# Taguchi Based Experimental Studies on Surface Roughness and Burr Formation during End Milling of Inconel 718

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*Abstract* - **High quality and productivity are two important but major criteria in several machining operations. End milling process operated by CNC is a widely accepted material removal process used to manufacture components with complicated shapes and profiles. Nickel based super alloy, Inconel 718 is a very hard material (48 HRC). Because of its hardness, work hardening and low thermal conductivity, machining is very difficult. Since machining is basically a finishing process with specified dimensions, tolerances and surface finish, the type of surface that a machining operation generates and its characteristics are of great importance in manufacturing.**

**Effects of numerous parameters of end milling process like cutting speed, depth of cut, feed rate have been examined to reveal their impact on surface finish using Taguchi Methodology. In the present experimental study, effect of cutting conditions such as cutting speed, feed rate and depth of cut on the milling ability of Incone1 718 is discussed. Workpiece surface roughness and burr formation while end milling is carried out using a CNC milling machine. Results indicate that the cutting speed and feed rate, play a significant role in determining the surface roughness and burr size when end milling of Inconel 718.**

*Keywords: Inconel 718, End milling, Surface roughness, Burr size*

## I. INTRODUCTION

EVERY DAY scientists are developing new materials and for each new material, need economical and efficient machining process. The main objective of industries are producing better quality products at minimum cost and enhance productivity. CNC milling is most commonly used in industry and machine shops for machining parts to precise sizes and shapes with desired surface quality and higher productivity within less time and cost. High quality and productivity are two important but major criteria in several machining operations.

End milling process operated by CNC is a widely accepted material-removal process used to manufacture components with complicated shapes and profiles. Nickel based super alloy, Inconel 718 is a very hard material (48 HRC). Because of its hardness, work hardening and low thermal conductivity, machining is very difficult. In that, the alloying element Niobium imparts enlarged strength without decrease in ductility. It can withstand wide temperature range from –220º to 780ºC, therefore it is used in cryogenic tankage. It has high oxidation resistance, corrosion resistance even at high temperatures and possesses high mechanical strength.

Inconel 718 is widely used in aircraft gas turbine, reciprocating engines, space vehicles (*e.g.*, rocket engine parts), nuclear power plants, chemical application, high temperature fasteners, springs, rings and pulp and paper industry [5]. Since machining is basically a finishing process with specified dimensions, tolerances and surface finish, the type of surface that a machining operation generates and its characteristics are of great importance in manufacturing. End milling is an effective method for making key ways of Inconel 718. Here, the material is removed by parent material from the end mill cutter. Effects of numerous parameters of end milling process like cutting speed, depth of cut, feed rate have been examined to reveal their impact on surface finish using Taguchi Methodology.

## II. REVIEW OF LITERATURE

Numerous researchers worked on machinability possibilities of Inconel 718 using Taguchi method. Some of their works are discussed in the present study.

Prajapati *et al*. [1] suggested CNC milling as one of the most commonly used in industry and machine shops today for machining parts to precise sizes and shapes. For analysis, input parameters like feed rate, spindle speed and depth-of-cut are selected as control factors in Taguchi technique of response variable optimization keeping operating chamber temperature and the usage of different tool inserts constant. Product quality in terms of Surface roughness and productivity as material removal rate is measured. An orthogonal array of L9 was used and Analysis of Variance, ANAOVA were performed to find out the significance of each of the input parameters on the Surface roughness and material removal rate.

Amit joshi *et al.* [2] reported that CNC End milling is a unique adaption of the conventional milling process which uses an end mill tool for the machining process. Here, the material is removed by the end mill cutter. Effects of various parameters of end milling process like spindle speed, depth-of-cut, feed rate have been investigated to reveal their impact on surface finish using Taguchi Methodology. Experimental plan is performed by a Standard Orthogonal Array. The results of analysis of variance (ANOVA) indicate that the cutting speed is most influencing factor for modeling surface finish. The graph of S-N Ratio indicates optimal setting of the machining parameters which gives the optimum value of surface finish. The optimal set of process parameters has also been predicted to maximize the surface finish and concluded from the graph of S-N ratio.

Yung-Kuang Yang *et al*. [3] investigated using the designs-of-experiments approach to optimize parameters of a CNC in end milling for high-purity graphite under dry machining. Planning of experiment was based on a Taguchi orthogonal array table. The analysis of variance (ANOVA) was adapted to identify the most influential factors on the CNC end milling process. Simultaneously, applying regression analysis a mathematical predictive model for predictions of the groove difference and the roughness average has been developed in terms of cutting speed, feed rate, and depth-of-cut. The feed rate is found to be the most significant factor affecting the groove difference.

Kuram *et al.* and Lahane *et al*. [6, 7] investigated the effects of cutting parameters on MRR and surface roughness during hard turning of Inconel 718 material by taking into account the Taguchi method. Karidkar *et al.* [9] discussed about utilization of Wire Electrical Discharge Machining (WEDM) technology, which is challenging for modern manufacturing industries to fulfill the customers' need using Inconel 718. Manohar *et al*. [10] used Box Behnken design approach to plan the experiments for turning Inconel 718 alloy with an overall objective of optimizing the process to yield higher metal removal, better surface quality and lower cutting forces using Response Surface methodology (RSM). Janos *et al*. [11] described milling possibilities of nickel alloy Inconel 718. In the beginning, the authors described the use of nickel alloys in industry and division of nickel alloys. Also, they discussed tests of machinability by recommended cutting materials for nickel alloys in milling. Shokrani *et al*. [12] reported a novel hybrid cryogenic and MQL (CryoMQL) cooling technique used for CNC milling of age hardened Inconel 718. The analysis indicated that using the proposed hybrid CryoMQL cooling/lubricating system can almost double the tool life and improve surface roughness by 18% resulting in significant improvement in machinability of Inconel 718. Nitin *et al.* [13] focused on estimating the optimal machining parameters required for photochemical machining (PCM) of an Inconel 718 and effects of these parameters on surface topology. An experimental analysis was carried out to identify optimal values of parameters using ferric chloride ($FeCl_3$) as an etchant using Taguchi $L_{27}$ orthogonal array.

Lu *et al.* [14] conducted experiments based on center composite rotatable design (CCRD). The cutting parameters considered are depth of cut, spindle speed and feed rate. Statistical methods, Analysis of Variance (ANOVA), are used to analyse the adequacy of the predictive model. The influence of depth-of-cut on surface roughness in micro-milling found to be the critical influence factor. At last, the parameters interaction on surface roughness of micro-milling Inconel 718 is discussed by graphical means through MATLAB. Borse *et al.* [15] studied effect of laser process parameters on the quality of the features obtained by laser milling operation on Inconel 718. Rahman *et al.* [16] discussed the effect of cutting conditions on the machinability of Incone1 718.

Extensive past researches were concerned with surface integrity and chip formation during machining. Therefore it is important to understand how the change of cutting speed affects the surface integrity in Inconel 718 alloy machining. In the present study, the effects of controllable cutting parameters (cutting speed, feed rate and depth of cut) on the surface roughness and burr formation during end milling of Inconel 718 have been investigated. The design of experiments was selected from Taguchi's L9 orthogonal array. Subsequent to the experiments, the effect of input parameters on output responses such as surface roughness and burr formation has been analyzed.

## III. SELECTION OF MATERIAL AND TOOL

The workpiece material used in the present study is Inconel 718 super alloy with an average material hardness of 48 HRC. Microstructure of Inconel 718 consists of austenite FCC matrix and can be strengthened by solid solution strengthening (Mo, Cr) and precipitation hardening (Ti, Nb, Al) by forming intermetallic phases. The specification of cutting insert and tool holder is CNMG 1204 08-MS-KC5525 and PCLNR 2020K12, respectively. Chemical composition and mechanical properties are depicted in Table 1 and Table 2.

TABLE 1–NOMINAL COMPOSITION OF INCONEL 718

| Elements | Ni | Cr | Cb | Mo | Ti | Al | Co | Si | Mn | Cu | C | P | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % of weight | 53.4 | 18.8 | 5.27 | 2.99 | 1.02 | 0.5 | 0.17 | 0.12 | 0.07 | 0.07 | 0.03 | 0.01 | Bal |

TABLE 2–PROPERTIES OF NICKEL ALLOY 718

| | |
|---|---|
| *Physical Properties* | Metric |
| Density | 8.19 g/cc |
| *Mechanical Properties* | |
| Tensile Strength, Ultimate | 1375 MPa |
| Tensile Strength, Yield | 1100 MPa |
| Elongation at Break | 25 % |
| *Thermal Properties* | |
| Specific Heat Capacity | 0.435 J/g-°C |
| Thermal Conductivity | 11.4 W/m-K |
| Melting Point | 1260 - 1336 °C |

## IV. EXPERIMENTATION AS PER TAGUCHI DESIGN METHOD

A plan of experiments based on Taguchi technique has been used to acquire the data. An orthogonal array, signal to noise (S/N) ratio and ANOVA are employed to investigate the cutting characteristics of Inconel 718 material using K10 carbide end mill. Finally, confirmation tests have been carried out to compare the predicted values with the experimental values to confirm its effectiveness in the analysis of surface roughness and chip thickness. The orthogonal array forms the basis for experimental analysis in the Taguchi method. The selection of orthogonal array is concerned with the total degree of freedom (DOF) of process parameters. DOF associated with three parameters is equal to 6 (3x2). DOF for the orthogonal array should be greater than or at least equal to that of the process parameters. Thereby, a L9 orthogonal array having degree of freedom equal to (9–1= 8) 8 has been considered.

In this study, the experiments are carried out on a CNC vertical machining center (KENT and ND Co. Ltd, Taiwan make) to perform 10 mm slots on Inconel 718 super alloy work piece by K10 carbide, four flute-end milling cutter as shown in Fig.1. Furthermore the cutting speed (A, rpm), the feed rate (B, mm/rev) and depth of cut (C, mm) are regulated in this experiment. Each experiment was conducted three times and the burrs are measured in mm using profile projector which are shown in Fig.6. Finally surface roughness is measured at five places on each slot and their average in μm is considered by a surface analyzer of Surf Test-211 series (Mitutoyo) shown in Fig 7.

Figure 1 (*b*) K10 Carbide 4 Flute Milling cutter.

Figure 1 (*a*). Experimental setup (CNC Vertical Machining Center, Kent India Co, Ltd, Taiwan).

## V. BURR FORMATION

An unwanted projection of material formed during machining, termed as *burr* is a part size error (Fig.4). Burr is plastically deformed material, generated on the part edge during cutting. Removal of burr is essential for any component to avoid damage of component after assembling due to abrasion, injuring workers while assembly and other related problems. So elimination of burr is mandatory which involves some cost, literally known as *deburring cost*.


Figure 2. Measurement of surface roughness using Surf Test-211 series (Mitutoyo).

Figure 3. Profile projector for measuring burr size.

Figure 4. Work piece before deburring.


Figure 5. Work piece after deburring.

The problem of deburring and edge quality (EQ) in the manufacturing environment is directly linked to the final use of the component [3,4]. The EQ is a function of the part design and is only necessary to edge finish within the design limits. To estimate cost of deburring and edge finishing operations certain standard procedure, human resources and extra machining time are required. If such straight forward EQ standards are available, then find out expenses over post processing operations. This cost is now added value to the manufacturing cost, so the burr must be minimized to save money and to reduce manufacturing lead time. In the present study, after experimentation burr height and thickness are measured using profile projector, then burrs are removed from the work piece by filing operation and obtained finished work piece shown in Fig. 5. The finished (after deburring) workpiece is taken out for measuring surface finish using surftest SJ211. The measured data is depicted in Table 4.

Table 3–Factors and Their Levels

| LEVELS | Rotational speed (A, rpm) | Depth of Cut (B, mm) | Feed Rate (C, mm/rev) |
|---|---|---|---|
| 1 | 1000 | 0.75 | 0.06 |
| 2 | 1500 | 1.00 | 0.09 |
| 3 | 2000 | 1.50 | 0.12 |

## VI. RESULTS AND DISCUSSION

The data obtained from experimentation is analyzed for hypothesis testing, whether considered factors for conducting experiments as per Taguchi design method are influenced or not over the output responses statistical methods are required. To identify this ANOVA is conducted using Minitab@18 design of experiments software. Main effects, interaction effect plots are obtained, which is helpful to discuss about influence of input factor on output parameters considered during end milling. Both surface roughness and burr size are minimum requirement, so smaller the better case considered for S/N ratio under the Taguchi method and obtained A2B3C1 order of preference of level of input parameters to attained optimum values of responses. Signal-to-noise (S/N) ratios for each level of process parameters are computed. Optimum setting of the process parameters contributes the minimization of the effect of noise. It means that the level of process parameters with the highest S/N ratio corresponds to the optimum level of process parameters. For smaller the better case, S/N ratio is given by

$$(S/N)_{LB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}(y_i^2)\right]$$

where, $y_i$ = experimental value in the i th test

$y_0$ = target value and

$n$ = number of replications

TABLE 4–TAGUCHI $L_9$ ORTHOGONAL ARRAY PLAN AND MEASURED RESPONSES

| Rotational speed (A, rpm) | Depth of Cut (B, mm) | Feed Rate (C, mm/rev) | Burr Height (Bh, mm) | Burr Thickness (Bt, mm) | Surface Roughness (Ra, µm) | S/N Ratio |
|---|---|---|---|---|---|---|
| 1000 | 0.75 | 0.06 | 5.75 | 0.22 | 5.86 | -13.5186 |
| 1000 | 1.00 | 0.09 | 8.75 | 0.24 | 6.07 | -15.7774 |
| 1000 | 1.50 | 0.12 | 5.90 | 0.26 | 4.54 | -12.6709 |
| 1500 | 0.75 | 0.09 | 9.00 | 0.34 | 7.05 | -16.3955 |
| 1500 | 1.00 | 0.12 | 3.50 | 0.48 | 0.43 | -6.2549 |
| 1500 | 1.50 | 0.6 | 8.00 | 0.66 | 0.69 | -13.3520 |
| 2000 | 0.75 | 0.12 | 2.50 | 0.36 | 0.99 | -3.8974 |
| 2000 | 1.00 | 0.06 | 5.50 | 0.38 | 0.29 | -10.0687 |
| 2000 | 1.50 | 0.09 | 6.50 | 0.52 | 0.32 | -11.5252 |

Analysis of Variance (ANOVA) for BURR HEIGHT

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 7 | 35.8135 | 5.1162 | 1.42 | 0.571 |
| ROTATIONAL SPEED (A) rpm | 2 | 6.1923 | 3.0961 | 0.86 | 0.607 |
| DEPTH OF CUT (B) mm | 2 | 0.3723 | 0.1861 | 0.05 | 0.952 |
| FEED RATE (C) mm/rev | 3 | 26.0340 | 8.6780 | 2.41 | 0.435 |
| Error | 1 | 3.6038 | 3.6038 | | |
| Total | 8 | 39.4172 | | | |

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 1.89835 | 90.86% | 26.86% | 91.52% |

Analysis of Variance (ANOVA) for BURR THICKNESS

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 7 | 0.159822 | 0.022832 | 2.38 | 0.463 |
| OTATIONAL SPEED (A) rpm | 2 | 0.060700 | 0.030350 | 3.16 | 0.370 |
| DEPTH OF CUT (B) mm | 2 | 0.013500 | 0.006750 | 0.70 | 0.645 |
| FEED RATE (C) mm/rev | 3 | 0.011378 | 0.003793 | 0.40 | 0.790 |
| Error | 1 | 0.009600 | 0.009600 | | |
| Total | 8 | 0.169422 | | | |

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.0979796 | 94.33% | 54.67% | 93.28% |

Analysis of Variance (ANOVA) for SURFACE ROUGHNESS

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 7 | 62.193 | 8.885 | 1.92 | 0.506 |
| ROTATIONAL SPEED (A) rpm | 2 | 36.897 | 18.448 | 3.99 | 0.334 |
| DEPTH OF CUT (B) mm | 2 | 9.635 | 4.818 | 1.04 | 0.570 |
| FEED RATE (C) mm/rev | 3 | 11.639 | 3.880 | 0.84 | 0.645 |
| Error | 1 | 4.629 | 4.629 | | |
| Total | 8 | 66.822 | | | |

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 2.15147 | 93.07% | 44.58% | 94.21% |

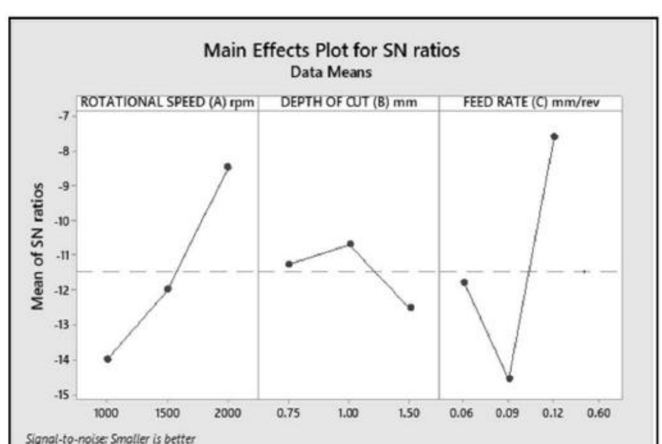


Figure 6. Main effect plot for S/N Ratio.

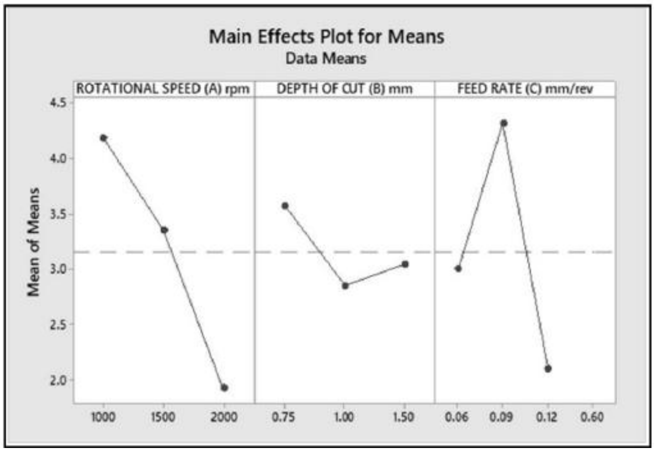


Figure 7. Main effect plot for means.

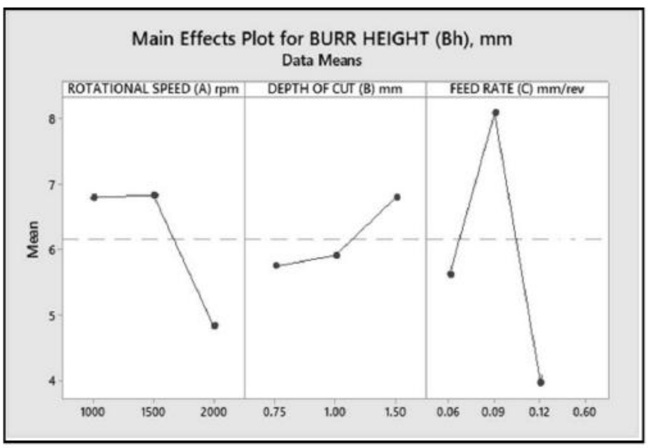


Figure 8. Main effect plot for burr height.

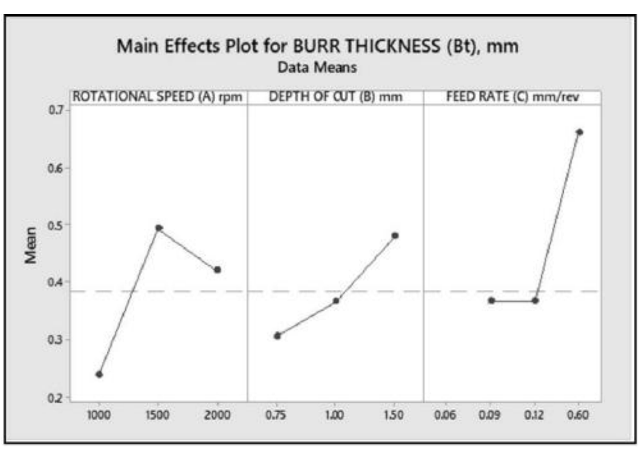


Figure 9. Main effect plot for burr thickness.

The effects of input parameters on data means of responses observed from Fig. 6 reveals that all input parameters under third level influence more on output responses *i.e.* increase of rotational-speed, feed-rate and depth-of-cut causes optimum values of surface roughness and burr-size simultaneously. Figure 7 shows that lower of rotational speed and depth-of-cut, medium range of feed rate effect on means of responses.

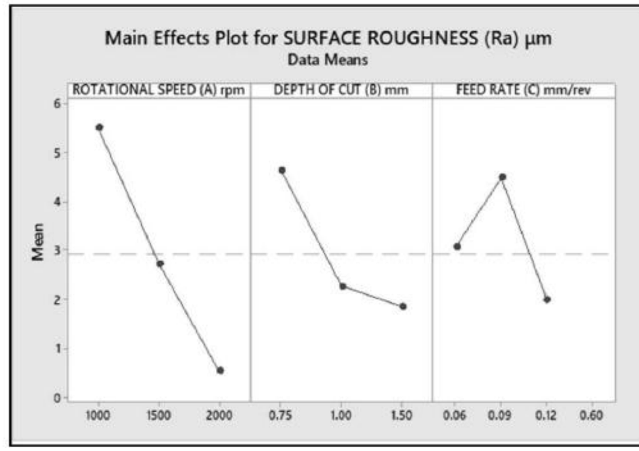


Figure 10. Main effect plot for surface roughness.

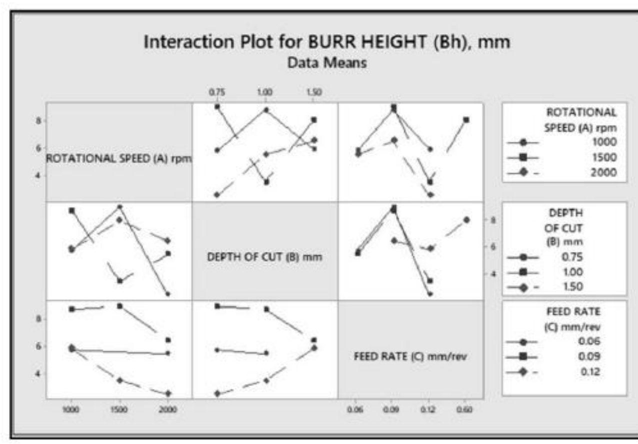


Figure 11. Interaction plot for burr height.

The main effect plots of burr height, thickness and surface roughness are affected by the medium range of rotational speed and feed rate simultaneously which is observed in Figures 8, 9 and 10.

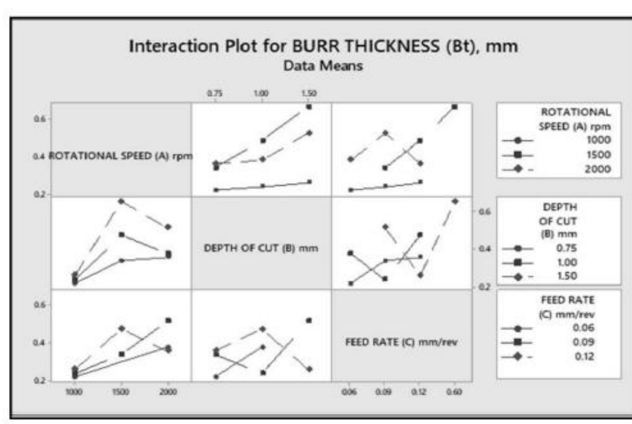


Figure 12. Interaction plot for burr thickness.

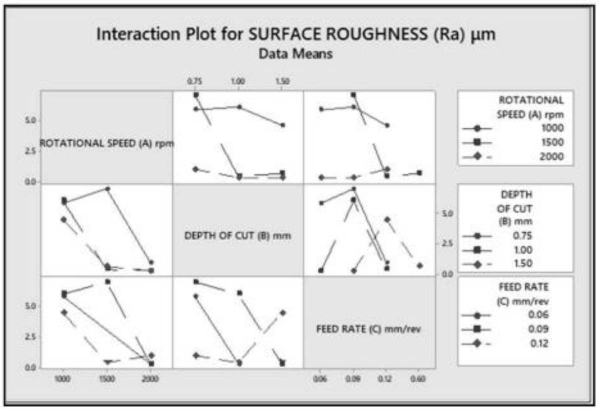


Figure 13. Interaction plot for surface roughness.

From Fig.11, 12 and Fig. 13 observations reveal that higher values of rotational speed and feed rates are more significant than depth-of-cut. After finding the most significant factors, confirmation test is conducted and good agreement obtained with experimental values. Also it is identified from ANOVA results R-sq and R-sq (pred) values are more than 90%, which shows that hypothesis is in good agreement with selection and conducting experimental method.

## VII. CONCLUSION

From the results and discussions, the following conclusions are drawn.

- The burr height and thickness are influenced by combined effect of rotational speed and feed rate, but in the case of surface roughness feed rate and depth of cut parallelally influenced.
- From confirmation experiment, 13.26% improvement towards surface roughness and burr size by adopting Taguchi method is observed.

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For biographical sketch of Mr. Reddy Sreenivasulu, please refer to *AKGEC International Journal of Technology*, vol.9, no.1, p.25. Five coauthors are students at his department.