INVESTIGATION OF FORCES, POWER AND SURFACE ROUGHNESS IN HARD TURNING WITH MIXED CERAMIC TOOL

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ABSTRACT: Hard turning has been explored as an alternative to cylindrical grinding used in manufacturing parts made of tool steels. In the present study, the effects of cutting speed, feed rate and Depth of Cut (DOC) on cutting force, specific cutting force, power and surface roughness in the hard turning were experimentally investigated. Experiments were carried out using mixed ceramic (Al_2O_3 + TiC) cutting tool having nose radius of 0.8mm, in turning operations on AISI D3 tool steel, heat treated to a hardness of 62 HRC. Response Surface Methodology (RSM) based Central Composite Design (CCD) in Design of Experiments (DOE), was adopted in deciding the number of experiments (20) to be performed with various combinations of input parameters. The range of each one of the three parameters was set at three different levels; namely low, medium and high. The validity of the model was checked by Analysis of Variance (ANOVA). The results yielded that most favorable parameter setting for superior surface finish was acquired at a medium speed of cutting (155 m/min), medium feed (0.075 mm/rev) and low DOC (0.3mm).

KEYWORDS: *Hard turning, Specific cutting force, Surface roughness, AISI D3 and Mixed ceramic.*

1.0 INTRODUCTION

Hard turning is the process of machining hardened steels where the value lies between 45 – 68 HRC (Rockwell hardness) with the latest cutting tools i.e., Poly-crystalline Diamond (PCD), Cubic Boron Nitride (CBN), Poly-crystalline Cubic Boron Nitride (PCBN), Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) Coated tools and Ceramics. Finishing operation like grinding requires many setups, hard turning is the best option to replace grinding and has several benefits such as coolant elimination, reduced cost of production, enhancement of material properties, reduction in power consumption and productivity. Ceramic tools are generally used as an alternative to CBN in the manufacturing sector for machining of hard materials such as alloy steels; bearing steels, die steels, graphite cast iron, high-speed steels and white cast iron [1-5]. Therefore hard turning is considered as an alternative process to grinding in a bid to reduce the setup changes, setup cost, setup time, process flexibility, compatible performance characteristics and higher material removal rate and less environmental problems.

Various studies have been conducted to investigate the performance of CBN tool in the machining of tool steels. Bouacha et al. [6] examine effect of cutting parameters on cutting parameters on cutting force and surface roughness in hard turning of AISI 52100 with CBN tool using response surface methodology. The results show that the surface roughness is influenced by feed rate and cutting speed. Aouici et al. [7] conduct extensive experiments on AISI D3 cold steel with mixed Ceramic CC 6050 (with a tool nose radius 0.8 mm, chamfered insert 0.1 mm × 20°), hence, the surface roughness is strongly influenced by the feed rate (87.334 %) and followed by square of feed rate (6.455 %). The surface finish has improved as speed of cutting increases to an extent of 5.03% and deteriorates with the feed rate of 36.672 followed by DOC (27.541%). Initially, cutting force enhances with an increase in feed rate and DOC and reduces with an increase in cutting speed. The lessening in the forces is probably due to temperature increase in the shear plane area, which resulted in the drop in shear strength of the material.

The experimental studies conducted by Aouici et al. [8] yield that the feed force and tangential force are strongly influenced by DOC and cutting speed has negligible influence on these forces while the machining of AISI H11 hardened steels (40, 45, and 50 HRC) is using CBN 7020. Al-Ahmari [9] present empirical models for surface roughness and cutting force in turning operation. The process parameters namely speed, feed, DOC and nose radius are used to develop the machinability model. Two methods used for developing aforesaid models are RSM and Neural Networks (NN). The effect of cutting conditions in a hard turning operation is analyzed by Dilbag and Venkateswara [10]. El Wardany et al. [11] study the quality and integrity of the surface produced during high speed turning of AISI D2 cold work tool steel in its hardened state (60 - 62 HRC) using CBN tool. Kirby et al. [12] predict surface roughness in turning operation using different prediction models. A regression model is developed by a single cutting parameter and vibrations along three axes are chosen for in process surface roughness prediction system. Linear relationship among the parameters and the response is carried out using multiple regression and ANOVA. The results reveal that for attaining an effective surface roughness prediction model, the cutting speed and DOC may not be necessarily fixed.

Horng et al. [13] present a model by applying RSM and ANOVA techniques to evaluate the machinability of Hadfield steel. Aouici et al. [14] conduct experiments on machining of X38CrMoV5-1 steel treated at 50 HRC by a CBN7020 tool to reveal the influence of the following cutting parameters: cutting speed, feed rate and DOC on surface roughness. They conclude that the surface roughness is sensitive to the variation of feed. Kribes et al. [15] present a statistical analysis to study the influence of cutting conditions on surface roughness in hard turning of 42CrMo4 steel using coated mixed ceramic inserts. Doniavi et al. [16] apply RSM in order to develop empirical model for the prediction of surface roughness by deciding the optimum cutting condition in turning. It is reported that the feed rate influences surface roughness remarkably. With the increase in the feed rate, surface roughness increases. ANOVA results show that feed and speed have more influence on surface roughness than DOC.

Quiza et al. [17] predict ceramic cutting tool wear in hard machining of AISI D2 steel using NN. The models are adjusted to predict tool wear for different values of cutting speed, feed rate, and machining time. One of them is based on statistical regression and the other is based on a multilayer perception neural network. The NN model has a better performance than the regression model in its ability to make accurate predictions of tool wear. Neseli et al. [18] use RSM to optimize the effect of tool geometry parameters on surface roughness in hard turning of AISI 1040 with P25 tool. Gaitonde VN et al. [19] conduct experiments to analyze the effects of DOC and machining time on machinability aspects such as machining force, power, specific cutting force, surface roughness, and tool wear during turning of AISI D2 cold work tool steel using traditional and wiper ceramic inserts.

The present work investigate the influence of process parameters in hard turning of AISI D3 cold work tool steel (62 HRC) using mixed ceramic tool insert (CC6050) on specific cutting force, power and surface roughness. A little work is reported so far in the literature for this combination of tool and work piece material.

2.0 EXPERIMENT PROCEDURE

The work piece material used for experimentation was AISI D3 steel. The circular bar of diameter 70 mm x 360 mm long was prepared. Test sample was trued, centered and cleaned by removing a 2 mm depth of cut from the outside surface, prior to actual machining tests.

2.1 Material, work piece and tool

Due to its high wear resistance, AISI D3 material is usually employed for the manufacture of blanking; drawing dies, punches, rollers profilers, stamping and wood tools and others. A new insert was employed for each run of experiments in order to provide completely identical cutting edge conditions for each test. The chemical composition of the work piece material is given in Table 1. The work piece was heat treated to attain 62 HRC. The process of heat treatment was as follows, the work piece was oil-quenched from 980^{o}C followed by tempering at 200oC. Its hardness value was mean of three readings taken at three different locations on the machined surface. Figure 1 shows the experimental setup.

Table 1: Chemical composition of AISI D3 (wt %)

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Zn	Fe
2.06	0.55	0.449	0.036	0.056	11.09	0.277	0.207	0.0034	0.13	0.27	Balance

Figure 1: Experimental setup

The tests on the work piece were conducted under dry environment on the lathe Kirloskar; model Turn Master-35, spindle power 6.6KW. The cutting forces were measured by *Kistler* piezoelectric dynamometer (model 9257B). This dynamometer can measure forces in three mutually perpendicular directions i.e. Fx, Fy (0 to 5000N) and Fz (0 to 10000N). The charge generated at the dynamometer was amplified by a Kistler charge amplifier (model 5070A). The signal was acquired by a data acquisition system consists of a personal computer as controller and cable for PC to charge amplifier connection. The Dyno ware software installed in the PC acquires the force data generated during turning in all three directions. The average value of this force data was used for further analysis. Surface roughness was measured using *Mitutoyo Surftest SJ 210* with measuring range of 17.5mm and skid force less than 400mN. The sample length was 0.8 mm. Average of four readings of surface roughness was recorded on different places of sample surface. These values were obtained without disturbing the assembly of the work piece in order to reduce uncertainties.

The cutting tool used for machining was mixed ceramic tool designated as SNGA 120408 T01020 (*Sandvik make*) that is CC6050. The high hot-hardness and the good level of toughness make the grade suitable as the first choice for hardened steel (50 – 65HRC) in applications with good stability or with light interrupted cuts. Commercial tool holder designated as PSBNR 2525 M 12 (ISO) with the geometry of active part characterized by the following angles: $\chi = 75°$; $\alpha = 6°$; $\gamma = -6°$; $\lambda = -6°$.

2.2 Experiments Design

RSM is a DOE technique used to optimize the number of experiments based on the number of process parameters and their levels on performance characteristics. The RSM is useful for emerging, refining and optimizing the processes, which provides an overall perception of the system outputs within the design space [20]. In order to know performance characteristics in advance, it is necessary to employ empirical models making it feasible to do predictions as a function of operational conditions. Using DOE and applying the regression analysis, the modelling of the desired output against several independent process parameters can be obtained. The RSM is exploited to designate and identify the impact of interactions of different process parameters on the performance characteristics when these are varied simultaneously. In the present investigation, the second-order RSM based mathematical models for surface roughness (R_a) is developed with cutting speed (V_c), feed rate (f), and DOC (a_p) as the process parameters. Figure 2 shows a flow diagram of methodology adopted for the present work.

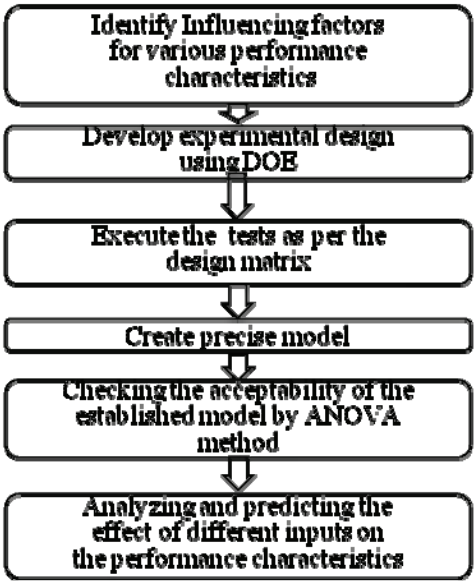

Figure 2: Proposed methodology

In the current study, the quantitative form of the relationship between the desired response and independent input process parameters [20] can be represented by

$$Y = \varnothing(V_c, f, a_p) \tag{1}$$

Where Y is the output and Ø is the acknowledgment function. In the present investigation, the RSM based algebraic models for cutting power, specific cutting force and surface roughness have been developed with speed of cutting(V_c), feed (f) and DOC (a_p) as the action parameters. The acknowledgment apparent blueprint for three factors [24] is accustomed by

$$Y = a_0 + a_1 V_c + a_2 f + a_3 a_p + a_{12} V_c f + a_{13} V_c a_p + a_{23} f a_p + a_{11} V_c^2 + a_{22} f^2 + a_{33} a_p^2 \tag{2}$$

Where Y is desired response and a_0 is the free term of the regression equation, the coefficients a_1, a_2, a_3 and a_{11}, a_{22}, a_{33}……. are the linear and quadratic terms, respectively, while a12, a13,..a23 are the interacting terms.

Three levels are identified for each cutting variable as given in Table 2. The levels of variable are chosen as per recommendations made by the cutting tool manufacturer. Three variables of cutting at three levels led to a total of 20 tests in DOE. The experimental plan is developed to evaluate the influence of cutting speed (V_c), feed rate (f) and DOC (a_p) on the power (P), specific cutting force (K_2) and surface roughness (R_a) determined from the following equations:

$$\text{Power (P)} = F_2 \times V_2 \qquad (3)$$

The value of specific cutting force is generally calculated by the formula given below

$$K_s = \frac{F_z}{f \times a_p} \qquad (4)$$

Where, a_p is the DOC. The experimental values of Power, specific cutting force and surface roughness are given in Table 3.

Table 2: Assignment of the levels to the variables

Parameters	Levels		
	-1	0	+1
Speed(m/min)	145	155	165
Feed(mm/rev)	0.05	0.075	0.1
DOC (mm)	0.3	0.6	0.9

3.0 RESULTS AND DISCUSSION

Table 3 shows all the values of the performance characteristics, power (P), three cutting forces (F_x), (F_y) & (F_z), specific cutting force (K_z) and surface roughness obtained when analyzing the influence of the cutting speed (V_2), feed rate (f), and DOC (a_p). The surface roughness is obtained in the range of 0.71 – 2.27μm; specific cutting force 3.1206 - 9.5333 kN/mm2 and power 0.273 - 0.951kW.

Table 3: Values of cutting forces, power, specific cutting force and surface roughness

Sl. No.	Speed (m/min)	Feed (mm/rev)	DOC (mm)	F_x (N)	F_y (N)	F_z (N)	Specific Cutting Force (kN/mm2)	Power P (kW)	R_a (µm)
1	145	0.050	0.3	106.0	138.0	113.0	7.5333	0.273	1.33
2	165	0.050	0.3	098.0	206.7	102.7	9.6000	0.396	1.88
3	145	0.100	0.3	115.0	242.0	150.0	5.2500	0.381	0.90
4	165	0.100	0.3	122.0	254.1	194.6	6.4866	0.535	0.82
5	145	0.050	0.9	321.5	300.0	289.0	6.4222	0.698	2.06
6	165	0.050	0.9	283.7	325.2	312.1	7.6888	0.951	2.11
7	145	0.100	0.9	341.2	340.0	335.0	3.7222	0.809	1.10
8	165	0.100	0.9	332.0	290.0	280.5	3.1206	0.772	0.91
9	145	0.075	0.6	212.6	279.0	220.0	4.8889	0.531	0.84
10	165	0.075	0.6	228.3	290.7	245.3	5.4511	0.674	0.93
11	155	0.050	0.6	213.1	256.0	216.4	7.2133	0.559	2.27
12	155	0.100	0.6	250.3	325.0	310.5	5.1750	0.802	0.93
13	155	0.075	0.3	104.9	170.0	125.0	5.5555	0.322	1.05
14	155	0.075	0.9	298.5	273.4	263.1	3.8996	0.679	0.83
15	155	0.075	0.6	230.0	284.7	252.2	5.6044	0.651	0.71
16	155	0.075	0.6	235.0	274.0	260.0	5.7777	0.671	0.71
17	155	0.075	0.6	245.0	282.0	258.0	5.7333	0.666	0.73
18	155	0.075	0.6	252.0	278.0	248.0	5.5111	0.640	0.75
19	155	0.075	0.6	253.0	280.0	262.0	5.8222	0.676	0.88
20	155	0.075	0.6	260.0	282.0	255.0	5.6666	0.658	0.92

3.1 Statistical Analysis

The results of ANOVA for power (P), specific cutting force (K_z) and surface roughness (R_a) are shown in Table 5, 7 and 9. Table 4, 6 and 8 show the details of estimated regression coefficients. This analysis is done out for a 5 % significance level, i.e., for a 95 % confidence level. ANOVA has been applied to check the adequacy of the developed models. ANOVA table consists of sum of squares and degrees of freedom. The sum of squares is performed into contributions from the polynomial model and the experimental value.

Power is influenced by Speed, DOC and DOC2 and is expressed by equation (5). Table 5 represents the ANOVA table for response surface quadratic model for Power P (kW). The value of "Prob." in Table 5 for model is less than 0.05 which specifies that the model is noteworthy, which is appropriate as it directs that the terms in the model have a major effect on the output.

$$Power\ (P) = 0.612465 + 0.063605 \times Speed + 0.200386 \times DOC - 0.098155 \times DOC^2 \quad (5)$$

Table 4: Estimated Regression Coefficients for Power (kW)

Term	Coef	SE Coef	T	P
Constant	0.612465	0.02408	25.434	0.000
Speed	0.063605	0.02215	2.871	0.017
Feed	0.042165	0.02215	1.904	0.086
DOC	0.200386	0.02215	9.046	0.000
Speed*Speed	0.003540	0.04224	0.084	0.935
Feed*Feed	0.080999	0.04224	1.918	0.084
DOC*DOC	- 0.098155	0.04224	-2.324	0.043
Speed*Feed	-0.032357	0.02477	-1.307	0.221
Speed*DOC	-0.007718	0.02477	-0.312	0.762
Feed*DOC	-0.039353	0.02477	-1.589	0.143
S = 0.0700472 PRESS = 0.464736 R-Sq = 91.29% R-Sq(pred) =17.46% R-Sq(adj) = 83.44%				

Table 5: Analysis of Variance for Power (kW)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Con	Remarks
Regression	9	0.513993	0.513993	0.057110	11.64	0.000		Significant
Speed	1	0.040456	0.040456	0.040456	8.25	0.017	7	Significant
Feed	1	0.017779	0.017779	0.017779	3.62	0.086	3	Insignificant
DOC	1	0.401545	0.401545	0.401545	81.84	0.000	72	Significant
Speed*Speed	1	0.000228	0.000034	0.000034	0.01	0.935	0	Insignificant
Feed*Feed	1	0.006249	0.018042	0.018042	3.68	0.084	1	Insignificant
DOC*DOC	1	0.026495	0.026495	0.026495	5.40	0.043	5	Significant
Speed*Feed	1	0.008376	0.008376	0.008376	1.71	0.221	2	Insignificant
Speed*DOC	1	0.000477	0.000477	0.000477	0.10	0.762	0	Insignificant
Feed*DOC	1	0.012389	0.012389	0.012389	2.53	0.143	2	Insignificant
Residual Error	10	0.049066	0.049066	0.004907			8	
Total	19	0.563059					100	

Table 6: Estimated Regression Coefficients for Ks (kN/mm2)

Term	Coef	SE Coef	T	P
Constant	5.2230	0.1665	31.362	0.000
Speed	0.453	0.1532	2.957	0.014
Feed	-1.4704	0.1532	-9.598	0.000
DOC	-0.9573	0.1532	-6.249	0.000
Speed*Speed	0.1262	0.2921	0.432	0.675
Feed*Feed	1.1504	0.2921	3.938	0.003
DOC*DOC	-0.3164	0.2921	-1.083	0.304
Speed*Feed	-0.3374	0.1713	-1.97	0.077
Speed*DOC	-0.3299	0.1713	-1.926	0.083
Feed*DOC	-0.234	0.1713	-1.366	0.202
S = 0.484431 PRESS = 10.8935 R-Sq = 94.55% R-Sq(pred) = 74.69% R-Sq(adj) = 89.64%				

$$Ks = 5.223 + 0.453 \times Speed - 1.4704 \times Feed - 0.9573 \times DOC + 1.1504 \times Feed^2 \quad (6)$$

From the analysis of Table 7, it can be seen that the Speed, Feed, DOC and Feed2 have significant effect on the specific cutting force (Ks). Specific cutting force increases with the increase in feed rate and DOC. Table 9 shows the ANOVA table for response surface. The major effect on surface roughness follows Feed (f) and the product f2. Feed (f) is the most important factor affecting surface roughness.

$$Surface\ roughness\ (Ra) = 0.85164 - 0.499 \times Feed + 0.064591 \times Feed^2 \quad (7)$$

Table 7: Analysis of Variance for Ks (kN/mm2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Con	Remarks
Regression	9	40.7003	40.7003	4.5223	19.27	0.000		Significant
Speed	1	2.0521	2.0521	2.0521	8.74	0.014	5	Significant
Feed	1	21.6204	21.6204	21.6204	92.13	0.000	50	Significant
DOC	1	9.1642	9.1642	9.1642	39.05	0.000	21	Significant
Speed*Speed	1	1.963	0.0438	0.0438	0.19	0.675	5	Insignificant
Feed*Feed	1	3.4062	3.6392	3.6392	15.51	0.003	8	Significant
DOC*DOC	1	0.2753	0.2753	0.2753	1.17	0.304	1	Insignificant
Speed*Feed	1	0.9105	0.9105	0.9105	3.88	0.077	2	Insignificant
Speed*DOC	1	0.8705	0.8705	0.8705	3.71	0.202	2	Insignificant
Feed*DOC	1	0.4382	0.4382	0.4382	1.87	0.202	1	Insignificant
Residual Error	10	2.3467	2.3467	0.2347			5	
Total	19	43.047					100	

Table 8: Estimated Regression Coefficients for Ra

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	0.85164	0.06381	13.347	0.000
Speed	0.042	0.0587	0.716	0.491
Feed	-0.499	0.0587	-8.502	0.000
DOC	0.103	0.0587	1.755	0.110
Speed*Speed	-0.06909	0.11193	-0.617	0.551
Feed*Feed	0.64591	0.11193	5.771	0.000
DOC*DOC	-0.01441	0.11193	-0.126	0.902
Speed*Feed	-0.10875	0.06562	-1.657	0.128
Speed*DOC	-0.07625	0.06562	-1.162	0.272
Feed*DOC	-0.08375	0.06562	-1.276	0.231
S = 0.185611 PRESS = 2.34923 R-Sq = 93.04% R-Sq(pred) = 52.54% R-Sq(adj) = 86.78%				

Table 9: Analysis of Variance for surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Con	Remarks
Regression	9	4.6053	4.6053	51170	14.85	0.000		Significant
Speed	1	0.01764	0.01764	0.01764	0.51	0.491	0	Insignificant
Feed	1	2.49001	2.49001	2.49001	72.28	0.000	50	Significant
DOC	1	0.10609	0.10609	0.10609	3.08	0.110	2	Insignificant
Speed*Speed	1	0.4805	0.01313	0.01313	0.38	0.551	10	Insignificant
Feed*Feed	1	1.31328	1.1473	1.1473	33.3	0.000	26	Significant
DOC*DOC	1	0.00055	0.00055	0.00055	0.02	0.902	0	Insignificant
Speed*Feed	1	0.09461	0.09461	0.09461	2.75	0.128	2	Insignificant
Speed*DOC	1	0.04651	0.04651	0.04651	1.35	0.272	1	Insignificant
Feed*DOC	1	0.05611	0.05611	0.05611	1.63	0.231	1	Insignificant
Residual Error	10	0.34452	0.34452	0.03445			8	
Total	19	4.94982					100	

From the above tables the R^2 value for Power (P), Specific cutting force (K_z) and Surface roughness (R_a) is 91.29%, 94.55% and 93.04% respectively.

3.2 Contour Plots

Power, Specific cutting force and Surface roughness should be should be kept to a minimum while machining. An analysis of all performance characteristics have been conducted with the help of contour plots. Contour plot shows a dynamic representation in the study of the performance characteristics. By creating contour plots using minitab16 software for response surface analysis, the optimum region is located by characterizing the shape of the surface. Circular shaped contour represents the independence of factor effects and elliptical contours may indicate factor interaction. The contours of the responses are shown in Figures 3a, 3b and 3c. From the following figures it is clearly understood that power is minimum at low speed and medium feed, minimum at low values of speed and DOC and maximum at high feed and high DOC.

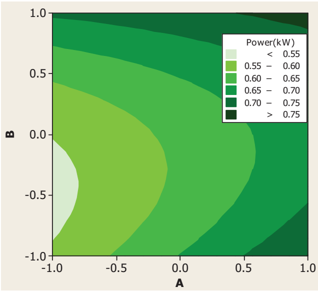

Figure 3(a): Power Vs Speed (A) and Feed (B)

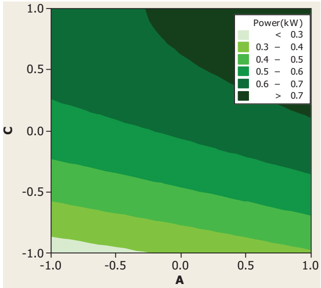

Figure 3(b): Power Vs Speed (A) and DOC (C)

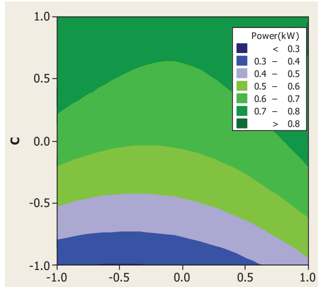

Figure 3(c): Power Vs Feed (B) and DOC (C)

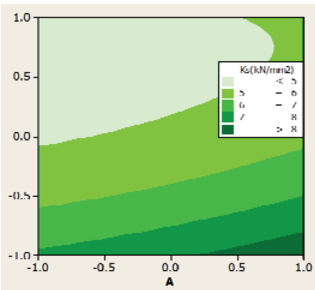

Figure 4(a): Specific cutting force Vs Speed (A) and Feed (B)

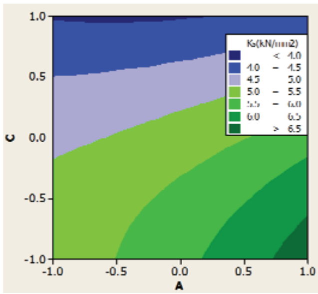

Figure 4(b): Specific cutting force Vs Speed (A) and DOC (C)

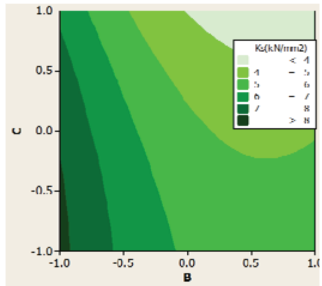

Figure 4(c): Specific cutting force (Ks) Vs Feed (B) and DOC (C)

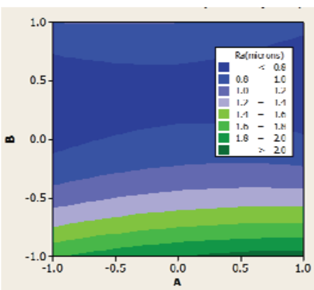

Figure 5(a): Surface roughness (Ra) Vs Speed (A) and Feed (B)

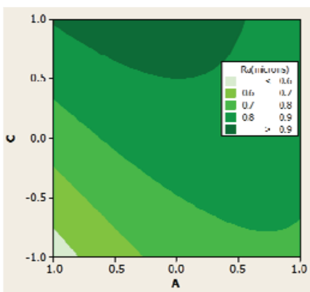

Figure 5(b): Surface roughness (Ra) Vs Speed (A) and DOC (C)

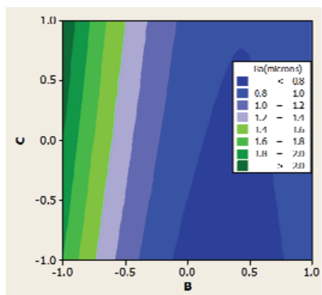

Figure 5(c): Surface roughnes (Ra) Vs Feed (B) and DOC (C)

4.0 CONCLUSIONS

In conclusion, few significant findings from the experiments are as follows;

1) The DOC (72%) has the highest physical as well statistical influence on the cutting power followed by Speed (7%) to perform the machining.
2) Specific cutting force (Ks) is mostly influenced by feed (50%) followed by DOC (21%), then Feed2 (8%) and speed (5%).
3) The surface roughness is strongly influenced by the feed (50%) and followed by feed2 (26%).

From the results, most favorable parameter setting for superior surface finish is acquired at a medium speed of cutting, medium feed and low DOC.

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