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Experimental Investigation of Cutting Parameters on Surface Roughness Prediction during End Milling of Aluminium 6061 under MQL (Minimum Quantity Lubrication)

Ojolo Sunday Joshua[1,*], Money Ochuko David[1], Ismail Oluwarotimi Sikiru[2]

[1]Mechanical Engineering Department, University of Lagos, Lagos, Nigeria
[2]Mechanical and Design Engineering Department, University of Portsmouth, UK

Abstract This work investigates the effect of cutting parameters such as cutting feed, depth of cut and spindle speed on end milling of 6061aluminium so as to predict the surface roughness. One hundred and twenty experiments were carried out on aluminum 6061 rectangular rods. The experiments were conducted in dry and MQL environments using Mac-power V-645 CNC machine with HSS cutting tool inserts where five spindle speeds (700, 1500, 2000, 3000 and 4000rpm), four cutting feeds (120, 200, 500 and 1000mm/min) and three depths of cut (0.4, 0.8 and 1.0mm) were selected. The surface roughness obtained from each experiment was measured using Mitutoyo surface tester. Response surface methodology (RSM) was employed in the experimental design using Design Expert 8.0.1. Two mathematical models were developed; one for dry and the other for MQL machining using multiple regression analysis which can be applied to surface roughness prediction of end milling of aluminium under dry and MQL environments; analysis of variance (ANOVA) was used to determine the significance of cutting parameters on surface roughness. The results obtained show that cutting feeds have the most significant effect on surface roughness, followed by spindle speed; depth of cut has the least effect on surface roughness. The results also show that machining under MQL environment apart from being environmentally friendly reduced the surface roughness value to about 20% leading to a better surface finish. It was also observed that combination of cutting feed and spindle speed have the best interaction, followed by spindle speed and depth of cut. Cutting feed and depth of cut combination have the least interaction, leading to a poor surface finish.

Keywords Cutting feed, Spindle speed, Depth of cut, Aluminium, Surface roughness

1. Introduction

Machining operations have been the core of the manufacturing industry since the industrial revolution [1]. Industries employing metal removing operations are now receiving great attention on cutting fluids in metal working to minimise the volume of lubricants due to occupational, economical and ecological reasons [2-6].

Milling is one of the most common metal cutting or removing processes. It is a process of generating machined surfaces by progressively removing a predetermined amount of material or stock from the work-piece at a relatively slow rate of movement or feed by a milling cutter rotating at a comparatively high speed. End milling is one of the most common metal removal operations encountered in industrial processes. It is widely used in the manufacturing industries which include the automotive and aerospace sectors, where quality is an important factor in the production of slots, pockets, precision molds, and dies. In end milling, the cutter generally rotates on an axis vertical to the work-piece. It can be tilted to machine tapered surfaces. Cutting teeth are located on both the end face of the cutter and the periphery of the cutter body [7, 8].

One of the problems which may arise in using the end milling process is that the finished part does not satisfy the product design specifications. During the machining process, fiction exists between the tool and the work material, giving rise to heat and more energy is required for the machining operation [9]. The friction, heat and high energy have effect on the tool life, surface quality and tool wear etc.

The quality of the surface plays a very important role in the performance of milling as a good-quality milled surface significantly improves fatigue strength, corrosion resistance, or creep life. Surface finish also affects several functional attributes of parts, such as contact causing surface friction,

* Corresponding author:
sojolo@unilag.edu.ng (Ojolo Sunday Joshua)
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wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, coating, or resisting fatigue [8, 10, 11]. Therefore the need to optimize cutting parameters to produce good surface finish is important.

Lou *et al* [11] developed a model for surface roughness technique for prediction of CNC end milling. The experiment was carried out on a vertical milling centre with the predictor variables being cutting speed, feed rate, and depth of cut. The material used was 6061 aluminium and multiple regression analysis was used to build the model. They were able to predict the surface roughness with about 90% accuracy and also noted that feed rate was the most significant machining parameter used to predict the surface roughness in the multiple regression model. It was recommended that further research should be considered using different cutting tools and materials of the work-piece. In addition, artificial intelligent systems such as the fuzzy logic system or neural networks technique might be included to enhance the ability of the prediction system.

Arokiadass *et al* [12] also studied the influence of four machining parameters including spindle speed (N), feed rate (f), depth of cut (d), and various percentage weight of silicon carbide (S) on surface roughness (Ra). The response surface methodology was employed to establish the mathematical relationship between the response and the various process parameters. The result obtained showed that the quadratic model is statistically significant for analysis of surface roughness. The value of regression coefficient (R) was 99.85 %, which indicated that the developed regression model is adequately significant at a 95% confidence level. The model also indicated that the feed rate was the most dominant parameter on surface roughness followed by spindle speed and %weight of SiC. Depth of cut has less influence on surface roughness. It was also concluded that the regression model is well fitted with the observed values and high correlation exists between fitted values and observed values.

The use of lubricant or cutting fluids in metal machining operations is to serve as a coolant i.e. to cool, as well as a lubricant i.e. to reduce friction and wash away chips. It is generally agreed that the application of cutting fluids can improve the tool life and results in good surface finish by reducing thermal distortion and flushing away of machined chips [13]. Better surface finish and dimensional accuracy are also obtained from cutting fluids [14]. The flooding method is the conventional method used in which a high volume of lubricant flow is applied and floods the entire machining area, effectively removing the heat generated from the machining process [15]. Flooding method required a large quantity of the cutting fluid and the cutting fluid is not able to reach the cutting zone due to obstruction from chips. This method has health implications on the operator(s) of the machining centre, environmental hazards and excessive waste of the cutting fluids and definitely high cost of production results. Ojolo *et al*. [16] made investigation into the effects of solid lubricant on the surface characteristics of some metals during orthogonal machining where it was shown that significant improvement in the surface finish of the machined steel surface and reduction in the surface roughness were obtained when compared to wet machining. The solid lubricant was also recoverable and more environmental friendly to the operator and surroundings when compared to wet machining.

The necessity to machine using less harmful cutting fluids has prompted many researchers to investigate the use of minimum quantity lubrication (MQL) [17]. MQL, also known as "Near-Dry Machining" [18] and as "Micro-lubrication" [19], is the latest technique of delivering metal cutting fluid to the tool/work interface. Dry machining, also known as green manufacturing is progressively becoming more popular as it protects the environment and reduces manufacturing cost [20-22]. MQL machining provides an economically and ecologically reasonable alternative to the traditional wet machining process [23].

Abhang *et al.* [24] investigated the use of minimum quantity lubricants in alloy steel turning where 10% boric acid is mixed with base oil SAE 40 proved to be a feasible alternative to the conventional cutting fluid. The result obtained indicated that there is a considerable improvement in machining performance with MQL machining compared to dry machining. It was concluded that MQL can reduce the chip tool interface temperature by 20 to 30% depending upon the level of process parameters and work material. The reduction in cutting temperature using MQL was high at lower level of machining parameters and low at high level of machining parameters. Also that the cutting forces is reduced by about 5% to 12% favorable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the minimum quantity of lubrication. Surface finish also significantly improved mainly due to significant reduction of wear and damage at the tool tip by the application of minimum quantity lubricantion.

Ali *et al.* [25] also investigated the role of MQL by cutting oil on chip thickness ratio, cutting temperature, cutting forces, tool wear and surface roughness in turning medium carbon steel at industrial speed-feed combinations by uncoated carbide insert. The result indicated reduction in tool wear rate, dimensional inaccuracy and surface roughness by MQL over a dry machining mainly through reduction in the cutting zone temperature and favorable change in the work-tool interaction. Also it showed that MQL improves productivity, product quality and overall machine economy even after covering the additional cost of designing and implementing MQL system.

The objective of this work is to investigate in MQL environment, the effect of cutting parameters such as cutting speed, depth of cut and feed on surface roughness of aluminium during end milling. It is also to compare these effects and to what extent surface roughness will be affected when machining in dry and MQL environment. To achieve the objective of ecological machining in manufacturing processes using MQL, it is essential to study and model the effects of MQL on the machining performance measures, in this case, surface finish. The key to successful incorporation of MQL in industrial machining processes is to be able to develop a capability to predict the effects and optimize the use of MQL.

2. Materials and Methods

2.1. Experimental Considerations

An extensive experimental work in end milling of 6061 aluminum rectangular block was carried out to establish inter-relationships between machining performance measures and cutting parameters such as speed, feed and depth of cut. The machining performance measure under consideration is surface roughness. These inter-relationships were estimated for end milling under two different lubrication conditions which were dry cutting, and MQL (coolant + water). Table1 shows the levels of cutting parameter and Table 2 shows the cutting condition for the dry and MQL environments.

Table 1. Levels of cutting parameters

Levels	Spindle speed (rpm)	Cutting feed (mm/min)	Depth of cut (mm)	code
High	4000	1000	1	+1
Low	700	120	0.4	-1

Table 2. Cutting conditions

Parameters	Dry condition	MQL condition
Spindle speed (rpm)	700, 1500, 2000, 3000 and 4000	700, 1500, 2000, 3000 and 4000
Cutting feed (mm/min)	120, 200, 500 and 1000	120, 200, 500 and 1000
Depth of cut (mm)	0.4, 0.8 and 1.0	0.4, 0.8 and 1.0

2.2. Work and Tool Materials

This investigation is limited to Aluminium material only in which 50% of the experiment is on dry machining and the other 50% required lubrication (MQL) at the machining zone. The lubricant used for the MQL system is CUMISTAR 600 which is a combination of water and coolant. The aluminium rectangular block used for the experiment was obtained from Owode-Onirin market; the cutting tool used is 25.4 mm diameter end mill holding four indexable cutting HSS inserts

2.3. Experimental Set up

The experiment was performed on a Macpower speed CNC machine vertical milling centre, model V-645 at Stanfrey Engineering Ltd., Lagos. The vertical milling center has three (3) planes namely x,y and z planes. The experimental set up is shown in Fig.1.

A controlled set of experiments is carried on rectangular 6061aluminium block to determine the relationship between cutting feed, spindle speed, depth of cut (DOC) and surface roughness. The selected depth of cut are 0.4mm, 0.8mm and 1.0mm, while four different cutting feeds (120, 200, 500 and 1000 mm/min) were selected. The spindle speeds selected for the experiment are 700, 1500, 2000, 3000 and 4000rpm. The experiments were performed on dry condition (no coolant or lubricant) and wet condition (minimum quality lubrication) where copious amount of coolant was provided at the cutting zone throughout the experiment.

A total of 120 experiments were performed, of which 60 were on dry machining where lubrication at the machining zone was turned off from the CNC operator's screen (HMI) and the other 60 experiment were performed with the lubrication system turned on at the machining zone. A full factorial of the cutting condition was employed for both dry and MQL condition where all cutting parameters interact with one another. The parameter of interest was the surface roughness at varying cutting feeds, spindle speeds and depths of cut which was measured using Mitutoyo surface tester. Design expert 8.0.1 was used for the design of experiment and analysis.

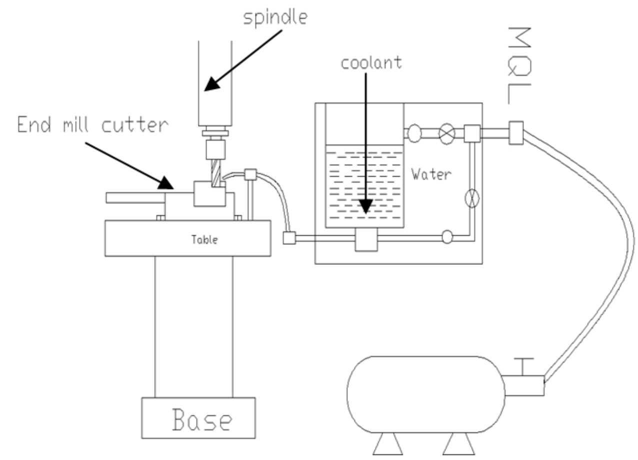

Figure 1. Schematic diagram of the experimental set up

3. Results and Discussions

3.1. Results

The basic objective of the experiments was to establish the polynomial constants for the surface roughness model and to know the effect of each parameter on the surface roughness or quality of aluminium. The constants for the correlation between input parameters (cutting speed, feed and depth of cut) and measured output parameter (surface roughness) were established for different lubrication conditions by applying non-linear regression analysis to the quantitative data obtained from the experiments. The results of the experiment in both dry and MQL condition are presented in Tables 3-4 and Figures 2-17.

Table 3. Experiments' result for dry condition

Exp. No.	Spindle speed, *N* (rpm)	Cutting feed, *f* (mm/min)	Depth of cut, *a* (mm)	Surface roughness R_a (µm)
1	700	120	0.4	1.64
2	700	120	0.8	1.68
3	700	120	1	1.70
4	700	200	0.4	2.33
5	700	200	0.8	2.39
6	700	200	1	2.42
7	700	500	0.4	4.43
8	700	500	0.8	4.52
9	700	500	1	4.56
10	700	1000	0.4	7.16
11	700	1000	0.8	7.32
12	700	1000	1	7.38
13	1500	120	0.4	0.88
14	1500	120	0.8	0.90
15	1500	120	1	0.93
16	1500	200	0.4	1.25
17	1500	200	0.8	1.28
18	1500	200	1	1.29
19	1500	500	0.4	2.37
20	1500	500	0.8	2.42
21	1500	500	1	2.46
22	1500	1000	0.4	3.85
23	1500	1000	0.8	3.93
24	1500	1000	1	3.96
25	2000	120	0.4	0.70
26	2000	120	0.8	0.72
27	2000	120	1	0.72
28	2000	200	0.4	0.99
29	2000	200	0.8	1.03
30	2000	200	1	1.04
31	2000	500	0.4	1.87
32	2000	500	0.8	1.92
33	2000	500	1	1.95
34	2000	1000	0.4	3.03
35	2000	1000	0.8	3.11
36	2000	1000	1	3.14
37	3000	120	0.4	0.50
38	3000	120	0.8	0.52
39	3000	120	1	0.54
40	3000	200	0.4	0.71
41	3000	200	0.8	0.74
42	3000	200	1	0.75
43	3000	500	0.4	1.35
44	3000	500	0.8	1.39
45	3000	500	1	1.41
46	3000	1000	0.4	2.18
47	3000	1000	0.8	2.23
48	3000	1000	1	2.27
49	4000	120	0.4	0.40
50	4000	120	0.8	0.42
51	4000	120	1	0.43
52	4000	200	0.4	0.56
53	4000	200	0.8	0.58
54	4000	200	0.1	0.57
55	4000	500	0.4	1.06
56	4000	500	0.8	1.10
57	4000	500	1	1.12
58	4000	1000	0.4	1.72
59	4000	1000	0.8	1.77
60	4000	1000	1	1.80

Table 4. Experiments' result for MQL condition

Exp No.	Spindle speed, x_1 (rpm)	Cutting feed, x_2 (mm/min)	Depth of cut, x_3 (mm)	Surface roughness Y_i (µm)
1	700	120	0.4	1.36
2	700	120	0.8	1.38
3	700	120	1	1.39
4	700	200	0.4	1.94
5	700	200	0.8	1.99
6	700	200	1	2.00
7	700	500	0.4	3.68
8	700	500	0.8	3.75
9	700	500	1	3.77
10	700	1000	0.4	5.96
11	700	1000	0.8	6.08
12	700	1000	1	6.13
13	1500	120	0.4	0.73
14	1500	120	0.8	0.75
15	1500	120	1	0.76
16	1500	200	0.4	1.04
17	1500	200	0.8	1.07
18	1500	200	1	1.07
19	1500	500	0.4	2.00
20	1500	500	0.8	2.01
21	1500	500	1	2.03
22	1500	1000	0.4	3.20
23	1500	1000	0.8	3.26
24	1500	1000	1	3.29
25	2000	120	0.4	0.58
26	2000	120	0.8	0.60
27	2000	120	1	0.60
28	2000	200	0.4	0.82
29	2000	200	0.8	0.85
30	2000	200	1	0.85
31	2000	500	0.4	1.55
32	2000	500	0.8	1.60
33	2000	500	1	1.61
34	2000	1000	0.4	2.53
35	2000	1000	0.8	2.58
36	2000	1000	1	2.60
37	3000	120	0.4	0.41
38	3000	120	0.8	0.42
39	3000	120	1	0.43
40	3000	200	0.4	0.59
41	3000	200	0.8	0.61
42	3000	200	1	0.61
43	3000	500	0.4	1.12
44	3000	500	0.8	1.15
45	3000	500	1	1.16
46	3000	1000	0.4	1.81
47	3000	1000	0.8	1.85
48	3000	1000	1	1.87
49	4000	120	0.4	0.32
50	4000	120	0.8	0.34
51	4000	120	1	0.34
52	4000	200	0.4	0.46
53	4000	200	0.8	0.48
54	4000	200	0.1	0.45
55	4000	500	0.4	0.87
56	4000	500	0.8	0.91
57	4000	500	1	0.92
58	4000	1000	0.4	1.43
59	4000	1000	0.8	1.47
60	4000	1000	1	1.48

The experiments were divided into two sections according to the lubrication/cooling conditions. Two different relationships were modeled for these lubrication/cooling conditions for each of the response variables, which is surface roughness. ANOVA was used to carry out the regression analysis to determine the partial regression coefficients. The relationship between the surface roughness and cutting independent variables can be represented by the following equation

$$R_a = K.N^x.f^y.a^z \quad (1)$$

Where, K is constant, and x, y, z are the exponents. Equation (1) can be represented in mathematical form as follows:

$$\ln R_a = \ln K + x.\ln N + y.\ln f + z.\ln a \quad (2)$$

The constant K and exponents $x, y, z,$ can be determined by least squares method. The introduction of a replacement gets the following expression:

$$Y = \ln R_a,\ \beta_0 = \ln K,\ x_1 = \ln N,\ x_2 = \ln f,$$
$$x_3 = \ln a,\ x = \beta_1,\ y = \beta_2,\ z = \beta_3 \quad (3)$$

Linear model developed from the equation can be represented as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad (4)$$

Where, x_1, x_2, x_3, are logarithmic transformation of factors: spindle speed, cutting feed and depth of cut and β values are the estimates of corresponding parameters

$$\text{Therefore, } e^{\beta_0} = K \quad (5)$$

Linear model developed from the equation can be represented as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad (6)$$

Where, x_1, x_2, x_3, are logarithmic transformation of factors: spindle speed, cutting feed and depth of cut and β values are the estimates of corresponding parameters.

Solving the linear regression developed from the logarithmic transformation yields the following models for both dry and MQL condition.

$Ra = (12.68 f^{0.69} a^{0.04})/N^{0.81}$ is the mathematical model for dry condition

$Ra = (10.80 f^{0.70} a^{0.04})/N^{0.82}$ is the mathematical model for MQL condition

3.2. Discussions

3.2.1. Effect of Spindle Speed on Surface Roughness at Varying Cutting Feed

The effects of spindle speed on surface roughness at varying cutting feed are presented in Figures 2 and 3.

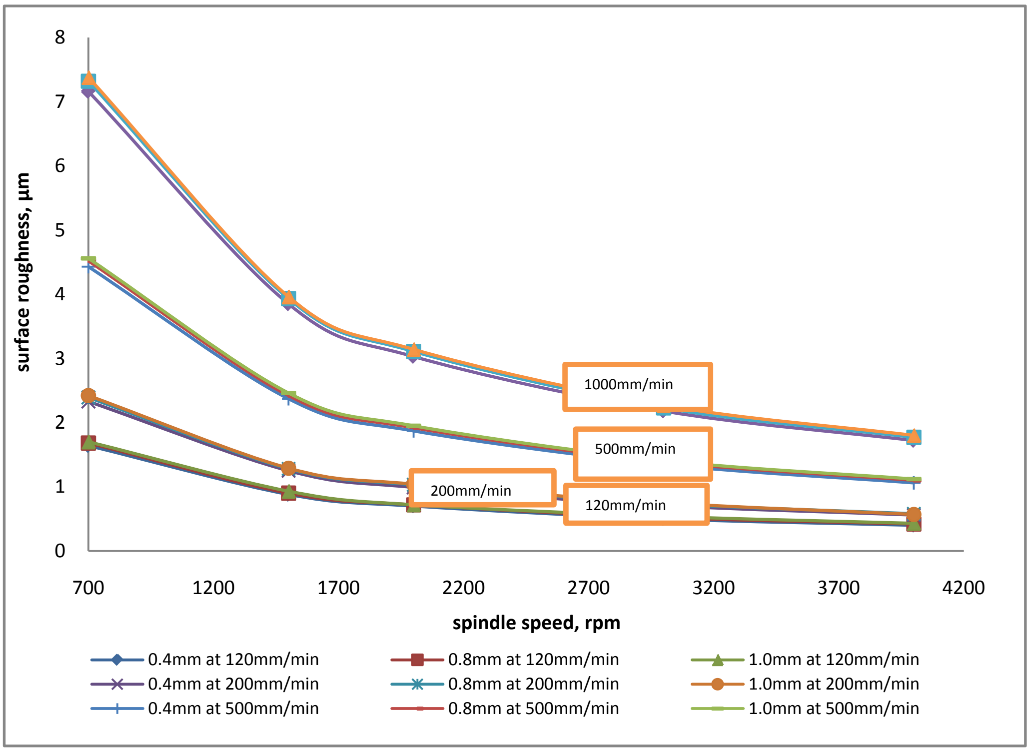

Figure 2. Effect of spindle speed on surface roughness at varying cutting feed (dry)

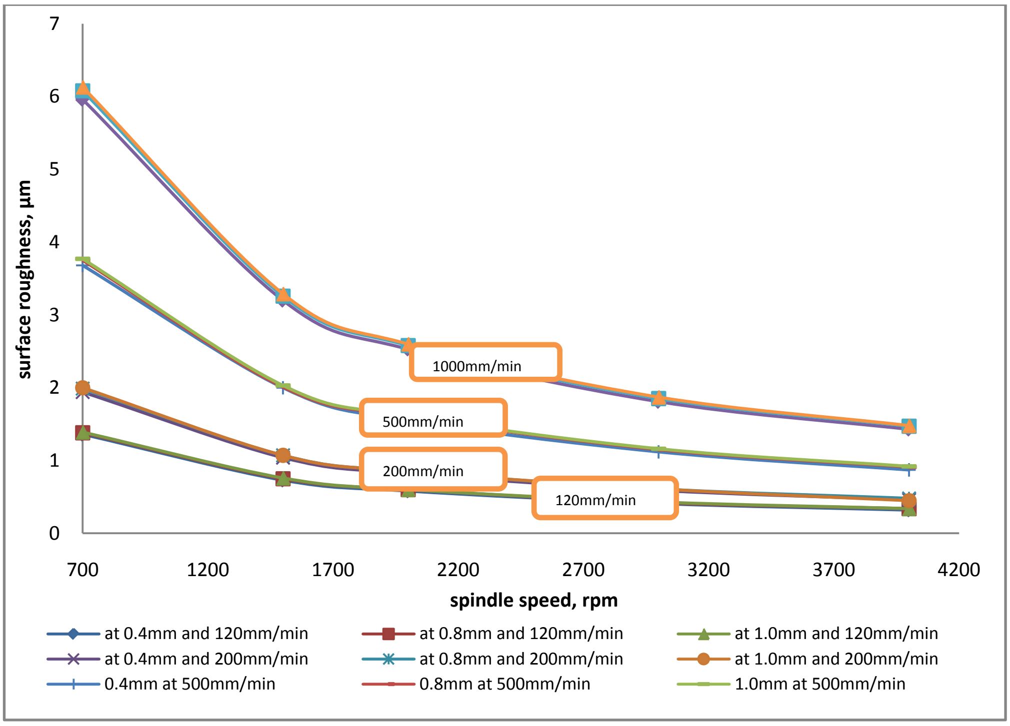

Figure 3. Effect of spindle speed on surface roughness at varying cutting feed (MQL)

From Figures 2 and 3, it is observed that for dry condition (Figure 2), and at a constant cutting feed of 120mm/min surface roughness value decreases with increase speed (1.64µm – 0.4µm). As the feed is increased to a maximum of 1000mm/min, the surface roughness decreases from 7.16 µm to 1.72µm. this trend is the same for MQL environment with the surface roughness values decreasing from 1.36µm to 0.34 µm with increase in spindle speed at constant feed of 120mm/min. As the feed is increased to a maximum of 1000mm/min, surface roughness values increases and then decreased from 5.96µm to 1.48µm with increase in spindle speed as shown in Figure 3. This result is expected because at low spindle speed, friction between the work-piece and the cutting tool is high due to discontinuous chips formed which are deposited in the workpiece and tool interface. This high friction existing in the tool-chip interface and workpiece-tool interface leads to interruptions during cutting operations, high force in machining, more energy, high temperature (heat) and leading to a poor surface quality. As the spindle speed is increased, there is a decrease in the coefficient of friction between the workpiece and tool interface, chips formed are continuous which have which make less contact between the workpiece and tool interface, resulting in lower coefficient of friction and better surface quality. This result is in agreement with the model developed for both dry and MQL condition where a higher spindle speed leads to a lower surface roughness value or better surface finish. This result is also confirmed by Mohammed *et al* [26] study on the effect of machining parameters on end milling of aluminium. A higher spindle speed decrease the coefficient of friction while working with cutting fluid which gives a lower roughness value which in this case, MQL condition when compared to dry condition as obtained by Ojolo *et al* [16]. It also reduces the temperature in the cutting zone and cutting force required.

Figures 4-6 show the effect of spindle speed on the surface roughness at constant depth of cut and varying cutting feed.

From Figures 4-6, it is observed that surface roughness values decreases as the spindle speed increases. But as the cutting feed is increased, the roughness values increases and then decreases with increase in spindle speed. It can be seen from Figure 5a that at constant depth of cut of 0.8mm, and varying cutting feed of 120mm/min–1000mm/min the surface roughness value decreased from 1.68µm to 0.42µm, 2.39µm to 0.58µm, 4.52µm to 1.1µm and 7.32µm to 1.77µm with increasing spindle speed for dry condition. This trend was observed for MQL environment with roughness values decreasing from 1.36µm to 0.32µm, 1.94µm to 0.46µm, 3.68µm to 0.87µm and 5.96µm to 1.43µm at constant depth of cut of 0.4mm (Figure 5b) with increase in spindle speed, but the surface roughness value is reduced when compared with machining performed in dry condition (Figure 4a-6a) due to a reduction in heat and friction between the work-piece and tool interface (Figure 4b-6b). This is in agreement with results obtained by Natarajan *et al* [27] for surface roughness of a non-ferrous material using artificial neural network in CNC turning. Kuram *et al* [13] obtained similar results that increase in spindle speed reduces roughness values. This result has a high correlation with the model developed for both dry and MQL condition and that for MQL environment; a lower roughness value is obtained compared to dry condition. This implies that an increase in spindle speed improves surface finish.

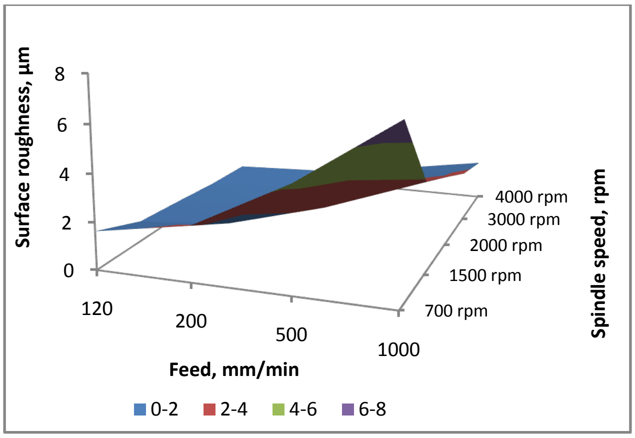

Figure 4a. Effect of spindle speed on surface **roughness** at constant DOC of 0.4mm (dry)

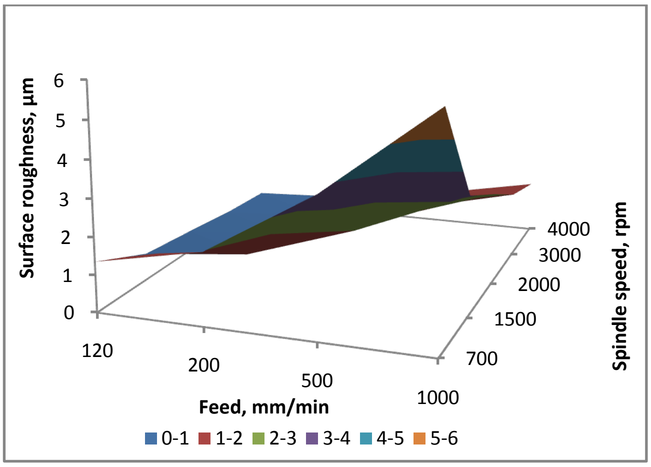

Figure 4b. Effect of spindle speed on surface roughness at constant DOC of 0.4mm (MQL)

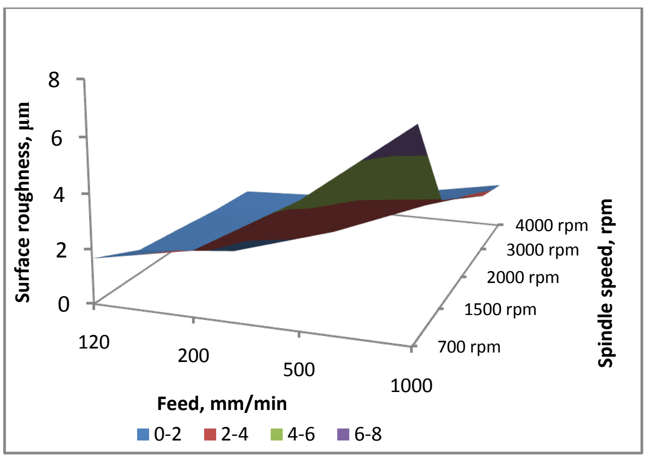

Figure 5a. Effect of spindle speed on surface roughness at constant DOC of 0.8mm (dry)

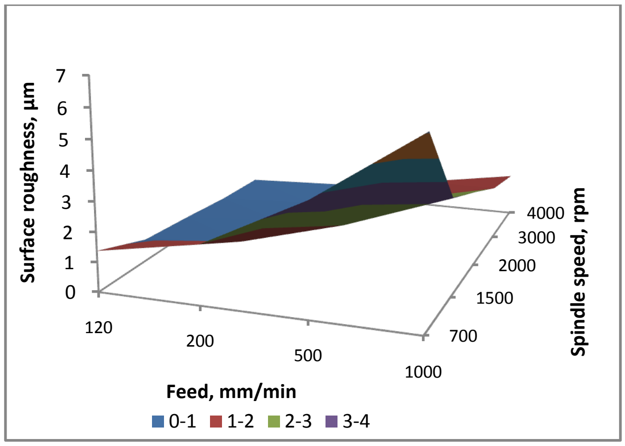

Figure 5b. Effect of spindle speed on surface roughness at constant DOC of 0.8mm (MQL)

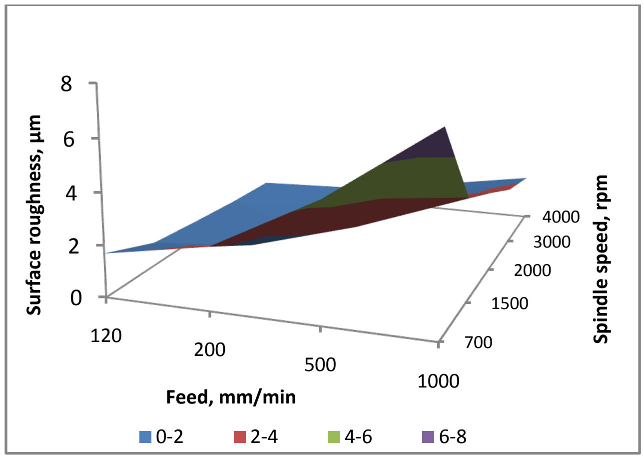

Figure 6a. Effect of spindle speed on surface roughness at constant DOC of 1.0mm (dry)

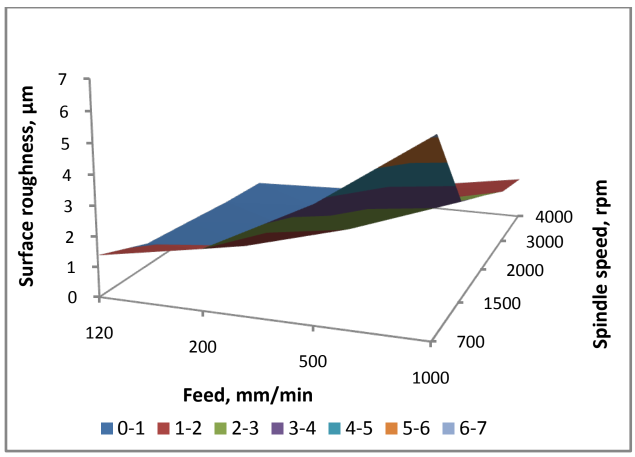

Figure 6b. Effect of spindle speed on surface roughness at constant DOC of 1.0mm (MQL)

3.2.2. Effect of Cutting Feed on Surface Roughness at Diffrent Spindle Speed

Figures 7-9 show the relationship between cutting feed and surface roughness at varying spindle speed of 700, 1500, 2000, 3000 and 400rpm respectively. The depth of cut was kept constant at 0.4, 0.8 and 1.0 mm.

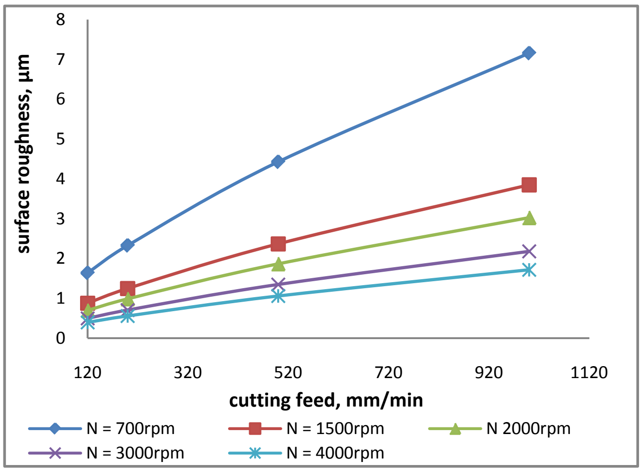

Figure 7a. Effect of cutting feed on surface roughness at constant DOC of 0.4mm (dry)

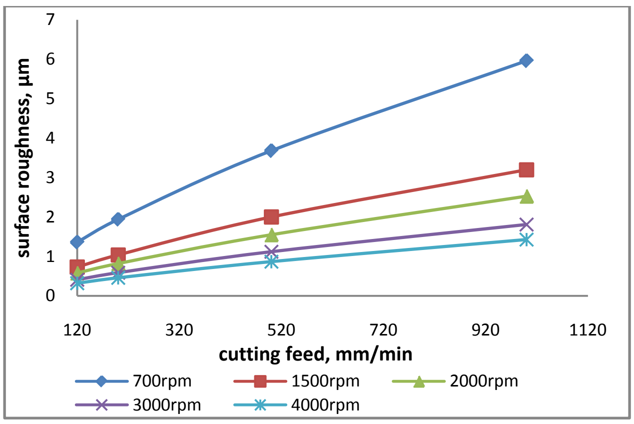

Figure 7b. Effect of cutting feed on surface roughness at constant DOC of 0.4mm (MQL)

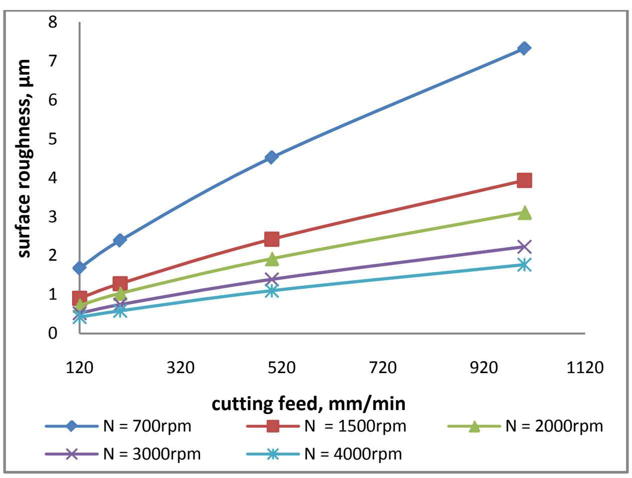

Figure 8a. Effect of cutting feed on surface roughness at constant DOC of 0.4mm (dry)

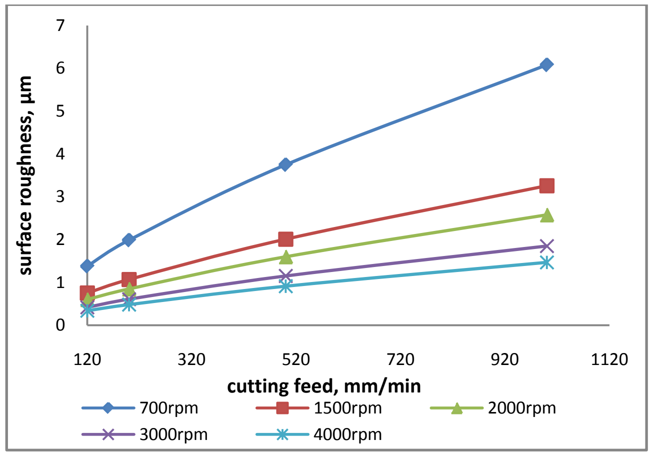

Figure 8b. Effect of cutting feed on surface roughness at constant DOC of 0.4mm (MQL)

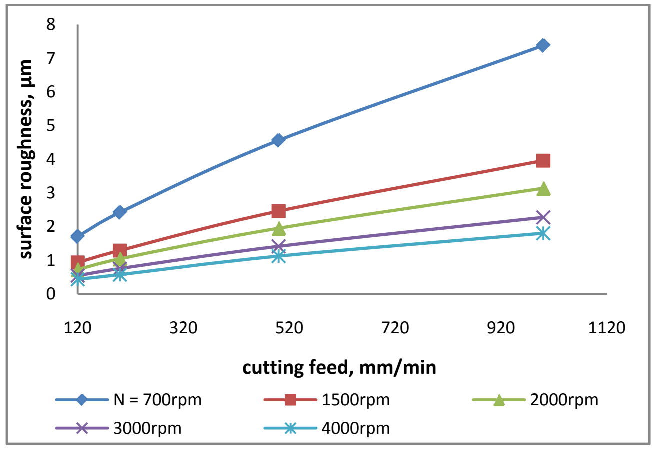

Figure 9a. Effect of cutting feed on surface roughness at constant DOC of 1.0mm (dry)

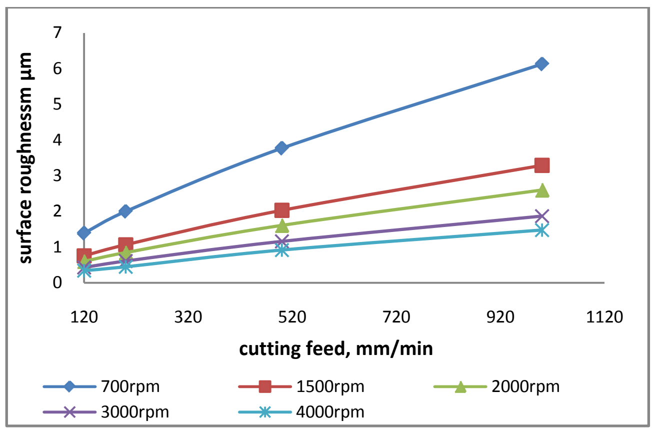

Figure 9b. Effect of cutting feed on surface roughness at constant DOC of 1.0mm (MQL)

Figures 7-9 show that at constant depth of cut, as the cutting feed is increased, there is also an increase in the value of the surface roughness. Surface roughness values increases with increase in cutting feed from 1.64µm to 7.16µm at constant depth of 0.4mm and varying spindle speed (Figure 7). With depth of cut of 0.8mm and 1.0mm surface roughness values increases from 1.68µm to 7.32µm and

1.7μm to 7.38μm respectively with increased cutting feed (Figures 8-9). The same trend was observed for MQL environment but with reduced surface roughness value as seen in Figures 7b-9b but with lower surface roughness value. This means, increased cutting feed leads to poor quality surface. This trend is expected because at increased cutting feed, more chips are deposited between work-piece and tool interface causing more friction, heat and interruption, thereby leading to poor surface finish. At low feed, chip formed during the cutting operations are continuous which have less interruption between tool-chips and workpiece-tool leading to a reduced friction between workpiece-tool interface. As the feed is increased, chips become discontinuous and are deposited between workpiece and tool leading to increased coefficient of friction and more interruption resulting in poor surface finish. In MQL environment, due to the lubricating effect at cutting zone during machining, friction between workpiece and tool is reduced and surface roughness values are reduced when compared with dry condition. This results agree with that obtained by Arokiadass *et al* [12] on predictive modeling of surface roughness in end milling of Al/SiC metal matrix composite, where roughness increases as cutting feed increased. It is also in agreement with the results obtained by Suhail *et al* [28] that surface roughness values increases as the cutting feed is increased.

3.2.3. Effect of Depth of Cut on Surface Roughness at Varying Cutting Feed

Figures 10-13 show the relationship between surface roughness and depth of cut at constant spindle speed of 700, 1500, 2000, 3000 and 4000rpm respectively with varying cutting feed. These graphs give an insight on how the surface responds with change in depth of cut for both dry and MQL environment.

From the result, it is observed that an increase in the depth of cut has little effect on the surface roughness of the milled aluminium rods. An increase in the depth of cut causes a little increase in the surface roughness. From Figure 10a, surface roughness value increased (1.64-1.7μm) as the depth of cut is increased at constant spindle speed of 700rpm and varying feed. As the cutting feed is increased to a maximum of 1000mm/min, there is a significant increase in the surface roughness value (7.16μm – 7.38μm) then a little increased is maintained with increased depth of cut. This variation in surface roughness value is the same for MQL environment with reduced surface roughness values (at constant speed of 700rpm, roughness value is 1.36μm – 1.39μm) because the frictional effect is reduced due to the lubrication at the workpiece and tool interface. The increase in surface roughness is expected because the width of contact between the material and cutting tool is more, giving rise to fiction between the workpiece and tool, leading to interruption in cutting operation. More force and energy will be required for the cutting operation and eventually affecting the surface roughness (poor surface quality). This result agrees with that obtained by Arokiadass *et al* [12] that the depth of cut has minimal effect on surface roughness.

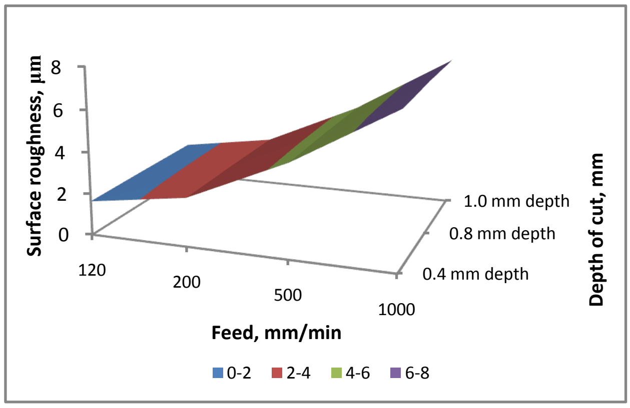

Figure 10a. Effect of DOC on surface roughness roughness at constant spindle speed of 700rpm (dry)

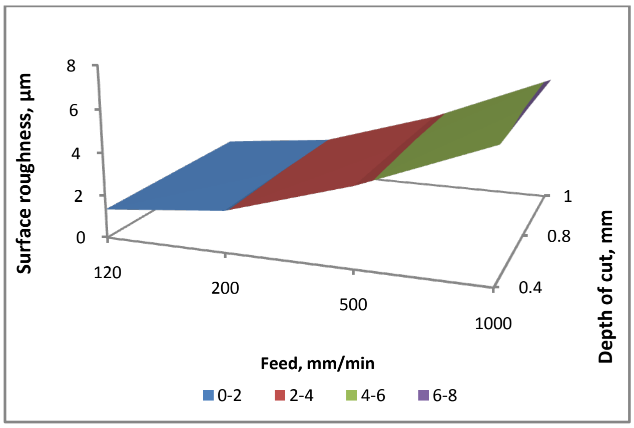

Figure 10b. Effect of DOC on surface at constant spindle speed of 700rpm (MQL)

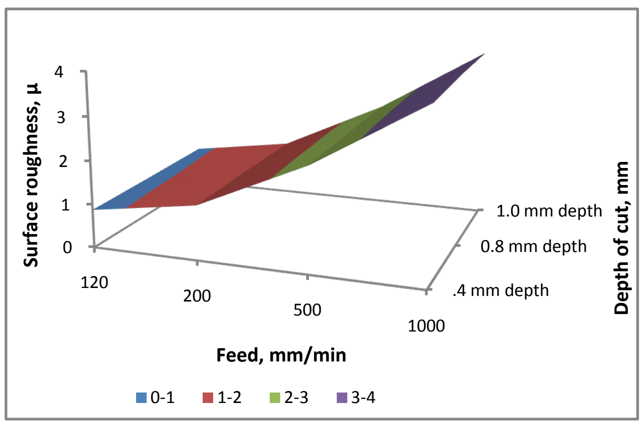

Figure 11a. Effect of DOC on surface roughness at constant spindle speed of 1500rpm (dry)

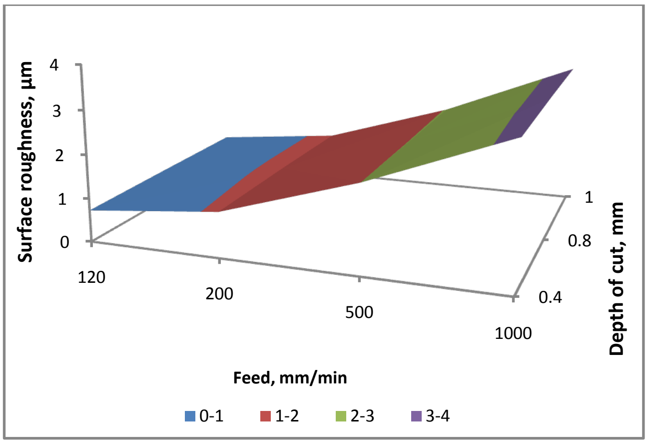

Figure 11b. Effect of DOC on surface roughness at constant spindle speed of 1500rpm (MQL)

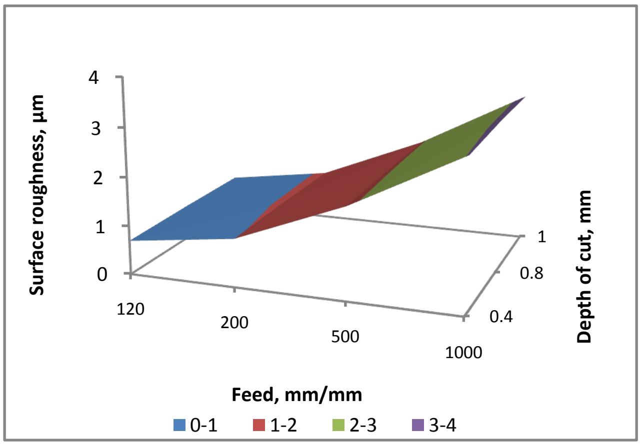

Figure 12a. Effect of DOC on surface roughness at constant spindle speed of 2000rpm (dry)

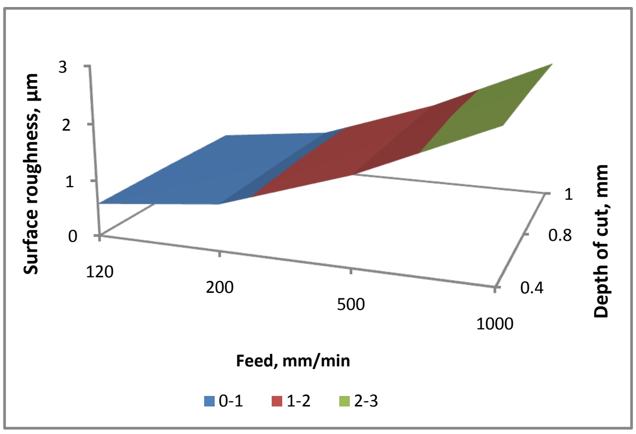

Figure 12b. Effect of DOC on surface roughness at constant spindle speed of 2000rpm (MQL)

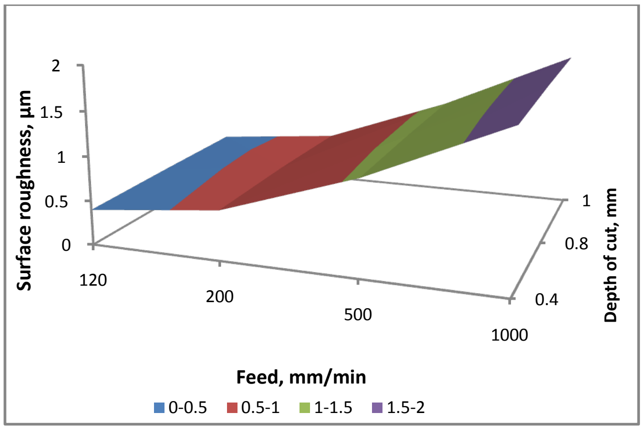

Figure 13a. Effect of DOC on surface roughness at constant spindle speed of 4000rpm (dry)

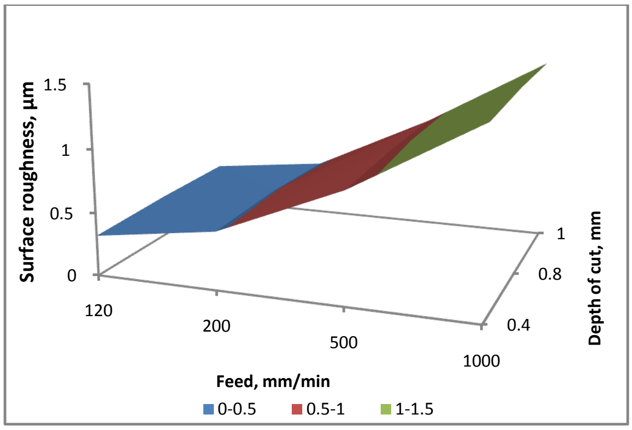

Figure 13b. Effect of DOC on surface roughness at constant spindle speed of 4000rpm (MQL)

Figures 14-17 show the the effects of depth of cut and varying spindle speed on surface roughness at constant cutting feed.

From Figures 14-17, it is observed that an increase in the depth of cut has little effect on the surface roughness of the milled aluminium rods. An increase in the depth of cut causes a little increase in the surface roughness (at constant feed of 500mm/min, 4.43-4.56µm). Therefore increase in depth of cut leads to increase in the surface roughness value. This is because the width of contact between the tool and work-piece material (aluminium) is more giving rise to formation of discontinuous (segmented) chips which also increase tool-chip friction and temperature of the cutting zone. Therefore a very large depth of cut leads to a poor surface finish. With the use of MQL, the tool-chip friction is reduced and temperature of the cutting zone is also reduced which leads to a lower surface roughness value when compared to dry environment (3.68µm – 3.77µm).

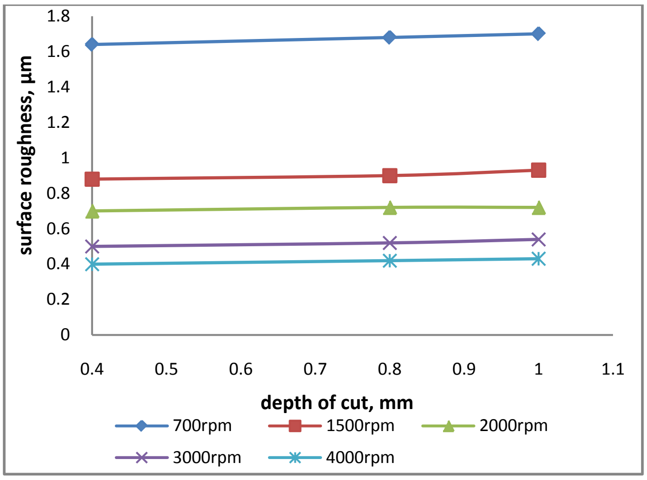

Figure 14a. Effect of DOC on surface roughness at constant cutting feed of 120mm/min (dry)

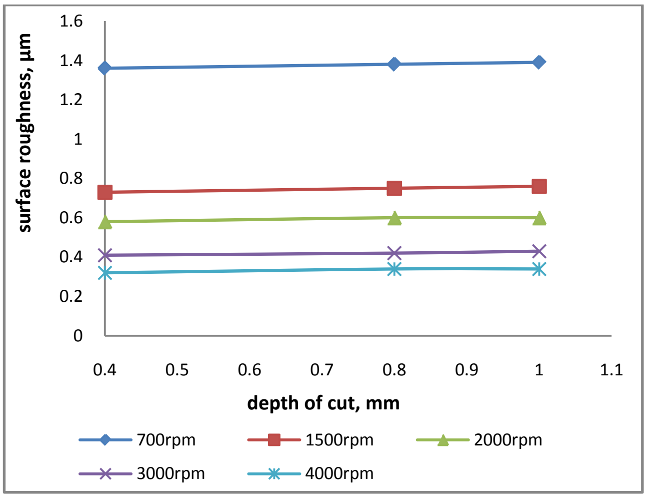

Figure 14b. Effect of DOC on surface roughness at constant cutting feed of 120mm/min (MQL)

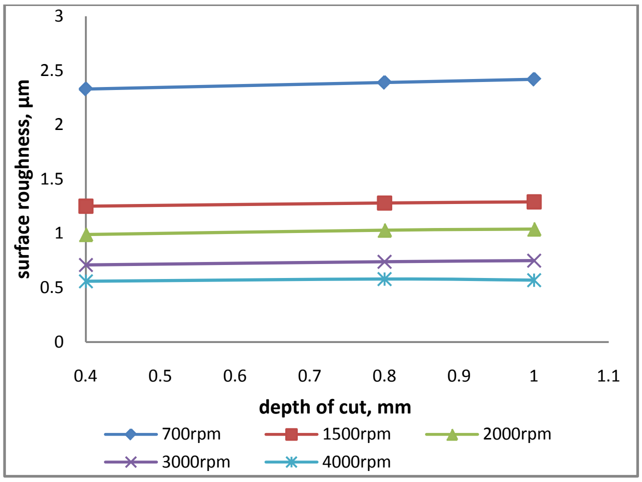

Figure 15a. Effect of DOC on surface roughness at constant cutting feed of 200mm/min (dry)

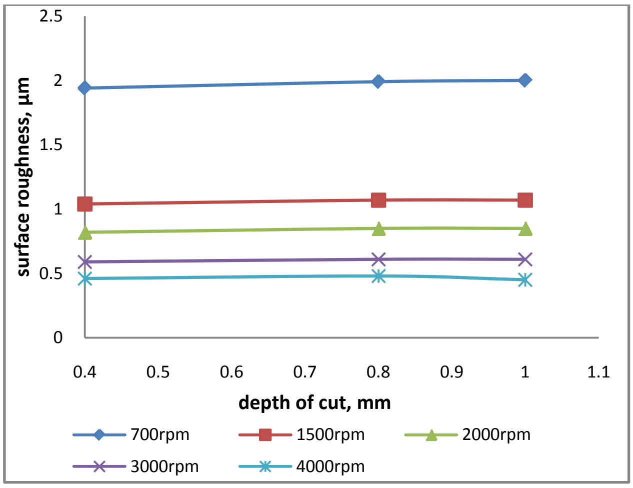

Figure 15b. Effect of DOC on surface roughness at constant cutting feed of 200mm/min (MQL)

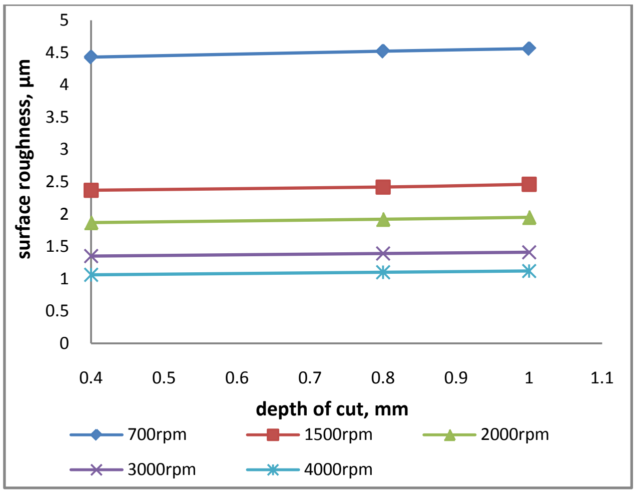

Figure 16a. Effect of DOC on surface roughness at constant cutting feed of 500mm/min (dry)

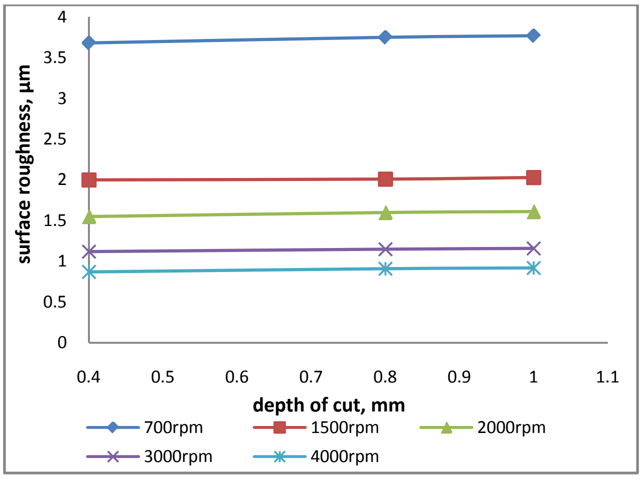

Figure 16b. Effect of DOC on surface roughness at constant cutting feed of 500mm/min (MQL)

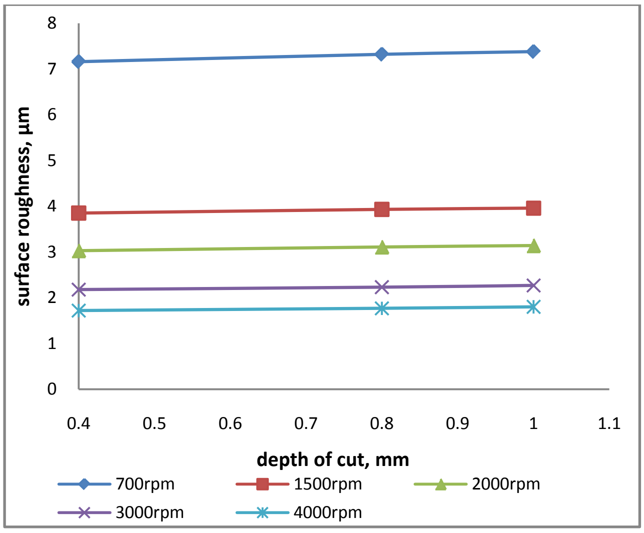

Figure 17a. Effect of DOC on surface roughness at constant cutting feed of1000mm/min (dry)

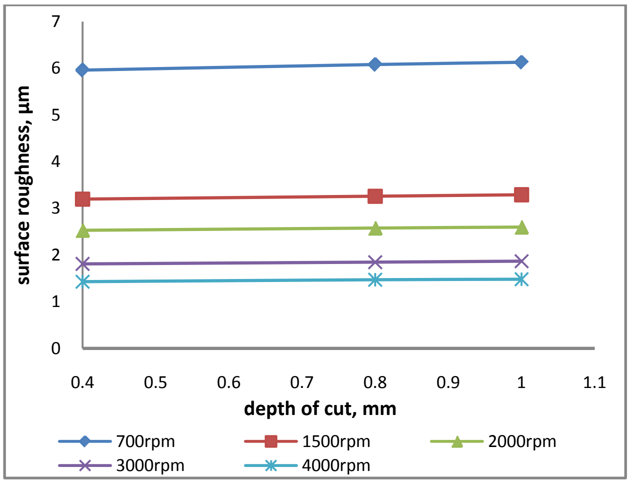

Figure 17b. Effect of DOC on surface roughness at constant cutting feed of 1000mm/min (MQL)

4. Conclusions

From the results and analysis of the experiments, it can thus be concluded that the surface roughness (Ra) of a machined surface whether obtained in a dry or MQL environment could be predicted effectively by combining two of these parameters- spindle speed, feed rate, depth of cut- while keeping one of them constant at a time and their interactions in the multiple regression model. It can also be concluded that machining with MQL (a good alternative to flooding lubrication/cooling), apart from being environmentally friendly, reduces the surface roughness value better when compared to dry machining. Surface roughness values were affected mostly by cutting feed, followed by spindle speed and depth of cut has the least impact on surface roughness values. The result also shows that spindle speed and cutting feed combination has the best interaction while combination of cutting feed and depth of cut has the worst interaction leading to a poor surface finish. The model developed can be used to select the best combination of cutting variables for achieving optimum conditions that will result in minimum surface roughness during cutting operation.

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