A THESIS REPORT

ON

EFFECT OF NOSE RADIUS ON SURFACE ROUGHNESS IN CNC TURNING USING DESIGN OF EXPERIMENTS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

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DECLARATION

I hereby declare that the work presented in this report, titled **"EFFECT OF NOSE RADIUS ON SURFACE ROUGHNESS IN CNC TURNING USING DESIGN OF EXPERIMENTS"**, in partial fulfillment for the award of the degree of M.Tech in production and industrial engineering, submitted in the Department of mechanical engineering, Delhi Technological University, Delhi, is original and to the best of my knowledge and belief, it has not been submitted in part or full for the award of any other degree or diploma of any other university or institute, except where due acknowledgement has been made in the text.

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CERTIFICATE

This is to certify that the research work embodied in this dissertation entitled **"EFFECT OF NOSE RADIUS ON SURFACE ROUGHNESS IN CNC TURNING USING DESIGN OF EXPERIMENTS "**submitted by Devendra Singh, Roll no. 2K13/PIE/29 student of Master of Technology in production and industrial engineering under Department of Mechanical Engineering, Delhi Technological University, Delhi is a bonafide record of the candidate's own work carried out by him under my supervision.

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ABSTRACT

The present work is concerned with an experimental study of turning of Aluminium 6061 alloy on computer numerical control(CNC) machine with cutting inserts having different tool nose radii. Turning of aluminium 6061 is carried out at three different nose radius, those are 0.4 mm, 0.8 mm and 1.2 mm. Our objective of the ensuing study was to determine the effect of cutting parameters viz. cutting speed, feed and depth of cut; and one of tool geometry parameter that is nose radius on the surface roughness of the machined material that is aluminium 6061 using Response Surface Methodology. The primary objective is to find the optimum machining parameters so as to minimize the surface roughness in the chosen domain of the performed experiments. A full-factorial Central Composite Design (CCD) is used to design an experimental matrix. Talysurf surtronic 3+ is used to measure average value of surface roughness. For analysis the data was compiled into MINITAB ®17. The relationship between the machining parameters (speed, feed, depth of cut and nose radius) and the response variable (surface roughness) were modelled and analysed using the Response Surface Methodology (RSM). Analysis of Variance (ANOVA) is being used to investigate the significance of these machine parameters on the response of the factor, and to generate a regression equation for the response as dependent variable, depending on parameters which are independent variables, through the help of a quadratic model. ANOVA is also used to generate main effects and interaction plots which are studied along with contour and 3-D surface plots. Results showed that feed is the most effective factor affecting the surface roughness, closely followed by nose radius, cutting speed. The optimum settings for carrying out the machining were obtained from Response Surface Optimizer.

Keywords : Nose radius, CNC, Design of Experiments, Response Surface Methodology, Central Composite Design, Turning, Speed, Depth of cut, Feed, Surface Roughness, Aluminium 6061.

Chapter 1 INTRODUCTION

The drastic increase of consumer needs for quality metal cutting related products (more precise tolerance and better surface finish) has driven the metal cutting industry to continuously improve quality control of the metal cutting processes. Quality of the surface roughness is an important requirement of many work pieces in the machining operations. This parameter is increasingly needed in automotive, aerospace, die and mold manufacturing application. Within the metal cutting processes, one of the most fundamental metal removal operations is turning process, which is used in the manufacturing industry. Thesurface roughness, which is used to determine and evaluate quality of a product, is one of the major quality attribute of the turned product. The surface roughness of a machined product could affect several of the product‘s functional attributes such as contact causing surface friction, light reflection,wearing, ability of distributing and holding a lubricant,heat transmission, resisting fatigue in material. Hence, surface roughness is one of the most important quality aspects in turning operations. Hence, there is a need to optimize the process parameters in a systematic way to achieve the output characteristics/responses by using experimental methods and statistical models. Therefore, in order to obtain better surface roughness, proper setting of cutting parameters is very crucial before the process takes place. Starting point for determining cutting parameters, technologists can use the hands on data tables that are furnished in the machining data handbooks. The trial and error approach could be followed previously in order to obtain the optimal machining conditions for particular operations. Recently, a Design of Experiment (DOE) has been implemented to select manufacturing process parameters that could result in a better quality product. The methods of design such as ResponseTaguchi‟s method, Surface Methodology (RSM), factorial designs etc., are finding unbound use nowadays replacing the earlier one factor at a time experimental approach which more costly as well as time-consuming. Surface roughness is the factor which is not only hard to measure but also it is very versatile and it depends upon every minute input parameter. So it becomes highly compulsive to have a detailed study of the process to keep the roughness in limits. The parameters on which it depends may be controllable or not.

Controllable parameters:-

1. Cutting speed

2. Tool geometry

3. Feed

4. Tool setup

Non controllable parameters:-

1. Tool wear

2. Machine vibration

3. Degradation of work piece

4. Tool material

These parameters are not put in the desired range easily. The cutting parameters which are included in this project work are:-

1. Depth of cut
2. Feed
3. Cutting velocity
4. Nose radius

The aim of this study is to investigate the surface roughness resulting from different geometry of insert at different cutting parameters.

1.1 OBJECTIVES OF PRESENT WORK

Surface roughness has been one of the most important parameters in the turning process and by changing the cutting parameters and tool geometry the surface finish can be improved. Surface roughness creates an index of quality which can be used to control the use of the work piece effectively and in a very better way. So, it becomes of high importance to control and understand the nuances of the surface roughness so as to use it in different ways in the industry and home.

a) To study the influence/effect of cutting parameters viz. speed, feed and depth of cut and tool geeometry that is nose radius, on the surface roughness of the CNC turned Aluminium alloy rods.

b) To determine optimum machining parameter settings for the chosen tool/work combination so as to minimize surface roughness using RSM.

c) To generate an empirical relation for the Surface Roughness for the chosen tool/work combination within the specified domain of parameters.

No work so far had been done to analyse the effect of nose radius on surface roughness of CNC turned aluminium 6061 alloy using RSM.

1.2 RESPONSE SURFACE METHODOLOGY

RSM is nothing but an amalgamation of the statistical methods available and their usage in the mathematical manner so that they could be utilized to find out the desired values which are to be controlled. It is a method which uses apt number of experiments to find out the solutions to the multi variable problems which depend upon the factors.

Graphical depictions of these obtained problems are coined as the response surfaces, which are used to depict the individual and combined effect of the input variables on the output variable and to develope a relationship that these variables share among themselves or share with the output also known as response.

Uses of RSM:-

1. To find out the factor level and this will be able to satisfy the desired dimensions.
2. To find the relationship of responses on individual input parameter.
3. To obtain a quantitative knowledge of the system performance in the area
4. To forecast the properties of the product and to find out the responses it would give when the obtained settings are given.
5. To find out the all the necessary situations for the stability of the process.

Hence, RSM is a better tool for optimization and able to forecast effectively the effect of parameters on response.

1.3 COMPUTER NUMERICAL CONTROL(CNC)

Modern precision manufacturing demands extreme surface finish and dimensional accuracy. Such performance is very difficult to be achieve if done manually, if not impossible, even with the expert operators. If it is possible, then it takes a larger time due to need of frequent dimensional measurement to prevent the overcutting. Its thus obvious that automated motion control will replace manual “handwheel” control in the modern manufacturing. The development of computer numerically controlled (CNC) machines has made it possible to think about automation of the machining processes which would provide flexibility in handling production which varies from small to medium batch of parts. In 1940s when, U.S. Air Force perceived the need to manufacture complex parts for the highspeed aircraft. This led to development of computer-based automatic machine tool controls which are also known as the Numerical Control (NC) systems. Commercial production of NC machine tools started around the fifties and sixties around the world. Note that at this time the microprocessor has not yet been invented.

Initially, the CNC technology was applied on milling machines, lathes, etc. which could perform a single type of metal cutting operation. Later, the attempt was made to handle the variety of workpieces that may require several different types machining operations and to finish them in a single set-up. Therefore CNC machining Centres which are capable of performing multiple operations were developed. Firstly, CNC machining centres were developed for machining prismatic components which needed combining operations like drilling, boring, milling and tapping. Gradually machines for manufacturing the cylindrical components, called turning centers were also developed.

1.4 MACHINING PARAMETERS

The turning operation is governed by geometry factors and machining factors. This study consists of the three primary adjustable machining parameters in a basic turning operation viz. speed, feed, depth of cut and nose radius. Fig 2 from shows these three parameters. Material removal is obtained by the combination of these three parameters . Other input factors influencing the output parameters such as surface roughness and tool wear also exist, but the latter are the ones that can be easily modified by the operator during the course of the operation.

1.4.1 Cutting Speed

Cutting speed may be defined as the rate at which the uncut surface of the work piece passes the cutting tool. It is often referred to as surface speed and is ordinarily expressed in m/min, though ft./min is also used as an acceptable unit. Cutting speed can be obtained from the spindle speed. The spindle speed is the speed at which the spindle, and hence, the work piece, rotates. It is given in terms of number of revolutions of the work piece per minute i.e. rpm. If the spindle speed is "N" rpm, the cutting speed V c (in m/min) is given as

V c = $\frac{\pi DN}{1000}$, where D = Diameter of the work piece in mm

1.4.2 Feed

Feed is the distance moved by the tool tip along its path of travel for every revolution of the work piece. It is denoted as "f"and is expressed in mm/rev. Sometimes, it is also expressed in terms of the spindle speed in mm/min as

F_m= f N where, f = Feed in mm/rev N = Spindle speed in rpm

1.4.3 Depth of cut

Depth of cut (d) is defined as the distance from the newly machined surface to the uncut surface. In other words, it is the thickness of material being removed from the work piece. It can also be defined as the depth of penetration of the tool into the work piece measured from the work piece surface before rotation of the work piece. The diameter after machining is reduced by twice of the depth of cut as this thickness is removed from both sides owing to the rotation of the work.

d = $\frac{D_1-D_2}{2}$where, D_1 = Initial diameter of job D_1= Final diameter of job

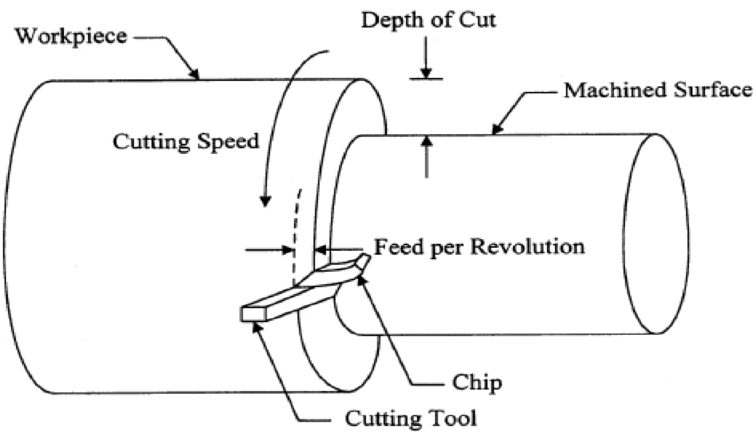

Fig 1 : The adjustable machining parameters [14]

1.5 Cutting Tool Insert

The term "Insert" refers to the condition when a cutting tool is screwed or clamped to a holder which is in turn fixed to the tool post. Inserts are clamped through various locking mechanisms. The advantage of inserts is that when one particular edge is worn out, it can be rotated to present a new cutting edge. In certain cases, if the geometry allows, after all such edges have been used up; the insert can be removed, turned upside down and clamped again to reveal a fresh array of cutting edges. Inserts come in a varied range of shapes and sizes some of which are shown in Fig 3.

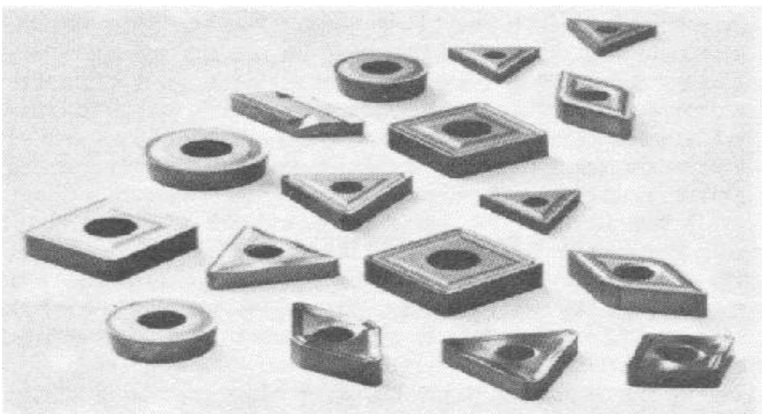

Fig 2: Various shapes of cutting tool inserts[45]

Insert Material

There is a large variety of cutting tool materials that are available, each having its own specific properties and performance abilities. Examples of insert materials are Carbides, HSS, CBN, Diamond, Carbon speed steels etc. Carbide tools find common use in the metal cutting industry due to their ability to machine at elevated temperatures and higher speeds.

1.6 SURFACE CHARACTERISTICS

The principal elements of surfaces are discussed below:

a. Surface: The surface of an object is the boundary which separates that object from another substance. Its shape and extent are usually defined by a drawing or descriptive specifications.

b. Profile: It is the contour of any specified section through a surface.

c. Roughness: It is defined as closely spaced, irregular deviations on a scale smaller than that of waviness. Roughness may be superimposed on waviness. Roughness is expressed in terms of its height, its width, and its distance on the surface along which it is measured.

d. Waviness: It is a recurrent deviation from a flat surface, much like waves on the surface of water. It is measured and described in terms of the space between adjacent crests of the waves (waviness width) and height between the crests and valleys of the waves (waviness height). Waviness can be caused by, Deflections of tools, dies, or the work piece, Forces or temperature sufficient to cause warping, Uneven lubrication, Vibration, or Any periodic mechanical or thermal variations in the system during manufacturing operations.

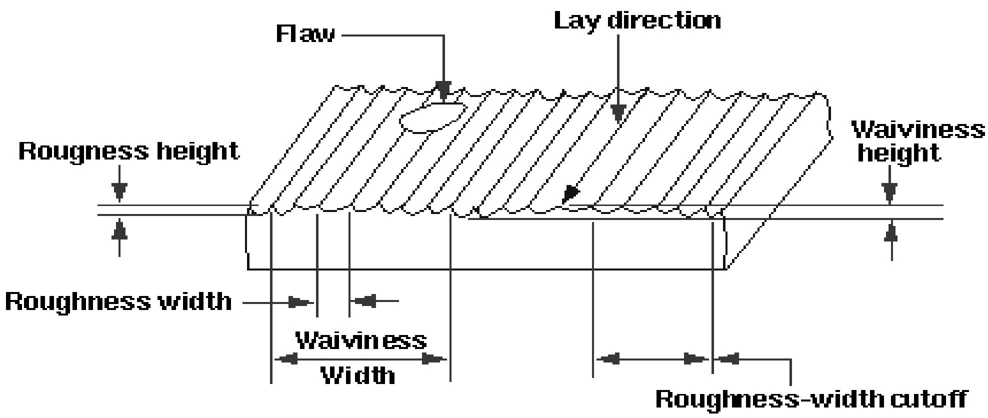

Fig 3 : Surface characteristics[21]

e. **Flaws:** Flaws, or defects, are random irregularities, such as scratches, cracks, holes, depressions, seams, tears, or inclusions as shown in Figure 4.

f. **Lay:** Lay, or directionality, is the direction of the predominant surface pattern and is usually visible to the naked eye. Lay direction has been shown in Figure 4.

1.6.1 SURFACE FINISH IN MACHINING

The resultant roughness produced by a machining process can be thought of as the combination of two independent quantities:

a. Ideal roughness, and

b. Natural roughness.

a. Ideal roughness:

Ideal surface roughness is a function of feed and geometry of the tool. It represents the best possible finish which can be obtained for a given tool shape and feed. It can be achieved only if the built-up-edge, chatter and inaccuracies in the machine tool movements are eliminated completely. For a sharp tool without nose radius, the maximum height of unevenness is given by:

$$R_{max} = \frac{f}{cos\emptyset + cos\beta}$$

Here *f* is feed rate, φ is major cutting edge angle and β is the minor cutting edge angle. The surface roughness value is given by, Ra = Rmax/4

Idealized model of surface roughness has been clearly shown in Figure 5.

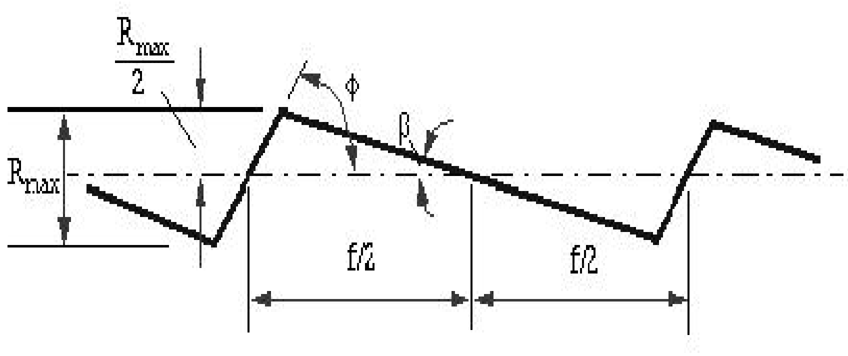

Fig 4 : Idealized model of surface roughness[12]

Practical cutting tools are usually provided with a rounded corner, and figure below shows the surface produced by such a tool under ideal conditions. It can be shown that the roughness value is closely related to the feed and corner radius by the following expression:

$$R_a = \frac{0.0321f^2}{r}$$, where r is the corner radius.

b. Natural roughness:

In practice, it is not usually possible to achieve conditions such as those described above, and normally the natural surface roughness forms a large proportion of the actual roughness. One of the main factors contributing to natural roughness is the occurrence of a built-up edge and vibration of the machine tool. Thus, larger the built up edge, the rougher would be the surface produced, and factors tending to reduce chip-tool friction and to eliminate or reduce the built-up edge would give improved surface finish.

1.6.2 FACTORS AFFECTING THE SURFACE FINISH

Whenever two machined surfaces come in contact with one another the quality of the mating parts plays an important role in the performance and wear of the mating parts. The height, shape, arrangement and direction of these surface irregularities on the work piece depend upon a number of factors such as:

A) The machining variables which include

a) Cutting speed

b) Feed, and

c) Depth of cut.

B) The tool geometry

Some geometric factors which affect achieved surface finish include:

a) Nose radius

b) Rake angle

c) Side cutting edge angle, and

d) Cutting edge.

C) Work piece and tool material combination and their mechanical properties

D) Quality and type of the machine tool used,

E) Auxiliary tooling, and lubricant used, and

F) Vibrations between the work piece, machine tool and cutting tool.

Table 1: **V**arious surface roughness parameters and their formula

Parameter	**Description**	**Formula**
R_a ,R_{aa} ,R_{yni}	Arithmetic average of absolute values	$R_a = \frac{1}{n}\sum_{i=1}^{n}\lvert y_i\rvert$
R_q ,R_{rms}	Root mean squared	$R_q = \sqrt{\frac{\sum_{i=1}^{n} y^2}{n}}$
R_v	Maximum valley depth	$R_v = min_i y_i$
R_p	Maximum peak height	$R_p = max_i y_i$
R_t	Maximum height of the profile	$R_t = R_p - R_v$
R_{sk}	Skew ness	$R_{sk} = \frac{1}{nR_q{}^3}\sum_{i=1}^{n} y_i{}^3$
R_{ku}	Kurtosis	$R_{ku} = \frac{1}{nR_q{}^4}\sum_{i=1}^{n} y_i{}^4$

Chapter 2 LITERATURE REVIEW

Aman Aggarwal et. al. [2] have presented the paper on the title "Optimizing Power Consumption for CNC Turned Parts Using Response Surface Methodology and Taguchi's Technique—A Comparative Analysis". This paper presented the findings of an experimental investigation into the effects of cutting speed, feed rate, depth of cut, nose radius and cutting environment on the power consumption in CNC turning of AISIP-20 tool steel. The cutting tool selected was TiN coated tungsten carbide. Design of experiment techniques, i.e. response surface methodology (RSM) and Taguchi's technique; have been used to accomplish the objective of the experimental study. L27 orthogonal array and face centered central composite design have been used for conducting the experiments. In order to quantify the influence of process parameters and interactions on the selected machining characteristic, analysis of variance (ANOVA) was performed. The analysis of the results for power consumption showed that the techniques, RSM and Taguchi methodology, gave similar results. Taguchi's technique revealed that cryogenic environment was the most significant factor followed by cutting speed and depth of cut. The 3D surface plots of RSM also revealed that cryogenic environment has very significant effect in reducing power consumption. They also found that RSM technique can model the response in terms of significant parameters, their interactions and square terms whereas, this facility is not provided by Taguchi's technique. Also 3D surfaces generated by RSM can help in visualizing the effect of parameters on response in the entire range specified whereas Taguchi's technique gives the average value of response at given level of parameters. Thus RSM can better predict the effect of parameters on response and is a better tool for optimization.

Anupam Agrawal et. al.[4] have presented paper on the title "Prediction of surface roughness during hard turning of AISI 4340 steel (69 HRC)". There 39 sets of hard turning (HT) experimental trials were performed on a Mori-Seiki SL-25Y (4-axis) computer numerical controlled (CNC) lathe to study the effect of cutting parameters in influencing the machined surface roughness. In all the trials, AISI 4340 steel workpiece (hardened up to 69 HRC) was machined with a commercially available CBN insert (Warren Tooling Limited, UK) under dry conditions.The surface topography of the machined samples was examined by using a white light interferometerand a reconfirmation of measurement was done using a Form

Talysurf. The machining outcome was used as an input to develop various regression models to predict the average machined surface roughness on this material. Three regression models – Multiple regression, Random forest, and Quantile regression were applied to the experimental outcomes. To the best of the authors' knowledge, this paper is the first to apply random forest or quantile regression techniques to the machining domain. The performance of these models was compared to ascertain how feed, depth of cut, and spindle speed affect surface roughness and finally to obtain a mathematical equation correlating these variables. It was concluded that the random forest regression model is a superior choice over multiple regression models for predictionof surface roughness during machining of AISI 4340 steel (69 HRC)

C. X. (Jack) Feng and X. Wang [8] have focused on developing an empirical model for the prediction of surface roughness in finish turning. The model considered work piece hardness (material); feed; cutting tool point angle; depth of cut; spindle speed; and cutting time as the working parameters. Nonlinear regression analysis along with logarithmic data transformation was applied in developing the empirical model. The values of surface roughness predicted by this model were then verified with extra experiments and compared with those from some of the representative models in the literature. To establish the prediction model, regression analysis was conducted with MINITAB. Hypothesis testing was done using t-test, F-test and Levene's test. They assumed that the three-, four-, and five-factor interactions are negligible, because these higher-order interactions are normally assumed to be almost impossible in practice. Therefore, a 2^{5-1} factorial design was selected. To consider system variations, such as tool wear and vibration in particular, the cutting time and a replicate number of three were selected, respectively. The experiments were conducted on a production type YAM CK-1 CNC Lathe with a FANUC OT10 controller. They concluded that the tool point angle had a significant impact on the surface roughness, in addition to feed, nose radius, work piece hardness, and cutting speed. The other factors do not significantly contribute to these smaller roughness values.

Hasan Gokkaya and Muammer Nalbant [9] investigated the effects of insert radii of cutting tools, depths of cut and feed rates on the surface quality of the work pieces depending on various processing parameters. The AISI 1030 steel work piece was processed on a digitally controlled Johnford T35 Industrial type CNC lathe machine using cemented carbide cutting tools, coated with three layer coating materials TiN, Al_2O_3, TiC (outermost is TiN) applied by the chemical vapour deposition (CVD) technique. It was seen that the insert radius, feed rate, and depth of cut have different effects on the surface roughness. In the range of importance, the effective parameters on the average surface roughness were determined as the following: speed rate, insert radius, and depth of cut. Thus a good combination among the insert radius, speed rate and depth of cut can provide better surface qualities.

H. K. Dave et. al. [10] presented an experimental investigation of the machining characteristics of different grades of EN materials in CNC turning process using TiN coated cutting tools. MINITAB statistical software was used for the analysis of the experimental work. Batliboi-make CNC turning centre was used to carry out the experimentation. Different materials like EN-8 and EN-31 were used as work piece. Five parameters viz. speed, feed, depth of cut, insert and work piece material were taken as input process factors. Initial and final weights of work piece and Machining time were recorded. Following equation was used to calculate the Material Removal Rate (MRR):

$$MRR\left(\frac{mm^3}{min}\right) = \frac{[Initial\,Weight\,of\,workpiece(gm) - Final\,Weight\,of\,workpiece(gm)]}{[Density\left(\frac{gm}{mm^3}\right) * Machining\,Time\,(min)]}$$

Optimal cutting parameters for each performance measure were obtained employing Taguchi technique by using an L8 orthogonal array. The signal to noise ratio and analysis of variance were employed to study the performance characteristics in dry turning operation. It was seen that with increase in all three parameters speed, feed and depth of cut, MRR would increase, remarkably, i.e. speed, feed and depth of cut are directly proportional to MRR. In addition, they concluded that positive inserts were better than the negative inserts and EN-31 materials were superior to EN-8 for MRR. ANOVA shows that depth of cut is the most significant factor for material removal rate. Effect of feed was insignificant as compared to other cutting parameters for material removal rate.

Ranganath M S et. al. [30] have presented a paper on “Surface Finish Monitoring in CNC Turning Using RSM and Taguchi Techniques”. This paper presented the findings of an experimental investigation into the effects of speed, feed rate and depth of cut on surface roughness in CNC turning of Aluminium (KS 1275). Response surface methodology and Taguchi techniques were used to accomplish the objective of the experimental study. L27 orthogonal array was used for conducting the experiments. For the design of RSM, central composite design (CCD) was used. The three factors speed, feed rate, depth of cut, which were selected in the screening experiment, were used in CCD. Minitab 15 was used to develop the experimental plan for Taguchi and response surface methodology. The same software was also used to analyze the data collected. The experiments were carried out on Aluminium workpiece using brazed diamond cutting insert using a CNC turning center (Fanuc 0i mate - TD/Siemens 828D Basic T).

The analysis of the results for surface roughness showed that the techniques - Taguchi technique and Response surface methodology, gave similar results. Taguchi's technique revealed that feed is the most significant factor followed by depth of cut and speed. The 3D surface plots of Response surface methodology also revealed that feed has very significant effect on surface roughness. Significance of interactions and square terms of parameters was more clearly predicted in Response surface methodology. The Response surface methodology showed significance of all possible combinations of interactions and square terms, whereas, in Taguchi's technique only three interactions are normally studied. This is because of the fact that the interactions between control factors were aliased with their main effects. Response surface methodology technique required almost double time for conducting experiments as that needed for Taguchi technique. Response surface methodology technique could model the response in terms of significant parameters, their interactions and square terms. This facility was not provided by Taguchi's technique. 3D surfaces generated by Response surface methodology could help in visualizing the effect of parameters on response in the entire range specified whereas Taguchi's technique gave the average value of response at given level of parameters. Optimization plot obtained from Response surface methodology was not a feature of Taguchi technique. Thus Response surface methodology is a better tool for optimization and can better predict the effect of parameters on response.

Harish Kumar et. al. [11] carried out experimental work for the optimization of input parameters for the improvement of quality of the product of turning operation on CNC machine. Feed Rate, Spindle speed & depth of cut were taken as the input parameters and the dimensional tolerances as output parameter. MS1010 work piece was dry turned using HSS tool on a CNC lathe. Three levels of each cutting parameters were selected. And L9 Array was used in design of experiment for optimization of input parameters. Taguchi parameter design and ANOVA were used to analyze the results. It was found that most important parameter affecting surface roughness was spindle speed, followed by feed and DOC.

Ilhan Asiltürk.et.al. [12], have presented a paper on "Determining the Effect of Cutting Parameters on Surface Roughness in Hard Turning Using the Taguchi Method". The study focused on optimizing turning parameters based on the Taguchi method to minimize surface roughness (Ra and Rz). Experiments were conducted using the L9 orthogonal array in a CNC turning machine. Dry turning tests were carried out on hardened AISI 4140 (51 HRC) with coated carbide cutting tools. The statistical methods of signal to noise ratio (SNR) and the analysis of variance (ANOVA) were applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. S/N ratios and level values were calculated by using Eq. ''the smaller-the better'' in the MINITAB 14 Program. Results of this study indicated that the feed rate has the most significant effect on Ra and Rz. In addition, the effects of two factor interactions of the feed rate-cutting speed and depth of cut-cutting speed appeared to be important.

Jakhale Prashant P. and Jadhav B. R. [13] have investigated the effect of cutting parameters (cutting speed, feed rate, depth of cut) and insert geometry (CNMG and DNMG type insert) on surface roughness in the turning of high alloy steel. Al2O3, TiCN and TiN coated cemented carbide inserts were used as the cutting tool material. The turning experiments were carried out in dry cutting conditions using TACCHI CNC lathe. The Taguchi method and L9 Orthogonal Array were used to reduce variance for the experiments with optimum setting of control parameters. The optimum combination of the cutting parameters was determined by the help of ANOVA and S/N ratios. Finally, confirmation experiments were done using the optimum machining parameters which were found by Taguchi optimization technique and thereby validation of the optimization was tested. A multi-response optimization problem was solved by obtaining an optimal parametric combination, capable of producing high surface quality turned product in a relatively lesser time. Best surface finish (lowest Ra) was obtained at a cutting speed of 100 m/min, feed rate of 0.24 mm/revolutions and a depth of cut of 1mm. Best surface roughness at high cutting speed (i.e. 150 m/min) was obtained from DNMG (12 06 08) insert. The results of ANOVA for surface roughness showed that depth of cut was most significant parameter which affects the surface finish as compared to other cutting parameters. The cutting speed and feed rate were least significant parameters.

M. Kaladhar et. al. [17], have focused on Taguchi method to determine the optimum process parameters for turning of AISI 304 austenitic stainless steel on CNC lathe. A CVD coated cemented carbide cutting insert was used. The influence of cutting speed, feed, depth of cut were investigated on the surface roughness and material removal rate (MRR). The Analysis

Of Variance (ANOVA) was also used to analyze the influence of cutting parameters during machining. A multiple linear regression model was developed for surface roughness and MRR using Minitab-14 software. The predictors were: Cutting speed, Feed, Depth of cut and Nose radius. The ANOVA and F-test revealed that the cutting speed was the dominant parameter followed by nose radius for surface roughness. In case of MRR response, the depth of cut was the dominant one followed by the feed. A number of multiple linear regression models were developed for surface roughness and MRR. The developed models were reasonably accurate and could be used for prediction within limits. The Optimal range of surface roughness and MRR of the work piece was also predicted. The regression equation for Ra was

$$Ra = 2.78 - 0.064 * Speed + 0.239 * Feed - 0.025 * depth\ of\ cut - 0.817 * Nose\ radius$$

whereas for MRR was

$$MRR = 15486 + 1154 * Speed - 294 * Feed + 12095 * depth\ of\ cut - 12416 * Nose\ radius$$

M. Kaladhar et. al. [18] have published a paper "Application of Taguchi approach and Utility Concept in solving the Multi-objective Problem when turning AISI 202 Austenitic Stainless Steel". In this, a multi-characteristics response optimization model based on Taguchi and Utility concept was used to optimize process parameters, such as speed, feed, depth of cut, and nose radius on multiple performance characteristics, namely, surface roughness (Ra) and material removal rate(MRR) during turning of AISI 202 austenitic stainless steel using a CVD coated cemented carbide tool. Taguchi's L8 orthogonal array was selected for experimental planning. The ANOVA and F-tests were used to analyze the results. The experiments were conducted on ACE Designer LT-16XL CNC lathe in dry working environment. In first stage (single response), optimal settings and optimal values of Ra and MRR were obtained individually, and from their corresponding ANOVA results. It was found that the feed (61.428%) was the most significant parameter followed by cutting speed (20.697%) for Ra, the depth of cut (63.183%) was the most significant parameter followed by cutting speed (20.697%) for MRR response. In second stage (multi-response), the analysis of means established that a combination of higher levels of cutting speed, depth of cut, nose radius and lower level of feed was necessary for obtaining the optimal value of multiple performances. Based on the ANOVA and F-test analysis, the most statistical significant and percent contribution of the process parameters for multiple performances were depth of cut, cutting speed, whereas feed and nose radius were less effective.

M. Kaladhar et. al. [20] have analyzed the optimization of machining parameters in turning of AISI 202 austenitic stainless steel using CVD coated cemented carbide tools. During the experiment, process parameters such as speed, feed, depth of cut and nose radius were used to explore their effect on the surface roughness (Ra) of the work piece. Commonly available (CVD) of Ti (C, N) +Al_2O_3 coated cemented carbide inserts were used in dry turning the work piece using ACE Designer LT-16XL CNC lathe. The experiments were conducted using full factorial design in the Design of Experiments (DOE). Further, the analysis of variance (ANOVA) was used to analyze the influence of process parameters and their interaction during machining. This analysis was carried out for a significant level of α=0.05 (confidence level of 95%). The effect of feed (the most significant parameter) and nose radius were to be significant. The optimal machining parameters for AISI 202 was obtained for the minimum value (Ra= 0.70 μm) of surface roughness. The correlation among the factors i.e. cutting speed, feed, depth of cut and nose radius and performance measure (Ra) were obtained. The polynomial model obtained was as follows: Ra=1.4731+ 0.4294 * C - 0.2819 * D. R^2 = 94.18% confirms the suitability of models and the correctness of the calculated constants. Also, it was observed that the predicted values and measured values were close to each other. Thus, the experiments were validated. So, in order to obtain a good surface finish on AISI 202 steel, higher cutting speed, lower feed rate, lower depth of cut and higher nose radius have to be preferred.

Ranganath M S, Vipin [31] carried out experimental investigation and parametric analysis of surface roughness in CNC turning using design of experiments. Their work integrated the effect of various parameters which affect the surface roughness. The important parameters discussed were cutting speed, feed, depth of cut, nose radius and rake angle Experiments were carried out with the help of factorial method of design of experiment (DOE) approach to study the impact of turning parameters on the roughness of turned surfaces. Secondly, a mathematical model was formulated to predict the effect of machining parameters on surface roughness of a machined work piece. Model was validated with the experimental data and the reported data of other researchers. Further, the performance of wiper insert tools was analyzed. Several statistical techniques were used to analyze the data. To develop the first order models (log transformed) for predicting the surface roughness values, a regression modelling was done. For establishing the second-order predictive models a full factorial design was used. Experiments were carried out on Aluminium 6061 alloy using cemented carbide inserts on a CNC Turning Machine. The geometry of tools selected was used with the combinations of Nose radius: 0.4mm, 0.8mm, 1.2 mm and Rake angles 16°, 18°, 20°. Minitab 13 was used for analyzing the results. The following conclusions have been made on the basis of results obtained and analysis performed: Increase in cutting speed improved the surface finish, thus the average surface roughness value decreased. Increase in depth of cut affected the surface finish adversely to a small extent, but as depth of cut increased beyond a certain limit surface finish deteriorated to a large extent. Small increase in feed rate deteriorated surface finish to a large extent as compared to same amount of increase of depth of cut. Surface roughness also decreased as the nose radius increased hence surface finish increased. With increase in back rake angle the surface roughness decreased and improved the surface finish. The ANOVA and F-test revealed that the feed is dominant parameter followed by depth of cut, speed, nose radius and rake angle for surface roughness.

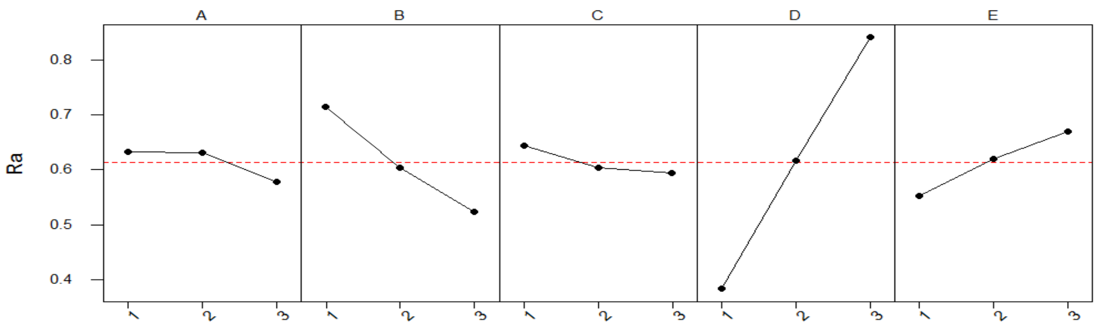

Fig 5 : Main effect plots for Ra [31]

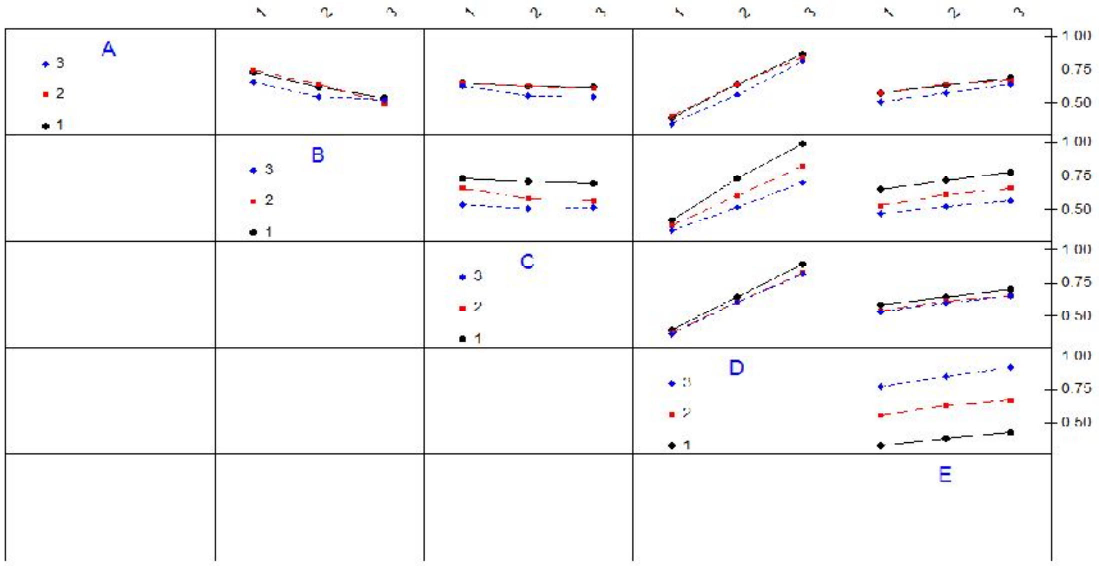

Fig 6 : Interaction plots for Ra [31]

M. Nalbant et.al [21] investigated to find the optimal cutting parameters for surface roughness in turning using Taguchi method. The orthogonal array, the signal-to-noise ratio, and analysis of variance were employed to study the performance characteristics in turning operations. An L9 orthogonal array was used. Three cutting parameters namely, insert radius, feed rate, and depth of cut, were optimized with considerations of surface roughness. The cutting experiments were carried out on a Johnford T35 CNC lathe using TiN coated tools with the grade of P-20 for the machining of AISI 1030 steel bars. Inserts used were TNMG160404-MA, TNMG160408-MA and TNMG160412-MA.They concluded that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the cutting parameters also the insert radius and feed rate were the main parameters among the three controllable factors (insert radius, feed rate and depth of cut) that influence the surface roughness. The confirmation experiments were conducted to verify the optimal cutting parameters. The percentage contributions of insert radius, feed rate and depth of cut are 48.54, 46.95 and 3.39, respectively. In turning, use of greater insert radius (1.2 mm), low feed rate (0.15 mm/rev) and low depth of cut (0.5 mm) were recommended to obtain better surface roughness for the specific test range.

N.E. Edwin Paul et al. [23] have described the Taguchi method based robust design philosophy for minimization of surface roughness in facing. Experimental works were conducted on CNC Lathe based on L9 orthogonal array. Based on the signal to noise ratio analysis, the optimal settings of the process parameters were determined. Three operating factors, viz., depth of cut, feed and cutting speed were selected for parametric optimization. The effect of different parameters in affecting variation in surface roughness while machining EN8 steel with TNMG 160404 EN-TF CTC 2135 insert was that the feed had greater influence on the surface roughness followed by the cutting speed. From the analysis it was revealed that the feed, cutting speed and depth of cut were prominent factors which affect the facing operations. Tugrul Ozel et. al. [14] have studied the effects of cutting edge geometry, work piece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel using four factor two level factorial design. CBN inserts with two distinct representative types of edge preparations were investigated in this study. These edge preparations include "chamfered" (T-land) edges and "honed" edges.

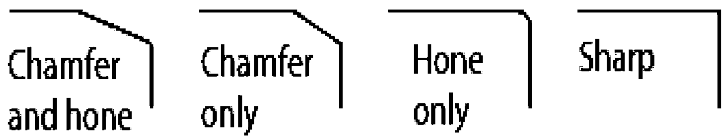

Fig 7 : Type of edge preparations used in CBN cutting tools [25]

The response variables were the work piece surface roughness and the cutting forces. Longitudinal turning was conducted on a rigid, high-precision CNC lathe (RomiCentur 35E).The results indicated that the effect of cutting edge geometry on the surface roughness was remarkably significant. The cutting forces were influenced not only by cutting conditions but also the cutting edge geometry and work piece surface hardness. This study showed that the effects of work piece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness were statistically significant. The effects of two-factor interactions of the edge geometry and the work piece hardness, the edge geometry and the feed rate, and the cutting speed and feed rate were also appeared to be important. Especially, honed edge geometry and lower work piece surface hardness resulted in better surface roughness. Cutting edge geometry, work piece hardness and cutting speed were found to be affecting force components. The lower work piece surface hardness and small edge radius resulted in lower tangential and radial forces.

Ranganath M S et. al. [27] have investigated the effect of the cutting speed, feed rate and depth of cut on surface roughness and material removal rate (MRR), in conventional turning of Aluminium (6061) in dry condition. The effect of cutting condition (cutting speed and feed rate) on surface roughness and MRR were studied and analyzed. Design of experiments (DOE) were conducted for the analysis of the influence of the turning parameters on the surface roughness by using Taguchi design and then followed by optimization of the results using Analysis of Variance (ANOVA) to find minimum surface roughness and the maximum MRR. MINITAB software was used for Taguchi's method and for analysis of variance (ANOVA). Strong interactions were observed among the turning parameters. Most significant interactions were found between work materials, feed and cutting speeds. A Systematic approach was provided to design and analyze the experiments, and to utilize the data obtained to the maximum extent. The following conclusions were drawn based on the experimental investigation conducted at three levels by employing Taguchi technique to determine the optimal level of process parameters. From the data collection it was observed that the increase in cutting speed tended to improve the finish, thus the average surface roughness value decreased. The increase in depth of cut influenced the finish slightly, but greater depth of cut marked the finish poor. Speed was the most critical parameter when finish was the criterion. Finish got poor as the feed increased, thus the average surface roughness value increased with increase in feed. The ANOVA and F-test revealed that the speed and depth of cut were dominant parameters followed by feed for surface roughness.

Ranganath M S et. al.[33] had predicted the suface roughness model for CNC turning of EN-8 steel using response surface methodology. In this prediction model of surface roughness had been developed for turning EN-8 steel with uncoated carbide inserts using response surface methodology. The model was developed in the form of multiple regression equations correlating dependent parameter surface roughness, with speed, feed rate and depth of cut, in a turning process.The box-behnken design was used to perform the experiments.the second order model was found suitable for this work. Moreaver a good agreement between the predicted and experimental surface roughness was observed within reasonable limit.

Ranganath M S, Vipin [32] have investigated the effect of rake angle on surface roughness in CNC turning of Aluminium (6061) while keeping other machining parameters such as cutting speed, feed rate and depth of cut as constant. Three positive rake angled tools were selected to study and analyze the effect of cutting conditions on surface roughness. Design of experiments were conducted for the analysis of the influence of the turning parameters on the surface roughness by using Taguchi design and then followed by optimization of the results using Analysis of Variance to find minimum surface roughness. Experiments were carried out on a CNC turning machine using cemented carbide insert type cutting tool. The geometry of tools selected was with the combinations of Nose radius: 0.4mm, 0.8mm, 1.2 mm and Rake angles 16°, 18°, 20°. Surtronic 3+ surface roughness measuring instrument was used for the measurement of surface texture.

It was observed that the surface roughness decreases with increase in rake angle. Strong interactions were observed among the turning parameters. Most significant interactions were found between work materials, feed and cutting speeds. A systematic approach was provided to design and analyze the experiments, and to utilize the data obtained to the maximum extent.

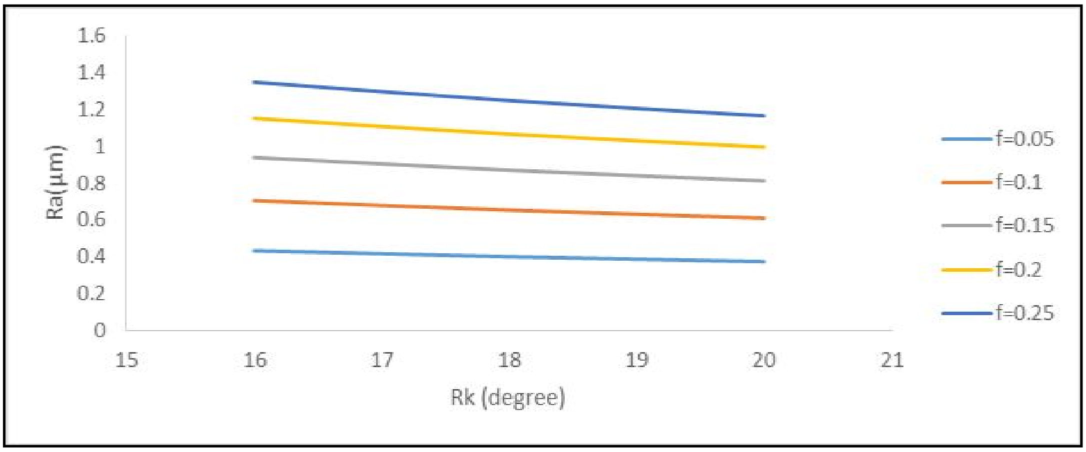

Fig 8 : Graph between Surface Roughness and Rake angle at Nr 1.2, V 225, d 0.1 [32]

Upinder Kumar Yadav et. al. [41], have investigated the effect and optimization of machining parameters (cutting speed, feed rate and depth of cut) on surface roughness. An L27 orthogonal array, analysis of variance (ANOVA) and the signal-to-noise (S/N) ratio have been used in this study. The effect of three machining parameters i.e. Cutting speed, feed rate and depth of cut and their interactions were evaluated using ANOVA and with the help of MINITAB 16 statistical software. The purpose of the ANOVA in this study was to identify the important turning parameters in prediction of Surface roughness. The conclusions showed that Surface roughness was mainly affected by feed rate and cutting speed. With the increase in feed rate, the surface roughness also increased and as the cutting speed decreased the surface roughness increased. From ANOVA analysis, parameters making significant effect on surface roughness were feed rate and cutting speed. The optimum setting of cutting parameters for high quality turned parts were as: Cutting speed 264 m/min, Feed rate 0.1 mm/rev, Depth of cut 1.5 mm. The optimum value of the surface roughness (Ra) came out to be 0.89. It was also concluded that feed rate was the most significant factor affecting surface roughness followed by depth of cut. Cutting speed was the least significant factor affecting surface roughness.

Zahari Taha et. al.[46] have investigated on Effect of insert geametry on surface roughness in the turning process of AISI D2 steel. The objective of his study was to compare measured surface roughness(from experiments) with theoritical surface roughness(from theoritical calculations) of two types of insert, 'C' type and 'T' type. The feed rate was varied between the recomended feed rate range.It was observed that there is large deviation between measured and theoritical surface roughness at low feed rates (0.05 mm/rev) for both inserts. The work material factor of AISI D2 affecting the chip character was presumably the cause of this phenomenon. Interestingly, at high feed rates (0.4 mm/rev) the 'C' type insert resulted in 40% lower roughness compared to the 'T' type due to differences in insert geometry.

RESPONSE SURFACE DESIGN

A set of advanced design of experiments (DOE) techniques that help you better understand and optimize your response. Response surface design methodology is often used to refine models after important factors have been determined using factorial designs; especially if you suspect curvature in the response surface.

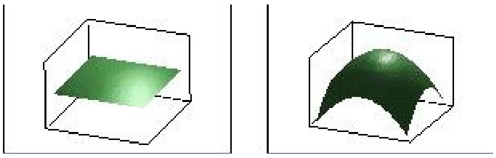

Fig 9 :SURFACE REPRESENTATION IN RSM AND OTHER TECHNIQUE[42]

The difference between a response surface equation and the equation for a factorial design is the addition of the squared (or quadratic) terms that allow you to model curvature in the response, making them useful for:

1. Understanding or mapping a region of a response surface. Response surface equations model how changes in input variables influence a response of interest.

2. finding the levels of input variables that optimize a response.

3. selecting the operating conditions to meet specifications.

For example, you would like to determine the best conditions for injection-molding a plastic part. You first used a factorial experiment to determine the significant factors (temperature, pressure, cooling rate). You can use a response surface designed experiment to find the optimal settings for each factor.

There are two main types of response surface designs:

a. **Central Composite designs** can fit a full quadratic model. They are often used when the design plan calls for sequential experimentation because these designs can incorporate information from a properly planned factorial experiment.

b. **Box-Behnken designs** typically have fewer design points, thus, they are less expensive to run than central composite designs with the same number of factors. They allow efficient estimation of the first- and second-order coefficients; however, they can't incorporate runs from a factorial experiment.

METHODOLOGY OF RSM:-

Whole process of rsm can be divided into different parts and those parts are the sequences in which the process has to be done.

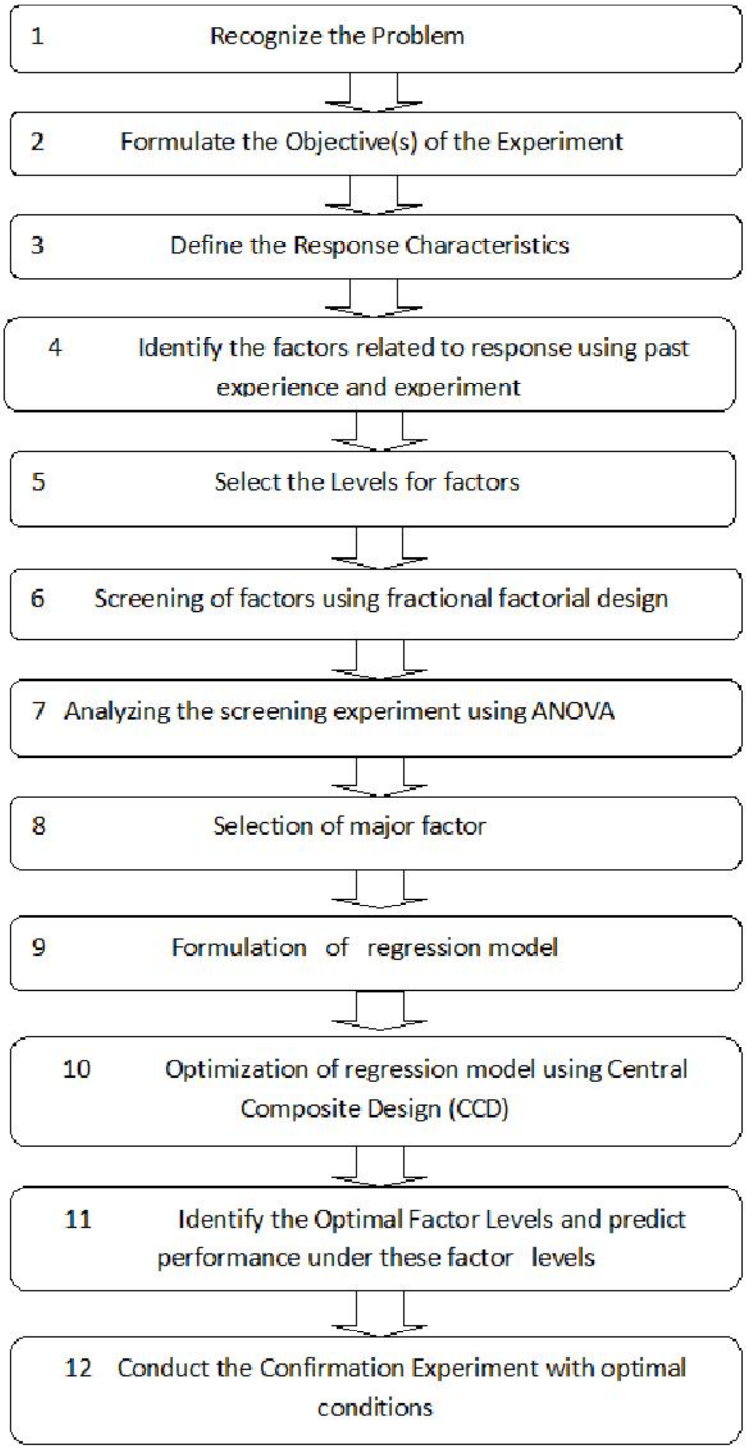

Fig 10: STEPS IN RSM [28]

In design optimization using RSM, the first task is to determine the optimization model, such as the identification of the interested system measures and the selection of the factors that influence the system measures significantly. To do this, an understanding of the physical meaning of the problem and some experience are both useful. After this, the important issues are the design of experiments and how to improve the fitting accuracy of the response surface models. DOE techniques are employed before, during, and after the regression analysis to evaluate the accuracy of the model. RSM also quantifies relationships among one or more measured responses and the vital input factors.

RSM, or RSM, is a collection of mathematical and statistical techniques in which a response of interest is influenced by several variables and the objective is to optimize this response. For example, suppose that a chemical engineer wishes to find the levels of temperature (x1) and pressure (x2) that maximize the yield (y) of a process. The process yield is a function of the levels of temperature and pressure, y = f (x1, x2) +e

Where e represents the noise or error observed in the response y. Then the surface depicted by h= f (x1, x2), which is called a Response surface. We usually represent the response surface graphically, where h is plotted versus the levels of x1 and x2. To help visualize the shape of a response surface, we often plot the contours of the response surface as well. In the contour plot, lines of constant response are drawn in the x1, x2 planes. Each contour corresponds to a particular height of the response surface. Objective is to optimize the response. In RSM, polynomial equations, which explain the relations between input variables and response variables, are constructed from experiments or simulations and the equations are used to find optimal conditions of input variables in order to improve response variables. For the design of RSM, many researchers have used central composite design (CCD) for their experiments. CCD is widely used for fitting a second-order response surface. CCD consists of cube point runs, plus centre point runs, and plus axial point runs.

The three factors speed, feed rate, depth of cut, selected in the screening experiment, will be used in CCD. The process can be studied with a standard RSM design called a Central composite design (CCD). The factorial portion is a full factorial design with all factors at three levels, the star points are at the face of the cube portion on the design which correspond to value of -1. This is commonly referred to as a face centered CCD. The center points, as implied by the name, are points with all levels set to coded level 0, the midpoint of each factor range, and this is repeated six times. Twenty experiments to be performed. For each experimental trial, a new cutting edge to be used. The latest version of the Minitab or Design Expert may be used to develop the experimental plan for RSM. The same software can also be used to analyze the data collected.

Objective

Our goal is to start from using our best prior or current base and find for the optimum spot where the response is either maximized or minimized.

Here are the models that we will use.

Screening Response Model :

$y=\alpha+\beta x_1+\gamma x_2+\delta x_1 x_2+\varepsilon$ ....(1)

The screening model that we used for the first order situation involves linear effects and a single cross product factor, which represents the linear x linear interaction component.

Steepest Ascent Model

If we ignore cross products which gives an indication of the curvature of the response surface that we are fitting and just look at the first order model this is called the steepest ascent model:

$y=\alpha+\beta x_1+\gamma x_2+\varepsilon$ ....(2)

Optimization Model :

After this, it is known that we are somewhere near the maximized or optimized value so, a second order model. This includes in addition the two second-order quadratic terms.

$y=\alpha+\beta x_1+\gamma x_2+\delta x_1 x_2+\theta x_1^2 x_2^2+\varepsilon$ ....(3)

If the plot is in more than 2 dimensions, the method is not best suited as per the obtained plot. The method of steepest ascent tells where to take new measurements, and the response at those points can be recorded. it might move a few steps and it may be seen that the response persistently strived to move up or perhaps not - then you might do another first order experiment and reorganize the efforts. The point is, when the experiments are done for the second order model, it is hoped that the optimum will be in the range of the experiment - if it is not, then, it is extrapolation to find the optimum. In this case, the safest thing to do is to do another experiment around this estimated optimum. Since the experiment for the second order model requires more runs than experiments for the first order model, it is required to move into the right region before starting fitting second order models.

Steepest Ascent - The Second Order Model

This second order model includes linear terms, cross product terms and a second order term for each of the x's. If in generalized way, various values have k first order terms, k second order terms and all possible pairwise first-order interactions. The linear terms just have one subscript. The quadratic terms have two subscripts. There are k*(k-1)/2 interaction terms. To fit this model, it is needed to have a response surface design that has more runs than the first order designs used to move close to the optimum.

This second order model is the basis for response surface designs under the approximation that optimized value is not a perfect quadratic polynomial in k dimensions, but it provides a good approximation to the surface near the maximum or a minimum.

Chapter 3 EXPERIMENT SET-UP

Experimental setup consists of the following:-

1. CNC turning machine
2. Aluminium 6061 bars
3. Talysurf Surtronic 3+
4. Minitab software
5. Cutting insert with different nose radius

3.1 CNC TURNING MACHINE

Fig 11 :- CNC turning machine at Metal Cutting Lab, DTU

Table 2 : CNC description on which experiments are performed

Tittle	**Description**	**Unit**	**LL20T L3**
Capacity	Swing over bed	mm	510
	Chuck dia. max.	mm	200
	Max. turning diameter	mm	320
	Maximum turning length	mm	310
	Admit between centre	mm	420
Spindle	Spindle nose	Type	A2-6
	Hole through spindle	mm	61
	Spindle speed	rpm	3500
	Spindle motor power(cont./15 min)	Kw	7.5/11
Feed System	Cross travel X-axis	mm	185
	Longitudinal travel Z-axis	mm	370
	Rapid traverse rate X/Z axis	m/min	30/30
Turret	Number of stations	Nos.	8
	Tool shank size	mm	25 X 25
	Maximum boring bar diameter	mm	40
	Turret indexing	Type	Hydraulic
Tail stock	Quill diameter	mm	75
	Quill stroke	mm	100
	Quill taper	-	MT-4
CNC system	Controller	-	FANUC
Machine size	Front x Side	mm	2065 X1925
	Machine weight (approximately)	kg	3500

3.2 ALUMINIUM 6061 BARS

Aluminium 6061 is a precipitation hardening aluminium alloy, which contains magnesium and silicon as its primary alloying elements. It was originally called "Alloy 61S," and was developed in 1935. 6061 has good mechanical properties and it also exhibits good weldability. For general purpose use mainly Aluminium 6061 alloy is used.

It is easily available in pre-tempered grades such as 6061-O which means it is annealed and tempered grades such as 6061-T6 which means it is solutionized and artificially aged and 6061-T651 which means it is solutionized, stress-relieved stretched and artificially aged.

The first digit of the four digits in the designation implies the alloy group in terms of the major alloying elements of which it is constituted.

Fig 12 : Aluminium 6061 bars after turning at Metal Cutting Lab, DTU

Table 3 : Naming of Aluminium Alloy

1XXX	Aluminium of 99,00% minimum purity and higher
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc
8XXX	Other elements
9XXX	Unused series

Table 4 : Composition of Aluminium 6061

ELEMENT	PERCENT PRESENT
Magnesium(Mg)	0.80-1.20
Silicon(Si)	0.40-0.80
Iron(Fe)	0.0-0.70
Copper(Cu)	0.15-0.40
Chromium(Cr)	0.04-0.35
Zinc(Zn)	0.0-0.25
Titanium(Ti)	0.0-0.15
Mangnese(Mn)	0.0-0.15
Others(Total)	0.0-0.15

Other(each)	0.0-0.05
Aluminium(Al)	Balance

Table 5: Properties of Aluminium 6061

PROPERTY	**VALUE**
Density	2.7 g/cc
Brinell Hardness Number	95
Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa
Modulus of Elasticity	68.9 GPa
Poisson's ratio	0.33
Fatique Strength	96.5 MPa
Machinability	50%(comparing with other aluminium alloys)
Shear Modulus	26 GPa
Shear Strength	207 MPa
Thermal Conductivity	167 W/m-k
Melting Point	582-652℃

Uses

6061 is mostly used for the following:

- constructing structure of aircraft, such as wings and fuselages. 6061 is more generally utilised as a part of homebuilt aircraft than business or military aircraft. Aluminium alloy 2024 has more strength, but 6061 aluminium alloy is easily workable and it also behaves resistant to corrosion even when the material surface is peeled off. Whereas, 2024 is corroded easily, hence it is used with a thin coating of Al-clad to make it corrosion resistive.

- yacht construction, including small utility boats.

- wheel spacers used as a automotive parts

- packaging of foodstuffs and beverages using aluminium cans.
- bicycle components and frames.

- The acclaimed Pioneer plaque had been made of this specific amulgum of aluminium.

- the auxiliary chambers and baffle systems in firearm sound silencer (essentially gun silencer for decreasing weight and enhancing mechanical operation). Lower and upper receivers of majority of the AR-15 rifle variants.

  Most of the aluminium the docks and the gangways are built with 6061-T6 extrusions, and welded into spot.

- aluminium 6061 is likewise utilized in some ultra-high vacuum (UHV) chambers

- parts for remote control model aircraft, for most of helicopter rotor segments.

Welding

6061 is highly weldable, for example using tungsten inert gas welding (TIG) or metal inert gas welding (MIG). Typically, after welding about 80% loss of strength is there. Material can be re-heat-treated to restore temper of the work material. After welding, the material age naturally and restore some of its strength. Alcoa Structural Handbook recommends the design strength of the material adjacent to the weld to be taken as 11,000 psi (75 MPa) without proper heat treatment after the welding.

Extrusions

Constant long-cross-section structural bars produced by pushing metal through a shaped die are produced by extrusion of 6061 alloy of aluminium.

Forgings

6061 is an alloy which is suitable for hot forging. Billet is heated by an induction furnace and forged by a process in which closed dies is used. Industrial parts and Automotive parts are just some of the uses as a forging.

3.3 TALYSURF SURTRONIC 3+

Surface roughness is an essential parameter which represents the quality of the product. Surface measurement is nothing but the comparison of the previously fixed value with the new value obtained.

The taylsurf instrument used in this experiment is a Taylor Hobson unit with surtonic3+ as its product name.

Surtronic 3+ is nothing but an amalgamation of technology so as to achieve high meticulousness and exactitude to have an accurate measurement of surface finish in the process no matter where the work is done, laboratory or the inspection room.

With Surtronic 3+, a beginner with no skills can achieve wide range of skills that can be understood within minutes. In this device the cycles in the function are minimum during the process of measurement and the variations are minute and the response can be obtained on the screen available. The process of measurement is easy and the whole machine can be operated or navigated through a wide variety of navigations and selection menu.

Surtronic 3+ instrument includes:-

- Display and traverse unit
- Pick up and diamond stylus
- Calibration standard
- Carrying case

- Battery
- Handbook

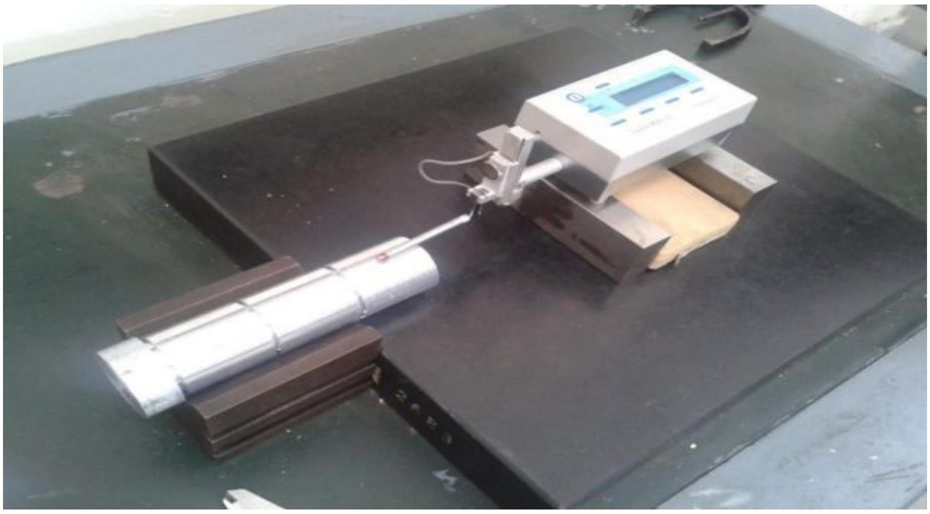

Fig 13 : Taylsurf instrument by Taylor Hobson Surtonic 3+ in Metrology Lab, DTU

The specifications of the handheld taylsurf used in the measurement are:

Table 6 : Specification of taylsurf , in metrology lab,DTU

Gauge range	$\pm 150\mu m$
Resolution	$0.01\mu m$
Traverse length(max.)	25.4mm
Traverse length(min.)	0.25mm
Pick up type	Variable reluctance
Stylus	Diamond tip radius $5\mu m$ Diamond tip radius $10\mu m$
Traverse speed	1mm/sec
Accuracy of parameters	2% of reading + LSD μm
Power	Battery or mains(optional)
Overall dimensions	130×80×65
Data processing module	185×140×50
Weight	450gm

The instrument is used on vertical, horizontal or inclined surfaces, along with selected mountings as a bench system for laboratory or batch measurement applications. The holder for measuring is placed at the slide so as to measure the vertical values and it can be easily revolved to various angles for measuring various dimensions.

Advantages of surtonic 3+:

1. Easy to handle in the workshop and laboratory.
2. Simple to use and also fast method.
3. Highly accurate and versatile in its working.
4. A wide range of parameters and high cutoff length for any measurement.
5. Easy to connect to software and automate the process.
6. Ability to process data.
7. Provides many languages.
8. Requires battery source.

3.4 MINITAB SOFWARE

The software used is minitab 17 which is used to draw the graphs and plots for the desired factors and responses. Minitab is a not only a software but a complete package of statistical tools designed and produced at the Pennsylvania State University by researchers namely, Thomas A. Ryan, Barbara F. Ryan, Jr., and Brian L. Joiner in 1972.

Minitab came to the market with its first soft version called as Omni-tab it was a program or algorithm use for the research work in the NIST ; the coding and the manual of omni-tab was printed in 1986.

Minitab is owned by Minitab Inc, it is a privately owned company with its headquarters situated in the State College of Pennsylvania, with its other branches in Coventry, England, Paris, France and Sydney, Australia.

In the present scenario, mini-tab is used in close usage and induction of other softwares which are also optimizers and can be used to bring better results.

Minitab 17, is the new version of this software, and is available in 8 languages: Japanese, Korean, Portuguese English, german , french, Simplified Chinese, & Spanish.

Minitab Inc. sells two other products that come in handy while using Minitab 17:

1. Quality Trainer: an eLearning file that allows in understanding the statistical tools.

2. Quality Companion 3: a tool integrated to the system so that it can be used to involve both the six sigma and the lean manufacturing so as to use the product in all types of fields and make it an all round.

3.5 CUTTING INSERTS USED

Cutting inserts used are having nose radius of 0.4 mm, 0.8 mm and 1.2 mm

INSERT DESIGNATION:-

The details of cutting insert CNMG 12 04 08 is mentioned below.
T: Insert Shape= Diamond shape(80°angle)
N: Clearance Angle= 0°
M: Medium Tolerance
G: Insert Type:Hole shape cylindrical and single sided type chip breaker
12: means length of each cutting edge, whose value is 12 mm
04: stands for nominal thickness of the insert, which is 4 mm
08: stands for nose radius whose value is 0.8 mm

TOOL GEOMETRY OF INSERT USED:-

Fig 14:- Cutting tool-inserts (1.2mm, 0.8mm, 0.4mm)

Table 7 : Cutting inserts used in performing Experiments

Insert	**Shape**	**Clearance angle**	**Inscribed circle size**	**Thickness**	**Nose radius**
CNMG120404	Diamond	0°	12.7 mm	4.76 mm	0.4 mm
CNMG120408	Diamond	0°	12.7 mm	4.76 mm	0.8 mm
CNMG120412	Diamond	0°	12.7 mm	4.76 mm	1.2 mm

3.6 PROCEDURE

Considering the basic aim of analysis of turning the material was chosen in the process. The material thus selected was aluminium 6061 which is almost used in every field.

The material was then brought in the desired shape that is 300 mm length and 40 mm diameter, so that the bars could be fitted between the hydraulic chuck and tail stock. For proper holding of work piece in CNC turning machine, centring of work piece is needed to be done. Centring is done on lathe machine with centring tool as shown in figure.

Fig 15 : Lathe machine in Metal cutting Lab, DTU

The specimen thus obtained was then turned on CNC with different cutting parameters (Speed, Feed and Depth of cut) and different nose radius. Program is either entered with the help of edit option or already saved programs are used. After the turning process the surface roughness was measured by the talysurf surtronic 3+. This gave the measurements of the surface roughness and thereby the roughness was measured.

Fig 16 : Working of CNC turning in Metal Cutting Lab, DTU

Figure 17 shows the turning operation performed on aluminium 6061 in CNC turning machine. After, this process results were fed in the minitab software and thus analysis is done and different plots were obtained.

3.7 PROGRAM USED

Mainly this program is used for turning program performed on CNC turning machine. Edit button is used to edit anything in the program. Hence we can edit speed, feed, depth of cut in the same program without writing a complete new program.

```
00001

N010 T0701;

N020 G21 X0.0 Z0.0;

N030 T0707;

N040 G00 X10.0 Z3.0;

N050 G92 M03 S1600 F0.12;

N060 G01 X -0.5;

N070 G99 Z-80.0;

N080 G99 F0.18 Z-160;

N090 G99 F0.24 Z-240;

N100 G00 X80.0;

N110 G00 Z0.0;

N120 M05;

N130 M30;

%
```

Chapter 4 DATA-ANALYSIS

The design table to be used was made by deciding the values of the parameters to be set in the experiment. Namely, the depth of cut, feed rate, speed or rpm and nose radius were set accordingly. The values were defined on basis of the values available in the machine so as to perform the experiment.

PROCESS PARAMETERS AND LEVELS

Table 8 : Process Parameters and Levels used in Experiments

Level	**Variables**			
	Speed, rpm (s)	**Feed, mm/rev (f)**	**Depth of cut, mm (d)**	**Nose radius, mm (n)**
-1	1600	0.12	0.25	0.4
0	1900	0.18	0.50	0.8
1	2200	0.24	0.75	1.2

The values or the factors were thus defined and with help of minitab, the rsm value table was then generated which would set the values or the order of the readings in the experiment.

Central Composite Design

Factors: 4 Replicates: 1
Base runs: 30 Total runs: 30
Base blocks: 3 Total blocks: 3

Two-level factorial: Full factorial

Cube points : 16
Center points in cube : 4
Axial points : 8
Center points in axial : 2
α: 1

Table 9 : Design Table (randomized)

RUN	BLOCK	A	B	C	D
1	3	0	0	0	1
2	3	0	0	0	0
3	3	0	-1	0	0
4	3	-1	0	0	0
5	3	0	0	0	-1
6	3	0	1	0	0
7	3	0	0	0	0
8	3	0	0	1	0
9	3	1	0	0	0
10	3	0	0	-1	0
11	1	1	1	1	-1
12	1	1	1	-1	1
13	1	-1	-1	-1	1
14	1	-1	-1	1	-1
15	1	-1	1	1	1
16	1	1	-1	1	1
17	1	-1	1	-1	-1
18	1	0	0	0	0
19	1	1	-1	-1	-1
20	1	0	0	0	0
21	2	-1	1	-1	1
22	2	0	0	0	0
23	2	-1	1	1	-1
24	2	1	1	-1	-1
25	2	1	1	1	1
26	2	-1	-1	-1	-1
27	2	-1	-1	1	1
28	2	0	0	0	0
29	2	1	-1	-1	1
30	2	1	-1	1	-1

After the process of turning and measuring surface roughness the record table obtained was:

Table 10 : Recorded data during surface roughness after performing CNC turning process

Nos.	Speed(rpm)	Feed(mm/rev)	Depth of cut(mm)	Nose radius(mm)	Roughness(µm)
1	1900	0.18	0.5	1.2	0.92
2	1900	0.18	0.5	0.8	2.86
3	1900	0.12	0.5	0.8	0.8
4	1600	0.18	0.5	0.8	1.56
5	1900	0.18	0.5	0.4	1.76
6	1900	0.24	0.5	0.8	2.48
7	1900	0.18	0.5	0.8	1.46
8	1900	0.18	0.75	0.8	1.4
9	2200	0.18	0.5	0.8	2.92
10	1900	0.18	0.25	0.8	1.38
11	2200	0.24	0.5	0.4	2.3
12	2200	0.24	0.25	1.2	1.95
13	1600	0.12	0.25	1.2	0.6
14	1600	0.12	0.75	0.4	0.94
15	1600	0.24	0.75	1.2	0.6
16	2200	0.12	0.75	1.2	0.92
17	1600	0.24	0.25	0.4	1.56
18	1900	0.18	0.5	0.8	0.96
19	2200	0.12	0.25	0.4	1
20	1900	0.18	0.5	0.8	1.48
21	1600	0.24	0.25	1.2	0.54
22	1900	0.12	0.5	0.8	0.64
23	1600	0.24	0.75	0.4	3.04
24	2200	0.24	0.25	0.4	2.64
25	2200	0.24	0.75	1.2	1.1
26	1600	0.12	0.25	0.4	1.36

27	1600	0.12	0.75	1.2	1
28	1900	0.18	0.5	0.8	1.56
29	2200	0.12	0.25	1.2	1.6
30	2200	0.12	0.75	0.4	1.08

ANALYSIS OF RESULTS AND PLOTS

After performing the experiments, the data was entered into MINITAB ® 17 for further analysis.

Optimal Design: s, f, d, n

Response surface design are selected according to the D-optimality

Number of candidate design points: 30
Number of design points in optimal design: 15

Model terms: A, B, C, D, AA, BB, CC, DD, AB, AC, AD, BC, BD, CD

Initial design generated by Sequential method
Initial design improved by Exchange method
Number of design points exchanged is 1

Optimal Design

Row number of selected design points: 11, 13, 15, 19, 28, 16, 17, 18, 21, 23, 24, 1, 2, 4, 6

Condition number : 10.8640
D-optimality (determinant of XTX) : 3.47892E+11
A-optimality (trace of inv(XTX)) : 5.48611

G-optimality (avg leverage/max leverage) : 1

V-optimality (average leverage) : 1

Maximum leverage : 1

Table 11 : Data Matrix

Run	A	B	C	D
11	2200.00	0.12	0.75	1.20
13	2200.00	0.24	0.25	1.20
15	2200.00	0.24	0.75	0.40
19	1600.00	0.24	0.75	1.20
28	1600.00	0.12	0.25	0.40
16	1600.00	0.12	0.25	1.20
17	1600.00	0.24	0.25	0.40
18	1600.00	0.12	0.75	0.40
21	2200.00	0.12	0.25	1.20
23	2200.00	0.24	0.25	0.40
24	2200.00	0.12	0.75	0.40
1	1900.00	0.18	0.50	0.40
2	1900.00	0.18	0.25	0.80
4	1900.00	0.24	0.50	0.80
6	2200.00	0.18	0.50	0.80

Response Surface Regression: Ra versus s, f, d, n

Stepwise Selection of Terms

α to enter = 0.15, α to remove = 0.15

The stepwise procedure added terms during the procedure in order to maintain a hierarchical model at each step.

Analysis of Variance

Table 12 : Analysis of variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	8.7527	1.45879	9.04	0.000
Linear	4	6.3277	1.58192	9.81	0.000
S	1	1.3566	1.35665	8.41	0.008
F	1	2.2339	2.23390	13.85	0.001
d	1	0.0348	0.03480	0.22	0.647
N	1	2.6971	2.69712	16.72	0.000
2-Way Interaction	2	2.4299	1.21494	7.53	0.003
s*d_1	1	0.9809	0.98091	6.08	0.022
f*n	1	1.2803	1.28027	7.94	0.010
Error	23	3.7097	0.16129		
Lack-of-Fit	18	3.7097	0.20610	*	*
Pure Error	5	0.0000	0.0000		
Total	29	12.4625			

Nose radius has the minimum P-Value, hence it is found to be the most influential parameter affecting the surface roughness among all the four parameters.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.401614	70.23%	62.47%	45.69%

After regression analysis we got the regression equation for surface roughness:-

Regression Equation in Uncoded Units

Initial equation:

$$r = -0.021s + 31.2735f + 6.77d + 3.29n - 74.01f^2 - 1.95d^2 - 2.43n^2 + 0.0051s*f - 0.0024s*d + 0.0014s*n + 5.52f*d - 13.049f*n - 1.39d*n + 15.3914$$

Improved equation:

$$r = -0.01s + 51.61f + 10.41d - 1.08n - 98.56f^2 + 4.322d^2 - 0.0027s*d + 0.00160s*n - 12.29f*n - 1.190d*n$$

RESIDUAL PLOT

The design was then set and the graphs were obtained between different values depending upon the required values and considerations.

Residual plots: The difference between the fitted value ($\hat{y}$) and its corresponding observed value (y) is called the residual and the plot of the variable with the fitted value is called residual plot.

Residual Plots for Ra

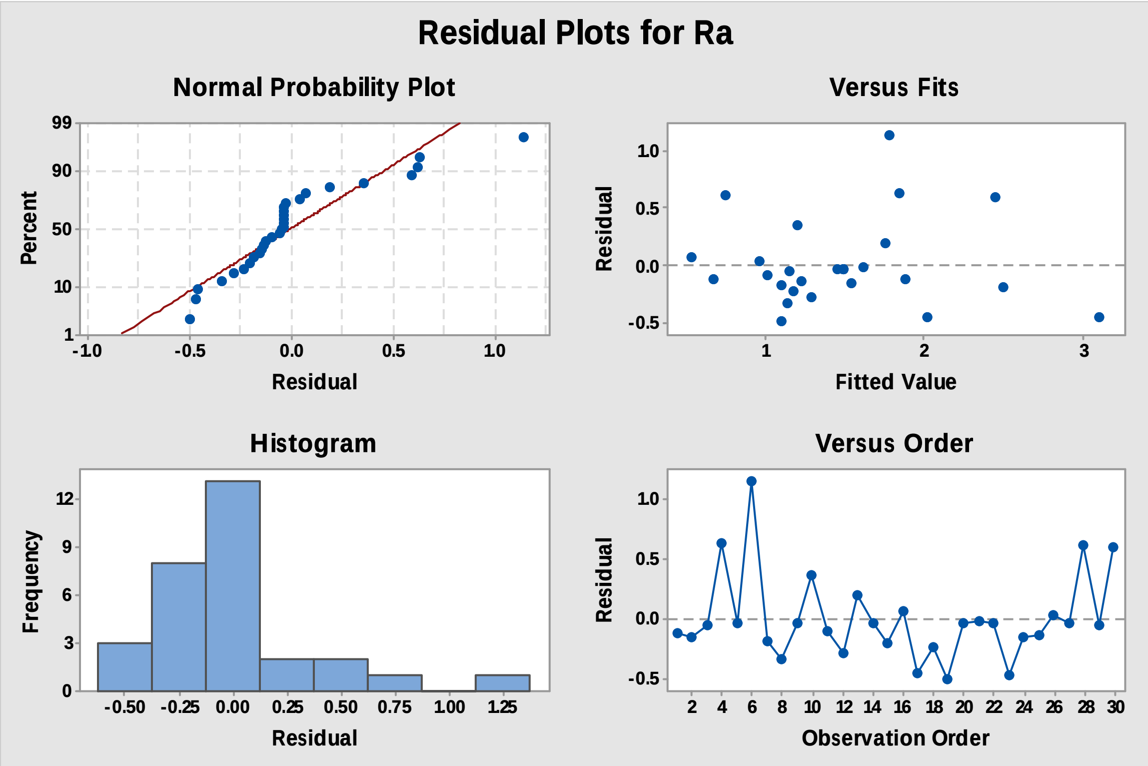

Fig 17 : Residual Plots for Ra

The model is adequate as represented by the points falling on a straight line in the normal probability plot. It denotes that the errors are normally distributed. Also, the plot of the residuals versus the predicted response is structure less i.e. containing no obvious pattern. With the help of histogram it can be easily seen that the residual are neatly in range of -0.25 to 0.00 which is very small so it is a good sign of controlled responses.

Interaction plots:

When a single factor depends upon the level of the other factors, Then the dependency can be seen easily or visualized possibly by the interaction plots

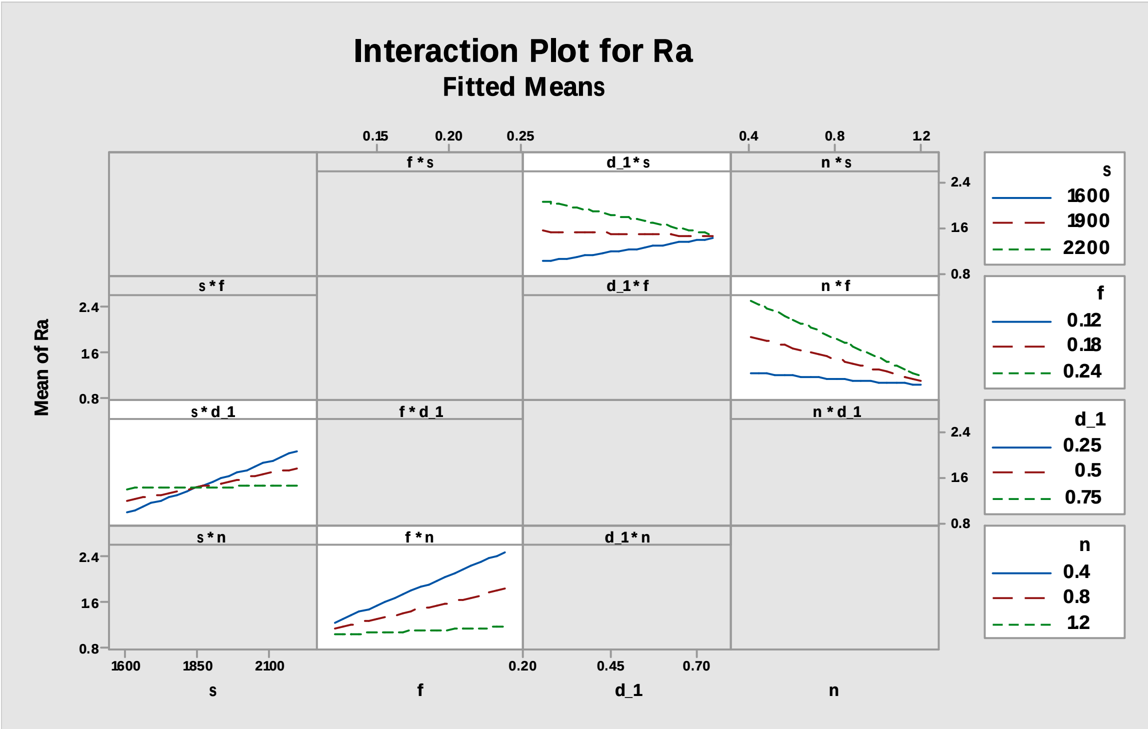

Fig 18 : Interaction Plot for Ra(Fitted means)

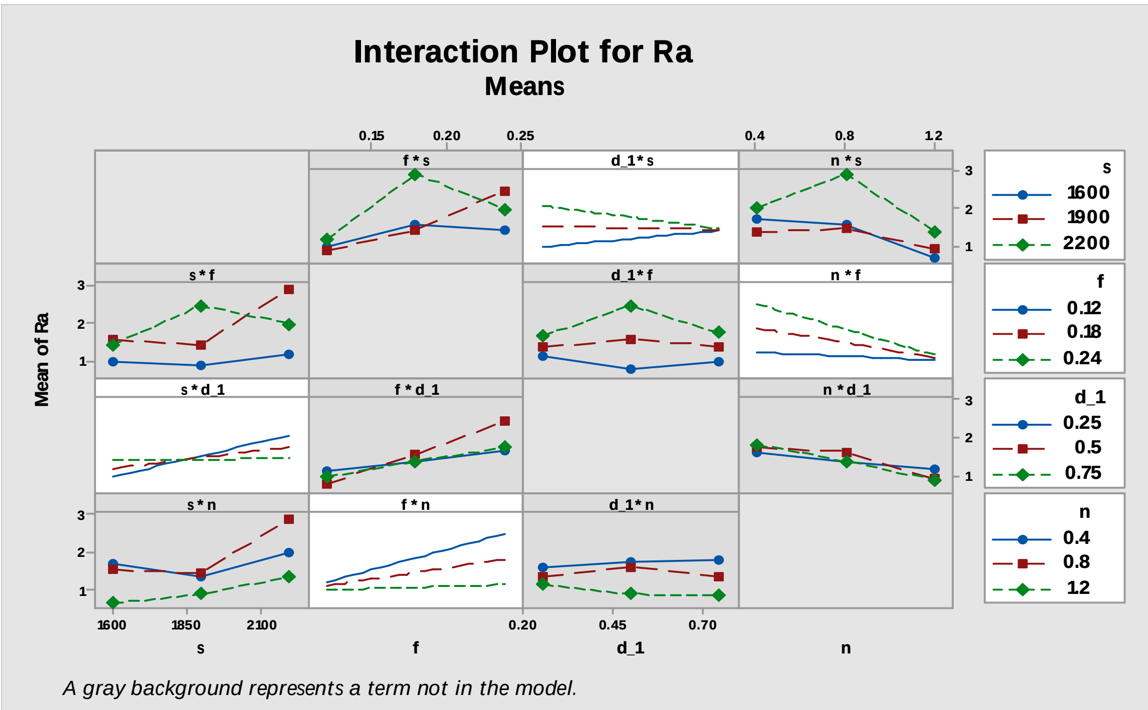

Fig 19 : Intraction plot for Ra(Means)

Main Effects Plot for Ra

A main effect is accessible when different levels of a factor influence the response factor distinctively and freely. In main effect graphs, the response factor mean or average for each factor level is connected by a line.

Patterns needed to be checked are :

When the line is parallel to the x-axis, then no main effect present in the graph. Every level of the factor influence the response in the same way, and the response mean is the same over all factor levels.

When the line is inclined to X-axis, then main effect is present there. Distinct levels of the factor affect the response distinctively. The more steeper the slope of the line, the more prominent the magnitude of the main effect.

The figure shows the variation with respect to the fitted mean.

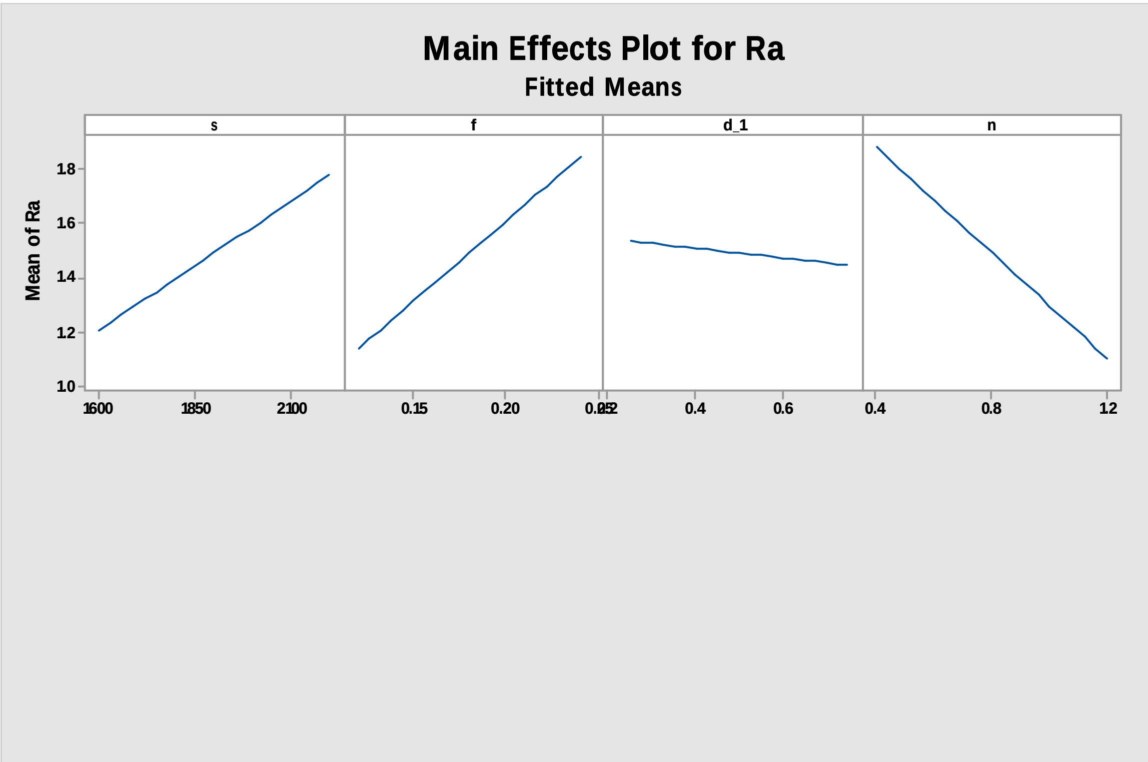

Fig 20 :Main Effects Plot for Ra(Fitted Means)

From this plot it can be clearly stated that with increase in speed(rpm) and feed rate the value of surface roughness is also increasing whereas it is nearly independent of depth of cut. With increasing nose radius the value of surface roughness is improved to a large extent.

The figure shows the vaiation with respect to the data means.

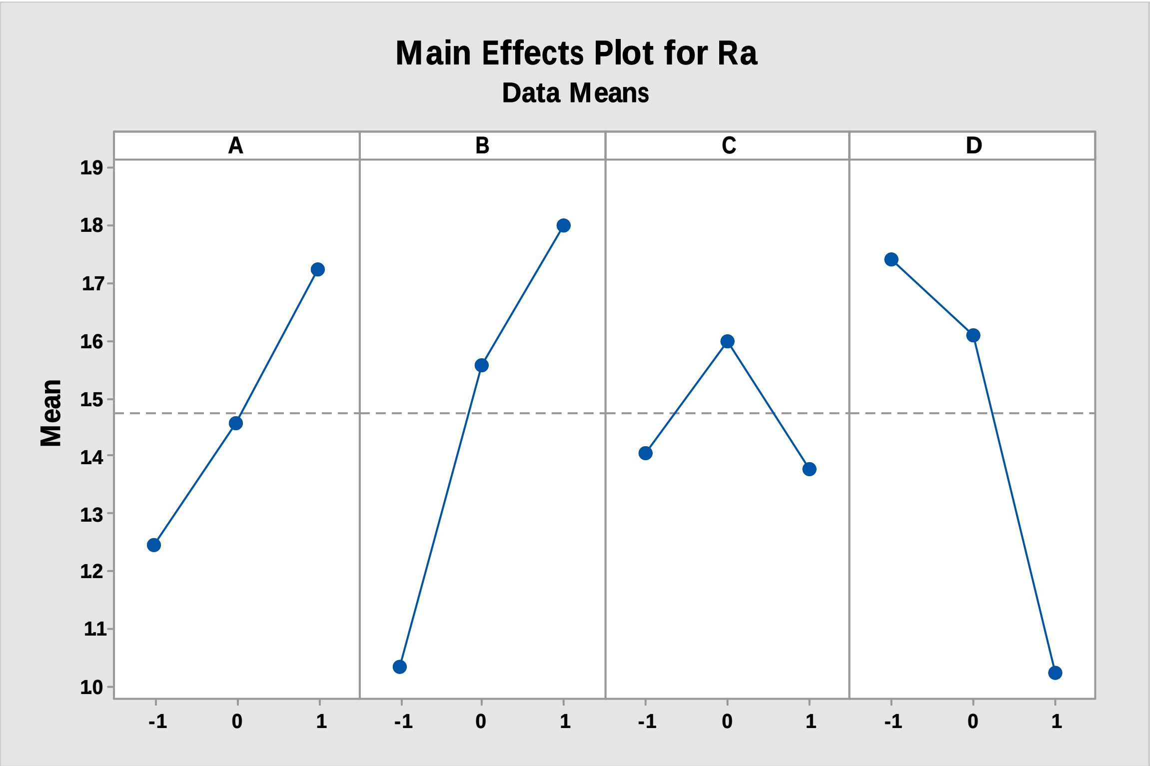

Fig 21 : Main Effects Plot for Ra(Data Means)

The above figure 22 shows the mean value of roughness at different levels of parameters selected. This plot shows that:

- With increase in speed, the value surface roughness also increases and the speed selected are 1600 rpm, 1900 rpm and 2200 rpm.
- With increase in feed, the value of surface roughness also increases and the feed selected are 0.12 mm, 0.18 mm and 0.24 mm.
- the value of surface roughness increases when the depth of cut is increased from 0.25 mm to 0.50 mm and it decreases when it is further increased to 0.75 mm.
- with increasing nose radius the value of surface roughness is decreased means surface quality is improved and nose radius selected are 0.4 mm, 0.8 mm and 1.2 mm.

CONTOUR PLOTS AND 3- D SURFACE PLOTS

Contour plot:

A contour graph is like a topographical map in which z-, y-, and x-values are plotted in place of latitude, elevation and longitude.

Surface plots:

3D surface graph shows the 3-D relationship in two dimensions, with independent variables on the x- and y-scales, and the response (z) or the desired variable is represented by a smooth surface (surface plot) or a grid (wireframe plot).

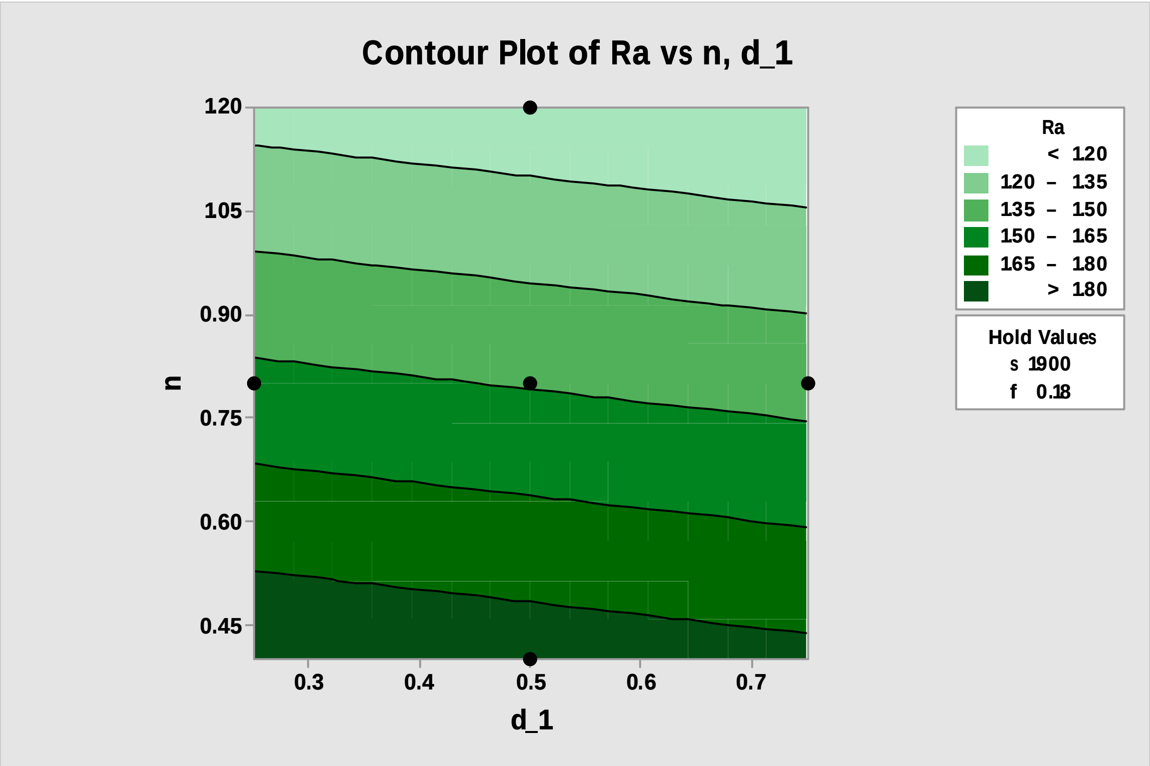

Fig 22 : Contour Plot for Ra vs n, d

It can be clearly stated from the plot shown in figure that the value of surface roughness is increasing with increasing nose radius and is nearly independent of depth of cut in the specified range.

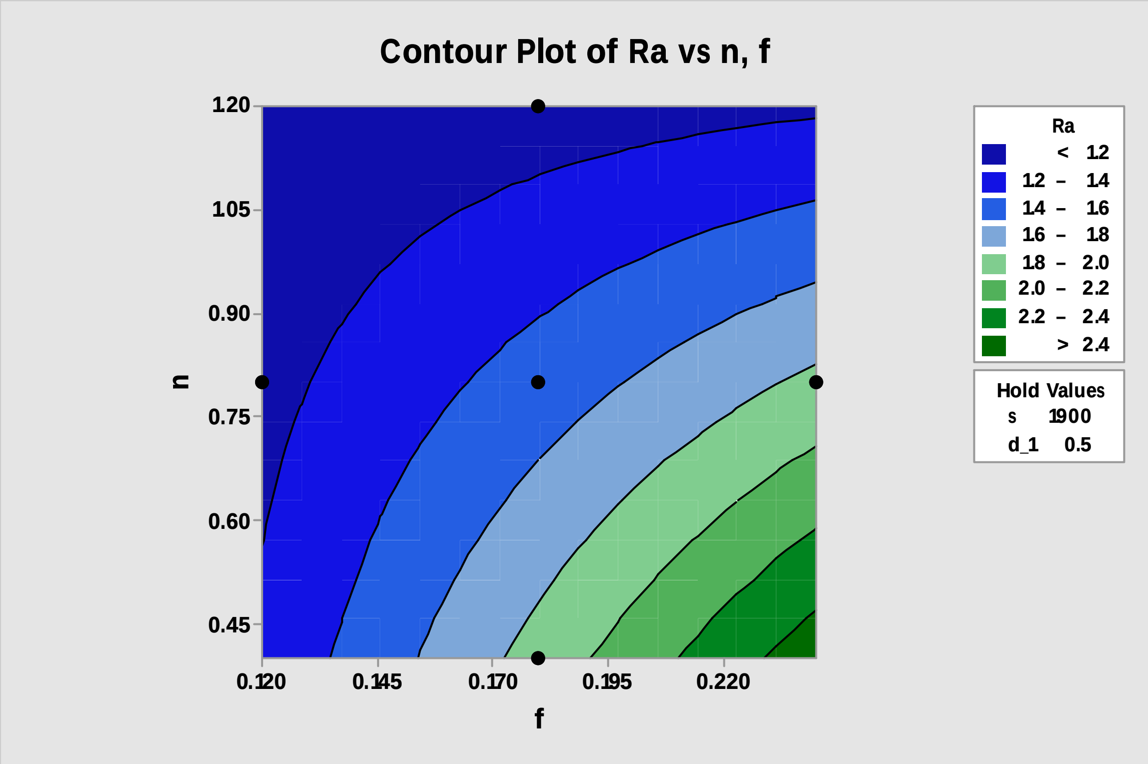

Fig 23 : Contour Plot for Ra vs n, f

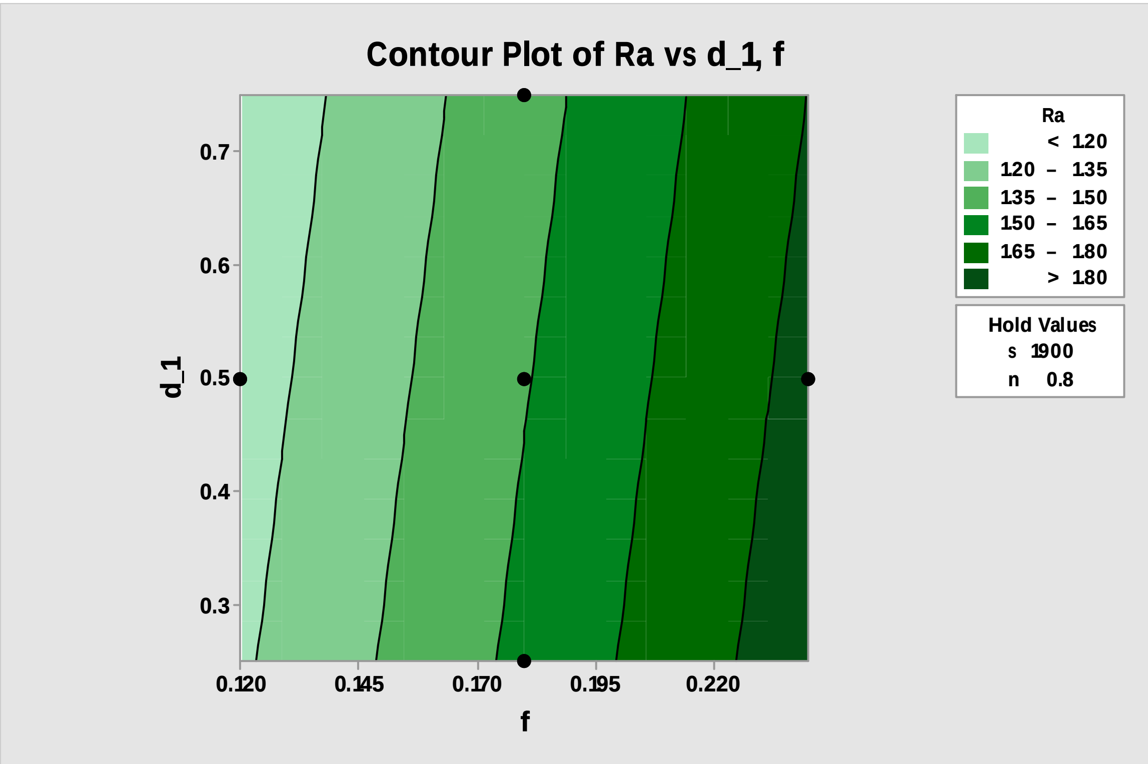

Fig 24 : Contour Plot for Ra vs d, f

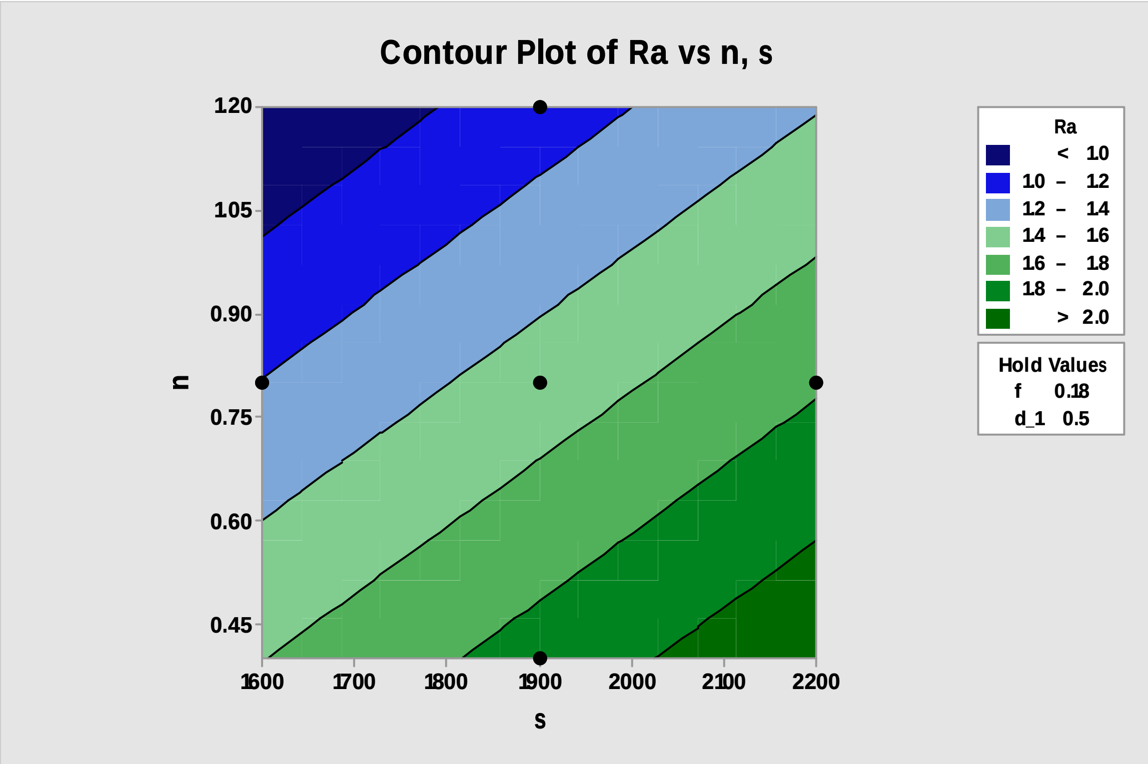

Fig 25 :Contour Plot of Ra vs n, s

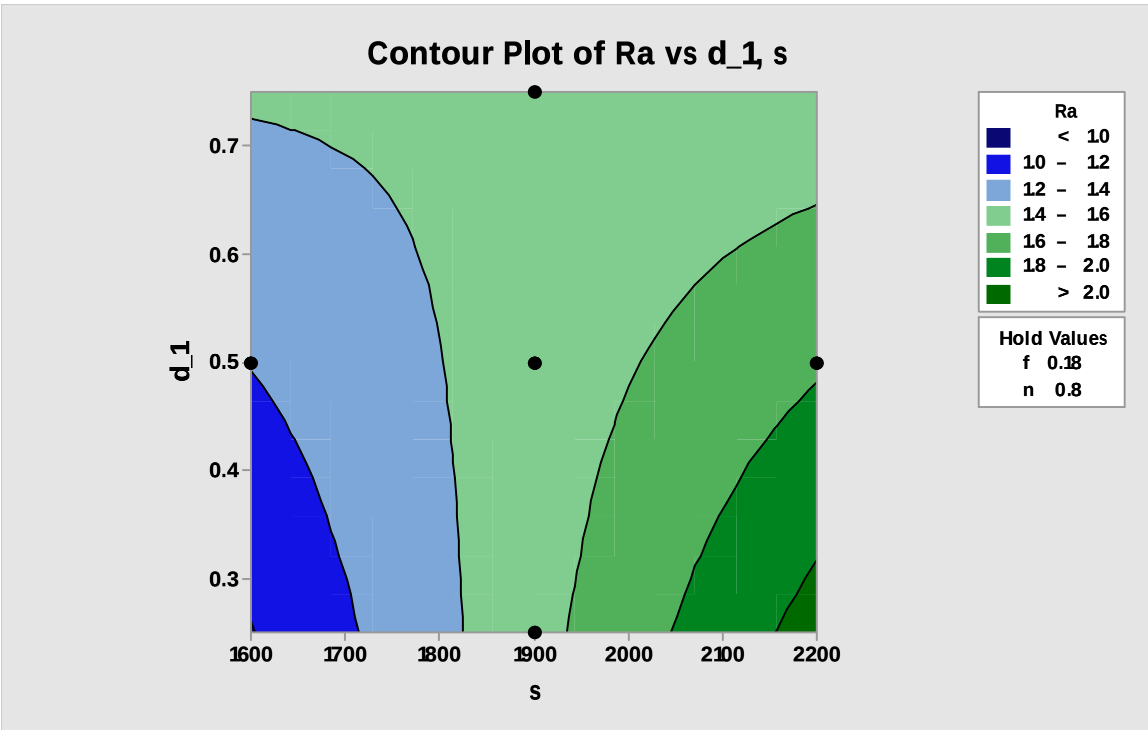

Fig 26 : Contour Plot of Ra vs d, s

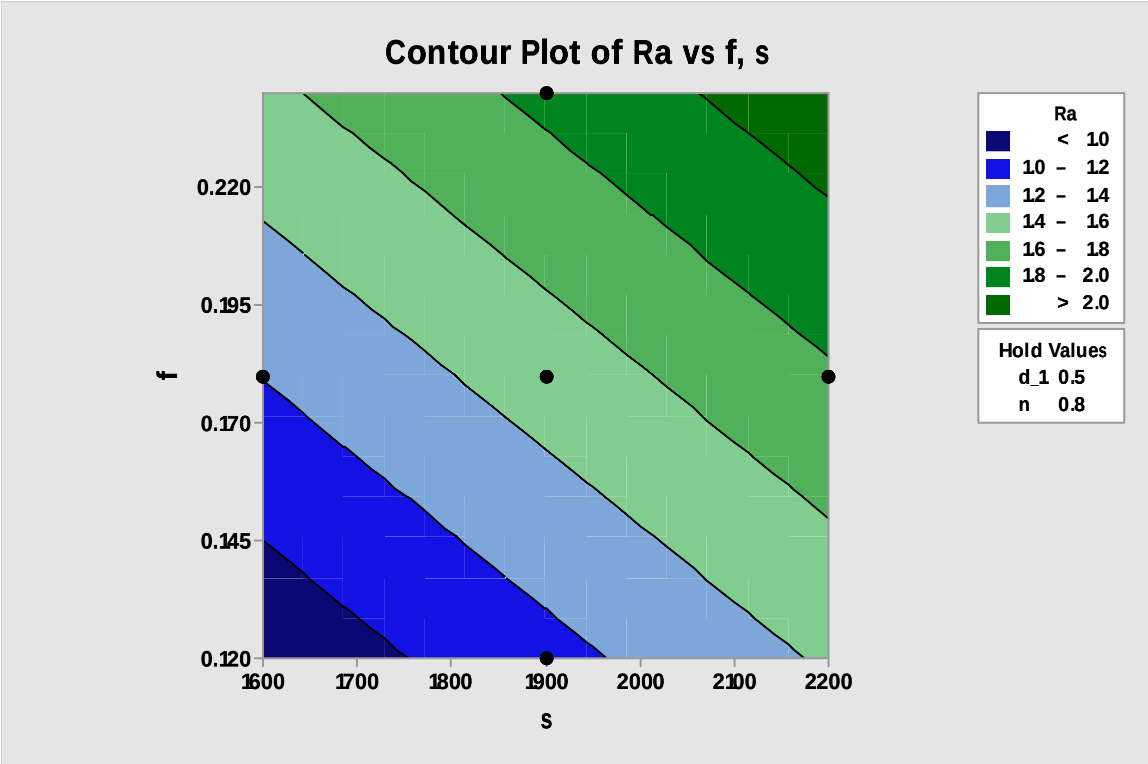

Fig 27 : Contour Plot of Ra vs f, s

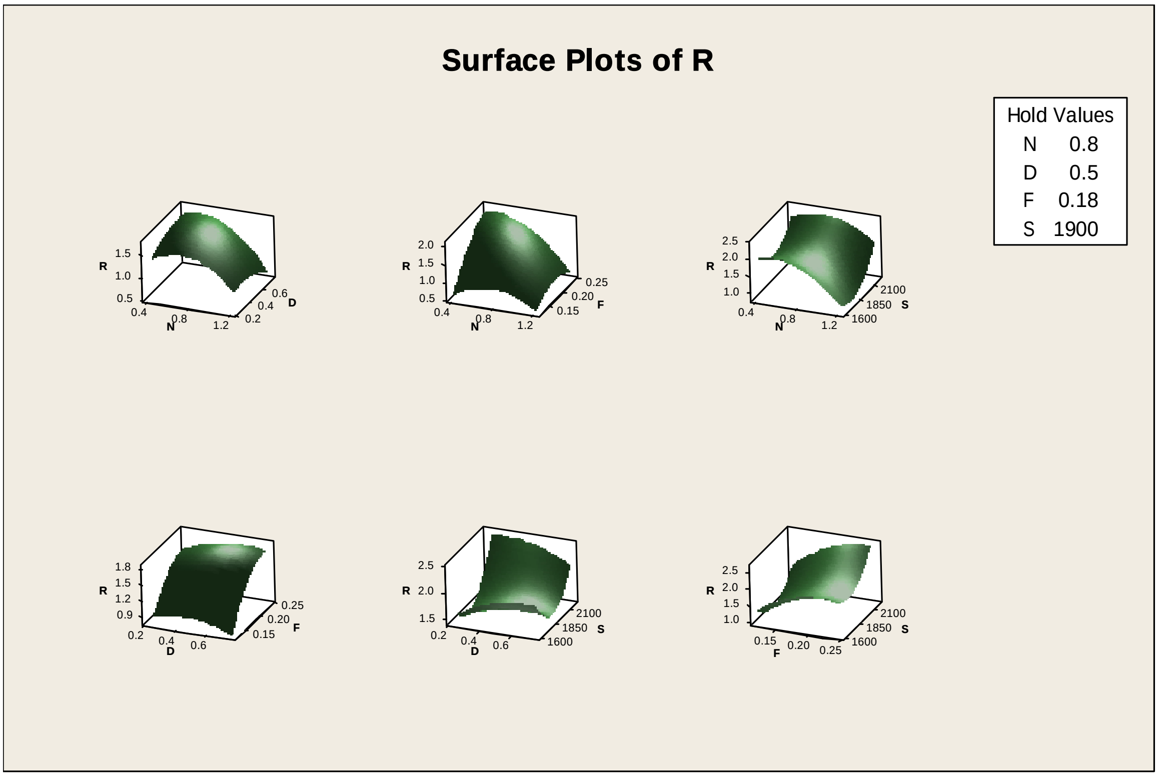

Fig 28 : Surface plot of R

It can be effortlessly comprehended from the plot shown in figure 23 that how the value of surface roughness is varying with respect to nose radius and feed rate. If we fix the nose radius and vary feed rate then value of roughness increases with increase in feed rate. Similarly if we fix feed rate and vary nose radius then it is clearly seen that the value of surface roughness decreases with increasing nose radius.

It can be clearly seen from the plot shown in figure 24 that how the value of surface roughness is varying with respect to depth of cut and feed rate. If we fix the depth of cut and vary feed rate then the value of roughness increases with increase in feed rate. Similarly if we fix feed rate and vary depth of cut then it is clearly seen that the value of surface roughness slightly increases or can be treated as independent with increasing depth of cut.

It can be clearly explained from the plot shown in figure 25 that how the value of roughness is varying with respect to nose radius and speed. If we fix the nose radius and vary speed then the value of roughness increases with increase in speed. Similarly if we fix speed and vary nose radius then it is clearly seen that the value of surface roughness decreases with increasing nose radius.

It can be effortlessly comprehended from the plot shown in figure 26 that how the value of roughness is varying with respect to depth of cut and speed. If we fix the depth of cut and vary speed then the value of roughness increases with increase in speed. Similarly if we fix speed and vary depth of cut then it is clearly seen that the value of surface roughness decreases slightly (or can be considered as independent) with increasing depth of cut.

It can be easily understood from the plot shown in figure 27 that how the value of roughness is varying with respect to speed and feed rate. If we fix the speed and vary feed rate then the value of roughness increases with increase in feed rate. similarly if we fix feed rate and vary speed then it is clearly seen that the value of surface roughness increases with increasing speed.

The surface plot of R shown in the figure 28 gives clear 3-D pictorial representation in variation of surface roughness with respect to any two selected between speed, feed rate and depth of cut. It can be stated from the plot that the value of surface roughness increases with increase in speed or feed rate and the value of surface roughness is nearly independent of depth of cut, whereas surface finish is improved by increasing nose radius of tool.

Optimisation plot

The optimal plot behaves as the reference for the graph — it can be modified for the settings interactively to obtain different responses. For the factorial and response surface designs, it is possible to adjust the factor levels. The reasons to change the selected input variables setting on the optimisation plot are specified below :

1. To find the input variables setting such that it has higher composite (user-defined) desirability
2. To generate near optimal properties with lower-cost input variable to save prorduction cost
3. To explore the sensitivity of response variables to changes in the design variables
4. To evaluate the predicted responses for any given set of input variable.
5. To develope new input variable settings around the neighborhood of a local solution

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Ra	Minimum	-	0.54	3.04	1	1

Solution:-

Solution	s	F	d_1	N	Ra fit	Composite Desirability
1	1600	0.12	0.25	1.2	0.533373	1

Optimization Plot (Minimise)

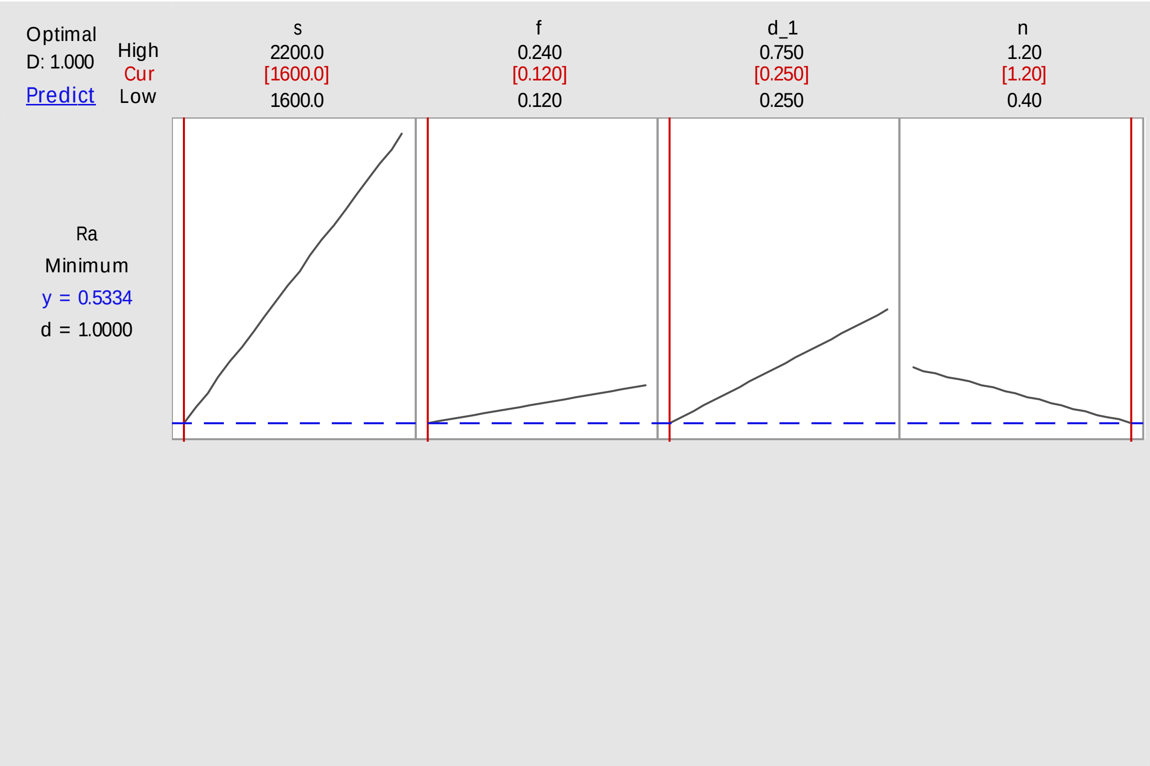

Fig 29 : Optimisation plot for desired value

Optimisation plot shown in figure 29 clearly indicates speed, feed, depth of cut and nose radius to achieve minimum value of surface roughness. Minimum of speed, feed and depth of cut selected whereas maximum of nose radius is selected for minimum surface roughness.

Chapter 5 CONCLUSION

In this project various research papers were studied and it was assessed that the surface roughness depended upon various cutting parameters as well as tool geometry(rake angle).
RSM was adopted to be used as the optimization technique so that the focused parameters could be obtained in a much better and comprehensive way in the process Anova and Taguchi were taken in consideration but due to the ability of RSM to control the surface parameters and also the ability to have a second order fitting curve the RSM was chosen to bring the optimality in the system.
The conclusions which have been drawn on the basis of results obtained and analysis performed are :

- CNC Turning always gives better results, as in CNC any value of speed, feed and depth of cut can be selected within a specified range, according to the requirement, compared with a conventional machine in which only some fixed values can be selected.
- Better results have been obtained in terms of DOE techniques such as ANOVA and RSM using MINITAB software.
- The average surface roughness value decrease with increase in Nose Radius. Hence, increasing nose radius improves surface finish.
- Increase in cutting speed deteriorate the surface finish, thus the average surface roughness value increases.
- Increase in depth of cut affects the surface finish adversely to a small extent.
- Small increase in feed rate deteriorates surface finish to a large extent.
- Empirical models for surface roughness has been determined based on which predictions can be carried out for output response for appropriate applications.
- ANOVA and F-tests reveal that the feed is dominant parameter followed by other parameters for surface roughness.
- The regression equation obtained after analysis of variance is

  Initial equation

$$r = -0.021s + 31.2735f + 6.77d + 3.29n - 74.01f^2 - 1.95d^2 - 2.43n^2 + 0.0051s * f - 0.0024s * d + 0.0014s * n + 5.52f * d - 13.049f * n - 1.39d * n + 15.3914$$

Improved eq:

$$r = -0.01s + 51.61f + 10.41d - 1.08n - 98.56f^2 + 4.322d^2 - 0.0027s*d + 0.00160s*n - 12.29f*n - 1.190d*n$$

- The opimisation plot for minimizing surface roughness gives the value of speed (1600 rpm), feed (0.12 mm/rev), depth of cut (0.25 mm) and nose radius (1.2 mm). The value of surface roughness will be minimum at the above specified values.

SCOPE FOR FUTURE STUDY

- Tool wear could be studied in the future to the same tool-work combination for the same domain of cutting parameters as chosen in the present study and its effects could be studied and analysed.

- Another improvement that can be made to the present study is that cutting forces could be added as an output response in addition to surface roughness. An attempt can then be made to find out optimum machining parameters so that multiple variables can be optimized via a single experimental trial.
- Mist application of cutting fluid could be applied in the future to the same tool-work combination for the same domain of cutting parameters as chosen in the present study and its effects on the surface roughness could be studied and analysed.

- Furthermore, other tool geometry parameter like rake angle, relief angle,etc, its effects on the output responses could be analysed in order to increase the effectiveness of the fitted model.

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APPENDIX A

Table 1 : General codes used in cnc programming

CODE	CATEGORY	FUNCTION
G00	Motion	Motion in a straight line at rapid speed
G01	Motion	Move in a straight line at last speed in a specified feed rate
G02	Motion	Clockwise circular arc at feed rate
G03	Motion	Counter clockwise circular arc at feed rate
G04	Motion	Dwell: Stop for a specified time
G17	Coordinate	Select X-Y plane
G18	Coordinate	Select X-Z plane
G19	Coordinate	Select Y-Z plane
G20	Coordinate	Program coordinates are inches
G21	Coordinate	Program coordinates are mm
G40	Compensation	Tool cutter compensation off(radius comp.)
G41	Compensation	Tool cutter compensation left(radius comp.)
G42	Compensation	Tool cutter compensation right(radius comp.)
G43	Compensation	Apply Tool length compensation(plus)
G44	Compensation	Apply Tool cutter compensation(minus)
G49	Compensation	Tool length compensation cancel
G70	Canned	Finish turning cycle
G71	Canned	Rough turning cycle
G90	Coordinate	Absolute programming of XYZ
G91	Coordinate	Incremental programming og XYZ
G92	Motion	Thread cutting cycle
G98	Motion	Linear feed rate per unit time
G99	Motion	Feed rate per revolution

Table 2 : Miscellaneous codes used in cnc programming

CODE	CATEGORY	FUNCTION
M00	M-Code	Program stop(non optional)
M01	M-Code	Optional stop: operator select to enable
M02	M-Code	End of program
M03	M-Code	Spindle on(CW rotation)
M04	M-Code	Spindle on(CCW rotation)
M05	M-Code	Spindle stop
M06	M-Code	Tool change
M07	M-Code	Mist coolant ON
M08	M-Code	Flood coolant ON
M09	M-Code	Coolant OFF
M13	M-Code	Spindle on(CW rotation) + Coolant ON
M14	M-Code	Spindle on(CCW rotation) + Coolant ON
M30	M-Code	End of program, rewind and reset modes