Vol. XI & Issue No. 6 June - 2018
INDUSTRIAL ENGINEERING JOURNAL

MULTI-OBJECTIVE OPTIMIZATION OF CUTTING PARAMETERS TO MINIMIZE ENERGY CONSUMPTION IN DRY TURNING OF AISI 4140 ALLOY STEEL

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Abstract

Manufacturing processes consume enormous amounts of electrical energy. Electrical energy generation uses fossil fuels. Reduction of energy consumption of manufacturing processes can considerably reduce environmental impact and also benefit manufacturer economically. Machining is one of the major manufacturing process.It is important to optimize the energy consumption of machining process while maintaining the quality parameters. Present work utilizes Response Surface Methodology (RSM) to optimize and study the effect of cutting parameters (cutting speed, feed rate and depth of cut) on Specific Energy Consumption (SEC), surface finish and tool wear during dry turning of AISI 4140 alloy steel. Results reveal that minimum SEC was achieved at higher levels of all cutting parameters. In case of tool wear, minimum tool wear was achieved at lower levels of cutting parameters. The most optimal solution for minimum SEC, surface roughness and tool wear was achieved at cutting speed equal 136.715 m/min, feed rate equal to 0.160 mm/rev and depth of cut equal to 1.168 mm.

I. INTRODUCTION

Environmental effects of energy generation necessitates wise use of energy resources. The yearbook 2012 of United States Energy information organization revealed that industries were the major consumer of energy. Industries consume 31% of total electricity. Out of it 90% of electric energy was consumed by manufacturing sector, in which machining consumed 75% of electricity [1]. Environmental studies showed that more than 99% impact on environment is caused by electrical energy consumption [2]. In India almost 69% of electricity is mainly generated by burning the fossil fuel. [3]. Hence it is critical to achieve reduction in energy consumption of machining processes. Dry machining (machining without cutting fluids) shows an advantage over wet machining. But dry machining results in reduced tool life and poor surface finish. Present work focuses on multi-objective optimization of cutting parameters of turning operation of AISI 4140 alloy steel in order to minimize energy consumed per unit material removed by machine tool and to achieve minimum surface roughness and tool wear.

II. LITERATURE REVIEW

Aggarwal et al. [4]studied influence of cutting parameters, cutting environment and tool nose radius on CNC turning of AISI P-20 tool steel and obtained minimum power consumption using both RSM and Taguchi methods. Bhattacharya et al.[5]studied effect of cutting variables on surface finish and power consumption during turning of AISI 1045 medium carbon steel. ANOVA was used as statistical tool. Results showed that surface finish was better at high cutting speed but the Power consumption also increased. Asiltruck and Neseli [6] used both Taguchi and RSM to determine optimized cutting parameters and develop models for responses in turning of AISI 304 stainless steel.

Bhushan [7]used RSM and desirability analysis to optimize cutting parameters in order to minimize power consumption and to increase tool life during machining of 7075 Al alloy SiC composite. Campatelli et al. [8] found optimum cutting parameters of milling carbon steel in order to minimize power consumption on modern CNC machine. Kant and Sangwan [9]obtained optimized values of cutting parameters in dry turning operation on AISI 1045 steel for minimizing power requirements and surface roughness by the development of a multi-objective prediction model applying grey relational analysis together with principle component analysis and RSM. Singarvel et al. [10] used utility concept based upon Taguchi, coupled with Principal component analysis to estimate the optimum cutting parameters like cutting speed, feed and depth of cut for simultaneously minimizing surface roughness, cutting force and maximizing MRR (material removal rate) during turning of EN 25 steel. Das et al. [11]examined effect of cutting parameters such as cutting speed, feed and depth of cut on surface roughness and flank wear during hard turning of AISI 4140 steel..Optimum cutting parameter combination was obtained using RSM to maximize tool life and minimize surface roughness. Negrete [12] employed RSM to find optimum process parameters for turning of AISI 6061 T6 aluminium.

Literature review reveals that number of researchers have used the RSM for optimizing and study effect of cutting parameters in machining processes. Many of them have used this technique to optimize responses like surface roughness, MRR (material removal rate), tool wear, tool life and cutting forces etc. But only few researchers have used this technique for multi-objective optimization while taking energy or power as one of response parameter.In present work, an attempt has been made to optimize the cutting parameters (speed, feed, depth of cut) to minimize the responses; specific energy, surface roughness and tool wear in dry turning of AISI 4140 (medium carbon alloy steel).

III .EXPERIMENTAL DETAILS

A. Material used and its Specification

AISI 4140 high strength alloy steel used as work piece material for present work with 50 mm diameter and 290 mm cutting length. Chemical composition and weight %age of AISI 4140 steel confirmed by spectroscopic analysis and is shown in table 1 below.

Table 1: Chemical Composition and weight %age of AISI 4140 stee

Element	C	S	P	Si	Mn	Cr	Mo	Fe
%	0.43	0.023	0.022	0.300	0.70	1.030	0.210	balance

B. Insert and Tool Holder Specification

CVD coated ($TiCN+Al_2O_3$) tungsten carbide inserts was used. Inserts used have 0.8 mm nose radius and ISO TNMG 160408-CQ designation, where CQ is the chip breaker geometry. Tool holder used has ISO designation as MTJNL 2020 K16, which provides 3° cutting edge angle.

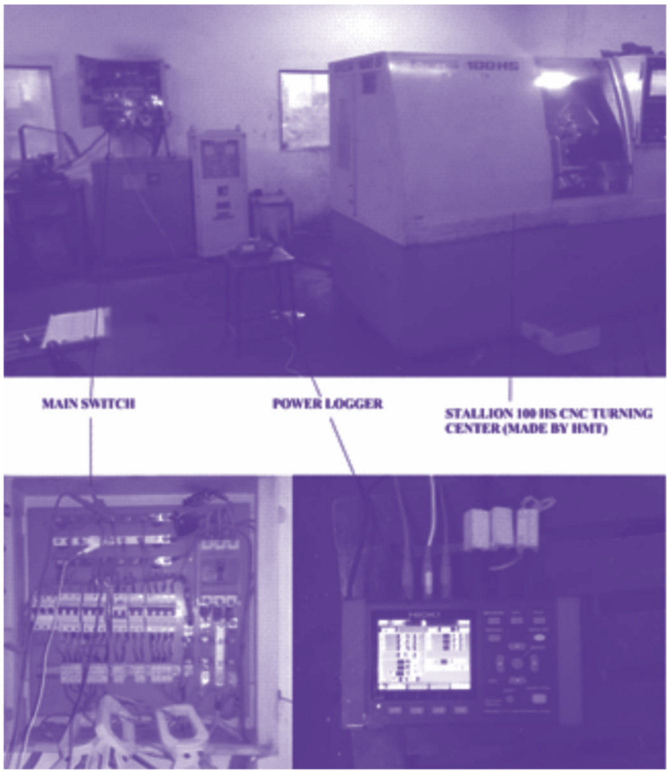

Fig.1: Photographic View of Experimental Setup

C. Experimental Setup

All experiments were conducted on STALLION 100 HS CNC turning center made by HMT.HIOKI PW3360 Clamp on Power logger was used to record power consumption of machining process at time interval of one second. The values of specific energy consumption (SEC)were calculated. Fig. 1 shows the experimental setup. An initial cut was made on each work piece in order make a uniform diameter of 49.4mm. Surface roughness of each work piece is measured by Mitutoyo SJ-410 roughness tester. Radicals make, RMM 7T metallurgical microscope fitted with micrometer was used to measure flank wear of cutting insert or tool. And a universal vice used to hold the insert's flank side parallel to objective lens.

D. Selection of Cutting Parameters

In present work cutting speed, feed rate and depth of cut were selected as main cutting parameters.

E. Selection of Response Parameters

Since objective was to achieve minimum SEC, minimum surface roughness and minimum tool wear. So response variable taken were SEC, surface roughness and tool wear.

1) Specific energy consumption (SEC)

SEC is quantity of energy consumed by machine tool to remove 1 mm^3 of material. And it can be calculated as:

$$SEC = \frac{POWER}{MRR}\ J/mm^3 \quad [13] \qquad (1)$$

Where *MRR (material removal rate)* indicates the quantity of material removed per unit time from work piece and is calculated as: (2)

$$MRR = \frac{1000 \times V_c \times F \times A_p}{60}\ mm^3/sec$$

2) Surface roughness (R_a)

It is arithmetic average of absolute values of roughness profile. Surface roughness was measured three times for each workpiece surface.

3) Tool wear

Tool wear measured in terms of width of flank wear land using metallurgical microscope at 100x magnification. Microscope is fitted with micrometer, which has least count of 0.001 mm.

f. *Design of Experiment*

1) Response Surface Method (RSM)

RSM is a mathematical and statistical tool which is generally used to identify the relationship between response variables and input parameters or variables in terms of an empirical model, and often used to find the input parameter setting that can optimize response. For present work, a quadratic model is used to determine optimum values of response and is given by equation (3)

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 \sum_{i=1<j}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \in \varepsilon \qquad (3)$$

Where k is number of input variables, x_i, x_j and x_i^2 are the input parameters. β_o, β_i, β_{ii} and β_{ij} are coefficients of models and ε is residual linked with experiments.

1) Central Composite Design

A Central composite design (CCD) consist of

- 2^K factorial points. These points are also known as cube points. Here, K denotes number of parameters or factors.
- 2K axial points. These are also star points.
- In addition to above CCD also consist of Centre points this represents experiments with same values of cutting parameters.

In present work, selected cutting variables or prameters were cuting speed (V_c), feed rate (F) and depth of cut (Ap). So, the CCD comprised of 2^3 or 8 factorial points and 2*3 or 6 axial points. The value of α is default value calculated by MINITAB software which is 1.68 in coded terms. Table 4 present the levels of cutting parameters, while table 5, which contains 8 factorial points, 6 axial points and 6 central points, presents the Central composite test plan according to which experiments were conducted.

3) Levels of Cutting Parameters

Levels of various cutting parameters were selected by conducting pilot experiments. Levels of cutting speed, feed rate and depth of cut were selected in view to lathe machine capacity, to avoid tool breakage and under the constraints of tool life which are shown in table 4.

Table 4: Levels of selected cutting parameters

Levels (coded variables)	Cutting Parameters		
	V_c (m/min)	F (mm/rev)	A_p (mm)
-1.68	89.32	0.09	0.50
-1	120	0.13	0.70
0	165	0.19	1.00
+1	210	0.25	1.30
+1.68	240.68	0.29	1.50

Spindle RPM of machine has been calculated by following relationship:

$$RPM = \frac{V_c \times 1000}{\pi \times A_p} \quad (4)$$

Table 5: Test Plan for Central Composite Design

Std Order	Run Order	Coded Values of Parameters			Real Values of Parameters		
		Vc (m/min)	F (mm/rev)	Ap (mm)	Vc (m/min)	F (mm/rev)	Ap (mm)
1	20	-1	-1	-1	120	0.13	0.70
2	12	1	-1	-1	210	0.13	0.70
3	2	-1	1	-1	120	0.25	0.70
4	13	1	1	-1	210	0.25	0.70
5	9	-1	-1	1	120	0.13	1.30
6	3	1	-1	1	210	0.13	1.30
7	11	-1	1	1	120	0.25	1.30
8	8	1	1	1	210	0.25	1.30
9	16	-1.68	0	0	89.32	0.19	1.00
10	19	1.68	0	0	240.68	0.19	1.00
11	15	0	-1.68	0	165	0.09	1.00
12	10	0	1.68	0	165	0.29	1.00
13	17	0	0	-1.68	165	0.19	0.50
14	7	0	0	1.68	165	0.19	1.50
15	14	0	0	0	165	0.19	1.00
16	18	0	0	0	165	0.19	1.00
17	1	0	0	0	165	0.19	1.00
18	6	0	0	0	165	0.19	1.00
19	5	0	0	0	165	0.19	1.00
20	4	0	0	0	165	0.19	1.00

IV. RESULTS AND DISCUSSION

Effect of cutting parameters (cutting speed, feed and depth of cut) on the three responses i.e. SEC, surface roughness and tool wear is discussed in this section. MINITAB software is used to obtain the regression models of different responses. Table 6 shows the values of response variables obtained from different experiments. At the end desirability function was used for multi-objective optimization of responses.

Table 6: Results of Experiment

Run Order	Vc (m/min)	F (mm/rev)	Ap (mm)	SEC (J/mm^3)	Roughness (Ra)	TW (V_b) (mm)
20	120	0.13	0.70	17.11	0.616	0.035
12	210	0.13	0.70	11.89	0.760	0.043
2	120	0.25	0.70	10.03	2.642	0.063
13	210	0.25	0.70	7.11	2.461	0.097
9	120	0.13	1.30	10.57	1.069	0.046
3	210	0.13	1.30	7.60	0.828	0.122
11	120	0.25	1.30	6.58	2.206	0.084
8	210	0.25	1.30	4.95	1.997	0.183
16	89.32	0.19	1.00	11.83	0.676	0.065
19	240.68	0.19	1.00	6.34	0.859	0.117
15	165	0.09	1.00	14.42	0.615	0.074
10	165	0.29	1.00	5.83	2.484	0.125
17	165	0.19	0.50	13.18	1.493	0.090
7	165	0.19	1.50	6.21	1.280	0.134
14	165	0.19	1.00	7.84	1.253	0.079
18	165	0.19	1.00	7.87	1.269	0.083
1	165	0.19	1.00	7.44	1.269	0.080
6	165	0.19	1.00	7.86	1.263	0.081
5	165	0.19	1.00	7.89	1.241	0.084
4	165	0.19	1.00	7.82	1.243	0.071

A. Analysis of Variance (ANOVA) And Regression Model ForSEC

ANOVA and F-test results for regression model were obtained at significance level α=0.05 or 95% confidence level. ANOVA results of SEC are presented in table 7. Small P-values (< 0.05) for factors V_c (cuting speed), F (feed rate) and A_p (depth of cut) indicates statistical significant of these parameters. High R-squares coefficient (99.64%) ensures a satisfactory relationship observed and calculated data. Percentage contribution (PC %) column indicates that feed rate has highest contribution of 40.98% to the total variation of SEC and depth of cut have 29.89% and then cutting speed have 18.21 % contribution.

Table 7: ANOVA for SEC (J/mm^3)

Source	DF	Seq SS	Adj MS	F	P	PC %
Regression Model	9	193.527	21.5030	308.46	0.000	99.64
V_c	1	35.370	35.3698	507.38	0.000	18.21
F	1	79.549	79.5494	1141.14	0.000	40.98
A_p	1	58.070	58.0695	833.01	0.000	29.89
V_c* V_c	1	1.125	2.3305	33.43	0.000	0.57
F* F	1	7.299	8.5330	122.41	0.000	3.75
A_p * A_p	1	5.496	5.4964	78.85	0.000	2.83
V_c*F	1	1.662	1.6623	23.85	0.000	0.86
V_c*A_p	1	1.555	1.5552	22.31	0.001	0.80
F*A_p	1	3.400	3.4002	48.78	0.001	1.75
Residual Error	10	0.697	0.0697		0.000	0.36
Total	19	194.224				100

R-Squared = 99.64%, R-Squared (pred) = 97.64%, R-Squared (adj) = 99.32%

Equation (5) presents the quadratic model for SEC. Graphs shown in fig.2 indicate that value of SEC was minimum when feed, cutting velocity and depth of cut were at their highest level.

$$SEC = 65.765 - 0.166032V_c - 185.523F - 32.8677A_p + 0.000198585V_c * V_c + 213.717F * F + 6.86190A_p * A_p + 0.168828V_c * F + 0.0326597V_c * A_p + 36.2188F * A_p$$

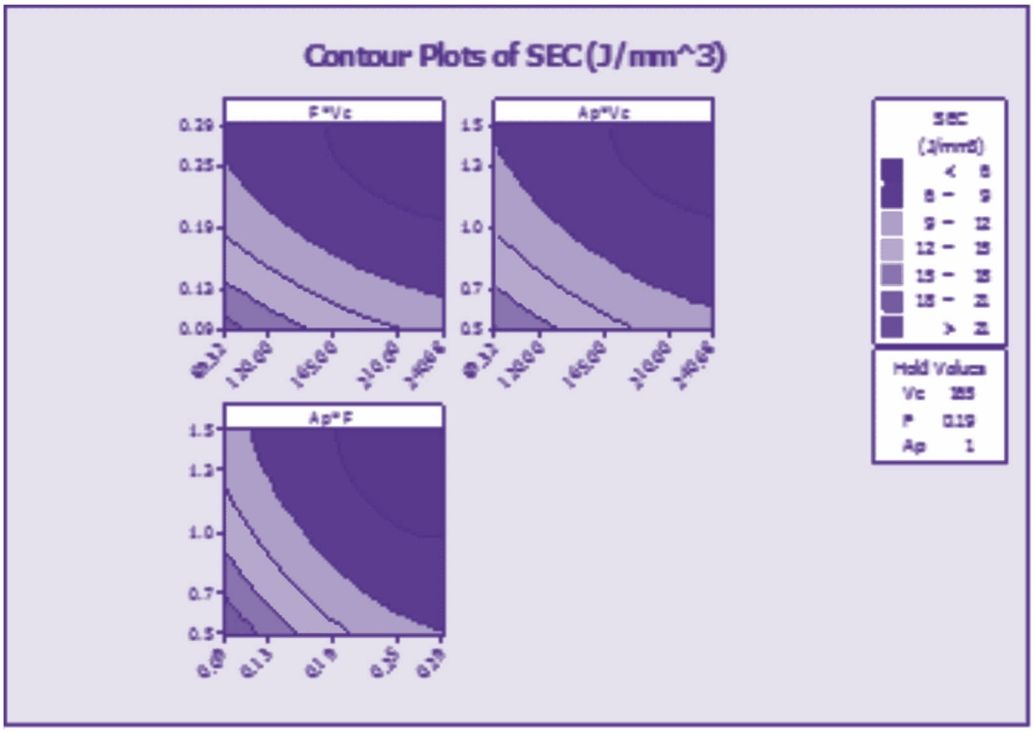

Fig.2: Contour Plots of SEC

A. Analysis of Variance (ANOVA) And Regression Model For Surface Roughness (R_a)

Table 8 presents the ANOVA and F-test of Surface roughness. P-value for feed rate was <0.05 which indicated that feed was the significant parameter, while for cutting speed and depth of cut P-value >0.05 which indicated that these were not the significant parameters for surface roughness. Percentage contribution (PC %) column shows that feed rate contributed 78.25% in total variation of surface roughness, while other terms have negligible contribution. R-squared value of 90.62% shows the accuracy of model. Equation (6) presents the regression model of surface roughness. Graphs presented in fig.3 showed that speed has negligible influence on surface roughness. Depth of cut has little influence on surface roughness, while a low feed rate is required to attain minimum surface roughness.

Table 8: ANOVA for Surface Roughness (R_a)

Source	DF	Seq SS	Adj MS	F	P	PC %
Regression Model	6	7.14044	1.19007	20.92	0.000	90.62
V_c	1	0.00235	0.00235	0.04	0.842	0.03
F	1	6.16569	6.16569	108.41	0.000	78.25
A_p	1	0.03980	0.03980	0.70	0.418	0.51
F* F	1	0.44302	0.49966	8.79	0.011	5.62
A_p * A_p	1	0.23718	0.23718	4.17	0.062	3.01
F*A_p	1	0.25241	0.25241	4.44	0.055	3.20
Residual Error	13	0.73938	0.05688			9.38
Total	19	7.87982				100

R-Squared = 90.62%, R-Squared (pred) = 71.19%, R-Squared (adj) = 86.29%

$$R_a = 0.664255 - 2.91643 * 10^{-4} V_c + 1.50904F - 1.14176A_p + 51.4674F * F + 1.41837\, A_p * A_p - 9.86806F * A_p$$

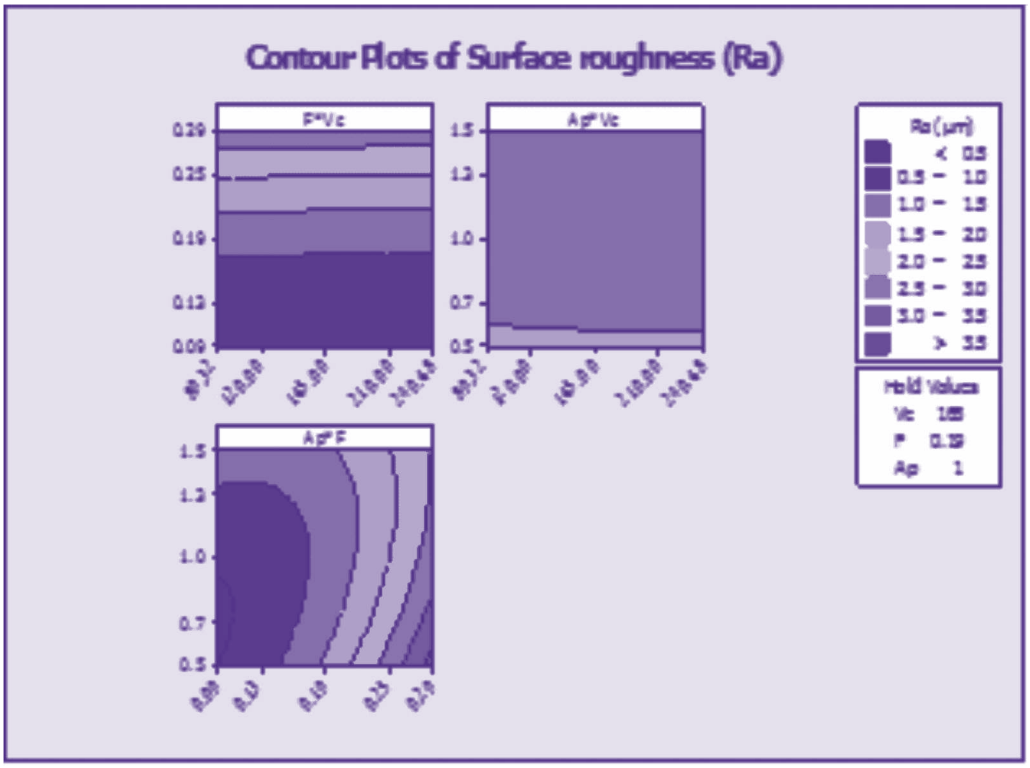

Fig.3: Contour Plots of Surface Roughness (R_a)

A. Analysis of Variance (ANOVA) and Regression Model For Tool Wear (TW)

Table 9 presents the ANOVA and F-test of Surface roughness.P-values <0.05 indicated that speed, feed, depth of cut and interaction between speed and depth of cut were statistically significant.

Table 9: ANOVA for Tool Wear (TW)

Source	DF	Seq SS	Adj MS	F	P	PC %
Regression Model	6	0.020374	0.004075	21.09	0.000	88.28
V_c	1	0.006787	0.006787	35.13	0.000	29.41
F	1	0.005211	0.005211	26.97	0.000	22.58
A_p	1	0.005378	0.005378	27.83	0.000	23.30
A_p * A_p	1	0.000787	0.000787	4.08	0.063	3.41
V_c*A_p	1	0.002211	0.002211	11.44	0.004	9.58
Residual Error	14	0.002705	0.000193			11.72
Total	19	0.023079				100

R-Squared = 88.28%, R-Squared (pred) = 67.59%, R-Squared (adj) = 84.09%

Percentage contribution values indicated that cutting speed contributed 29.41% in total variation of tool wear and depth of cut contributes 23.30% and feed gives 22.58% contribution. R-squared value of 88.28% and difference of R-squared(adj) and R-squared(pred) which was less than 20%, implied that model is satisfactory. Equation (7) presents the regression model obtained. Graphs shown in fig. 5 revealed that tool wear is minimum at lowest values of feed, cutting speed and depth of cut.

$$TW = 0.157642 - 7.36080 * 10^{-4} V_c + 0.325565F - 0.299835A_p + 0.813927\, A_p * A_p + 0.00123148 V_c * A_p$$

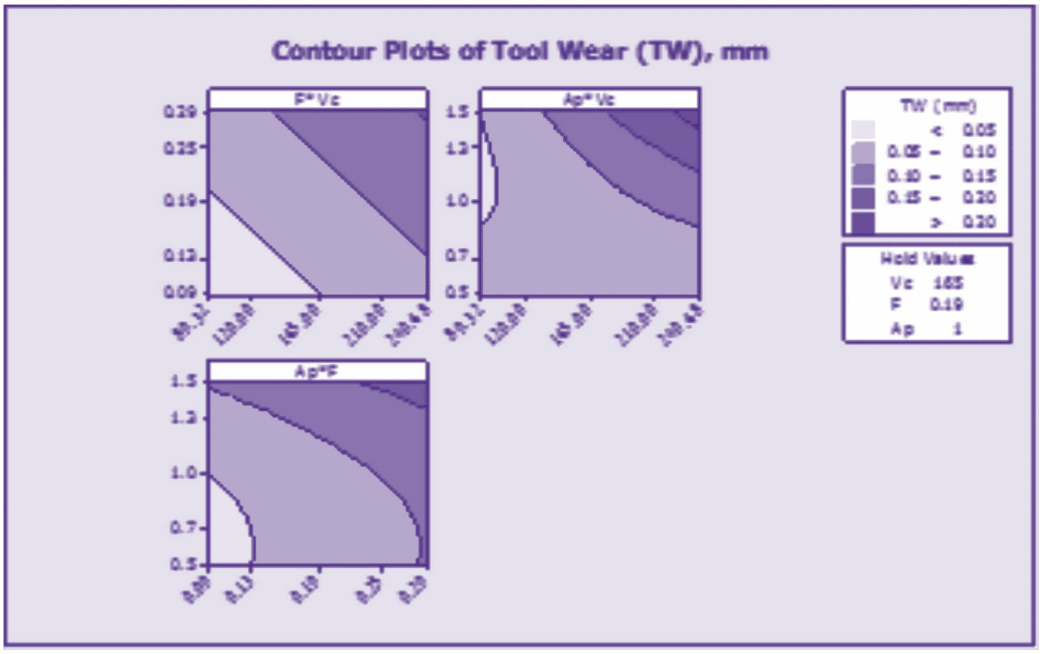

Fig.4: Contour Plots of tool wear

D. Multi-Objective Optimization

The desirability function approach was used to minimize energy consumption, improve surface quality (surface finish) and to minimize tool wear. MINITAB software was used to carry out this optimization analysis. Constraints used for optimization are shown in table 13. Fig.5 shows optimization plot obtained with the help of Response optimizer in MINITAB software, which shows values of desirability alongside of all responses. Table 14 shows the results obtained after multi-objective optimization.

Table 13: Constraints for Multi-objective optimization

Parameters & Responses	Goal	Lower limit	Upper limit	Weight	Importance
V_c (m/min)	In range	89.34	240.68	1	1
F (mm/rev)	In range	0.09	0.29	1	1
A_p (mm)	In range	0.5	1.5	1	1
SEC (J/mm^3)	Minimize	4.95	17.11	1	1
Surface Roughness (µm)	Minimize	0.615	2.642	1	1
Tool Wear (mm)	Minimize	0.035	0.183	1	1

Table 14: Optimal Solution

Responses	Goal	Optimum Parameters			Optimum Values of Responses obtained by RSM analysis	Desirability
		V_c (m/min)	F (mm/rev)	A_p (mm)		
SEC (J/mm^3)	Minimize				9.187	0.6516
R_a (µm)	Minimize	136.715	0.160	1.168	0.944	0.8379
TW (mm)	Minimize				0.067	0.7856
Composite Desirability = 0.7541						

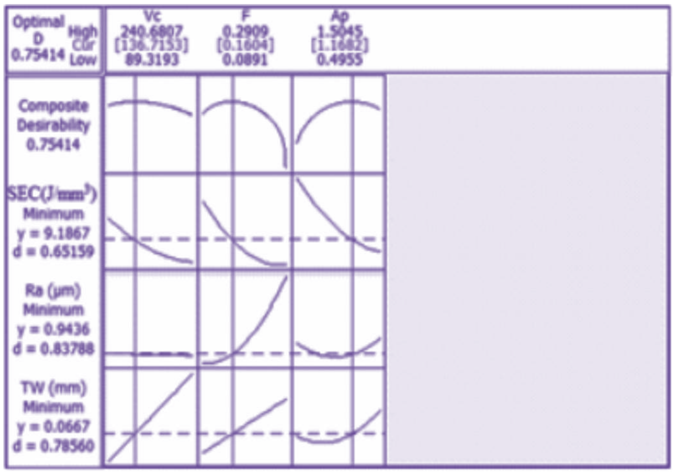

Fig.5: Optimization Plot

A. Conformation Test

Conformation test was carried out in order to verify results obtained after multi-objective optimization. Experiment was carried out at optimized cutting parameters i.e. V_c= 136.715 m/min., F= 0.160 mm/rev., A_p= 1.168 mm. Measured values of responses obtained from conformation experiments were compared with predicted optimum values of responses. Results of conformation test are shown in table 15 which shows the accuracy of RSM technique.

Table 15: Conformation Test Results

Responses	Predicted Values obtained by RSM analysis	Measured Value (Conformation Experiment)	Accuracy $= \left\lvert 1 - \frac{\lvert Pred.Value - Measured\ Value \rvert}{Measured\ Value} \right\rvert \times 100$
SEC (J/mm^3)	9.187	8.952	97.44 %
R_a (µm)	0.944	1.080	87.41%
TW (mm)	0.067	0.071	94.40%

V. *CONCLUSION*

Response Surface Methodology was employed to optimize process parameters in dry turning of AISI 4140 steel for multi objective optimization of responses; Specific Energy Consumption, surface roughness and tool wear. Results showed that,

1) A minimum value SEC equal to 4.95 J/mm^3 was achieved at cutting speed of 210 m/min., feed rate of 0.25 mm/rev. and depth of cut of 1.30 mm.
2) In case of surface roughness minimum value was 0.615 µm. This value was achieved at cutting speed of 165 m/min., feed of 0.09 mm/rev. and depth of cut of 1 mm.
3) And for tool minimum tool wear equal to 0.035 was achieved at cutting speed of 120 m/min., feed rate of 0.13 mm/rev. and depth of cut of 0.70 mm.
4) The most optimal solution for SEC (9.187 J/mm^3), surface roughness (0.944 µm) and tool wear (0.067 mm) were obtained at cutting speed of 136.715 m/min., feed of 0.160 mm/rev. and depth of cut of 1.168 mm. These results are also confirmed by conformation test.

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