An experimental investigation to optimize the process parameters of AISI 52100 steel in hot machining

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Abstract - ***In this work, cutting force, feed force and surface roughness was studied under the influence of machining parameters namely cutting speed (Vs), feed rate (fs) and depth of cut (ap) at 200 °C, 400 °C and 600 °C. The optimum result was achieved in the experimental study by employing Design of Experiment with full factorial design. The ANOVA analysis was used to obtain optimum cutting parameters and optimum parameters are cutting speed - 965 rev/min, Depth of Cut - 0.8 mm, Feed - 0.265 mm/rev and Temperature - 600 °C. Also the relation between the parameters and the performance measure were determined using multi regression equation.***

Keywords: Hot machining, Cutting speed, Feed rate, Depth of cut, cutting force, feed force and surface roughness.

I. Introduction

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 recrystallisation 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].

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 [7]. 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 [8]. 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 [9]. 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 [10]. 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[11]. Tosum and Ozler conducted hot machining experiments up to 600 °C to optimize the performance characteristics of manganese steel using LPG [12]. 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 [13]. Maity and Swain investigated the tool life during hot machining by using manganese steel as work piece material [14]. Larin and Martynow discussed the method of heating during machining of steel [15]. Ranganathan and Senthilvelan studied the influence of the cutting parameters on 316 stainless steel using analysis of variance (ANOVA).[16]

III. Experimental Details

The experiment was conducted on an auto feed lathe for hot machining operation of Bearing Steel using a Tungsten Carbide cutting tool. The temperature was controlled by a thermocouple and furnace heating system.

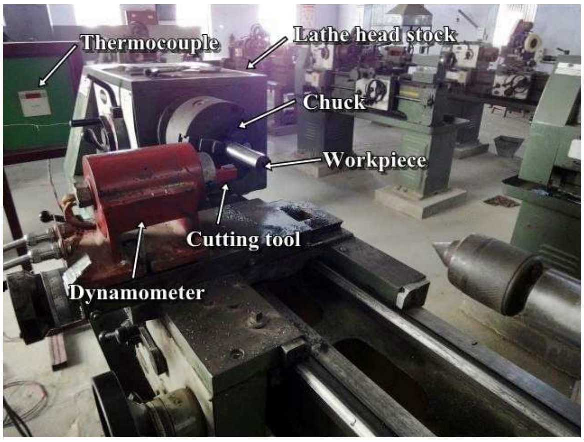

Figure-1 Experimental setup of hot turning of bearing steel

A. Workpiece material and cutting tool:

Bearing steel (AISI 52100) is a high-carbon chromium steel, with small quantities of silicon and manganese. Bearing Steel is exceptionally hard and wear-resistant, and is an excellent choice for applications where high operating temperatures is needed. It has a higher dynamic load capacity than 440C stainless steel and is substantially lower in cost. The chemical compositions and physical properties of bearing steel (AISI 52100) are given in Table-1.

Tungsten carbide was used as a cutting tool during the experiment. The mechanical properties of the cutting tool are shown in Table-2.

B. Design of Experiment:

Design of experiments (DoE) method are among the most effective and useful statistical quality control technique to investigate the individual and interaction effects of the process parameters, DoE methods can be an important part of system optimization, yielding definitive system design or redesign recommendations. These methods also involve the activity experimental planning, conducting experiments, and fitting models to the outputs. An essential ingredient in applying DOE methods is the use of experimental design can have a large influence on the accuracy and the construction cost of the approximations. Several experimental design techniques have been used to aid in the selection of appropriate points.

In a factorial design creates 3^n 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 (ap) had total of $3^3 = 27$ experiment runs at a temperature 200 ^oC, 400 ^oC and 600 ^oC

The range of process parameters are shown in Table-3.

Table-1 Chemical composition and Physical Properties of Bearing Steel (AISI 52100)

Elements	C (Carbon)	Si (Silicon)	Mn (manganese)	Cr (Chromium)	S (Sulfur)	P (Phosphorous)
%	1.28	0.267	0.653	1.295	0.017	0.023
Hardness: 53 HRc			**Density:** 7.60 g/cm^3			

Table-2 Properties of Tungsten Carbide Tool

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

Table-3 Process parameters and their levels

PROCESS PARAMETERS	LEVEL-1	LEVEL-2	LEVEL-3
Cutting speed (m/min)	25.43	58.87	90.903
Feed (mm/rev)	0.265	0.344	0.430
Temperature (^{0}C)	200	400	600

Table-4 Result table for Analysis

Sr. no.	Temperature (^{0}C)	Cutting Speed (m/min)	Feed rate (mm/rev)	Cutting Force (N)	Feed Force (N)	Surface Roughness (R_a)
1	200	25.43	0.265	13	20	2.54
2	200	25.43	0.344	15	18	2.8
3	200	25.43	0.43	17	15	3.07
4	200	58.87	0.265	12	18	2.15
5	200	58.87	0.344	18	11	2.58
6	200	58.87	0.43	22	9	3.42
7	200	90.903	0.265	9	16	1.62
8	200	90.903	0.344	15	10	2.42
9	200	90.903	0.43	20	6	3.33
10	400	25.43	0.265	10	18	2.36
11	400	25.43	0.344	15	17	2.49
12	400	25.43	0.43	15	15	2.71
13	400	58.87	0.265	10	18	1.92
14	400	58.87	0.344	13	10	2.39
15	400	58.87	0.43	17	8	3.05
16	400	90.903	0.265	7	13	1.36
17	400	90.903	0.344	12	8	1.59
18	400	90.903	0.43	15	5	2.09
19	600	25.43	0.265	10	18	1.8
20	600	25.43	0.344	11	15	2.07
21	600	25.43	0.43	13	13	2.5
22	600	58.87	0.265	6	13	1.67
23	600	58.87	0.344	10	8	1.69
24	600	58.87	0.43	15	6	1.74
25	600	90.903	0.265	5	11	1.24
26	600	90.903	0.344	8	5	1.34
27	600	90.903	0.43	12	2	1.44

Table-5 Results of ANOVA for Cutting Force

Source of variation	d.o.f	Sum of squares	Variance (mean square) v	Variance ratio F	Percent contribution P
Temperature	2	144.67	72.33	32.23	32.68
Cutting Speed	2	24.89	12.44	5.54	5.62
Feed Rate	2	228.22	114.11	50.84	51.56
Error (e)	20	44.89	2.24	1	10.14
Total	26	442.67			

Table-6 Results of ANOVA for Feed Force

Source of variation	d.o.f	Sum of squares	Variance (mean square) v	Variance ratio F	Percent contribution P
Temperature	2	58.74	29.37	15.52	9.01
Cutting Speed	2	305.85	152.93	80.80	46.92
Feed Rate	2	249.41	124.70	65.89	38.26
Error (e)	20	37.85	1.89	1	5.81
Total	26	651.85			

Table-6 Results of ANOVA for Surface Roughness

Source of variation	d.o.f	Sum of squares	Variance (mean square) v	Variance ratio F	Percent contribution P
Temperature	2	3.96	1.98	25.49	39.29
Cutting Speed	2	2.05	1.03	13.20	20.34
Feed Rate	2	2.52	1.26	16.19	24.95
Error (e)	20	1.55	0.08	1	15.42
Total	26	10.08			

IV. Results and Discussion

A. Effect on Cutting Force:

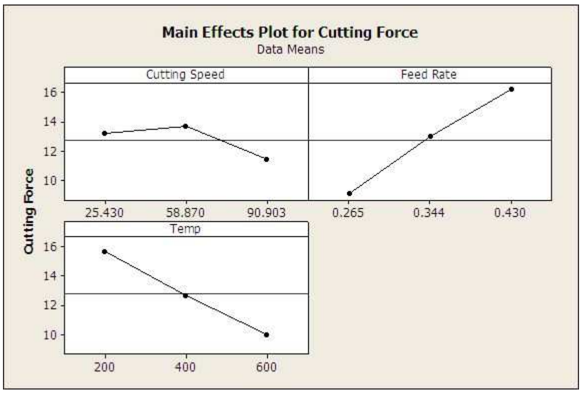

Figure-2 Main effect plot: average for Cutting Force

Figure-2 shows the main effect plot of Cutting Force at different parameters like cutting speed, feed rate and temperature in hot machining process of bearing steel.

From the figure-2, it can be seen that minimum cutting force obtained is at cutting speed of 90.903 m/min, feed rate of 0.265 mm/rev and temperature 600 ^{0}C

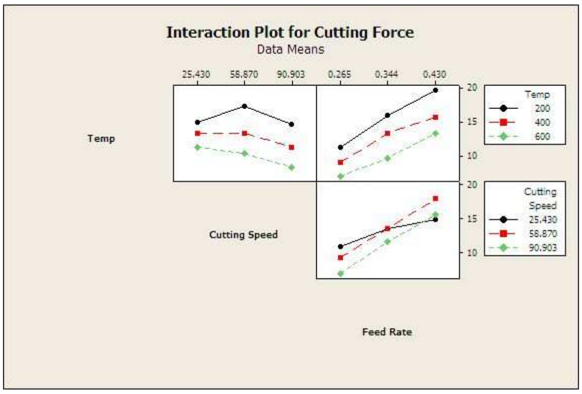

Figure-3 Interaction plot: average for Cutting Force

Figure-3 shows the interaction among temperature, cutting speed and feed rate. The minimum cutting force is achieved when temperature is 600 ^{o}C, cutting speed is 90.903 m/min and feed rate is 0.265 mm/rev.

Table-5 shows the percentage contribution of process parameters for cutting force and it is seen that except cutting speed, all parameters are significant.

B. Effect on Feed Force:

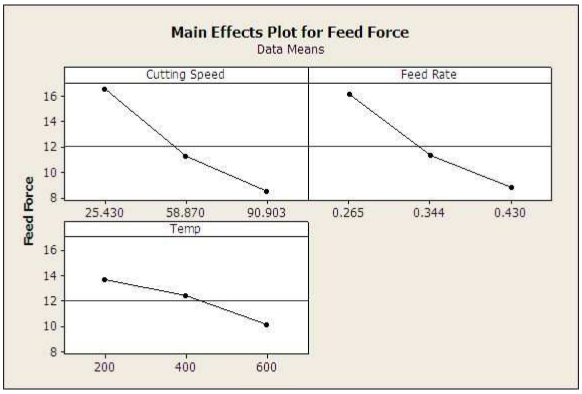

Figure-4 Main effect plot: average for Feed Force

Figure-4 shows the main effect plot of Feed Force at different parameters like cutting speed, feed rate and temperature in hot machining process of bearing steel.

From the figure, it can be seen that minimum feed force obtained is at cutting speed of 90.903 m/min, feed rate of 0.430 mm/rev and temperature 600 ^{o}C.

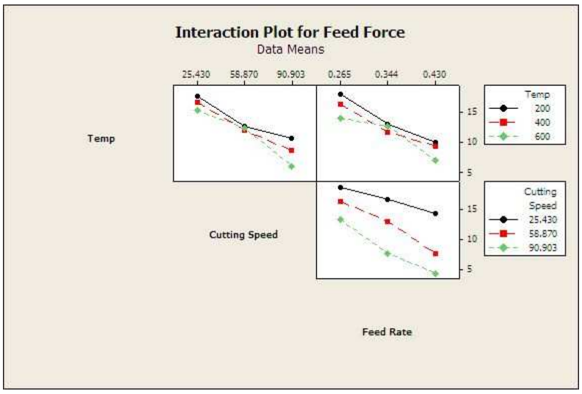

Figure-5 Interaction plot: average for Feed Force

Figure-5 shows the interaction among temperature, cutting speed and feed rate. It can be concluded that the minimum feed force is achieved when temperature is 600 0C, cutting speed is 90.903 m/min and feed rate is 0.430 mm/rev.

Table-6 shows the percentage contribution of process parameters for feed force and it is seen that except temperature, all parameters are significant.

C. Effect on Surface Roughness:

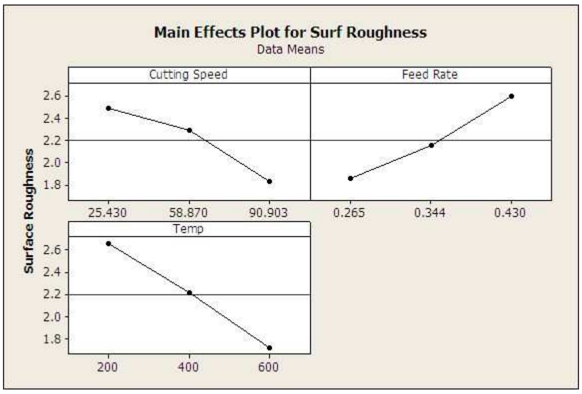

Figure-6 Main effect plot: average for Cutting Force

Figure-6 shows the main effect plot of Cutting Force at different parameters like cutting speed, feed rate and temperature in hot machining process of bearing steel.

From the figure, it can be seen that minimum cutting force obtained is at cutting speed of 90.903 m/min, feed rate of 0.265 mm/rev and temperature 600 0C

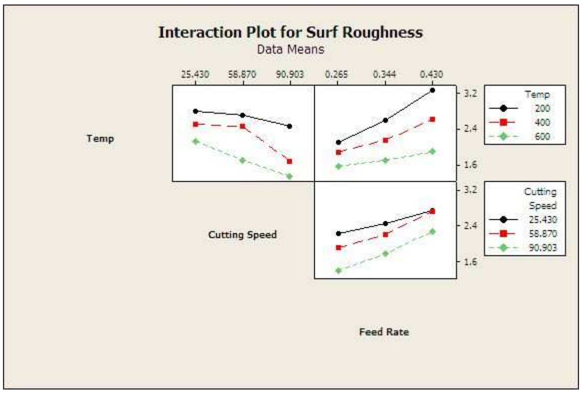

Figure-7 Interaction plot: average for Surface Roughness

Figure-7 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 ^{o}C, cutting speed is 90.903 m/min and feed rate is 0.265 mm/rev.

Table-7 shows the percentage contribution of process parameters for surface roughness and it is seen that all the parameters are significant.

V. MULTIPLE REGRESSION EQUATIONS

The relationship between the factors and performance measures were modeled by multiple regressions. The regression equations obtained were as follows:

Cutting Force = 5.08 - 0.0147 Temp - 0.0178 Vs + 42.7 fs

Feed Force = 37.1 - 0.00820 Temp - 0.117 Vs - 42.2 fs

Surface Roughness = 1.96 - 0.00240 Temp - 0.00845 Vs + 4.96 fs

These equations give the expected values of the cutting force, feed force and surface roughness for any combination of factor level given that the levels are within the ranges in Table-2.

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 low feed rate and it is also beneficial in terms of low cutting force and feed force.
- Optimum results are achieved when Cutting speed is 965 rev/min, Depth of Cut is 0.8 mm, Feed is 0.265 mm/rev and Temperature is 600 ^{o}C
- During hot machining, the change of the workpiece surface color was also observed at temperature of 600 ^{o}C

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