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PREDICTION AND OPTIMIZATION OF SURFACE ROUGHNESS IN TURNING BASED ON RESPONSE SURFACE METHODOLOGY

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Abstract--Surface roughness and tolerances are among the most critical quality measures in many mechanical products. Critical quality measure and surface roughness (Ra) in machined parts depends upon metal cutting parameters during the turning process. Researchers have predicted and developed various models for the optimum turning parameters for the desired surface roughness. Surface of a mechanical product can be created with a number of manufacturing processes. As competition grows closer, customers now have increasingly high demands on quality, making surface roughness become one of the most competitive dimensions in today's metal cutting industry.

This paper utilizes regression modeling in turning of Aluminum using response surface methodology (RSM) coupling with of factorial design. A linear and quadratic model will develop for the prediction and analysis of the relationship between the cutting conditions (variables) and surface roughness as well as to study the effect of cutting variables on surface roughness. In the development of predictive models, cutting parameters of cutting speed, feed rate and depth of cut will considered as model variables and surface roughness will considered as a response variables.

Keywords: surface roughness, tolerances

I. INTRODUCTION

Surface finish obtained in manufacturing processes mainly depends on the combination of two aspects: the ideal surface finish provided by marks that manufacturing process produces on the surface and the actual surface finish which is generated taking into account irregularities and/or deficiencies that may appear in the process, changing manufacturing initial conditions. Surface finish is a very important aspect for designing mechanical elements and is also presented as a quality and precision indicator of manufacturing processes [1], being necessary a proper knowledge of part geometry taking into account both its macro geometry and micro geometry.

Manufacturing processes do not allow to achieve the theoretical surface roughness due to defects appearing on machined surfaces and mainly generated by deficiencies and imbalances in the process. These aspects make necessary measuring procedures which permit us to establish the real state of surfaces. This requires to measure surface quality of manufactured parts with accuracy. An optimum selection of process conditions is extremely important as these ones determine surface quality and dimensional precision of manufactured parts [2]. Thus, in material removal processes, an improper selection of cutting conditions will cause to obtain surfaces with high roughness and dimensional errors, being even possible that dynamic phenomena due to auto excited vibrations appear (chatter). In order to know surface quality and dimensional precision properties in advance. It is necessary to employ theoretical models making it feasible to do predictions in function of operation conditions such as part dimensions, rotating speed of spindle, feeds, cutting depth and so on. Moreover, it is necessary to determine which process conditions will meet specifications related to roughness and form errors. This means fulfilling requirements and making it possible to maximise some objective function (material removal rate, profit and so on).

2. Design of the experiment

Design of experiments is a powerful analysis tool for modeling and analysing the influence of process variables over some specific variable which is an unknown function of these process variables [3]. In general, the roughness parameters will mainly depend on the manufacturing conditions employed, such as: feed, depth of cut, cutting speed, machine tool and cutting tool rigidity, etc. So, a complete modeling of these parameters should take into account the previous factors. Nevertheless, it can be shown that the main parameters affecting the surface roughness are cutting speed, depth of cut &feed.

Methodology

In this work, experimental results were used for modeling using response surface roughness methodology (RSM). Response surface methodology (RSM) is a collection of Mathematical and statistical techniques that are useful for the modeling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response. The RSM is practical, economical and relatively easy for use and it was used by lot of researchers for modeling metal cutting process [1, 2, and3]. RSM was also successfully used for application in tool life testing [4, 5] surface analysis and tool wear rate in metal cutting [5].The experimental data was utilized to build Mathematical model (first order, second order and exponential model) by regression method. This mathematical model was taken as objective function and was optimized using a lingo- solver programmer to obtain the machining conditions for the required surface finish The following linear relationship is commonly used for representing the mathematical models in metal cutting.

$$Y = \O\ (v, f, d) + \in \qquad (1)$$

Where, v, f, & dare speed, feed, and depth of cut respectively of the metal cutting processes, and $\in$ is the error, which is normally distributed with mean= 0 according to observed response Y and Ø is the response function. The relationship between surface roughness and other independent variables is modeled as shown below.

$$Ra = c\, v^{a} f^{b}\ d^{c} \qquad (2)$$

Where (c is constant, a, b, and c ,d, are the exponents. Equation (2) can be represented in linear mathematical from as shown.

$$In\ Ra = lnc + alnv + blnf + C\ lnd \qquad (3)$$

The constants and exponents c, a, b, c can be obtained by the method of least squares. The first-order linear model developed from the equation, can be represented as follows.

$$Y_1 = y - \in = b_o x_o + b_1 x_1 + b_3 x_3 \qquad (4)$$

Where, Y_1 is the estimated response based on first-order equation, y is the measured surface roughness on a logarithmic scale, x_o (=1) is a dummy variable, x_1, x_2, and x_3 are logarithmic transformations of cutting speed, feed rate, and depth of cut respectively $\in$ is the experimental error, b values are the estimates of corresponding parameters. If this model is not sufficient to represent the process, then the second-order model will be developed. The general second order model is as given below,

$$Y_2 = Y- \in\ = boxo + b_1x_1 + b_1x_2 + b_3x_3 + b_4x_4 + b_{12}\, x_1x_2 + b_{23}x_2x_3 + b_{14}\, x_1x_4 + b_{24}x_2x_4 + b_{13}x_4x_3 + b_{34}x_3x_4 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 \qquad (5)$$

Where, Y_2 is the estimated response based on second order equation. The parameters b_o, b_1, b_2, b_3, b_4, b_{11}, b_{12}, $b_{13}$and b_{44} are to be estimated by the method of least squares

II. EXPERIMENTAL DETAILS

A detailed survey has been carried out to find out how metal cutting parameters, namely cutting speed, feed rate, and depth of cut of the single point cutting tool were selected for experimentation. The range of each parameter is set at three different levels, namely low, centre and high based on industrial practice as shown in Table1. Full factorial experiments (3^3) were carried out to estimate the values of the regression coefficients. The complete design consists of 27 experiments as shown in Table2. The variables were coded by taking into account the capacity and the limiting cutting conditions of the lathe machine. The coded values of variables to be used in Eqs.4 and Eqs.5 were outlined from the following transforming equations.

$$X1 = \ln V – \ln 112/ \ln 112- \ln 39 \qquad (6)$$

$$X2 = \ln F – \ln 0.10/ \ln 0.10 - \ln 0.06 \qquad (7)$$

$$X3 = \ln D – \ln 0.4/ \ln .4- \ln 0.2 \qquad (8)$$

$$X4 = \ln r – \ln 0.8/ \ln 0.8- \ln 0.4 \qquad (9)$$

Where x_1 is the coded value of cutting speed v, x_2 is the coded value of feed rate f and x_3 is the coded value of depth of cut d,

The experiments were carried out on H.M.T.(L.T.M. 20) heavy duty lathe machine and has wide range of parameter settings (variety of speeds, feeds and depth of cut).It has a dead center mandrel to hold the heavy work-piece firmly. The lathe has provision for automatic translator motion so as to minimize the variations in metal cutting conditions. The cutting performance tests were performed on commercial aluminum work piece, with 99% purity, melting point 660^0 C & 30 BHN The cutting tool used for the turning operation was 'WIDAX tool holder SCLCR 12 12Fog T3 and inserts are SM diamond shape uncoated carbide inserts (CNMA 120408) and no coolant was used. Surface roughness was measured by Mitutoyo SURFTEST- model SV-500 with cut-off length 0f 0.8mm and sampling length of 4.0mm. The machining operations were carried out as per the condition given by the design matrix at random to avoid systematic errors. The work piece material used has a dimension of 500 mm in length and 50 mm in diameter. This material is suitable for a wide variety of automotive type applications.

Table 1 Process variables and their levels

Level	V m/min	F mm/rev	D mm	coding
Low	39	0.2	0.2	-
Middle	112	0.10	0.4	0
High	189	0.15	0.6	+

Table 2 Design Matrix

Exp.N0.	Cutting speed(m/min)	Feed rate (mm/rev)	Depth of (cut mm)	Measured Ra(µm)	Pred.Ra RSM1	Pred.Ra RSM2
1	39	0.05	0.2	1.24	1.3912	1.399
2	189	0.15	0.4	2.02	1.8316	1.854
3	112	0.05	0.6	1.37	1.5615	1.527
4	112	0.15	0.2	2.00	2.0234	1.989
5	112	0.1	0.4	1.8	1.7924	1.808
6	189	0.15	0.2	1.5	1.497	1.544
7	189	0.1	0.2	0.88	0.9314	0.998
8	189	0.05	0.2	0.45	0.3658	0.335
9	112	0.15	0.6	2.75	2.6927	2.637
10	39	0.1	0.2	2.01	1.9568	1.999
11	39	0.1	0.4	2.45	2.2915	2.345
12	39	0.15	0.4	2.67	2.8571	2.82
13	189	0.1	0.4	1.2	1.266	1.317
14	112	0.15	0.4	2.41	2.358	2.313
15	39	0.05	0.6	2.17	2.0605	2.108
16	112	0.05	0.2	0.55	0.8922	0.845
17	112	0.1	0.6	2.00	2.1271	2.141
18	39	0.15	0.6	3.1	3.1917	3.157
19	112	0.05	0.2	1.2	0.8922	0.845
20	39	0.05	0.2	1.48	1.3912	1.399
21	189	0.1	0.6	1.8	1.6007	1.636
22	39	0.15	0.2	2.51	2.5224	2.482
23	112	0.1	0.2	1.5	1.4578	1.475
24	189	0.05	0.4	0.57	0.7004	0.663
25	189	0.05	0.6	1.08	1.0351	0.99
26	39	0.1	0.6	2.78	2.6261	2.691
27	189	0.15	0.6	2.02	2.1663	2.164

III. RESULTS AND DISCUSSION

Turning is very important machining process in which a single point cutting tool removes unwanted material from the surface of a rotating cylindrical work piece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried out on a lathe that provides the power to turn the work piece at a given rotational speed and to feed to the cutting tool at specified rate and depth of cut. Therefore three cutting parameters need to be determined in a turning operation. The turning operations are accomplished using a cutting tool; the high forces and temperature during machining create a harsh environment for the cutting tool. Therefore tool life is important to evaluate cutting performance. The purpose of turning operation is to produce low surface roughness of the parts. Surface roughness is one of the important factors to evaluate cutting performance. Proper selection of cutting parameters and tool geometry can produce longer tool life and lower surface roughness. Hence design of experiments by factorial design & RSM method on cutting parameters was adopted to study the surface roughness. The cutting parameters are chosen are shown in the table 1.In this article only surface roughness prediction model developed by response surface method is reported.

Surface properties such as roughness are critical to the function ability of machine components. Increased understanding of the surface generation mechanism can be used to optimize metal cutting process and to improve component function ability. The research is conducted with two purposes. The first was to demonstrate the use of response surface methodology and design of experiments in order to identify the optimum surface roughness, with particular combination of cutting parameters. The second was to demonstrate a systematic procedure using factorial design of experiments with RSM in process design of turning operations.

After conducting twenty seven experiments, the surface roughness readings are used to find the parameters appearing in the postulated first order and second-order model (Equation 1 and 4). In order to calculate these parameters, the least square method is used with the aid of Minitab Software (Statistical data analysis Software). The first-order and second-order equation developed to predict the surface roughness as shown below.

$$Ra = 0.758 - 0.00684\,V + 11.3\,F + 1.67\,D, \quad \text{for first order model} \qquad (10)$$

$$Ra = 0.6521 - 0.0088V + 15.3646\,F + 1.8537\,D - 23.4210\,F^2 - 0.0043\,D^2 + 0.0084VF - 0.0009VD - 0.8639\,FD, \quad \text{for second order model} \qquad (11)$$

$$Ra = 81.45\,(V^{-0.41}\,F^{+0.69}\,D^{+0.38}), \quad \text{exponential model} \qquad (12)$$

Where v, f and d are the cutting speed, feed rate and depth of cut respectively, the equation shows that the surface roughness increased with increase of feed rate and depth of cut but decreased with cutting speed. The feed rate has the most dominant effect on surface value produced by tungsten carbide tools. The results show that the cutting speed has lesser impact on surface roughness in the studied range. So higher cutting speed could be used to improve the productivity. The results for analysis of variance for the second order model reveal that the interaction terms and the square terms are statistically insignificant. The increase in feed rate increases surface roughness, but decreases with increasing cutting velocity. During machining, if feed rate is increased, the normal load on the tool also increases and it will generate heat which in turn increases the surface roughness. This is anticipated as it is well known that for a given tool nose radius, the theoretical surface roughness ($Ra = f^2 / (32*r)$) is mainly a function of the feed rate (4). With the increase in depth of cut, the surface roughness value increases, because with increase in depth of cut chatter may result causing degradation of the work piece surface [7]. The major effect on the surface roughness is due to the feed rate. Hence smaller values of feed rate and depth of cut must be selected in order to achieve better surface finish during aluminum turning.

As seen from Fig.1, the predicted surface roughness using the first order second order RSM model is closely match with the experimental results. It exhibits the better agreement as compared to those from the values are measured by experiments.

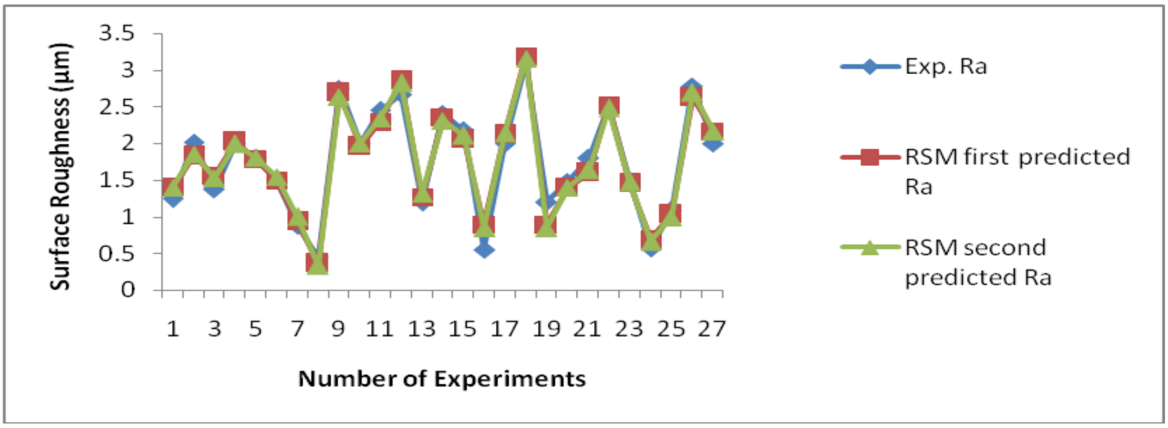

Fig1. Comparison between the experimental and predicted results (Ra)

Further analysis can be conducted with the aid of main effects and interaction effects. Fig2 shows the main effects plot for surface roughness value. From fig1, can be concluded that a smoother surface can be produced by a smaller feed rate or using higher cutting speed. Again it is evident that the surface roughness value decrease as the feed rate and depth of cut decreases and cutting velocity increases. Fig.3 shows interaction effects plot for surface roughness values, from this fig.2 it indicates that no interaction between the cutting parameters.

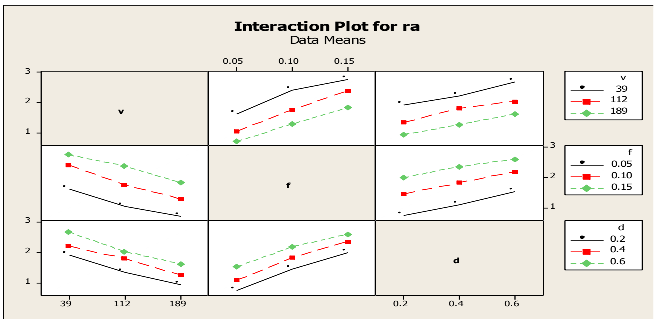

Fig.2. Main effect plot

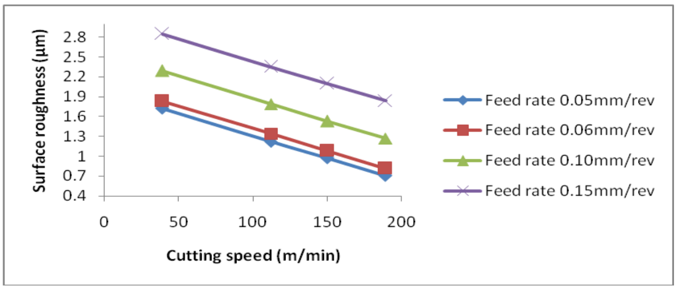

Fig 3nteraction effect plot

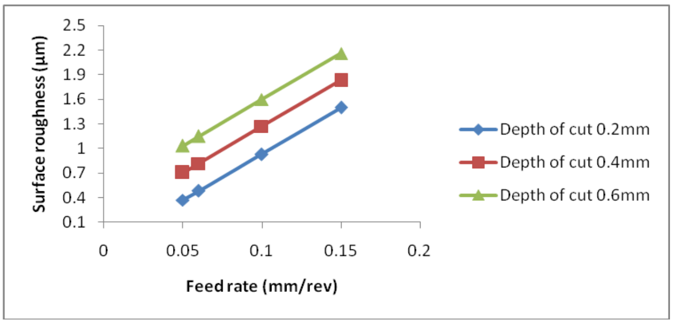

Fig.04.Relationship between depth of cut and feed rate with Ra (cutting speed 189m/min)

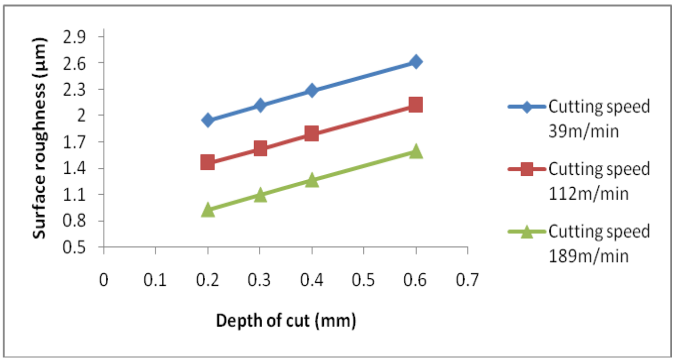

Fig.05.Relationship between cutting speed and depth of cut with surface roughness (feed rate 0.10mm/rev)

Table No.3 Confirmation test results

Cutting speed(m/min)	Feed rate(mm/rev)	Depth of cut (mm)	Predicted Ra(µm)	Experimental Ra(µm)
189	0.05	0.2	0.3718	0.3349
189	0.06	0.2	0.4848	0.4946
189	0.06	0.4	0.8188	0.8279
112	0.05	0.2	0.8954	0.9010
189	0.05	0.4	0.7058	0.6968
39	0.15	0.6	3.1898	3.2980
112	0.06	0.4	1.3424	1.3618

IV. CONCLUSIONS

Full factorial design of an experiment can be successfully employed using tungsten carbide cutting tools in machining aluminum work piece. The following conclusions have been drawn:

[a] First –order and second-order mode predicting equations for surface roughness have been developed using response surface methodology combined with factorial design for machining the aluminum work piece under different cutting conditions.

[b] The established equations clearly show that the feed rate was main influencing factor on the surface roughness followed by depth of cut. It increased with increasing feed rate but decreased with increasing cutting speed. Among the other parameters, depth of cut was found to be less sensitive than the feed rate and cutting speed. However, feed rate and depth of cut had a similar positive effect on surface roughness.

[c] The predicted values and measured values are fairly close which indicates that the developed surface roughness prediction model can be effectively used to predict the surface roughness from the cutting process, with 95% confidence level for both case.

[d] All the cases showed that a higher speed would smoothen surface within the range of experiments.

[e] With the model equations obtained a designer can subsequently select the best combination of design variables for achieving optimum surface roughness. This eventually reduces the machining time, cost and save the cutting tools

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