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Procedia Manufacturing 30 (2019) 396–403

Procedia MANUFACTURING

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14th Global Congress on Manufacturing and Management (GCMM-2018)

Machinability study and multi-response optimization of cutting force, Surface roughness and tool wear on CNC turned Inconel 617 superalloy using Al_2O_3 Nanofluids in Coconut oil

K. Venkatesan[a], Arun Tom Mathew[b*], S. Devendiran[c], Nouby M Ghazaly[d], S.Sanjith[e], R. Raghul[f]

[a,b,c,e,f]*School of Mechanical Engineering, Vellore Institute of Technology, Vellore and 632014, India.*
[d]*Department of Mechanical Engineering, South Valley University, Quena and 83523, Egypt.*

Abstract

Inconel 617 alloy is corrosion and oxidation resistant, nickel-based alloy and emanates under tough to turn material. Moreover, turning off this alloy under MQL need attention. In this context, this work aims to examine the machinability study under MQL on CNC turning of 617 alloys by AlTiN PVD carbide cutting inserts. As a methodology, the Taguchi L_9 orthogonal array parameter design and response surface optimization has been employed. 1D and 3D plots have been used to analysis on the collected machining data based on fitted regression model. The statistical analysis revealed % concentration impacted for force, cutting velocity influenced for surface roughness and tool wear. From the optimization analysis, 0.25% Al_2O_3 Nano-fluid in coconut oil along with a cutting speed of 40 m/min and 0.14 mm/rev feed rate. Abrasion, adhesion and diffusion wear are identified as wear mechanisms. The diameter of produced helical and tubular chips are different, and at high % concentration, the curl diameter is found to be increased due to the decrease in lubricity and increase tool friction on turning of Inconel 617.

Keywords: Alloy 617, force; Nanofluid; Coconut oil; Optimization;

* Corresponding author *E-mail address:* arun.mathew@vit.ac.in

10.1016/j.promfg.2019.02.055

1. Introduction

Superalloys constituent of nickel in aero engine bags a contribution of 50% [1]. The metal-based alloys have high-temperature strength, excellent resistance to corrosion and oxidation, and creep strength [2, 3]. Due to properties above, the nickel materials are found in rocket motor casing, aerospace engines, cryogenic tank, and industries like nuclear and petrochemical applications [2]. Superalloys of Inconel 617 [4], Nimonic C-263, Haynes 282, Haynes 230, and Inconel 740 are being industrialized for ultra-supercritical power plants [5]. Inconel 617 is a nickel (Ni)-chromium (Cr)-cobalt (Co)-molybdenum (Mo) alloy and considered as hard to machine materials [6]. The sustainable assisted machining techniques have been suggested by the various researcher to improve the machining performance of hard to turn material [7, 8]. Also, MQL environments are waste-free, eco-friendly and reduce the coolant cost along with environmental hazards [9]. The spray oil mist in MQL machining of Inconel 718 increases the tool life [10]. Reported that MQL environment shows the surface finish is at par that of wet conditions on machinability study of alloy 718 [11]. The presence of NPs in nMQL improves the thermal and tribological property and also form a tribo-oil film at contact pairs [12]. The dispersion MWCNTs and Al_2O_3 nanofluids in vegetable oil reduce the deformation of chip thickness due to an increase of shear angle have been observed on the turning of 718 alloy with the uncoated tool [13]. Results show that using Al_2O_3 NP in vegetable oil reduces the measure of force ratio, specific grinding energy, and surface roughness that of pure palm oil and MoS_2 NF on grinding of Alloy 718[14]. The reduction of nose wear, abrasion and carter wear is low in PPTE added vegetable oil (Bechem™ Berecut) MQL that of solid lubrication assisted strategies on finish turning of Titanium alloy [15]. Compared to dry machining, borax and boric added cutting fluid increased the tool life by 110% and 50% and surface roughness by 52% and 38% on the milling of AISI O2 using MQL system [16]. Reduction in roughness, force and tool under MQL- GnP with 0.2 vol.% particle than dry on turning of Inconel 718 [17]. 0.25% concentration of nano boric acid in coconut oil and SAE 40 resulted in improving the machining effort regarding cutting temperature, surface roughness and tool wear on turning of AISI 1040 steel [18]. The effect of nAl_2O_3 in water with and without surfactant on turning of Ti-6Al-4V has studied and revealed that nanoparticles in nanofluids with surfactant decreases the machining effort of tool wear and surface roughness [19]. On grinding of Ti-6Al-4V with different NPs of Al_2O_3 and CuO has been studied with 0.05-1.00 Vol. % and reported that 0.1 vol% concentration of nAl_2O_3 performed better by establishing a tribo-layer which led to lessening of the friction coefficient at the contact surface of wheel/work surface [20]. Effect of speed, feed and cutting depth for surface roughness, tool wear, and material removal rate on AISI 1060 steel with MQL are examined with Taguchi S/N based optimization. The results show that the cutting speed for surface roughness, cutting depth for tool wear and feed rate for material removal rate has the mostly high influence factor under MQL [21]. A mechanistic model has been developed to predict cutting forces, chip thickness, chip contact length, and coefficient of friction as a function of cutting parameters and MQL parameters. Results show that the average assessment error for cutting force and the thrust force is 6.53% and 8.3% respectively [22, 23].

On the discussion of the above note, the application of MQL and nMQL improves the machining effort and also eco-friendly sustainable. As nAl_2O_3 in vegetable oil brings down the friction coefficient, but no note on n Al_2O_3 in MQL machining of Alloy 617. Also, the determination of optimal parameters by the inclusion of % concentration n Al_2O_3 along with control factors (cutting velocity and feed rate) is not found a note in the previous studies. Therefore, the present study aims to study the effect of % concentration nAl_2O_3 gamma and control factors (cutting speed and feed rate) on machinability characteristics using AlTiN coated carbide tool insert of Inconel 617 under MQL conditions in a machine tool.

2. Experimental details

Inconel 617 has been chosen for the machining trials to collect the machining data in this study. The work part is having a dimension of 32mm diameter and 300 mm length. Table 1 represents the nominal composition of Inconel 617 material. The workpiece is then mounted and machined in a computerized numerical controlled (Simple Turn 5075-SPM) machine lathe with a capacity of 4000 rpm and power of 7.5 kW. For turning, the PVD (AlTiN) coated cutting tool with an ISO labeled CNMG120408-MP has been mounted on an ISO marked tool holder PCNRL2525. Each machining trials are conducted for a machining length of 30 mm at a constant cutting depth of 0.5 mm. The

MQL experimental setup and research methodology is represented in Figure 1. The flow rate and compressed air have been kept constant at 20 ml/min and 4MPa for all cutting experiments. Taguchi L_9 orthogonal array has been chosen, and corresponding machining data are listed in Table 2. The Dinolite Edge 3.0 – 5MP digital microscope, Mahrsurf, piezoelectric dynamometer (Kistler type 9257B) are used to measure the tool wear and chip shape, surface roughness and force, respectively.

Table 1. Chemical composition of Inconel 617

Element	Ni	Cr	Co	Mo	Fe	Mn	Si	Al	Fe	Ti	Cu
Weight %	44.5	20~24	10~15	8~10	3 Max	1 Max	1 Max	0.8-1.5	0.05-0.15	0.6 max	0.5 max

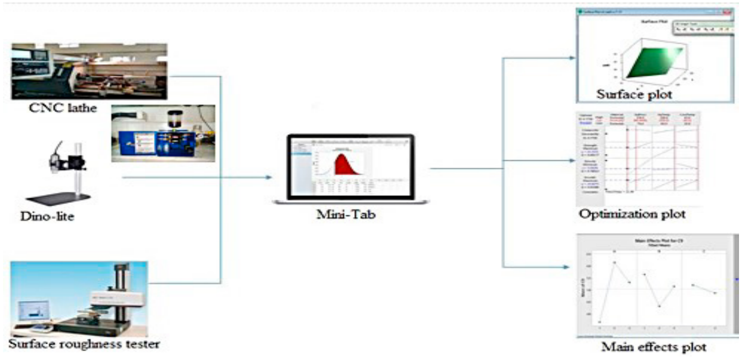

Fig. 1. Work Methodology adopted for the present study.

Table 2.The control factors and experimental trials for three measures.

Trial	Con.(%)	V (m/min)	F(mm/rev)	Fz (N)	Ra(μm)	Vba (μm)
1	0.25	40	0.14	50.7	0.7325	40.5
2	0.25	60	0.17	359.8	0.8399	72.2
3	0.25	100	0.20	219.0	1.3914	331.6
4	0.50	40	0.17	334.2	1.0646	240.5
5	0.50	60	0.20	266.2	0.6613	93.7
6	0.50	100	0.14	245.0	0.7958	247.1
7	1.00	40	0.20	393.0	0.7836	146.5
8	1.00	60	0.14	337.0	0.5208	212.3
9	1.00	100	0.17	294.0	0.9037	258.9

3. Results and Discussion

3.1. 3D surface plots for cutting force

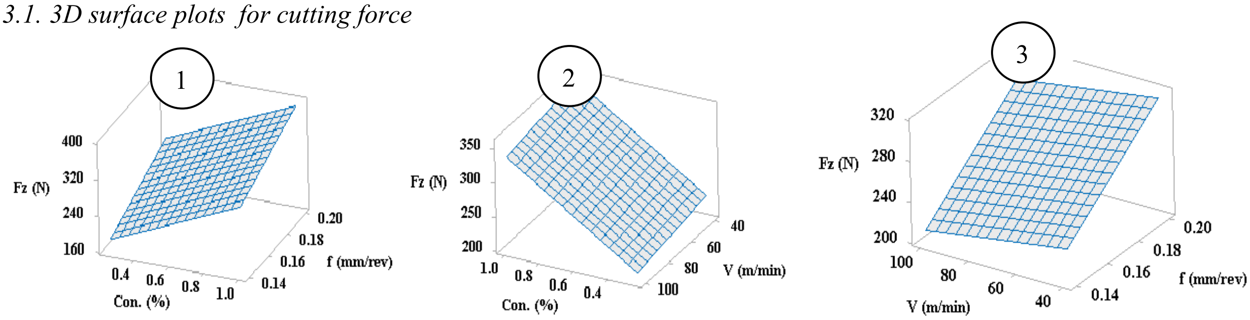

Fig. 2. Response plots for cutting force.

Table 3. Signal-to-Noise (S/N) and Variance (ANOVA) table for Fz.

Response	S/N : Fz			ANOVA: Fz				
	Con. (%)	F (mm/rev)	V (m/min)	Source	DF	SS	F-Test	PCR (%)
Level 1	-44.01	-44.15	-45.49	Con. (%)	2	26014	0.98	31.27
Level 2	-48.92	-50.32	-50.06	F (mm/rev)	2	22061	0.83	26.52
Level 3	-50.60	-49.07	-47.99	V (m/min)	2	8520	0.31	10.24
Delta	6.59	6.18	4.57	Error	2	26585		31.96
Rank	1	2	3	Total	8	83181		R^2=78.04%

From plot 1 in Fig. 2 by holding third factors at 60 m/min, at higher feed rate and % concentration, the magnitude of 400 N is observed that of 160 N at low feed rate and % concentration. For the given value of feed rate, the increase in the magnitude of % concentration resulted in increasing the cutting force. For example at a low feed rate, the magnitude is increased from 160 N to 310 N while the % concentration is increased. From plot 2 at hold values at 0.17 mm/rev, at low cutting velocity and higher-level of % concentration, the magnitude of 350N is observed that of 200N at higher-level cutting velocity and lower-level of feed rate. The decrease of cutting force is noticed for all the level of cutting speed with a given value of percentage concentration. At 0.5% concentration in Plot 3, the magnitude is increased from 200 N at a higher level of cutting velocity and lower level of feed rate to 320N at a low level of cutting speed and high level of feed rate. From plot 3, the obtained value of force is found to be an increased relationship with an increase in the feed rate for all level of cutting velocity. From the plot, it indicates that a low-level of feed rate is beneficial for reducing the cutting force. From 1D main effect plots in Fig. 3, it may be inferred that 0.25% concentration, 100 m/min speed and 0.14 mm/rev feed is optimum condition for reduction of cutting force of 169 N. Table 3 is computed value of Taguchi Signal to Noise (S/N) ratio and variance test. The influence of control factor on force is percentage concentration (6.59, 31.27%) with an error of 31.96% and R^2=78.04%.

3.2. 3D surface for surface roughness

From the 1D main effect plots in Fig. 4, it may be inferred that 1.00% concentration, 60 m/min speed and 0.14 mm/rev feed is optimum condition for reduction of surface roughness of 0.58 µm. The 3D surface graphs in Fig. 5 are plotted to understand the effect of control factors against surface roughness. Plot 1 shows the effect of % concentration and feed rate at 60 m/min. From plot 1, it can be seen that the value of roughness whose magnitude is reduced from 0.75 µm to 0.60 µm with an increment of % concentration at the low-level feed rate. A dynamic rise in surface roughness from 0.6 µm to 1.05 µm is observed at a higher feed rate and low-level of concentration. Plot 2 shows the effect of % concentration and cutting velocity of 0.17 mm/rev. From plot 2, the magnitude of surface roughness is decreased from 0.9 µm to 0.6 µm with a steady rise in % concentration at the low level of cutting velocity. There is a significant increase in the surface roughness of 1.05 µm when the cutting speed increases at low-level of concentration. Thus low cutting speed and a higher level of % concentration lead to minimize the value of roughness.

Fig. 3. Main effect plots for cutting force

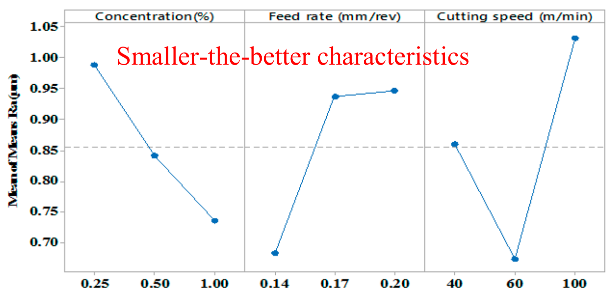

Fig. 4. Main effect plots for surface roughness.

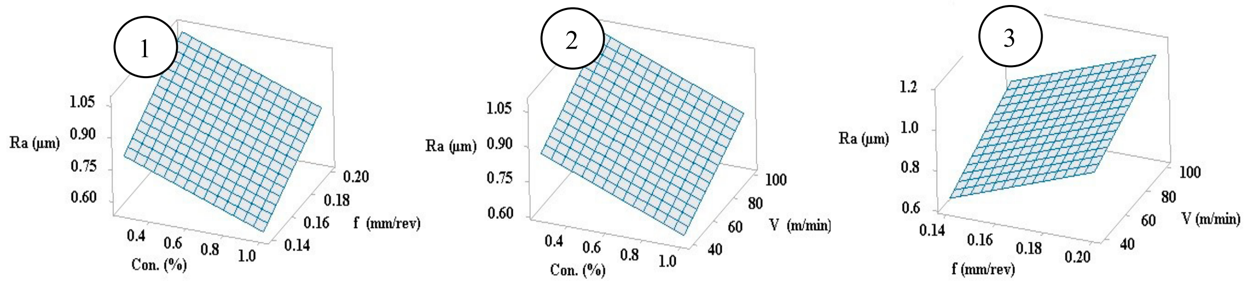

Fig. 5. Response plots for surface roughness.

The influence of feed rate and cutting velocity at 0.5% concentration is shown in Plot 3 of Fig. 5. It can be noticed that the with an increase in feed rate an increase in surface roughness is observed for all levels of cutting speed. High feed rate increases the chatter and thus increases roughness values on the machined part. The value of 1.20 µm is obtained at higher cutting velocity and feed rate that of 0.60 µm at a low feed rate and velocity. The computed value of Taguchi Signal to Noise (S/N) ratio in Table 4 shows the cutting velocity (3.592, 37.57%) the influence control factor on roughness with an inferred error of 17.23% and R^2=82.27%.

Table 4. Signal-to-Noise (S/N) and Variance (ANOVA) table for Ra.

Response	S/N : Ra			ANOVA: Ra				
	Con. (%)	F (mm/rev)	V (m/min)	Source	DF	SS	F-Test	PCR (%)
Level 1	0.450	3.441	1.425	Con. (%)	2	0.0961	1.10	18.95
Level 2	1.677	0.617	3.591	F (mm/rev)	2	0.1329	1.52	26.21
Level 3	2.888	0.946	0.017	V (m/min)	2	0.1905	2.18	37.57
Delta	2.438	2.834	3.592	Error	2	0.0874,		17.23
Rank	3	2	1	Total	8	0.5070		R^2=82.75%

3.3. 3D surface for flank wear

The 3D surface effect of the process parameter (cutting velocity and feed rate) and % concentration is shown in Fig. 6. The results of % concentration and feed rate at 60 m/min on tool wear are enclosed in Plot 1 of Fig. 6. As an increment of percentage concentration of nanofluids, the magnitude of tool wear is observed to increase by 28.57% from 140 µm to 180 µm at the low-level of feed rate. The higher-level of concentration and feed rate is to be avoided to minimize the tool wear as it contributes to increasing the tool wear by 42.85% from 140 µm to 200 µm. Thus, it can be observed that an increase of % concentration gives way to increase tool wear.

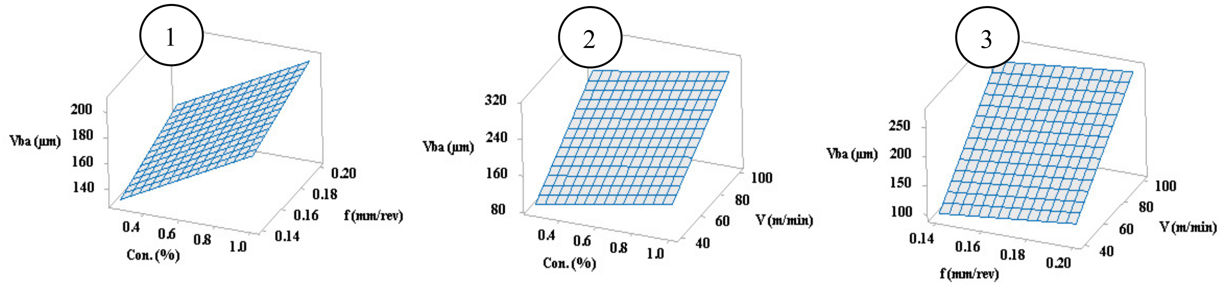

Fig. 6. Response plots for flank wear.

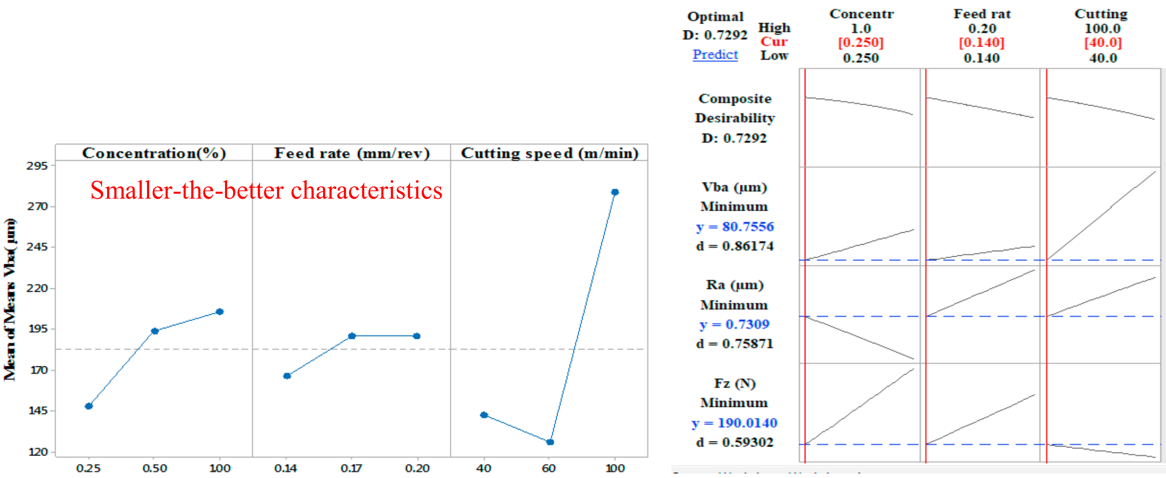

Fig. 7. (a) Main effect plots for flank wear; b) Optimization search using desirability function analysis.

Table 5. Signal-to-Noise (S/N) and Variance (ANOVA) table for Vb.

Response	S/N : Vb			ANOVA: Vb				
	Con. (%)	F (mm/rev)	V (m/min)	Source	DF	SS	F-Test	PCR (%)
Level 1	-39.91	-42.18	-41.03	Con. (%)	2	5570	0.19	7.13
Level 2	-44.97	-44.35	-41.05	F (mm/rev)	2	1146	0.04	1.46
Level 3	-46.04	-44.39	-48.84	V (m/min)	2	42403	1.47	54.35
Delta	6.13	2.21	7.81	Error	2	28897		37.03
Rank	2	3	1	Total	8	78016		R^2=72.31%

The 3D surface graph of % concentration and cutting velocity shown in Plot 2 at 0.17 mm/rev reveals that the tool wear is low at low cutting speed and % concentration. The increase of cutting velocity increase the tool wear for all given values of % concentration. For example, the tool wear magnitude increased by 75% from 80 µm to 320 µm with a steady rise in cutting speed. The 3D surface results of cutting velocity and feed rate at 0.5% concentration are enclosed in Plot 3. At low feed rate, the tool wear is increased by a factor of about 60% from 100 µm to 250 µm with an increase of cutting speed. The 3D plot of Plot 3 shows that increase in feed rate increases the tool wear. The surface graph reveals lower tool wear of 100 µm at 60 m/min cutting velocity and 0.14 mm/rev of feed rate. From the 1D main effect plots in Fig. 7(a), 0.25% concentration, 60 m/min speed and 0.14 mm/rev feed is optimum condition for reduction of cutting force of 158 µm. Table 5 shows the order of contribution is as cutting velocity, % concentration and feed rate to minimize tool wear is 54.35% 7.13% 26.21% and 1.46% with an error of 37.03% and R^2=72.31%. After investigating and optimizing the experimental data using the optimality technique reported [24-27], multi-response optimization plot is plotted in Fig. 7(b). It is inferred that the highest desirability (d) value is 0.7292. This gives the 0.25% of percentage concentration, 40 m/min of cutting velocity and 0.14 mm/rev of feed rate.

3.4. Tool flank wear mode

The tool flank wears style during the MQL turning process of Inconel 617 under the investigated machining, and three weight concentrations are discussed in this section. The optical, photographic images of the tool flank face for the experimental cutting trials, listed in Table 2, are shown in Fig. 8. From the optical image analysis, abrasion, adhesion and diffusion wear are observed as the tool flank wear mode in all weight concentration lubricated samples. At Trail 1 from Fig. 8(a), the abrasion wear on the flank surface is low at low cutting speed and feed rate.

The abrasion marks and there exists a small built-up-edge is observed for Trail 2. These abrasion marks are increased its magnitude in Trail 3 as an increase of cutting velocity and feed rate with no built-up-edge. The abrasion marks observed in Trial 1 is due to tool material peeled off by hard abrasive particles between the tool/workpiece interfaces. It also well-known from literature [23] that the increase of cutting speed along with feed rate is counterproductive of adhesion. But the balance of strain rate and material softening resulting in suppresses the adhesion at higher cutting velocity and feed rate with adequate lubrication. Furthermore, it can be seen In Fig. 8(b) that, diffusion wear (Trial 5) appeared as a portion of tool lubricated with 0.5% concentration. The big abrasion marks are visible to the tool flank face, due to the occurrence of sliding wear at the tool/workpiece interface, can be attributed to the general effect created by cutting speed and percentage concentration. As observed in Fig. 8(c) Trial 9 both 40 m/min and 60 m/min at 1.00% concentration resulted in higher built-up edge due to insufficient lubrication of the nanofluids. Short/long helical and tubular chips are formed with considered cutting parameters at different trials is depicted in Fig.9. It can be observed from the Fig. 9 that with 1.00 % concentration the distance between the tubular teeth is increased when compared to 0.25 % concentration. From this, 0.25% of nAl_2O_3 in coconut oil protects the tool and workpiece region with thin lubrication film leading to lower wear on the tool surface when compared to another concentration percentage.

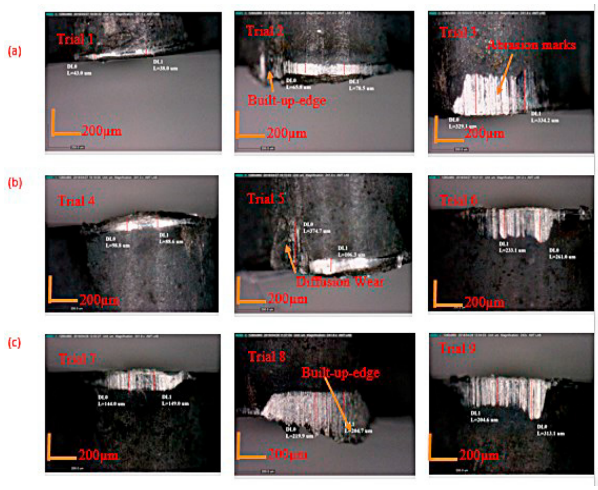

Fig. 8. Optical micrograph of tool wear image.

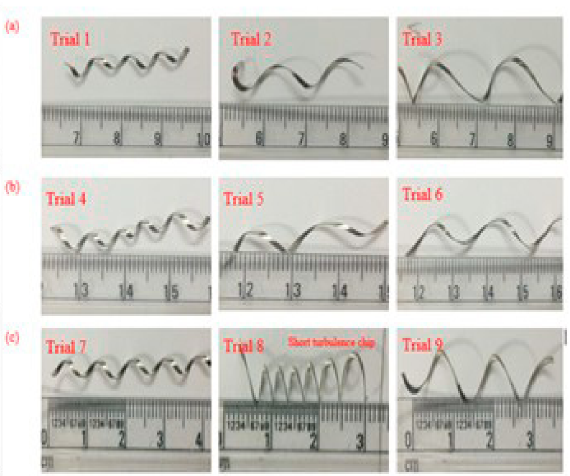

Fig. 9. Chip morphology

4. Conclusions

The present work has concentrated on machinability studies using minimum quantity lubrication (MQL) on CNC turning of 617 alloys. From the investigations, the increment of feed rate increase the force, surface roughness, and tool wear. The tool wear and surface roughness value are increased as cutting velocity increased and declined for force. The force and tool wear data are raised with the increment of weight percentage of nanoparticle in vegetable oil while decrementing for surface roughness. Taguchi signal-to-noise ratio plot and 3D surface plot revealed that a feed rate of 0.14 mm/rev and cutting velocity of 60 mm/min are responsible for minimum surface roughness and tool wear with a magnitude of 0.58 µm and 158 µm at 0.25% (tool wear) and 1.00% (surface roughness). For cutting force of 169N is observed at 0.14 mm/rev, 100 m/min along with 0.25%.From Signal-to-noise and ANOVA results, cutting velocity is more devoted that of feed rate and percentage concentration for minimizing the measured responses. Lower cutting velocity 40 m/min, lower feed rate 0.14 mm/rev and lower percentage concentration of nAl_2O_3 in coconut oil are the optimal cutting conditions. Based on tool wear mode analysis, it is found that the abrasion, adhesion, and diffusion are the three tool wear. Lower abrasion marks and smaller adhesion is observed at 0.25% as it has higher extraction of heat and reduced friction force at the tool/chip interfaces. Based on chip shape analysis, the optical image of the chip revealed that the increase rate of curly due to higher friction and decrease in lubricity under MQL conditions at investigated cutting parameters.

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