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AN EXPERIMENTAL INVESTIGATION AND OPTIMISATION OF ECOLOGICAL MACHINING PARAMETERS ON ALUMINIUM 6063 IN ITS ANNEALED AND UNANNEALED FORM

S.P. Sundar Singh Sivam, M.Gopal, Siddhartha Singh

Department of Mechanical Engineering, SRM University, Kancheepuram District, Kattankulathur- 603203, Tamil Nadu, India

***Corresponding author: Email: sundar.sp@ktr.srmuniv.ac.in,**

ABSTRACT

The cost of using coolant and its disposition in machining industry world-wide is very high. Furthermore, chemical substances contained in coolant are very harmful to environment and machine shop workers. Ecological machining is inevitably the future trend in machining industry. This project applies the Designs of Experiments (DOE) approach to optimize parameters of a computer numerical control (CNC) in end milling for Aluminum 6063 alloy and its annealed form under Ecological machining. The work piece employed was in the form of rectangular block of 100 mm length, 100 mm breadth and 25 mm depth. The groove difference (i.e., dimensional accuracy of groove width) and the roughness average at the bottom plane of the inside groove (i.e., the plane of end milling) were studied. 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, by 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 and the roughness average in end milling process for Aluminum 6063

Key words: Ecological machining, Annealing, DOE, End milling, Mini Tab

INTRODUCTION

The increasingly strict environmental regulations are eliminating much of the flexibility in the use of cutting fluids. The cutting fluid manufacturers are developing new formulations which are devoid of lead, sulphur, or Chlorine elements. These elements improve machinability but are detrimental from the health and environmental point of view. The costs associated with the use of cutting fluids are estimated to be several billion dollars/year. However, to pursue dry machining, one has to compensate for the several beneficial effects of the cutting fluids without actually using them. It may even be necessary for industries to lower their expectations by cutting back on speeds or removal rates (if the tool materials cannot withstand the stringent conditions of Ecological machining) when forced to limit or not use cutting fluids. One such approach is to improve the properties of the tool material by making them more refractory, or generate less heat during machining.

Need for the study: This study intends to prove that end milling without cutting fluid is feasible with optimized cutting conditions. In general usage, Design of Experiments (DOE) is the design of any information-gathering exercises where variation is present, irrespective of experimental control.

EXPERIMENTAL TESTING

Material: This alloy is named as the 6063 Aluminium alloy. Al–Mg–Si alloy is also known as architectural and decorative alloy, because of its high extrudability, weldability, distinctly superior finish quality, high corrosion resistance and anodizing strength.

Chemical Composition: A scrap piece of Aluminum 6063 was tested for chemical composition which provided the following results given in Table1.

Sample description: Aluminum slab

Table 1 Chemical Composition of Al 6063

FE%	Si%	Mn%	Cu%	Ni%	Cr%	Ti%
0.341	0.581	0.096	0.026	0.007	0.000	0.041
Sn%	V%	Co%	Zn%	Pb%	Mg%	Al%
0.000	0.007	0.000	0.003	0.019	0.460	98.399

Table 2 Physical Properties of Aluminium 6063

Property	Value
Density	2700 kg/m^3
Melting Point	600°C
Modulus of Elasticity	69.5 GPa
Electrical Resistivity	0.035x10^{-6} Ωm
Thermal Conductivity	200 W/m K
Thermal Expansion	23.5 x 10^{-6} /K

Annealing: Aluminum 6063 slab is prepared with the dimension of 100mm x 100mm x25 mm. The slab is kept in furnace for 4 hours at a temperature of 350°C and then cooled at uniformly decreasing temperature at the rate of 25°C per hour till 250°C. Then the slab was self-cooled in the furnace. The process helped in relieving the stress in the specimen and hence increasing the ductility and softening the work piece.

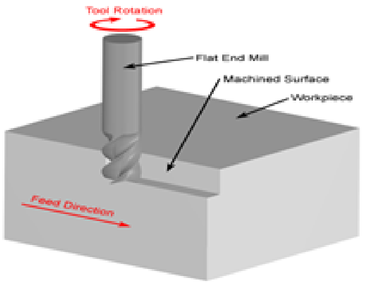

Fig 1 Muffle furnace for annealing **Fig 2 End milling schematic diagram**

CNC vertical machine setup: Investigations of Ecological milling process were carried out at special machine shop, SRM University. The CNC vertical milling machine was an LV 45 model manufactured by Lakshmi Works with Maximum transverse (X- Axis) 450mm, Maximum transverse (Y- axis) 350 mm, Maximum transverse (Z-axis) 350 mm table base of 600 * 350mm, a spindle bore of A40, positioning accuracy of .01mm (JIS standard), repeatability of .005mm (JIS standard) and spindle speed ranging from 80 to 8000 Rpm

Schematic milling operation: The milling machining was setup for end milling process. The experiments were carried out on a rigid CNC machine center. The machine tool adapted in this investigation is HSS end mill cutter. The tool used is "12mm diameter tapered shank end mill cutter" made up of micro grain carbide manufactured by Shree Enterprise & Co Bengaluru.

Surface roughness tester: Figure no. 3 shows the surface roughness instrument using TR200 to find the roughness of any surface having a dimension of standard model TS200 with inductive diamond tip radius 5µ, a bore diameter of 6.00mm, and depth 15mm (TS 100). The Ra values were found at three different places on each sample and their average value was taken as the final value. Since the surface might be not even at all places, the Ra value is checked at three different places.

Fig.3.Surface roughness measured using TR200

Brinell hardness test and measurement: The brinell hardness test was conucted at a commercial Strength laboratory in SRM university in accordance with ASTM E10-12. The value of Brinell Hardness Number is calculated using the formula:

$$HB=2f/\pi D(D-(sqrtD^2-d^2)$$

The Brinell Hardness numbers for Aluminium 6063- unannealed and annealed specimens for 500kgf load and 10 mm indenter diameter are 70 and 58 respectively.

Experimental design: In this study, further procedure for Ecological machining of Aluminium 6063 is carried out using end milling. In the process, coding was done in the CNC milling machine which included various parametric combinations for machining. The rectangular slab specimens for both annealed and unannealed forms have 100mm length, 100 mm breadth and 25 mm width. Nine trials were conducted as given in Table 3.

Machining operation: The specimen is machined in CNC Vertical milling Centre using HSS tool at various machining feed rates, cutting speeds and depth of cut combinations. While machining the unannealed specimen, the milling occurred smoothly which is indicated by the machined surface as shown in figure 4. on the contrary end, during machining of the annealed specimen the tool underwent vibrations with increase in feed rate while other parameters were kept constant. Also, with increase in depth of cut adhesion layers were formed on specimen due to heat, which lead to the formation of uneven surface. It clearly indicates that the machinability has reduced for annealed specimen. It can be seen in figure 5.The surface roughness test is performed using TR200 surface roughness meter at three points and the average roughness coefficient is tabulated in table 4 and table 5 for annealed Aluminium 6063 and unannealed Aluminium respectively.

Table.3.Machining parameters used in milling

Trials	Cutting Speed(Mm/Sec)	Feed Rate(Mm/Rev)	Depth Of Cut(Mm)
1	300	0.05	1.0
2	600	0.05	1.0
3	900	0.05	1.0
4	300	0.10	0.5
5	600	0.10	1.0
6	900	0.10	1.5
7	300	0.05	0.5
8	600	0.10	0.5
9	900	0.15	0.5

Fig 4 unannealed of Aluminium 6063 Top & bottom view

Fig 5 Annealed of Aluminum 6060 Top & Bottom view

Table 4 Surface roughness coefficient for annealed Aluminium 6063

Trials	Feed Rate (mm/rev.)	Cuting Speed mm/sec)	Depth Of Cut(mm)	SURFACE ROUGHNESS ($Ra \times 10^{-6}$)			
				1	2	3	mean
1	0.05	300	1.0	2.652	2.753	2.965	2.832
2	0.05	600	1.0	1.645	1.743	1.821	1.753
3	0.05	900	1.0	1.655	1.824	2.003	1.888
4	0.10	600	1.5	2.146	2.268	2.365	2.238
5	0.10	600	1.5	2.435	2.589	2.754	2.625
6	0.10	600	1.5	2.883	2.995	3.103	3.004
7	0.05	900	0.5	1.754	1.869	1.921	1.886
8	0.10	900	0.5	2.355	2.562	2.694	2.564
9	0.15	900	0.5	2.542	2.599	2.793	2.634

Table 5 Surface roughness coefficient for unannealed Aluminium

Trials	Feed Rate(mm/rev.)	Cutting Speed(mm/sec)	Depth Of Cut(mm)	SURFACE ROUGHHNESS ($Ra \times 10^{-6}$)			
				1	2	3	mean
1	0.05	300	1.0	0.721	0.831	0.934	0.841
2	0.05	600	1.0	0.890	0.965	1.103	0.952
3	0.05	900	1.0	1.124	1.156	1.780	1.159
4	0.10	600	0.5	1.034	1.244	1.446	1.301
5	0.10	600	1.0	2.012	2.084	2.123	2.062
6	0.10	600	1.5	0.965	0.974	1.002	0.983
7	0.05	900	0.5	1.324	1.550	1.703	1.552
8	0.10	900	0.5	1.903	1.954	2.032	1.967
9	0.15	900	0.5	2.112	2.245	2.346	2.244

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RESULT AND DISCUSSION

Experimental design approach: The parameter design is the key step in achieving high quality without increasing the costs. The Taguchi method was used specially to design orthogonal arrays to study the entire parameter space. This design is sufficient to investigate three main effects and the influence of their interactions on the surface roughness. With S/N ratio analysis, the optimal combination of the testing parameters can be determined. Three levels were specified for each of the factors. The orthogonal array chosen was L9. The ANOVA analysis helps to find out the relative contribution of machining parameter in controlling the response of milling operation. The optimal parametric setting value will directly influence the objective function for determining the surface roughness.

Taguchi method: This paper uses Taguchi method, a powerful DOE tool which is commonly used in improving industrial product quality due to the proven success.

Selection of control factors: The most appropriate milling parameters are selected and these are: Cutting speed (V), depth of cut (D), and feed rate (f) .The parameters and their levels are shown on the table 6.

Table 6 Control Factor and Their Level

Item	Control Factor	Level 1	Level 2	Level 3
A	Cutting Speed (mm/sec)	300	600	900
B	Feed Rate (mm/rev)	0.05	0.10	0.15
C	Depth Of Cut(mm)	0.5	1.0	1.5

Orthogonal array: In the Taguchi method, 9 experiments are conducted on both annealed and unannealed Aluminium 6063 alloy. Thus, three levels and three parameters help in forming L9 orthogonal array for Taguchi design of experiments given in table 7.

Table.7.L9 Orthogonal Array

Expt No.	A	B	C
1	1	1	2
2	2	1	2
3	3	1	2
4	2	2	1
5	2	2	2
6	2	2	3
7	3	1	1
8	3	2	1
9	3	3	1

Analysis of the Signal-to- Noise(S/N) ratio: In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (SD) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the SD that measures the variations of the experimental design. The equation of "smaller is the better" was selected for the calculation of S/N ratio since the lowest values of surface roughness were the desired results in terms of good product quality. Values are tabulated with mini tab software for the two specimen used in Table 8.The formula used for calculating S/N ratio is given below:

S/N ratio (S/N) = $-10 \log_{10} \sum (y^2)$

i=1 Where n=no. of factors and y= no. of response value. Thus S/N ratio is calculated and tabulated in Table 8.

Table 8 surface roughness and S/N ratio values for specimen

Exp N0.	CODED VALUES			ACTUAL VALUES			S/N FOR UNANNEALED Al	S/N FOR ANNEALED Al
	A	B	C	A	B	C		
1	1	1	2	300	0.05	1.0	1.58316	-9.00330
2	2	1	2	600	0.05	1.0	-0.461619	-5.06739
3	3	1	2	900	0.05	1.0	-3.87749	-5.7466
4	2	2	1	600	0.10	0.5	-2.99516	-7.26242
5	2	2	2	600	0.10	1.0	-4.74630	-8.02547
6	2	2	3	600	0.10	1.5	0.17143	-9.51309
7	3	1	1	900	0.05	0.5	-2.12635	-4.98384
8	3	2	1	900	0.10	0.5	-6.41103	-7.94192
9	3	3	1	900	0.15	0.5	-6.99094	-8.39607
	Mean=						-2.8726	-7.3266

In the given figure 6, level 1 of A and level 3 of B and level 3 of C show the maximum effect of improving Surface roughness. Hence, A1, B3 and C3 is the best combination i.e. cutting speed of 300 rpm and feed rate of 0.15 mm/rev and depth of cut of 1.5 mm provides the minimum surface roughness for annealed Aluminium 6063.

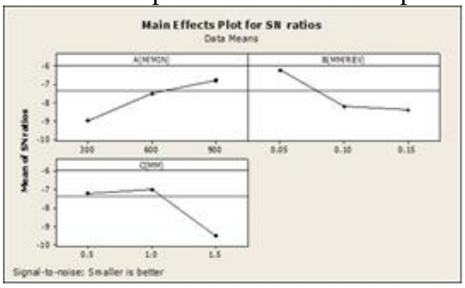

Fig. 6 Factor Effect diagram of S/N ratio for annealed Aluminium specimen

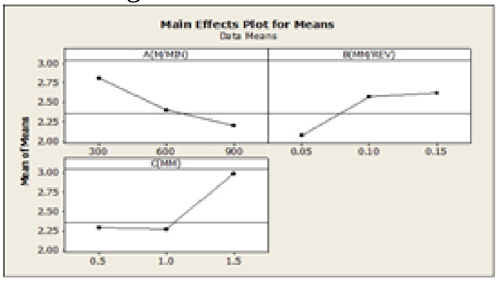

Fig 7 Mean of Surface roughness means against factors for annealed Aluminium 6063

Table 9 shows response table of S/N ratio of the surface roughness for each level of the factors of Aluminium 6063. The difference of SNR between level 1 and 3 indicates that feed rate (B) contributes the highest effect(Δmax-min= 2.396) on the surface roughness followed by cutting speed (Δmax-min= 2.236) and depth of cut (Δmax-min= 1.552) .The graph shown on figure 7 shows the main effect of all the three factors on the mean of means of surface roughness.From the given figure 8, level 3 of A and level 3 of B and level 1 of C show the maximum effect of improving Surface roughness. Hence, A3, B3 and C1 is the best combination i.e. Cutting speed of 900 rpm and feed rate of 0.01 mm/rev and depth of cut of 0.5 mm will provide the minimum surface roughness for unannealed Aluminium 6063. Using S/N ratio, factor affecting the maximum is determined in Table 9.

Table 9 Response Table for S/N ratio in annealed Aluminium

LEVEL	A(m/min)	B(mm/rev)	C(mm)
1	-9.003	-6.200	-7.146
2	-7.467	-8.186	-6.961
3	-6.767	-8.596	-8.513
Delta	2.236	2.396	1.552
Rank	2	1	3

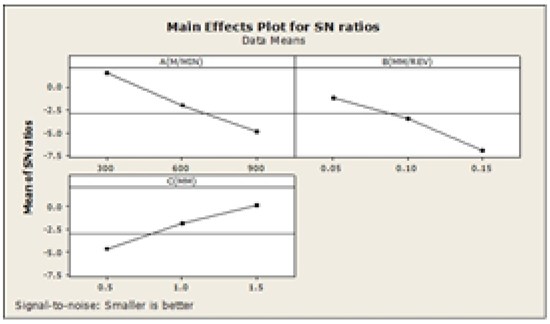

Fig.8.Factor Effect diagram of S/N ratio for unannealed Aluminium specimen 6063

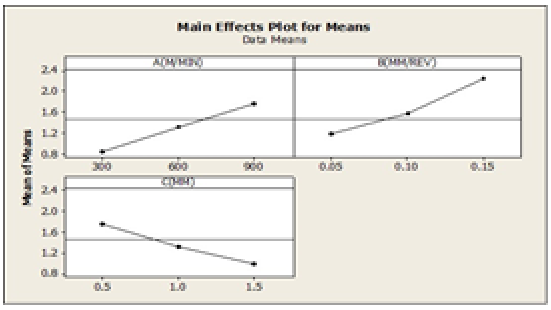

Fig.9.Mean of Surface roughness means against factors for annealed Aluminium 6063

Table 10 shows response table of SNR of the surface roughness for each level of the factors of Aluminium 6063. The difference of SNR between level 1 and 3 indicates that feed rate (B) contributes the highest effect (Δmax-min= 5.7699) on the surface roughness followed by cutting speed (Δmax-min= 5.4328) and depth of cut (Δmax-min= 4.8023).

Table.10.Response Table for S/N ratio of unannealed Aluminium 6063

LEVEL	A(m/min)	B(mm/rev)	C(mm)
1	1.5814	-0.2210	-4.6309
2	-2.0079	-3.4953	-1.8760
3	-3.8515	-6.9909	0.1714
Delta	5.4328	5.7699	4.8023
Rank	2	1	3

The graph shown in figure 9 shows the main effect of all the three factors on the mean of means of surface roughness.

REGRESSION ANALYSIS

Multiple regression analysis is performed to indicate the fitness of experimental measurements as presented with statistical software, named as MINITAB. In the typical application of ANOVA, the null hypothesis is that all groups are simply random samples of the same population. This implies that all treatments have the same effect (perhaps none). Rejecting the null hypothesis implies that different treatments result in altered effects ANOVA and the Equations of Surface Roughness. First, a linear polynomial model is developed to control whether the surface roughness data represents a fitness characteristic as below:

Surface Roughness (μ) = $b_o+b_1A+b_2C+b_3C$, where b_1 and b_2 are estimates of the process parameters. The empirical equation is then derived to describe a functional relationship between the surface roughness (T) and process parameters including A – (spindle speed), B – (feed rate) and C-(depth of cut) as below for Al 6063 material.

The regression equation for annealed Aluminium is: Ra = 1.93 - 0.000916 A (M/MIN) + 9.38 B(MM/REV)+ 0.372 C(MM). In multiple regression analysis, R^2, which is called R-sq, is the correlation coefficient and should be between (0.8) and 1. In this study, R2 is found to be 0.877 which is greater than (0.8). This shows that multiple regression model for surface roughness matches the experimental data.

The regression equation for unannealed Aluminium is: Ra = 0.562 + 0.000768 A (M/MIN) + 8.22 B (MM/REV) + 0.372 C (MM). In this study, R^2 is found to be 0.975 which is greater than (0.8). As seen from this, the multiple regression models for the surface roughness in unannealed aluminium matches very well with the experimental data.

ANOVA ANALYSIS

Analysis of Variance (ANOVA) is a statistics based approach, where objective is decision-making tool for detecting any differences in the average performance of groups of items tested. A test result (calculated from the null hypothesis and the sample) is called statistically significant if it is deemed unlikely to have occurred by chance, assuming the truth of the null hypothesis. A statistically significant result (when a probability (p-value) is less than a threshold (significance level)) value justifies the rejection of the null hypothesis. ANOVA results are illustrated in Table 11. In the analysis, F-ratio is a ratio of mean square error to residual, and is traditionally used to determine the significance of a factor. An F ratio corresponding to 95% confidence level in calculation of process parameters accurately is 0.05. The P value reports the significance level (suitable and unsuitable). Percent (%) is defined as the significance rate of process parameters on Surface roughness.

Examination of the calculated values of variance ratio (F), which is the variance of the factor divided by the error variance for all control factors showed a much higher influence of factor feed rate on the surface roughness of the both Aluminium specimens. A "Model F-Value" is calculated from a model mean square divided by a residual mean square. If the variances are close to the residual variance, it is less likely that any of the factors have a significant effect on the response. In addition, if the "Model P-Value" is very small (less than 0.05) then the terms in the model have a significant effect on the response. Similarly, an "F-Value" on any individual factor terms is calculated from a term mean square divided by a residual mean square that compares a term variance with a residual variance. If the variances are close to the same, it is less likely that the term has a significant effect on the response. Furthermore, if a "P-Value" of any model terms is very small (less than 0.05), the individual terms in the model have a significant effect on the response. If a model is adequate the distribution of residuals should be normally distributed. Minitab program is utilized to perform a normality test, the hypotheses are listed as follows:

1. Null hypothesis: data follow a normal distribution.
2. Alternative hypothesis: data do not follow a normal distribution.

The vertical axis has a probability scale and the horizontal axis with a data scale. Squares line is then fit to the plotted points. The line forms an estimate of the cumulative distribution function for the population from which data are drawn. As a "P-Value" that is smaller than 0.05, it will be classified as "significant", and then the null hypothesis has to be rejected. It can be observed from Table 11 that cutting speed, feed rate and depth of cut affect surface roughness by 17.07%, 37.67% and 26.87% for the Al 6063 annealed material, consecutively. A "Model F-Value" of 1.75 with a "Model P-Value" of 0.252 implies that the selected model is significant model term "B" is significant.

Table 11 Anova table for annealed Aluminium 6063

Variables	Sum of squares	DOF	Mean square	Contribution (%)	F	P
A(m/min)	0.282	2	0.141	17.07	0.62	0.570
B(mm/rev)	0.609	2	0.304	36.87	1.75	0.252
C(mm)	0.444	2	0.222	26.87	1.10	0.391
Error	0.316	2	0.158	19.19		
TOTAL	1.651	8				

Figure 10 shows the effect of feed rate on surface roughness at its 3 values for annealed aluminium. Similarly, in Figure 11 the individual point of feed rate against Ra, gives an idea about various surface roughness for a single value of feed rate. Figure 12 gives residual plots against several parameters such as frequency, percentage, etc. Thus impacts of feed rate on various points are plotted in these graphs.

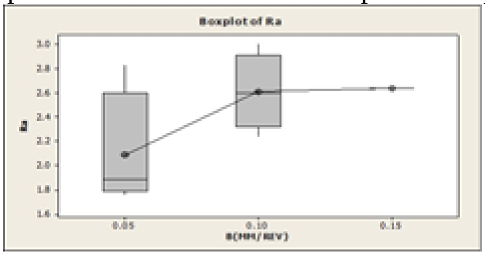

Fig 10 Box plot graph for annealed Aluminium 6063

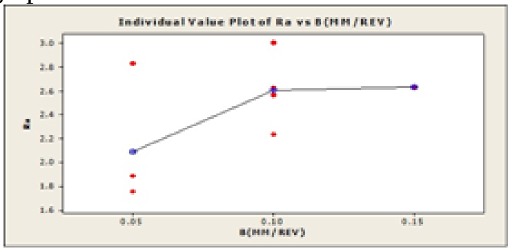

Fig 11 Individual value Plot of Ra vs feed rate

It can be observed from Table 12 that cutting speed, feed rate and depth of cut affect surface roughness by 33.39%, 48.64% and 9.4% for the Aluminium 6063 unannealed material. Thus it is clear that feed rate has major effect on surface roughness followed by cutting speed and depth of cut. "Model F-Value" of 2.84 with "Model P-Value" of 0.135 implies that the in selected model "B" is significant.

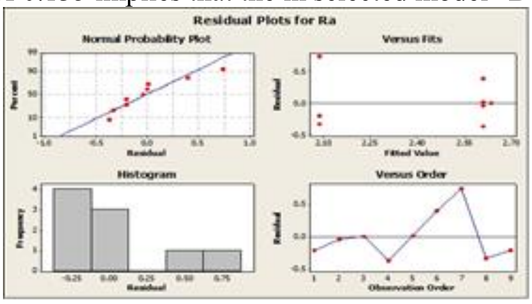

Fig 12 Residual graph with various parameters for annealed Aluminium 6063

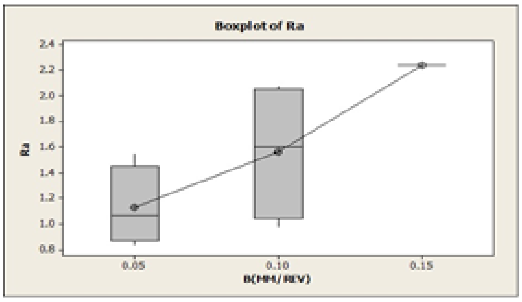

Fig 13 Box plot graph for unannealed Aluminium 6063

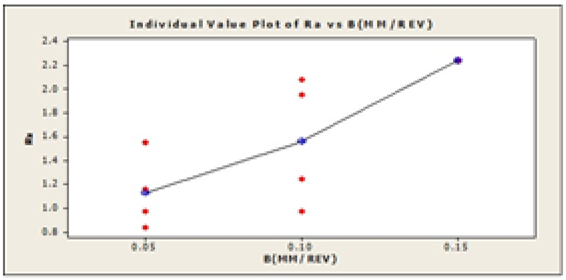

Fig 14 Individual value Plot of Ra vs feed rate

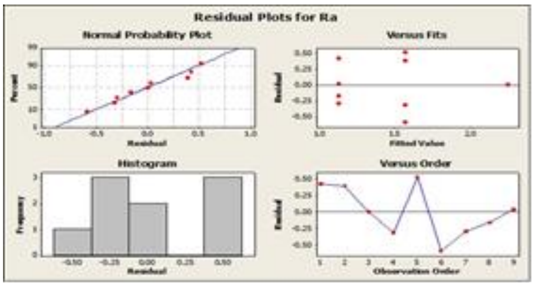

Fig 15 Residual graph with various parameters for unannealed Aluminium 6063

Table.12.Anova table for unannealed Aluminium 6063

variables	Sum of squares	DOF	Mean square	Contribution (%)	F value	P value
A(m/min)	0.758	2	0.379	33.39	1.5	0.296
B(mm/rev)	1.104	2	0.552	48.64	2.84	0.135
C(mm)	0.213	2	0.364	9.4	0.6774	0.632
Error	0.1946	2	0.097	8.57		
Total	2.270	8		100		

Similarly, various graphs are plotted for surface roughness for unannealed aluminiun with most significant parameter as feed rate in fig. 13 and 14. Also given is the graph for residual against various parameters in fig. 15.

CONCLUSION

This study of the machinability of Al 6063 alloy material with HSS tool inserts has produced some useful results and has shown an application of the Taguchi method and ANOVA method for investigating the effects of milling parameters on the surface roughness in the Ecological milling of Al 6063 material. Multiple regression analysis is performed to indicate the fitness of experimental measurements. Normality tests on the residuals of the regression models ensure that the models have extracted all applicable information from the experimental data, and these tests also validate the adequacy of the models. The following results are concluded from it:

Statistically designed experiments based on Taguchi methods were performed using L9 orthogonal arrays to analyze the metal removal rate as response variable.

1. Statistical results (at a 95% confidence level) show that the speed(A), feed rate (B), and depth of cut (C) affect the surface roughness by 17.07%, 38.09% and 27.507% in the end machining of annealed Aluminium respectively.
2. Similarly, Statistical results (at a 95% confidence level) show that the speed(A), feed rate (B), and depth of cut (C) affects the surface roughness by 33.39% ,48.09% and 9.83% in the end machining of non-annealed Aluminium respectively.
3. In this study, the analysis of the confirmation experiment surface roughness has shown that Taguchi parameter design can successfully verify the optimum cutting parameters (A1B3C3), which are cutting speed=300 rpm, feed rate = 0.15 mm/rev and depth of cut=1.5 mm. for annealed Aluminium 6063
4. The analysis of the confirmation experiment surface roughness has shown that Taguchi parameter design can successfully verify the optimum cutting parameters (A3B1C1), which are cutting speed=900 rpm, feed rate = 0.05 mm/rev and depth of cut=0.5 mm. for non-annealed Aluminium 6063.
5. The experiments clearly show the machinability characteristics decrease for annealed Aluminium 6063 in comparison to its non-annealed counterpart. Surface roughness of both states are highly affected by feed rate followed by depth of cut for annealed Aluminium 6063, while for non-annealed Aluminium cutting speed is the second highest impact factor.

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