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AN INVESTIGATION ON DEVELOPING A DRILLING BURR PREDICTION MODEL

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Abstract: Presence of burr after a manufacturing process is a potential problem. Prediction of burr size in machining plays an important role in process planning. The present work deals with the study and development of a burr height prediction model during machining aluminium alloy, using Response Surface Methodology (RSM). Drilling parameter such as cutting velocity, feed rate and drill diameter are considered in conducting experiments in a radial drilling machine to find out height of burr formed in aluminium alloy flats. By performing ANOVA, it is found that drill diameter is the most significant factor to influence formation of burr height. Combination of process parameters giving small burr height is found out within the experimental constraints. Three-dimensional surface and contour plots show the variation in burr height with different process parameters. A comparison of modeled and experimental results corresponding to a low burr height shows an error of less than 3%.

Keywords: Drilling; burr height; RSM; ANOVA; size effect.

1. INTRODUCTION TO DRILLING BURR

Burr formed in drilling operation is a topic of research in manufacturing industries, and particularly in aerospace and automotive sectors. The exit burr is usually much large in size. On the other hand, interlayer burr for a composite material is a major problem requiring the need of an additional process, named deburring. Though several studies are there concerning tool wear or quality of hole, few of these are only on burr formation in drilling aluminium alloy. Burr can be reduced by controlling different process parameters responsible for burr formation in drilling process.

Gillespie [1] was one of the first researchers to study the effects of process conditions, tool geometry and material properties on burr formation over a wide range of test conditions and proposed a basic model of burr formation in drilling. Dornfeld et al. [2] explored the effect of drill geometry and cutting conditions on burr formation during drilling of Ti–6Al–4V titanium alloy plates with solid carbide and high-speed cobalt drills and reported that cutting conditions had little effect, while drill geometry had major effect on burr size. Sofronas [3] made a fundamental study of burr formation in drilling for carbon steel, whereas Ko et al. [4] carried out drilling tests under various cutting conditions using drills of various shapes with several materials, and suggested step drill with specific step angle and step size to minimize burr formation. Shikata et al. [5] studied burr formation in carbon steel sheet drilling and proposed a basis for characterizing burr size. Min [6] and Kim et al. [7] developed control charts for control and prediction of burr height during drilling different steels. The significant effect of point angle and lip clearance angle on drilling of stainless steel 316L work material were proved by Gaitonde et al. [8]. Several researchers [9-14] chose finite element models for analyzing burr formation in drilling in order to develop a basic model and reduce burr size. Drill size effects were analyzed by Kundu [15] and Neugebauer et al. [16]. Pande and Relekar [17] proved response surface methodology (RSM) using statistical design of experiments based on central composite rotatable design as an efficient modelling tool in reduction of burr size in drilling through holes. A number of modelling methods in drilling were tried to relate process variables with burr formation. Artificial neural network (ANN) was applied by Mondal et al. [18], Gaitonde et al. [19] and others, while Singh et al. [20] and Nandi et al. [21] used fuzzy logic.

In this work, an attempt has been made to study and develop a burr height prediction model for machining light weight aluminium alloy using HSS twist drills by applying response surface methodology (RSM). The influence of cutting velocity, feed and drill diameter on exit side burr height is tried to find out.

2. RESPONSE SURFACE METHOD

Response surface method (RSM) adopts both mathematical and statistical techniques which are useful for modelling and analysis of problems in which a response is influenced by several variables. The RSM is attempted to analyze the influence of independent variables on a specific dependent variable (response). The independent variables denoted by x_1, x_2, ..., x_k are presumed to be continuous and can be controlled with negligible error. The response (D) is postulated to be a random variable. For two independent variables x_1 and x_2, the response D can be represented as a function of x_1 and x_2 as follows [22] :

$$D = f(x_1, x_2) + \varepsilon \tag{1}$$

where ε represents an error component.

If the expected response is denoted by $E(D-\varepsilon) = \hat{D}$, then the surface represented by $\hat{D} = f(x_1, x_2)$ is termed as the response surface. A second or higher order RSM model is necessary to approximate the surface around a curvature. In most cases, a second-order RSM model is adequate which can be represented by the following equation:

$$D = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \hat{\beta}_{ij} (i<j) x_i x_j + \varepsilon \tag{2}$$

and the best-fit equation is represented by

$$\hat{D} = E(D-\varepsilon) = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_i x_i^2 + \sum_{i}^{k} \sum_{j}^{k} \hat{\beta}_{ij} (i<j) x_i x_j \tag{3}$$

3. EXPERIMENTAL INVESTIGATION

The workpiece material chosen is an aluminium alloy in the form of rectangular flat with 100 mm in length, 50 mm in breadth and a thickness of 5 mm. Taper shank uncoated HSS twist drill has been used for experimentation. The chemical composition of the chosen material is given in Table 1.

Table 1 Chemical composition of aluminium alloy workpiece in wt. %

Cu	Fe	Mg	Zn	Pb	Si	Al
0.1	0.74	0.6	0.28	0.02	0.37	rest

Drilling on the workpieces has been conducted under dry condition on a radial drilling machine which has a maximum spindle speed of 1415 rpm and power rating of 1.5 kW. Drilling burr is generally characterized by its height and thickness, but for the present study, burr height is considered only as the response. Burr observed in drilling of aluminium alloys are measured by Mitutoyo (Japan) make vernier caliper and averaged burr heights are considered for RSM analysis. The detail of experimental setup and conditions are given in the Table 2.

Three factors have been selected for this experiment. These are cutting velocity, feed rate and drill diameter with three levels as shown in Table 3. To find out size effect, at a cutting velocity, three different drill diameters have been selected with suitable RPMs. Experiments have been carried out according to the experimental plan based on face centred cubic (FCC) design**.** Therefore, by applying RSM, there will be 20 experimental observations. The lower limit for low (level: -1) was added for cutting velocity (20 m/min), feed rate (0.032 mm/rev) and drill diameter (6 mm). While the upper limit for (level: +1) was added for cutting velocity (31 m/min), feed rate (0.125 mm/rev) and drill diameter (12 mm).

Table 2 Experimental setup and conditions

Machine tool	Radial drilling machine, make: Energy Limited, India, model: RDH-32/930
Workpiece material	Aluminium alloy, hardness: 153 HB
	Size:100 mm× 50mm× 5mm
Cutting tool	Uncoated HSS taper shank twist drill, make: Addison & Co. Ltd., India, diameter: 6, 9 and 12 mm
Machining conditions	Cutting velocity: 20, 25, 31 m/min Feed: 0.032, 0.08, 0.125 mm/rev Environment: Dry

4. RESULTS AND DISCUSSION

Experiment has been conducted to assess the effect of cutting velocity, feed rate and drill diameter on burr height during drilling of aluminium alloy. Table 4 illustrates experimental results of burr observed in drilling. A low burr height is found to be 3.16 mm and the large one appears to be 9.26 mm.

According to experimental results, drilling aluminium alloy in dry condition always yields crown type burr as shown in Fig. 1. This type of burr formation is

Table 3 Symbols, levels and values of process parameters

Process parameters	Unit	Symbols		Actual Levels					
		Actual	Coded				Coded		
Cutting velocity	m/min	A	x_1	20	25	31	-1	0	+1
Feed rate	mm/rev	B	x_2	0.032	0.08	0.125	-1	0	+1
Drill diameter	mm	C	x_3	6	9	12	-1	0	+1

Table 4 Observed data for second-order RSM

Run No.	Actual values of parameters			Coded values of parameters			Burr type observed	Burr height (mm)
	A	B	C	x_1	x_2	x_3		
1	25	0.08	12	0	0	1	Crown	6.1
2	25	0.08	9	0	0	0	Crown	5.12
3	25	0.08	9	0	0	0	Crown	5.12
4	31	0.125	6	1	1	-1	Crown	3.5
5	31	0.125	12	1	1	1	Crown	6.66
6	20	0.125	6	-1	1	-1	Crown	3.2
7	25	0.08	9	0	0	0	Crown	5.12
8	31	0.08	9	1	0	0	Crown	5.2
9	25	0.032	9	0	-1	0	Crown	5.14
10	25	0.08	9	0	0	0	Crown	5.12
11	20	0.125	12	-1	1	1	Crown	9.26
12	25	0.08	9	0	0	0	Crown	5.12
13	20	0.032	12	-1	-1	1	Crown	6.48
14	31	0.032	12	1	-1	1	Crown	7.22
15	31	0.032	6	1	-1	-1	Crown	4.3
16	20	0.032	6	-1	-1	-1	Crown	3.16
17	25	0.08	9	0	0	0	Crown	5.12
18	25	0.125	9	0	1	0	Crown	4.92
19	25	0.08	6	0	0	-1	Crown	3.18
20	20	0.08	9	-1	0	0	Crown	5.5

usual as reported by earlier investigators [1,3,8,9,15] also.

Among all the process parameters, drill diameter is found to have maximum influence on formation of burr, and burr height is found to be quite low in the present experimental investigation where lower diameter of 6 mm (level: -1) is used. This may be due to less need of thrust and torque while drilling with small diameter drill. When less thrust and torque are required, less need of support material is there thereby reducing the extent of burr formation. This is because of the fact that burr is formed when there is an occurrence of negative shear plane close to the exit portion while chip formation starts, and this causes rotation of material ahead of the cutting tool with respect to a pivot point without the presence of any sizeable material support at the exit edge. With crown type burr formation, burr height would be close to the radius of drilled hole, and the same is also clearly observed in this investigation.

4.1 Mathematical Modelling by Response Surface Method

Based on the experimental data gathered, statistical regression analysis is done to find out the correlation of process parameters with burr height.

Both linear and non-linear regression models are examined; acceptance is based on high to very high coefficients of correlation (r). Coefficients of regression model can be estimated from experimental results. Effects of variables and interaction between them are included in this analysis and the developed model is expressed as interaction equation. The second order response surface equations in terms of the coded values of the independent variables are shown as:

$$h = 5.01927 - 0.072Vc + 0.124\,So + 1.838\,D + 0.4818\,Vc^2 - 0.5225\,Vc\,So - 0.4125\,Vc\,D + 0.1618\,So^2 + 0.3725\,So\,D - 0.2282\,D^2 \quad (4)$$

when,
h = burr height
Vc = cutting velocity
So = feed rate
D = diameter

The mathematical model is obtained using Minitab software [23]. Differentials between minimum and maximum of experimental and calculated values are 6.5% and 5% respectively. Further, the average error between experimental and calculated surface roughness is calculated as 4.7%. Fig 2 shows the variation of experimental and predicted values of burr height at different experimental runs.

i) Exp. No. 1 (Diam.: 12mm) ii) Exp. No. 2 (Diam.: 9mm) iii) Exp. No. 4 (Diam.: 6mm) iv) Exp. No. 5 (Diam.: 12mm) v) Exp. No. 6 (Diam.: 6mm)

vi) Exp. No. 8 (Diam.: 9mm) vii) Exp. No. 9 (Diam.: 9mm) viii) Exp. No. 11 (Diam.: 12mm) ix) Exp. No. 13 (Diam.: 12mm) x) Exp. No. 14 (Diam.: 12mm)

xi) Exp. No. 15 (Diam.: 6mm) xii) Exp. No. 16 (Diam.: 6mm) xiii) Exp. No. 18 (Diam.: 9mm) xiv) Exp. No. 19 (Diam.: 6mm) xv) Exp. No. 20 (Diam.: 9mm)

Fig. 1 Photographic view of typical burrs obtained in drilling of aluminium alloy indicating experiment numbers and respective drill diameters

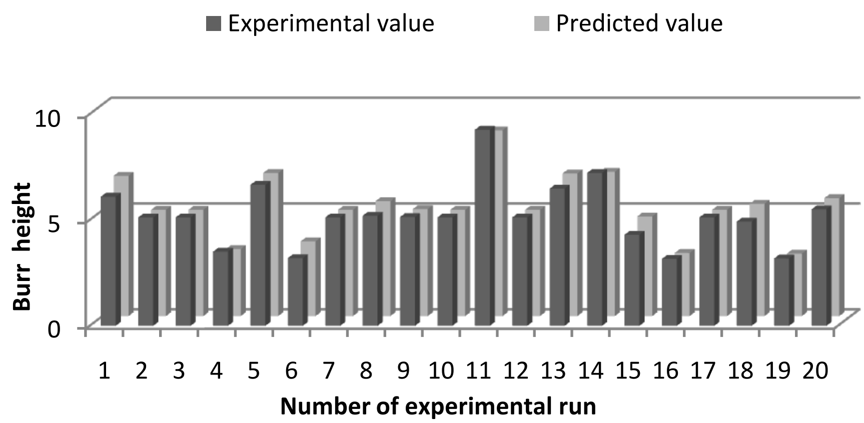

Fig. 2 Plot of experimental and predicted values of burr height (mm) against the number of experimental run

4.2 Checking the Adequacy of the Developed Model

The adequacy of the model is checked by using the analysis of variance (ANOVA) technique using Minitab software [23]. As per this technique, if the calculated value of the F ratio of the developed model does not exceed the standard tabulated value of F ratio for a desired level of confidence (say 95%), then the model is considered to be adequate within the confidence limit. As the square term F-table value is larger than the calculated F-value (Table 5), it is insignificant. Even interaction effect is only slightly significant compared to linear model and regression model. The regression model results indicate that the model is significant and adequate to predict the response at 95% confidence level. It means that the p-value is less than 0.05. Table 5 presents the result of ANOVA. For second order regression model of burr height, the calculated value of F-ratio is more than the table value of F-ratio for responses. It means the model is adequate at 95% confidence level to represent the relationship between the response and process parameters. Further, the experimental data and the predicted data by the using the afore-said model are plotted as shown in Fig. 2, which indicates a good correlation.

The mean effects plot for burr height is shown in Fig. 3. It is clear from the figure that drill diameter has the highest inclination, So, this is the most significant factor affecting burr height among the factors chosen in this work.

To see the effect of process parameters on burr height, three dimensional surface and contour plots (Fig. 4– Fig. 6) are developed using MATLAB software. These plots can also give further assessment of the correlation between process parameters and the response. It is seen that burr height increases with an increase of drill diameter and feed rate keeping cutting velocity as constant at central level (Fig. 4). This may be due to higher thrust and torque required with larger drill diameter that corresponds to larger requirement of support to prove at the exit edge while the drill reaches near to, or exits, the rear surface of the job. Therefore, without a suitable support, the shear plane responsible for machining operation, may have rotated with respect to a pivot point [2,11,15,16,18] to a negative shear angle producing large size burr. However, the gradient is more at the higher side of drill diameter and feed rate than that of lower side.

Table 5 ANOVA table for the model of burr height

Source	DF	Sum of square	Mean square	F-value	F-table	P
Regression	9	39.782	4.4202	29.47	3.15	0
Linear	3	33.988	11.3293	75.54	8.795	0
Square	3	1.1386	0.3795	2.53	8.795	0.116
Interaction	3	4.6554	1.5518	10.35	8.795	0.002
Residual error	10	1.4998	0.15			
Lack-of-Fit	5	1.4998	0.3			
Pure error	5	0	0			
Total	19	41.2818				

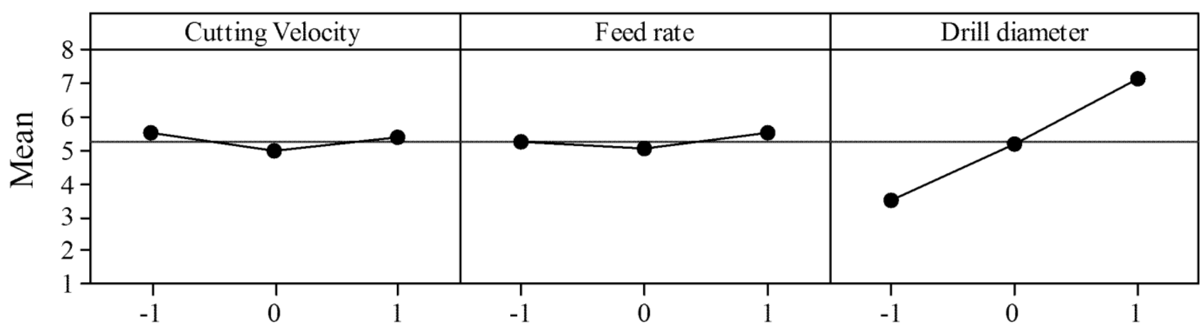

Fig. 3 Mean effect plots for burr height

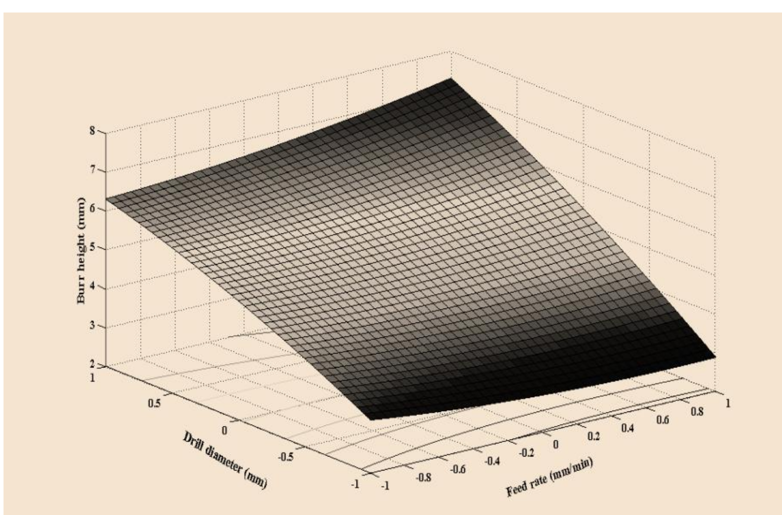

Fig. 4 Surface and contour plot of burr height with drill diameter and feed rate at central level of cutting velocity

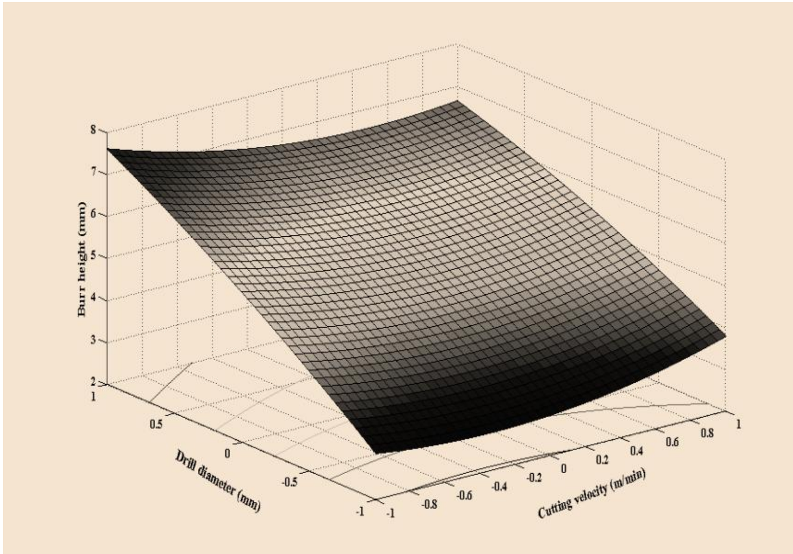

Fig. 5 Surface and contour plot of burr height with drill diameter and cutting velocity at central level of feed rate

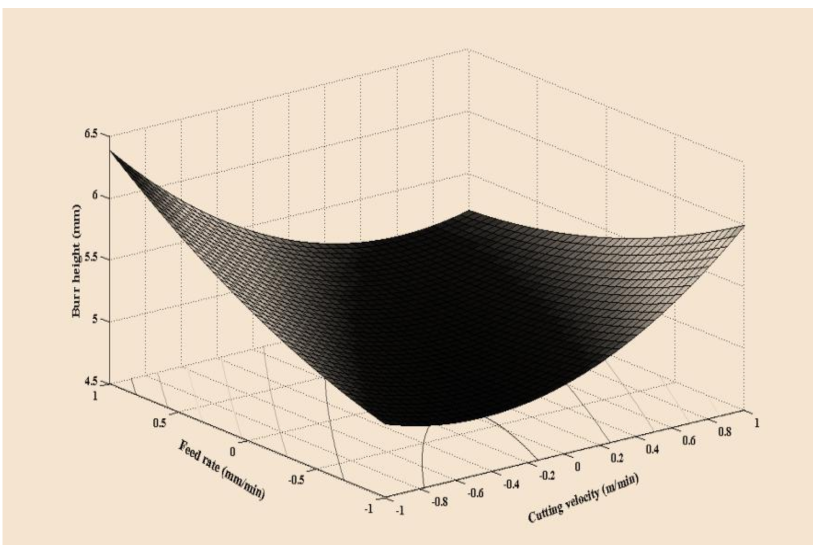

Fig. 6 Surface and contour plot of burr height with feed rate and cutting velocity at central level of drill diameter

Fig. 5 presents the variation of burr height with drill diameter and cutting velocity keeping feed rate at its central level. General trend is that with an increase in drill diameter, burr height increases as discussed in the previous paragraph. The effect of feed rate and cutting velocity on burr height is illustrated in Fig. 6. It is seen that there is a sharp increase of burr height with feed rate. This is natural as hike in feed causes a proportionate increase in thrust, and this may favour formation of a large negative shear angle causing bending of the soft job material at the exit end to a large extent making large value of burr height. However, no appreciable increase in burr height is there with an increase in cutting velocity when drill diameter is kept constant with mid-level value. Increase in cutting velocity does not ideally affect thrust; however, it causes hike in torque. As thrust shows more effect on burr formation than the torque, expectedly, cutting velocity increase shows less effect on burr formation than feed.

4.3 Confirmatory Test

The response surface equation in this work has been derived from quadratic regression fit. Values of the independent variables have been derived through confirmation tests related to burr height. Standard procedure as detailed in reference [23] has been followed in this work for this confirmatory test. Results of the test are shown in Table 6. It is observed that the calculated error is very small. This confirms the reproducibility of experimental conclusion. Finally, response optimizations have also been done based on the experimental data, and Table 6 shows the optimum combination of experimental conditions for a relatively low burr height.

From the present work, modeling the experimental data has been successfully done to find out a relationship between varying process parameters and their interaction effects, and to assess their relative significance on the formation of burr height during drilling aluminium flats, such that the same model can be used for assessing burr height within the experimental domain.

5. CONCLUSION

In the present study, second order equations have been developed for modeling burr height using RSM in drilling an aluminium alloy. The developed model has been validated using ANOVA. Response plots are analyzed to study the effect of process parameters on the response. It is observed that drill diameter is the most significant factor as with the increase in drill diameter, thrust force and torque increase and so the burr height without having required support at the exit end. Low burr height is obtained at a low drill diameter of 6 mm corresponding to low thrust and torque requirement.

Table 6 Confirmatory test result of experimental burr height and estimated value

Burr height	Actual parameters			Coded parameters			Observed burr	Experi-mental value	Predicted value	Error (%)
	A	B	C	x_1	x_2	x_3				
Initial condition	25	0.08	9	0	0	0		5.12	5.02	1.95
Estimated optimal condition	25	0.125	6	0	+1	-1		2.94	2.87	2.38

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