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RESEARCH

Optimization of Cutting Parameters for MRR, Tool Wear and Surface Roughness Characteristics in Machining ADC12 Piston Alloy Using DOE

H.D. Kumar[a], S. Ilangovan[a], N. Radhika[a,*]

[a]*Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Tamilnadu, India.*

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* Corresponding author:

N. Radhika
E-mail: n_radhika1@cb.amrita.edu

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A B S T R A C T

This paper presents the optimization of cutting parameters for MRR, tool wear and surface roughness characteristics in machining of ADC12 alloy. Milling experiments were performed on CNC Milling machine using uncoated carbide inserts. The objective is to minimize the surface roughness, tool wear and maximize the MRR. Process parameters that included speed (1000, 2000, 3000) rpm, feed (0.05, 0.075, 0.1) m/min and Depth of Cut (DOC) of (0.5, 1.0, 1.5) mm were varied for three levels to determine the test cases with the help of Taguchi's Orthogonal Array (L9), following which, surface roughness, MRR and tool wear was calculated. MRR and tool wear showed similar trends where the responses increase with speed, feed and DOC, whereas the surface roughness tends to increase with feed but lowers on increasing the speed and DOC. Minimum surface roughness and tool wear obtained was 0.25 µm and 0.001 mm respectively, whereas maximum MRR obtained was 0.1144 mm³/min. Speed had major influence on MRR and tool wear whereas, feed had highest impact on surface roughness. ANOVA results also depicted the same rankings. Regression analysis was performed to estimate the surface roughness, MRR and tool wear which was further validated using confirmation tests.

1. INTRODUCTION

Machining processes like Milling, Drilling and Turning operations preserve their importance even with the advancements in technology. Aluminium alloys are used in a wide variety of applications such as automobiles, aircraft, spacecraft, marine, transformers etc. An escalation in customer requirements should be met by good quality products (precisely better surface finish). The grade of surface roughness is an indispensable factor in most of the work pieces. Surface roughness of a machined product can affect many of the functioning aspects like light friction, heat transmission, ability of distributing and holding a lubricant, wearing, surface friction, withstand fatigue of a material. Hence surface roughness is the predominant qualitative aspect in machining processes. Material removal rate (MRR) is an important factor which indicates the machining rate. Failure of cutting tools due to continuous operation results in tool wear. Bin yan et al. [1] experimentally examined the impact of high speed cutting, rake angle and DOC on milling of ADC12 alloy. MRR, tool wear and surface roughness were the responses obtained. It was reported that axial DOC does not significantly affect the surface roughness. Radhika et al. [2]used Taguchi's Design of Experiments(DOE) to analyze the machining characteristics of hybrid composites in Electrical discharge machining (EDM) process. This method gave an optimized set of control parameters that minimizes the surface roughness and tool wear and maximizes the MRR. Rabindra Behera et al. [3] used uncoated carbide inserts to evaluate the machinability of cast composite at constant feed rate. It was concluded that discontinuous second phase particles significantly influence the machinability, as their presence led to rapid tool wear. Radhika et al. [4] focused on designing a hybrid composite and further optimized the turning conditions in order to obtain minimum surface temperature and roughness. It was inferred that, surface roughness increased with feed and DOC and decreased when the speed rates are high. S. Ramesh and P. Elangovan [5] studied the effect of machining parameters on surface quality of certain aluminium alloys through milling using a high speed steel tool. It was concluded that, feed rate was the significant factor that affects surface roughness. Through this experiment it was able to reduce the machining time, machining cost and tool life. Jithin and Ramesh [6] employed Taguchi methodology to estimate the surface roughness in turning of aluminium alloy. Analysis of Variance (ANOVA) was used to calculate the percentage contribution of each factor governing surface roughness. The surface roughness of aluminium alloys was enhanced by using optimum parameters. Ranganath et al. [7] conducted experiments on aluminium (6061) for optimizing the surface roughness and MRR. Increasing the speed and feed rates yielded optimum MRR, thus ensuring the product quality. MRR is crucial in the selection of cutting tools and it's designing.

Puneet Saini et al. [8] developed an empirical model to optimize the surface roughness and studied the effect of coated insert on EN-24 steel alloy. It was reported that feed rate was the prime factor that influenced surface roughness. Ravi Aryan et al. [9] utilized MINITAB for the experimental work on AA6082 alloy. ANOVA was employed for optimizing the cutting parameters for surface roughness and MRR in turning process followed by regression analysis. The tool material was varied and the results showed that flank angle was the most significant factor that affected both High speed steel (HSS) and carbide tool, while spindle speed was most significant factor that affected cobalt tool. Muley et al. [11] analyzed the influence of process parameters in turning of AISID2. It was found that the productivity and cost of manufacturing was affected by MRR. Surface roughness decreased with the increase in cutting speed as, the high temperature attained due to high cutting speed made the work piece material soft. Thangarasu and Shivasubramanian [12] applied DOE based on a genetic algorithm optimization methodology, which was used to solve multi-objective optimization problems. MRR and surface finish were identified as quality characteristics that influence the productivity. Box-benkhen method was adopted to get the optimized result. Manna and Bhattacharya [13] used uncoated tungsten carbide to study the machinability of aluminium composite. The combined effect of cutting parameters on flank wear was also investigated during the experimentation. It was reported that feed was less sensitive to flank wear compared to speed. Gaurav and Rahul [14] conducted a comparative study on AISI 410 steel and Aluminium 6061 to optimize their surface roughness and MRR. Speed, feed and DOC were the parameters chosen and a carbide cutting tool was utilized. The optimization results showed that speed was the important parameter for AISI 410 Steel while there were no significant factors for milling of Aluminium 6061. Deepthi and Prasadrao [15] considered spindle speed, cut feed, step over and depth of cut as the machining parameters in a CNC vertical milling machine. Optimized results were found to be at minimum speed and feed. Kinjal et al. [16] aimed to increase the productivity without compromising the product quality. The inference was that feed rate and cutting speed were prime factors that affected the surface finish and MRR. Malvade and Nipanikar [17] reported that MRR was significantly affected by DOC and the surface finish was influenced by the cutting speed. These cutting parameters were optimized for the milling process of OHNS steel using Taguchi methodology. Lin et al. [18] demonstrated the machinability of SiC reinforced aluminium composite. Polycrystalline Diamond (PCD) inserts was selected and a Scanning Electron Microscope (SEM) was used to measure the maximum flank wear. Tool life was analyzed using regression techniques and Taylor's equation. Sai Charan et al. [20] used grey scale analysis to optimize the MRR, tool wear and surface roughness in EDM process. Surface plots indicated that peak current influenced MRR and surface roughness whereas, tool wear rate was lowered by an increase in pulse on time. Kilickap et al. [21] investigated the effect of tool wear and surface roughness in machining of homogenized SiC-p reinforced aluminium composite. These materials were difficult to machine owing to their hardness and abrasive nature of SiC particles. Tool wear was lowered by using coated cutting tools compared to uncoated tools. It was observed that tool wear increased with cutting speed.

In the present work, Taguchi methodology (L9) has been employed to optimize the process parameters of cutting speed, feed and DOC in milling of ADC12 alloy. The optimum values and percentage influence is obtained using ANOVA. Surface roughness, MRR and tool wear are predicted. Regression equation is modeled and validated using confirmation experiments.

2. SELECTION OF MATERIALS

Al-Si alloys showcase high wear characteristics, low thermal coefficient and good strength. They are lightweight alloys with corrosion resistant properties and their density is low compared to other such alloys. Some important features of Al-Si include high flow-ability, excellent weld-ability and are heat treatable alloys [19]. The microstructure flow-ability of the alloy increases with the addition of silicon. High silicon content converts to high flow property. Silicon also helps in increasing the wear resistance of the alloy [10]. ADC12 has a density of 2.76 g/cm^3 with a thermal conductivity of 10-40 W/mK at 1100 ºC. It has a specific heat of 96.2 J/gK. Other properties of ADC12 include: Elastic Modulus = 68.90 GPa, Thermal Expansion Coefficient = 31.1 x 10^{-6} K^{-1} and Poisson Ratio = 0.33. The elemental composition of ADC12 is shown in Table 1.

Table 1. Elemental composition of ADC12.

Elements	Al	Si	Fe	Cu	Mn
(%)	85.03	10.49	0.983	1.963	0.216
Elements	Mg	Cr	Ni	Zn	Ti
(%)	0.224	0.089	0.078	0.817	0.057
Elements	Pb	Ca	Sr	Zr	Bi
(%)	0.031	0.005	0.001	0.007	0.014

3. FORMULATION AND PLAN OF EXPERIMENT

Plan of experiments was completed using Taguchi's technique and L9 orthogonal array was chosen for obtaining optimum results with minimum number of experiments as shown in Table 2 followed by confirmation test. Experiments were performed by considering three process parameters such as speed, feed and DOC, which were varied for three levels. Surface roughness, MRR and Tool wear were the three responses evaluated using S/N ratio and ANOVA. This was done using MINITAB which is exclusively used for DOE applications. These values were converted into S/N ratio to obtain the measure of performance and process insensitive to noise factors. For surface roughness and tool wear, S/N ratio is taken as smaller is better (Eq.1) and for Material Removal Rate (MRR) it is taken as Larger is better (Eq.2).

Smaller – is – better : The formulation for smaller – is – better S/N Ratio using base 10 log is calculated for each factor level combination as $S/N = -10x\log(\Sigma(Y^2)/n)$ (Eq.1)

Larger – is – better : The formulation for Larger – is – better S/N Ratio using base 10 log is calculated for each factor level combination as $S/N = -10x\log(\Sigma(1/Y^2)/n)$ (Eq.2)

Table 2. Machining parameters and levels.

Level	**Parameters**		
	Speed(rpm)	Feed(m/min)	DOC(mm)
Level 1	1000	0.050	0.5
Level 2	2000	0.075	1.0
Level 3	3000	0.100	1.5

4. EXPERIMENTAL SETUP

Milling was performed on blocked pieces of dimensions 85x63x43 mm respectively. A BFW CNC machine was used for machining as shown in Fig. 1.This CNC is a Fanuc OiMC controlled system which is a 3 phase system with a clamping area of 350 x 600 mm and feed rates ranging from 1-10000 m/min. After the completion of each experiment, the surface roughness was measured using a Zeiss Tokyo surface tester (Fig. 2), with traversing length of 12.5 mm, a resolution of 0.02 µm with probing force of 4mN and diamond as stylus material. Tool wear in the inserts was measured using a vision inspection system (Rapid-I) shown in Fig. 3 with a small field view of 2.8x2.2 mm, state-of-the-art USB 3.0 digital cameras and XYZ movements with 0.5 µm resolution. An uncoated carbide insert (SEGT-13T3AGFN-JPHTi10) with nose radius of 1 mm shown in Fig. 4 was used.

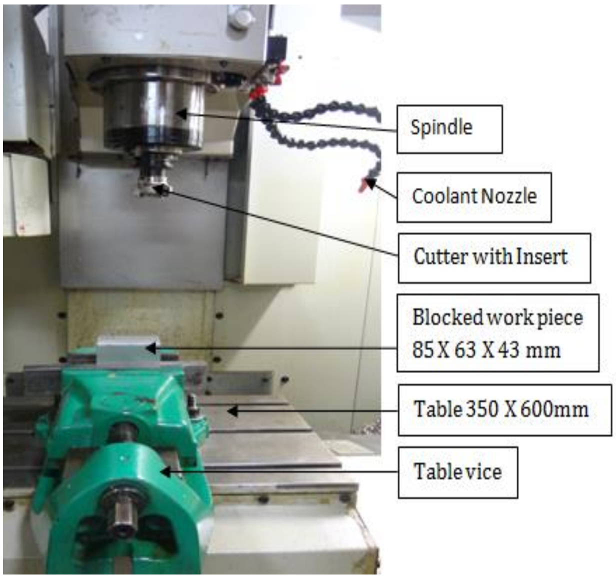

Fig. 1. Closer view of BFW CNC Machine.

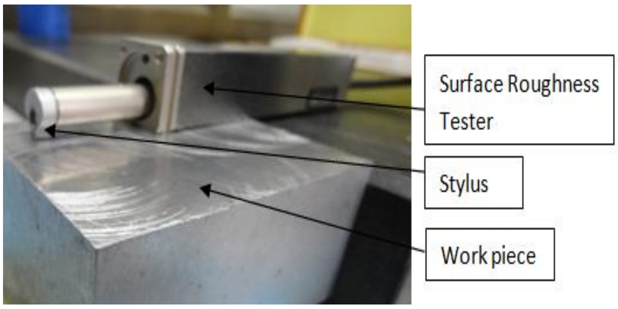

Fig. 2. Zeiss Tokyo surface roughness.

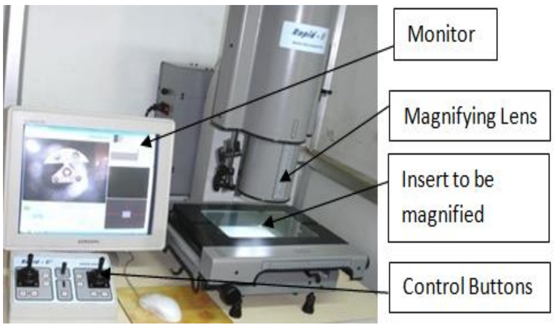

Fig. 3. Vision inspection system.

Fig. 4. Tool wear in Insert.

5. RESULTS & OBSERVATION

Table 3 shows the experimental conditions and the responses such as surface roughness, tool wear and MRR.

Table3. Experimental level and responses for Ra, MRR and Tool wear.

S (rpm)	F (m/min)	D (mm)	Ra (µm)	S/N (dB)	MRR (mm^3/min)	S/N (dB)	TW (mm)	S/N (dB)
1000	0.050	0.5	2.25	-7.04	0.0106	-39.49	0.00100	60.00
1000	0.075	1.0	2.70	-8.62	0.0362	-28.82	0.00130	57.72
1000	0.100	1.5	3.55	-11.00	0.0844	-21.47	0.00175	55.13
2000	0.050	1.0	1.38	-2.79	0.0557	-25.08	0.00159	55.97
2000	0.075	1.5	1.57	-3.91	0.1138	-18.87	0.00201	53.93
2000	0.100	0.5	2.85	-9.09	0.0736	-22.66	0.00200	53.97
3000	0.050	1.5	0.25	12.04	0.1050	-19.57	0.00238	52.46
3000	0.075	0.5	2.10	-6.44	0.0644	-23.82	0.00217	53.27
3000	0.100	1.0	2.30	-7.23	0.1144	-18.83	0.00221	53.11

5.1 INFLUENCE OF PROCESS PARAMETERS ON SURFACE ROUGHNESS

From Fig. 5, it is observed that an increase in speed and DOC lowers the surface roughness, whereas an increase in feed rates causes the surface roughness to increase. Similar trends in cutting speed was obtained by Muley et al. [11] for turning of AI-SI D2. The quality of the surface is greatly influenced by the feed rate. At high feed rates, large chips are formed, which inturn increases the tool interface and the temperature in the work piece. This leads to an increase in friction and hence leads to high surface roughness. Chatter vibration is induced while varying the cutting speeds which lead to decrease in surface roughness. For high DOC, surface finish is poor, which is due to HAZ (Heat affected zone) and shear angle, which depends on DOC. High friction and temperature rise is also observed when the material is removed, which inturn lowers the surface quality of the material. Figure 6 gives the optimum values for speed, feed and DOC which are 3000 rpm, 0.050 m/min and 1.5 mm respectively. It is inferred from Table 4 that, delta values are highest for feed followed by speed and DOC. Feed and speed are significant factors that affect surface roughness whereas, DOC is not significant when in comparison.

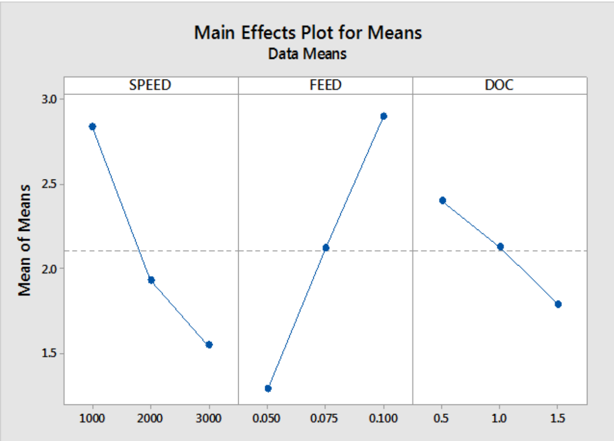

Fig. 5. Plot for means of Ra.

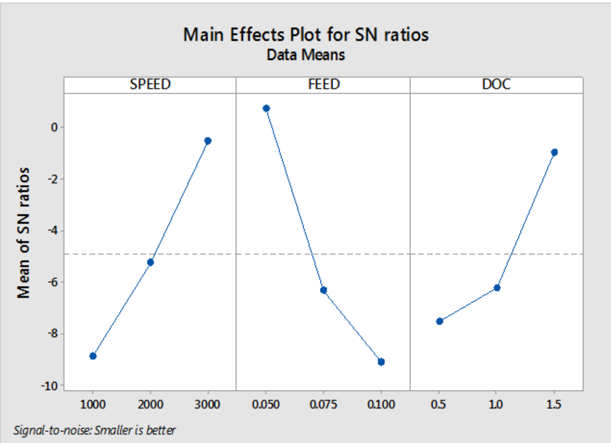

Fig. 6. Plot for S/N ratio for Ra.

Table 4. Response table for S/N ratio.

Level	SPEED	FEED	DOC
1	-8.8918	0.7333	-7.5283
2	-5.2708	-6.3299	-6.2198
3	-0.5459	-9.1120	-0.9605
Delta	8.3459	9.8453	6.5679
Rank	2	1	3

5.2 INFLUENCE OF PROCESS PARAMETERS ON MRR

From Fig. 7, it is deduced that, as process parameters (speed, feed, DOC) increases, MRR also increases. This is due to the decrease in cutting time required to remove the material. As the feed rate is more, the tool movement per unit time increases. Chip removal is higher on increasing the DOC and hence the quantity of the metal removed is also high. The optimum values of speed, feed and depth of cut are 3000 rpm, 0.1 m/min and 1.5 mm respectively which can be seen in Fig. 8. Deepthi and Prasad Rao [15] showcased identical results while milling of Al alloys. From Table 5 it is perceived that the noteworthy factor which affects the MRR is speed, followed by DOC and feed. Delta values refer to a change in variables where speed is the highest factor when compared to DOC and feed.

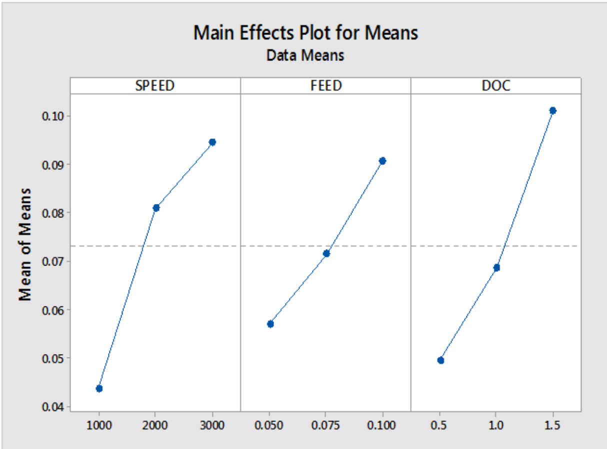

Fig. 7. Plot for means of MRR.

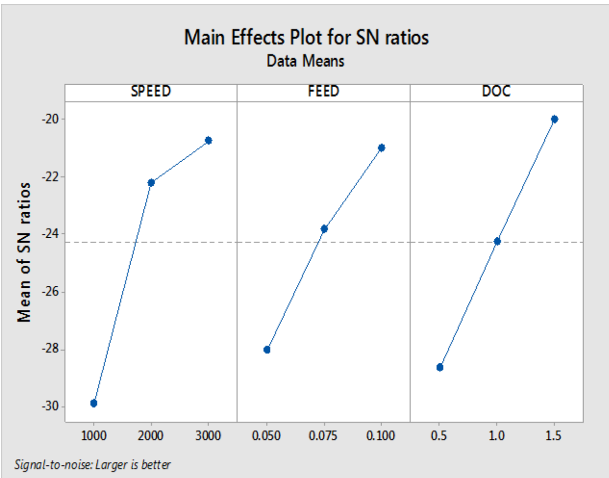

Fig. 8. Plot for means of MRR

Table 5. Response table for S/N ratio.

Level	SPEED	FEED	DOC
1	-29.93	-28.05	-28.66
2	-22.21	-23.84	-24.25
3	-20.74	-20.99	-19.98
Delta	9.19	7.06	8.68
Rank	1	3	2

5.3 INFLUENCE OF PROCESS PARAMETERS ON TOOL WEAR

From Fig. 9, it is noted that, when the value of independent variables (speed, feed, DOC) increases, tool-wear increases. Initially, DOC decreases up to 1 mm and thereafter it increases. This happens because DOC is chosen as a value that is less than or equal to the nose radius. As a result, the insert is exposed to ultimate pressure and temperature which leads to serious wear or sudden fracture of the insert. The major factor that contributes to tool-wear is the low cutting speed. The edge of the cutting tool comes in contact with work piece several times per second resulting in chipping, cracks or breakage of edge either at the entrance or at the exit of the cutting edge from the work piece. When feed increases, the temperature in the tool builds up which results in tool wear and reduces the tool life. The optimum values of 1000 rpm (speed), 0.05 m/min (feed), and 0.5 mm (DOC) is being obtained from Fig. 10. Relatable result was obtained by E. Kilickap et al. [21] in turning of SiC-p reinforced aluminium composite. The most significant factor which affects the tool wear is speed, followed by feed and DOC. Delta values also showcase similar trends which can be observed in Table 6.

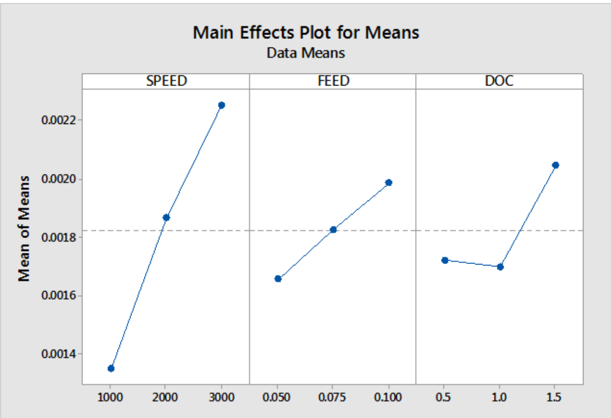

Fig. 9. Plot for means of Tool wear.

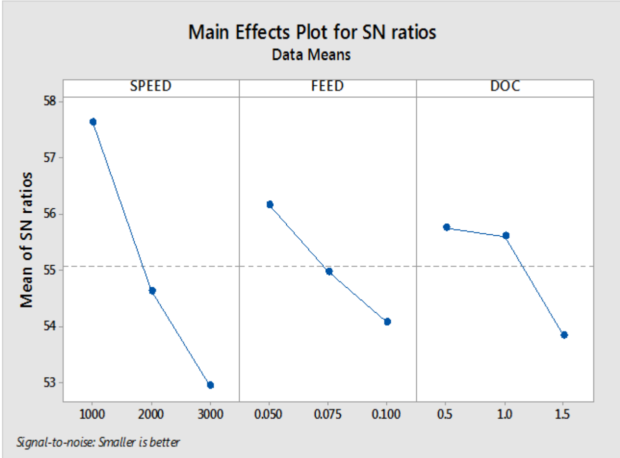

Fig. 10. Plot for means of Tool wear.

Table 6. Response table for S/N ratio.

Level	SPEED	FEED	DOC
1	57.62	56.15	55.75
2	54.63	54.98	55.60
3	52.95	54.08	53.85
Delta	4.67	2.07	1.90
Rank	1	2	3

6. ANALYSIS OF VARIANCE (ANOVA)

ANOVA is carried out to study the percentage significance of each parameter on the response. Speed, Feed and DOC are the parameters analyzed in this study. The percentage contributions of Ra, MRR and Tool wear is shown in Tables 7, 8 and 9 respectively. A significance level of 5 percentage & confidence level 95 percentage is achieved using ANOVA. The possibility of reproducing the experimental results is viewed by the level of significance. For example, the significance level of 5 percentage implies that 95 out of 100 times, the results are repeated. For the significance level of 5 percentage, the corresponding P value is 0.05. P value should be less than 0.05. The percentage contribution is calculated and shown in the last column of table. It is observed from table 7 that feed has the highest significance (52.97 %) on surface roughness followed by speed (33.79 %) and DOC (7.63 %) and is inferred from the table 8 that, DOC has the highest significance (39.23 %) on MRR followed by speed (38.22 %) and feed (16.78 %). It is depicted from the table12, that speed has the highest significance (50.00 %) on tool wear followed by feed and DOC.

Table 7. ANOVA for Surface Roughness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
Regression	3	6.9006	2.30021	28.16	0.001	
SPEED	1	2.4704	2.47042	30.25	0.003	33.79
FEED	1	3.8721	3.87207	47.41	0.001	52.97
DOC	1	0.5581	0.55815	6.83	0.047	7.63
Error	5	0.4084	0.08168			5.58
Total	8	7.3090				100

Table 8. ANOVA for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
Regression	3	0.009568	0.003189	27.22	0.002	
SPEED	1	0.003881	0.003881	33.12	0.002	38.22
FEED	1	0.001704	0.001704	14.54	0.012	16.78
DOC	1	0.003984	0.003984	34.00	0.002	39.23
Error	5	0.000586	0.000117			5.77
Total	8	0.010154				100

Table 9. ANOVA for Tool wear.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
Regression	3	0.000004	0.000001	22.77	0.002	
SPEED	1	0.000002	0.000002	54.15	0.001	50.00
FEED	1	0.000001	0.000001	7.23	0.043	25.00
DOC	1	0.000001	0.000001	6.94	0.046	25.00
Error	5	0.000000	0.000000			0.00
Total	8	0.000004				100

7. REGRESSION ANALYSIS

Minitab18 is utilized to develop the regression model which gives the correlation between the experimental results and predictions using the Taguchi technique. A linear regression model is constructed based on the surface roughness, MRR and tool wear and is mentioned in equation 3, 4 and 5 respectively. This regression model correlates the relation between surface roughness, MRR, tool wear with speed, feed and DOC.

$$Ra = 1.589 - 0.000642S + 32.13F - 0.610\,D \quad (3)$$

$$MRR = -0.0798 + 0.000025S + 0.674F + 0.05153D \quad (4)$$

$$TW = 0.00102 + 0.000001S + 0.00660F + 0.000323 \quad (5)$$

Where S is the speed (rpm), F is the feed (m/min), D is the DOC (mm).

In the above equation it is observed that the parameter prefixed with –ve sign indicates that, surface roughness/MRR/Tool wear diminishes with the increment of parameter and the parameter prefixed with +ve sign indicates that surface roughness/ MRR/Tool wear increases with increase of parameter.

8. CONFIRMATION TEST

A new set of parameter levels are selected to check the acceptability of the statistical model, which are values other than those used for construction of the L9 Orthogonal array. These values are substituted in the model following which, the confirmation experiments are performed for different set of values and the results obtained for surface roughness, MRR and tool wear are shown in Tables 10, 11 and 12 respectively. The percentage error is found to be minimum and hence validates the developing model.

Table10. Confirmation test for surface roughness.

Sl.no	S rpm	F m/min	D mm	SR Microns		Error %
				Using confirmation test	Using regression formula	
1	1500	0.06	0.75	1.89	2.09	9.56
2	2500	0.09	1.25	2.37	2.11	10.97

Table11. Confirmation test for MRR.

Sl.no	S rpm	F m/min	D mm	MRR mm^3/m		Error %
				Using confirmation test	Using regression formula	
1	1500	0.06	0.75	0.0406	0.0367	9.61
2	2500	0.09	1.25	0.1207	0.1077	10.77

Table12. Confirmation test for Tool Wear.

Sl.no	S rpm	F m/min	D mm	TW mm		Error %
				Using confirmation test	Using regression formula	
1	1500	0.06	0.75	0.00345	0.00315	8.69
2	2500	0.09	1.25	0.00497	0.00451	9.25

9. CONCLUSION

Machining of ADC12 alloy was performed successfully. Taguchi's L9 orthogonal model was developed following which, Surface roughness, MRR and tool wear values were tabulated. Optimum surface finish was observed at high speed, low feed and maximum DOC. Feed was found to be the crucial parameter governing surface finish. MRR was optimum for higher speed, feed and DOC. Speed was found to be the critical parameter governing MRR. Tool wear was optimum at lower speed, feed and DOC. Speed was found to be the noteworthy parameter governing tool wear. All significant parameters were decided based on the response table for S/N Ratio, which was validated using ANOVA. The optimized conditions obtained were 3000 rpm (speed), 0.050 m/min (feed) and 1.5 mm (DOC) for surface roughness. In the case of MRR, 3000 rpm (speed), 0.1 m/min (feed) and 1.5 mm (DOC) was found to be optimum and 1000 rpm (speed), 0.05 m/min (feed), and 0.5 mm (DOC) for Tool wear. The above mentioned results were best suited to achieve better surface finish, MRR and least tool wear for ADC12 alloy as obtained from the experimental calculations.

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