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Investigate the effect of various cutting parameters on the surface roughness of aluminum alloy 5052 by using Taguchi method

Asmail Alfrjani Alshanta [1 *], Saleh A. Almajdup [2], Mohamed Etuhami Swei [3]
[1.2] the Mechanical Engineering Department at the Higher Institute of Science and Technology in Zintan, Libya,
[3] College of Engineering Technology, Janzur, Libya
Corresponding author: asmil76alshntama@gmail.com
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Abstract:
The characteristic surface finish of machining is a key indicator of product quality and an indispensable customer requirement. Taguchi robust parameter design for optimizing surface finish in the turning of 5052 AL alloy using carbide cutting has been utilized in this paper. Using the Taguchi method for AA5052 aluminum alloy machining reveals that feed rate, cutting speed, and depth of cut significantly impact surface roughness, with feed rate often being the dominant factor, followed by speed, then depth. The results showed that lower feed rates (e.g., 0.1 mm/rev) and higher cutting speeds (e.g., 900 rpm) generally yield the best (lowest) surface roughness (Ra), while optimal depth of cut varies but often favors lower values. ANOVA and Signal-to-Noise (S/N) ratio analyses confirm parameter significance, allowing prediction of optimal settings for improved quality. Finally, we developed the relationship between cutting parameters and response using MINITAB-16 and performed regression analysis. The predicted values were compared with the experimental values, and it was observed that both values were very close; hence, the models prepared were more accurate and adequate.
Keywords: surface roughness, CNC, Taguchi, parameters, ANOVA

دراسة تأثير معاملات القطع المختلفة على خشونة سطح سبيكة الألومنيوم 5052 باستخدام طريقة تاغوتشي

إسماعيل الفرجاني الشنطة [1*]، صالح ابوراوي المجدوب[2]، محمد التهامي الصويعي[3]
[1] قسم الهندسة الميكانيكية بالمعهد العالي للعلوم والتقنية في الزنتان، ليبيا
[2] قسم الهندسة الميكانيكية بالمعهد العالي للعلوم والتقنية في الزنتان، ليبيا
[3] كلية التقنية الهندسية جنزور، ليبيا

الملخص
تُعدّ جودة السطح الناتجة عن عمليات التشغيل مؤشراً رئيسياً على جودة المنتج ومتطلباً أساسياً للعملاء. يتناول هذا البحث استخدام منهجية "تاجوشي" (Taguchi) لتصميم المعاملات القوية (Robust Parameter Design) بهدف تحسين جودة السطح أثناء عملية الخراطة لسبائك الألومنيوم 5052 باستخدام أدوات قطع من الكربيد. وقد أظهر تطبيق منهجية "تاجوشي" على سبائك الألومنيوم (AA5052) أن معدل التغذية، وسرعة القطع، وعمق القطع تؤثر بشكل جوهري على خشونة السطح؛ حيث يُعد معدل التغذية العامل الأكثر تأثيراً، تليه سرعة القطع، ثم عمق القطع. وأوضحت النتائج أن استخدام معدلات تغذية منخفضة (على سبيل المثال، 0,1 مم/دورة) وسرعات قطع عالية (على سبيل المثال، 900 دورة في الدقيقة) يؤدي عموماً إلى الحصول على أفضل (أقل) قيمة لخشونة السطح (Ra)، بينما يختلف عمق القطع الأمثل، وإن كان يميل غالباً نحو القيم المنخفضة. كما أكد تحليل التباين (ANOVA) ونسبة الإشارة إلى الضجيج (S/N ratio) أهمية هذه المعاملات، مما أتاح التنبؤ بالإعدادات المثلى لتحسين الجودة. وفي الختام، تم تحديد العلاقة بين معاملات القطع ومخرجات العملية باستخدام برنامج (MINITAB-16) وإجراء تحليل الانحدار. وعند مقارنة القيم المتنبئ بها مع القيم التجريبية، وُجد تقارب كبير بينهما؛ مما يشير إلى دقة النماذج المُعدّة وكفاءتها.
الكلمات المفتاحية: خشونة السطح , التحكم الرقمي بالحاسوب (CNC)، منهجية تاجوشي، المعاملات، تحليل التباين (ANOVA)

1. Introduction

Nowadays, manufacturing industries are strongly concerned about the quality of their products. They focused on producing high quality products in time with minimum cost. Surface finish is one of the crucial performance parameters that have to be controlled within suitable limits for a particular process. Therefore, prediction or monitoring of the surface roughness of machined components is has become an important area of research. Cutting parameters such as speed, feed and depth of cut strongly influence the surface roughness of the machined product. Producing a

desired surface roughness, which is one of the most important factors in measuring the quality of machined products producing the appropriate surface roughness Not only affects the functional attributes of products also affects manufacturing costs [1]. 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. In order to obtain better surface roughness, the proper setting of cutting parameters is crucial before the process takes place. The aim of this study is to investigate optimize the process parameters for minimum surface roughness in CNC turning process for Aluminum 5052.In this experiment only the (Ra) value is taken into consideration. Several works have been reported in the broad field of tool condition monitoring. Develop a robust and accurate model that can find a correlation between the cutting parameters and the surface roughness of the machined products [2]. The dramatic 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 process. The quality of surface roughness is an important requirement of many work pieces in machining operations. Within the metal cutting processes, the turning process is one of the most fundamental metal removal operations used in the manufacturing industry. Surface roughness, which is used to determine and evaluate quality of a product, is one of the major quality attributes of a turned product. Surface roughness of a machined product could affect several functional attributes of the products such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, and coating and resisting fatigue. Therefore surface roughness is one of the most important quality aspects in turning operations [3].This study is concerned the the optimum combination of machining process parameters in an efficient and quantities manner, the experiments will be design based on the response surface methodology, with central composite rotatable design and mathematical models for five different surface profile parameters and for both surface micro hardness and out-of-roundness will be developed to give the production engineers more details about the product external surface.

2. Research Problem Statement

The primary challenge in manufacturing high-quality components from Aluminum Alloy 5052 using CNC turning centers is the systematic control and optimization of the finished surface integrity. Achieving minimized surface roughness (Ra) is critical for structural and functional compliance, yet it remains hindered by several operational complexities:

- **Parametric Interdependence**: The highly non-linear and coupled interaction between key cutting parameters—specifically feed rate, cutting speed, and depth of cut—renders empirical or trial-and-error adjustments highly inefficient, costly, and time-consuming.

- **Built-Up Edge (BUE) Instability**: Under intermediate machining conditions, the sporadic formation and subsequent breakage of a Built-Up Edge (BUE) on the carbide tool tip induces highly unstable surface integrity, leading to severe erratic fluctuations in both surface finish and overall tool life.

- **Economic-Quality Tradeoff**: Modern precision manufacturing sectors demand a strategic equilibrium where tight geometric tolerances and superior surface finishes must be accomplished within tight timeframes and minimized production costs.

2. Research Objectives

To address the aforementioned challenges, this research establishes the following primary objectives:

1. To systematically identify and isolate the optimal combinations of CNC turning parameters (feed rate, cutting speed, and depth of cut) that yield the minimum quantifiable surface roughness (Ra) for AA5052 using standard carbide inserts.

2. To implement a robust parameter design via the Taguchi optimization methodology, utilizing an L9 (3^3) orthogonal array to systematically minimize experimental trials, costs, and statistical errors.
3. To execute an Analysis of Variance (ANOVA) and Signal-to-Noise (S/N) ratio analysis to statistically quantify the percentage contribution and significance of each machining variable on surface quality.
4. To develop and validate a robust mathematical predictive model using MINITAB-16 regression analysis, ensuring high correlation, adequacy, and precision between the estimated analytical values and physical experimental results.

3. Experiment Work:

3.1 Work piece material:

The workpiece in this study aluminum alloy 5052, the workpiece used for the testes was in the form of Round rod, diameter of 20 mm and length of 200mm was shown in the Figure (3.1).



Figure (3.1) Workpieces aluminum ally 5052

The turning tests on the workpiece were conducted under wet conditions on a CNC (Computer Numerical Control) lathe (DX 200, JOBBER XL) having maximum spindle speed of 4000 rpm and maximum power of 7.5 KW. Prior to actual machining, the rust layers were removed by 0.5 mm depth of cut in order to minimize any effect of homogeneity on the final results. Machined components after machining were shown in the Figure (3.2).



Figure (3.2) Machined Components of AA 5052

4. Procedure and Step of Taguchi Parameter Design

The procedure of Taguchi design method can be divided into seven steps. The steps of Taguchi optimization are presented in as following; select the quality characteristic, select noise factors and control factors, select orthogonal array, conduct the experiments, analyze results: determine

optimum factor-level combination, predict optimum performance and confirm Experimental Design.

4.1 Software analysis

MINITAB statistical software is used in this study for selecting the types of design to be used for running the experiments, to display all possible combination controllable factors and analyzing data representing main and interaction relationship between them. This software provides a wide range of basic and advanced data analysis capabilities.

5. Results and Discussion:

5-1- Selection of Quality Characteristic:

There are three types of characteristics in the Taguchi methodology, such as smaller-the –better, larger-the-better, and nominal-the-best. The goal of this research was to produce optimum surface roughness (Ra) in turning operation. Smaller Ra values represent better or improved surface roughness. Therefore, a smaller-the-better quality characteristic was implemented and introduced in this study [4].

5.2 Selection of Control Factors:

The previous studies [6], indicated that feed rate, cutting speed, and depth of cut had significant effects on surface roughness in the machining operation. In this study, the controllable factors are feed rate (A), cutting speed (B), and depth of cut (C), with one nose radius of tool, which were selected because they can potentially affect surface roughness performance in turning operations. Since these are controllable in the machining process, they are considered as controllable factors in the study. Table 1 listed all the Taguchi design parameters and levels.

Table 1. Illustrate the variable factor levels of aluminum 5052

Factor	Level 1	Level 2	Level 3
Feed rate(mm /rev)	0.1	0.2	0.3
Cutting speed (rpm)	700	800	900
Depth of cut (mm)	0.5	1.0	1.5

5.3 Selection of Orthogonal Array:

One of Taguchi method steps is selecting the proper orthogonal array (OA) according to number of controllable factors (parameters). Since three factor were selected to study in this research, three levels of each factor were considered. Therefore, L9 Taguchi method has used special design of orthogonal. arrays L9(3*3) to study the entire parameter with only a small number of experiments for surface roughness as illustrate in figure 2.

Table 2. Illustrate the L9 (3*3) Taguchi orthogonal array

Experiment number	Feed rate A	Cutting speed B	Depth of cut C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

5.4 Conducting the Experiments:

The signal-to-noise ratio is often written as S/N or represented by the Greek letter (η). In the Taguchi method, the term (signal) represented the desirable value (mean) for the output characteristic and the term (noise) represented the undesirable value Standard deviation (S.D) for

output characteristic because of some other factors which called (noise factors). Noise factors are those factors that are not controllable, and whose influences are not known [5]. Such as tool deflection and vibration, which may be occur on cutting tool and work piece material because of cutting force during machining. The effect of uncontrollable noise factors is not the subject of this therefore, the S/N ratio is the ratio of the mean to the (S.D) [6] . Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratios seek out the strong effects and ascertain the best levels .The most desired situation is reached when the signal is strong and the impact of the noise is weak. There are several S/N ratios available depending on type of characteristic, lower is better (LB), nominal is better (NB), or higher is better (HB) [7].

The smaller is better quality characteristic can be explained as:

$$S/N = -10 \text{ Log MSD} \quad (1)$$

Where: MSD = the mean square deviation.

The mean square deviation for smaller-the characteristic is:

$$MSD = \frac{y_1^2 + \dots y_n^2}{n}$$

Where n = number of measurements in trial / row, in this case, n=3 and y_i is the measured value in a run/row. We can rewrite the S/N equation as:

$$S/N = -10 \log \left| \frac{y_1^2 + \dots y_n^2}{n} \right|$$

5.5. The results for Surface Roughness:

The results for Surface Roughness in this experimental run illustrate in table 3.

Table 3. Illustrate the results of surface roughness

EX Number	Feed rate A (mm/rev)	Cutting speed B (rpm)	Depth of cut C (mm)	R 1	Ra2	Ra3
1	0.1	700	0.5	1.073	0.975	1.05
2	0.1	800	1.0	1.091	0.95	1.185
3	0.1	900	1.5	0.894	1.08	0.899
4	0.2	700	1.0	1.33	1.074	0.98
5	0.2	800	1.5	3.044	1.98	1.99
6	0.2	900	0.5	1.012	0.878	0.893
7	0.3	700	1.5	2.109	1.69	1.46
8	0.3	800	0.5	0.844	1.0987	0.833
9	0.3	900	1.0	0.94	1.099	0799

Table 3 illustrate that the best surface roughness value was at machining the sample No (6) under the cutting parameters (feed rate 0.2 mm/min, cutting speed =900 rpm and depth of cut = 0.5 mm). All these results data can be represented graphically illustrated in figure 3.

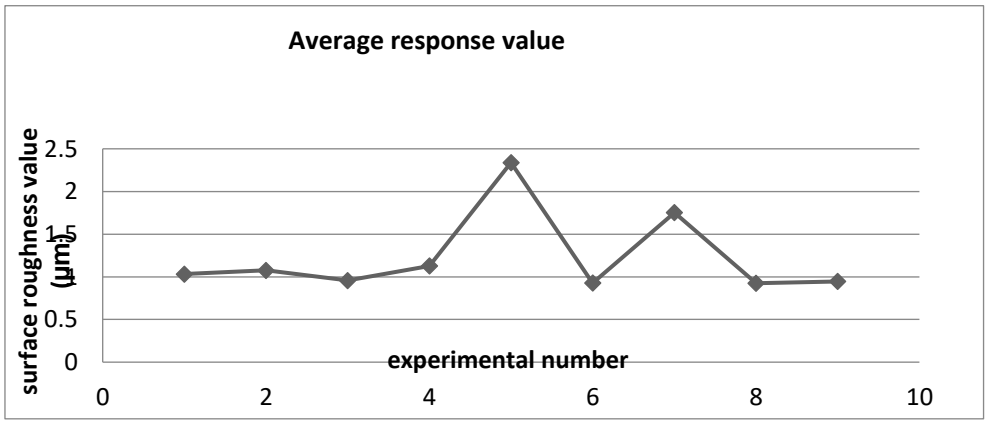


Figure 3. Illustrate the experimental Results of Surface Roughness

Table 4. Ilustrate the experimental Results of aluminum alloy 5052

Experiment number	Response value			Average response value	Sum of squares	MSD	S/N value
	Ra 1	Ra2	Ra3				
1	1.073	0.975	1.05	1.032666667	3.204454	1.068151	-0.28633
2	1.091	0.95	1.185	1.075333333	3.497006	1.165669	-0.66575
3	0.894	1.08	0.899	0.957666667	2.773837	0.924612	0.340403
4	1.33	1.074	0.98	1.128	3.882776	1.294259	-1.12021
5	3.044	1.98	1.99	2.338	17.14644	5.715479	-7.57053
6	1.012	0.878	0.893	0.927666667	2.592477	0.864159	0.634063
7	2.109	1.69	1.46	1.753	9.435581	3.145194	-4.97647
8	0.844	1.0987	0.833	0.925233333	2.613367	0.871122	0.599209
9	0.94	1.099	0.799	0.946	2.729802	0.909934	0.409901

Table 5. Illustrate the Response of Means for S/N value

Level	A	B	C
1	-0.20389	-2.12767	0.315648
2	-2.68556	-2.54569	-0.45869
3	-1.32245	0.461456	-4.06887
Delta	2.481666	3.007145	4.384514
Rank	3	2	1

Table 6. Illustrate the Means of surface roughness

5.6 Analyzing the experimental data to determine the optimum cutting conditions

For the process observing the effect influence degree of cutting parameters (feed rate (A), cutting speed (B), and depth of cut (C)- with one nose radius of tool, of aluminum alloy 5052 in CNC turning for better surface roughness. The effects process are parameters resulting from the optimization process are plotted in figure 4 (a,b,c) . these figure show many graphs, each of graphs contains a line representing the mean of the S/N ratio and curve representing the control factor.The values of the graphs are from table 4. The objective the objectives of using the S/N ratio as a performance measurement are to develop process insensitive to noise factors. The S/N ratio indicates of the predictable performance of process in the presence of noise factors. In this study, it is the smaller the better in surface roughness case, which means the smallest surface roughness, would be the ideal situation; this is criteria employed in this study to determine the optimal cutting condition. By following the criteria of smaller surface roughness and larger S/N ratio, the graphs in figures 4(a,b,c) and 5(a,b,c) were used to determine the optimal set of parameters from the experimental design.

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Table 6. Illustrate the Means of surface roughness

Level	A	B	C
1	**1.021889**	**1.304556**	**1.431967**
2	**1.464556**	**1.446189**	**1.049778**
3	**1.208078**	**0.943778**	**1.682889**
Delta	**0.442667**	**0.502411**	**0.633111**
Rank	**3**	**2**	**1**

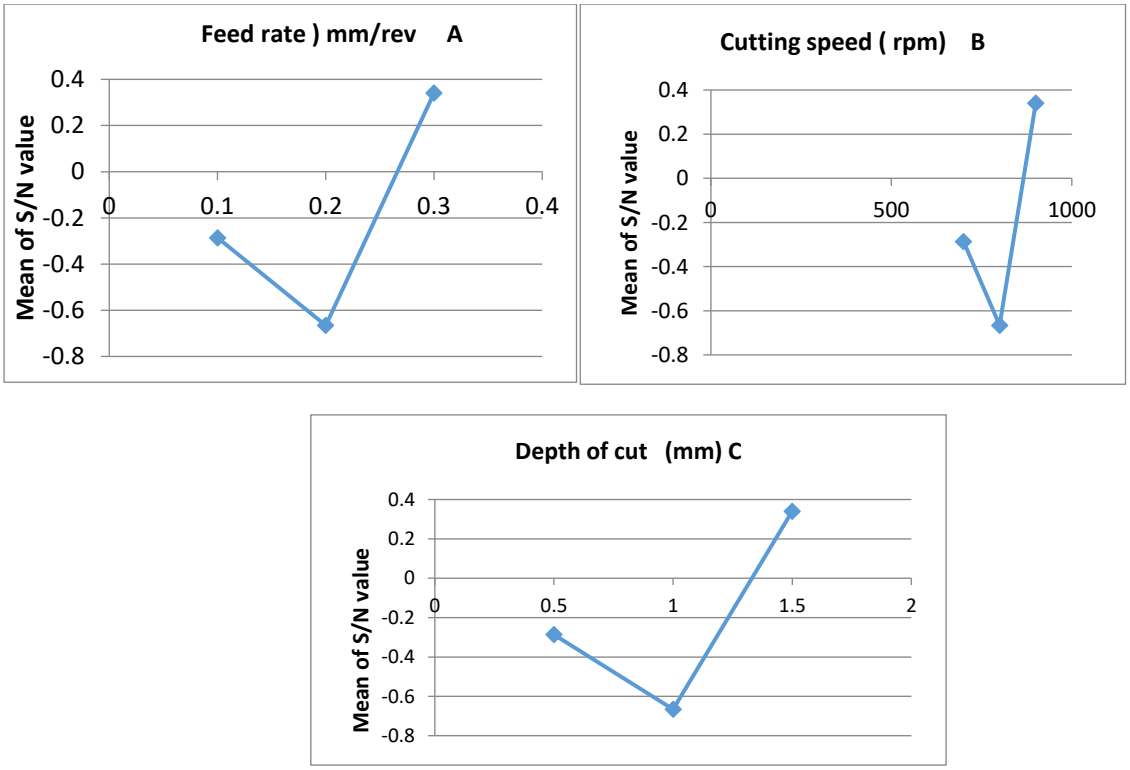
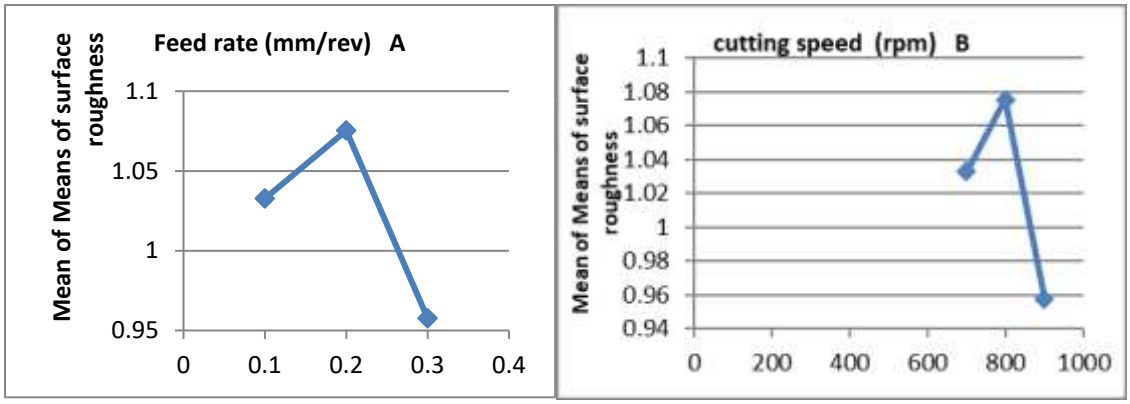


Figure 4: (a,b,c). Illustrate the plot of S/N value



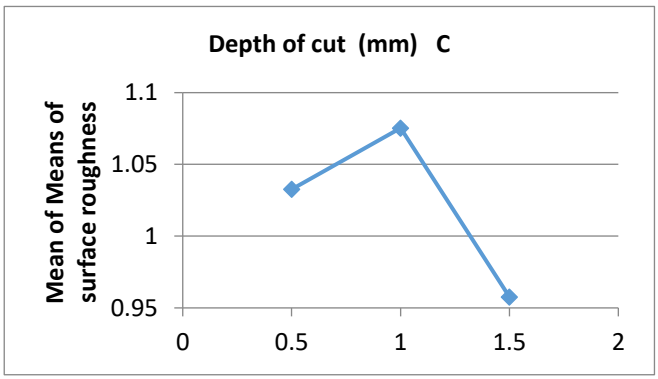


Figure 5(a,b,c). Illustrate the plot of means for surface roughness

Figure 5(a,b,c) illustrate the control factor of feed rate (A) at level one (0.2 mm/min) provided the best result. Because it has the highest S/N ratio value, which indicated that the machining performance at such level produced minimum variation of the surface roughness. In addition, the lower surface roughness value had a better machining performance. And shows the control factors of cutting speed (B) at level three (900rpm), and depth of cut (C)at level two (1.0 mm), provided the best results. Therefore, the optimum cutting condition will be (feed rate = 0.1 mm/min (A1), cutting speed = 900 rpm (B3), and depth of cut = 0.5mm (C2).

The comparison of the optimal set of parameters by graph with the data in table 5 which represent the experimental design, new parameters arises and obtained and these parameters are not exist in table 6. To predict the mean for the treatment condition average of the result for the trail is set at this particular level is calculated by the following equation [9].

$$\eta calc = \eta avg + (\bar{A}i - \eta avg) + (Bi - \eta avg) + (C\,I - \eta avg)$$

Where: The calculated S/N ratios at optimal machining conditions:

ηavg: The average S/N ratios of all control factors:

Āi : average S/N ratio when the factor a (feed rate) is at level i.

BI : average S/N ratio when the factor B (cutting speed) is at level i.

CI: average S/N ratio when the factor C (depth of cut) is at level i.

The expression for surface roughness value is:

Racalc = 10ηcalc /20

The average S/N ratio for all control η average and the average S/N ratio for each control factor A2 , B2 , and C3 can be obtainable from the table 7.

Table 7. Illustrate the S/N ratios average value

S/N average e	η_{avg}	$\bar{A}_2$	B_2	C_3
Value	-1.4039	-2.6855	-2.54567	-4.0688

Then the values of S/N ratios is substituted in Equation 4 and we obtain .

$$\eta calc = -1.4039 + (-2.6855 - (-1.4039)) + (-2.54567 - (-1.4039)) + (-4.0688 - (-1.4039)); \quad \eta calc = -1.16237 \text{ dB}$$

Substituting this value in Equation 5 we obtain the surface roughness value as:Racalc=1.143190 µm

5.8. The conformation experiment results:

In the engineering analysis, a conformation experimental is very important in validating the minimum surface roughness.

5.9. Surface Roughness:

The optimum cutting parameters are feed rate 0.1mm/erv, cutting speed 900 m/min and depth of cut 0.5mm. Three samples were machined under the optimal parameters that optimized in the study for purpose of conformation experimental. shows the results of the conformation experimental. Compared with the predicted value table 8 , the mean surface roughness of three conformation experimental samples(1.1531 µm), which was very close to the predicted value of surface roughness that from references(1.143190µm).There for, the conformation run indicated that the selection of the optimal levels for all the parameters produced the best surface roughness.

Table8. Illustrate the results of conformation experiment for Surface Roughness

Sample Number	Mean of Ra (µm)
1	1.143
2	1.201
Mean	1.1531

In this research, the analysis of variance (ANOVA) and F-test were performed to see statistically significant process parameters and the percent contribution of these parameters on surface roughness. Larger F value indicates that the variation of the process parameters makes a big change on the performance characteristics.

$$F = \frac{MSA}{MSW}$$

Where: MSA: mean squares among variances; MSW: mean squares within variances

The percentage contribution by each of the process parameter in the total sum of the squared deviations SST can be used to evaluate the importance of the process-parameter change on the performance characteristics. In addition, the F-test can also be used to determine which process parameters have a significant effect on the performance characteristic. Usually, the change of the process parameter has a significant effect on the performance characteristic when the F value is large. The purpose of the analysis of variance (ANOVA) is to determine which cutting parameters significantly affect the quality characteristic surface roughness.

Table 9. Illustrate the ANOVA for Means surface roughness on of aluminum 5052

Factor	DF	AdjSS	AdjMS	F- value	P- value	P %
Feed Rate	1	0.2372	0.23721	3.79	0.109	15.42
Depth of Cut	1	0.3641	0.36408	5.82	0.061	23.65
CuttingSpeed	1	0.6253	0.62533	10.00	0.025	40.62
Error	5	0.3127	0.06255			20.31
Total	8	1.5394				100

Table 9 illustrate the results of ANOVA analysis of raw data for surface roughness on the aluminum alloy 5052. Form table 9 it is apparent that the F values of factor A (feed rate), factor C (Depth of cut) and factor B (Cutting speed), were all greater than F0.05,2,2=19.

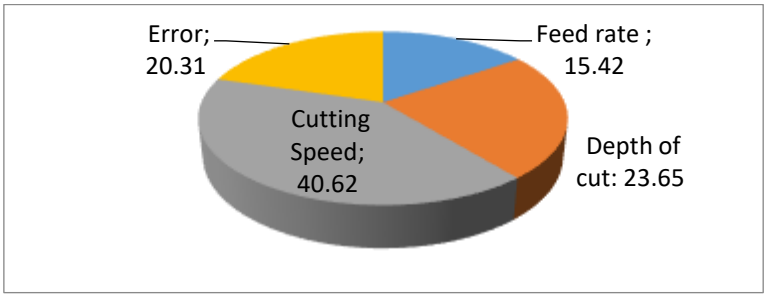


Figure6. Illustrate the percent of control parameters on surface roughness of aluminum alloy 5052

Robust design performs an analysis of variables (ANOVA) of the experimental results in order to evaluate the relative importance of the process parameters and the error variances. The ANOVA analysis results can be seen in table 9 and figure 6 shows the influence of each factor on the performance of the turning process. According to ANOVA analysis of surface roughness on aluminum alloy 5052, the feed rate influences the performance by 15.42%, the depth of cut by 23.65% and cutting speed by 40.62%.

5.10 Tool Life and Tool Wear:

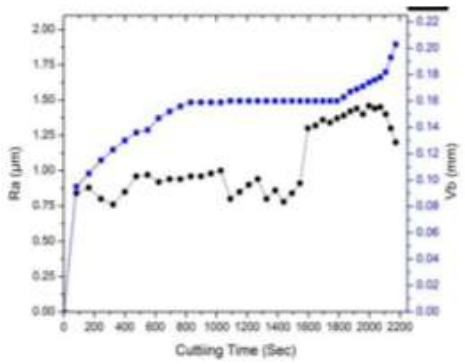
In this study cutting speed and feed rate variations mostly affectedsurface roughness and tool life, illustrates effect of cutting speed and feed rate on tool life indifferent conditions, which reveals, by increasing cutting speed and feed rate tool life decreased.According to results of the tool life in table 10, longest cutting time achieved at 700 m/min cutting speed and 0.10 mm/rev feed rate, whereas the shortest tool life achieved at 900 m/min cutting speed and 0.30 mm/rev feed rate

Table 10. Illustrate the Cutting conditions, tool life

Experiments number	Feed rate (Mm/rev)	Cutting speed (m/min)	Depth of cut (mm)	Tool life(min)
1	0.3	700	0.5	18.8
2	0.3	800	0.5	15.4
3	0.3	900	0.5	9.3
4	0.2	700	1.0	36
5	0.2	800	1.0	27
6	0.2	900	1.0	25
7	0.1	700	1.5	62.4
8	0.1	800	1.5	44.2
9	0.1	900	1.5	34.38

5.11. Surface Integrity.

Surface roughness varied within range of 0.60 µm to 2.2µm. The best surface roughness achieved at lower feed rate and highest cutting speed (900m/min, 0.10 mm/rev). Impact of feed rate on surface roughness was dominant comparing to cutting speed. Built up edge caused unsteady surface integrity by sporadic formation and breakage of developed BUE.Surface roughness was mostly affected in intermediate cutting conditions with moderate temperatures which largest amount of BUE observed in these conditions, on the other hand the best surface roughness noticed in highest cutting speed with elevated temperatures which had the lowest amount of formed BUE.figure 7(a) , indicates flank wear and surface roughness relations at 700 m/min and 0.2mm/rev, BUE formed on tool edge, and protected flank face from wear growth, which resulted in unsteady surface roughness until BUE removed from cutting edge. Figure(b) , illustrate surface roughness and flank wear propagation at 900m/min and 0.2 mm/rev in different cutting times.



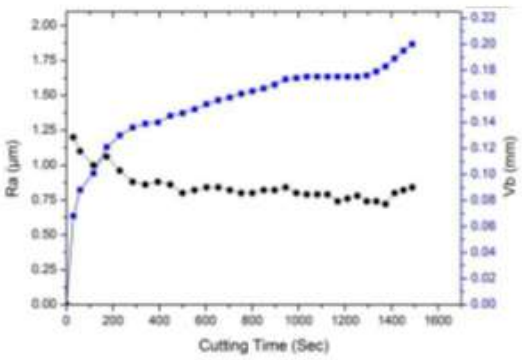


Figure 7(a) Effect of various cutting speeds and feed rates on tool life at 700 m/min and 0.2mm/rev

Figure7(b) Tool wear and surface roughness relations in different cutting time 00m/min and 0.1 mm/rev

6. Conclusions:

In this study the Taguchi orthogonal array is employed to optimize the machining parameters, with respect to surface roughness, which produced by CNC turning machine using one material (aluminum alloy 5052).

Taguchi method used to study effect of three factors, such as feed rate, cutting speed and depth of cut.

1. The optimum parameters for best surface roughness are obtained at a feed rate of 0.1 mm/min, cutting speed of 900 rpm, and depth of cut 1.0 mm. A2, B2 and C3. It has been observed that feed rate has got the most significant influence on the surface roughness.
2. A confirmation experiments were carried out to obtained the optimal conditions. The minimum surface roughness is calculated was 1.143190 µm, which is smaller than the 1.153 µm obtained in confirmation experiments.
3. Dry turning of Al 5052 using carbide inserts revealed following conclusions: in all experiments dominant wear mechanisms determined as abrasive and adhesion on flank and rake faces. Best surface finish recorded at highest cutting speed, and lowest feed rate.
4. In moderatecutting conditions, adhesion wear and BUE noticeably observed and caused unsteady surface and erratic tool life. Adhesion and breakage of material on the cutting edge resulted in brittle coating spalls and chipping spread to adjacent coating. Friction and adhesion of chips on rake face caused crater wear in all of the conditions, however it found significantly destructive in severe conditions.

7. Strategic Recommendations

Based on the empirical findings, statistical modeling, and experimental verifications documented in the study, the following actions are recommended for industrial practice and future academic expansion:

Industrial Implementation Strategy

- **Configure for Optimal Parameters**: Production engineers and CNC operators should rigorously configure machining parameters to a low feed rate of 0.1 mm/rev coupled with a high cutting speed of 900 rpm to reliably guarantee minimized surface roughness (Ra) during finishing operations.
- **Mitigate Adhesion and BUE Formation**: Avoid operating within intermediate or moderate cutting zones where moderate temperatures facilitate rapid adhesion wear and severe BUE development, which drastically degrades tool flank faces and destabilizes surface profiles.

Methodological and Future Research Expansion

- **Standardize Statistical Design Control**: Integrate software-driven statistical modeling (such as MINITAB or Response Surface Methodology) into standard manufacturing pipelines to simulate, predict, and lock in optimal tool trajectories and settings prior to physical production runs.
- **Incorporate Multi-Variable Boundary Conditions:** Future research should build upon this baseline by integrating additional independent variables—such as tool nose radius variations, diverse cooling/lubrication techniques (e.g., MQL), and structural tool vibrations—to develop a completely

holistic tool life and surface integrity model.

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