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Theoretical and Experimental Analysis of Hard Material Machining

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***Abstract*—**Machining of hard materials is a recent technology for direct production of work-pieces. The primary challenge in machining these materials is selection of cutting tool inserts which facilitates an extended tool life and high-precision machining of the component. These materials are widely for making precision parts for the aerospace industry. Nickel-based alloys are typically used in extreme environment applications where a combination of strength, corrosion resistance and oxidation resistance material characteristics are required. The present paper reports the theoretical and experimental investigations carried out to understand the influence of machining parameters on the response parameters. Considering the basic machining parameters (speed, feed and depth of cut) a study has been conducted to observe their influence on material removal rate, surface roughness, cutting forces and corresponding tool wear. Experiments are designed and conducted with the help of Central Composite Rotatable Design technique. The results reveals that for a given range of process parameters, material removal rate is favorable for higher depths of cut and low feed rate for cutting forces. Low feed rates and high values of rotational speeds are suitable for better finish and higher tool life.

***Keywords*—**Speed, feed, depth of cut, roughness, cutting force, flank wear.

I. Introduction

HARD machining is one of the emerging technologies for making direct components which can be used in various defense applications. The process is challenging in nature for the selection of cutting tools and inserts to improve the machining performance without the loss and breakage of inserts during machining. Hard machining presents several advantages when compared to traditional methods which are based on finish grinding operations after the heat treatment of work-pieces. This technique offers a greater contribution towards sustainable manufacturing. Hard materials comprises of hardened steels, high-speed steels, heat-treatable steels, tool steels, bearing steels and chilled/white cast irons. Inconel, Hastelloy, Cobalt alloys for biomedical applications are also classified as hard materials. These are highly used in automobile sectors, aerospace applications for bearing production and also for machining of dies and molds. Machining of hard materials aims to provide the fundamentals and advances in their machining.

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In machining of titanium and nickel based alloys, computer simulation and machining tests can greatly reduce the number of expensive design iterations by bracketing the optimal ranges of process parameters. Today, hard turning has replaced the grinding processes of hardened steel components in practice [2], [3]. Machining of the hardened steels can be achieved using super-hard cutting tool materials such as cubic boron nitride (CBN) tools and improved ceramic tools [1]. According to the survey conducted [4], hard turning is used for the maintenance of part accuracy and finish with the reduction in machining time as high as 60% compared to grinding process. A combination of insert nose radii and feed rate, hard turning can produce a better finish. The knowledge of cutting forces is very much essential while designing machine tools and cutting tools for hard machining so as to predict the life of these tools.

During hard machining, both material and tool are subjected to high strain rate and temperatures which makes analytical prediction very difficult [5]. In machining hardened materials, strain rates (about 10^5) and high temperatures (about 1400°C) in secondary deformation zone are observed [6]. The work carried on AISI 4140 steels to predict the temperatures various zones shows that the temperatures are 300 to 500°C in the primary zone and approximately 1000°C at the tool-chip interface [8].

Nickel-based alloys are typically used in extreme environment applications where material characteristics such as strength, corrosion and oxidation resistance are required. Depending on the choice of alloy, surface temperatures range from cryogenic to temperatures as high as 1800°F. In general, machining of hard materials requires a negative rake angle to prevent chipping of the cutting edge. A negative rake angle would offer predominantly compressive stress and a stronger edge during machining [12]. Machining of hard materials requires a small depth of cut, while comparing the force components (cutting and thrust forces) thrust force is usually the largest in magnitude. Here, small depth of cut can be defined as having a ratio of depth of cut (d) to tool nose radius (r) less than one ($d/r < 1$) [9], [13], [14]. Here a material with hardness of 60 HRc using CBN tools is machined and found that thrust force is larger than cutting component and this increases greatly with nose radius of the tool.

Machining of AISI 4340 alloy steels with different hardness levels (35-60 HRc) using CBN tools indicated that a high shear angle and saw tooth chip formation were produced due to poor ductility, thus reducing the cutting forces in hardened materials [10]. Prediction of cutting forces while machining hardened AISI H2 steel (hardness 46 HRc) using the same type of tools but with two different thermal properties is also attempted [11] where, the inserts differ in the CBN content, 50% and 90% while performing orthogonal machining. A modified Oxley's machining theory by analytically describing the primary and secondary heat source behavior is performed.

The surface roughness values can be determined from cutting speed, feed rate and tool's nose radius [12]. Moreover, the built-up-edge [13] and tool wear [7] can affect the qualities of the surface roughness. Experimentally the behavior of average surface roughness for different cutting conditions and tool nose radii [14] and conducted while machining several steel bars (AISI 1020, 1045, 4140, D2), which are harder in nature. Some of the works carried [14] stated that the depth of cut exerted no influence upon the roughness values and a better finish can be obtained for harder materials has been reported. Case-hardened 27MnCr5 steels are investigated [15] for surface integrity under the influence of feed rate, cutting speed and tool wear. It was reported that cutting speed has less influence on surface roughness and tool wear than feed rate. This could be that the tools are quickly worn out after few seconds of machining. As a consequence of this, in suitable machining areas, surface roughness is not significantly influenced by the cutting speed, but is mainly influenced by the feed rate. While performing end milling of Inconel 718, response surface methodology has been applied to optimize surface finish and suitable machining parameters are suggested [16].

This paper aims to study the effect of machining parameters on the milling performance of high chromium and nickel composition work piece material. The input parameters considered are speed (N), depth of cut (d) and feed (V_f) while the response parameters are material removal rate (MRR), cutting forces (F_x, F_y & F_z), surface roughness (R_a) and flank wear (h_f).

II. Theoretical Aspects

A. Material Removal Rate (MRR)

The experimental and theoretical material removal rates are calculated as follows:
Measured (Experimental) MRR

$$\frac{\text{Initial Weight} - \text{Final Weight}}{\text{Machining Time}}$$

Calculated (Theoretical) MRR

$$T_m = \frac{L}{V_f} \tag{1}$$

$$V_c = L \times d \times D \tag{2}$$

$$MRR = \frac{V_c}{T_m} \tag{3}$$

B. Cutting Forces

Cutting force is the force generated by the motion of cutting tool against work-piece. F_x, F_y and F_z are the forces in in x, y and z-direction respectively. The resultant force is given by,

$$F = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \tag{4}$$

C. Surface Roughness (Ra)

The surface roughness is defined as the deviation of the actual surface topography from an ideal atomically smooth and planer surface.

D.Tool Wear (h_f)

Tool wear describes the gradual failure of cutting tool which takes place along the surfaces where there is a relative sliding action is present. The wear reports in this paper are flank wear only. Flank wear is measured in terms of width of the land. Fig. 1 shows a typical wear of an insert.

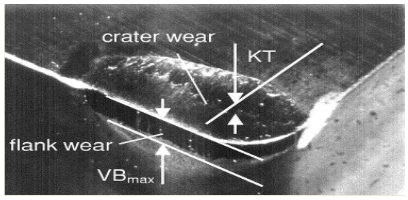

Fig. 1 Flank Wear and Crater Wear

E. Design of Experiments

The principle of experimental design refers to planning, designing and analyzing an experiment so that valid and objective conclusions can be drawn effectively and efficiently. CCRD technique is used for designing the experiments which consists of three distinct sets of experimental runs namely factorial runs (2^k), axial runs (2k) and central runs ($3 \leq n_c \leq 6$). ANOVA is generally used to find the variability within a regression model and form a basis for test of significance. Comparing the t-value, p-value significant parameters can be predicted based on the experimental values. Details of these analyses are not a part of this paper.

III. Experimentation

A. Experimental Setup

The experimental setup is shown in Fig. 2. It consists of a work piece (mechanical properties as specified in Table I) is fitted to dynamometer (Model No. 9275B, Kistler make) which is mounted on an EMCO Concept Mill 155 CNC machining center. The dimensions of the work piece are 181 mm x 154 mm x 40 mm which weighs 8.5 Kg approximately. A 16mm end mill cutter (T490 ELN D16-2-W16-08-C) manufactured by ISCAR consisting of two inserts (T490 LNMT 0804 PNR-IC810), each having four cutting edges are used. The selection of process parameters and their values are elaborated in the later part of the paper.

B. Measurements of the Responses

The response parameters considered are MRR, forces; Ra and h_f. The MRR (theoretical and experimental) is measured as specified above. All the forces (F_x, F_y, F_z) are measured using an universal cutting tool dynamometer and surface roughness is measured using a surface analyzer by TESA RUGOSURF 10 Roughness Gauge. Fig. 3 shows a typical surface profile of the specimen measured.

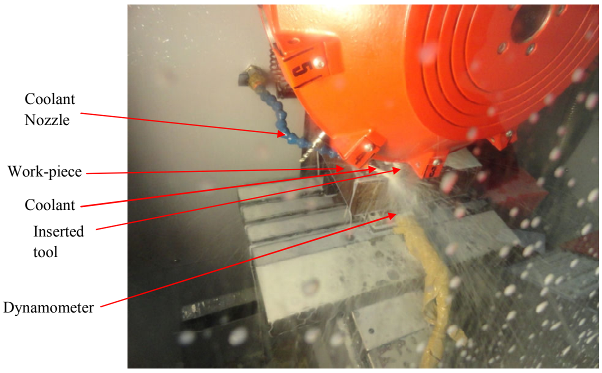

Fig. 2 Experimental Setup

TABLE I
MECHANICAL PROPERTIES OF THE WORKPIECE MATERIAL

Property	Value
0.2% Proof Stress (MPa)	LP 784
Impact Charpy at -40ºC ±2ºC (J)	34.3
% Reduction of area	25
Hardness (BHN), (HRC)	302-341, 32

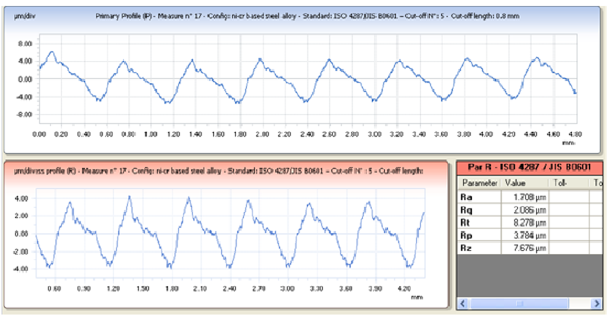

Fig. 3 Surface roughness profile

Since, the machining time is very less, so flank wear is more prominent than the crater wear. In the present study, the tool wear is measured in terms of flank wear only. Fig. 4 gives the image of a typical tool wear of the insert which is measured using a USB MICROSCOPE (GSAS-UM05).

IV. PLAN OF EXPERIMENTS

A. Exploratory Experiments

The ranges of the parameters are decided based on the exploratory experiments conducted considering the machine capacity and the literature available. The upper limit of all the parameters are restricted by overloading of the machine and the surface roughness obtained while the lower limits are considered according to the high speed machining values. Table II gives the feasible range of process parameters for conducting experiments.

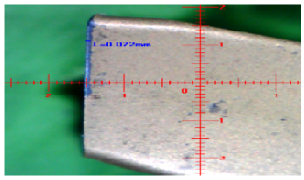

Fig. 4 Tool wear of an insert

TABLE II
FEASIBLE RANGE OF PARAMETERS

Parameters	Min. Value	Max. Value
Rotational speed, N (rpm)	500	3500
Depth of cut, d (mm)	0.1	0.3
Feed rate, V_f (mm/min)	500	2000

B. Parametric Analysis

In order to conduct a designed experimental set based on the CCRD, it is necessary to explore the input parameters into the range [-1, 1]. Apart from the high and low levels, zero level (center point) and α_d (axial points) are also included in CCRD. In the present work, number of variables (k) has been taken as 3, the total required number of experiments to be performed in a full factorial was 20, i.e., (8 factorial + center 6+ axial 6). In order to make the design rotatable, the value of α_d was taken as $2^{k/4}$ (for full factorial) so for a three variable $\alpha_d = (2^3)^{1/4}$ and the 6 points are ($-\alpha_d$, 0, 0), (α_d, 0, 0), (0, $-\alpha_d$, 0), (0, α_d, 0), (0, 0, $-\alpha_d$), (0, 0, α_d) where α_d=1.682.

The intermediate values of all input parameters, a linear relation between the input and coded values are assumed using the CCRD technique. Upon calculations for the various process parameters, Table III gives the coded values and absolute values for input machining parameters.

TABLE III
CODED AND ABSOLUTE VALUES FOR INPUT PARAMETERS

Factor	Levels				
	$-\alpha_d$	-1	0	1	α_d
N (rpm)	500	1108.09	2000	2891.91	3500
d (mm)	0.10	0.14	0.20	0.26	0.30
V_f (mm/min)	500	804.05	1250	1695.95	2000

Table IV gives the observations of the CCRD runs and the corresponding responses along with the resultant force respectively.

V. RESULTS AND DISCUSSION

The curves are drawn using MATLAB from the results obtained from experiments no. 1, 3, 8 (rotational speeds (N)) 3, 12, 13 (depth of cut (d)) 3, 4, 17 (feed rate (V_f)). Each graph corresponds to a single output parameter. The variation in N, d and V_f are uniformly taken along x-axis and the responses on the y-axis and are displayed together in a single graph to facilitate comparison.

TABLE IV
OBSERVATIONS WITH THE CCRD RUNS AND THE CORRESPONDING RESPONSES

Run	N (rpm)	d (mm)	V_f (mm/min)	MRR (mm^3/sec)	F_x (N)	F_y (N)	F_z (N)	F (N)	Ra (μm)	h_f (μm)
1	3500.00	0.20	1250.00	71.70	19.561	25.577	36.921	48.990	1.003	47.00
2	1108.09	0.26	804.05	59.96	32.086	50.943	44.893	75.100	1.385	65.00
3	2000.00	0.20	1250.00	71.70	31.155	45.014	47.886	72.732	1.708	70.00
4	2000.00	0.20	2000.00	114.72	37.943	62.679	65.361	98.185	2.130	90.00
5	2000.00	0.20	1250.00	71.02	30.880	43.964	46.121	70.807	1.692	69.00
6	1108.09	0.26	1695.95	126.46	47.798	109.480	79.920	143.728	2.987	116.00
7	2000.00	0.20	1250.00	72.89	33.675	47.679	48.675	76.004	1.731	72.00
8	500.00	0.20	1250.00	71.70	37.520	95.804	73.236	126.291	2.657	105.84
9	2891.91	0.14	1695.95	68.10	22.459	26.184	48.355	59.399	1.297	62.00
10	1108.09	0.14	1695.95	68.10	28.607	58.064	62.884	90.245	2.470	60.00
11	2000.00	0.20	1250.00	69.87	29.779	42.035	44.088	67.805	1.678	68.00
12	2000.00	0.10	1250.00	35.85	13.563	24.455	36.636	46.089	1.125	44.00
13	2000.00	0.30	1250.00	107.55	36.491	60.845	53.286	88.730	1.996	90.00
14	2891.91	0.26	804.05	59.96	25.468	27.405	36.773	52.459	1.147	85.00
15	2000.00	0.20	1250.00	71.98	31.788	46.568	46.987	73.395	1.711	70.00
16	2891.91	0.14	804.05	32.28	12.105	24.275	27.013	38.282	0.619	28.00
17	2000.00	0.20	500.00	28.68	13.111	14.743	19.198	27.528	0.820	31.00
18	1108.09	0.14	804.05	32.28	11.095	27.395	34.959	45.779	0.998	38.00
19	2000.00	0.20	1250.00	70.65	30.679	42.988	45.022	69.398	1.691	68.00
20	2891.91	0.26	1695.95	126.46	26.593	43.955	45.663	68.734	1.489	67.00

A. Effect of Rotational Speed

Fig. 5 shows the variation in MRR at different rotational speeds and in general, MRR remains constant with the increase in the rotational speed of the cutter. This is because that with increase in rotational speed, the rate of cutting increases while the volume remains the same along with the machining time.

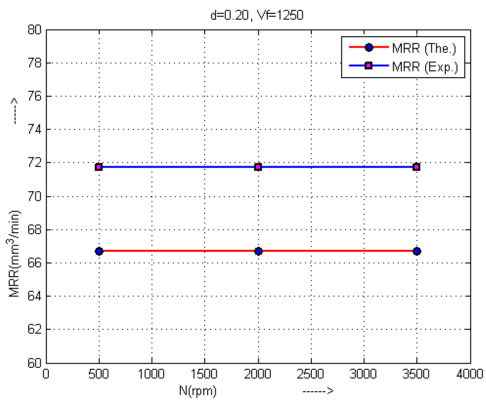

Fig. 5 Effect of rotational speed on MRR

The cutting force values decrease with increase in rotational speed as shown in Fig. 6. The rate of cutting increases with increase in rotational speed, hence cutter passes through the work piece quickly leading to reduced forces. And the power relation indicates that forces have to decrease with an increase in rotational speed.

$$\text{Power, } P = U_c \times MRR = F_c \times V_c \quad (5)$$

$$V_c = \pi DN \quad (6)$$

$$MRR = B \times d \times V_f \quad (7)$$

$$U_c \times B \times d \times V_f = F_c \times \pi \times D \times N \quad (8)$$

$$F_c \propto \frac{1}{N}, \text{ keeping d and Vf constant} \quad (9)$$

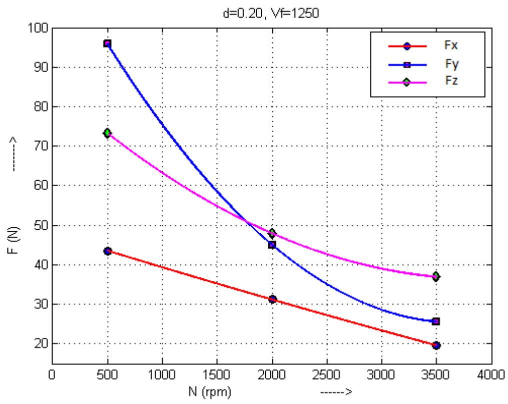

Fig. 6 Effect of 'N' on the forces

This shows that an increase in rotational speed lowers the forces while keeping other parameters constant, which is clearly shown in Fig. 6. The surface finish improves with increase in 'N' as shown in Fig. 7. At low speeds a larger built up edge (BUE) are formed and also chips are fractured readily generating a poor surface. With increasing speed, the BUE vanishes reducing the chip fracture resulting in better finish.

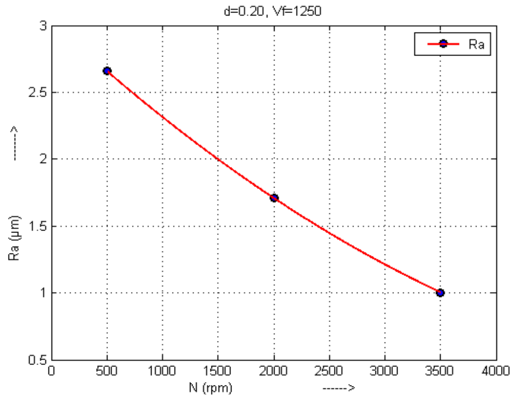

Fig. 7 Effect of 'N' on the surface roughness

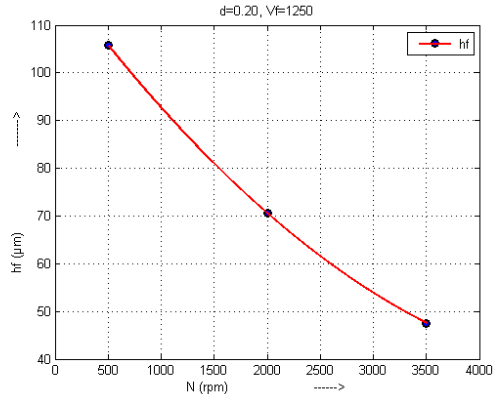

Fig. 8 Effect of N on the flank wear

The wear on the tool decreases with increase in rotational speed. The trend shown in Fig. 8 is because of higher cutting forces at low speeds creating high tool wear and poor finish.

B. Effect of Depth of Cut

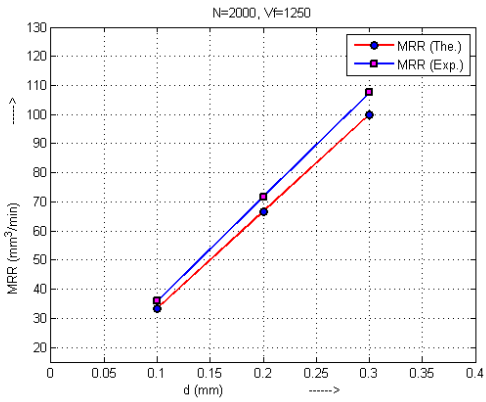

Fig. 9 Effect of depth of cut on MRR

The effect of depth of cut on MRR is shown in Fig. 9. It is observed that MRR increases linearly with increase in depth of cut as the amount of material to be removed is more and this is also seen from (7) for a constant width and feed rate.

The cutting forces increase with depth of cut as the cutter has to remove more material as indicated by (8). Fig. 10 shows this effect which means that $F_c \propto d$ (for same N, V_f)

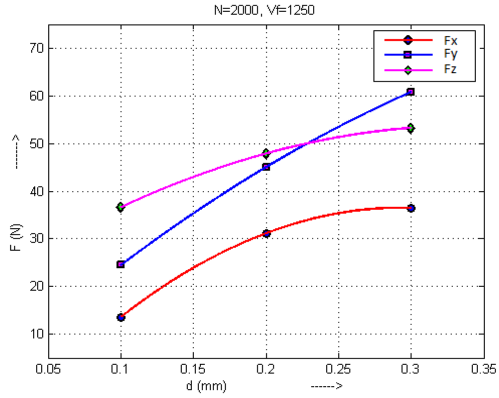

Fig. 10 Effect of depth of cut on Forces

The plots in Fig. 11 show that an increase in depth of cut increases the surface roughness, as both cutting forces and self-excited vibrations are increased which are responsible for increased roughness and tool wear.

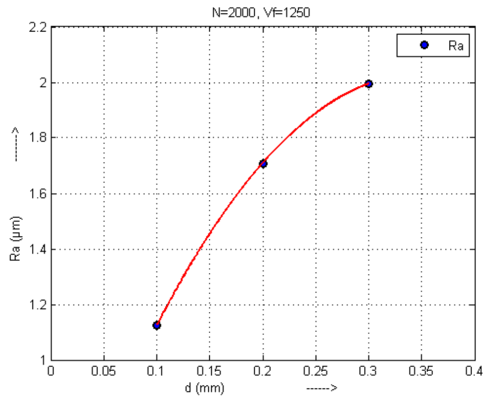

Fig. 11 Effect of depth of cut on surface roughness

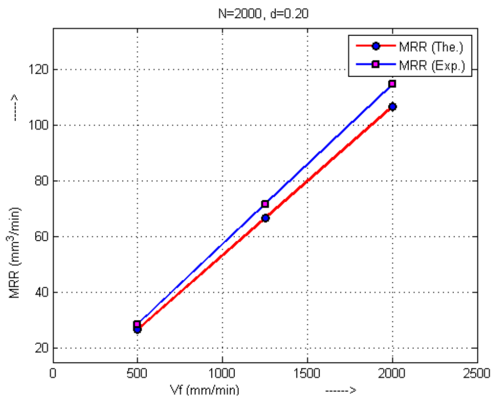

Fig. 12 Influence of feed rate on MRR

C. Influence of Feed Rate

The effect of feed rate on MRR is shown in Fig. 12. MRR increases linearly with increase in feed rate (7) for constant width and depth of cut. The cutting forces keep on increasing with the increase in the feed rate because the cutting force is directly dependent on the feed rate as per (8 which is shown in Fig. 13.

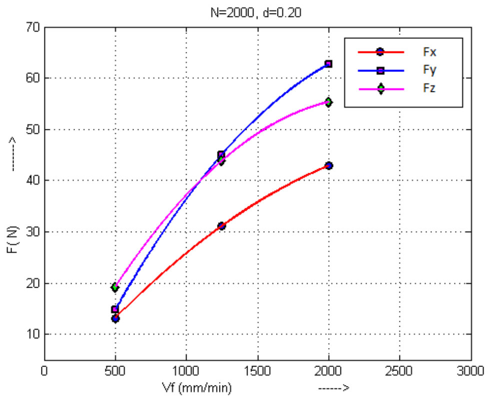

Fig. 13 Effect of feed rate on forces

Fig. 14 shows that an increase in feed rate will increase surface roughness, this is due to chatter.

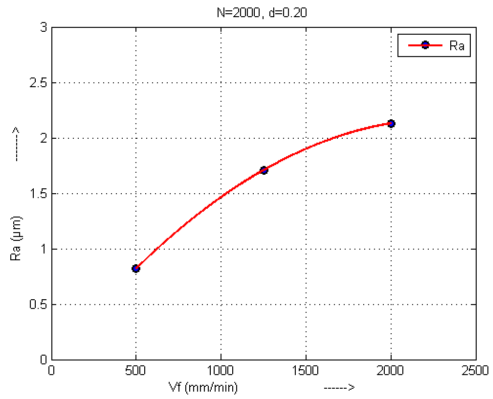

Fig. 14 Effect of feed rate on surface roughness

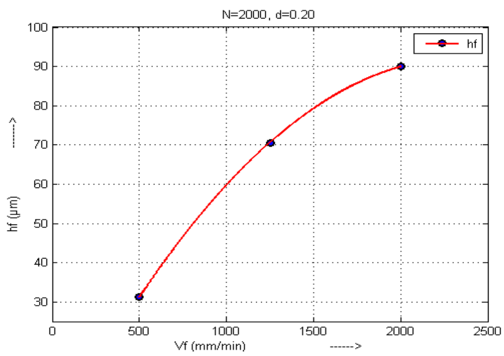

Fig. 15 Result of feed rate on tool wear

Increase in feed rate increased the tool wear due to large loads acting at the tool tip because of the increased MRR. Fig. 15 shows the effect of feed rate on tool wear.

VI. Conclusions

It has been observed that high speed milling processes are feasible in presence of coolant for a certain range of rotational speeds, depth of cuts and feed rates. It reduces cutting forces, formation of BUE, chattering, roughness, and tool wear. From the experiments it is found that MRR increased linearly with the increase in depth of cut and feed rate while it is not affected with rotational speeds. The increase in rotational speed helps in lowering cutting forces while increase in the feed rate and depth of cut increases the same. Surface roughness and tool wear are decreased at higher rotational speeds and it is increased with increase in depth of cut and feed rate. Among all the input parameters, feed rate is observed to have more effect on MRR and rotational speed and feed rate had equal contribution on cutting forces and surface roughness while the least contribution is made by depth of cut. This had a higher contribution on tool wear in comparison to feed rate. A better quality surfaces are obtained in the chosen range of input parameters. The surface roughness ranges from 1-3 microns which was really low as far as good surface is concerned.

Nomenclature

N:	revolutions per minute (rpm)
d:	depth of cut (mm)
V_f	feed rate (mm/min)
B:	width of cut (mm)
D:	diameter of cutter (mm)
U_c:	specific energy per unit volume (J/mm^3)
P:	power consumed (W)
MRR:	Material Removal Rate (mm^3/sec)
F_x:	force along x-direction (N)
F_y:	force along y-direction (N)
F_z:	force along z-direction (N)
Ra:	center line average surface roughness (µm)
h_f:	flank wear (µm)
d_c:	crater depth (µm)
k:	number of input factors
f:	factorial runs
n_c	number of center runs
α_d:	distance of axial points from the center point in CCRD

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