Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2,Issue 5, May -2015

Investigation of Cutting Force and Tool Wear Behaviour in Dry Turning of Inconel 625

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Abstract — *Central Composite Design has been used to study the effect of the turning parameters such as spindle speed, feed rate and depth of cut on the feed force, cutting force and flank wear acting on the cutting tool while dry turning Inconel 625. A mathematical prediction model of the output responses were developed in terms of above parameters. The effect of these parameters on the surface roughness has been investigated by using Response Surface Methodology (RSM). Response surface contours were constructed for determining the optimum conditions for a required output response. The developed predicted equation showed that feed rate is the main factor followed by depth of cut that influences the response. It was observed that there was a significant increase in response parameters with increase in input parameters.*

Keywords- *Inconel 625, Turning, PVD coated tool, CCD, RSM, Cutting Force, Flank wear*

I. INTRODUCTION

During machining of Inconel 625 the machinist faces several problems due to its strength, low thermal conductivity, abrasiveness, and tendency to work harden. Work hardening occurs whenever a tool makes a cut. The machined surface of the component is deformed slightly during the cut, leaving it substantially harder than the original material. This results in notching and chipping during subsequent machining passes. To overcome these problems industries have started using sharper, more positive cutting edges, typically PVD (physical vapor deposition) coated tools, reduce this phenomenon, and are therefore preferred. An additional complication, related to the toughness of this alloy, is that chips are difficult to break. All of these factors dictate that a correct combination of tool, tool geometry, cutting data and tool path is essential for good machining results. This research paper presents the use of coated tool for dry turning of Inconel 625 and investigating the cutting force acting and the tool wear behavior for different machining parameters.

II. LITERATURE REVIEW

A super alloy is an alloy that exhibits excellent mechanical strength and resistance to creep (tendency for solids to slowly move or deform under stress) at high temperatures; good surface stability; and corrosion and oxidation resistance. [1] They represent the largest group of materials in current aero engine manufacture. Kumar, G. et al [2], the turning operation is a basic metal machining operation that is used widely in industries dealing with metal cutting. The selection of machining parameters for a turning operation is a very important task in order to accomplish high performance. Makadia A.J. et al [3], Tool wear is an inherent phenomenon in every traditional cutting operation. Researchers strive towards elimination or minimization of tool wear as tool wear affects product quality as well as production costs. In order to improve tool life, extensive studies on the tool wear characteristics have to be conducted. Some of the factors that affect tool wear are machining parameters like cutting speed, feed, depth of cut etc., tool material and its properties, Work material and its properties and tool geometry. Minimal changes in the above mentioned factors may bring about significant changes in the product quality and tool life.
Sharma V.K. et al (2010) [4] In order to achieve desired results, optimization is needed. Optimization is the science of getting most excellent results subjected to several resource constraints. In the present world scenario, optimization is of utmost importance for organizations and researchers to meet the growing demand for improved product quality along with lesser production costs and faster rates of production. Statistical design of experiments is used quite extensively in optimization processes. Statistical design of experiments refers to the process of planning the experiments so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions. Methods of design such as Response Surface Methodology (RSM), Taguchi's method, factorial designs etc., and find unbound use nowadays replacing the erstwhile one factor at a time experimental approach which more costly as well as time-consuming.

A.Devillez et al [5] a good correlation was observed between the evolution of the cutting forces and the tool wear observations. The occurrence of an important wear on the rake face of the tool has an immediate effect in increasing the cutting force ratio. These results help us to determine the optimal cutting conditions for dry machining of Inconel 718.The AlTiN coating seems to be the best coating. R.S. Pawade et al [6] showed that radial and feed forces are almost equal and the main cutting force is two to three times the radial component. It was noted that specimens showing larger cutting forces generated poor surface finish as well as extensive surface damage.

S.K. Choudhury et al [7] developed a reliable mathematical model for on line monitoring of tool flank wear in a turning process by establishing relation between the flank wear and the ratio of the feed and the cutting force. . It was found that force ratio seems to monitor the flank wear reliably and cutting speed was found to be the most dominating factor among all. Comparison of predicted values obtained from the mathematical model and experimental values for the flank wear shows good agreement. Force signals are highly sensitive carriers of information about the machining process and, hence, they are the best alternative for monitoring tool wear (flank wear height). Thus the ratio between the feed force and cutting force components (Ff/Fc) has to be found to provide a practical method for the quantification for tool wear. Kejia Zhuang et al [8] Ding developed a notch wear predictive model considering the influence of the work hardened layer. . From the proposed model, no notch wear occurred when hardened layer is limited and the increasing hardening layer results in sharp increase in the notch wear depth. The proposed notch wear model is based on the depth of hardening and the notch wear geometry.

A Thakur et al [9] investigated the effect of tool wear and the corresponding chip characteristic while machining Inconel 825 bar. It was observed that the chip thickness ratio decreased with the machining duration which was due to the increase in the wear. Chip curl radius increased with the progression of machining duration when machined with uncoated inserts. It was recommended to use coated carbide inserts for machining Inconel 825 at high velocity for better tool performance and productivity. N. H. Rafia et al [10] shows that for certain combinations of cutting parameters, dry turning produced better dimensional accuracy compared to that produced by flood turning. This indicates that, in the future, it will be possible, through modeling the cooling process; to develop a system for finding in which situations dry turning will be beneficial, thus reducing the application frequency of cutting fluids and, consequently, their negative impact on the environment. The results also show that no considerable difference in surface roughness is produced by dry and flood turning. Some clear trends that appear in the traditional analyses are difficult to explain. Therefore, further research is needed to investigate these trends. P.S. Sreejith et al [11] paper presents recent developments in the dry machining operation Machining without the use of any cutting fluid (dry or green machining) is becoming increasingly more popular due to concern regarding the safety of the environment. Most industries apply cutting fluids/coolants when their use is not necessary. The coolants and lubricants used for machining represents 16-20% of the manufacturing costs, hence the extravagant use of these fluids should be restricted. However, it should also be noted that some of the benefits of cutting fluids are not going to be available for dry machining and also dry machining will be acceptable only whenever the part quality and machining times achieved in wet machining are equaled or surpassed. Technology has to be further improved if dry cutting is to be fully employed in industries.

III MATERIAL AND METHOD

In this study, a work piece made of Inconel 625 was used with dimensions of 60 mm diameter and 150 mm length. Material properties of Inconel 625 are given in table 1. The experiments were conducted under dry cutting conditions on Champions made all geared lathe machine. The cutting tool used was ISCAR VNMG12T308-Nf IC3028 with grade coating of TiN/TiCN PVD coated. IEICOS Lathe Tool Dynamometer – Model 621C: 500 KgF with 3 channel multi component digital force indicator was used for detecting and measuring the cutting force acting on the tool. Mitutoyo's Tool Maker's microscope was used measure tool flank wear.

Table 1: Mechanical Properties of Inconel 625

Material properties	Inconel 625
Physical density	8.44 gm./cm^3
Mechanical hardness, HB	220 HB
Tensile strength, Ultimate	760 N/mm^2
Tensile strength, yield	345 N/mm^2
Elongation of break	30 %
Modulus of elasticity	207.5 Gpa

In this study cutting experiments are planned using 3 level full factorial experimental designs. Machining tests are conducted by considering three cutting parameters: spindle speed (rev/min), feed rate (mm/min) and depth of cut (mm). For design of experiments Central Composite Design (CCD) was used. Total runs = 2^3+2(3) + 1 = 15 experimental runs were carried out (8 factorial points, 6 axial points and 1 center point). Low-Medium-High level of cutting parameters is shown in space of three level full factorial experimental designs as shown in the table 2. Ranges of cutting parameters are selected basis on machine specifications, cutting tool catalogue, Inconel 625 material cutting standards. The level of cutting parameter ranges and the initial parameter values were chosen from the manufacturer's handbook recommended for the tested material. These cutting parameters are shown in Table 2.and the design of experiment in Table 3.

Table 2: Input parameters and their levels

Cutting Parameters	Low level	Medium level	High level
Spindle speed (rev/min)	270	540	830
Feed rate (mm/min)	0.13	0.8	0.2
Depth of Cut (mm)	0.3	0.4	0.5

Table 3: Design of Experiment

RUN ORDER	SPINDLE SPEED (R.P.M.)	FEED (mm/min)	CUT DEPTH (mm)
1	270	0.13	0.3
2	830	0.13	0.3
3	270	0.2	0.3
4	830	0.2	0.3
5	270	0.13	0.5
6	830	0.13	0.5
7	270	0.2	0.5
8	830	0.2	0.5
9	270	0.18	0.4
10	830	0.18	0.4
11	540	0.13	0.4
12	540	0.2	0.4
13	540	0.18	0.3
14	540	0.18	0.5
15	540	0.18	0.4

IV RESULTS AND DISCUSSIONS

The Analysis of Variance (ANNOVA) was used to study the effect of the input parameters on the responses. Quadratic model was used which gives the estimated regression coefficients for the responses. The P- value of the model were 0.004, 0.014, 0.019 for feed force, main cutting force and flank wear respectively. This indicates that the developed model is significant which is desirable as it indicates that the term used in model have a significant effect on the response.

From the Response model, the most significant factor on all the three response was feed rate. The next contribution on feed force was spindle speed while depth of cut for the cutting force and flank wear. It is seen that R^2 value is 0.9664, 0.9397 and 0.9326 which is high and close to 1 which is desirable. It can be seen that predicted R^2 value and Adj.R^2 shows reasonable agreement.

Estimated regression coefficient for feed force, cutting force and flank wear for uncoded units are show in in the table 4 below.

Table 4(a): Estimated coded regression coefficients for feed force (fx)

Term	Coef	SE Coeff	T-Value	P-Value
Constant	99.1	27.1	3.65	0.015
Vc	-0.0062	0.0180	-0.34	0.747
F	-1118	326	-3.43	0.019
D	1.8	81.3	0.02	0.983
Vc*Vc	-0.000002	0.000012	-0.15	0.886
F*F	3410	976	3.49	0.017
D*D	-4.8	95.4	-0.05	0.962
Vc*F	0.1078	0.0542	1.99	0.103
F*D	163	152	1.08	0.331
Vc*D	-0.0043	0.0193	-0.22	0.832

Table 4(b): Estimated coded regression coefficients for main cutting force (Fy)

Term	Coef	SE Coef	T-Value	P-Value

Constant	95.8	58.4	1.64	0.162
Vc	0.0385	0.0388	0.99	0.367
F	-1094	703	-1.56	0.181
D	30	175	0.17	0.872
Vc*Vc	-0.000028	0.000026	-1.08	0.330
F*F	3552	2102	1.69	0.152
D*D	-8	205	-0.04	0.970
Vc*F	0.104	0.117	0.89	0.415
F*D	77	327	0.23	0.824
Vc*D	-0.0068	0.0416	-0.16	0.876

Table 4(c): Estimated coded regression coefficients for flank wear (Vb)

Term	Coef	SE Coef	T-Value	P-Value
Constant	1.063	0.341	3.11	0.026
Vc	0.000290	0.000227	1.28	0.258
F	-12.85	4.11	-3.13	0.026
D	-0.13	1.02	-0.13	0.903
Vc*Vc	-0.000000	0.000000	-0.12	0.910
F*F	40.7	12.3	3.32	0.021
D*D	0.19	1.20	0.16	0.879
Vc*F	-0.000331	0.000682	-0.49	0.648
F*D	1.69	1.91	0.88	0.418
Vc*D	-0.000311	0.000243	-1.28	0.256

The experimental results were fed into MINITAB-17 to develop the mathematical models using Response Surface Methodology method. The proposed developed mathematical model developed is

Feed force (Fx) = 99.1 - 0.0062 Vc - 1118 F + 1.8 D – 0.000002 Vc*Vc + 3410 F*F – 4.8 D*D + 0.1078 Vc*F +163F*D – 0.0043 Vc*D

Cutting Force (Fy) = 95.8 + 0.0385 Vc - 1094 F + 30 D - 0.000028 Vc*Vc +3552 F*F - 8 D*D + 0.104 Vc*F + 77 F*D 0.0068 Vc*D

Flank wear (Vb) = 1.063 + 0.000290 Vc - 12.85 F - 0.13 D - 0.0000 Vc*Vc + 40.7 F*F + 0.19 D*D - 0.000331 Vc*F + 1.69 F*D - 0.000311 Vc*D

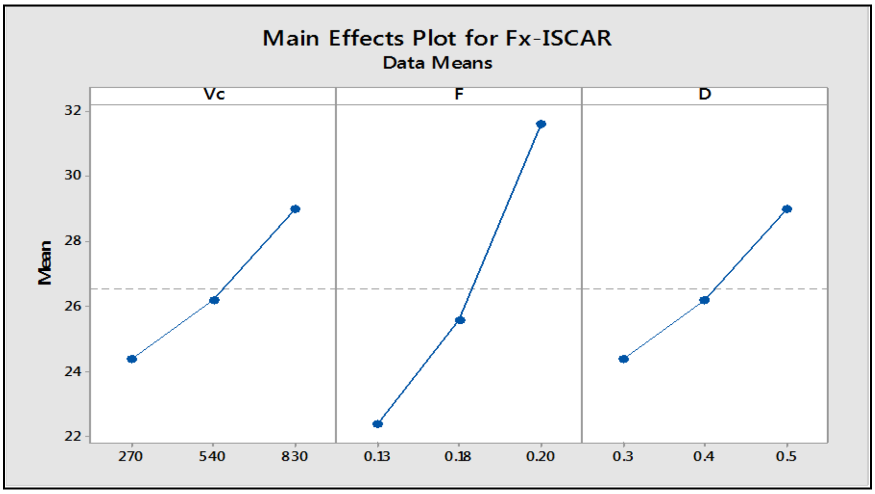


Figure 1: Main effect plot for Feed force

From figure 1 among all the parameters there is a great change in feed force with increase in the feed. Large amount of force is generated at feed of 0.2 mm/min and surface quality is highly affected. The spindle speed affects the feed force less and is of no concern. Cut depth has intermediate effect on feed force, large amount of forces are generated at 0.5 mm depth of cut. From this graph we conclude that feed force is affected mainly by feed taken followed by cut depth. So less feed, moderate cut depth and spindle speeds are suitable for the operations.

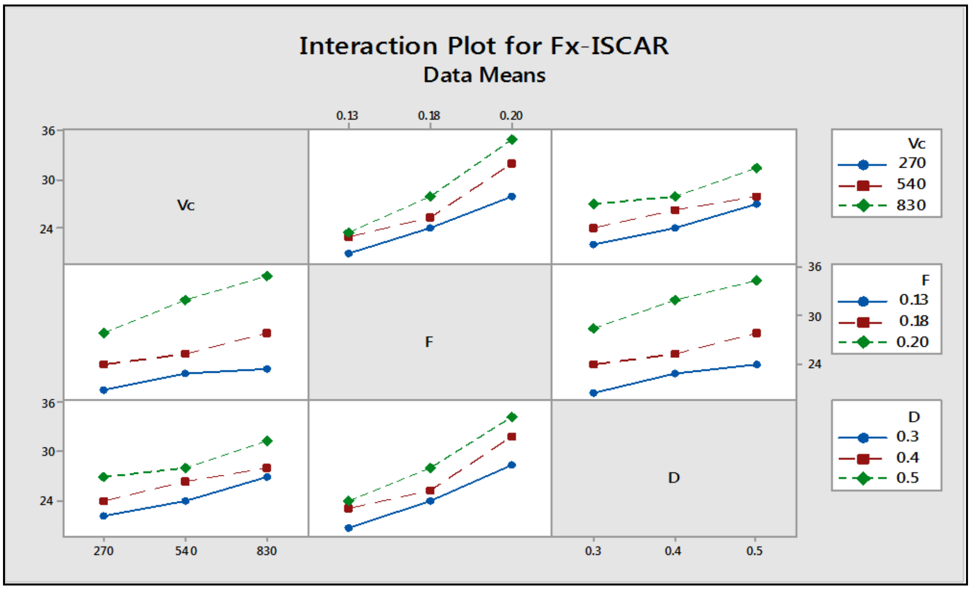


Figure 2: Interaction plot for feed force

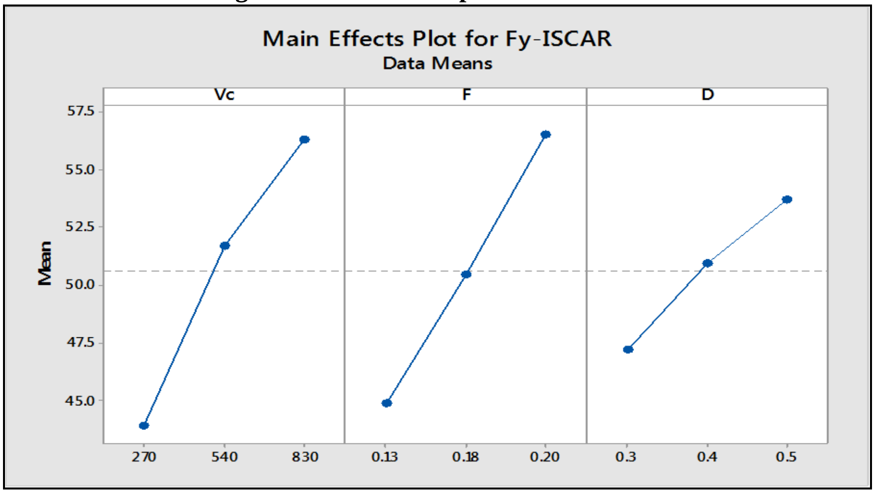


Figure 3: Main effect plot for main cutting force

It can be concluded from the figure 3 that even at low depth cut there is large tangential force generated but with increasing cut depth less variation of force is observed. There is a sharp increase in force by increasing spindle speed from 270 to 540 rev/min. A large variation in tangential force is observed by increasing feed but the change observed is linear.

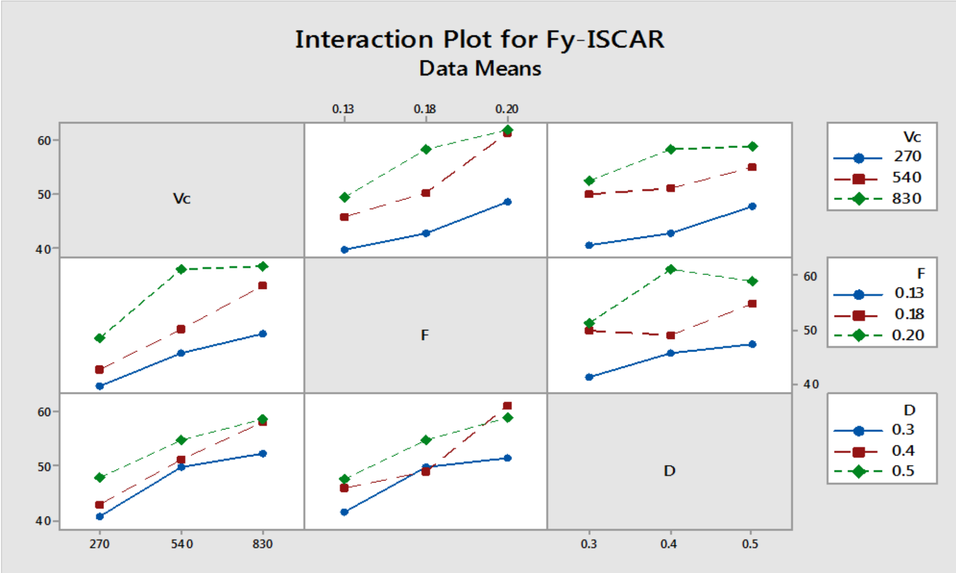


Figure 4: Interaction plot for cutting force

It can be seen from the figure 5 that spindle speed and flank wear shows more increase in flank wear as compared to cut depth. For change in feed, wear is low at 0.13 mm/min and 0.18 mm/min but it increases suddenly due to large feed forces generated and cutting force ratio is also large. There is an increase in flank wear with the spindle speed. The wear increases more sharply at highest spindle speed. For 0.3 mm and 0.4 mm cut depth the flank wear observed has been close. With increasing cut depth to 0.5 mm there is a sharp increase in flank wear.

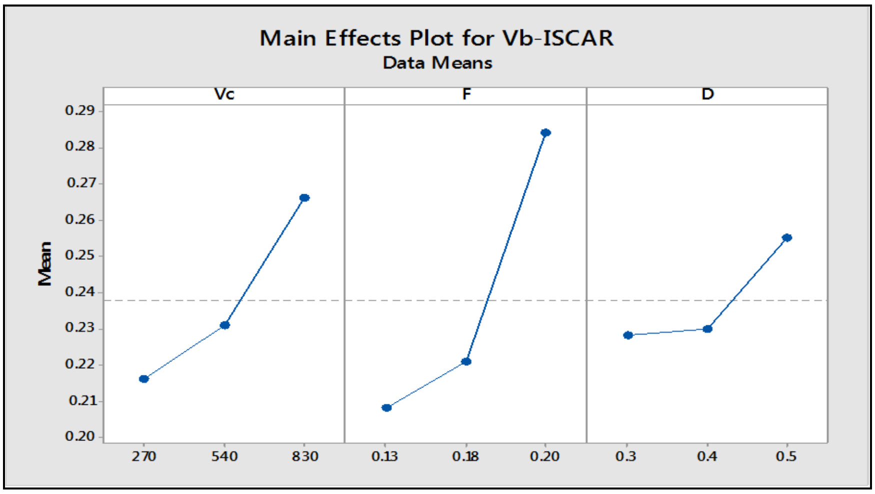


Figure 5: Main effect plot for flank wear

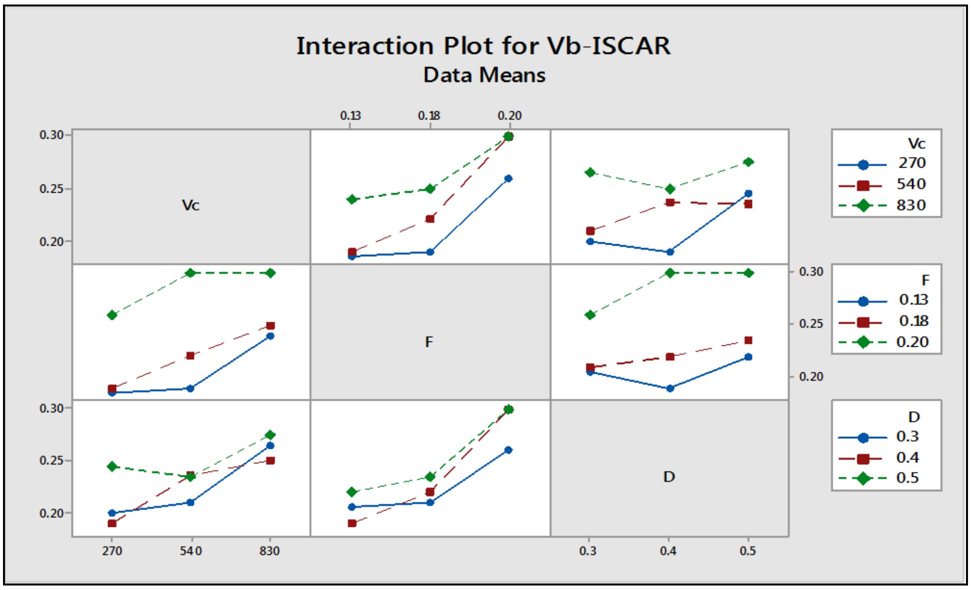
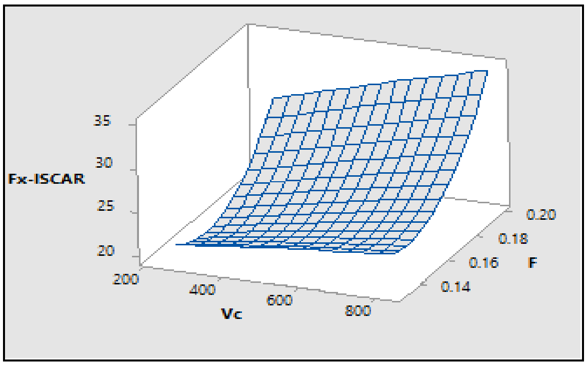


Figure 6: Interaction plot for flank wear

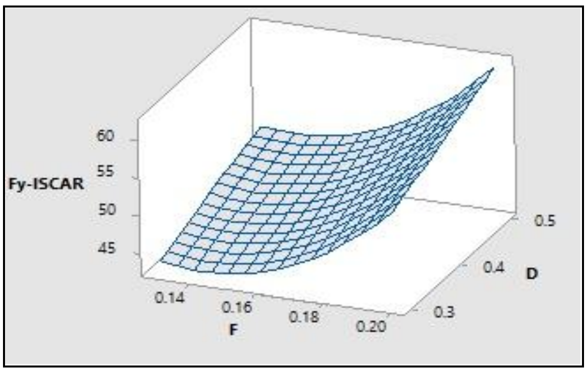
The 3D surface graphs for the feed force, cutting force and flank wear are shown in the figure. 7-9 as the model is adequate these 3-D surface plots can be used for estimating the response for any cut. It can be concluded from all the above graphs that feed is the most dominating factor for the increase in response followed by depth of cut and spindle speed.

Normal probability plot for residuals reaveled that residuals genera;;y fall on a astraight line. So the errors are distributed normally. The plot of residualsvs fits reaveled no obvious pattern or any unusual structure. So it proves that the model obtained is adequate. Experimental scheme of the whole reseachis shown below in the figure 10..



Hold value D = 0.4

Figure 7: 3D surface plot for feed force vs spindle speed and feed



Hold value Vc = 546

Figure 8: 3D surface plot for main cutting force vs feed and depth of cut

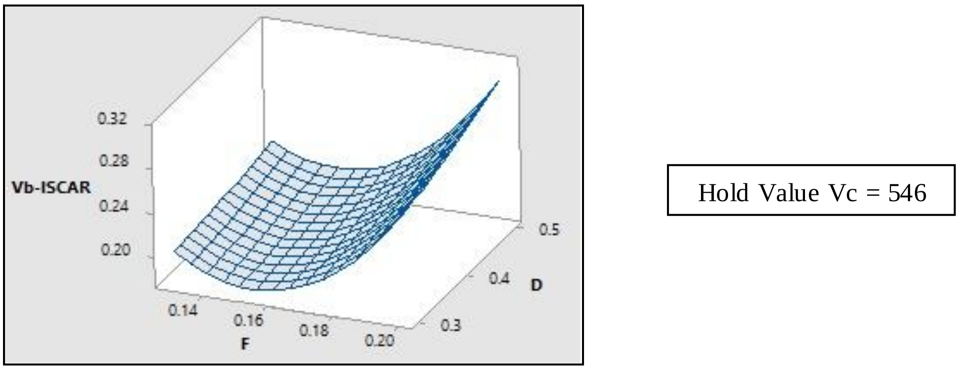


Figure 9: 3-D surface plots for flank wear vs feed and depth of cut

Table 5: Response optimization for surface roughness parameters

Parameters	Goal	Optimum conditions			weight	desirability
		Lower	Target	Upper		
Feed force (Fx)	Minimum	20	20	37	1	1
Cutting force (Fy)	Minimum	37	37	64	1	1
Flank wear (Vb)	Minimum	0.18	0.18	0.3	1	1

From the optimization plot the best result found was spindle speed = 270 rev/min, feed = 0.1470 mm/rev an depth of cut = 0.30mm

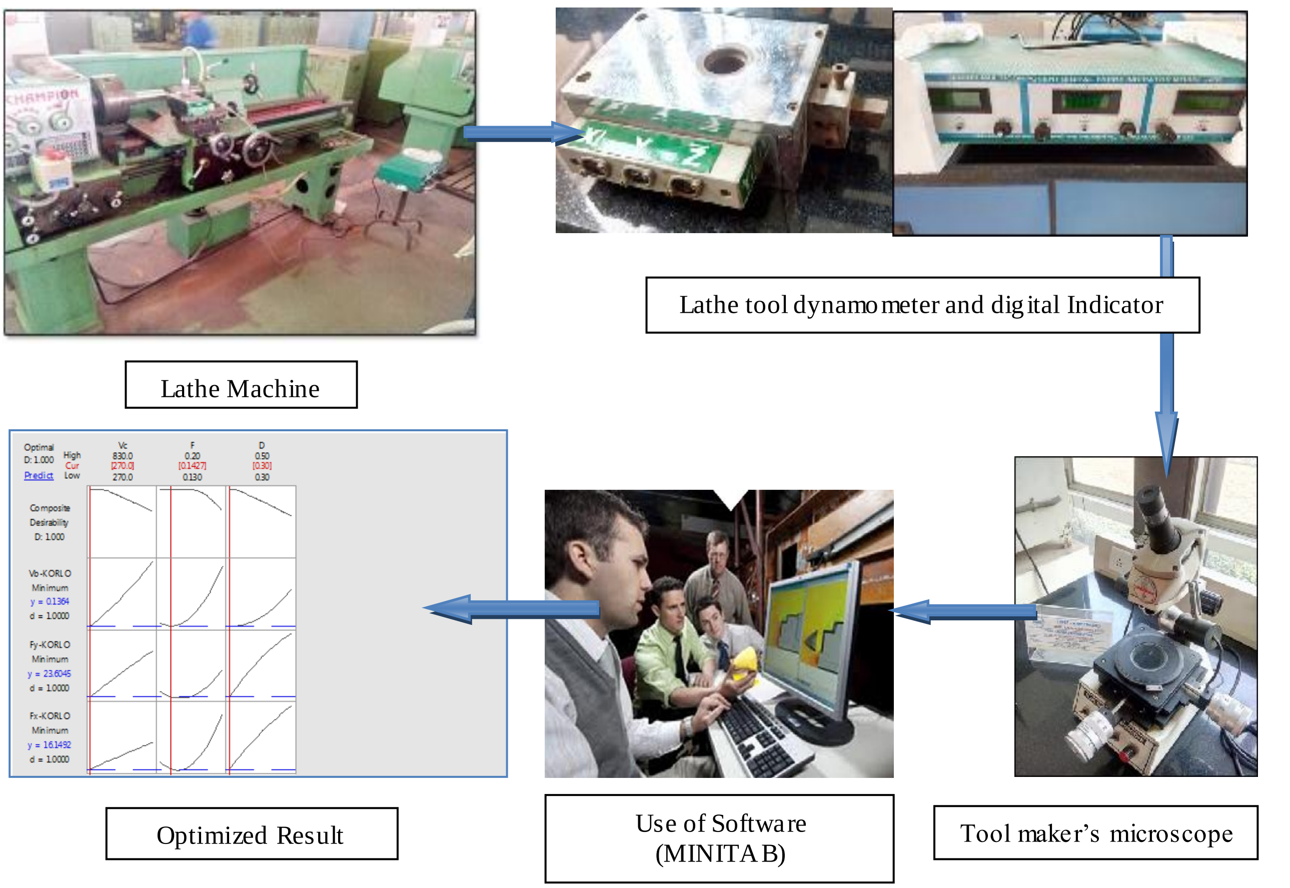


Figure 10: Experimental Scheme

V CONCLUSION

In this paper, application of RSM on the Inconel 625 is carried out for dry turning operation. A quadratic model was developed for feed force; cutting force and flank wear to investigate the influence of cutting parameters. The result is as follows:

1. Feed rate is the main influencing factor among all the parameters followed by depth of cut. Large federate shows sudden increase in the cutting force. Spindle speed has less effect on the responses.
2. 3D surface contour plots are useful in determining the optimal conditions of the responses.
3. Higher feed rate and cut depth shows sharp increase in tool wear as at that point the cutting force generated are large, leading to more tool wear.
4. Ratio of feed force to cutting force shows an increase in flank wear
5. From the response surface optimization plot, the optimum combination of machining parameters are spindle speed = 270 rev/min, feed = 0.1470 mm/rev an depth of cut = 0.30mm.
6. Coated tools are preferred especially for dry turning among which PVD coated TiAlN is the best coating.

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