

Balakrishnan Deepanraj

Associate Professor
Department of Mechanical Engineering
Jyothi Engineering College
Thrisur, Kerala
India

Lakshmipathi Anantha Raman

Assistant Professor
Department of Mechanical Engineering
S.A Engineering College
Avadi, Chennai, Tamil Nadu
India

Natarajan Senthilkumar

Professor
Department of Mechanical Engineering
Adhiparasakthi Engineering College
Melmaruvathur, Tamil Nadu
India

Jayakumar Shivasankar

UG Scholar
Department of Mechanical Engineering
Manakula Vinayagar Institute of Technology
Kalitheerthalkuppam, Puducherry
India

Investigation and Optimization of Machining Parameters Influence on Surface Roughness in Turning AISI 4340 Steel

This paper focuses on the experimental investigation of machining parameters such as cutting speed, feed rate and depth of cut influence over surface roughness parameters (R_a , R_y and R_t) during turning AISI 4340 steel. Further, in order to achieve smaller surface roughness parameter values, the machining parameters are optimized using Taguchi's technique Signal-to-Noise ratio (S/N ratio). Analysis of Variance (ANOVA) is performed to determine the most contributing factor that influences the surface roughness parameters. It is observed that the feed rate is the most significant factor contributing by 70.50%, depth of cut by 18.54% and cutting speed by 9.15%. From the optimum condition obtained, a confirmation experiment is performed and the results obtained shows that the surface roughness parameter values are reduced by 31.63% than the designed experimental values.

Keywords: Machining parameter; Surface roughness; Taguchi's Technique; ANOVA.

1. INTRODUCTION

Turning is a process of producing axisymmetric surface by removing unwanted material from the work-piece to produce a desired shape, where the tool moves in a perpendicular plane and the workpiece is hold on a spindle and rotated [1]. The interesting parameters that were associated with the process of turning were cutting speed, feed and depth of cut [2]. The cutting speed can be defined as the relative surface speed of the workpiece with respect to the tool, which is responsible for material removal. The relative motion of the tool with respect to the job in perpendicular direction to cutting speed for the purpose of reaching unmachined surface is called feed [3]. The penetration of the cutting tool into the job, that is beneath the job surface is depth of cut, which is the radial distance in turning, from the unmachined surface of the job to the tool tip [4]. Turning is the finishing operation performed on components to produce final shape of the component with adequate dimension and tolerances [5], for which optimization of machining parameters is performed by most of the researchers.

Surface roughness parameters such as R_a – Average roughness value, R_t – Maximum height of roughness profile and R_y – Average maximum height of profile are of importance in dimensional stability of a machined component subjected to assembly. Fig. 1 shows the surface roughness profile of various parameters [6].

Asilturk and Akkus [7] minimized surface roughness by optimizing the turning parameter using Taguchi's

technique during dry turning and found that feed rate has the most significant effect on surface roughness. Tamizharasan and Senthilkumar [8] analyzed the effect of various cutting tool geometries over surface roughness and MRR using Taguchi's technique and by ANOVA. Nalbant et al. [9] optimized the cutting parameters in turning AISI 1030 steel based on the surface roughness produced and found that insert radius and feed rate are the most contributing factors. Ramesh et al. [10] predicted the effect of cutting parameters on surface roughness during turning aerospace titanium alloy (gr5) using response surface methodology model and found that feed rate is the most influencing factor. Kopac et al. [11] determined optimal conditions to achieve desired surface roughness in turning C15 E4 steel by varying the cutting speed, tool and workpiece material, depth of cut and no. of cuts and using coated inserts.

Asilturk and Neseli [12] determined optimum machining parameters for better surface roughness during dry turning of AISI 304 steel using coated carbide insert by response surface methodology and predicted it using the developed mathematical model and found that feed rate is the most contributing factor. Bernardos and Vosniakos [13] have presented various methodologies that are to be followed in predicting the surface roughness and how to reduce it. Sahin and Motorcu [14] used response surface methodology to develop a mathematical formula to predict surface roughness and found that feed rate is the most significant parameter contributing towards surface roughness using ANOVA. Palanikumar and Karthikeyan [15] determined the factors that influence surface roughness during turning Al/SiC particulate composite using carbide tool insert and found that feed rate is the most significant factor, responsible for surface roughness. Verma et al. [16] used Taguchi's technique to optimize machining parameters in turning ASTM A242 Type-1 steel over sur-

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Correspondence to: Mr Anantha Raman Lakshmipathi
Department of Mechanical Engineering,
S.A Engineering College, Chennai, India.
E-mail: raman3366@gmail.com

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face roughness and found that cutting speed is the most significant parameter responsible for surface roughness.

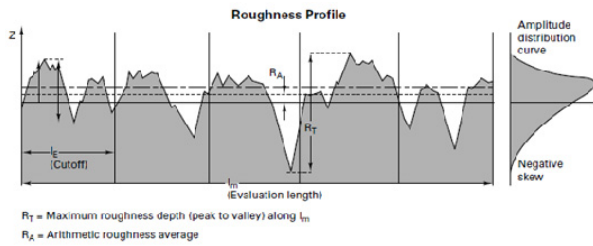


Figure 1. Surface roughness parameters [6]

Akhyar et al. [17] optimized the cutting parameters during turning Ti-6%Al-4%V with coated and uncoated cemented carbide tool and found that cutting speed and tool grade have a significant effect on surface roughness. Mahdavinejad and Bidgoli [18] used an adaptive neural fuzzy intelligent system to predict the roughness in turning process and found that surface quality decreases with depth of cut. Ramesh et al. [19] optimized the turning conditions based on surface roughness while turning Duplex stainless steel 2205 using CVD triangular carbide insert and developed a regression equation to predict it. Aruna and Dhanalakshmi [20] optimized surface roughness, when turning Inconel 718 with cermet inserts based on response surface methodology and developed a second order quadratic models to predict it and concluded that cutting speed has the strongest effect on surface roughness. Saini et al. [21] developed an accurate predictive model using response surface methodology for surface roughness and tool wear and predicted it for various cutting conditions and found that decrease in feed rate and increase in cutting speed results in increased surface quality with higher tool wear. Bhushan et al. [22] investigated the influence of machining parameters on surface roughness during machining 7075 Al alloy and 10% SiC particulate MMC and found that for optimum surface roughness, cutting speed should be within 180 to 220 m/min, feed rate between 0.1 to 0.3 mm/rev and depth of cut within 0.5 to 1.5 mm.

Singh and Rao [23] determined the effects of cutting conditions and tool geometry on the surface roughness in the finish hard turning of AISI 52100 bearing steel using mixed ceramic inserts made up of aluminium oxide and titanium carbonitride and found that feed is the dominant factor determining the surface finish followed by nose radius and cutting velocity. Chavoshi and Tajdari [24] studied the influence of hardness (H) and spindle speed (N) on surface roughness (Ra) in hard turning operation of AISI 4140 using CBN cutting tool has been studied and predicted it using ANN and regression models. Senthilkumar and Tamizharasan [25] predicted flank wear and surface roughness using artificial neural network model, based on the experiments performed using Taguchi's DoE for different tool geometries and machining parameters during turning practically used automobile axles. Cakir et al. [26] examined the effects of cutting parameters onto the surface roughness during turning AISI P20 steel with CNMG 120408 carbide inserts having completely the same geometry and substrate but different coating layers through mathematical models.

From the literature review, it was identified that, most of the research works were centered towards optimization of average surface roughness (Ra) and not on the other surface roughness parameters such as Ry, Rt, etc, which is targeted through the experimental investigation. In this work the dimensional accuracy and surface integrity of low alloy steel used in shafts is analyzed for better fit and tolerances through analysis and optimization using Taguchi's approach for various surface roughness parameters, which is the novelty of the present study. Apart from this, the influence of machining parameters on the surface roughness conditions were evaluated and the optimized conditions were identified.

2. WORKPIECE AND CUTTING INSERT MATERIAL

For analysis, the workpiece material selected is AISI 4340 steel, which is highly ductile, resistance to shock, wear resistance and having high tensile strength used in construction of aircrafts and heavy vehicle crankshaft, gear shaft, camshaft and propeller shaft etc. The elemental composition of the workpiece is shown in Table 1.

Table 1. Chemical composition of AISI 4340 steel

Sl. No	Elements Present	Alloying %
1	Carbon	0.372
2	Silicon	0.278
3	Manganese	0.570
4	Phosphorus	0.030
5	Sulphur	0.026
6	Chromium	1.106
7	Molybdenum	0.320
8	Nickel	1.467
9	Aluminum	0.023
10	Copper	0.14
11	Niobium	0.064
12	Vanadium	0.033
13	Iron	95.571

The chemical composition of the sample is in agreement with the specified value as per B.S. 970 grade EN-24. The Hardness is 217 BHN. The SEM image of the workpiece material is shown in Fig. 2. The microstructure shows fine pearlite grains in a matrix of ferrite, with fine dispersion of the chromium carbides. The size of the grains shows that the material is in mild annealed condition and the hardness measured is in agreement with it.

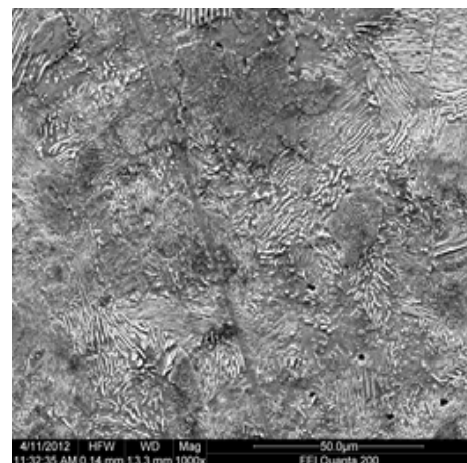


Figure 2. SEM image of AISI 4340 steel

The cutting tool insert used in this study is uncoated cemented carbide insert, whose ISO designation is CNMG 120404, whose hardness is 1433 BHN. The cutting tool insert chemical composition is given in Table. 2.

Table 2. Chemical composition of cutting insert

Sl. No	Elements/compound	Alloying %
1	Tungsten carbide	96.4
2	Titanium carbide	0.5
3	Tantalum carbide	0.8
4	Cobalt	2.19

The SEM photomicrograph of the tungsten carbide cutting tool insert is shown in Fig. 3. The SEM image of the cutting insert shows tungsten carbide (WC) particles which are predominant with titanium carbide (TiC). The structure is variable composition of solid solution phases of WC and TiC.

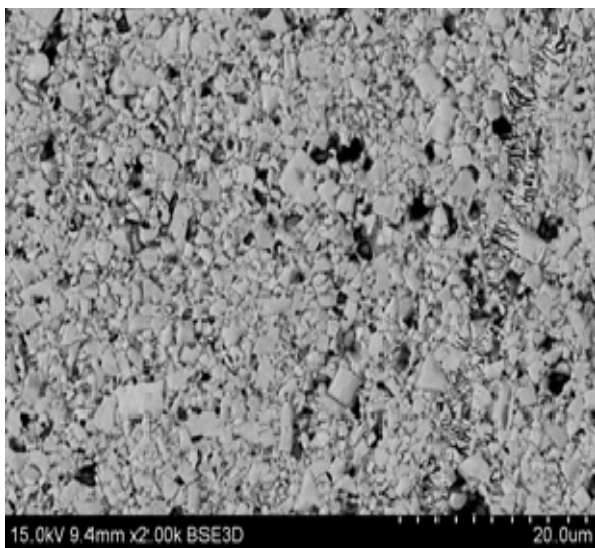


Figure 3. SEM image of cutting insert

3. METHODOLOGY USED

3.1 Taguchi's Technique

In optimization, Taguchi's tool is a powerful technique, which applies a special design of Orthogonal Array (OA), used to examine the output characteristics through lesser number of experiments [27-31]. For evaluating the outputs, experimental results determined from the orthogonal array are transformed into Signal-to-Noise (S/N) ratios [32-33]. Considering 3 parameters varied through 3 levels in this research, Taguchi's Design of Experiments (DoE) is applied. The control parameters and their levels chosen [34] are shown in Table 3.

In parametric optimization, least number of experiments identified is calculated as, Minimum experiments = [(L-1) x P] + 1 = [(3-1) x 3] + 1 = 7 ≈ L₉ [35-37]. The various combinations of feed rate, cutting speed and depth of cut based on which the experiments were to be conducted is presented in Table 4.

For analyzing the output responses, three categories were available, (i.e.) Smaller-the-better, Larger-the-better and Nominal-the-better to determine the S/N ratio in Taguchi's technique. For larger S/N ratio, the process

will be robust against the noise parameters [38]. For Smaller-the-better analysis, the obtained outputs are usually an undesired output and for Larger-the-better category, output responses are usually a desired one and for Nominal-the-best category, the quality characteristics are usually a nominal output.

Table 3. Control Parameters and their Levels

Parameter / Level	Symbol	Level I	Level 2	Level 3
Cutting Speed (m/min)	A	136	122	108
Feed Rate (mm/rev)	B	0.203	0.330	0.432
Depth of Cut (mm)	C	0.1	0.2	0.3

Table 4. Inner Array of Taguchi L₉ Orthogonal Array

Sl. No	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	136	0.203	0.1
2	136	0.330	0.2
3	136	0.432	0.3
4	122	0.203	0.2
5	122	0.330	0.3
6	122	0.432	0.1
7	108	0.203	0.3
8	108	0.330	0.1
9	108	0.432	0.2

Smaller-the-better (Minimize):

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

Larger-the-better (Maximize):

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

Nominal-the-best:

$$S / N = 10 \log \left(\frac{\bar{y}}{s_y^2} \right) \quad (3)$$

3.2 Analysis of Variance

A statistical tool for evaluating the difference between the available set of scores are Analysis of variance (ANOVA), which is applied to data set for dividing the total variance measured into sources [39]. Depending upon the type of analysis, it may be important to determine which factors have a significant effect on the response, and how much of the variability in the response variable is attributable to each factor [40-41]. For determining the significant factor, which contributes more, ANOVA is done [42]. The contribution of each parameter is determined by means of ANOVA.

3.3 Experimental Setup

The experiments are conducted on a CNC Turning centre, Lokesh make 2 axes CNC TL-20 lathe. After performing the machining process, the surface roughness values of the machined surfaces are recorded by

using Surfcoorder SE3500. Its specification is, measuring range of Z: 600 μm X: 100 mm, measuring magnification of Z: 50-500,000 X: 1-5,000, measuring speed of 0.05-2 mm/s, Z traverse range of 250 mm. Fig. 4 shows the machining operation performed, along with cutting insert and insert holder. Specification of cutting insert holder used is WIDAX D 9K, CCLNL 25 25 M12.



Figure 4. Experimental setup with cutting insert and tool holder

4. RESULTS AND DISCUSSION

Based on the L_9 orthogonal array designed using Taguchi's DoE, experiments are conducted. In this study, 9 different workpieces are taken and for each experiment a separate workpiece is used. After performing the operation, the surface roughness is measured with a Surfcoorder. The various surface roughness values measured are given in the Table 5, along with the combined S/N ratio [43].

Fig. 5 shows the area graph for surface roughness values determined. It is observed that all the surface roughness values Ra, Ry and Rt increases or decreases in the same trend [44]. When the cutting speed is increased from 108 m/min to 122 m/min, Ra value decreases by 13.3% and when increased to 136 m/min, it further decreases by 35.5%. When feed rate is increased from 0.203 mm/rev, the Ra value increases by 50.9% and then by 65.7%. When depth of cut is increased from 0.1 mm to 0.2 mm, Ra value decreases by 16.3% and when it is further increased to 0.3 mm, Ra increases by 0.8%.

Table 5. Surface roughness values measured

Sl. No	Ra	Ry	Rt	Combined S/N Ratio
1	2.46	13.39	14.89	-21.3253
2	2.34	13.38	14.87	-21.3099
3	3.71	16.75	18.58	-23.2875
4	1.43	8.39	10.35	-17.7709
5	2.44	12.73	13.39	-20.6358
6	3.37	16.67	19.50	-23.4863
7	2.18	10.01	10.87	-18.7140
8	2.57	16.23	19.83	-23.4455
9	3.45	16.29	20.16	-23.5774

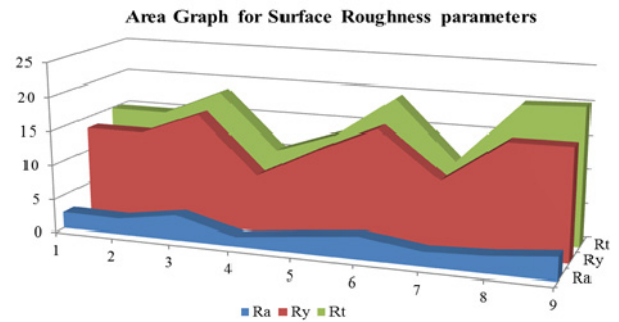


Figure 5. Area graph of surface roughness parameters

Initially, Ry value decreases by 12.5%, when cutting speed is increased from 108 m/min to 122 m/min and then it increases by 2.3% when cutting speed is increased to 136 m/min. when feed rate is increased, Ry value increases initially by 24.9% and then by 36%. When depth of cut increases from 0.1 to 0.2, Ry decreases by 21.6% and then by 17.2% when depth of cut is 0.3 mm.

17.6% decrease in Rt value is obtained when cutting speed is increased from 108 m/min to 122 m/min and 5.2% decrease when cutting speed is increased from 122 m/min to 136 m/min. When feed rate is increased from 0.203 mm/rev to 0.33 mm/rev and then to 0.432 mm/rev, an increase in Rt value by 24.9% and 38% is observed. A decrease in Rt value by 19.5% and then by 26.6% is observed when depth of cut is increased from 0.1 mm to 0.3 mm.

For this analysis, the surface roughness values have to be lower for a given set of input parameters. Hence, the Smaller-the-better condition is selected as given in Eq. 1. From the combined S/N ratio determined, average values are calculated for each level of cutting speed, feed rate and depth of cut, which is given in Table 6. From the response table, main effects plot is drawn as shown in Fig. 6. Based on this, the optimum machining parameters determined are cutting speed of 122 m/min, feed rate of 0.203 mm/rev and depth of cut of 0.3 mm ($A_2B_1C_3$).

Table 6. Surface roughness values measured

Level / Parameter	Cutting Speed	Feed Rate	Depth of Cut
1	-21.91	-19.27	-22.75
2	-20.63	-21.80	-20.89
3	-21.97	-23.45	-20.88
Max – Min	1.34	4.18	1.87

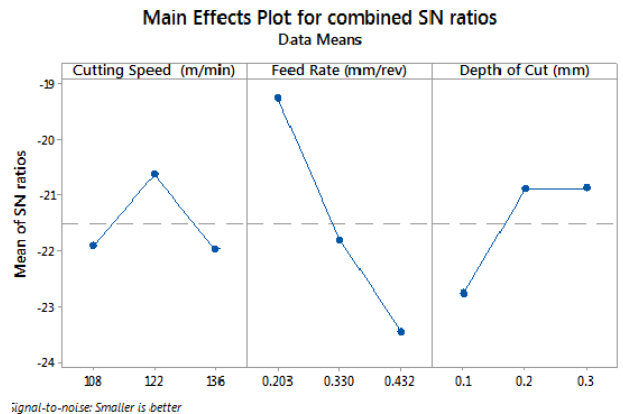


Figure 6. Main effects plot for combined S/N ratio

3.4 Interaction Effect of Machining Parameters

Interaction plot is drawn to study the combining influence of chosen input parameters [45]. Fig. 7 shows the interaction plot for Ra surface roughness value. No interaction effect is visualized between cutting speed and feed rate. A higher correlation effect is observed between cutting speed and depth of cut. For a cutting speed of 108 m/min and for a depth of cut of 0.3 mm, lower Ra value is obtained. In between feed rate and depth of cut, except for a feed rate of 0.203 mm/rev, no interaction effect is seen.

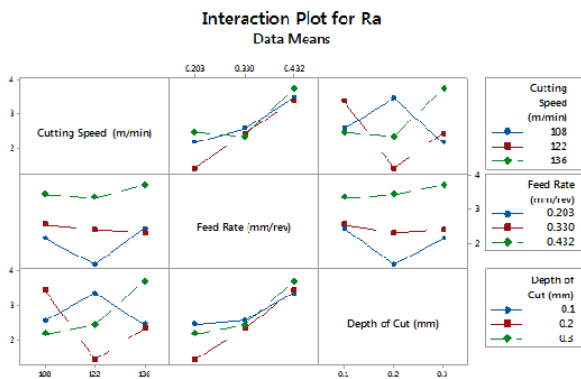


Figure 7. Interaction plot for Ra

Fig. 8 shows the interaction effect for Ry values. A lower interaction effect is observed between cutting speed and feed rate for a cutting speed of 108 m/min than the other cutting speeds. Higher interaction effect is seen between cutting speed and depth of cut, and for a cutting speed of 122 m/min, the effect is higher. No significant interaction effect is seen between feed rate and depth of cut and for a feed rate of 0.203 mm/rev, a lower interaction effect is seen.

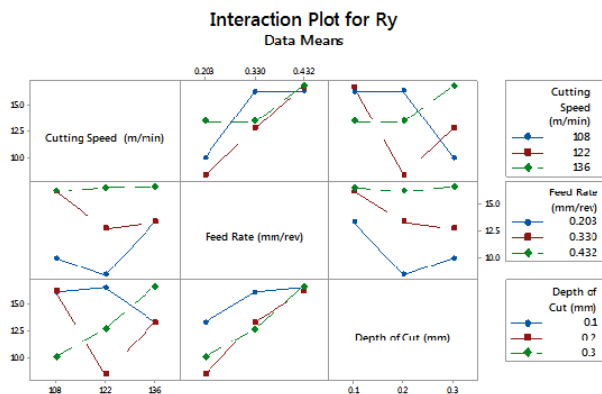


Figure 8. Interaction plot for Ry

Fig. 9 shows the interaction plot for Rt values of surface roughness. A smaller interaction is seen between cutting speed and feed rate. For a cutting speed of 108 m/min, Rt value is more corresponding to the feed rate of 0.330 mm/rev.

A higher interaction effect is observed between cutting speed and depth of cut and for a cutting speed of 122 m/min and for a depth of cut of 0.2 mm, the surface roughness value is lower. No interaction effect is seen between feed rate and depth of cut except for a feed rate of 0.432 mm/rev. From all the interaction plots, it is

observed that a higher level of interaction effect exists in between the cutting speed and depth of cut.

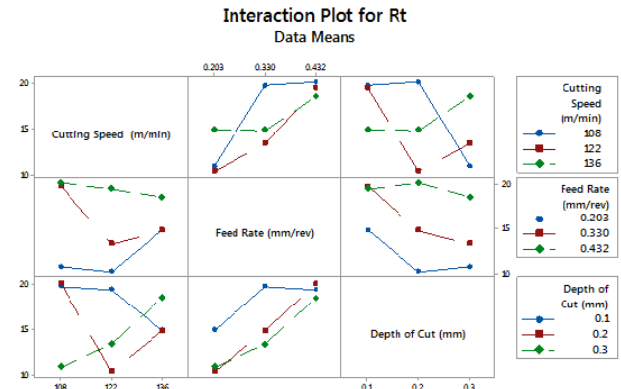


Figure 9. Interaction plot for Rt

3.5 Confirmation Experiment

Based on the optimum machining parameters determined, experiment is conducted and the surface roughness values are measured. The surface roughness parameter values obtained are, Ra-1.58 μm , Ry-9.57 μm and Rt-12.06 μm .

The output results obtained shows that the optimum machining parameters produces a lower surface roughness values than the experiments conducted based on orthogonal array by 31.63%. Fig. 10 shows the surface roughness profile obtained for the validation experiment based on the optimum condition reached. It shows the P-profile and F-profile of the surface roughness values obtained.

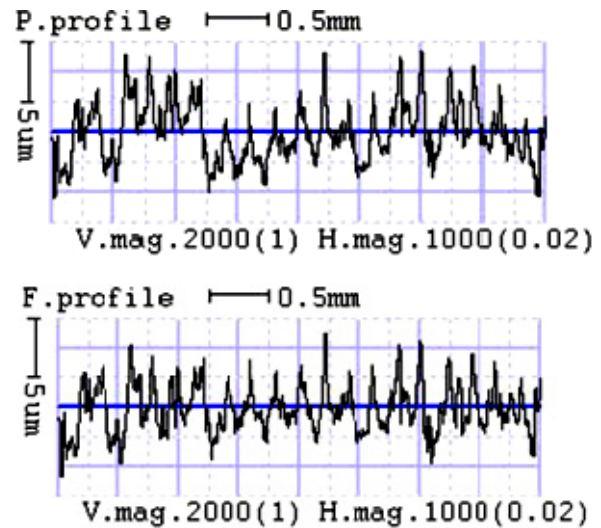


Figure 10. Surface roughness profile of validated experiment

ANOVA is performed to determine the most contributing machining parameter using Minitab-18 software and the results obtained are shown in Table. 7. From the ANOVA table, it is observed that the feed rate is the most significant factor that contributes 70.50% of surface roughness in the machined surface. Depth of cut contributes up to 18.54% and the least contributing factor is cutting speed, contributing by 9.15%.

Table 7. ANOVA for Combined S/N ratio

Source	DoF	Seq. SS	Adj. MS	F	P	% Contribution
Cutting speed	2	3.4500	1.725	5.03	0.166	9.15%
Feed rate	2	26.5944	13.2972	38.78	0.025	70.50%
Depth of cut	2	6.9924	3.4962	10.20	0.089	18.54%
Residual error	2	0.6858	0.3429	-	-	1.82%
Total	8	37.7226	-	-	-	100%

5. CONCLUSIONS

In this work, Taguchi's technique is used to optimize the machining parameters such as cutting speed, feed rate and depth of cut. From the analysis, some of the outcomes are,

- The optimum condition obtained is cutting speed of 122 m/min, feed rate of 0.203 mm/rev and depth of cut of 0.2 mm.
- The most significant parameter responsible for surface roughness values is feed rate, contributing by 74.20%. The least contributing factors are depth of cut and cutting speed, contributing by 14.31% and 9.35% respectively.
- It is observed that the interaction effect between cutting speed and depth of cut is higher than the interaction between cutting speed and feed rate and between feed rate and depth of cut.
- Confirmation experiment shows a reduction in various surface roughness values by 31.63% when compared to the experimental results. The obtained surface roughness parameter values are Ra-1.58 μm , Ry-9.57 μm and Rt-12.06 μm .

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**ИСТРАЖИВАЊЕ И ОПТИМИЗАЦИЈА
УТИЦАЈА ПАРАМЕТАРА ОБРАДЕ НА
ХРАПАВОСТ ПОВРШИНЕ КОД ОБРАДЕ AISI
4340 ЧЕЛИКА**

**Б. Депанрап, Ј.А. Раман, Н. Сентилкумар, Ј.
Шивансанкар**

Рад се бави експерименталним истраживањем утицаја параметара обраде као што је брзина резања, брзина помоћног кретања и дубина резања на параметре храпавости површине приликом обраде на стругу AISI 4340 челика.

Да би се добиле мање вредности параметара храпавости површине, параметри обраде су оптимизирани применом Тагучијеве технике односа сигнал-бука. АНОВА је коришћена да би се утврдило који фактор највише утиче на параметре храпавости. Утврђено је да фактор брзина помоћног кретања има највећи утицај (70,50%), дубина резања (18,54%) и брзина резања (9,15%).

На основу добијеног стања извршен је експеримент чији резултати показују да су вредности параметара храпавости површине редуковане за 31,63% у поређењу са вредностима пројектованим експериментом.