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Modeling and Analysis for Surface roughness in Machining EN-31 steel using Response Surface Methodology

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ABSTRACT- This paper utilizes the regression modeling in turning process of En-31 steel using response surface methodology (RSM) with factorial design of experiments. A first-order and second-order surface roughness predicting models were developed by using the experimental data and analysis of the relationship between the cutting conditions and response (surface roughness). In the development of predictive models, cutting parameters of cutting velocity, feed rate, depth of cut, tool nose radius and concentration of lubricants were considered as model variables, surface roughness were considered as response variable. Further, the analysis of variance (ANOVA) was used to analyze the influence of process parameters and their interaction during machining. From the analysis, it is observed that feed rate is the most significant factor on the surface roughness followed by cutting speed and depth of cut at 95% confidence level. Tool nose radius and concentration of lubricants seem to be statistically less significant at 95% confidence level. Furthermore, the interaction of cutting velocity/feed rate, cutting velocity/ nose radius and depth of cut/nose radius were found to be statistically significant on the surface finish because their p-values are smaller than 5%. The predicted surface roughness values of the samples have been found to lie close to that of the experimentally observed values.
Keywords: Response surface method, surface roughness, metal cutting, factorial design

1. INTRODUCTION

Surface roughness determines how a real object interacts with its environment. Rough surfaces usually wear more quickly and have high friction coefficient than smooth surfaces. Roughness is often a good predictor of the performance of mechanical components, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of surface will usually increase its metal cutting costs exponentially. Surface quality is an important requirement for many machine parts. The purpose of the metal cutting process is not only to shape machined components but also to manufacture them so that they can achieve their functions according to geometric, dimensional and surface considerations. Due to the increasing demand for quality products, manufacturing engineers are faced with the difficult problem of increasing productivity without compromising quality.

A proper combination of cutting conditions is extremely important because this determines surface quality of manufactured parts. The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, insists high material removal rate and high stability and long life of the cutting tools. But machining and grinding with high cutting velocity, feed rate and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product by inducing tensile residual stresses, surface and subsurface micro-cracks in addition to rapid oxidation and corrosion [1]. The cutting fluids serve many useful functions including, cooling of the cutting tool at higher speeds, lubricating at low speeds and high loads, increasing tool life, improving the surface finish, reducing the distortion due to temperature rise in the work piece, facilitating chip handling and disposal, providing a protective layer on the machined surface from oxidation and protecting the machine tool components from rust.

But the application of conventional cutting fluids creates some environmental problems like environmental pollution, water pollution, and biological problems to operators [2]. Further, the cutting fluids also incur a major portion of the total manufacturing cost [3], Machining with solid lubricants [4, 5], and MQL [6] and cryogenic cooling by liquid nitrogen [7] are some of the alternative approaches in this direction. Minimum quantity lubrication refers to the use of cutting fluids of only a minute amount typically of a flow rate of 50 to 500 ml/hour, which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid can be dispensed per minute. Varodarajan et al. [8] used 2ml/hr oil in a flow high pressure air at 20 Mpa, while hard turning AISI4340 steel. This may call to be near dry turning. It was found that cutting under near dry had better performance than that in dry or wet cutting in terms of cutting forces, cutting temperature, surface roughness, tool life, cutting ratio and chip-tool contact length. Lower cutting force, lower cutting temperatures, better surface finish, shorter chip-tool contact length, larger cutting ratio and longer tool life were observed in near dry cutting compared with those in dry or wet cutting.

Application of solid-liquid lubrication in cutting has proved to be feasible alternative to cutting fluids, if it can be applied properly. If the friction at the machining zone can be minimized by providing effective lubrication, the heat generated can be reduced to some extent. If a suitable lubricant can be successfully applied in the machining zone, it leads to process improvement. Researchers Deshmukh et al. [9] studied the significance of different solid lubricants in metal cutting like MoS_2, MoS_2 base grease, graphite based grease and silicon compound mixed with SAE-20 oil. It was found that the surface finish quality improves at different proportions while machining aluminum and brass [9]. Latkar et al. [10] assessed the effect of machining on tool wear and surface roughness with graphite based grease mixed with base oil in varying proportions applied in MQL and compared the results with dry machining using response surface methodology while medium alloy steel was machined with tungsten carbide tool. Graphite and MoS_2 assisted end milling process has reported considerable improvement in the process performance as compared to that of machining with cutting fluid in terms of cutting forces, surface quality and specific energy (Suresh kumar et al. 2006).

Ingole and Bhendwar [11] studied the effect of lubricants on the surface finish in burnishing of En8 specimens. Using 2^3 factorial designs, in terms of surface roughness, model equations were developed. The burnishing parameters considered were speed, feed and force and the other parameters were constant. The lubricants studied were SAE-40, grease and mixture of the two. Out of these SAE-40 was found to be better. Venugopal and Rao [12] investigated the use of graphite as a lubricating medium in grinding process to reduce the heat generated at the grinding zone. The effective role of graphite as lubricant is evident from the overall improvement in the grinding process. Different process performance parameters like cutting forces, cutting zone temperatures specific energy and surface roughness were observed and reported to be reduced when compared to those with grinding with conventional coolant. Shirsat et al. [13] studied the influence of burnishing parameters on surface finish in burnishing of aluminum specimens. The finishing parameters considered were speed, feed rate, burnishing force. It was found that the surface roughness improves initially with an increase in these parameters. After a certain stage, the surface finish deteriorates and fatigue life decreases. The lubricant studied were Kerosene, SAE-30 oil, 5% graphite by weight in SAE-30 oil and 10% graphite by weight in SAE-30 oil. Out of this Kerosene was found to be better. Abhang et al. [14, 15] developed the mathematical models for predicting the chip-tool interface temperatures and power consumption of EN-31 steel during turning operation using tungsten carbide tools. The parameters considered were cutting speed, feed rate, depth of cut and tool nose radius.

A recent investigation performed by Alauddin et al. [16] has revealed that when the cutting speed is increased, productivity can be maximized and surface quality can be improved. According to Hasegawa et al. [17] surface finish is characterized by various parameters such as average roughness (Ra), smoothening depth (Rp), root mean square (Rq) and maximum peak to valley height (R_t). This study used average roughness for the characterization of surface finish, since it is widely used in metal cutting industry. Bardie [18] developed a surface roughness model for gray C.I. (154 BHN) using carbide tool under dry conditions turning and for constant depth of cut. Dilbag et al. [19] developed a surface roughness prediction model for hard turning process, using mixed ceramic inserts (turning) having different nose radii and different rake angles, of the cutting tools. They found that the feed rate is the dominant factor determining the surface finish followed by nose radius and cutting velocity. Abhang et al. [20] developed the mathematical models for predicting the surface roughness produced by wet turning using soluble oil-water mixture lubricant. They found that the feed rate is the dominant factor determining the surface finish followed by tool nose radius and depth of cut. It increases with increase in the feed rate but decreases with increase in the cutting velocity and tool nose radius, respectively. In the present study experimental investigation are conducted by turning En-31 steel alloy with tungsten carbide cutting tool using concentration of solid-liquid mixture lubricant under different conditions of cutting speed, feed rate, depth of cut and tool nose radius. Surface roughness values are recorded and statistically analyzed by Minitab software. First and second- order surface roughness prediction models are developed and reported.

II. RESPONSE SURFACE METHOD

Response surface methodology is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [21]. RSM also quantifies relationships among one or more measured responses and the vital input parameters.

Factorial designs are used widely in experiments involving several factors on a response. The meaning of factorial design is that each complete test or replications of all the possible combinations of the levels of the factors are investigated [18]. Factorial design with eight added centre points (2^5+8) used in this work is a composite design, which had been initially proposed by Box [21], [22]. The proposed linear model correlating the responses and independent variable can be represented by the following equation.

Y = m* (cutting speed) + n*(feed rate) + p *(depth of cut) +q*(tool nose radius) +e (1)

Where, Y is the response, e, m, n, p and q are the constants. Equation (1) can be written in the following form.

$$Y = Ø(v, f, d, r) + \in \quad (2)$$

$$Y_1 = \beta_o X_o + \beta_1 X_1 + \beta_2 X_3 + \beta_4 X_4 \quad (3)$$

Where Y_1 is the response, X_o = 1 (dummy variables),

X_1 = cutting speed, X_2 = feed rate, X_3 = depth of cut and X_4 = tool nose radius,

β_o= c and β_1, β_2, β_3 and β_4 are the model parameters.

The general second order model can be expressed as equation (4)

$$Y_2 = \beta_o X_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + B_4 X_4 + \beta_{12} X_1 X_2 + \beta_{23} X_2 X_3 + \beta_{14} X_1 X_4 + \beta_{24} X_2 X_4 + \beta_{13} X_1 X_3 + \beta_{34} X_3 X_4 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{44} X_4^2 \quad (4)$$

Where, Y_2 is the estimated response based on second order equation. The parameters β_o, β_1, β_2, β_4, β_{12}, β_{23} and β_{14}, are to be calculated by the method of least squares. The basic formula is

$$\beta = (X^T X)^{-1} X^{T.} Y \quad (5)$$

Where the calculation matrix X and the variance matrix $(X^T.X)^{-1}$. Hence the β values can be determined by using eqn. (5).

III. EXPERIMENTAL SET-UP AND CUTTING CONDITIONS

The experiments are carried out on HMT heavy duty lathe machine [LTM-20]. Commercial alloy steel work-piece (EN-31) is machined on HMT lathe. Table I and Table II shows chemical composition of work piece material and three levels of factors respectively. Each experiment was repeated three times using new cutting tool every times to obtain accurate readings of the surface roughness. The averages of three readings of surface roughness values have been recorded. The work piece material used has a dimension of 400 mm in length and 50 mm in diameter. The cutting tool holder used for turning operation is WIDAX tool holder SCLCR 1212 Fog 13 and diamond shape carbide insert (CNMA 1204-04, CNMA 120408 and CNMA 1204 12).

This method classifies and identifies the parameters at three different levels (i.e. low, middle and high) as shown in table1. The process variables or control variables such as cutting speed, feed rate, and depth of cut tool nose radius and concentration of lubricants are identified to carry out the experiments and to develop the statistical empirical models. The experiments are performed on EN-31 alloy steel cutting speed (v) m/min, feed rate (f) mm/rev, depth of cut (d) tool nose radius (r) mm and concentration of lubricants (c) (minimum quantity lubricant). In the present study, the minimum quantity lubrication is provided with solid lubricant mixed with SAE-40 base oil (10%, 15% and 20% graphite powder mixed with SAE-40 base oil by weight separately). Minimum quantity of lubrication without formation foam is applied to the work piece that seeps to chip-tool contact area while machining. So the quantity is negligible this may be called as near dry machining. In this investigation the surface roughness was measured on an optical microscope (Carl-zesis, Japan made lens factor is 0.89). The surface roughness was taken perpendicular to the turning direction. In this work the centre line average surface roughness (Ra) values were measured by taking average of the three readings.

TableI:
CHEMICAL COMPOSITION OF (EN-31) WORK PIECE

contents	**C**	**Si**	**Mn**	**Cr.**	**Co**	**S**	**P**
Wt. %	0.9	0.10	0.30	1.0	0.025	0.04	0.04

TABLE II:
LEVELS OF THE INDEPENDENT VARIABLES AND CODING IDENTIFICATION

Levels	**Cutting speed (m/min)**	**Feed rate (Mm/rev.)**	**Depth of cut (mm)**	**Nose radius (mm)**	**Lu %**	**Code**
High	189	0.15	0.6	1.2	10%	+1
Middle	112	0.10	0.4	0.8	15%	0
Low	39	0.06	0.2	0.4	20%	-1

IV. RESULTS AND DISCUSSION

This 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 and tool geometry (tool nose radius). The second was to demonstrate a systematic procedure for using factorial design of experiments with RSM in process design of turning operations. The effect of tool nose radius was also considered apart from the effects of the process parameters on the surface roughness. A factorial design with eight added centre points is sufficient to investigate the main and interaction effects on surface roughness. The first order and second order equation developed to predict the surface roughness are given in equation (6) and (7).

$Ra_1 = 10.1 - 0.00341\ v + 16.1\ f + 2.08\ d - 0.47\ r - 0.0165\ c$ (6)

Where, V, F, D, R and C are the cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants respectively. Equation (6) shows that the surface roughness increases with increase of feed rate and depth of cut but decreased with cutting speed, tool nose radius and concentration of solid-liquid lubricants. The feed rate has the most dominant effect on surface roughness value produced by tungsten carbide tools. 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 steel turning operation.

$R_{a2} = 9.7939 - 0.0122\ v + 21.6739\ f + 3.8072\ d - 0.4815\ r - 0.274\ c - 0.00000\ v^2 - 0.0511\ vf - 0.027\ vd + 0.41\ vr + 1.0417\ fd - 1.1806\ fr + 0.0417\ fc - 1.4063\ dr - 0.0269\ dc + 0.0150\ rc$ (7)

By examining the coefficients of the second order terms, it can be seen that the cutting speed, feed rate and depth of cut has the most dominant effect on the surface roughness. The tool nose radius and concentration of lubricants has less significant effect on the surface roughness, because their p-values are higher than 5% at 95% confidence level. After examining the experimental data, it can be seen that the interaction terms of cutting speed/feed rate, cutting speed/ tool nose radius and depth of cut/ tool nose radius and square terms of cutting speed are significant effect on the surface finish quality at 95% confidence level. As seen from Fig.1, the predicted surface roughness using the second order RSM model closely match with the experimental results. It exhibits the better agreement as compared to those from the first-order RSM mode. The analysis of variance and the F ratio test have been performed to justify fitness of the mathematical model. The F-ratio of the predictive model is calculated and compared with the standard tabulated value of the F-ratio for a specific level of confidence.

The adequacy of the first and second order model was verified using the analysis of variance (ANOVA) as shown in Table III and Table IV. At a level of confidence of 95.00%, the model was checked for its adequacy. As shown in table III and IV, P -value of first-order model is 0.83 and the second-order model is 0.995. Because these values are greater than 0.05 the lack-of fit is not significant for both the models that means the fit is significant and the models are adequate [21].

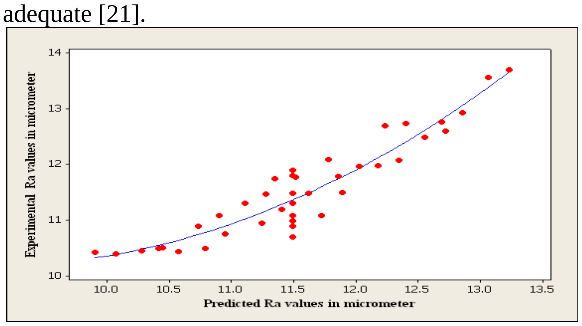

Fig .1: Comparison between the Experimental and Predicted values of Surface Roughness (Quadratic model)

The results show that the cutting speed has lesser impact on surface roughness in the studied range. This observation is in agreement with the findings of previous researchers [16], [17] and [20]. Therefore higher cutting speed could be used to improve the productivity. The result for analysis of variance for the second order model reveals that the interaction and square terms are statistically significant at 95% confidence level. They have larger effect on surface roughness. This observation is in agreement with the findings of dry machining [20]. The developed equations clearly show that the feed rate is the most influencing factor on surface roughness followed by cutting speed and depth of cut. This is in agreement with the work of Dilbag et al. [19] .The increase in feed rate increases surface roughness, but decreases with increasing cutting velocity, tool nose radius and concentration of lubricants. 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 is generally ($Ra = f^2 / (32*r)$) (23). Thus, with increase in depth of cut, the surface roughness value increases, because with increase in depth of cut chatter may result cause degradation of the work piece surface and larger tool nose radius reduces surface roughness. The surface roughness values obtained by using insert radius of 1.2mm were less than the surface roughness values obtained by using the insert radii of 0.8mm and 0.4mm .The reason for obtaining better surface quality with in insert radius of 1.2mm than with the other two inserts may be ascribed to the form of better roundness of this insert than the other two. This result agrees with Kevin et al [24]. During solid-liquid mixture (MQL) lubricant machining surface finish is improved by reducing the cutting forces and tool wear rate as well as increasing heat transfer rate as compared to dry machining [20]. Solid-liquid mixture lubricant provides good lubrication and cooling action between chip-tool and chip-workpiece interface during machining that leads to improved surface finish.

The relationship between cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants are shown in figures (2to 5). The response surface plots (Fig. 2) indicates that the minimum surface roughness is at about 189m/min and 0.06mm/rev, the response surface plot (Fig. 3) indicates that the minimum surface roughness is at about 189m/min and 0.2mm, the response surface plot (Fig.4) indicates that the minimum surface roughness is at about 189m/min and 1.2mm and the response surface plot (Fig.5) indicates that the minimum surface roughness is at 189m/min and 10% concentration of solid-liquid lubricants

Table III:
Analysis of Variance for First order Equation

Source	D.F	S.S.	M.S.	F-value	P-value
Regression	5	25.7412	5.1482	39.88	0.000
Linear	5	25.7412	5.1482	39.88	0.000
Res error	34	4.3888	0.1291	-	-
Lack-of fit	27	3.0854	0.1143	0.61	0.83 ns
Pure error	7	1.3034	0.1862	-	-
Total	39	30.1300	-	-	-

S = 0.359281, Rsq = 85.40%, Rsq(adj) = 83.30%, Rsq(pred) = 80.73%, press = 5.80554

Table IV:
Analysis of Variance for Quadratic Equation

Source	D.F	S.S.	M.S.	F-value	P-value
Regression	16	28.2221	1.76388	21.26	0.000
Linear	5	26.7412	0.68692	8.28	0.000
Square	01	0.4925	0.49064	5.91	0.023
Interaction	10	1.9884	0.19884	2.40	0.040
Res error	23	1.9079	0.08295	-	-
Lack-of fit	16	0.6045	0.03778	0.20	0.995 ns
Pure error	7	1.3034	0.18620	-	-
Total	39	30.1300	-	-	-

S = 0.288015, Press = 4.12045, Rsq = 93.67%, Rsq(pred) = 89.54%, Rsq(adj) = 91.36%

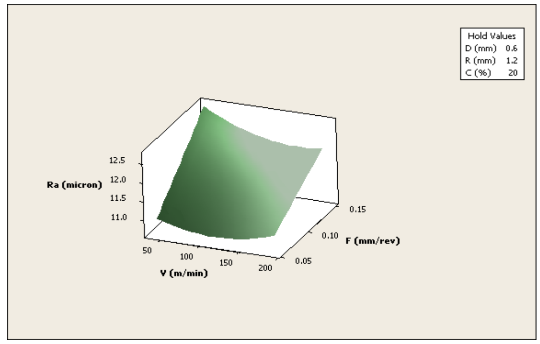

Fig. 2 Surface plots for Ra vs speed/feed

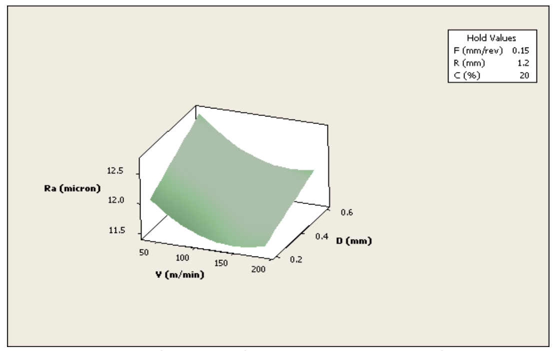

Fig.3 Surface plots for Ra vs speed/ depth of cut

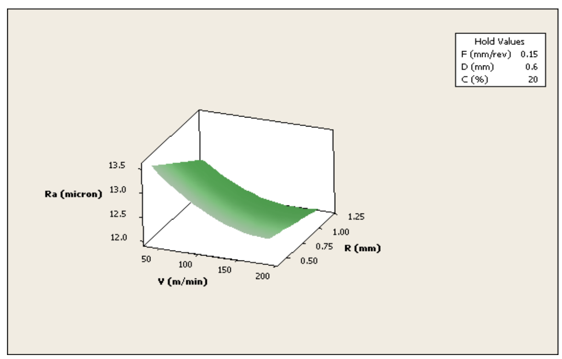

Fig.4 Surface plots for Ra vs speed/ nose radius

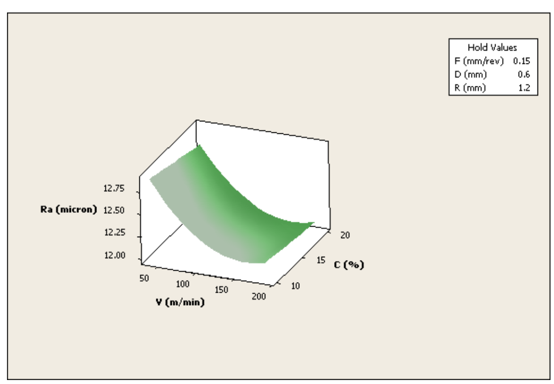

Fig.5 Surface plots for Ra vs speed/ concentration of lubricants

V. CONCLUSION

1) Response surface methodology combined with the factorial design of experiment is found to be a successful technique to perform trend analysis of surface roughness with respect to various combinations of design variables (metal cutting velocity, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants).

2) The first order and second-order mathematical models are found to adequately represent the surface roughness.

3) The surface roughness increases with increase in feed rate followed by depth of cut but decreases with increase in the cutting velocity, tool nose radius and optimum concentration of solid-liquid lubricants respectively.

4) It is observed that the predicted and measured values are close to each other. Therefore the proposed model can be used to predict the corresponding specific surface roughness (Ra) of En-31 steel at different parameters in turning.

5) With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum or minimum surface roughness and corresponding machining parameters during steel turning process. This eventually reduces the machining time, operation efforts, cost and save the cutting tools. A good combination among the cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants can provide better surface quality.

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