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EXPERIMENTAL INVESTIGATION ON THE MACHINING BEHAVIOUR, SURFACE INTEGRITY AND TOOL WEAR ANALYSIS IN ENVIRONMENT FRIENDLY MILLING OF INCONEL 825

The study investigated end milling of Inconel 825 with varying spindle speed (N), feed rate (f) and axial depth of cut (d_a) with Minimum Quality Lubricant (MQL) and flooded lubrication. Molybdenum disulfide (MoS_2) with the average particle size of 10 μm was used as lubricating agent. Work considered, center line average of roughness profile as a measure of surface roughness which was measured with a surface roughness tester. Material Removal Rate (MRR) was also measured experimentally using weight difference. The influence of spindle speed (N), feed rate (f) and axial depth of cut (d_a) during end milling of Inconel 825 on surface roughness and MRR were studied. Prediction of surface roughness by ANOVA linear model for MQL condition was found functionally adequate with R^2 = 89.25% which fits with the experimental values. Also, the prediction and optimization of surface roughness using Response Surface Methodology (RSM) was proposed. It was found that, RSM model for MQL condition produced good agreement with the measurement of the given range of input cutting conditions with the prediction capability of 91.66%. Further, the machined surfaces and tool wear were analyzed using Scanning Electron Microscope (SEM) to understand the mechanisms of wear.

Keywords: Inconel 825; Flooded lubrication; Minimum Quantity Lubrication; Surface Roughness; Material Removal Rate

1. Introduction

Inconel 825 is an austenitic nickel-iron-chromium alloy which is added with other alloying elements to improve its chemical corrosion resistance property. Inconel 825 can be machined using conventional machining methods which are used for iron-based alloys. High-speed machining operations such as grinding, milling and turning, are performed while using water-based commercial coolants. It specifically provides an exceptional corrosion resistance to aqueous corrosion. Beside this, it exhibits oxidizing resistance and reducing acids such as phosphoric and sulfuric acids. Inconel 825 work-piece material in the manufacturing of automobile and aircraft components is known for its resistance to high temperature, high strength and high hardness. Precision Manufacturing demands high quality machined surface. Poor surface finish and burr formation prevent achievement of required surface quality [1]. On workpiece surface, undesirable projections due to plastic deformation during cutting is called burr [2]. Since burrs are not desirable and unavoidable, means are needed to reduce burr formation and to maintain surface quality. Conventional machining of Inconel 825 is challenging due to high cutting forces and due to high tool wear. Machinability studies of varieties of Nickel based super alloys attract researchers owing to their advantageous mechanical properties and excellent corrosion resistance. Different formation of chips indicates its machinability characteristics [3]. Inconel 825 exhibits high resistance to chemical environment and can tolerate very high temperature hence it has been classified as difficult-to-cut material [4]. Components made of Nickel based super alloys are manufactured with variety of conventional machining processes as well as non-conventional machining processes. Hence optimization of machining parameters for achieving economic advantages needs attention. Surface roughness and material removal rate are the performance parameters of any machined surface [5]. Due to increased wear rate in un-coated conventional cutting tools in the machining of difficult-to-cut materials, coated tools are preferred. In coated tools, AlTiN Physical Vapor Deposition coated tool with high hardness and high oxidation resistance at higher temperature can be used for machining Nickel based super alloys [6]. Machining with cutting fluids is one of the solutions to maintain surface quality. Although dry machining

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is suitable method for reducing severe impact on environment and health of workers to some extent, several issues like improper chip removal in cutting zone, poor surface quality, high temperature rise at machining zone and excessive tool wear exist [7]. Hence, metal cutting lubricants are employed as coolant as well as lubricant at the tool/ work-piece interface during machining operation. The metal cutting, lubricants are used to serve several important functions such as reduced friction, heat generation and dissipation at cutting tool- work-piece interface and hence reduced tool wear. However, their exposure to machine operators induces growing occupational health hazards. Occupational Safety and Health Administration recommends that; machine operators should not be exposed to metal cutting fluid aerosols greater than 0.4 mg/m^3 for 10 hours per day per week [8]. Excess amount of cutting fluid exposure will cause safety issues and health problems, like respiratory problems, skin tissue disorder, toxicity and cancer [9]. Hence reduced usage of flooded lubrication has brought attention towards new solutions. One such solution is to use micro-lubrication or near dry lubrication or Minimum Quantity Lubrication technique in a machining process. Experimental analysis or hybrid of experimental and numerical analysis were used to study tool wear and cutting [10]. The effect of coating on machined surface integrity and cutting speed were studied under dry turning of Inconel 825. Machining of Inconel 825 is found challenging due to its work hardening tendency [11]. The design of experiment (DOE) is considered one of the widely used techniques to optimize the manufacturing processes. Taguchi technique is a user-friendly and economical method used to solve analytically with minimum number of experiments and hence minimum time required for experimental investigations [12-13]. In this article Orthogonal Array (OA) is used to minimize the number of experiments. ANOVA and RSM were practiced investigating the effects of process parameters on MRR and surface roughness. Investigators tried to investigate machining performance of Inconel 825with both dry as well as MQL cutting environment. MQL application with vegetable oil as lubricant improves the machinability by reducing cutting temperature, cutting force and surface finish with increased tool life [14]. The Authors deployed the reliable Grey Relational Analysis for optimized productivity and lowered surface roughness of Inconel 825 by Wire-cut Electric Discharge Machining (WEDM) used in aerospace industries [15]. The ability of the WEDM process was studied by considering the performance metrics MRR and surface roughness in the article. The experimental analysis and response surface method were used to optimize the MRR and surface roughness [16]. Turning of Inconel 718 under MQL cutting condition found much influenced by speed on surface roughness, depth on tool wear and feed rate on MRR [17]. Milling of Inconel 718 components under MQL environment using cutting speed, feed rate, and depth-of-cut as process parameters was carried out in order to optimize cutting parameters using meta heuristic optimization techniques such as particle swarm optimization (PSO) and bacteria foraging optimization (BFO) algorithm. They found better tool wear characteristics under MQL compared to PSO and BFO [18]. Extensive research works were found in machining of Inconel 718 than current grade of Inconel 825 [17,19]. But, Inconel 825 has been used in major engineering applications such as marine industries, pickling operation, acid processing, nuclear fuel processing and radioactive waste disposal. Recently, researchers have started working on Inconel alloys with uncoated and coated tools [20]. In another study, in the turning of Titanium alloy grade 5 depicts increase in the hybrid nano cutting fluid concentration with MQL, which decreases wear compared to conventional bio-cutting fluid.

Although machining of Inconel 825 alloy has many engineering applications, limited works have been found in Inconel 825 alloy surface roughness and MRR prediction with MQL. This research work proposes the performance of MQL for end milling of novel Inconel 825 alloy by comparing the surface roughness under MQL and flooded condition. The relationship of MRR with spindle speed, feed rate and axial depth of cut was also studied. Also, Response surface model (RSM) has been developed to predict surface roughness with cutting conditions under MQL. Further optimization of controllable parameters for the minimum surface roughness has been proposed using optimizer tool RSM. Investigation of the effectiveness of MQL in comparison with flooded condition in end milling of Inconel 825 alloy with a PVD AlTiN coated insert under varying spindle speed, feed rate and axial depth of cut become the prime objective of this research work.

2. Materials and methods

Commercially available Inconel 825 blocks of 50 mm × 50 mm × 25 mm are the work-piece material used for this study. Both MQL condition and flooded lubrication end milling operation is planned using the same dimensions of work pieces and cutting tool. The work tool arrangement for flooded lubrication and Minimum Quantity Lubrication is shown in Fig. 1(a) and Fig. 1(b) respectively. The experimental investigation is explained below:

A CNC Vertical Machining Centre "AMS MCV –450" by Ace Micromatic Group, India has been utilized for end milling operation. The specifications of the CNC Vertical machining center are displayed in TABLE 1. Pre machining and work piece setting has been done for doing the end milling operation. Out of 54 work pieces, 27 for the flooded lubrication cutting condition and 27 for MQL condition were used. An end milling cutter of 12 mm [21] diameter with Al-TiN coated inserts by a physical vapor deposition (Kennametal-12A1R026B16SAD10) with twist flutes was mounted on the tool holder. The specification of the cutting tool is tabulated in TABLE 2. The geometric features of the end mill cutter have been shown in Fig. 2. Inconel 825 work piece is clamped on machine table. CNC part program for tool path is developed using Fanuc software for the selected values of spindle speed (N), feed rate (f), and axial depth of cut (d_a), by setting machine home position with respect to work piece home position. Up milling condition was adopted. A new insert has been employed for each experiment. Surface roughness measurement was carried out by “Mitutoyo SJ-120” surface roughness tester according to IS: 2488:1996 standard with 0.5 mm/s of tip transverse speed, appropriate values of cut-off length and sampling-length have been adopted as per the manufacturer’s catalogue. In this article, surface roughness centerline average (CLA) was measured. Average of five trials has been recorded against each experiment. Initially, machining was carried out with conventional cutting fluid of 90% water with 10% mineral oil based emulsion. Then the same experiments were performed with MQL environment with Aerosol of 90% water with 10% mineral oil emulsion. The end milled specimen is shown in Fig. 1(c).

TABLE 1

Specifications of Machine Tool

Sl. No:	Parameters	Values
1.	Table feed rate	30 m/min
2.	Max. Load on table	400 kg
3.	X axis travel	800 mm
4.	Y axis travel	450 mm
5.	Z axis travel	500 mm
6.	Spindle nose taper	7/24 No: 40
7.	Spindle speed	60-6000 rpm
8.	Tool Changer	20 Nos. Twin Arm
9.	CNC Control	Fanuc 01-MF
10.	Spindle power	11 kW

TABLE 2

Specifications of cutting tool

Sl. No:	Particular	Value
1	Model	Kennametal-12A1R026B16SAD10
2	Standard	DIN4000-87
3	Cutting diameter	12 mm
4	Depth of cut maximum	9 mm
5	Protruding length	26 mm
6	Overall length	75 mm
7	Shank type	cylindrical shank
8	Tool cutting edge angle	90 Degree

2.1. Minimum Quantity Lubrication unit

The objective of the design of MQL unit is to reduce the usage of lubricating oil which is harmful to environment without losing cutting quality. In this study MoS_2 reinforced lubricating oil was used as lubricating agent while performing the machining operation. The controlled way of lubricating cutting zone is obtained by this custom designed micro lubrication unit. A custom designed micro lubrication unit has been made as an attachment on the milling machine to spray an Aerosol of 90% water with 10% mineral oil emulsion. The nozzle position, nozzle tip distance to the cutting zone and spray angle are kept constant. TABLE 3 depicts the components used to build the micro lubrication unit. The details of experimental cutting condition levels are shown in TABLE 4.

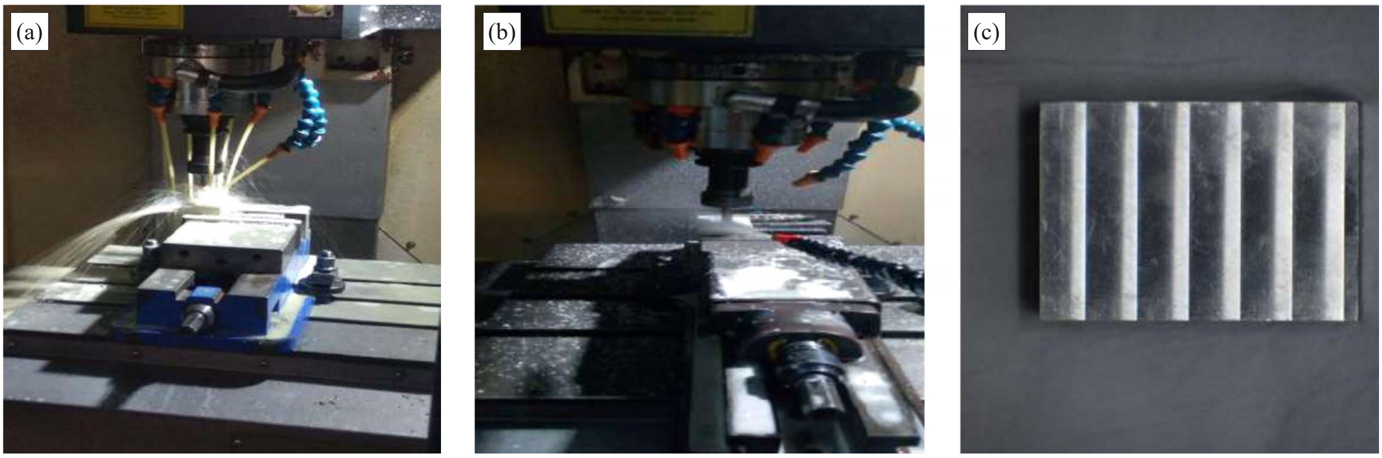


Fig. 1. (a) Flooded lubrication, (b) Minimum Quantity Lubrication and (c) End milled specimen

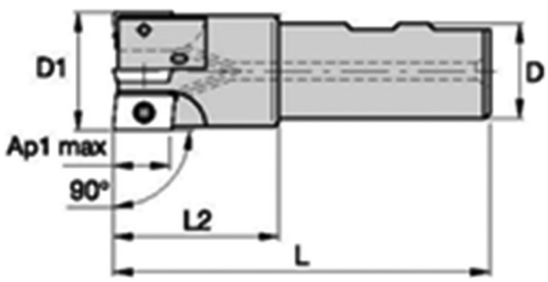


Fig. 2. Geometrical features of end mill cutter

TABLE 3

MQL unit Specification

Description	Specifications
Tank height	640 mm
Tank capacity	3 Liters
FRL unit	0-8 bar
Aerosol Feed direction	45° approx.
Distance between nozzle tip and tool work-piece interface	150 mm approx.

TABLE 4

Machining Parameters for MQL and flooded lubrication condition

Sample No.	Spindle Speed N (rpm)	Feed Rate f (mm/min)	Axial depth of cut d_a (mm)	Average Value of Ra with MQL (Ra mql)	Average value of Ra with Flood cooling ($Ra\ f$)	Material Removal Rate (mm^3/min)
1	700	200	0.4	0.6802	0.560	2532.8
2	700	200	0.8	0.9452	0.682	5108.4
3	700	200	1.0	0.8194	0.546	6420
4	700	500	0.4	1.2646	1.014	6458.2
5	700	500	0.8	1.7786	1.008	12920.4
6	700	500	1.0	1.3108	1.030	16158.4
7	700	1000	0.4	1.2414	1.965	12792.8
8	700	1000	0.8	1.6370	2.161	25848.6
9	700	1000	1.0	2.0424	2.157	32158.1
10	1500	200	0.4	0.326	0.527	2568.1
11	1500	200	0.8	0.4762	0.542	5138.8
12	1500	200	1.0	0.5398	0.540	6462.3
13	1500	500	0.4	0.7358	0.534	6488.8
14	1500	500	0.8	0.8704	0.633	12820.7
15	1500	500	1.0	0.5582	0.709	16188.1
16	1500	1000	0.4	1.2484	0.919	12802.2
17	1500	1000	0.8	1.4512	0.960	25900.1
18	1500	1000	1.0	1.2916	0.809	32280.5
19	2000	200	0.4	0.2874	0.514	2506.1
20	2000	200	0.8	0.3514	0.511	5166.2
21	2000	200	1.0	0.2936	0.467	6440.7
22	2000	500	0.4	0.6006	0.478	6447.6
23	2000	500	0.8	0.6670	0.432	12922.2
24	2000	500	1.0	0.5766	0.444	16100.4
25	2000	1000	0.4	0.9384	0.566	12882
26	2000	1000	0.8	1.1026	0.624	25910.2
27	2000	1000	1.0	0.9164	0.694	32182.5

2.2. Design of Experiments (DOE)

Preliminary study was carried out to decide the range of input conditions for the influence of surface roughness. Although there are many parameters involves in deciding the surface roughness values of the end milled surface, spindle speed with 700 rpm to 2000 rpm, feed rate 200 mm/ min to 1000 mm/ min and axial depth of cut 0.4 mm to 1.0 mm have been considered to study the effect of these conditions on surface roughness of end milled Inconel 825 alloy on MQL application and flooded lubricating conditions. An Orthogonal Array (OA) is deployed on the basis of levels of input parameters for the various experiments. In this article, the three levels of controllable parameters of spindle speed, feed rate and axial depth of cut were considered. L_{27} OA covers three levels of the combinations of controllable machining conditions. Hence, L_{27} OA was considered to find the influence of three parameters and the interaction among them [21]. Each experiment was performed five times and the average values are reported.

2.3. Response Surface Methodology (RSM)

Response Surface Method is a combined tool which utilizes mathematical and statistical techniques [20]. The output response can be predicted with respect to independent input parameters by Multiple Regression Analysis using a few experiments. In this work, a quadratic RSM model for surface roughness has been developed to study the three cutting parameters namely, spindle speed (N), feed (f) and axial depth of cut (d_a).

From RSM, the nonlinear equation for surface roughness under MQL condition is given by Eq. (1),

$$\text{Ra-M} = c_0 + c_1 N + c_2 f + c_3 d_a + c_{12} N * f + c_{23} f * d_a + c_{13} N * d_a + c_{11} N^2 + c_{22} f^2 + c_{33} d_a^2 \quad (1)$$

Where, Ra-M is the response, that is surface roughness value with MQL condition; $c_0 \dots c_{33}$ are the regression coefficients of the second order response surface equation.

3. Results and discussion

3.1. Comparison of surface roughness values for flooded and MQL conditions

Surface roughness is one of the measures to decide the product's machined surface quality. Therefore, the influence of input parameters on surface roughness under flooded and MQL lubrication conditions has been discussed in this study. TABLE 5

TABLE 5

ANOVA table for linear model of MQL

Source	DF	Adj SS	Adj MS	F-Value	P-Value
speed	2	2.1023	1.05117	33.85	0.000
feed	2	2.8406	1.42032	45.74	0.000
doc	2	0.2129	0.10645	3.43	0.052
Error	20	0.6210	0.03105		
Total	26	5.7769			

gives the results of surface roughness values for experiments with various set of cutting conditions of flooded and MQL conditions and percentage variations. 27 trials were conducted using flooded lubrication and MQL conditions respectively. A line graph in Fig. 3 depicts the surface roughness values achieved by flooded lubrication and MQL conditions. It was found that for both flooded lubrication and MQL conditions the variations in surface roughness followed the same trend. In flooded lubrication, heat removal at the tool work piece interface is higher, this avoided the sticking phenomena. Hence resulted in easy chip removal and reduced friction between machining surface and tool flank surface. Thereby, a reduction in surface roughness was observed. MQL achieved surface quality close to flooded condition, with modifications in flow rate, lubricating oil, position, and angle of nozzle tip. This was observed because of extensive study of MQL for the effect cutting conditions on surface roughness of Inconel 825. The study indicated range of values for cutting conditions which lead to optimization. As the feed rate and spindle speed increases, the surface roughness value increases matching the classical theory of metal cutting [18].

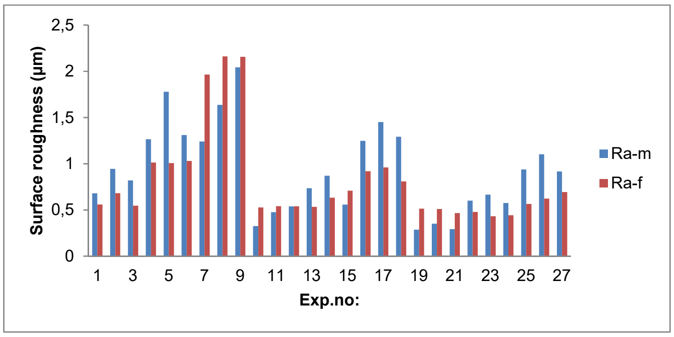
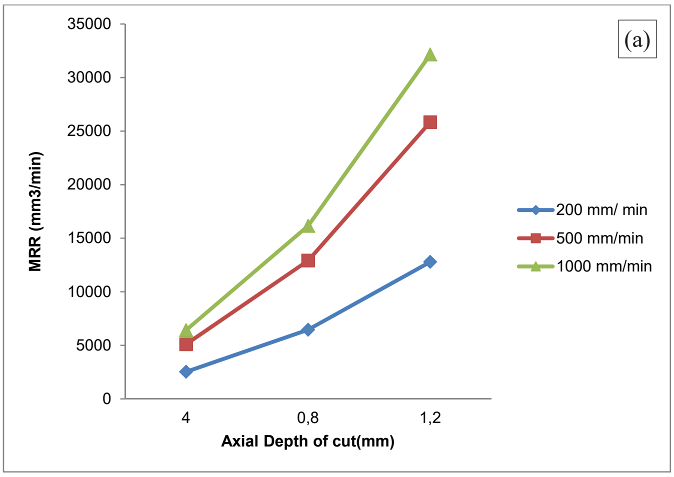
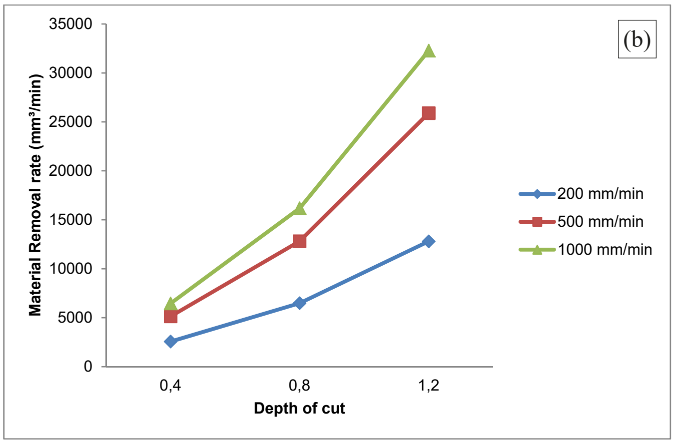


Fig. 3. Comparison of surface roughness between flooded lubricating condition and MQL

3.2. Effect of feed, speed and depth of cut under MQL on MRR

The variation of MRR with respect to speed, feed and axial depth of cut was studied by plotting them against constant spindle speed as depicted in Figs. 4(a), (b) and (c). On comparing the three plots, as the spindle speed increases, MRR increases





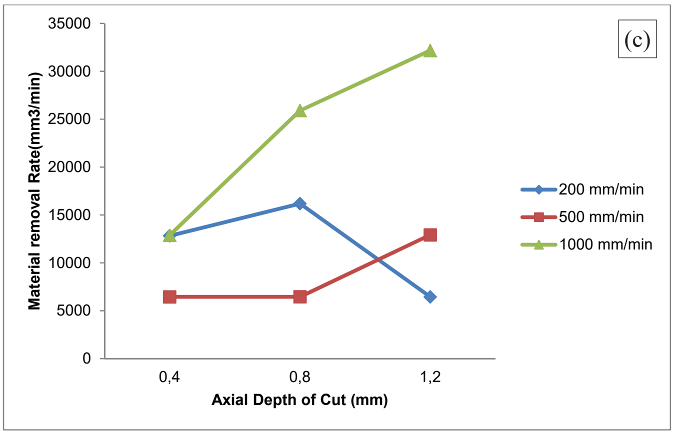


Fig. 4. Effect of axial depth of cut with MRR at different speed a) 700 rpm, b) 1500 rpm and c) 2000 rpm

gradually. Increase in spindle speed resulted in higher chip removal that increased MRR. On the other hand, MRR was low in lower speed and formed mechanically continuous chips of Inconel alloy, eventually increasing cutting forces and the specific energy required for cutting. Similarly as feed increased due to fast table movement which resulted in higher chip removal MRR increased. Oblique cutting; reduced friction coefficient in increased feed rate caused quick removal of chips at tool and work-piece interface. As the depth of cut increased, the thickness of the chip increased and hence increased MRR. Increase in axial depth of cut caused increased cutting force which in turn increased shearing of material leading to higher MRR.

3.3. Results of Analysis of Variance of linear model for MQL condition

ANOVA was used to determine the most influential factor whose effect was studied under optimum set of input parameters on output state by percentage of contribution of each factor (F-value) and p value. In this article, the set of experiments has been used to build linear model using MINITAB software and its fitness was checked with ANOVA. From the TABLE 6, feed was found to be the most influential (F-value 45.74) followed by speed (F-value 33.85) and then by depth of cut (F-value 3.43) in predicting surface roughness. It is necessary to check developed model for the adequacy of approximation of response with the measured values [20]. Earlier studies reported that model validation could be one of the graphical techniques [16-21]. Residual was measured as a difference between an observed value and its predicted value by the model. From Fig. 5, the normality plot was shown approximately straight line and hence normal distribution of the residuals. The random distribution of residuals was also observed in a plot between residual and fitted value. The residual versus observation order plot depicted very few outliers in the experiments. The histogram plot of residual and frequency shows that most of the residuals lie in the range of –0.1 to 0.1. Hence the model satisfies the basic needs of the model fitting. Goodness-of-fit statistics show that $R^2 = 89.25\%$ for experimental and $R^2 = 80.41\%$ for predicted values of surface roughness.

TABLE 6

ANOVA table of linear model for flooded lubrication

Source	DF	Adj SS	Adj MS	F-Value	P-Value
speed	2	2.49834	1.24917	14.35	0.000
feed	2	2.16466	1.08233	12.44	0.000
doc	2	0.01307	0.00654	0.08	0.928
Error	20	1.74067	0.08703		
Total	26	6.41675			

3.4. ANOVA of linear model for flooded lubrication

ANOVA was used to decide the main effect and interaction effect under optimum set of input parameters on output state by percentage of contribution of each factor (F-Value) and p value. In this article, the set of experiments has been used to build linear model using MINITAB software. TABLE 7 specifies the result of the linear model under flooded lubrication condition. From the TABLE 4, in the prediction of surface roughness, spindle speed was the most affecting parameter (F-value 14.35) followed by feed (F-value 12.44) and then depth of cut (F-value 0.08). Fig. 6 depicts the sufficiency of model fitting. The normal distribution of residual was shown as near straight line. In a plot between residual *Vs* fitted value, clusters ie, some dependency in residuals were observed. The residual versus observation order plot indicates drift in chip removal in experiments with extended duration. Also, the histogram plot of residual and frequency shows unusual pattern. Hence the model lack in satisfying the basic needs of the model fitting. In addition, coefficient of deter-

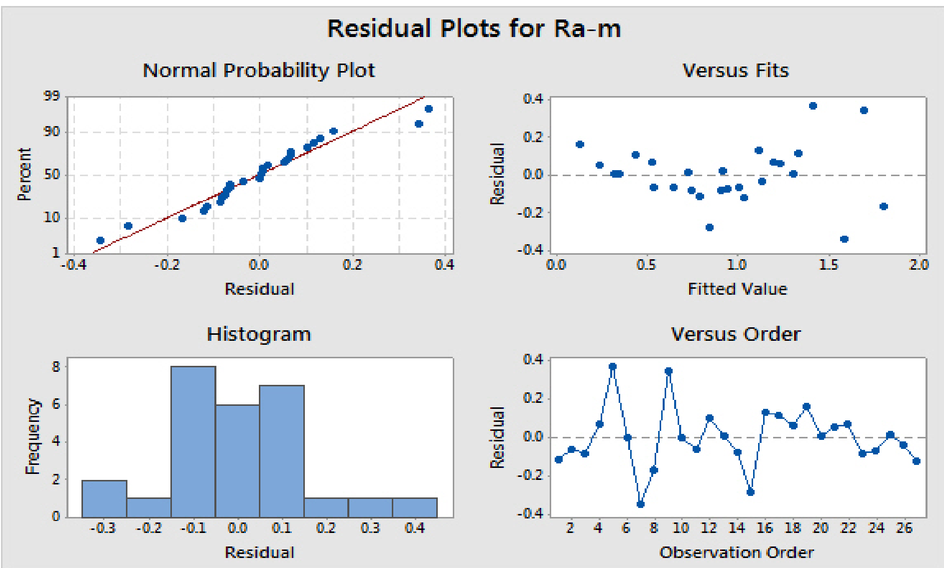


Fig. 5. Residual plots of Ra-M

TABLE 7

ANOVA table for RSM model for MQL condition

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	5.29524	0.58836	20.77	0.000
Linear	3	4.61987	1.53996	54.35	0.000
Spindle Speed (rpm)	1	1.83749	1.83749	64.85	0.000
Feed Rate (mm/min)	1	2.71827	2.71827	95.94	0.000
Axial depth of cut(mm)	1	0.08155	0.08155	2.88	0.108
Square	3	0.20399	0.06800	2.40	0.104
Spindle Speed (rpm)*Spindle Speed (rpm)	1	0.02111	0.02111	0.75	0.400
Feed Rate (mm/min)*Feed Rate (mm/min)	1	0.06716	0.06716	2.37	0.142
Depth of cut(mm)*Depth of cut (mm)	1	0.11572	0.11572	4.08	0.059
2-Way Interaction	3	0.13937	0.04646	1.64	0.218
Spindle Speed (rpm)*Feed Rate (mm/min)	1	0.00465	0.00465	0.16	0.690
Spindle Speed(rpm)*Depth of cut (mm)	1	0.10809	0.10809	3.82	0.067
Feed Rate (mm/min)*Depth of cut (mm)	1	0.02663	0.02663	0.94	0.346
Error	17	0.48165	0.02833		
Total	26	5.77689			
S	R-sq	R-sq (adj)	R-sq (pred)		
0.168323	91.66%	87.25%	77.49%		

mination was found to be, $R^2 = 72.82\%$ variation of the surface roughness values fits with the experimental values. Whereas, $R^2 = 50.56\%$ was predicted values for new experiments. Hence, this model has large lack of fit compared to model developed under MQL condition. Low R-square value explains the data have high variability and noisy, hence the model developed need to be reconsidered and repeated for another set of inputs.

3.5. Results of RSM of MQL condition

The significance of the model, individual model terms, and lack of fit of the quadratic RSM model can be tested with help of ANOVA. Model terms were tested for its significance when "Prob>F" value is in the range between 0.05 and 0.1. If the "Prob>F" value is lower than 0.05, under 95% confidence interval found significant, otherwise, it was insignificant due to noise. The TABLE 7 shows the ANOVA result of the quadratic RSM model. From the TABLE 7, the model adequately satisfies the stated hypothesis. In this study, it is evident from the TABLE 7 that the input cutting conditions, spindle speed and feed were significant. Axial depth of cut, all the square terms and interaction terms were found to have no significance. The model prediction capability was described by the coefficient of determination (R). Squared R value and Predicted R^2 had better agreement of 91.66% and 77.49%

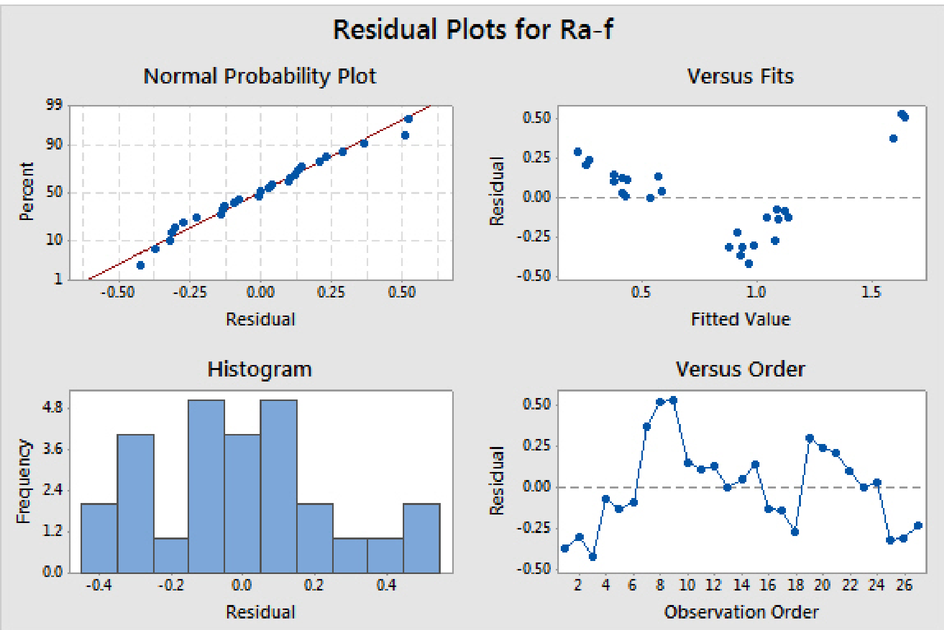


Fig. 6. Residual plots for surface roughness model under flooded lubrication

respectively. The regression equation for the model is presented in Eq. (2).

$$\begin{aligned} \text{Ra-M } (\mu\text{m}) &= -0.152 - 0.000526 \text{ Spindle Speed} + \\ &+ 0.001673 \text{ feed rate} + 3.11 \text{ Axial depth of cut} + \\ &- 1.768 \text{ Axial depth of cut}^2 - 0.000474 \text{ Spindle speed} \\ &* \text{Axial depth of cut} + 0.000382 \text{ feed rate} \\ &* \text{Axial depth of cut} \end{aligned} \tag{2}$$

Normality plot for the developed quadratic RSM model is presented in Fig. 7. This plot was used to check the normality assumption. Fig. 7, normal probability plot depicts that residuals were normally distributed and plotted close to a straight line, showing agreement between experimental and predicted values. The normality plot does not show any abnormality and hence the model was effective. The plot between residual and fitted value does not follow any pattern hence model have not been subjected to any other influence. The histogram plot shows the residues occurred mostly near zero. Also residual vs observation order plot shows less outlier and independent. Hence, the proposed RSM model was adequately fitted with the observed values.

3.6. Validation of predicted results

Correlation between the measured and predicted surface roughness values under MQL condition were checked. The actual and predicted plot is presented in Fig. 8. The predicted values on the plot were distributed closer to the straight line, indicating a fair agreement between the experimentally measured and predicted values of the surface roughness. Analysis confirms that the assumptions were found appropriate as described in a similar work [20]. The above results also confirm that the developed RSM quadratic was adequate in predicting the surface roughness values for the experimental data.

3.7. 3D surface plots

The response surface plot describes the relationship between the model response and experimental values of each input parameters. Figs. 9(a), (b) and (c) illustrate the response surface plots for the surface roughness (Ra-M). The surface plots corresponding to the quadratic model fitted and all plot of interactions for surface

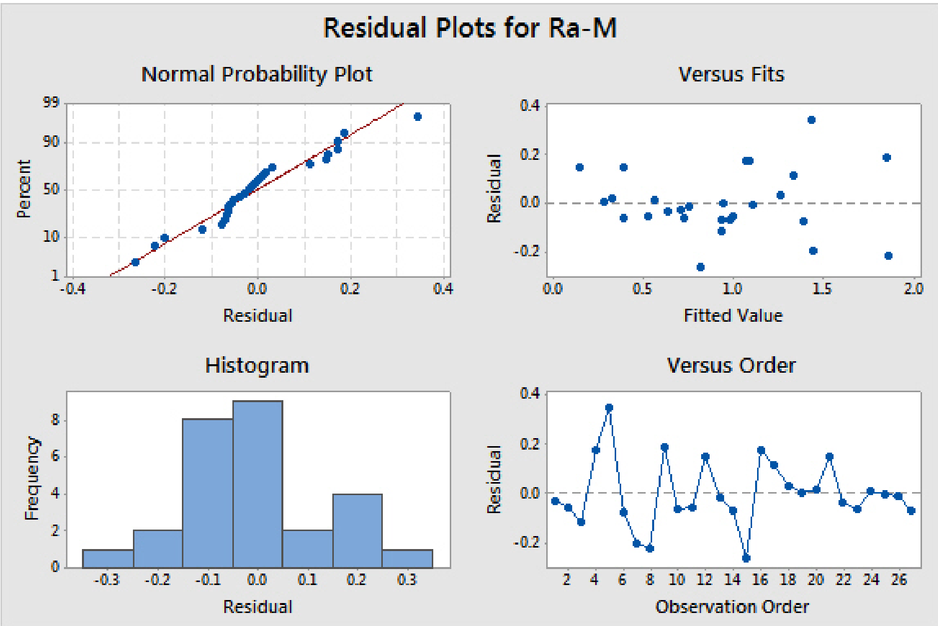


Fig. 7. Residual plots for RSM of MQL condition

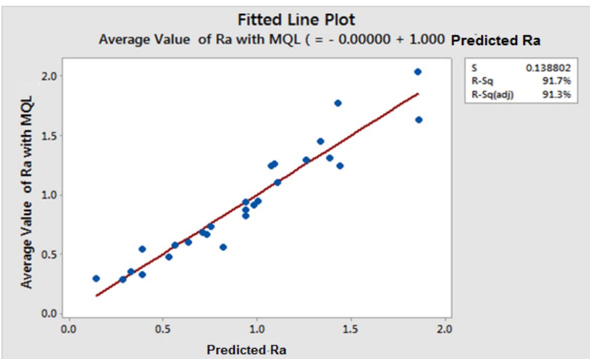


Fig. 8. Predicted vs Measured surface roughness value plot

roughness was found to be significant. Fig. 9(a) shows that surface roughness value decreases at higher spindle speed. At low level spindle speed and feed rate, medium level of surface roughness was produced due to more chips stuck at tool work-piece interface [21]. From Fig. 9(b), it is observed that at higher spindle speed, chip velocity was faster at lower depth of cut which lead to shorter contact with new machined surface and lesser chance of chip left over and hence minimum surface roughness. Also, it could be observed that the variation in axial depth of cut found little influence on surface roughness values at feed rate of 600 mm/min. Fig. 9(c) depicts that low surface roughness obtained at lower feed rate and depth of cut, due to low chatter and complete ma-

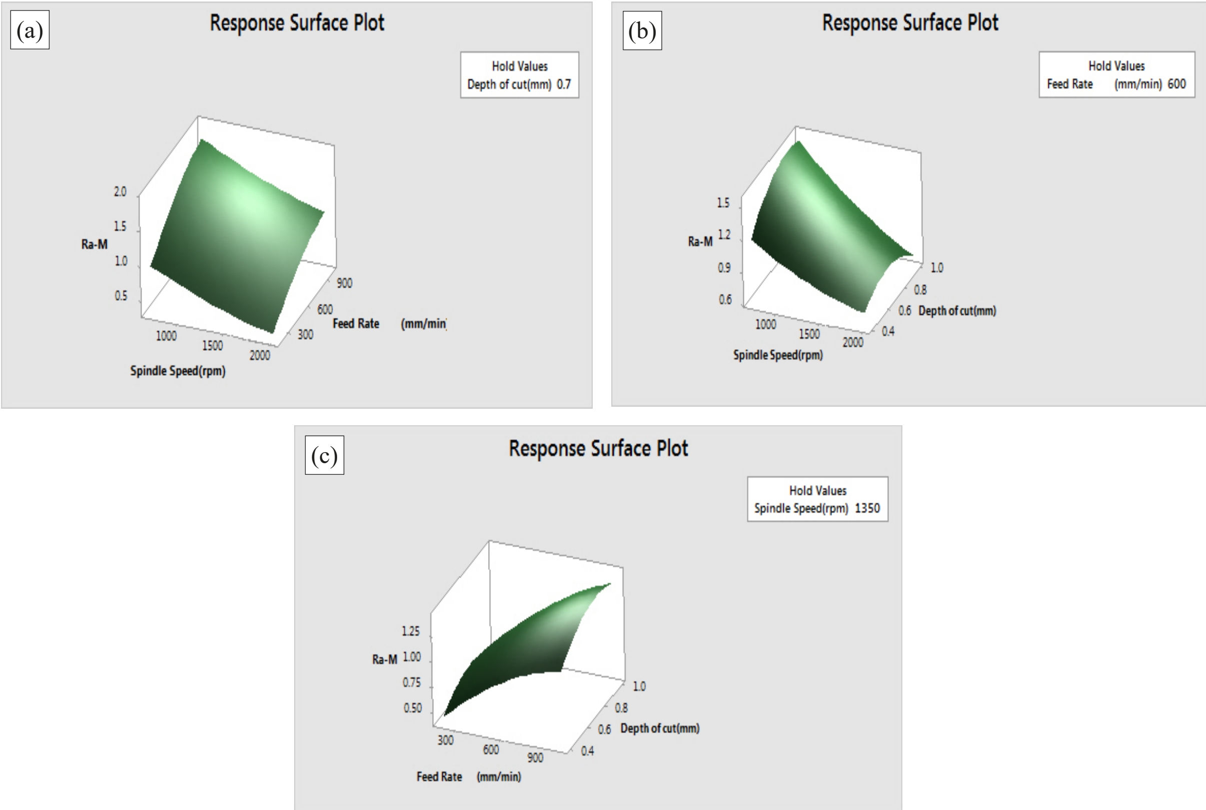


Fig. 9. (a) Response surface plot of spindle speed and feed rate, (b) Response surface plot of spindle speed and depth of cut and (c) response surface plot for feed rate and depth of cut

chining. In addition, at the highest spindle speed, higher surface roughness value is observed at high feed rate and axial depth of cut due to high tool vibrations and built up edge chip formation.

3.8. Confirmation Test

Figs. 10(a) and (b) depicts the variation between measured values and predicted responses. This reveals that obtained results from developed model are in close agreement with each other and can predict the values of surface roughness (*Ra*) accurately with a 95% confidence interval [17].

3.9. Analysis of optimized cutting conditions under MQL

Response optimizer is an interactive tool in MINITAB16 proposes the optimized input cutting conditions for the required surface roughness. The built in optimizer graph is presented in the Fig. 11.The plot shows the variation of different cutting conditions that affect the predicted responses of surface roughness. Each column specifies the input factors such as spindle speed, feed rate and axial depth of cut that affected the roughness values. The red line on the plot represents the current input factors setting. The numbers in red at the top of a column represent the

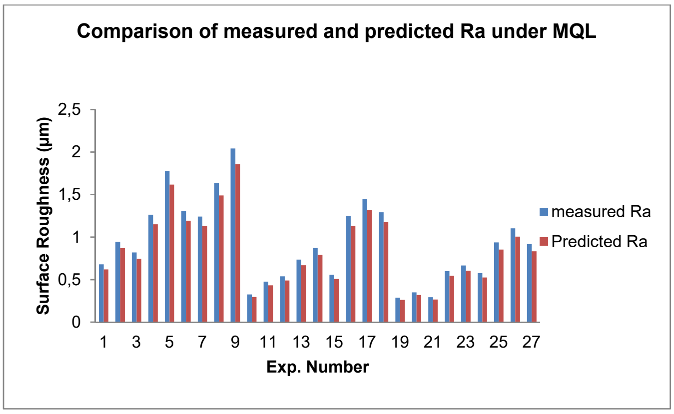


Fig. 10(a). Comparison of surface roughness values between measured and predicted model under MQL

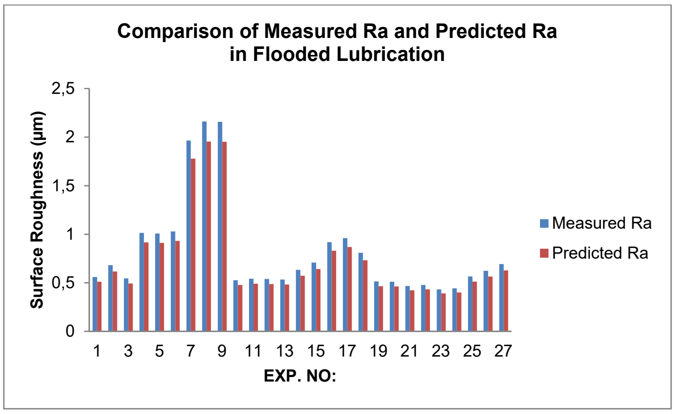


Fig. 10(b). Comparison of surface roughness values between measured and predicted model under flooded lubrication current factor level settings. The horizontal blue lines and numbers depicted the responses for the current factor level.

3.10. Tool and surface wear

Fig. 12(a & b) shows the surface wear of Inconel 825 for both MQL and flooded conditions. Flooded environment possessed higher amount of feed marks compared to MQL environment. Various defects such as feed marks and burnt surface were viewed on the flooded environment sample. This is due to the tendency of forming built-up edges under this condition for higher feed rate. At MQL condition, higher wettability at tool surface was observed. This lubricant was deeply penetrated to the tool surface interface and to chips. It prevents the tool and work-piece from heat generation during friction. Even though tool is with Al-TiN coated insert, exhibits higher degree of severe plastic deformation due to the direct metal contact between the tool and work-piece. Analogous to the flooded condition, MQL condition possessed lower tool wear shown in Fig. 13(a & b).

In flooded condition the formation of chips are unstable and it could increase with feed and cutting speed due to high friction. High temperatures tend to reduce the formation of built up edge chips (Refer Fig. 13(a)). It influences the work hardening of the chips and it increases the surface roughness. The heat generation will affect the chip serration and grain elongation at the localized region of machining region. At MQL condition, an unique chip was observed, it had heat dissipation rate due to Al-TiN coated insert (Refer Fig. 13(b)). Fig. 13(c) shows the unused tool blade for Al-TiN coated insert and it illustrates that there is no evidence of pores at the surface and hence coated insert is perfect for end milling.

4. Conclusion

- MRR increase with feed due to fast table movement which resulted in higher chip removal. In oblique cutting; reduced friction coefficient with increased feed rate caused quick removal of chips at tool and work-piece interface.
- For both MQL and flooded lubrication condition, the variations in surface roughness follow the same trend. But, observations reveal that significant increase was found for surface roughness values in MQL condition compared to flooded condition.
- ANOVA for linear model for surface roughness prediction under MQL condition brought R^2 = 89.25% variation of the surface roughness fits with the experimental values. Similarly, R^2 = 80.41% of the surface roughness values was predicted.

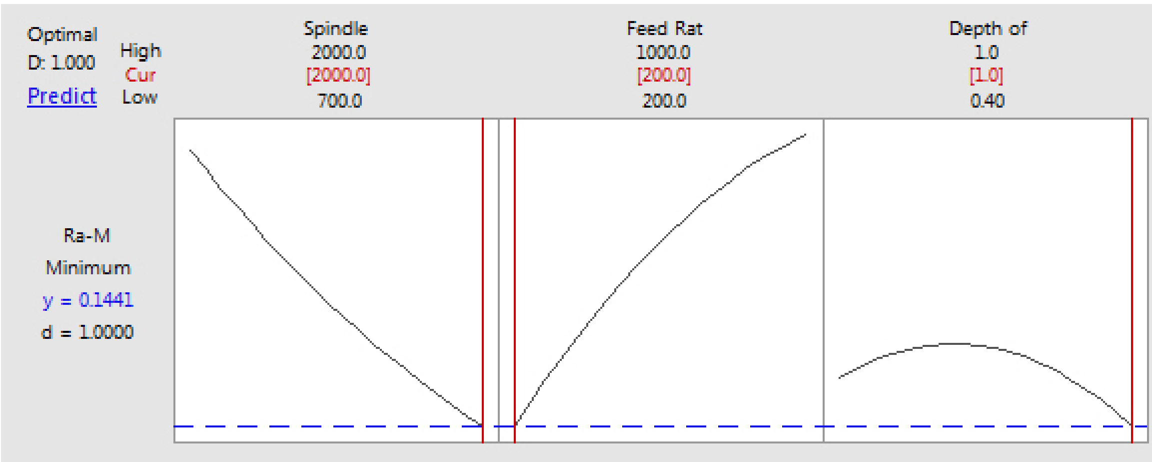


Fig. 11. Interactive optimized surface roughness plot from MINITAB

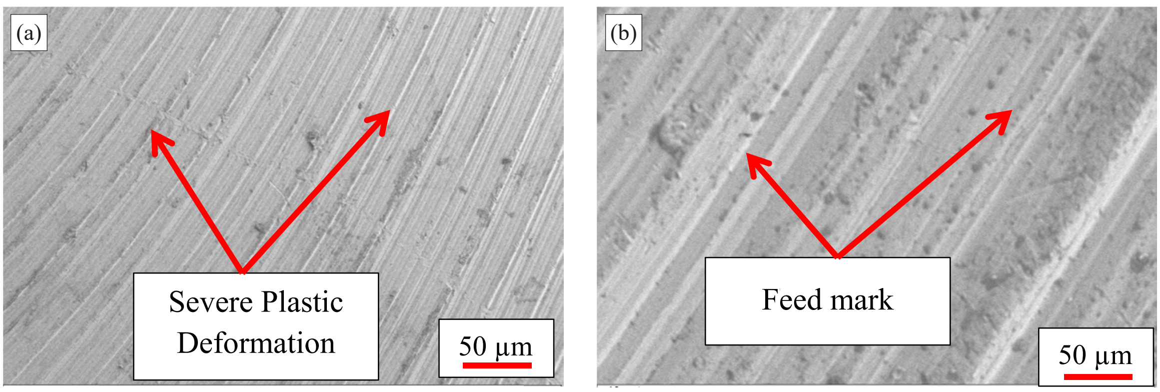


Fig. 12. Surface morphology of Sample 8. a) MQL condition and b) flooded condition

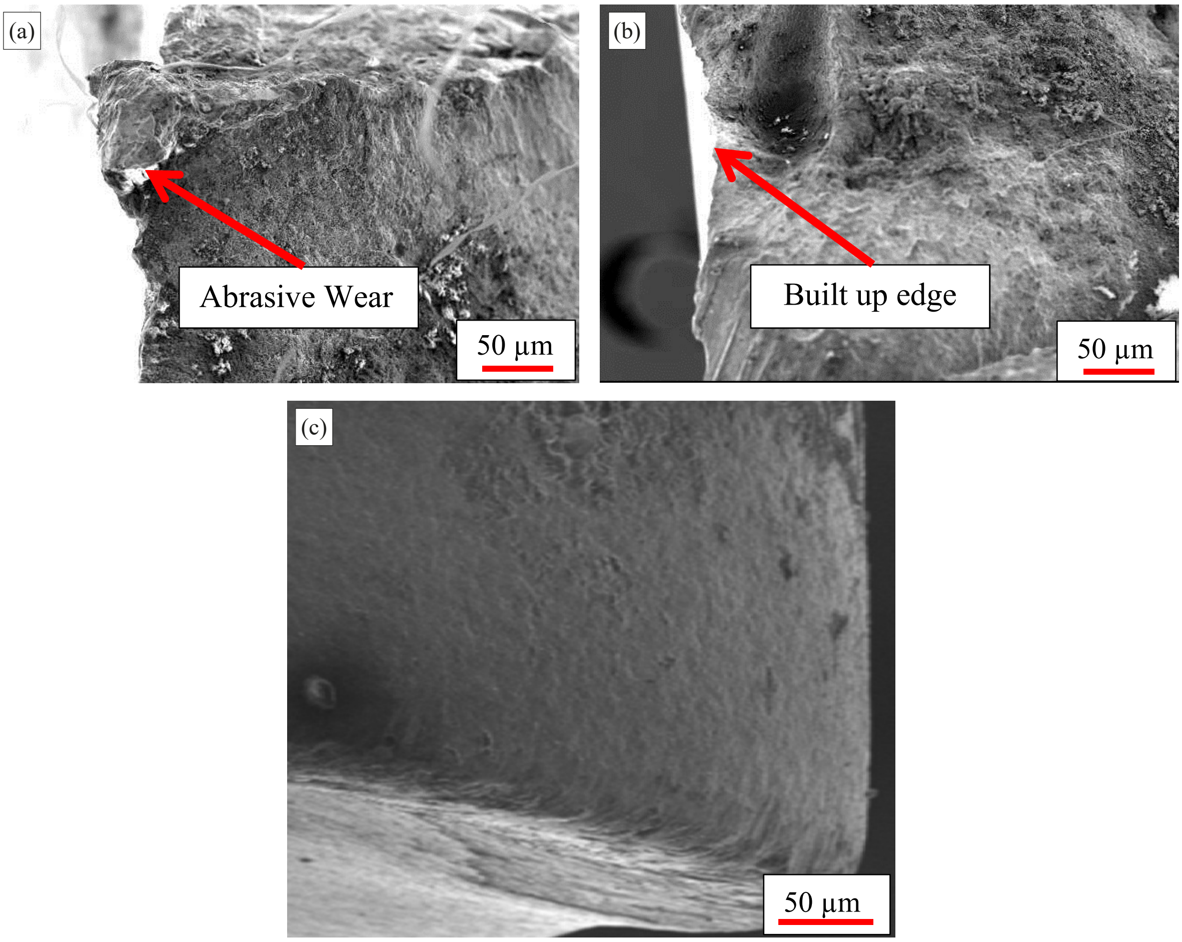


Fig. 13. Tool wear morphology of a) MQL condition, b) flooded condition, c) unused tool blade

- The quadratic RSM model was developed and ANOVA was used to check functional accuracy. The prediction capability of the RSM model is found to be 91.66% and the predicted result is also validated with the measured result.
- MoS_2 in MQL environment reduced tool and surface wear significantly. This is happening because of lubrication effect and also MoS_2 reduced the tool and specimen surface heat generation.

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