A smooth surface finish can be achieved by this process as it reduces heights and valleys through application of force. Surface roughness plays a vital role in quality control of machined work piece. Deterioration in surface quality or manufacturing discontinuity can lead to surface failure which might lead to component failure. Roller burnishing facilitate manufacturers to phase out secondary operations thereby reducing manufacturing time and production cost and simultaneously rising the quality of the commodity. Electrical conductivity is the measure of capability of a material to conduct electricity. It is measured in Siemens/meter.

High electrical conductivity makes Aluminum alloys suitable for use in electrical and electronics applications. Grain size affects the properties like hardness, yield, tensile, fatigue and toughness. All of the properties increase with decrease in grain size. Smaller grain size causes the crack length to be shorter leading to better fracture toughness.Aluminum alloy Al6061 has wide range of applications in automobile, aircraft industries, production of parts used in medical purposes and in food processing industries. Due to high ductility of Aluminum alloys, it is difficult to get good surface finish after machining. In order to get good finish, the parts have to be burnished.

Many researchers worked on optimizing burnishing parameters. Patel, K. A., & Brahmbhatt, P. K. [1] performed roller burnishing on Aluminum alloy AA6061 with carbide tool roller. Performance of speed, feed, no of passes and interference on surface roughness was studied. Artificial neural network (ANN), RSM (Response surface methodology) together with ANOVA (14 experiments) methodology was used and results were compared. They found that ANN models predicted better than RSM model. Basak, H., & Yücel, M. [2]

performed burnishing on Al6061-T6 alloy and studied the effects of force, ball diameter, burnishing passes and progression on hardness and surface finish and developed two models based on artificial neural network and neuro – fuzzy interaction. Deshmukh, A., & Patil, R. N. [3] investigated the influence of speed, passes and penetration on micro hardness of the burnished surface and found that penetration depth most significantly affected the micro hardness. ANOVA results were also validated using Analytic Hierarchy Process. Kumar, N. et al. [4] performed burnishing on C40E steel and investigated the influence of burnishing speed, condition, passes, feed and penetration on hardness and roughness.

L18 orthogonal array was used and optimal levels of parameters which minimizes surface roughness and hardness separately were identified. Amini, S., Bagheri, A., & Teimouri, R. [5] performed conventional ball burnishing and ball burnishing with ultrasonic on aluminium alloy and steel to investigate the effect on properties. While conventional burnishing, feed rate: 5000mm/min and five passes gave highest hardness. For burnishing with ultrasonics, maximum hardness was achieved at feed rate of 1000mm/min with five passes Lad, S. P et al. [6] studied roller burnishing process on EN-8 specimens with high speed steel roller. Effect on roughness and hardness of surface was studied by performing 9 experiments (3-levels). Taguchi L9 Orthogonal methodology was used. Better surface finish up to 0.26 micron is obtained and hardness is improved by 20% and increased up to 254 BHN. Yuan, X. L. et al. [7] investigated influence of different parameters on roller type burnishing of TA2 alloy in terms of surface roughness and micro hardness. Box-Behnken design experiments were used. They identified spindle speed and burnishing depth as significant parameters which reduced the surface roughness and improved microhardness. John, M. S. et al. [8] performed burnishing on D3 tool steel to study the influence of speed, feed and force on surface finish, hardness, residual stresses and roundness. Generated surface roughness is used to model and replicate ball type burnishing in Deform 3D. Deviation between simulated and experimental results was found to be less than 10%. Kowalik, M., Mazur, T., & Trzepiecinski, T. [9] simulated roller burnishing to estimate depth of top layer which is plastically deformed in terms strength and diameter of roller material and force. Results obtained numerically are found to be in line with experimentation results. Rao, M. J., Reddy, C. K. A., & Rao, R. P. [10] studied the effects of burnishing on mild steel work piece. Effect of burnishing parameters on roughness and micro hardness was studied by performing six experiments. Patel, P. N., Patel, N. B., & Patel, T. M. [11] investigated effect of ball burnishing on hardness and roughness of Aluminum work piece with chromium high carbon burnishing tool by performing 25 experiments (5-levels). Sanchez et al. [12] investigated the significance of hot – burnishing on integrity of surface of AISI1045 workpiece. Performance of speed, number of passes and depth on roughness, micro hardness and residual stress was studied. Kumar, a et al. [13] performed magnetorheological finishing (MRF) process with ball end on polylactic acid (PLA) work piece manufactured by fusion deposition modelling process. It it observed that the surface roughness was reduced from 20 µm to 81nm after secondary finishing. They also found optimum magnetorheological polishing (MRP) fluid for best finish of the surface. Maximov, J. T. et al. [14] performed analysis experimentally and using numerical technique to determine influence of parameters of slide burnishing on AISI 316Ti stainless steel. Slide burnishing decreased surface roughness, increased microhardness, wear resistance and fatigue strength and introduced residual stresses Nguyen, T. T., & Le, X. B. [15] investigated the relation between parameters of machining and quality of surface while interior roller burnishing of AISI1040 steel. Micro genetic algorithm was used to obtain optimum solutions to determine best machining conditions. Integration of response surface model with AMGA was suggested as an excellent method to perform optimization. Good amount of work is done on studying the effect of burnishing parameters, but most of them are limited to effect on surface roughness and hardness. Also, many researchers optimized burnishing parameters using single response optimization. In real time applications, where multiple responses are measured, optimum results from single response optimization may not be useful. In such case, multi- response optimization has to be performed. Such optimization is applied successfully. Raghuraman, S. et al. [16] optimized parameters of electric discharge machining using Grey relational method. Combined objective of high rate of metal removal, low tool wear and low roughness of surface was achieved. Bhuyan, B. K., & Yadava, V. [17] used Taguchi and response surface methodology to optimize process parameters while machining Pyrex glass using electrochemical spark machining. Performing of voltage, time of pulse on and off and feed velocity of wire on surface roughness Ra, rate of material removal and kerf width was studied. Tzeng, C. J. et al. [18] optimized parameters while turning SKD11 using grey relational analysis. L9 orthogonal array was used. Ratio of cutting fluid: 12%, speed: 155m/min, d.o.c: 0.8mm and feed:0.12mm/rev was found to minimize average and maximum values of roughness and roundness simultaneously. Leite, W. O. et al. [19] manufactured a product of polystyrene using vacuum thermoforming and minimized geometrical and dimensional errors using multiple response optimization(MRO) models and validated the results proving the efficiency of MRO method. Padmaja, M., & Haritha, D. [20] used Taguchi and GRA method to determine optimal software process parameters for minimizing effort of software project. Optimal parameters resulted in improved grey relational grade resulting in improved estimation of effort of software.

Wide range of applications of aluminum alloys in electrical and electronics field is due to its excellent electrical conductivity. Lower grain size at surface improves the mechanical property of the material. To the best of authors' knowledge, less research is done to understand the influence of burnishing process on electrical conductivity and grain size. Most of the works deal with single response optimization, which is not applicable practically. Present work shows the difference of output obtained with single and multi-response optimization. Work on multi response optimization of burnishing parameters on Al6061 alloy considering surface roughness, electrical conductivity and grain area has not been considered till date. In the present paper, a burnishing tool is built in house and performance of burnishing parameters on surface roughness, electrical conductivity and grain area of Al6061 alloy is evaluated. Single response optimization as well as multi response optimization is performed to minimize surface roughness and grain size and maximize electrical conductivity and results are compared.

Figure 1(a) Components of burnishing tool (b) Congregated view of burnishing tool

II. MATERIALS AND METHODS

A burnishing tool is fabricated in-house. The main body is a hollow tool shank of 20mm x 20mm of cast iron material. The tool roller is made of chromium steel as it has good corrosion resistance and hardness. It can withstand static load up to 2.36 kN and dynamic load up to 5.4 kN. Inside spring material used is of stainless steel of diameter 15.5 mm. All parts are assembled using bolt, nut and bush. Figure 1(a) exhibits the components of burnishing tool and Figure 1(b) shows the congregated view.

In order to determine the force exerted by the burnishing tool on the work piece, the stiffness of the spring used in the burnishing tool is evaluated. The spring to be tested is fixed rigidly at one end and loads of 20 to 60 N are added at the other end. The deflection of the spring under each load is determined. Graph is plotted between applied force and deflection and the slope of the best fit line is used as the spring stiffness. Aluminum alloy Al6061 of diameter 25mm is used as work piece for burnishing. Assembled burnishing tool is held in tool post of conventional “All Geared” lathe machine. Burnishing force is applied by giving sufficient movement to the tool post perpendicular to the work piece. Initially a layer of the material is removed by performing tuning operation on the work pieces. Surface roughness and electrical conductivity are measured before burnishing operation. Microstructural images of the unburnished part is taken and grain area is evaluated. In order to determine the influence of process parameters i.e burnishing speed, feed and burnishing on roller burnishing Al6061 alloy, each parameter is considered in three levels. Parameters and levels considered are shown in Table 1.

Table 1: Parameters and levels

Parameters\ Levels	1	2	3
(A)Burnishing speed (rpm)	100	290	465
(B) Feed(mm/rev)	0.193	0.223	0.243
(C) Burnishing force (N)	54	90	120

Full factorial experiments are conducted (33 = 27 experiments). Each experiment is conducted thrice and average of the three readings are considered for analysis. Number of passes is taken constant as three. Block diagram of set up for burnishing operation is shown in Figure 2. Kerosene oil is used as coolant during burnishing. Performance of burnishing processes are evaluated by measuring the responses: Surface roughness, electrical conductivity and grain area. Surface roughness is measured using Surftest SJ301, which was calibrated with the standards provided in the equipment, which showed a deviation of 3.12%. Electrical conductivity is measured using Kelvin double bridge. Electrical conductivity of a standard specimen of copper supplied with the specimen is determined and percentage error is found to be less than 5% when compared with the standard value. Grain area is determined by mounting the burnished surface on metallurgical microscope and applying threshold of 80%.

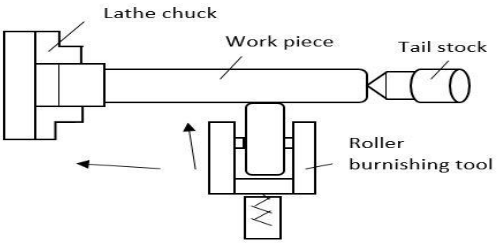

Figure 2: Block diagram of set up for burnishing operation

Single response optimization is performed to evaluate burnishing parameters, which minimizes surface roughness and grain area and maximizes electrical conductivity separately. But optimization for a single response may provide result which may have diverse effect on other responses. So, multi-response optimization is performed which simultaneously minimizes surface roughness, grain size and maximizes electrical conductivity based on importance given to different responses. Grey relational Taguchi method is used to perform multi response optimization.

III. RESULTS AND DISCUSSION

Fig. 3 shows the variation of applied force verses deflection of spring. Slope of the graph is the stiffness of the spring and is found to be 16.828 N/mm. Figure. 4(a), (b) and (c) shows the surface roughness, electrical conductivity and grain area for unburnished surface and burnished surface for all experiments. Surface roughness and grain size has decreased after burnishing process while the electrical conductivity has increased. Burnishing operation caused plastic

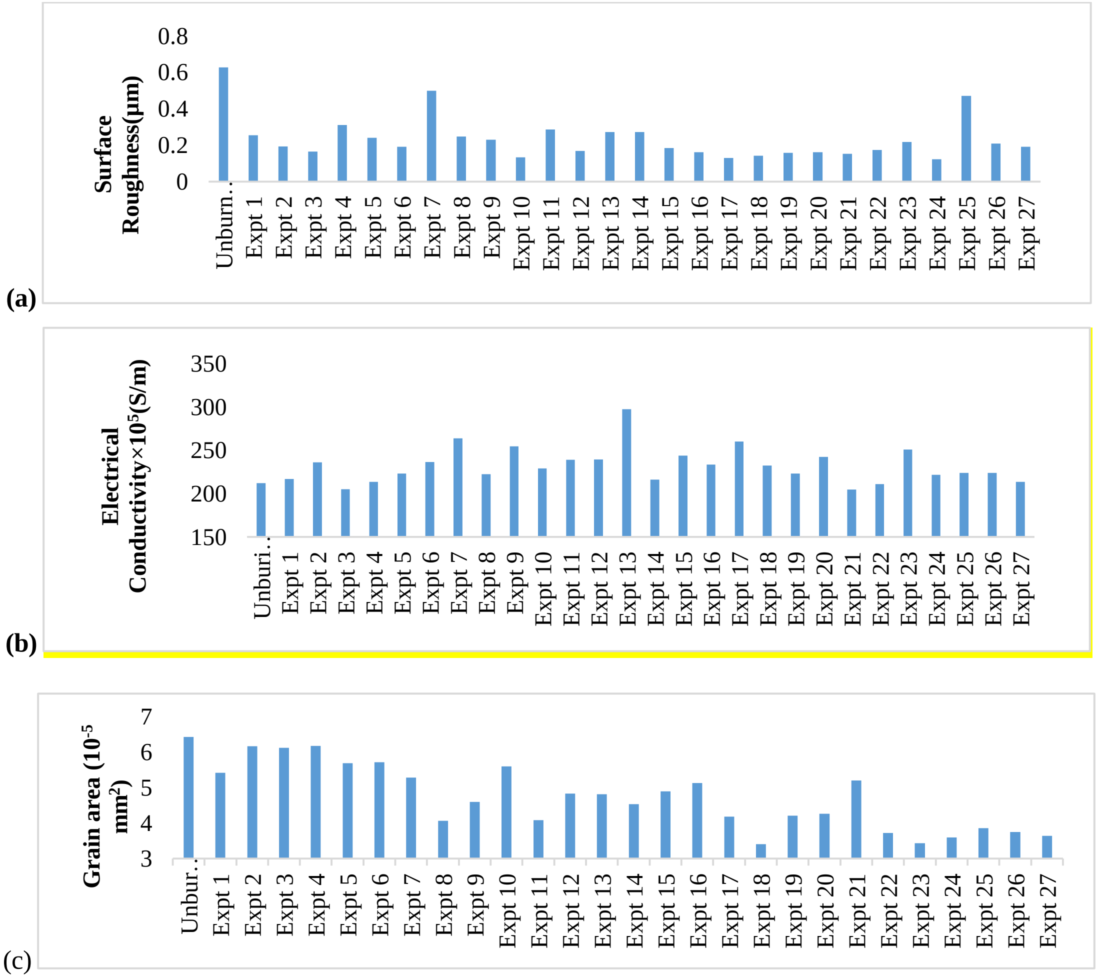

Figure 4: (a) Surface roughness (b) Electrical conductivity (c) Grain area for unburnished surface and burnished surface for all experiments

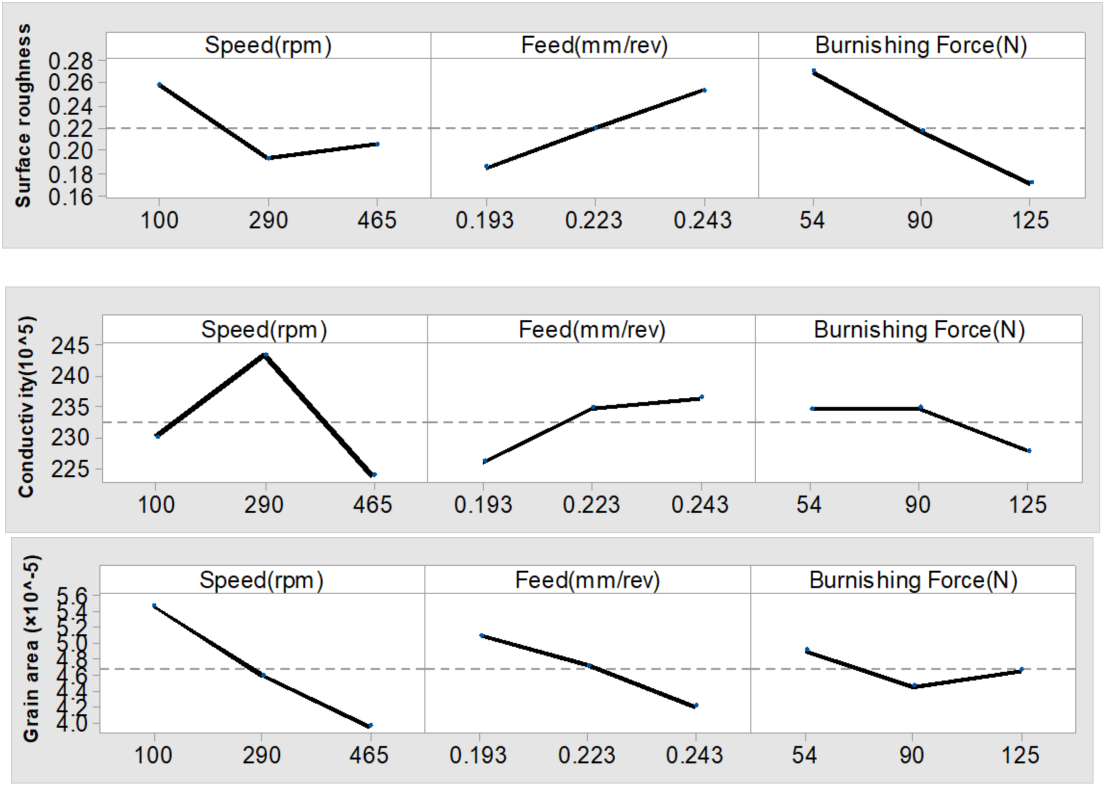

Figure 5: Main Effect Plots for roughness, electrical conductivity, grain area of surface

deformation of irregularities on the surface and hence decreased surface roughness. Plastic deformation of the surface layer may also have reduced the grain area after burnishing. Electrical conductivity is found to increase after burnishing. This may be due to uniformity of surface in burnished part, as compared to unburnished part. When the roughness of the surface is more, two layers are not in contact over the whole surface, but are in contact only at few points which is the peak of the asperities. Current passes only through these contact areas, which increases the contact resistance, which in turn decrease the electrical conductivity. As with burnishing, the surface roughness has decreased, it may have led to increase in electrical conductivity.

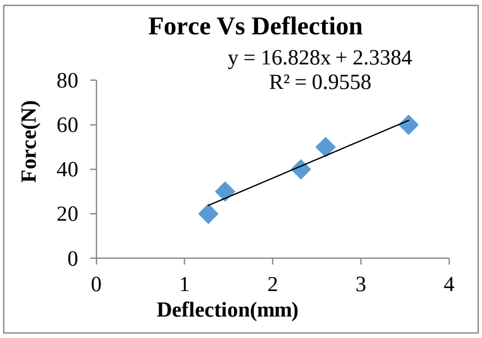

Figure 3: Variation of applied force verses deflection of spring

Single response optimization is performed to find optimum burnishing process parameters which minimizes roughness of surface and grain area and maximizes electrical conductivity separately. In order to determine the influence of burnishing process parameters i.e. speed, feed & burnishing force on roughness, electrical conductivity & grain area, main effect plots (MEP) are plotted in Minitab 18.1 software and presented in Fig. 5. MEPs give the relation between each independent variable i.e. burnishing parameters and dependent variables i.e responses. From the MEP of roughness with burnishing speed it is noticed that with increase in burnishing speed from 100 rpm to 290 rpm, roughness of the surface has decreased. But an additional rise in speed of burnishing to 465 rpm, roughness of the surface increased. This shows that 290 rpm is the optimum burnishing speed, where the surface roughness value is minimum. Below this speed, good surface finish could not be obtained. This may be due to formation of buildup edge caused by sticking of work piece particles to the burnishing tool. With increase in burnishing speed above 290 rpm, time may not be sufficient to compress the peaks on the work piece, leading to increase in surface roughness. Slope of surface roughness is more which shows that spindle speed has more influence on roughness of the surface. MEPs of roughness of surface with burnishing feed displays that with rise in burnishing feed, roughness of surface has increased. This is because, with increase in feed, the tool movement along longitudinal direction increases per revolution. This gives less time for the peaks on the surface to get plastically deformed. Also, at higher feeds, fast movement of burnishing roller on the work piece causes rubbing action. This might have damaged the work piece surface. Also at higher feeds, vibration may have spoiled the surface finish leading to higher roughness of the surface. MEPs of roughness of surface with burnishing force shows that with rise in force of burnishing, roughness of burnished surface has decreased. With rise in burnishing force, tool is applying more pressure on the irregularities on the work piece surface. This causes plastic deformation of the peaks and thereby reducing their size and producing better finish. Main effect plot of electrical conductivity with burnishing speed shows that with increase in burnishing speed from 100 rpm to 290 rpm, there is an increase in electrical conductivity. But with additional increase in speed of burnishing to 465 rpm, electrical conductivity decreased. This shows that 290 rpm is the optimum burnishing speed, where the electrical conductivity value is maximum. The same speed gives minimum surface roughness. Number of contact points on two rough surfaces is less compared to finished surfaces. Current passes only through these contact areas, which increases the contact resistance in rough surface, which in turn decrease the electrical conductivity. Thus, minimum surface roughness may have led to increase in electrical conductivity at 290 rpm. Slope of electrical conductivity is more which shows that spindle speed has more influence on electrical conductivity. Main effect plot of electrical conductivity with burnishing feed shows that with increase in burnishing feed, electrical conductivity has increased. Main effect plot of electrical conductivity with burnishing force shows that with increase in burnishing force, electrical conductivity has slightly increased and then decreased. Main effect plot of grain area with burnishing speed shows that with increase in burnishing speed from 100rpm to 465rpm, grain area has decreased. This shows that 465rpm is the optimum burnishing speed, where the grain area is minimum, for the considered range of speed. As the speed increases, the heat at the zone of burnishing also increases. This causes easy rearrangement of grains. This may have caused the grain area to decrease with increase in burnishing speed. Slope of grain area is more which shows that spindle speed has more influence on grain area. Main effect plot of grain area with burnishing feed shows that with increase in burnishing feed, grain area has decreased. The main effect plot of grain area with burnishing force shows that with increase in burnishing force, grain area has initially decreased and then increased. This is because, with increase in burnishing force, tool is applying more pressure on the irregularities on the work piece surface. This causes plastic deformation of the peaks and thereby reducing their size and producing better grain area.

Analysis of variances (ANOVA) gives the amount of variation in response data explained by parameters. Table 2 (a), (b), (c) shows ANOVA table for surface roughness, electrical conductivity and grain area. “p” value < 0.05 represents significant relation amid input process parameters and response. F value is used to test null hypothesis. Comparing F value from the data with $F_{\alpha, \Upsilon_1, \Upsilon_2}$ from standard tables, null hypothesis is accepted or rejected at a particular confidence level. If $F > F_{\alpha, \Upsilon_1, \Upsilon_2}$, null hypothesis is rejected at (1-α) % confidence level i.e. the chosen parameters have no significant influence on the response is rejected, where α = risk level = 1-confidence level = 0.01 (for 99% confidence), Υ_1 is degree of freedom (DF). For single interaction it is 2 and for two-way interaction it is 4. Υ_2 is degree of freedom (DF) for residual error = 27. $F_{0.01, 2, 27} = 5.49$ and $F_{0.01, 4, 27} = 4.11$ from standard tables at 99% confidence. From ANOVA table of surface roughness and electrical conductivity, p – value for all input parameters as well as two way and three way interactions are less than 0.05

showing that there is a significant relation between all parameters individually as well as their interactions with surface roughness and electrical conductivity. Since, F from ANOVA table for individual effects as well as for all two way interactions are greater than $F_{\alpha, \Upsilon 1, \Upsilon 2}$, null hypothesis is rejected i.e. “the chosen parameters have no significant influence on the response i.e. roughness and electrical conductivity” is rejected.

Table 2: ANOVA table for (a) surface roughness (b) Electrical Conductivity (c) Grain area

(a)	Terms	df	Adj ss	Adj ms	F	F from Table	‘p’-Value	Percentage contribution (%)
Model		26	0.437	0.016	19.61		0<0.05	95
Linear		6	0.170	0.028	33.18		0<0.05	36.95
Speed		2	0.042	0.021	24.68	5.49	0<0.05	9.13
Feed		2	0.041	0.020	23.92	5.49	0<0.05	8.91
Force		2	0.087	0.043	50.95	5.49	0<0.05	18.91
2-Way Interactions		12	0.231	0.019	22.5		0<0.05	51.52
Speed×Feed		4	0.097	0.024	28.32	4.11	0<0.05	21.08
Speed×Force		4	0.048	0.012	14.26	4.11	0<0.05	10.43
Feed×Force		4	0.085	0.021	24.93	4.11	0<0.05	18.47
3-**Way Interactions**		8	0.035	0.004	5.1		0.001<0.05	7.60
Speed× ×Feed×Force		8	0.035	0.004	5.1		0.001<0.05	7.60
Error		27	0.023	0.0008				
Total		53	0.460					

(b)	Terms	df	Adj ss	Adj ms	F	F from Table	‘p’-Value	Percentage contribution (%)
Model		26	21895.5	842.13	60.15		0<0.05	98.30
ar		6	5262	877.00	62.64		0<0.05	23.62
Speed		2	3584.1	1792.0	128.0	5.49	0<0.05	16.09
Feed		2	1112.7	556.35	39.74	5.49	0<0.05	4.99
Force		2	565.1	282.57	20.18	5.49	0<0.05	2.53
2-Way Interactions		12	6720.4	560.04	40.00		0<0.05	30.17
Speed×Feed		4	2512.0	627.99	44.86	4.11	0<0.05	11.27
Speed×Force		4	2614.9	653.71	46.69	4.11	0<0.05	11.73
Feed×Force		4	1593.6	398.41	28.46	4.11	0<0.05	7.15
3-Way Interactions		8	9913.0	1239.1	88.51		0<0.05	44.50
Speed×Feed×Force		8	9913.0	1239.1	88.51		0<0.05	44.50
Error		27	378.0	14.00				
Total		53	22273.5					

(c) Terms	df	Adj ss	Adj ms	F	F from Table	'p'-Value	Percentage contribution (%)
Model	26	40.38	1.553	2.29		0.018	68.77
Linear	6	29.52	4.921	7.25		0	50.28
Speed	2	20.53	10.26	15.12	5.49	0<0.05	34.96
Feed	2	7.158	3.579	5.27	5.49	0.012<0.05	12.19
Force	2	1.837	0.918	1.35		0.276	3.12
2-Way Interactions	12	7.388	0.615	0.91		0.553	12.58
Speed×Feed	4	3.42	0.855	1.26		0.31	6.25
Speed×Force	4	1.819	0.454	0.67		0.619	3.32
Feed×Force	4	2.15	0.537	0.79		0.541	3.92
3-Way Interactions	8	3.467	0.433	0.64		0.739	5.90
Speed×Feed×Force	8	3.467	0.433	0.64		0.739	5.90
Error	27	18.33	0.679				
Total	53	58.71					

df: Degree of freedom, ss: Sum of squares, ms: Mean squares

Hence, choice of parameters is justified. Percentage contribution for roughness shows that interaction effect of speed and feed is maximum (21.08 %) followed by burnishing force (18.91 %). Percentage contribution for electrical conductivity shows that the three-way interaction effect of speed, feed and force is maximum (44.50 %) followed by burnishing speed (16.09 %) followed by two-way interaction of speed and feed; speed and force (11%). This is in accordance with F test and p-test. From ANOVA table of grain area, p-value for speed and feed is less than 0.05 showing that it has significant effect on grain area. F for speed is greater than $F_{0.01,\,2,\,27} = 5.49$, justifying choice of parameter "speed". Percentage contribution shows that the effect of speed on grain area is maximum (34.96%). Burnishing feed showed next higher influence on grain area i.e. 12.19 %. This is in accordance with F test and p-test. From the experimental values, optimum burnishing parameters which minimize surface roughness, maximize electrical conductivity and minimize grain area are shown in Table 3.

In real time applications, where multiple responses are measured, optimum results from single response optimization may not be useful. In such case, based on the importance given to different responses, multi- response optimization has to be performed.

Step-1

Grey relational approach is used to accomplish multi response optimization. Response values of roughness & grain area are normalized using relation Eq. (2), as they have to be minimum and electrical conductivity is normalized using relation Eq. (1), as it has to be maximized.

Higher is better: $x_i'(a) = \frac{x_i^p(a)-\min x_i^p}{\max x_i^p(a)-\min x_i^p(a)}$ (1)

Lower is better: $x_i'(a) = \frac{\max x_i^p - x_i^p(a)}{\max x_i^p(a)-\min x_i^p(a)}$ (2)

Here, $x_i'(a)$ is response after normalization. In $x_i^p(a)$, 'i' represents number of experiments i.e from 1 to 27 and 'p' represents number of responses i.e 1 to 3.Deviation sequences are evaluated using relation Eq. (3), where $x_0'(a)$ is a maximum of normalized values.

$\Delta_{0,i}(a) = |x_0'(a) - x_i'(a)|$ (3)

Step-2

Grey relational coefficient, $\xi_{0,i}(a)$ is evaluated using relation Eq. (4) where Δ_{min} and Δ_{max} are lowest and highest values from deviation sequences. Usually, ζ is taken as 0.5.

$\xi_{0,i}(a) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{0,\,i}(r)+\zeta\,\Delta\,max}$ (4)

Step-3

Grey relational grade (GRG) ($\gamma_{0,i}$) is evaluated using weighted mean based on importance given to each response using the relation Eq. (5) [18].

$\gamma_{0,i} = \frac{1}{p}\sum_{n=1}^{p} \boldsymbol{w_n}\, \xi_{0,1}(\text{n})$ (5)

Table 3: Optimum burnishing parameters

	Minimum surface roughness	**Maximum electrical conductivity**	**Minimum grain area**
Optimum Parameters	A3B2C3	A2B2C1	A2B3C3
Burnishing speed (rpm)	465	290	290
Feed (mm/rev)	0.223	0.223	0.243
Burnishing force (N)	125	54	125

Normalized values, deviation sequences, GRGs & ranks are shown in Table 4. ANOVA in Table2 shows that surface roughness and electrical conductivity depends on all the three parameters as well as on their interactions but grain area depends only on speed. So, equal importance is given to surface roughness and electrical conductivity and hence same weightage i.e 0.4 and less importance and hence less weightage is given to grain area i.e 0.2. Table 5 shows the table of response for GRG. It gives ranking for input parameters based on the order in which they influence the output. Speed is found to influence GRG the most, followed by burnishing force and feed. Main effect plot for Grey Relational Grade is shown in Figure 6. With rise in burnishing speed from 100rpm to 290rpm, plots for grey relational grade has increased and then decreased from 290rpm to 465rpm. This shows that 290rpm is the optimum burnishing speed, where the plots for GRG is maximum, in the considered range of speed. Slope of grey relational grade is more which shows that spindle speed has influence on grey relational grade. MEP of GRG with burnishing feed demonstrates that GRG has initially raised and then remained stable. MEP of GRG with burnishing force shows that with increase in burnishing force, grey relational grade has increased.

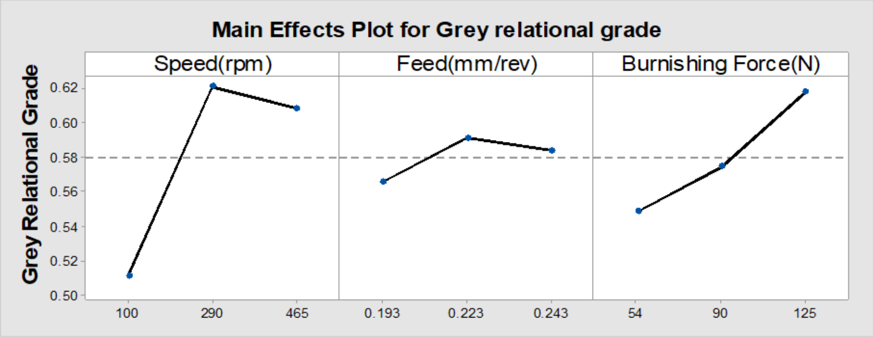

Fig 6: Main Effect Plots for Grey Relational Grade

Table 4: Normalized values, deviation sequences, Grey relational grade and rank

				Normalized values			**Deviation Sequences**			**Grey relational grade**	**Rank**
Experiment No.	Speed (rpm)	Feed (mm/rev)	Force (N)	Surface Roughness (μm)	Electrical Conductivity (S/m)	Grain Area (10^{-5} mm^2)	Surface Roughness (μm)	Electrical Conductivity (S/m)	Grain Area (10^{-5} mm^2)		
1	100	0.193	54	0.651	0.1344	0.2725	0.3488	0.8655	0.7274	0.4635	24
2	100	0.193	90	0.8135	0.3387	0.0054	0.1864	0.6612	0.9945	0.5304	18
3	100	0.193	125	0.8908	0.0053	0.0216	0.1091	0.9946	0.9783	0.5297	19
4	100	0.223	54	0.5019	0.0967	0	0.4980	0.9032	1	0.4095	27
5	100	0.223	90	0.6870	0.1989	0.1750	0.3129	0.8010	0.8249	0.4752	23
6	100	0.223	125	0.8215	0.3440	0.1660	0.1784	0.6559	0.8339	0.6427	17
7	100	0.243	54	0	0.6397	0.3231	1	0.3602	0.6768	0.4508	25
8	100	0.243	90	0.6697	0.1935	0.7617	0.3302	0.8064	0.2382	0.5294	20
9	100	0.243	125	0.7150	0.5376	0.5703	0.2849	0.4623	0.4296	0.5701	15
10	290	0.193	54	0.9720	0.2634	0.2075	0.0279	0.7365	0.7924	0.6179	8
11	290	0.193	90	0.5659	0.3709	0.7545	0.4340	0.6290	0.2454	0.5253	21
12	290	0.193	125	0.8788	0.3763	0.4855	0.1211	0.6236	0.5144	0.5985	11
13	290	0.223	54	0.6058	1	0.4909	0.3941	0	0.4061	0.7227	4
14	290	0.223	90	0.6058	0.1236	0.5938	0.3941	0.8763	0.5361	0.4793	22

15	290	0.223	125	0.8388	0.4247	0.4638	0.1611	0.5752	0.5361	0.5850	14
16	290	0.243	54	0.8974	0.3118	0.3772	0.1025	0.6881	0.6227	0.5893	13
17	290	0.243	90	0.9840	0.5967	0.7202	0.0159	0.4032	0.2797	0.7372	1
18	290	0.243	125	0.9507	0.3010	1	0.0492	0.6989	0	0.7309	2
19	465	0.193	54	0.9081	0.1989	0.7093	0.0918	0.8010	0.2906	0.6181	7
20	465	0.193	90	0.8988	0.4086	0.6913	0.1011	0.5913	0.3086	0.6395	6
21	465	0.193	125	0.9214	0	0.3519	0.0785	1	0.6480	0.5661	16
22	465	0.223	54	0.8641	0.0698	0.8844	0.1358	0.9301	0.1155	0.6168	9
23	465	0.223	90	0.7483	0.500	0.9891	0.2516	0.5	0.0108	0.6618	5
24	465	0.223	125	1	0.1827	0.9296	0	0.8172	0.0703	0.7271	3
25	465	0.243	54	0.0745	0.2096	0.8375	0.9254	0.7903	0.1624	0.4462	26
26	465	0.243	90	0.7709	0.2096	0.8772	0.2290	0.7903	0.1227	0.5899	12
27	465	0.243	125	0.8189	0.0967	0.9158	0.1810	0.9032	0.0841	0.6077	10

Table 6 shows the Analysis of Variance for GRG. F value from ANOVA table for individual effect of speed is greater than $F_{0.01,\ 2,\ 20}$= 5.84, null hypothesis is rejected i.e. "the parameter speed has no significant influence on the response i.e. grey relational grade" is rejected. Hence, choice of parameter "speed" is justified. P – value for speed is < 0.05, shows that speed have significant influence on GRG. This is in accordance with F test. Percentage contribution shows that the influence of speed on GRG is maximum (34.35 %). This is in accordance with F test and p-test. Maximizing Grey relational grade will ensure minimizing surface roughness and grain area with 40% and 20% importance and maximizing electrical conductivity with 40% importance. From GRGs shown in Table 4, maximum GRG is obtained at experiment 17 i.e at A2B3C2 i.e. at spindle speed of 290 rpm, feed 0.243mm/rev and 90N force. Assuming that initial design is taken as A1B1C1.

Table 5: Table of response for GRG

Parameters\Levels	1	2	3	Rank
Speed(rpm)	0.5	0.6207	0.6081	1
Feed (mm/rev)	0.5654	0.58	0.5835	3
Force (N)	0.5483	0.5742	0.6064	2

Table 7 shows the result of single response optimization and multi response optimization and percentage improvement w.r.t initial design. With single response optimization for surface roughness, optimum condition is obtained as A3B2C3. The percentage improvement in surface roughness is found to be 51.57 %, in electrical conductivity is found to be 2.07 % and in grain area is found to be 33.57 % with respect to initial condition. With single response optimization for electrical conductivity, optimum condition is obtained as A2B2C1. The percentage improvement in electrical conductivity is found to be 37.6 %, in surface roughness is found to be 6.69 % and in grain area is found to be 11.25 % with respect to initial condition. With single response optimization for grain area, optimum condition is obtained as A2B3C3. The percentage improvement in grain area is found to be 37.26 %, in surface roughness is found to be 44.48 % and in electrical conductivity is found to be 7.14 % with respect to initial condition. With multi response optimization, optimal parameters which simultaneously minimize surface roughness, maximize electrical conductivity and minimize grain area, with 40% importance to surface roughness and electrical conductivity and 20% importance to grain area, are A2B3C2. GRG obtained is 0.737. GRG for single response optimization is also found out and shown in Table 7. Grey relational grade from multi response optimization (0.737) is higher than grey relational grade for initial design (0.463), single response optimization for surface roughness (0.727), for electrical conductivity (0.722) and grain area (0.730). Higher the grey relational grade, better is the result.

Hence optimal process parameters in roller burnishing of Al6061 alloy: Speed of burnishing**:** 290rpm, feed: 0.243mm/rev, and burnishing force: 90N which would lead to minimum surface roughness and grain area and maximum electrical conductivity.

Table 6: Analysis of Variance for GRG

Terms	df	Adj ss	Adj ms	"p"Value	Percentage contribution (%)
A	2	0.0719	0.0359	0.008	34.35
B	2	0.0029	0.0014	0.78	1.38
C	2	0.0186	0.0093	0.226	8.88
Error	20	0.1158	0.0057		
Total	26	0.2093			

Table 7: Comparison of Single Optimization & Multi Response Optimization

	Surface Roughness (µm)	Percentage Improvement (%)	Electrical Conductivity (x10^5 S/m)	Percentage Improvement (%)	Grain Area (x10^{-5}mm^2)	Percentage Improvement (%)	GRG	GRG Percentage
Initial Design A1 B1 C1	0.254		217		5.42		0.4635	
Optimum Surface Roughness A3 B2 C3	0.123	51.57	221.5	2.07	3.6	33.57	0.7271	56.87
Optimum Electrical Conductivity A2 B2 C1	0.271	6.69	297.5	37.09	4.89	11.25	0.7227	55.92
Optimum Grain Area A2 B3 C3	0.141	44.48	232.5	7.14	3.405	37.26	0.7309	57.69
Multi response Optimization A2 B3 C2	0.132	48.03	260	19.81	4.8	11.09	0.7372	59.05

IV. CONCLUSIONS

1. Burnishing operation has improved surface roughness, electrical conductivity and grain area compared to unburnished surface. Speed, feed and burnishing force with their 2 way interactions and 3-way interaction showed significant influence on the roughness and electrical conductivity of the surface.
2. Single response optimization is performed and optimum parameters for minimum surface roughness is found to be Speed = 465rpm, Feed = 0.223mm/rev, and Burnishing force = 125N with a percentage improvement of 51.57% with respect to the initial conditions. Optimum parameters for maximum electrical conductivity is found to be Speed = 290rpm, Feed = 0.223mm/rev, and Burnishing force = 54N with a percentage improvement of 37.09% with respect to the initial conditions. Optimum parameters for minimum grain area is found to be Speed = 290rpm, Feed = 0.243mm/rev, and Burnishing force = 125N with a percentage improvement of 37.26% with respect to the initial conditions.
3. Optimum parameters from multi response optimization parameters which minimizes surface roughness, maximizes electrical conductivity with 40% importance to both and minimizes grain size with 20% importance are Speed = 290rpm, Feed = 0.243mm/rev, and Burnishing force = 90N with a percentage improvement in GRG of 59.05% with respect to the initial conditions.
4. GRG comparison shows that multi response optimization gave best result compared to single response optimization for the considered weightage given to the responses.
5. This parameter (Speed = 290rpm, Feed = 0.243mm/rev, and Burnishing force = 90N) gave best results compared remaining conditions.

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