An Experimental Investigation to Optimize the Process Parameters of AISI 4340 Steel in Hot Machining

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Abstract--- In this work, the influence of the cutting parameters namely cutting speed (Vs), feed rate (fs) and depth of cut (a_p) at 200°C, 400°C and 600°C hot machining of AISI 4340 steel on surface roughness are studied. The optimum results can be achieved in the experimental study by employing full factorial techniques. Combined effects of three cutting parameters i.e. cutting speed, feed rate and depth of cut on the performance measure, surface roughness are investigated by employing an full factorial and the analysis of variance (ANOVA) at 200°C, 400°C and 600°C hot machining. Optimal cutting parameters for each performance measure were obtained; also the relationship between the parameters and the performance measure is determined using multiple linear regression equation.

Keywords: surface roughness, AISI 4340 steel, hot machining parameters, cutting speed, feed rate, depth of cut, temperature.

I. INTRODUCTION

The turning of materials, which have the high strength, wear resistance and toughness exhibit lot of difficulties while doing by conventional machining methods, and yields desirable results only by the selection of optimum machining parameters. Such materials are widely used commonly in aerospace, nuclear industries and food processing industries. AISI 4340 Steel one such material, which possess above mentioned challenges during machining. It is also requires a high strength and robust and costlier cutting tool. The production of super alloys, high hard and smart materials have become extremely essential to satisfy the design requirements for critical equipments, aerospace and defense industries. The machining of such materials has always been a great challenge before the production engineer. These alloys and materials can be machined by cutting tools of vary high hardness and strength but during the machining process, instead of increasing the quality of the cutter materials, softening of the work piece is the preferred approach [1]. One of the methods of softening the work piece is hot machining. In hot machining, a part or whole work piece is heated. Heating is performed before or during machining. Hot machining prevents cold working hardening by heating the work piece above the recrystallization temperature and this reduces the resistance to cutting and consequently favours the machining.Hot machinable materials are classified in four groups according to their composition and properties [2]. These classes are (i) Chilled cast iron (ii) Steel with hardness over 50 HRc (iii) Steel whose surface is hardened with cobalt and other additional alloys and (iv) Steels hardened by cold working.

The selection of a heating method for obtaining ideal heating of metals for machining is critical. Faulty heating methods could induce unwanted structural changes in the workpiece and increase the cost. In research, many heating methods are utilized [3, 4]. The methods mostly used are Furnace Heating, Flame Heating, Electrical resistance and plasma arc heating. However, other methods are also used [5,6].Non- conventional machining techniques such as electrical discharge machining; abrasive jet machining and electro- chemical machining processes remove a very small amount of material in every pass, which is expensive and consuming more time as well. Hence, hot machining process has been developed in industries to remove large amount of materials without compromising machining and quality. In hot machining the work piece is heated, which imparts softening of the material and thereby reduces the shear strength of the material.

II. LITERATURE REVIEW

Pal and Basu, investigated the tool life during hot machining of Austenitic Manganese Steel and they reported that the tool life is dependent on work piece temperature and relative cutting speed [1]. Chen and Lo presented the experimental investigation of the factors that affect the tool wear in the hot machining of alloy steel. In this study, alloy steels of different hardness were machined using several grades of carbide tools, over a range of cutting speeds and heating current [2]. Raghuram and Muju reported that tool life has been improved by magnetization and also by a reduction in tool wear was observed due to an external magnetic field in hot machining [3]. Hinds and Almedia studied the plasma arc heating for hot machining, which improved the efficiency of heat transfer under high speed heating of the materials [4]. Kitagawa and Maekawa discussed plasma hot machining for glasses and engineering materials, such as Pyrex, Mullite, Alumina, Zirconia, Silicon nitride and sintered high speed steel[5]. Tosum and Ozler conducted hot machining experiments up to 600 ^{o}C to optimize the performance characteristics of manganese steel using LPG [6]. Madhavulu and Ahmed compared the metal removal of stainless steel (SS 410), alloy steel and forged stainless steel rotor by hot turning operation with undulations on the surface by applying a plasma arc heating [7]

III. DESIGN OF EXPERIMENT [DOE]

The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations. DOE is a technique of defining and investing all possible combinations in an experiment involving multiple factors and to identify the best combination. In this, different factors and their levels are identified. Design of experiments is also useful to combine the factors at appropriate levels, each with the respective acceptable range, to produce the best results and yet exhibit minimum variation around the optimum results.

Therefore, the objective of a carefully planned designed experiment is to understand which set of variables in a process affects the performance most and then determine the best levels for these variables to obtain satisfactory output functional performance in products.

A. The advantages of design of experiments are as follows:

– Numbers of trials is significantly reduced.
– Important decision variables which control and improve the performance of the product or the process can be identified.
– Optimal setting of the parameters can be found out.
– Qualitative estimation of parameters can be made.
– Experimental error can be estimated.
– Inference regarding the effect of parameters on the characteristics of the process can be made.

Thus Design of experiment (DOE) is a method to identify the important factors in a process, identify and fix the problem in a process, and also identify the possibility of estimating interactions.

B. DOE for study of process parameter effects in welding

Following are the DOE techniques used process parameter optimization work in welding.

1. Full factorial technique
2. Fractional factorial technique
3. Taguchi orthogonal array
4. Response Surface method (Central Compsite deisgn)

ANOVA stands for Analysis for Variance and it is the tool used for the analysis of contribution of each process parameter on response parameter. Mathematical models are used to establish the relationship between the input and output parameters in welding processes."MINITAB" and "Design Expert" are the softwares used for DOE techniques and ANOVA.

In a full factorial design creates 3n training data, where n is the number of variables. In these studies, three variables such as cutting speed (Vs), feed rate (fs) and depth of cut (apt) had total of 3= 27 experiment runs at a temperature 200 ^{0}C, 400 ^{0}C and 600 ^{0}C The range of process parameters are shown in Table.

Table no.1 Parameter selection range levels

Control Factors	LEVEL-1	LEVEL-2	LEVEL-3
Cutting speed (m/min)	13.84	21.71	32.21
Feed (mm/rev)	0.065	0.102	0.152
Temperature (^{0}C)	200	400	600

IV. EXPERIMENTAL DETAILS

The experiment was conducted on an auto feed lathe for hot machining operation of AISI 4340 Steel using a Tungsten Carbide cutting tool. The temperature was measured by an infrared thermometer for different condition .Experimental set up is shown in figure-1.Oxi-Acetylene gas flame is used to heat the work piece material

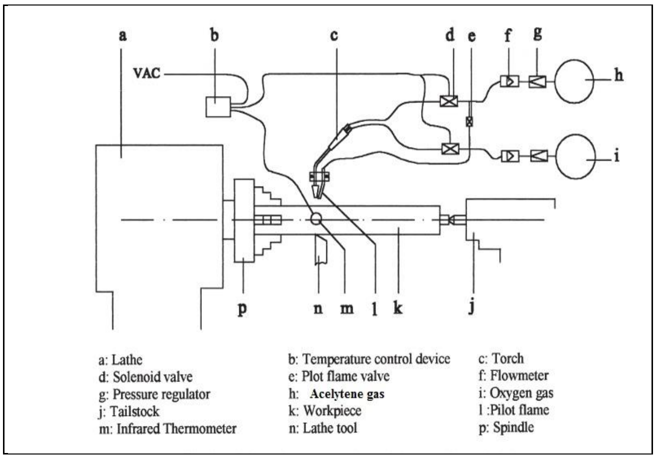

Fig. 1: Experimental setup of hot turning

AISI 4340 steel is high-carbon chromium steel, with small quantities of silicon and manganese. AISI 4340 Steel is exceptionally hard and wear-resistant, and is it is widely used for aircraft landing gear, power transmission gear, shaft and other parts.an excellent choice for applications where high operating temperatures is needed. The chemical compositions and physical properties of AISI 4340 steel are given in Table-2.

Tungsten carbide was used as a cutting tool during the experiment. The mechanical properties of the cutting tool are shown in Table-3.

Table 2 Chemical composition of AISI4340

Elements	C	Si	Mn	Cr	S	P
%	0.43	0.26	0.65	0.9	0.04	0.03

Table 3 Cutting Tool properties tungsten carbide

Density	15.7g/cm^{3}
Poisson's ratio	0.28
Hardness	90 HRc
Yield strength	2683 Mpa
Young's modulus	669-696 KN/mm^{2}

Fig. 2: Cutting tool with WC insert

In, the experiment result shown in the table 4 and after the machining is performed for all input parameters, the surface roughness is measured using surface roughness tester

Table 4: Surface roughness result for Hot M/cing

Sr. no.	Temp. (^{0}C)	Cutting Speed (m/min)	Feed rate (mm/rev)	Surface Roughness

				(R_a)µm
1	200	13.84	0.065	1.520
2	200	13.84	0.102	1.450
3	200	13.84	0.152	1.301
4	200	21.71	0.065	1.412
5	200	21.71	0.102	1.234
6	200	21.71	0.152	1.090
7	200	32.21	0.065	1.140
8	200	32.21	0.102	1.023
9	200	32.21	0.152	1.145
10	400	13.84	0.065	1.542
11	400	13.84	0.102	1.427
12	400	13.84	0.152	1.250
13	400	21.71	0.065	1.427
14	400	21.71	0.102	1.190
15	400	21.71	0.152	1.176
16	400	32.21	0.065	1.227
17	400	32.21	0.102	1.139
18	400	32.21	0.152	0.976
19	600	13.84	0.065	0.987
20	600	13.84	0.102	0.923
21	600	13.84	0.152	0.912
22	600	21.71	0.065	1.023
23	600	21.71	0.102	0.896
24	600	21.71	0.152	0.878
25	600	32.21	0.065	0.824
26	600	32.21	0.102	0.792
27	600	32.21	0.152	0.678

Table 5 Results of ANOVA for Surface Roughness

Source of variation	**F**	**Sum of squares**	**Variance (mean square) v**	**Variance ratio F**	**Percent Contribution P**
Factor A	2	0.867772	0.435	90.73	59.80
Factor B	2	0.31	0.15	32.89	21.68
Factor C	2	0.16	0.08	16.97	11.18
Error (e)	20	0.09	0.004	1	
Total	26	1.44			

Following is the Minitab 15 window in which ANOVA results for Surface Roughness is shown, which is mostly nearer to the calculated value

Table 6 Analysis of Variance for Surface roughness, using Adjusted SS for Tests

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Temp	2	0.86724	0.86724	0.43362	90.73	0.000
Cutting Speed	2	0.31443	0.31443	0.15721		
Feed	2	0.16220	0.16220	0.08110	32.89	0.000
Error	20	0.09559	0.09559	0.00478	16.97	0.000
Total	26	1.43946				
S = 0.0691335 R-Sq = 93.36% R-Sq(adj) = 91.37%						

V. RESULTS AND DISCUSSION

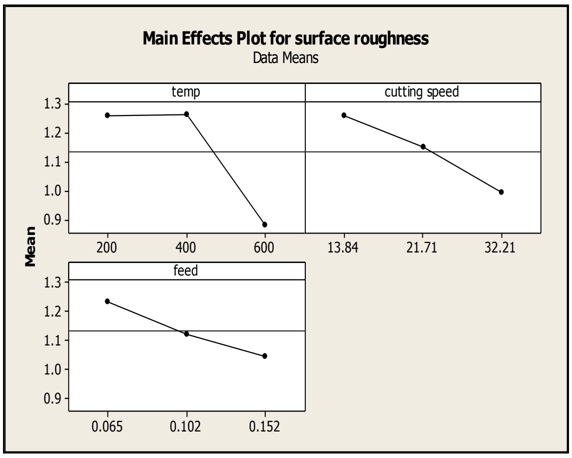

Fig. 2: Main effects plot for Surface roughness

Figure2 shows the main effect plot of surface roughness at different parameters like cutting speed, feed rate and temperature in hot machining process of AISI 4340 steel. From the figure, it can be seen that minimum surface roughness obtained is at cutting speed of 32.21 m/min, feed rate of 0.152 mm/rev and temperature 600 ^{0}C.

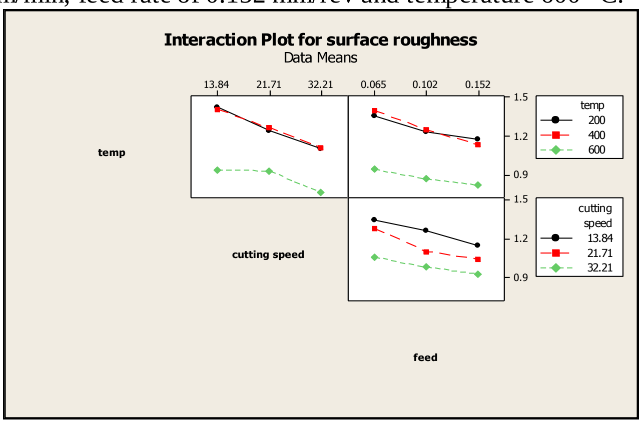

Fig. 3: Interaction plot: average for Surface Roughness

Figure 3 shows the interaction among temperature, cutting speed and feed rate. It can be concluded that the minimum surface roughness is achieved when temperature is 600 C, cutting speed is 32.21 m/min and feed rate is 0.152 mm/rev.

A. Regression Model Analysis of Surface Roughness:

Weighted analysis using weights in Surface Roughness.
Surface roughness = 2.06 - 0.000945 Temp
- 0.00860 Cutting speed - 2.13 Feed

Table 7 Estimated Model Coefficients for Ra

Predictor	Coef	SE Coef	T	P
Constant	2.0606	0.1145	18	0.000
Temp	-0.000945	0.0001405	-6.73	0.000
Cutting Speed	-0.008600	0.001828	-4.70	0.000
Feed Rate	-2.1273	0.6435	-3.31	0.003
S = 0.119207 R-Sq = 77.3% R-Sq(adj) = 74.3%				

The coefficients of model for Surf Roughness are shown in Table 7. The parameter R^2 describes the amount of variation observed in Surf Roughness is explained by the input factors. $R^2 =$ 77.3 % indicate that the model is able to predict the response with high accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model. If unnecessary terms are included in the model, R2 can be artificially high, but adjusted R^2 (=74.3 %.) may get smaller.

The standard deviation of errors in the modeling, S= 0.119207 Comparing the p-value to a commonly used α-level = 0.05, it is found that if the p-value is less than or equal to α, it can be concluded that all the effects are significant.

The residual plot of surface roughness is shown in Figure 6.9. The residual plots in the graph and the interpretation of each residual plot are explained below:

1. Normal probability plot indicates the data are normally distributed and the variables are influencing the response. Outliers don't exist in the data, because standardized residues are between -0.5 and 0.5.
2. Residuals versus fitted values indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data.
3. Histogram proves the data are not skewed and not outliers exist

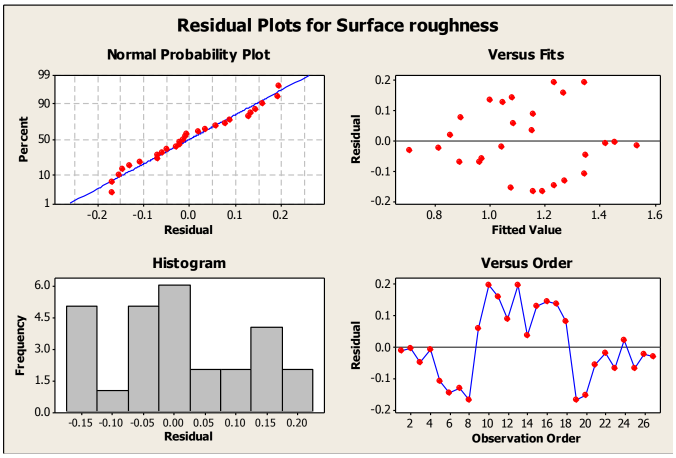

Fig. 4: Residual Plots for Surface Roughness

4. Residuals versus order of the data indicate that there are systematic effects in the data due to time or data collection order

VI. CONCLUSION

After completing the experiments and analysis, the following conclusions were derived.

- Hot machining process gives good surface finish at high cutting speed, high temperature and high feed rate.
- The minimum surface roughness is achieved when temperature 600^{0}C is, cutting speed is 32.21 m/min and feed rate is 0.152 mm/rev.
- During hot machining, the change of the Workpiece surface color was also observed at temperature of 600 ^{0}C

VII. SCOPE OF THE WORK

Although the Hot machining experiments has been thoroughly investigated for AISI4340 steel work material, still there is a scope for further investigation. The following suggestions may prove useful for future work:

- Efforts should be made to investigate the effects of Hot Machining process parameters on performance measures by different heating environment like, plasma arc heating, induction heating and electric current resistance heating.
- Depth of cut remained constant throughout the experiment, it can be varied and further optimum results can be obtained

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