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Optimization of Surface Roughness and Material Removal Rate on Conventional Dry Turning of Aluminium (6061)

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ABSTRACT

The work and study presented in this paper aims to investigate the effect of the cutting speed, feed rate and depth of cut on surface roughness and material removal rate (MRR), in conventional turning of Aluminium (6061) in dry condition. The cutting tool was prepared with positive Rake angle 20. The effect of cutting condition (cutting speed and feed rate) on surface roughness and MRR were studied and analyzed. Design of experiments (DOE) were conducted for the analysis of the influence of the turning parameters on the surface roughness by using Taguchi design and then followed by optimization of the results using Analysis of Variance (ANOVA) to find minimum surface roughness and the maximum MRR. The feed and speed are identified as the most influential process parameters on surface roughness. The optimum MRR was obtained when setting the cutting speed and feed rate at high values, but the optimum surface roughness was reached when the feed rate and depth of cut were set as low as possible. Low surface finish was obtained at high cutting speed.

Keywords: *Aluminium (6061); ANOVA; Surface Roughness; Taguchi Method; Material Removal Rate (MRR).*

1.0 Introduction

Most of automotive components are manufactured using a conventional machining process, such as turning, drilling, milling, shaping and planning, etc. Aluminium (6061) is widely used for producing automotive components by turning process. This study aims to investigate the effect of the cutting speed, feed rate and depth of cut on surface roughness, and material removal rate (MRR), in conventional turning of Aluminium (6061) in dry condition. Surface roughness is mainly a result of process parameters such as tool geometry (i.e. nose radius, edge geometry, rake angle, etc) and cutting conditions (feed rate, cutting speed, depth of cut, etc). Surface roughness is harder to attain and track than physical dimensions are, because relatively many factors affect surface roughness. Some of these factors can be controlled and some cannot. Controllable process parameters include feed, cutting speed, tool geometry, and tool setup. Other factors, such as tool, work piece and machine vibration, tool wear and degradation, and work piece and tool material variability cannot be controlled as easily.

The important cutting parameters discussed here are cutting speed, feed and depth of cut. It is found in most of the cases surface roughness decreases with increase in cutting speed and decrease in feed and depth of cut. Since these cutting parameters will decide about the type of chips which we expect at the time of machining of a single constant material thus we have to analyze them for no such built-up edge chips formation.

The Taguchi method is statistical tool, adopted experimentally to investigate influence of surface roughness by cutting parameters such as speed, feed and depth of cut. Many researchers developed many mathematical models to optimize the cutting parameters to get lowest surface roughness by turning process.

The variation in the material hardness, alloying elements present in the work piece material and other factors affecting surface finish. Proper selection of cutting parameters and tool can produce longer tool life and lower surface roughness. Hence, design of experiments by Taguchi method on cutting parameters was adopted to study the surface roughness.

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Taguchi's parametric design is the effective tool for robust design it offers a simple and systematic Taguchi method of off-line (Engineering) quality control encompasses all stages of product/process development. However the key element for achieving high quality at low cost is Design of Experiments (DOE).

In this paper Taguchi's (DOE) approach is used to analyze the effect of process parameters like cutting speed, feed, and depth of cut on Surface Roughness of Aluminium 6061 work material while machining with The cutting tool which was prepared with positive Rake angle 20 and to obtain an optimal setting of these parameters that may result in good surface finish. Analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are all equal, and therefore generalizes *t*-test to more than two groups.

ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. The statistical significance of the experiment is determined by a ratio of two variances. This ratio is independent of several possible alterations to the experimental observations: Adding a constant to all observations does not alter significance.

Multiplying all observations by a constant does not alter significance. So ANOVA statistical significance results are independent of constant bias and scaling errors as well as the units used in expressing observations.

2.0 Material Removal Rate

The effects of machining parameters on MRR and surface roughness in turning process were widely investigated by previous researchers. According to Qian and Hosan (2007), the cutting force and feed force increased with increasing feed, tool edge radius, negative rake angle, and work piece hardness. Cutting force and feed force also increased linearly with the depth of cut.

According to Jaharah et al. (2009a), the *Ra* produced was significantly affected by the feed rate, followed by the cutting speed and depth of cut where the contribution of feed rate, the cutting speed and depth of cut were 45%, 32%, and 23% respectively. Ghani et al. (2002) investigated that surface finish of the work piece was not influenced by the tool wear; however, increasing cutting speed, feed rate or depth of cut will affect the surface finish.

Tool performance was evaluated with respect to tool wear, surface finish produced and cutting forces generated during turning (Yigit et al., 2008). Jaharah et al. qualitative optimal design to a relatively low cost.

The (2009b) said that the width formation of microstructure changes increases with the increase in wear land and feed rate. Taguchi methods DOE was used to optimize the surface roughness and MRR value. Taguchi methods is a powerful tool for designing a high-quality system that provides smaller, less costly experiments and yet withdraw a valid conclusion. Taguchi's parameter design also offers a simple, systematic approach and can be used to optimize design for performance, quality and cost. Signal-to-noise (S/N) Ratio and orthogonal array are two major tools used in robust design.

Signal-to- noise (S/N) ratio, which measures quality with emphasis on variation, and orthogonal arrays, which accommodates many design factors simultaneously (Park 1996, Phadke 1998). Taguchi method also offers the quality of product which is measured by quality characteristics such as: nominal is the best, smaller is better and larger is better (Phadke 1998).

Taguchi techniques were widely used in engineering analysis in the system, parameter and tolerance design (Pease, 1993). Other researchers (Hascalik and Caidas, 2008; Pawade et al., 2008; Kurt et al., 2009) also utilized Taguchi methods in their various research activities.

Understanding of material removal concept (MRR) in metal cutting is very important in designing process and cutting tool selection to ensure the quality of the product. The material removal rate (MRR) in turning operations is the volume of material/metal that is removed per unit time in mm³/min. For each revolution of the work piece, a ring shaped layer of material is removed.

Therefore, MRR in mm³/min is: $1000 Vf$
Where V is: $\pi dn / 1000$, is cutting speed in mm/min, d is diameter of the work piece in mm, n is spindle speed in rpm, f is machine feed rate mm/revolution. a is depth of cut.

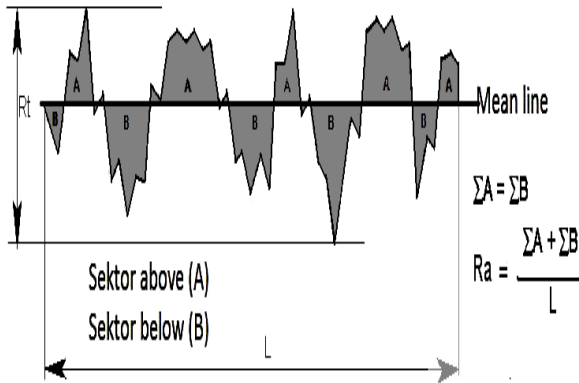
3.0 Surface Roughness

Out of all the surface condition criteria, *Ra* and *Rt* (expressed in μm) are often used to characterize the roughness of machined surfaces.

Rt is total roughness (maximum depth or amplitude of the roughness), and *Ra* is arithmetic roughness (mean arithmetic deviation from the mean line of the roughness) as $Ra = (\Sigma A + \Sigma B) / L$. (H. Yanda et.al. 2010). Definition of the mean line is $\Sigma A = \Sigma B$ as shown in Figure 1. Surface condition is being determined by several factors:

- Cutting parameters (cutting speed, feed)
- Tool geometry (angle and sharpness of the cutting edge, corner radius, etc)
- The material the cutting tool is made from the rigidity of the assembly and of the machine
- The forming of chips, cutting forces, etc.

Fig 1: Schematic of parameter definition used to compute the mean arithmetic deviation (R_a) and total roughness (R_t) (H. Yanda et.al, 2010)



4.0 Experiment Set Up

The machining trials were carried out in dry condition without coolant on conventional Lathe Machine model Kirloskar Turnmaster-35. The work piece material used was 6061 Aluminum HINDALCO made. The cylindrical work piece was prepared in the form of round bar 50 mm in diameter and 150 mm in length. The machining condition parameters were the cutting speed of 180, 450 and 710 rpm, feed rate of 0.2, 0.315 and 0.4 mm/rev, while the depth of cut (DOC) was 0.2,0.4,0.6 mm. The effect of cutting condition (cutting speed and feed rate) on surface roughness and material removal rate (MRR) were studied and analyzed.

Experiments were conducted based on the Taguchi design of experiments (DOE) with orthogonal L27 array, and then followed by optimization of the results using Analysis of Variance (ANOVA) to find minimum surface roughness and the maximum MRR.

4.1 Work piece material

Standardized material were selected to ensure consistency of the alloy, which was a common wrought alloy used in industry 6061 Aluminum HINDALCO made in the form of bars with the size of diameter 50 mm 150 mm length so as to fit under the chuck.

Table: 1. Chemical Composition of Aluminum Alloy

Element	Cu	Mg	Si	Fe	Mn	Other
Weight %	0.15-0.4	0.7-1.2	0.4-0.8	0.7 max	0.2-0.8	0.4

The aluminum we have chosen for turning is actually a Heat Treatable Alloy manufactured in the form of bars by HINDALCO. The inputs which were fed in the form of part program include dimensions of the work piece, cutting parameters depth of cut in mm, Speed available was 50-3500 rpm and feed in mm/min. This standard structural alloy, one of the most versatile of the heat-treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Applications range from transportation components to machinery and equipment applications to recreation products and consumer durables.

Alloy 6061 has excellent corrosion resistance to atmospheric conditions and good corrosion resistance to sea water. This alloy also offers good finishing characteristics and responds well to anodizing. Alloy 6061 is easily welded and joined by various commercial methods. (Caution: direct contact by dissimilar metals can cause galvanic corrosion). For screw machine applications, alloy 6061 has adequate machinability characteristics in the heat-treated condition.

The different alloying elements present in a work piece are shown in the Table 1. The control factors and their levels are illustrated in Table 1. The cutting parameters ranges were selected based on machining guidelines provided by manufacturer of cutting tools

Table: 2. Cutting Parameters and Levels

Code	Cutting Parameter	Level 1	Level 2	Level 3
	Speed „s“ (rpm)	180	450	710
	Feed „f“ (mm/rev)	0.2	0.315	0.4
	Depth of cut „d“ (mm)	0.2	0.4	0.6

The surface roughness of machined surface has been measured by a Surface Roughness Measuring instrument, the Surtronic 3+, is a portable, self-contained instrument for the measurement of surface texture and is suitable for use in both the workshop and laboratory.

Parameters available for surface texture evaluation are: Ra, Rq, Rz (DIN), Ry and Sm. The parameters evaluations and other functions of the instrument are microprocessor based. The measurements results are displaced on an LCD screen and can be output to an optional printer or another computer for further results.

The dependent variable is surface roughness. Table 3 shows standard L27 (33) orthogonal array designed by Taguchi with experimental results. the Table 3 includes coding values of control factors ,real values of cutting parameters and the results of the measured values of the surface roughness and calculated values. The different units used here are: speed- rpm, feed - mm/ rev, depth of cut -mm and surface roughness Ra - μm . Design – MINTAB software was used for Taguchi’s method and for analysis of variance (ANOVA).

4.2 Surface roughness

Surface properties such as roughness are critical to the function ability of machine components. Increased understanding of the surface generation mechanisms can be used to optimize machining process and to improve component function ability.

The present study has shown two purposes. The first was to demonstrate the use of Taguchi parameter design in order to identify the optimum surface roughness with particular combination of cutting parameters and a systematic procedure using Taguchi design in process design of turning operations. The second was to determine the optimum combination of process parameters more accurately by investigating the relative importance of process parameters using ANOVA. The obtained results are analyzed using Minitab software and all the values are shown in the Table 4.

Table: 3. Machine Readings and Calculations of Roughness

Experi- ent.No	Control Factors			Speeds (s) (Rev/min.)	Feed (f) (mm per rev.)	Depth of cut (d) (mm)	Measured Ra (μm)	MRR mm ³ /min)	MRR mm ³ /sec)
	A	B	C						
	(s)	(f)	(d)						
1	1	1	1	180	0.2	0.2	1.04	113.927	8.56545
2	1	1	2	180	0.2	0.4	0.98	212.018	6.86697
3	1	1	3	180	0.2	0.6	2.2	261.698	4.36163
4	1	2	1	180	0.315	0.2	2.44	672.129	7.86882
5	1	2	2	180	0.315	0.4	3.84	333.569	5.55948
6	1	2	3	180	0.315	0.6	2.4	897.738	1.62897
7	1	3	1	180	0.4	0.2	2.06	022.443	3.70738
8	1	3	2	180	0.4	0.4	2.3	953.491	5.89151
9	1	3	3	180	0.4	0.6	3.66	901.732	8.3622
10	2	1	1	450	0.2	0.2	0.9	780.859	6.34764
11	2	1	2	450	0.2	0.4	0.94	528.915	2.14858
12	2	1	3	450	0.2	0.6	2.9	145.761	35.7627
13	2	2	1	450	0.315	0.2	1.42	176.76	9.61266
14	2	2	2	450	0.315	0.4	3.38	303.637	38.3939
15	2	2	3	450	0.315	0.6	1.34	2263.05	04.3842
16	2	3	1	450	0.4	0.2	1.74	040.271	4.00451
17	2	3	2	450	0.4	0.4	1.94	890.513	64.8419
18	2	3	3	450	0.4	0.6	2.88	4822.2	47.0366
19	3	1	1	710	0.2	0.2	0.86	130.586	8.84311
20	3	1	2	710	0.2	0.4	0.92	744.814	45.7469
21	3	1	3	710	0.2	0.6	1.98	2862.91	14.3818
22	3	2	1	710	0.315	0.2	1.14	592.809	09.8802
23	3	2	2	710	0.315	0.4	1.22	3098.48	18.308
24	3	2	3	710	0.315	0.6	1.16	9365.24	22.7539
25	3	3	1	710	0.4	0.2	1.2	948.858	32.481
26	3	3	2	710	0.4	0.4	1.38	5658.57	60.9762
27	3	3	3	710	0.4	0.6	2.68	3305.82	88.4304

Table: 4. ANOVA: Analysis of Variance for Raversus s, f, d

Source	DF	SS	MS	F	P
ss	22	3.9387	1.9693	33.97	0.035
ff	22	3.1307	1.5653	33.16	0.064
dd	22	3.9207	1.9604	33.95	0.036
Error	220	9.9167	0.4958		
Total	226	20.9069			

Table: 5. ANOVA: Analysis of Variance for MRR versus s, f, d

Source	DF	SS	MS	F	P
s	2	107200	53600	7.86	0.000
f	2	24922	12461	8.80	0.002
d	2	74221	37110	6.21	0.000
Error	20	28317	1416		

Table: 6. Ranking of Cutting Parameters

Level	1	2	3	Rank
Speed	180	450	710	1
Feed	0.2	0.315	0.4	2
Depth of cut	0.2	0.4	0.6	3

It can be seen from ANOVA table 4 that feed is the maximum contributing factor and other details of DOF - Degrees of freedom, S.S - Sum of Squares, M.S - Mean of Squares and Error are mentioned. Hence as a result the individual ranking of cutting parameters on the average value of mean on surface roughness are shown in Table 5.

Fig: 2. Residual Histogram for Ra

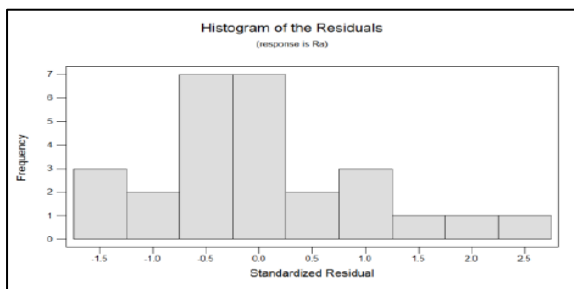


Fig: 3. Normplot of Residuals for Ra

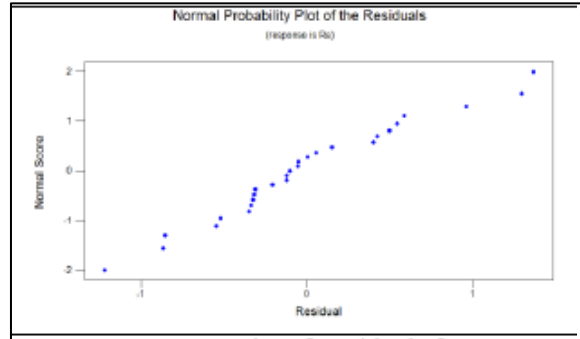


Fig: 4. Normplot of Residuals for MRR

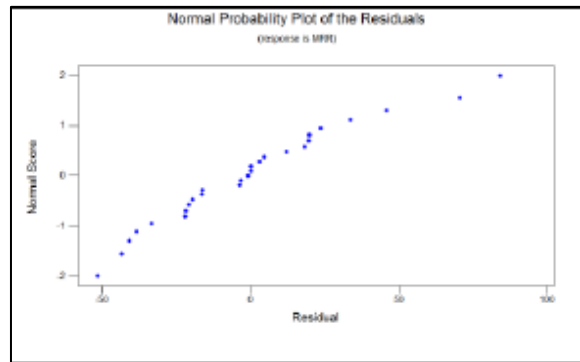


Fig: 5. Residuals vs Order for Ra

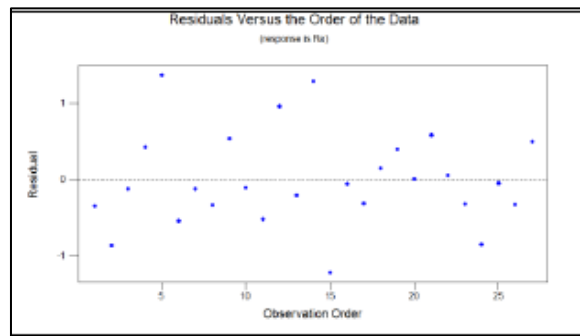
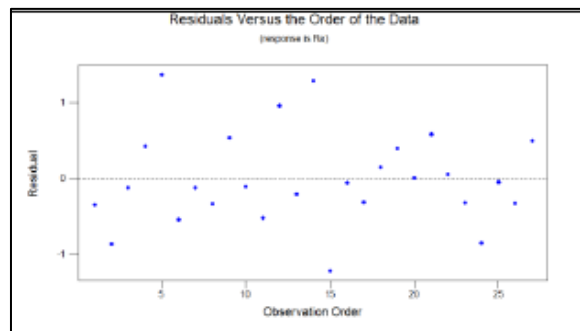


Fig: 6. Residuals vs Order for MRR



5.0 Main effect plots analysis for Ra and MRR

The analysis is made with the help of software package MINITAB. The main effect plot for Ra and MRR are shown in following figures .They show the variation of individual response with three parameters i.e. speed, feed and depth of cut separately. In the plot x-axis represents the value of each process parameter and y-axis is response value. Horizontal line indicates the mean of the response. The main effect plots are used to determine the optimal design conditions to obtain the optimal surface finish.

According to this main effect plot, the optimal conditions for minimum surface roughness are speed at level 3 (710 RPM), feed rate at level 1 (0.2 mm/rev) and depth of cut at level 1 (0.2mm). The main effect plot for S/N ratios of the Surface roughness for data means is shown in Fig 7, 8, 9,10,11,12. Signal-to-Noise ratio of common interest for optimization for surface roughness is smaller the better.

The diagnostic checking has been performed through residual analysis for the developed model. The residual plots for surface roughness are shown in Fig. These are generally fall on a straight line implying that errors are distributed normally. From Fig .4, 5, 6, 7, it can be concluded that all the values are within the control range, indicating that there is no obvious pattern and unusual structure and also the residual analysis does not indicate any model inadequacy.

Hence these values yield better results in future predictions.

5.1 Main effect plots analysis for Ra

Fig: 7. Main Effects for S/N Ratios: Ra

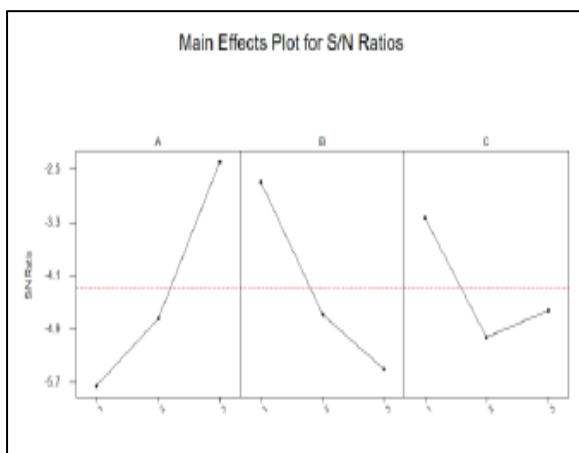


Fig: 8. Main Effects for Means: Ra

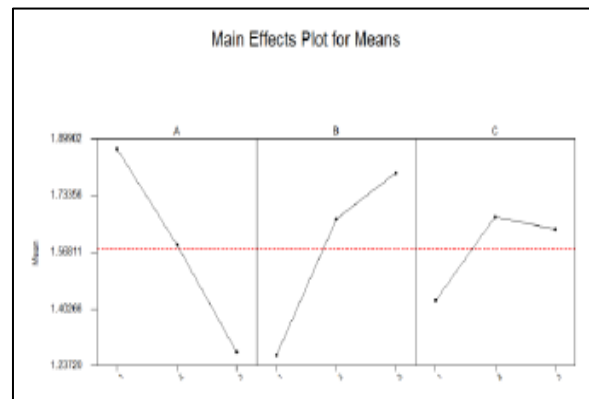
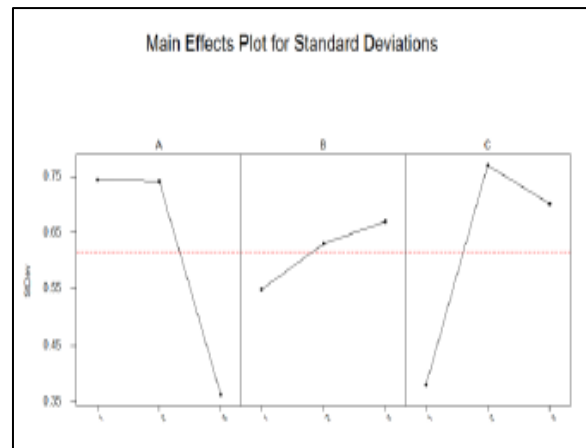


Fig: 9. Main Effects for St Devs: Ra



5.2 Main effect plots analysis for MRR

Fig: 10. Main Effects for S/N Ratios: MRR

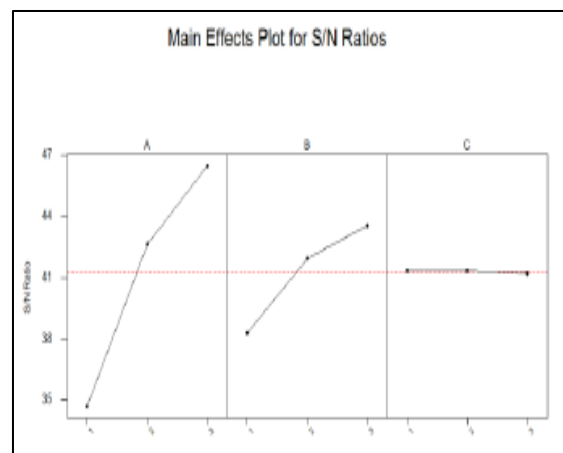


Table: 7. Response Table for Signal to Noise Ratios for Ra and MRR

Response Table for Signal to Noise Ratios for Ra				Response Table for Signal to Noise Ratios for MRR			
Smaller is better				Larger is better			
Level A	B	C		Level A	B	C	
1	-5.74857	-2.68229	-3.22270	1	34.6822	38.2777	41.3009
2	-4.73456	-4.68106	-5.02022	2	42.6291	41.9417	41.3000
3	-2.37977	-5.49955	-4.61998	3	46.4629	43.5548	41.1734
Delta	3.36880	2.81726	1.79752	Delta	11.7807	5.2772	0.1275
Rank	1	2	3	Rank	1	2	3
Response Table for Means				Response Table for Means			
Level A	B	C		Level A	B	C	
1	1.86893	1.26729	1.42604	1	1602.31	2755.25	4258.54
2	1.58814	1.66609	1.67230	2	4007.47	4162.88	4138.52
3	1.27651	1.80020	1.63525	3	6309.44	5001.09	3522.15
Delta	0.59243	0.53292	0.24626	Delta	4707.13	2245.84	736.39
Rank	1	2	3	Rank	1	2	3
Response Table for Standard Deviations				Response Table for Standard Deviations			
Level A	B	C		Level A	B	C	
1	0.744674	0.549658	0.378507	1	1958.01	3384.97	5209.71
2	0.742362	0.630062	0.769872	2	4901.91	5089.40	5059.80
3	0.362392	0.669709	0.701050	3	7732.96	6118.51	4323.37
Delta	0.382283	0.120051	0.391365	Delta	5774.95	2733.55	886.33
Rank	2	3	1	Rank	1	2	3

Fig: 12. Main Effects for St Devs: MRR

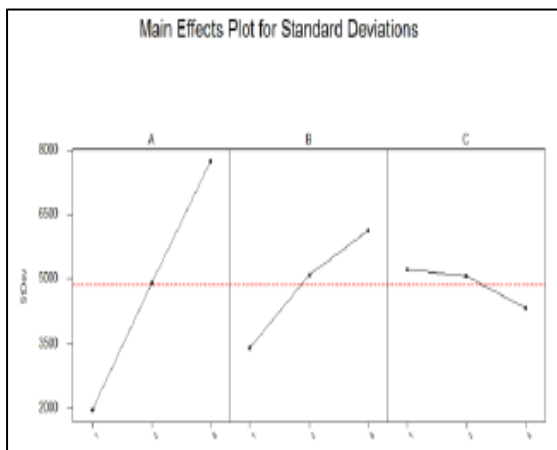
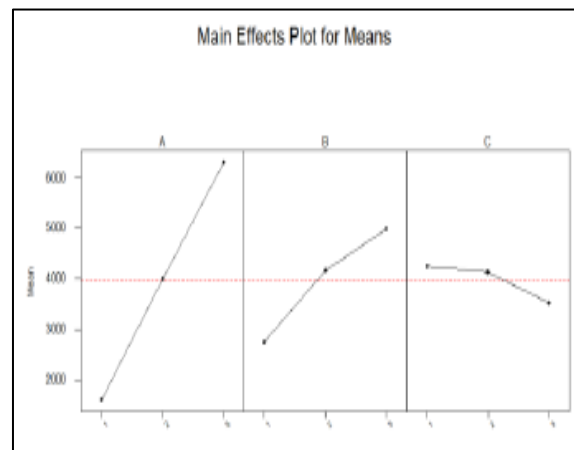


Fig: 11. Main Effects for Means: MRR



6.0 Conclusions

This work presented an experimentation approach to study the impact of machining parameters on surface roughness. Strong interactions were observed among the turning parameters. Most significant interactions were found between work materials, feed and cutting speeds. A Systematic approach was provided to design and analyze the experiments, and to utilize the data obtained to the maximum extend. The following are conclusions drawn based on the experimental investigation conducted at three levels by employing Taguchi technique to determine the optimal level of process parameters.

- From the data collection it has been observed that the increase in cutting speed tends to improve the finish, thus the average surface roughness value decreases.
- The increase in depth of cut influences the finish slightly, but greater depth of cut marks the finish poor.
- Speed is the most critical parameter when finish is the criterion.
- Finish gets poor as the feed increases, thus the average surface roughness value increases with increase in feed.
- The ANOVA and F-test revealed that the speed and depth of cut are dominant parameters followed by feed for surface roughness.
- The optimal combination process parameters for minimum surface roughness are obtained at 710 rpm, 0.2 mm/rev and 0.2mm.
- Taguchi gives systematic simple approach and efficient method for the optimum operating conditions.

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