

# Evaluation of Optimum Cutting Parameters In Turning of NIMONIC 75 using RSM

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**Abstract** - Nickel based superalloys pose a real threat to industries when it comes to machining, due to their strength and hardness. Despite of this disadvantage, they are in high demand just because of their excellent performance at high temperature. NIMONIC 75 is one of such alloys which exhibits all the essential properties of a superalloy and has hardness less than INCONEL 718. This paper investigates the effect of AlTiN coated cemented carbide tool and various cutting parameters – speed, feed and depth of cut – on the surface integrity of NIMONIC 75 under dry machining condition using response surface methodology (RSM). Since no data related to machining of NIMONIC75 is available so far, so to find the initial values of each parameter preliminary experiments had to be conducted. These preliminary experiments showed that the value of surface roughness is less between the speeds from 100 m/min to 250 m/min and feed rate from 0.02 mm/rev. to 0.04 mm/rev. The final result shows the significance of each machining parameter individually on the surface integrity and a model to predict the value of surface roughness between that particular range of cutting parameters.

**Keywords**— *Dry Machining, Response Surface Methodology, Superalloys, and Surface Integrity.*

## I. INTRODUCTION

Machining of hard materials has always remain as a challenging task to the researchers and industries. Machining does not simply imply cutting of metal, but it accounts surface integrity and cost effectiveness to evaluate the success of machining operation, which will depend on the machinability of a work material and suitability of a tool material for that particular purpose. As the hardness of a material increases, its machinability decreases as the cutting force required to cut the work piece increases, which in turn spoil the surface integrity of the surface generated. Other than aesthetic point of view, surface roughness is of vital importance because machined surface characteristics such as surface

roughness and surface damage have significant influence on the surface sensitive properties such as fatigue strength, corrosion resistance and creep strength, which in turn affect the service-life of components and also its importance lies in applications involving friction, lubrication, and wear. The situation now demands the best tool material for a particular workpiece material with best suited cutting parameters so as to achieve best possible surface with minimum cost. The cost effectiveness of a tool for a particular workpiece depends on tool material properties like toughness, hardness, wear resistance and co-efficient of friction and is dictated by wear rate, tool life, and initial cost.

It is just because of this reason that the tools are now coated with different compound layers to improve its properties.

Thus finding the best tool and workpiece material combination is of prime importance.

Superalloys are among such hard material which due to their exceptional properties - excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance - are in heavy demand these days and are the subject to be focused on because of their extensive application in gas turbines (commercial and military aircraft, power generation, and marine propulsion); space vehicles; submarines; nuclear reactors; military electric motors; racing and high performance vehicles, chemical processing vessels and heat exchanger tubing. Nickel based alloys are part of this family of superalloys which has nickel as its major component in its composition (more than 50 %). The poor machinability of Nickel-based alloys is due to the tendency of these alloys to galling and welding especially on the tool rake face, the tendency to form built-up-edge (BUE) at lower speed conditions, the presence of hard abrasive carbides in their

microstructures that can accelerate the tool wear and low thermal conductivity. The nickel-chromium based alloys which find wide utility in industries are HASTELLOY, INCOLOY, INCONEL, NICROFER, and NIMONIC.

Nimonic75 is a nickel-chromium alloy with good high-temperature mechanical properties and outstanding oxidation-resistance whose applications include gas turbine engineering and thermal processing. But along with these properties it also exhibits very high hardness which causes problem in its machining. Turning processes comprise a very big portion of metal cutting process in industry. For the determination of ideal machinability properties, those parameters such as mechanical material properties, machine tool rigidity, feed rate, depth of cut, cutting speed and cutting tool geometry play an important role in machining. Cutting tool geometry and type of chip formation also affects cutting forces. Increasing the negative rake angle increases the tool-chip contact area, causing larger cutting forces because of high friction forces in tool-chip interface. Tool materials with improved room and elevated temperature hardness like cemented carbides (including coated carbides), ceramics and cubic boron nitride (CBN) are now frequently used for machining nickel base superalloys.

In machining superalloys, the consumption of cooling fluids remain very important, the coolant acquisition, use, disposal and the cleaning of the machined components lead to significant costs, up four times the one of consumable tooling used in cutting operations. Thus, minimising machining costs and making the processes environmentally safe must be the objective. The goal for the machining manufacturers is then to move toward dry cutting by eliminating or minimising the cutting fluids use and to improve material removal rate with high speed machining. This goal may be achieved by the development and the use of new materials for tools and coatings.

In this study, NIMONIC 75 is machined under dry conditions by using coated carbide cutting tool, at three different speeds, feeds and depth of cut. The effect of cutting tool material quality and cutting parameters on surface integrity are investigated by using RSM methodology and also the MRR is being calculated.

## II. LITERATURE REVIEW

Research on various work material-cutting tool combinations over the years have brought to the surface number of interesting facts regarding the behaviour of tool and workpieces in varied cutting conditions and helped the research in the field of high temperature alloys take long stride. Also these researches have

shown major advances in machining techniques that have resulted to step increase in productivity, hence lower manufacturing cost, without adverse effect on the surface finish, surface integrity, circularity and hardness variation of the machined component.

Problems associated with the machining of nickel-based alloys as well as tool wear and the mechanisms responsible for tool failure are identified and discussed. The integrity of the machined surfaces and tool life are the most important considerations during machining. These and other factors governing the machinability of nickel-based alloys are mainly affected by notching of the cutting tool, primarily at the depth of cut region, as well as by flank wear and insert chipping; fracture; and by failure modes caused singly or jointly by diffusion, attrition, and abrasion wear mechanisms in addition to mechanical and thermal fatigue loading of the cutting tools. Most of the failure modes can be minimized when machining in the presence of coolants and in an oxygen-rich environment. The use of a high pressure coolant supply, despite improved chip segmentation and machining in the presence of argon and nitrogen-rich environments, tend to accelerate tool wear rate leading to lower tool life. Improvements in tool performance can be achieved with an increase in the included angle and/or the nose angle of cutting tools due to the increased edge strength and tool-chip contact area plus a reduction in the approach angle. Recently developed cutting tool materials such as mixed oxide, SiC whisker reinforced alumina ceramics; sialon and multi-layer coated cemented carbide cutting tool material have all exhibited the capability to machine nickel-based alloys at higher speed conditions than those achieved with conventional cemented carbide tools.

In the machining of heat resistant super alloys used in aeronautical applications and classified as difficult-to-machine materials, the consumption of cooling lubricant during the machining operations is very important. The associated costs of coolant acquisition, use, disposal and washing the machined components are significant, up to four times the cost of consumable tooling used in the cutting operations. To reduce the costs of production and to make the processes environmentally safe, the goal of the aeronautical manufacturers is to move toward dry cutting by eliminating or minimizing cutting fluids. This goal can be achieved by using coated carbide tools at high cutting speeds.

Rajesh Y. Patil et al. 2010 described the different wear mechanisms. Wear of cutting tool which affects the useful life of tool and which is one of the most important parameter affecting machining economics. Importance and need of research in wear mechanisms particularly for hard machining, high speed machining

for currently used work piece-tool materials is described.

Hard coatings if applied by physical vapour deposition (PVD) are principally known to have the ability to reduce tool wear of high speed steel (HSS) and carbide metal cutting tools. Among the commercially available coatings, PVD TiN is today probably the most commonly used. TiN coatings according to their high hardness, corrosion and wear resistance as well as gold-like appearance, are widely used in industrial applications for a range of different applications including machining tools to decorative items [1]). Many scholars and researchers have published several works showing the successful use of TiN coatings both to improve wear resistance in sliding wear tests and to increase tool life in metal cutting. Several explanations to this valuable influence of TiN coatings resulted in abundance of more or less interconnected theories. This paper sets out to explain how and why TiN coatings really improve the performance of cutting tools by organizing previously published results on the properties of TiN and tool substrates fusion. Sue and Troue [2] stated that TiN and TiAlN PVD coatings could reduce friction in tribological contacts and increase the abrasive wear resistance. Schulz et al [3] stated that cutting edges of cemented carbide tools coated with TiC, TiN or (Ti, Al)N by chemical vapour deposition (CVD) and or by physical vapour deposition (PVD) processes can show an increase of the service lifetime of tools by a factor of ten compared to uncoated tools. This paper, therefore; looks at the coating relevance, inherent properties of the coating and adhesion of the coating to substrates.

### III. EXPERIMENTAL DETAILS

#### A. Experimental Design

Response surface methodology (RSM) explores the relationships between several process variables and responses. It is the most convenient way to estimate a first-degree polynomial model using factorial experiment or a fractional factorial designs. This is sufficient to determine which explanatory variables have an impact on the response variable(s) of interest. Once it is suspected that only significant explanatory variables are left, then a more complicated design, such as a central composite design can be implemented to estimate a second-degree polynomial model, which is still only an approximation at best. However, the second-degree model can be used to optimize a response.

Experiments based on RSM – which were 28 in numbers and two trails were recorded for each setting - were performed to determine the optimum process

parameters viz. surface roughness and material removal rate, to optimize the responses. Desirability function was used to optimize both the responses together and one optimum setting was found.

#### B. Workpiece Material

NIMONIC® alloy 75 (UNS N06075/W.Nr. 2.4951 & 2.4630) is an 80/20 nickel-chromium alloy with controlled additions of titanium and carbon. First introduced in the 1940s for turbine blades in the prototype Whittle jet engines, it is now mostly used for sheet applications calling for oxidation and scaling resistance coupled with medium strength at high operating temperatures. It is still used in gas turbine engineering and also for industrial thermal processing, furnace components and heat-treatment equipment. It is readily fabricated and welded. Table I gives the details of chemical composition of NIMONIC 75.

TABLE I

Limiting Chemical Composition, %

Carbon	0.08 – 0.15
Chromium	18.0 – 21.0
Copper	0.5max.
Iron	5.0max.
Manganese	1.0 max.
Silicon	1.0 max.
Titanium	0.2 – 0.6
Nickel	Balance

#### C. Cutting Tool

NIMONIC75 is hard and tough material, so for the finishing purpose PVD TiAlN coating carbide tool is used which is “KENNAMETAL” made, KC5010 grade Tungsten carbide insert. An advanced PVD TiAlN coating over a very deformation-resistant unalloyed carbide substrate. KC5010’s new and improved coating allows for speeds to be increased by 50 to 100%. The KC5010 grade is ideal for finishing to general machining of most workpiece materials at higher speeds. Excellent for machining most steels, stainless steels, cast irons, non-ferrous materials and super alloys under stable conditions. It also performs well machining hardened and short chipping materials.

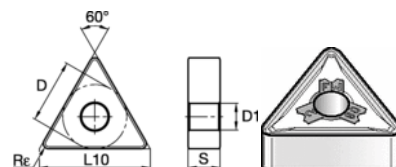


Fig. 1 Insert geometry

ISO catalog number	ANSI catalog number	D		L10		S		Re		D1		ANSI catalog number
		mm	in	mm	in	mm	in	mm	in	mm	in	
TNMG160404FW	TNMG331FW	9.53	3/8	16.50	.650	4.76	3/16	0.4	1/64	3.81	.150	TNMG331FW

Fig. 2 Insert specification

**D. Machine Tool**

A rigid high power lathe model “SPINNER.COM: COMPACT CNC TURNING CENTRE” equipped with specially designed experimental setup. For increasing rigidity of machining system, work-piece material will be held between chuck (three jaws) and tailstock (revolving centre) and the tool overhang will be kept at the minimum possible value.

Power supply	3- phase
Voltage	415 V
Current	20 Amp.
Frequency	50 Hz
Rated power	4 KW
Spindle speed	4000 rpm
Max. turning length	275 mm
Max. turning diameter	220 mm
Job holding	Hydraulic chuck
Turret	8 stations
Machine weight	3300 Kgs

**E. Cutting Conditions**

Since no research related to machining, has been done on this particular material so far, Hence preliminary experiments have to be conducted to find the optimum range of speed and feed, as these two are the most significant parameters while machining. The literature shows, the effect of depth of cut on the surface integrity of the work surface generated on machining is not much significant when compared with the other two cutting parameters (feed and speed), so the values of depth of cut for the experiments was taken according to convenience. Based on those preliminary experiments, the feasible range of cutting parameters for a given cutting tool–work-piece system is selected as follows:

Factor	Unit	Low level(-1)	Centre level (0)	High level (+1)
Speed	m/min	100	175	250

Feed rate	mm/rev	0.02	0.03	0.04
Depth of cut	mm	0.1	0.125	0.15

**F. Surface roughness measurements**

The measurements of average surface roughness (Ra) were made on HANDYSURF E 35 B. Three measurements of surface roughness were taken at different locations and the average value is used in the analysis. It directly gives the value in digital format.

**Specifications:**

- Measuring Range: Z axis +/- 160 um, X Axis 12.5mm
- Resolution: 0.01 um
- Standards: JIS 2001, JIS-1994, JIS-1982, ISO-1984, DIN-1990, ASME-1995, CNOMO
- Parameters: Pt, Ra, Rq, Rz, Rzmax, Rp, Rt, R3z, RSm, Pc, Rk, Rpk, Rvk, Mr1, Mr2, VO, K, Rmr, Rx, AR, W, Wx, AW, Wte
- Evaluation Curves: Section Profile Curve, Roughness Curve, ISO 13565Equations

**E. Experimental Procedure**

1. Selection of objectives and variables affecting the objectives.
2. Selection of cutting conditions
3. Selection of tools
4. Selection of tool holder
5. Selection of range of “Speed”
6. Selection of range of “Feed”
7. Selection of range of “depth of cut”:
8. Selection of experimental design
  - a. Comparative objective
  - b. Screening objective
  - c. Response Surface (method) objective
  - d. Optimizing responses when factors are proportions of a mixture objective (mixture design)
  - e. Optimal fitting of a regression model objective: Regression design
9. Observation sheet: Enter the selected range of the Parameters in the “Design expert software”, and enter the number of blocks, replications

and the responses and generate the observation sheet in Run Order.

10. Data collection: Conduct the experiments according to the run order generated from software and collect the response data.
11. Analysis: Enter the responses in the software (design expert) and analyze the results by seeing the trend of output responses with respect to input parameters and model the responses.

#### IV. RESULT AND DISCUSSION

In this study, to begin with, absolute magnitude of cutting forces as a function of time was analyzed. Further, the values of force components as well as surface roughness obtained with the three cutting edge geometries in the turning process at three different feed rates, cutting speeds and depths of cut were analyzed by MINITAB software. The main effects plots for SN ratio were drawn. The ANOVA (at 95% confidence level) was performed to identify the parameters that have statistically significant effect on response variables as discussed below.

##### A. Effect of Process Variables on Surface Roughness

Statistical Inferences:

- The Model F-value of 14.42 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case B, C, BC, A2, B2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.
- The "Lack of Fit F-value" of 1.52 implies the Lack of Fit is not significant relative to the pure error. There is a 25.64% chance that a "Lack of Fit F-

value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

- The various R2 statistics (i.e. R2, adjusted R2 (R2adj) and predicted R2 (R2pred)) of the surface roughness are given in Table 5.8. The value of R2 = 0.884193 for surface roughness indicates that 88.41% of the total variations are explained by the model.
- The adjusted R2 is a statistic that is adjusted for the "size" of the model; that is, the number of factors (terms). The value of the R2adj = 0.822884 indicates that 82.28% of the total variability is explained by the model after considering the significant factors.
- R2pred = 0.662933 is in fair agreement with the R2adj and shows that the model would be expected to explain 66.29% of the variability in new data (Montgomery, 2001).
- 'C.V.' stands for the coefficient of variation of the model and it is the error expressed as a percentage of the mean ((S.D./Mean)×100). Lower value of the coefficient of variation (C.V. = 17.50%) indicates improved precision and reliability of the conducted experiments.

$$\text{Surface Roughness} = +1.80482 - (6.52062E-003 \times V - (70.93346 \times f) - (3.53472 \times d) + (183.75 \times f \times d) + (1.84505E-005 \times V^2) + (1087.83784 \times f^2) \quad (1)$$

##### C. Analysis of Response Curve Generated

The response surfaces are plotted to study the effect of process variables on the surface roughness. It is known from the fundamental theory of machining that the feed rate and nose radius play an important role in roughness of the machined surface when the cutting edge is sharp, as given by

$$R_a = \frac{f^2}{32r} \quad \dots (2)$$

TABLE IV  
OBSERVATION TABLE

Standard Order	Run Order	Speed m/min	Feed mm/rev	DOC mm	R <sub>a1</sub> micron	R <sub>a2</sub> micron	R <sub>avg</sub> micron	MRR <sub>1</sub> mm <sup>3</sup> /min	MRR <sub>2</sub> mm <sup>3</sup> /min	MRR <sub>avg</sub> mm <sup>3</sup> /min
1.	18	100	0.02	0.1	0.35	0.40	0.375	199.38	199.36	199.37
2.	20	100	0.02	0.1	0.33	0.25	0.29	199.37	199.38	199.38
3.	9	250	0.02	0.1	0.43	0.38	0.405	498.45	498.45	498.45
4.	12	250	0.02	0.1	0.20	0.32	0.26	498.54	498.37	498.46
5.	8	100	0.04	0.1	0.68	0.76	0.72	398.78	398.77	398.78

6.	19	100	0.04	0.1	0.37	0.60	0.485	398.74	398.72	398.73
7.	1	250	0.04	0.1	0.50	0.65	0.575	996.95	996.86	996.91
8.	10	250	0.04	0.1	0.28	0.70	0.49	996.95	996.87	996.91
9.	17	100	0.02	0.15	0.36	0.30	0.33	298.62	298.58	298.60
10.	13	100	0.02	0.15	0.31	0.26	0.285	298.58	298.59	298.59
11.	5	250	0.02	0.15	0.39	0.43	0.41	746.63	746.43	746.53
12.	15	250	0.02	0.15	0.23	0.57	0.40	746.58	746.31	746.45
13.	2	100	0.04	0.15	0.70	1.00	0.85	597.20	597.14	597.17
14.	16	100	0.04	0.15	0.73	0.83	0.78	597.31	597.20	597.26
15.	14	250	0.04	0.15	0.76	0.73	0.745	1493.14	1492.95	1493.05
16.	6	250	0.04	0.15	0.66	0.79	0.725	1493.22	1492.99	1493.11
17.	3	175	0.03	0.125	0.26	0.46	0.36	653.82	653.64	653.73
18.	7	175	0.03	0.125	0.44	0.22	0.33	653.68	653.70	653.69
19.	4	175	0.03	0.125	0.20	0.24	0.22	653.74	653.67	653.71
20.	11	175	0.03	0.125	0.20	0.27	0.235	653.73	653.60	653.67
21.	28	100	0.03	0.125	0.41	0.47	0.44	373.58	373.48	373.53
22.	23	250	0.03	0.125	0.43	0.49	0.46	933.88	933.81	933.85
23.	27	175	0.02	0.125	0.15	0.26	0.205	435.81	435.74	435.78
24.	25	175	0.04	0.125	0.86	0.55	0.705	871.64	871.53	871.59
25.	21	175	0.03	0.1	0.23	0.44	0.335	523.37	523.26	523.32
26.	22	175	0.03	0.15	0.29	0.32	0.30	783.87	783.72	783.80
27.	26	175	0.03	0.125	0.47	0.35	0.41	653.64	653.49	653.57
28.	24	175	0.03	0.125	0.51	0.40	0.455	653.66	653.59	653.63

roughness as a function of three input process variables was developed using experimental data and is given below.

**B. Mathematical Model Generated After Regression Analysis**

The regression coefficients of the second order equation are obtained by using the experimental data in Table IV. The regression equation for the surface

Final Equation in Terms of Actual Factors after eliminating insignificant terms:

TABLE V ANOVA FOR RESPONSE SURFACE QUADRATIC MODEL (SURFACE ROUGHNESS)						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Block	0.014	1	0.014			
Model	0.80	9	0.89	14.42	< 0.0001	Significant
A-Speed	4.014E-004	1	4.014E-004	0.065	0.8020	
B-Feed	0.54	1	0.54	87.15	< 0.0001	
C-DOC	0.044	1	0.044	7.11	0.0162	
AB	0.015	1	0.015	2.48	0.1340	
AC	1.914E-003	1	1.914E-003	0.31	0.5853	
BC	0.034	1	0.034	5.46	0.0320	
A <sup>2</sup>	0.034	1	0.034	5.48	0.0316	
B <sup>2</sup>	0.037	1	0.037	5.99	0.0256	
C <sup>2</sup>	1.208E-003	1	1.208E-003	0.20	0.6641	
Residual	0.11	17	6.186E-003			
Lack of fit	0.041	5	8.143E-003	1.52	0.2564	Not significant
Pure error	0.064	12	5.370E-003			
Cor Total	0.92	27				
Std. Dev: 0.078649      C.V. %: 7.50545      Adj R-Squared: 0.822884						
Mean:0.449286      R-Squared: 0.884193      Pred R-Squared: 0.662933						

Where,  $f$  is feed rate and  $r$  is nose radius. It is clear that from fig. 2 that the surface roughness has an increasing trend with increase in feed and at the same time it first decreases and then increases with the increase in speed. The surface roughness is most affected by the cutting angle with respect to X-axis which increases with increase in feed. The surface roughness decreases with increase in speed because temperature of the work-piece increases which in turn make the workpiece little ductile and continuous chips start coming off but excessive spindle speed will cause premature tool wear, breakages, and can cause tool chatter, all of which can lead to potentially dangerous conditions and poor surface finish. Using the correct spindle speed for the material and tools will greatly enhance tool life and the quality of the surface finish. Since the machining was carried out under dry conditions, the machined surfaces could remain at high temperature and cause adhesion of the residual chip (or tool) particles to them which has also affected the machined surface greatly and also the color of chip was changed to golden due to heat generated while machining at high speeds and very long continuous chips were generated due to softening of work material.

Now nose radius, which is another important parameter which affects surface finish, in this case is 0.4mm but as the tool travel increases the nose radius also increases due to rubbing and become more pronounced which in turn improves the surface finish. Normal probability plot has been drawn for residuals in Fig.2. Linearity of this normal plot confirms the normal distribution of the data. It can be seen from Fig. 2(d) that how the actual values are following the predicted values and Fig. 2(a)-Fig. (c) shows how each of the parameter is interacting with other.

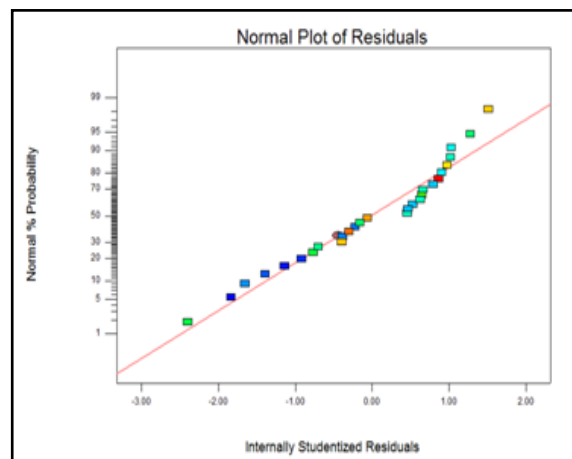
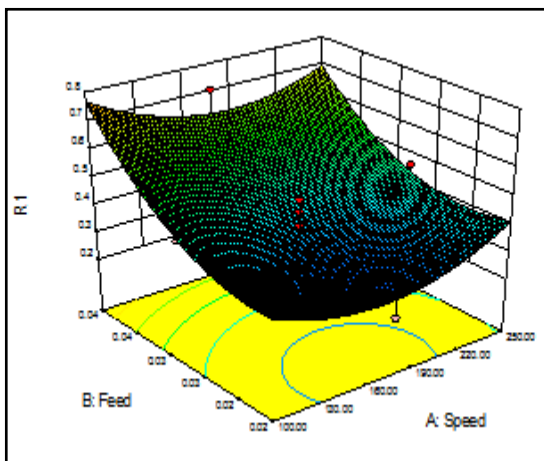
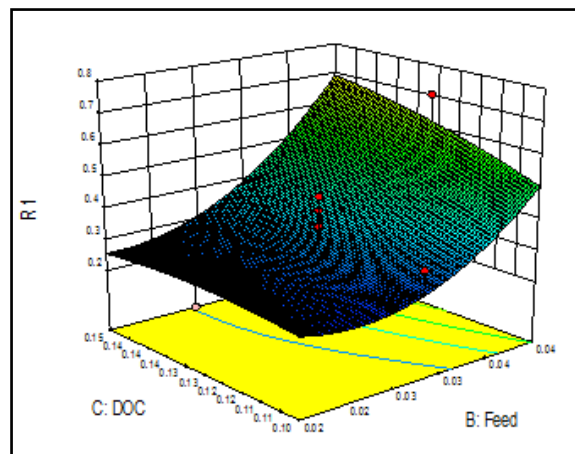
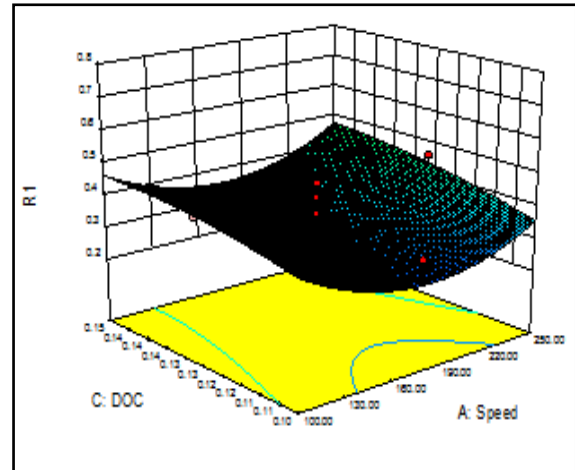


Fig.2 Response surface for various parameters and surface roughness and Normal Probability curve for Surface Roughness

D. Effect of Process Variables on MRR

- The Model F-value of 227118891.97 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, A2, B2, C2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.
- The "Lack of Fit F-value" of 1.30 implies the Lack of Fit is not significant relative to the pure error. There is a 32.86% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.
- The "Pred R-Squared" of 1.0000 is in reasonable agreement with the "Adj R-Squared" of 1.0000.
- The various R2 statistics (i.e. R2, adjusted R2 (R2adj) and predicted R2 (R2pred)) of the MRR are given in Table 5.14. The value of R2 = 1.0000 for MRR indicates that 100% of the total variations are explained by the model.
- The adjusted R2 is a statistic that is adjusted for the "size" of the model; that is, the number of factors (terms). The value of the R2adj = 1.0000 indicates that 100% of the total variability is explained by the model after considering the significant factors.
- R2pred = 1.0000 is in fair agreement with the R2adj and shows that the model would be expected to explain 100% of the variability in new data (Montgomery, 2001).
- 'C.V.' stands for the coefficient of variation of the model and it is the error expressed as a percentage of the mean ((S.D./Mean)×100). Lower value of the coefficient of variation (C.V. = 9.054E-004%) indicates improved precision and reliability of the conducted experiments.

TABLE VI

ANOVA FOR RESPONSE SURFACE QUADRATIC MODEL (MRR)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	0.056	1	0.056			
Model	6.79	9	6.79	2.271E+008	< 0.0001	Significant
A-Speed	3.78	1	3.78	1.137E+009	< 0.0001	
B-Feed	2.16	1	2.16	6.508E+008	< 0.0001	
C-DOC	0.73	1	0.73	2.210E+008	< 0.0001	
AB	3.958E-011	1	3.958E-011	0.012	0.9144	
AC	1.673E-010	1	1.673E-010	0.050	0.8251	
BC	2.318E-009	1	2.318E-009	0.70	0.4151	
A <sup>2</sup>	0.028	1	0.028	8.455E+006	< 0.0001	
B <sup>2</sup>	9.462E-003	1	9.462E-003	2.848E+006	< 0.0001	
C <sup>2</sup>	1.139E-003	1	1.139E-003	3.429E+005	< 0.0001	
Residual	5.648E-008	17	3.322E-009			
Lack of fit	1.980E-008	5	3.960E-009	1.30	0.3286	Not significant
Pure error	3.668E-008	12	3.057E-009			
Cor Total	6.85	27				
Std. Dev:	5.764E-005	C.V. %:	9.054E-004	Adj R-Squared:	1.0000	
Mean:	6.37	Squared:	1.0000	Pred R-Squared:	1.0000	

E. Analysis of response curve generated

The response surfaces are plotted to study the effect of process variables on the MRR and are shown in Fig. 3(a)-Fig. 3(d). It is known from the fundamental theory of machining that the feed rate, speed and depth of cut

play an important role in MRR of the turning process, as given by:

$$MRR = f \times d \times v \tag{3}$$

It is clear that from above equation (3) and Fig. 3(a)-Fig. 3(d) that the MRR is directly proportional to feed, cutting speed and depth of cut. MRR is an important parameter in determining the machining cost. Larger is the MRR, lesser will be the machining cost. Thus for higher value of MRR the speed, feed and depth of cut has to high but these parameter play an important role in adjudging the surface roughness and surface roughness may lead to poor quality and failure prone parts. So there has to be a tradeoff between MRR and surface roughness and the best value of parameters should be chosen. Now this trade off depends upon the desirability, if we desire to have best surface finish for precise parts then MRR should be given least importance and our focus should be surface roughness and vice-versa. The next section in this chapter discusses about the desirability function to get the optimized value. Normal probability plot has been drawn for residuals in Fig. 3(d). Linearity of this normal plot confirms the normal distribution of the data. It is evident from Fig. 3(d) that the experimental and predicted values from model comply to each other very closely. And Fig. 3(a)-Fig. 3(d) shows how each of the parameter is interacting with other.

f. Multi Response Optimization Using Desirability Function

To overcome the problem of conflicting responses of single response optimization, multi response optimization was carried out using desirability function in conjunction with response surface methodology. Various multi-characteristic models have been developed. Goals and limits were established for each response in order to accurately determine their impact on overall desirability. A maximum or minimum level is provided for all response characteristics which are to be optimized. Weights are assigned in order to give added emphasis to upper or lower bounds or to emphasize a target value. The importance is assigned to each response relative to the other responses. Importance varies from the least important (1), to the most important (5).

The ranges and goals of input parameters viz. speed, feed and depth of cut and the response characteristics viz. material removal rate and surface roughness are given in Table VII Cutting rate has been assigned an importance of 5 relative to surface roughness with an importance of 2.

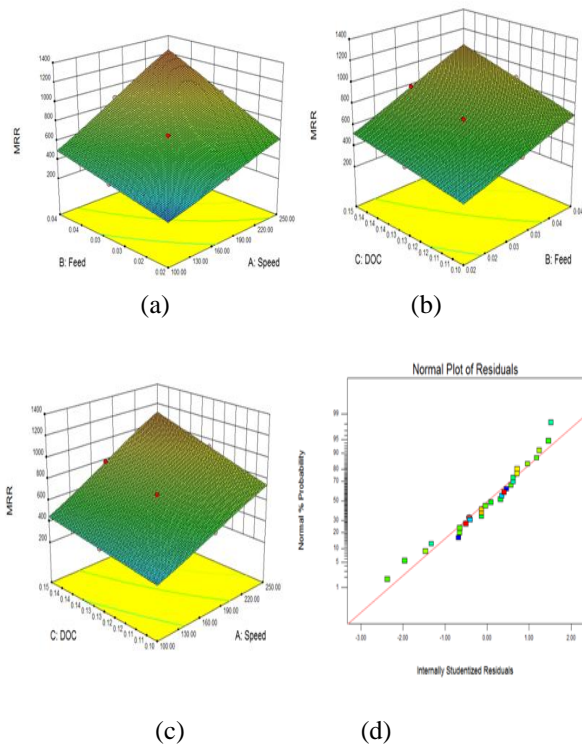


Fig.3 Response surface for various parameters and MRR and Normal Probability curve for MRR

Process param-eters	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Impo-rtance
Cutting speed	In range	100	250	1	1	3
Feed	In range	0.02	0.04	1	1	3
Depth of cut	In range	0.1	0.15	1	1	3
MRR	Maxi-mize	199.37	1493.1	1	1	2
Surface roughness	Mini-mize	0.205	0.85	1	1	5

The goal of optimization is to find a good set of conditions that will meet all the goals. It is not necessary that the desirability value is 1.0 as the value is completely dependent on how closely the lower and upper limits are set relative to the actual optimum. A set of 12 optimal solutions is derived for the specified design space constraints (Table 5.16) for MRR and surface roughness using Design expert statistical software. The set of conditions possessing highest desirability value is selected as optimum condition for the desired responses. Table VIII shows the optimal set of condition with higher desirability function required for obtaining desired response characteristics under specified constraints

NO.	Speed	Feed	DOC	R1	MRR	Desirability	
1	204.93	0.03	0.15	0.314282	797.566	0.702581	Selected
2	205.55	0.03	0.15	0.315257	800.268	0.702571	
3	203.88	0.03	0.15	0.313504	795.291	0.702544	
4	202.50	0.03	0.15	0.312175	791.204	0.702405	
5	208.92	0.03	0.15	0.319158	810.093	0.702153	
6	204.86	0.03	0.15	0.322185	818.202	0.701931	
7	196.85	0.03	0.15	0.296267	743.416	0.700137	
8	198.71	0.03	0.15	0.33468	835.428	0.695456	
9	217.63	0.03	0.10	0.287643	659.186	0.674692	
10	217.83	0.03	0.10	0.288764	661.462	0.674681	
11	217.12	0.03	0.10	0.284881	653.477	0.674644	
12	226.00	0.03	0.10	0.29594	671.397	0.672584	

Desirability 3D-plots were first drawn keeping input parameters in range, MRR at minimum and surface roughness at maximum. A plot of desirability function is a distribution of desired responses for NIMONIC 75 according to speed and feed. It can be interpreted that overall desirability value is less in the region of feed and high in the region of speed. To show the sensitivity of results to condition, contour plots for overall desirability for the considered model. The near optimal region was located close to the right hand bottom region (circle) of the plot, which had overall desirability value greater than 0.67 that gradually reduced while moving left and upwards. Sensitivities are obtained using the shape of the contour lines.

Table IX shows point prediction of optimal responses at optimal setting of parameters. The 95% CI (confidence interval) is the range in which one can expect the process average to fall into 95% of the time. The 95% PI (prediction interval) is the range in which one can expect any individual value to fall into 95% of the time. The prediction interval will be larger (a wider spread) than the confidence interval since one can expect more scatter in individual values than in averages.

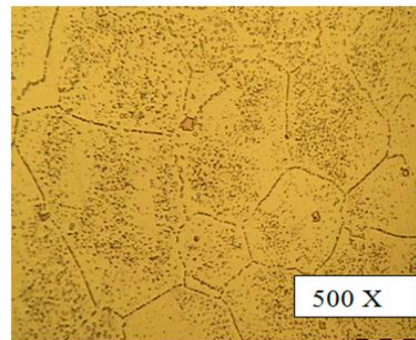
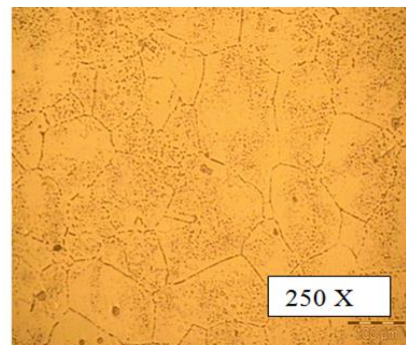
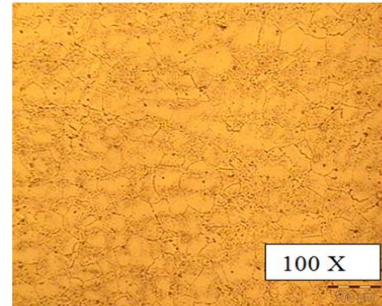
Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	Speed	204.9343	100	250	0	Actual
B	Feed	0.025958	0.02	0.04	0	Actual
C	DOC	0.15	0.1	0.15	0	Actual

Response	Prediction	95% CI low	95% CI high	95% PI low	95% PI high
R1	0.31415	0.212458	0.415842	0.119532	0.508767
MRR	797.1962	797.1368	797.2556	797.0825	797.3099

## V. MICROSTRUCTURAL STUDY

### A. Optical Microscopy

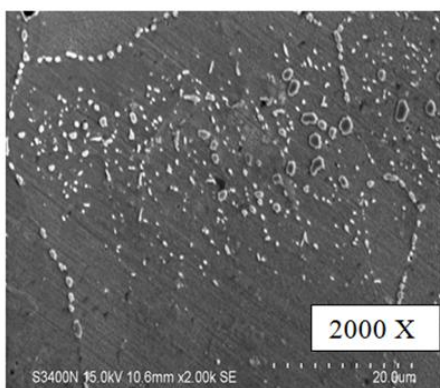
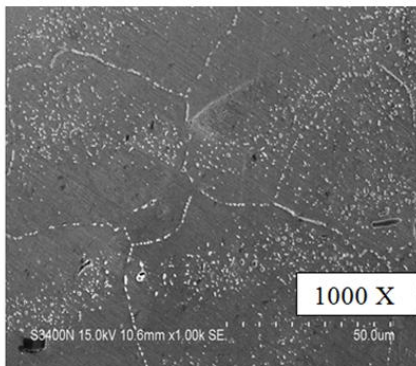
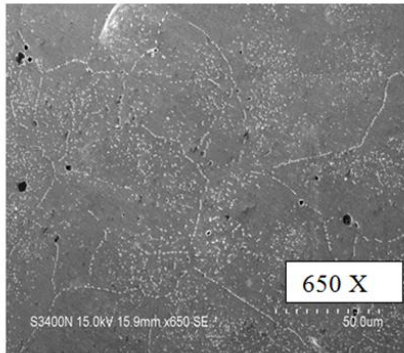
Samples of Nimonic 75 are observed using an optical microscope. Optical Micrographs at 100X, 250X and 500X are recorded.



The micrographs clearly depict the austenitic structure with grain boundaries. The intergranular small dots are assumed to be the oxide/silicate inclusions or carbides/nitrides precipitates which will be confirmed by elemental analysis in the later part of the discussions. We can also observe precipitates along the grain boundary in the micrograph taken at 500X. However for clear analysis of the precipitate we need to employ higher magnifications. The presence of precipitates makes it very difficult to distinguish the grain boundaries at lower magnifications. The grains are more circular in pattern.

### B. Scanning Electron Microscopy (SEM), EDAX and Elemental Mapping

The SEM is used to study the microstructure of the specimens at higher magnification. Here electron beam is used instead of the light beam of optical microscope, which is the main reason to achieve higher magnification. The SEM images of the superalloy samples have been taken at higher magnification and then discussed.



The observation of the SEM Micrographs reveals the presence of precipitates in grain boundary very clearly than optical images. The precipitates observed

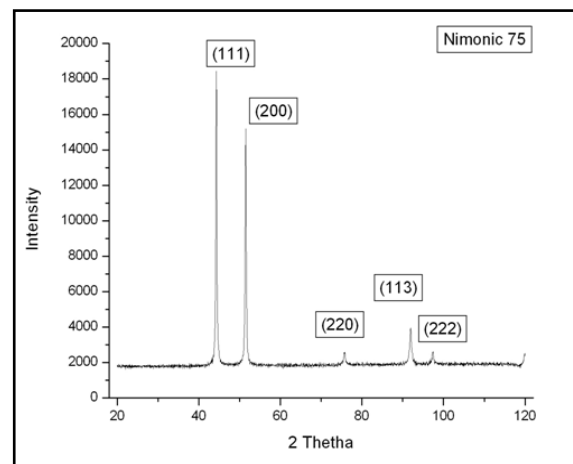
are of a fairly narrow size range and are randomly distributed within the gamma Matrix. Large quantities of precipitation are observed along the grain boundaries which indicate the precipitation of a specific phase along the grain boundary area. The grains are found to be rather curved in shape. The grain sizes are more uniform.

From the elemental analysis we could observe that the precipitates are silicates and carbides (mostly chromium carbides). It is also inferred that along the grain boundary carbides are precipitated. The larger precipitates are nitrides of the form  $M(CN)$  with M as Ti. These are corresponding to the Elemental Mapping analysis pictographs.

### C. X-Ray Diffraction

XRD is a non-destructive analytical technique which is used to reveal information about the crystal structure, chemical composition and physical properties of materials and thin films. These techniques are based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, polarization, and wavelength or energy.

The given superalloy samples were exposed to X-Rays in the XRD machine from an angle of 20 to 120 degrees. The output obtained is in the form of a graph plotted by taking intensity on the y-axis and the diffraction angle on the x-axis.



The (hkl) values, the Miller Indices are calculated from the obtained  $2\theta$  values. After the indexing of the plots is completed the Crystal Structure of the materials is determined. It is found that both the alloys exhibit a FCC type of crystal lattice. The lattice parameter calculation is further carried out and it is approximately  $a=3.52$  Angstroms for both the materials.

VI. CONCLUSION

This experimental work involves analysis of surface roughness and material removal rate (MRR) in turning operation on NIMONIC 75 and leads to the following conclusions:

- The surface roughness follows the quadratic trend in the given ranges of speed (100 to 250 m/min), feed (0.02 to 0.04 mm/rev) and depth of cut (0.1mm to 0.15mm).
- The material removal rate undergone natural log transformation and fitted to the quadratic model in the given range of parameters.
- Feed rate is the most significant parameter in judging the surface roughness. Feed rate is contributing 58.69% to the surface roughness.
- Optimum value of parameters to maximize the material removal rate is

Cutting speed = 250 m/min, Feed = 0.04 mm/rev & Depth of cut = 0.15 mm

- Optimum value of parameters to minimize the value of surface roughness is

Cutting speed = 175 m/min, Feed = 0.02 mm/rev & Depth of cut = 0.1mm

- Optimum value of parameters to optimize the multiple responses by using desirability function on giving more importance to surface roughness (5 units) and less importance to MRR (2 units) is

Cutting speed = 204 m/min, Feed = 0.03 mm/rev. and Depth of cut = 0.15 mm

- Table XI gives optimum value of parameters and predicted responses at various importance combinations of the MRR and surface roughness. This table will provide a fair idea while selecting the cutting parameters on the basis of priority levels set.

**TABLE XI**  
OPTIMUM VALUE OF PARAMETERS AND PREDICTED RESPONSES AT VARIOUS IMPORTANCE COMBINATIONS OF THE MRR AND SURFACE

Importance		Optimum Parameter			Predicted Response	
Surface Roughness	MRR	Speed	Feed	DOC	Surface Roughness	MRR
1	1	229.19	0.03	0.15	0.415055	1023.82
1	2	246.06	0.03	0.15	0.520739	1202.62
1	3	250.00	0.03	0.15	0.577251	1283.98

1	4	250.00	0.04	0.15	0.612936	1328.81
1	5	250.00	0.04	0.15	0.640456	1360.43
2	1	210.69	0.03	0.15	0.333243	847.63
2	2	229.20	0.03	0.15	0.414913	1023.55
2	3	239.50	0.03	0.15	0.475475	1130.68
2	4	246.06	0.03	0.15	0.520977	1202.98
2	5	250.00	0.03	0.15	0.554975	1253.35
3	1	200.44	0.03	0.15	0.301266	759.536
3	2	218.36	0.03	0.15	0.363141	917.889
3	3	229.20	0.03	0.15	0.415142	1023.99
3	4	236.56	0.03	0.15	0.457206	1099.83
3	5	241.95	0.03	0.15	0.492055	1157.73
4	1	193.93	0.02	0.15	0.285467	707.24
4	2	210.59	0.03	0.15	0.333012	847.05
4	3	221.56	0.03	0.15	0.377197	948.252
4	4	229.22	0.03	0.15	0.415261	1024.21
4	5	234.99	0.03	0.15	0.447474	1082.92
5	1	189.42	0.02	0.15	0.276348	672.195
5	2	205.01	0.03	0.15	0.314309	797.641
5	3	215.56	0.03	0.15	0.351517	891.597
5	4	223.29	0.03	0.15	0.385211	964.948
5	5	229.21	0.03	0.15	0.41504	1023.79

VII. FUTURE SCOPE

- At higher speed (250 m/min), a lot of heat was generated which accelerated the tool wear rate. The coefficient of friction of PVD TiAlN coating is 0.35 and micro hardness is 2300-2500HV. But if some better coating with higher micro hardness and lower coefficient of friction is used then the tool life can be extended. Few coatings with better properties than TiAlN coating are as follows:

Coating Type (Process)	Coating composition	Coating color	Thickness (microns)	Coefficient of friction	Micro Hardness (HV 0.5)
PVD	AlTiN - CrN	Gray	2-10	0.3	3200-3500
PVD	TiAlSiCN	Gray	2-10	0.3	3200-3500
PVD	TiN/TiCN	Bronze/ Gray	1-5	0.3	2800-3200
PVD	TiN/TiCN	Blue/ Gray	1-5	0.3	2800-3200

- Ceramic tools can also be preferred for better performance better with NIMONIC 75.

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