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Application of Taguchi-Response surface analysis to optimize the cutting parameters on turning of Inconel X-750 using Nanofluids suspended Al_2O_3 in coconut oil

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Abstract

Inconel X-750, a nickel-chromium alloy, is found as a component in applications of the airframe and hot-air duct system. This paper presents the effect of different nanofluids (NF) concentration along with cutting speed and federate on Fz: cutting force, Ra: surface roughness and Vba: tool wear with the application of vegetable oil NF on turning of Alloy 750. The NF and vegetable oil taken for present investigation are nAl_2O_3 and coconut oil. Experimental is carried out using L_9 orthogonal array and turned with PVD (AlTiN) coated carbide inserts. From the experimental research, 1.00% nAl_2O_3 nanofluids in coconut oil along with cutting speed of 87m/min and 0.14 mm/rev feed rate has proved the better machining performance to minimize the responses. Based on optical micrograph analysis, abrasion, adhesion and small BUE wear are three modes of wear mechanisms. Ribbon chips are produced with a different diameter, and curl diameter is increased with the increment of percentage concentration on turning of Inconel X-750.

Keywords: turning responses; coated carbide inserts; nanofluid; coconut oil; optimization;

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1. Introduction

Nickel-based superalloys have high strength at an elevated temperature that makes it wieldy used in aerospace engines and applications in nuclear and petrochemical industry [1]. Inconel X-750, found in rocket-engine thrust chambers, thrust reversers and hot-air ducting systems [2]. However, X-750 is considered as hard to machine materials due to its presence of hard abrasive and carbide compounds, low heat conductivity and the high work-hardening [3]. Conversion of raw material into components turning is unavoidable as its bags 60% on turning of casing and discs [4]. Appropriate selection of parameters plays an essential role in the turning process. Dry machining has several limitations on nickel-based alloy like tool face stick, the deprived finishing of the machined surface and high rate of tool wear [5]. The cooling strategy plays a vital role in turning of hard turn material. Efforts have been made to study the MQL effect in different machining processes [6]. The biodegradable vegetable oil is more economical than others as they preserve their properties at higher temperature [5, 6]. The dispersion of MoS_2 NF in vegetable oil reduce the tool wear and improve surface roughness on the milling of AISI 420 with uncoated tool due to effective lubrication of MoS_2 NF [7]. The MQL-cryogenic treated cutting tool enhanced the performance on turning of Alloy 718 that of dry, dry-cryogenic and MQL with a spray of pure cutting oil [5]. The effect of vegetable oil (BioCut 4600) is studied on the turning of X-750 using response surface analysis and statistical variance tests. Cutting depth for force and feed rate for roughness are found to be a significant factor on turning of X-750 alloy [3]. Òn another study, for the same vegetable oil, studied on Inconel 738 reveals that cutting depth, feed rate and cutting velocity are the order of effectiveness [8]. The effect of MQL with Al_2O_3 NF has investigated on turning of Inconel 600 and reported that be reduced in roughness, temperature, force and tool under MQL-nAl_2O3 with 6 vol.% particle than dry and MQL [9]. Reported that MWCNTs showed better performance than Al_2O_3 nanofluids due to enhanced lubricity at the tool/workpiece contact region on turning of Inconel 718 [10]. Effect of copper (Cu) nanofluids (NF) soyabean oil on drilling on AA 5052 alloy has been investigated and reported that the tool wear by 36 and 24% surface roughness by 92 and 76%, and lessened cutting temperature by 51% and 27% that of dry and oil lubrication [11]. The 0.5% nanofluids suspensions of nMoS_2 in coconut shows better machining performance on turning AISI 1040 steel [12]. Response surface methodology (RSM) has been established as a prediction and optimization model on surface roughness on turning of grade-2 titanium with three NFs (Al_2O_3, MoS_2, and Gr) in MQL with CBN tool [13]. The genetic algorithm optimization in sustainable measures provides with better convergence competence having a deviation of 4% on the turning of 825 [14]. With application RSM, Cu-NF under MQL decreases 40% and 66% of roughness and tool wear at determined optimal levels and mathematical models [15]. The quantifiable analysis based on Taguchi S/N discloses that the speed influenced the roughness; the turning depth impacted the tool wear; the feed rate afflicted the MRR principally [16]. Based on the previous note, there is very few literatures is found on machinability of alloy X-750 under vegetable oil in MQL. The present work 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 X-750 under MQL conditions in a machine tool. Then optimal search using desirability function analysis is reported. The morphology of chip and tool wear are studied of Inconel X-750.

2. Experimental details

For turning experiments, Inconel X-750 having a hardness value of 32 HRC is selected. The cylindrical round bar of 300 mm length and 32 mm diameter. Chemical composition for this Inconel X-750 alloy is 71.80% Ni, 0.50% Si, 0.70% Mn, 14.72% Cr, 0.20% Mo, 6.67% Fe, 0.75% Co, 2.4% Ti, 0.8% Al, 0.8% Cb [2]. The computerized numerical controlled (SimpleTurn5075-SPM) machine lathe having 3 controlled axis (X, Y and Z axis) with a capacity of 4000 rpm and power of 7.5 kW is used for turning experiments for the given X-750 alloy. For lubrication, MQL setup is used. The flow rate of the MQL used 20 ml/ min and compressed air at a pressure of 4MPa is fixed for all cutting experiments. The experimental setup and its MQL adopted is presented in Figure 1. An ISO PCNRL2525 tool holder and CNMG120408-MP: KCU25 PVD (AlTiN) coated inserts are used for experiments. The experiments are designed based on a standard L_9 orthogonal array design. The experimental results are collected at a constant cutting depth of 0.5 mm for a machining length of 40 mm. A total of 9 experiments are performed to evaluate the relationship between control factors and given output response shown in Table 1.

Fig. 1. a) Experimental setup b) MQL setup with Nanofluids.

Table 1. Experimental results for cutting trials.

Trial	Con.(%)	V (m/min)	F(mm/rev)	Fz (N)	Ra(μm)	Vba (μm)
1	0.25	40	0.14	243	0.5745	103.2
2	0.25	60	0.17	289	0.6469	143.6
3	0.25	100	0.20	313	0.7565	201.6
4	0.50	40	0.17	350	0.5176	207.0
5	0.50	60	0.20	380	0.3925	361.0
6	0.50	100	0.14	295	0.2335	462.5
7	1.00	40	0.20	400	0.8155	227.4
8	1.00	60	0.14	257	0.3269	176.7
9	1.00	100	0.17	278	0.3650	209.6

3. Results and Discussion

3.1. 3D surface for cutting force

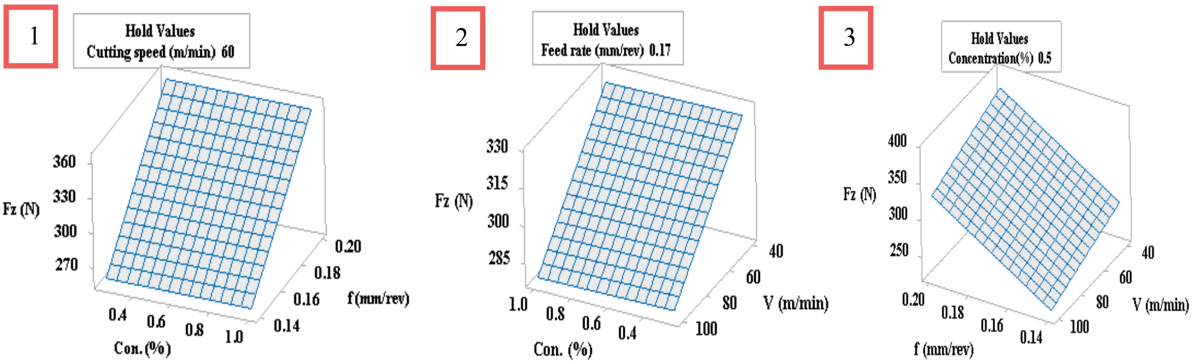


Fig. 2. Response plots for cutting force.

From the 3D surface plot 1 in Figure 2, the magnitude of 360 N is observed at higher feed rate for a given value of % concentration. The increment in feed rate and % concentration, the magnitude of the force is increased. A maximum 330 N is noticed at low cutting velocity and higher-level of % concentration in Plot 2. It also inferred that higher cutting velocity and low % concentration resulted in the decrement in force value from 330 N to 285 N. It is inferred from the Plot 3 that increment of velocity for the given amount of feed rate shows a decrement in force magnitude. The magnitude of 400N observed at low velocity, and higher-level of feed rate is decreased to 250N at a high level of cutting velocity and low-level of feed rate. From the % concentration plot in Figure 3, the magnitude is increased from 281N to 341N with an increment of 0.25% to 0.5% and contributes to an increase of about 21%. Further increment in % concentration, the magnitude is found to decline of about 8.7%. From the feed rate plot, the increment in the magnitude of force from 264N to 364N is observed for an increment of feed rate and contributes to increase by 27.4%. After 0.17 mm/rev, the contribution factor is increased to a value of 16%. This may be to concern the fact of varying in feed rate from 0.17 mm/rev to 0.20 mm/rev lead to a rise in temperature at workpiece surface, damage to cutting edge and forms BUE for given % concentration of nAl_2O_3 under MQL. From cutting velocity plot, the magnitude is decreased from 331N to 281N with increment in speed and contributes to 15%. In case of nAl_2O3 NF in MQL, as MQL + 0.25% nAl_2O_3 have a higher convective heat transfer coefficient that of other two concentration which resulted to decrement in cutting force of about 15%. From the study of Taguchi Signal to Noise (S/N) ratio and Analysis of variance as refereed from Table 2, the feed rate has a substantial effect on force than % concentration and cutting velocity along with an error of 5.27% and R^2=94.73%.

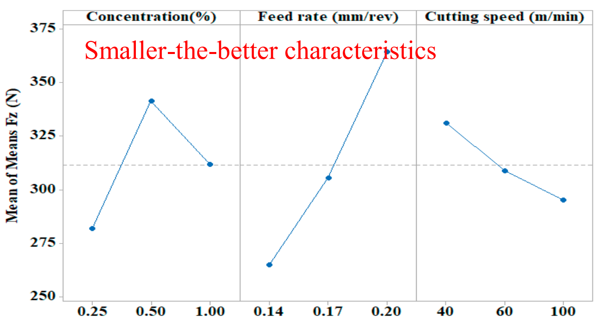


Fig. 3. Main effect plots for cutting force.

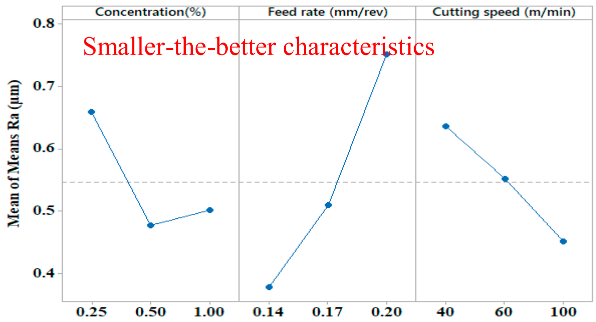


Fig. 4. Main effect plots for surface roughness.

Table 2. 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	-48.95	-48.43	-50.21	Con. (%)	2	5340	4.29	22.65
Level 2	-50.62	-49.66	-49.67	F (mm/rev)	2	15043	12.10	63.81
Level 3	-49.07	-51.19	-49.39	V (m/min)	2	1947	1.57	8.25
Delta	1.67	2.75	0.82	Error	2	1243		5.27
Rank	2	1	3	Total	8	23574		R^2=94.73%

3.2. 3D surface for surface roughness

Figure 4 shows the 1D main effect plots for surface roughness Ra. From the % concentration plot, the magnitude is declined from 0.65 µm to 0.47 µm with an increment of 0.25% to 0.5% and contributes to an increase of about 38%. However, when compared to 0.25% the surface declined is decreased to 25%. This may be exhibiting the enhanced thermal properties along with rolling friction between tool flank/chip compared with the other two concentrations leads to reduced surface roughness. From the feed rate plot, the increment in the magnitude of roughness from 0.37 µm to 0.75 µm is observed for an increment of feed rate. From 0.14 mm/rev to 0.17 mm/rev, it contributes to increase by 50%. After 0.17 mm/rev, the contribution factor is increased to a value of 33%. It is observed that MQL + 0.5% Al_2O_3 nanofluids along with 0.14 mm/rev facilitated a lessening of 21% than other two concentrations. From cutting velocity plot, the magnitude is decreased from 0.63 µm to 0.45 µm with an increment in speed and contributes to 28.5%. The inclusion of 0.5% nAl_2O_3 in coconut oil has their ability to penetrate to the tool/chip interface by absorbing the latent heat from the tool surfaces, work, and chips. And finally, the lessened friction of the imposed coolant can be attributed to this performance enhancement. On examine Plot 1 Figure 5 the value is higher of about 0.75 μm at a higher feed rate and low value of % concentration that of 0.30 μm at a low feed rate and higher concentration. Plot 2 in Figure 5 shows the value of 0.7 μm is obtained at low cutting velocity and % concentration that of 0.4 μm at higher cutting velocity and % concentration. Plot 3 in Figure 5 shows the value of 0.80 μm is obtained at low cutting velocity and higher feed rate that of 0.20 μm at a low feed rate and higher velocity. From Table 3, the feed rate has a substantial effect on force than cutting velocity and %concentration along with an error of 0.5% and R^2=99.49%.

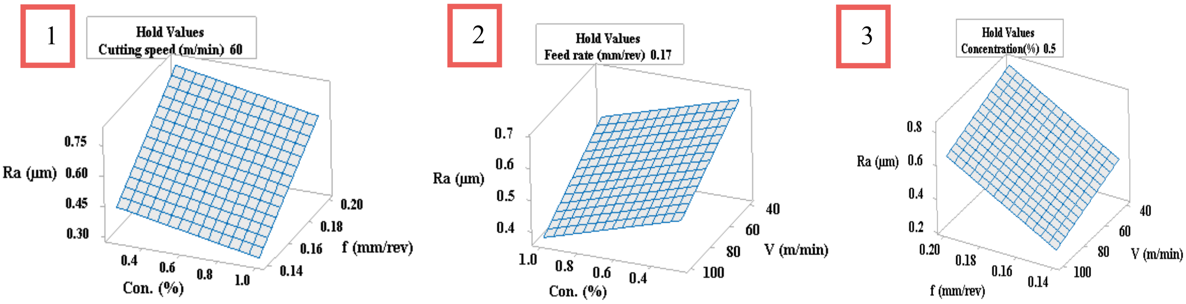


Fig. 5. Response plots for surface roughness.

Table 3. 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	3.674	9.053	4.102	Con. (%)	2	0.0581	35.04	17.85
Level 2	7.225	6.086	5.606	F (mm/rev)	2	0.2148	129.43	65.95
Level 3	6.746	2.506	7.938	V (m/min)	2	0.0510	30.74	15.69
Delta	3.552	6.548	3.835	Error	2	0.0016		0.5
Rank	3	1	2	Total	8	0.3257		R^2=99.49%

3.3. 3D surface for flank wear

On evaluating Plot 1 in Figure 6, the value is higher of about 240 μm at higher feed rate and % concentration that of 210 μm at a low feed rate and concentration. Therefore, the larger feed rate along with higher concentration should be avoided to minimize the value of tool wear. Plot 2 in Figure 6 shows that the value of 320 μm is obtained at higher cutting velocity and % concentration that of 200 μm at lower cutting velocity and % concentration. Plot 3 in Fig.6 shows the value of 280 μm is obtained at higher cutting velocity and feed rate that of 160 μm at a low feed rate and low velocity. For given of cutting velocity, the increment in feed rate resulted in increasing in tool wear for given value of cutting velocity. From the % concentration plot in Figure 7, the magnitude is inclined from 150 μm to 350 μm with an increment of 0.25% to 0.5% and contributes to an increase of about 57%. This is because at low % concentration facilitated to remove the heat accumulated at the tool surface and chip which leads to the lesser forms of built-up edge and decrease the tool wear. From the feed rate plot, decrement in the magnitude of tool wear from 247 μm to 186 μm is observed for an increment of feed rate and contributes to 24%. After 0.17 mm/rev, the contribution factor is increased to a value of 41%. From cutting velocity plot, the magnitude is increased from 179μm to 291 μm with an increment in speed and contributes to 62%. This may be attributed to the fact that at higher cutting speed the impinged of coolant may not sufficient time to reduce the latent heat accumulated at tool/chip interface, resulting in less decline of temperature, which leads to more tool wear rate. From the Table 4, the %concentration has a substantial effect on force followed by cutting velocity than feed rate along with an error of 10.62% and R^2=89.38%.

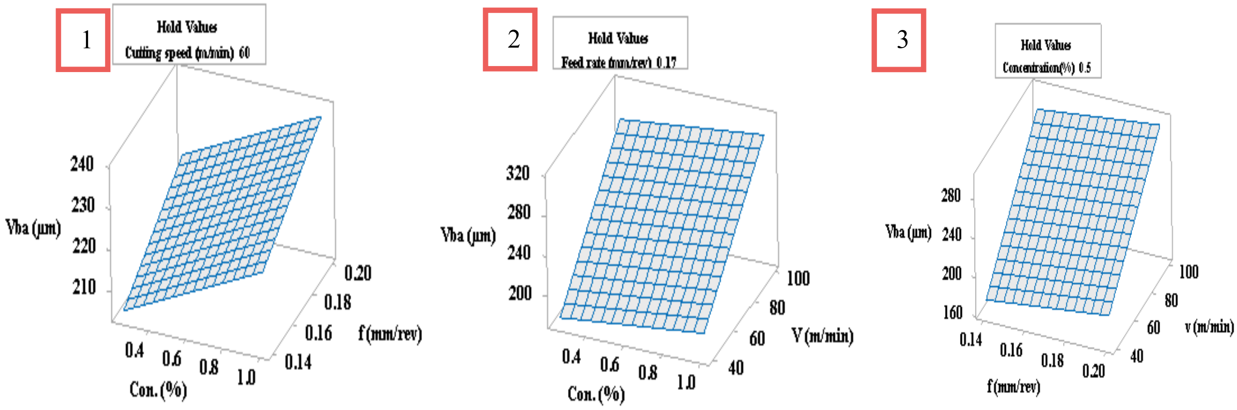
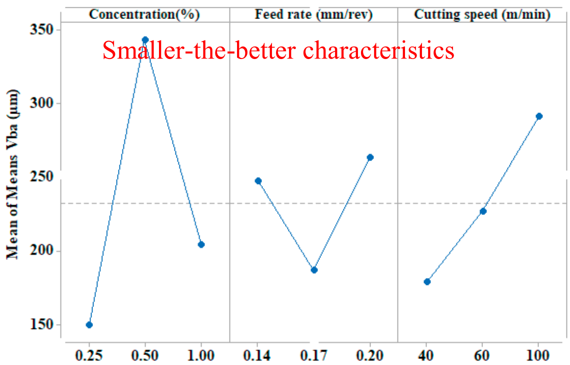


Fig. 6. Response plots for flank wear.



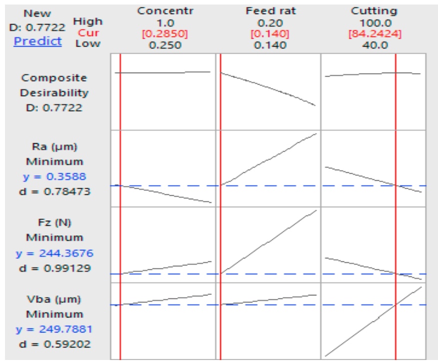


Fig. 7. Main effect plots for flank wear

Fig. 8. Optimization Plot.

In a machining process, the determination of optimal control factors plays a vital role for any experimental study. Response surface desirability function optimization (DFO) is the best procedure to find out the distinguished optimal mixture of control factor in any process for given response with high desirability value [17]. The optimization plot is plotted in Figure 8 shows the optimal consideration that has the higher desirability value is 0.7772 is achieved.

Table 4. 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	-43.17	-46.17	-44.58	Con. (%)	2	59987	5.69	60.40
Level 2	-50.26	-45.30	-46.41	F (mm/rev)	2	9808	0.93	9.87
Level 3	-46.17	-48.13	-48.61	V (m/min)	2	18959	1.80	19.09
Delta	7.09	2.83	4.03	Error	2	10549		10.62
Rank	1	3	2	Total	8	99303		R^2=89.38%

3.4. Investigation on Tool wear and chip shape

The experiment's result in Figure 9 shows that an increase in % concentration, the tool wear also increases and then declined. For instance, in Trial 1, there is abrasive wear and adhesion, and this is attributed to low cutting speed. This is attributed to an insufficient lubrication effect of nanofluids could the surface prone to coarse wear mechanism as similar observations reported [16]. Increase the cutting velocity and feed rate, the abrasive wear pattern is very less, and the accumulation of built-edge is small on the tool flank surface for 0.25% concentration. From Fig. 9 (b) harsh groove marks are formed parallel to the tool flank face due to the occurrence of sliding wear. The presence of the parallel groove is higher at 0.5% concentration that of 0.25% concentration. From Fig. 9(c) it is noticed at 1.00% concentration resulted in lowering flank wear that of 0.5% concentration due to effective lubricating ability and this decreased cutting force and generated high temperature at the tool/workpiece interface. Thus small adhesion appears on the tool flank face. To conclude, in Trial 7, the tool flank surfaces is noted dark color which represents the heat affected zone reproduced by the heat effect of friction of tool/work at 1.00% concentration. Then, it is claimed that increased % concentration is mostly affecting the flank of tool wear land. This outcome brings into line with the obtained results of the ANOVA of tool wear. Short/long ribbon chip and short helical chip are produced in Figure 10 during cutting trials. For the tests with varying concentration, the ribbon chips are generated with longer helix angles at 1.00% compared to 0.25% and 0.5% concentration. In Trial 6 and 9 curled chips is produced with a different diameter due to less friction and superior thermal effect of nAl_2O_3 NF in coconut oil on the contact surfaces on turning of Alloy X-750. Also, no built-up edge chips are observed as examined in Figure 10 (a-c) as it offers good cooling and lubrication.

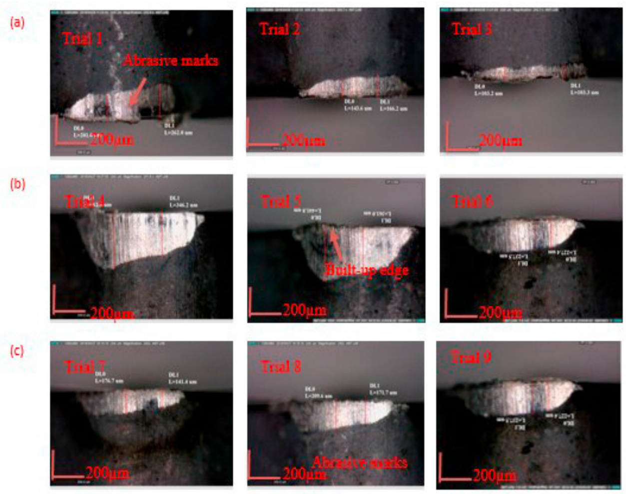


Fig. 9. Optical micrograph of tool wear image

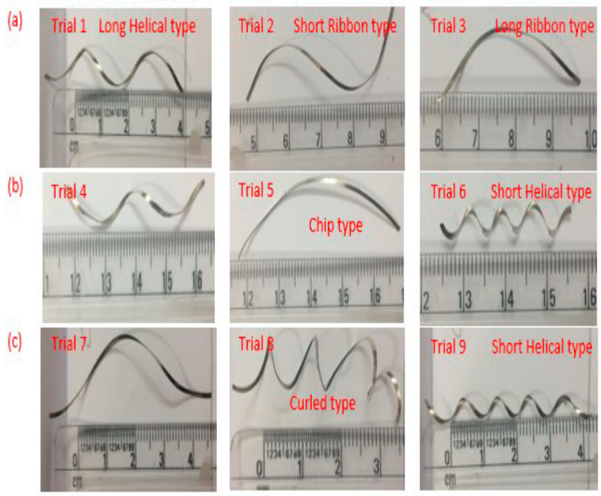


Fig. 10. Chip morphology under-investigated cutting parameters (a) 0.25% (b) 0.5% (c) 1.00% concentration

4. Conclusions

The present study examined the cutting properties of cutting velocity, feed and % concentration on three sustainable measures of force, roughness and tool wear on tuning of Alloy X-750 under MQL. The following conclusions are derived:

1. In MQL conditions, an increment in feed rate leads to increase the force, surface roughness, tool wear. In case of cutting velocity increment resulted to decrement in force and surface roughness while incrementing in tool wear. In case of % concentration, an increase in force and tool wear with an increment of % concentration from 0.25% to 0.5% then decline. For surface roughness, the decrement is observed at 0.5% than the 0.25% and 1.00%.
2. From the results of variance test (ANOVA), feed rate (63.81%) for force, feed rate (65.95%) for roughness and % concentration (69.40%) for tool wear are found as a significant factor. In overall, % concentration bags, the maximum contribution factor compared to feed rate and cutting velocity in reducing the force, surface roughness and tool wear.

3. Using DFO, the optimum conditions at which the machining process shows the better performance is identified. It is observed that at 0.25% concentration of nAl_2O_3 in coconut oil, when applied at 87 m/min and 0.14 mm/rev result in better machining performance. These cutting parameters are exhibited lessening in cutting forces along with surface roughness and tool wear.
4. In the analysis of the optical images of tool flank face abrasion, adhesion and small BUE are found to be the dominant wear mechanisms under the investigated parameters. Increase the cutting velocity and feed rate, the abrasive wear pattern is very less, and the accumulation of built-edge is small on tool flank surface for 0.25% concentration that of other two concentration. This confirms that 0.25% in coconut oil prone to protect the tool/workpiece region with thin lubrication film which established lower tool wear and adhesion on cutting trials that of other % concentration.
5. Ribbon chips with more extended helix angles are generated at 1.00% compared to 0.25% and 0.5% concentration. This is attributed to establishing a thin oil film boundary layer between the chip/tool flank face. This oil film increased the chip helix angle is observed a few trials. In few tests, curled chips are produced with a different diameter due to less friction and superior thermal effect of nAl_2O_3 NF in coconut oil on the contact surfaces on turning of Alloy X-750.

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