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Modeling and Optimization of surface roughness and microhardness for roller burnishing process using response surface methodology for Aluminum 63400 alloy

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Abstract

In the present investigation response surface methodology (RSM) is used to fit the quadratic model for surface roughness and microhardness of roller burnishing process on Aluminum alloy 63400 Grade. The desirability function technique is utilized to optimize the responses. Central composite design (CCD) technique is used to prepare the experiment matrix. Single roller carbide burnishing tool is employed for preparing experiment samples. The individual and interaction of effect each controllable parameter is analyzed using analysis of variance (ANOVA) and quadratic regression analysis is performed to compute the correlation coefficient. It is observed that for surface roughness, feed and for microhardness, force and number of tool passes is the most significant parameter. To find the optimum value for both the responses, desirability function approach is used.

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1. Introduction

Machining marks of irregular heights and spacing called asperities are always seen on the surface of the component. The irregularities on the surface are in the form of a succession of hills and valleys of varying in height and spacing. These peaks and valleys contact each other so the real area of contact will generally be much less than

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the apparent contact area. Adams and Nosonovsky [1] explain the phenomenon of asperity deformation in detail, as the initial contact between workpiece and tool comes at few points and as load increase, the contact further grows. The deformation occurs at contact point which may be elastic, plastic, viscoelastic or viscoplastic. The stresses at the point of contact are very high compared to the nominal stresses. When these stresses exceed the yield point, permanent plastic deformation takes place. This will reduce the height and spacing of the irregularity, resulting in the smooth surface is explained by K.O. Lowa [2]. The plastic deformation changes the mechanical and metallurgical properties.

Hongyun Luoa [3], Korzynski [4], and Djordje Vukelic [5] obtain mathematical model with number of assumptions. The work concludes that force or depth of penetration is the significant factor for the process. For the development of mathematical model extensive data of sample piece and tool material is needed such as mechanical properties of sample and tool (Young's modulus, Poisson's ratio, density, and hardness), surface properties of sample and tool (radius of asperity and surface roughness, a standard deviation of surface height). This limits the use of the model hence empirical models are generally used in the machining process. Statistical model is developed by several researchers. Hassan, Al-Jalil [6] studied the effect of burnishing force and number of ball passes for the optimum surface finish of brass components. A second order mathematical model has been developed with the response surface technique to relate the surface roughness and therefore the two main burnishing parameters force and tool passes. Work on various nonferrous metals is studied by El-Axir [7], M.H. El-Axir* [8], M.H. El-Axir [9], M.H. El-Axir [10]. Klocke and Liermann [11] used the burnishing technique for the hard-turned surface. Recently researcher is using an artificial neural network(ANN) to fit the nonlinear data. Roller burnishing AL6061 in parallel burnishing orientation and cross burnishing orientation was investigated by Tang, Hakim [12].This study developed an ANN technique. Optimization is done with feed-forward back-propagation network trained by Levenberg–Marquardt training algorithm.

2. Experiment methodology and characterization

The workpiece material used in this study is Aluminum 63400 alloy. The chemical composition of the material is tested in the laboratory using Optical Emission Spectroscopy. Aluminum rod of diameter 30 mm and length 600 mm is turned on Computer numerical control (CNC) lathe. For initial machining parameters defined are as speed = 400 rpm, feed = 0.2 mm/rev. After turning, the tool is replaced by single roller carbide burnishing tool. Burnishing operation is performed as shown in the Fig. 1. The independently controllable parameters; speed, feed, force and number of passes, are varied in the experiment. The design in the randomized way depicted in Table 1 is used to perform thirty-one experiments on sample workpiece that are previously turned on CNC lathe. The responses are quantified using MITUTOYO model -SJ211 and Vickers microhardness tester for surface roughness and microhardness respectively. Though there are several parameters used to describe the surface roughness, it is generally measured in terms of roughness average Ra value. In the calculation of roughness average, first sampling length is decided, and mean line is marked over the profile. Deviation of profile height from mean line is calculated. Its absolute value gives Ra. The microhardness of the burnished workpiece is measure with Vickers microhardness tester. The component is firmly held in V Block, 500g force is applied by using diamond indenter on the workpiece. The load is applied for 5 to 15 seconds. After removal of the load, the workpiece is viewed by employing a microscope (400X magnification). The two diagonals of the indentation on the surface are measured.

Fig. 1. Experiment setup of roller burnishing process.

Table 1. Experiment matrix

standard order	speed (m/min)	Feed (mm/rev)	Force (N)	Tool passes	Roughness (µm)	Microhardness (HV)	standard order	speed (m/min)	Feed (mm/rev)	Force (N)	Tool passes	Roughness (µm)	Microhardness (HV)
5	20	0.5	40	2	1.0	114	4	40	0.7	20	2	1.7	76
17	10	0.6	30	3	0.6	96	12	40	0.7	20	4	2.2	106
2	40	0.5	20	2	0.9	88	23	30	0.6	30	1	0.9	98
24	30	0.6	30	5	0.9	138	15	20	0.7	40	4	1.7	120
7	20	0.7	40	2	1.4	117	20	30	0.8	30	3	2.9	107
16	40	0.7	40	4	1.7	110	3	20	0.7	20	2	1.5	93
27	30	0.6	30	3	0.5	102	22	30	0.6	50	3	0.8	116
19	30	0.4	30	3	0.5	116	18	50	0.6	30	3	0.6	106
14	40	0.5	40	4	0.6	120	1	20	0.5	20	2	0.8	91
31	30	0.6	30	3	0.8	115	10	40	0.5	20	4	0.9	117
8	40	0.7	40	2	0.8	93	11	20	0.7	20	4	1.5	109
9	20	0.5	20	4	0.8	106	26	30	0.6	30	3	0.7	101
13	20	0.5	40	4	0.4	116	6	40	0.5	40	2	0.8	103
21	30	0.6	10	3	0.8	81	25	30	0.6	30	3	0.52	103
30	30	0.6	30	3	0.5	114	29	30	0.6	30	3	0.73	113
							28	30	0.6	30	3	0.47	103

3. Model fitting for surface roughness and microhardness

Sequential model sum of squares [type I], lack-of-fit test, and the model summary statistic is prepared using Design-Expert 7. For the experimental data, different models (first-order or linear, first-order with interaction, second -order, and cubic) are prepared. Adequacy of the quadratic model is confirmed by the ANOVA. It is used to study the effect of the controllable parameters on responses. Source, sum of squares (SS), degrees of freedom, mean square (MS), F-ratio and p-value are calculated for surface roughness and microhardness. The source consists of factors, error, and total. The 5% significance level, i.e. 95% confidence level is considered for the analysis. The p-value for both models shown in Table 2 is less than 0.0001 which well below 0.005. Significance of the model is also confirmed by an insignificant Lack-of-Fit and R^2 value presented in Table 3. Hence the fitness of the quadratic mathematical model is confirmed for the experimental data. The mathematical model for both the responses is expressed in coded form is presented in Table 4.

4. Optimization of process parameters

Table 2. Sequential model SS

Source	Roughness	Micro hardness
	p-value	p-value
Linear vs Mean	0.0003	< 0.0001
2FI vs Linear	0.6900	0.0967
Quadratic vs 2FI	< 0.0001	0.0183
Cubic vs Quadratic	0.1433	0.6368

Table 3 Lack-of-fit and model summary statistics

Source	Lack-of-fit		Model summary statistics					
	Roughness	Micro hardn	Roughness			Micro hardness		
	p-value	p-value	R^2	Adjusted	Predicted	R^2	Adjusted	Predicted
Linear	0.003	0.269	0.5	0.4	0.3	0.6	0.6	0.5
2FI	0.002	0.392	0.6	0.4	0.1	0.7	0.6	0.6
Quadra	0.063	0.773	0.9	0.8	0.5	0.8	0.8	0.6
Cubic	0.091	0.697	0.9	0.9	-0.1	0.9	0.8	0.01

Table 4. Mathematical models.

Response	Mathematical model in coded form
Surface roughness	$\text{Roughness} = 0.62 + 0.026*A + 0.47*B - 0.079*C + 0.048*D + 0.011*A*B -0.11*A*C + 0.084*A*D - 0.049*B*C + 0.16*B*D + 7.062E - 003*C*D + 0.033*A^2 + 0.32*B^2 + 0.078*C^2 + 0.11*D^2$
Microhardness	$\text{Microhardness} =107.488571 - 1.354173889*A - 2.072492778*B + 7.375840556*C + 8.750826111*D - 3.483760833*A*B - 1.818760833*A*C + 3.57001083*A*D + 0.35376083*B*C + 0.054989167*B*D -3.33001083*C*D -1.860057718*A^2 + 0.729942282*B^2 -2.512557718*C^2 + 2.34369228 *D^2$

For any process, every response may have distinctive objectives to accomplish, like maximization, minimization, contingent on the quality requested. Desirability function approach consolidates every one of the objectives put for every response. The importance is assigned to each response. Numerical iterative techniques are used by optimization tool to obtain the solution. In the study, criteria selected for optimization are summarized in Table 5. The equal importance is given to surface roughness and microhardness, other factors speed, feed, force and a number of tool passes is kept in the range. The iterative numerical technique is used by Design-Expert 7.0 to solve desirability function, which is a geometric mean of all transformed responses; surface roughness and microhardness in the current work. The few iterations having maximum desirability value of the responses are presented in Table 6. The optimum solution is the input parameters, which shows maximum desirability value. Hence, the most desirable burnished condition desirability value 0.872 is, speed 37.9 m/min, feed 0.5 mm/rev, force 35.49 N and number of passes four. Surface roughness obtained is 0.524 µm and microhardness 125.02 HV. This is the optimum condition for minimum surface roughness and maximum microhardness.

5. Effect of different parameters on surface roughness and microhardness

The three-dimensional plot of feed versus a force for surface roughness is shown in the Fig.2.It is observed an increase in the feed considerably affects the surface roughness. As feed is increased the contact area between the tool and work surface increases due to which the asperities deform plastically. But as soon the surface attains minimum value further increase in feed and force distortion of the micro-profile the surface takes place which deteriorates surface profile. The three-dimensional plot of force versus a number of passes for microhardness is shown in the Fig.3.It is observed that an increase in the force and number of tool passes improves microhardness. Increase in both the parameters, the tool penetrates beyond the maximum asperity height which causes surface hardening.

6. Conclusions

Single roller carbide burnishing tool is used to burnish Aluminum 63400 alloy. Experimentation is performed with Box and Wilson CCD. The machining factors controlled during the experiments are speed, feed, force and number of tool passes. The response parameter is surface roughness and microhardness. ANOVA is employed to determine the most significant control factors on the surface roughness and microhardness. ANOVA is performed for statistical

Table 5. Criteria for optimization.

Factors and response	Criteria	Importance
Speed	In range	+++
Feed	In range	+++
Force	In range	+++
Number of passes	In range	+++
Surface roughness	Minimize	+++++
Microhardness	Maximize	+++++

Table 6. Optimal solutions obtained by desirability function.

A	B	C	D	roughness	microhardness	Desirability
38.1	0.5	35.49	4	0.527	125.186	0.873
37.79	0.5	35.49	4	0.524	125.072	0.872
37.05	0.5	39.04	4	0.522	124.549	0.868
38.2	0.5	39.93	4	0.531	124.461	0.866
20	0.56	40	4	0.653	117.290	0.778

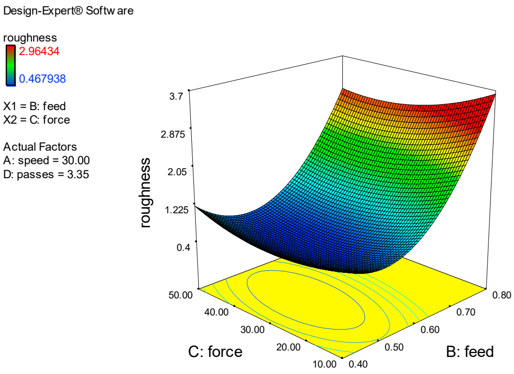

Fig. 2. Three-dimensional plot of roughness

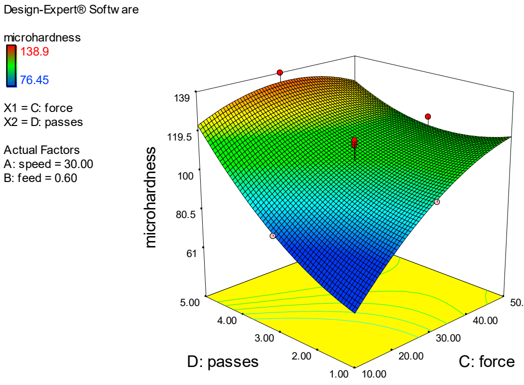

Fig. 3. Three-dimensional plot of microhardness

significance of the model. Mathematical models correlating process parameters with response surface roughness and microhardness were established. Experimental values and values predicted by Design-Expert 7.0 were compared. The desirability function approach is used to obtain minimum surface roughness and maximum microhardness. Following are the main conclusion of the study.

Feed is the most significant parameter affecting the surface roughness. For microhardness, the significant parameters are force and number of tool passes. A lot of interaction between various controllable parameters is observed for both responses, surface roughness, and microhardness. For surface roughness interaction between feed and force is significant. The interaction between force and number of tool passes influences microhardness significantly. Paradoxical behaviour between the surface roughness and microhardness is observed. In the initial stage of the burnishing process, surface smoothing mechanism takes place because of the plastic deformation of the asperities. In the later stage, work hardening takes place which increases microhardness. Besides the burnishing parameters, initial surface roughness affects the responses.

RSM allows us to fit the quadratic model for various responses. The validity of the model can be checked with ANOVA. The most desirable burnished condition desirability value 0.872 is, speed 37.9 m/min, feed 0.5 mm/rev, force 35.49 N and number of passes four. Surface roughness obtained is 0.524 µm and microhardness 125.02 HV. A desirability function technique can be used to optimize both the surface roughness and microhardness. The equal importance is given to both the responses surface roughness and microhardness both. Also, the importance of the different parameters is to be given manually. Based upon the importance given to the different parameters results may vary. Hence this is not a generalized model for multi-response optimization. Multiobjective optimization for surface roughness and microhardness need be carried out to obtain Pareto front which helps to visualize and quantify trade-offs amongst both responses.

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