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Experimental investigation on the performance of the TiO_2 and ZnO hybrid nanocoolant in ethylene glycol mixture towards AA6061-T6 machining

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ABSTRACT

This paper presents an experimental investigation on the coated carbide cutting tool performance of aluminium alloy AA6061-T6 machining through end mill processes using the minimum quantity lubrication (MQL) technique. The process parameters including the cutting speed, depth of cut and feed rate are selected. The effect of the base fluid ratio (water: EG) to the hybrid nanocoolant was investigated in this experiment. The hybrid nanocoolant with 80:20 of volume concentration up to 0.1% was prepaid with a 21 nm particle size of TiO_2 and 10-30 nm ZnO nanoparticle for measurement purposes and tested at cnc end milling machines. The analysis of the variance method is utilised to validate the experimental data and to check for adequacy. The response surface method was used to develop the mathematical models and to optimise the machining parameters. It is observed that the material removal rate depends significantly on the depth of cut and feed rate, followed by the spindle speed. The results can be used as an example of the minimum quantity lubricants (MQL) technique applied to the machining of aluminium alloys, providing economic advantages in terms of reduced the machining costs and better machinability.

INTRODUCTION

Machinability is one of the most important properties of a material. It is about cutting the material with maximum metal removal, shortest time, maximum tool life and a smooth surface finish [1-6]. Nowadays, the demand in various applications for fluids with more efficient heat transfer has led to enhance heat transfer to meet the cooling challenge necessary, such as in the electronics, photonics, transportation and energy supply industries. In the present study, the effect of different parameters on the surface finish of the material is investigated using a CNC end milling machine [7-14]. The tool geometry parameters play an important role in determining the overall machining performance, including cutting forces, tool wear, surface finish, chip formation and chip breaking [15-17]. The value of surface roughness increased linearly with the increase of the tool diameter and spindle speed; the feed rate played an important role when other parameters remained constant [18]. The principal wear mechanisms in aluminium alloys machining are the burr formation, built-up-edge as well as surface roughness. The surface finish and burr formation in aluminium alloy machining are mainly used as tool life criteria as it is difficult to observe tool wear in aluminium alloys [19-22].

The minimum quantity lubrication has been proved to be an effective near dry machining technique as well as an efficient alternative to completely dry and wet cutting conditions from the viewpoint of cost, ecological and human health issues and machining process performance [23-28]. The purpose in sustainable machining is to produce the parts using an optimised minimum quantity of metal working fluids so that the workpiece, chips and environment remain dry after cutting. Besides environmental and health issues, the costs associated with the applications, storage and disposal of cutting fluids are also a concern. About 15-20 % of the overall machining costs are related to cooling and lubricating fluids [29-32]. Most of the research studies involving machining with MQL, as a cutting medium, have been mainly concerned with the turning, drilling and grinding process. There have been very few articles published which use MQL in end milling [14, 29, 33-37]. The usual applied in the end milling process is the application of abundant amounts of liquid coolant, whereby the liquid coolant as intermittent cooling increases the temperature variations and build up edge. Hence, simply cutting off the amount of coolant used is not a practical answer for end milling due to the intermittent nature of the cutting action at the tool tip resulting in increased temperature variations at the tip of the tool. Thus, the role of MQL as a potential method is still to be explored for minimising the consequences of thermal shock in end milling for removing the generated heat during the entire cutting cycle. End milling is one of the most widely used metal removal operations in the industry because of its ability to remove material faster, giving a reasonably good surface finish. Owing to the significant role that milling operations play in today's manufacturing world, there is a vital need to optimise the machining parameters for this operation, particularly when CNC machines are employed.

The objective of the present work is to study the effect of the hybrid nanocoolant with 80:20 volume concentration of TiO_2:ZnO towards the material removal rate, surface roughness and tool wear using the end milling machine. The investigation on these rheological properties is very important to expand the application of the hybrid nanocoolant with addition of EG in the coolant of machining. The selection of ZnO and TiO_2 nanoparticles with a 21nm particle size and 10-30 nm ZnO are due to its stability period that withstand up to two months. The purpose of this study is to optimise the process of minimum quantity lubrication in the end milling of the aluminium alloy AA6061T6.

METHODS AND MATERIALS

Hybrid Nanocoolant Preparation

The hybrid nanocoolant used in the sample preparation is 21 nm in particle size of TiO_2 and 10-30 nm ZnO in powder form, respectively. The nanoparticles were suspended in 80:20 TiO_2:ZnO by volume percent. Figure 1 shows the process flow of the preparation of the hybrid nanocoolant. A two-step method was used in the preparation of the hybrid nanofluid. The sonication process was employed to help improve the dispersion of nanoparticles in the base fluid. The nanoparticles are dispersed in the base fluid using a magnetic stirrer and sonicated in an ultrasonic bath for two hours [38-40]. The samples prepared for a ratio of 80:20 of TiO_2 and ZnO have been found to be stable for two months. Equation (1) was used to determine the mass of ZnO and TiO_2 to disperse in the base fluid.

$$\phi = \frac{\frac{m_{Tio2}}{\rho_{Tio2}} + \frac{m_{ZnO}}{\rho_{ZnO}}}{\frac{m_{Tio2}}{\rho_{Tio2}} + \frac{m_{ZnO}}{\rho_{ZnO}} + V_{mixture}} \quad (1)$$

Viscosity Measurement

The viscosity was measured with a Brookfield LVDV III Ultra Rheometer. The range of applicability of the measurement is from 1 to 6 × 106 mPa.s. Figure 2 shows the setup of the experiment for measuring the viscosity. The rheometer is used to make accurate and reproducible measurements on low viscosity materials. A hybrid nanocoolant with a 16 ml volume sample was inserted into a cylinder jacket and attached to the rheometer. A *RheoCal* program was installed for the data measurement at the designated torque and temperature. The sample was heated from 50 to 70 °C for the viscosity measurement. To validate the data, the reading of the torque from the measurement was selected within the range of 10-100%.

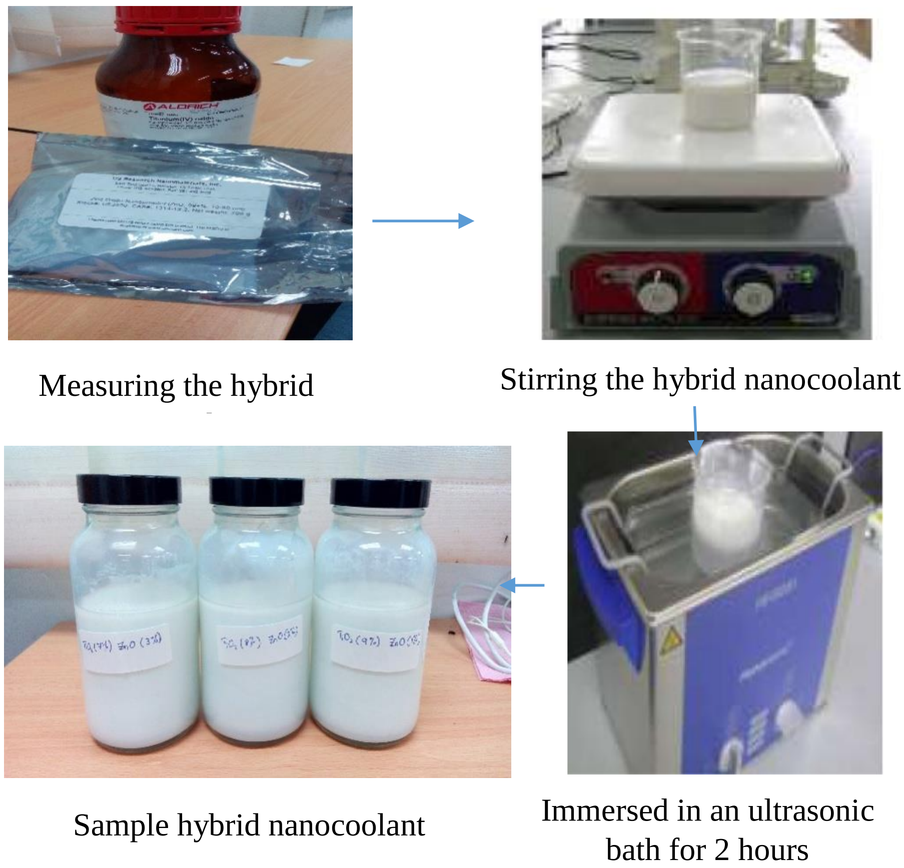


Figure 1. Process flow in the preparation of the hybrid nanocoolant.

Thermal Conductivity

The thermal conductivity of nanofluids is one of the reasons for the enhancement of heat transfer. The large (100 mm long, 2.4 mm diameter) single needle TR-1 sensor from KD2Pro measures the thermal conductivity and the thermal resistivity has been used. For the dual-needle sensor, the needles must remain parallel to each other during insertion to make an accurate reading. Because the sensors give off a heat pulse it is necessary to allow a minimum of 1.5 cm of material parallel to the sensor in all directions, or errors will occur. When the temperature of the sample is different from the temperature of the needle, the needle must equilibrate to the surrounding temperature before beginning a reading. Thus, the calibration process has also been used with a standard fluid (Glycerin), which was already brought with devices. Validating the data error of the reading from the measurement was less than 0.01.

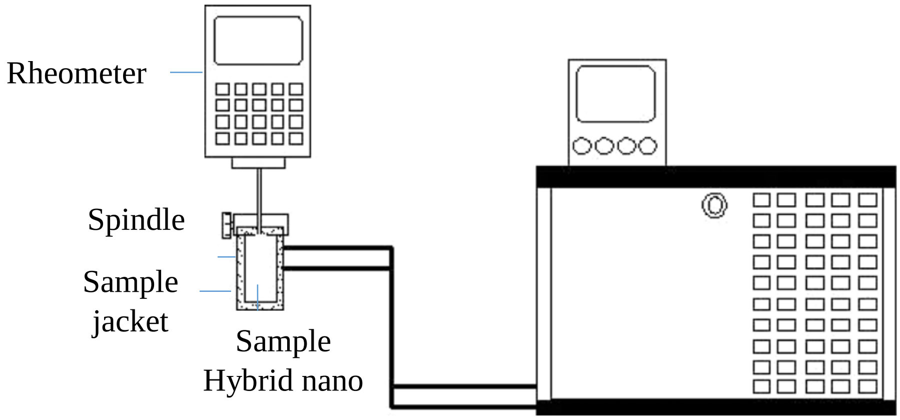


Figure 2. Viscosity measurement with the Brookfield Rheometer.

Experimental Details

The machining parameters selected in this research are the spindle speed, feed rate, depth of cut and the minimum quantity lubricant flow rate to investigate the material removal rate, surface roughness and tool wear. The central composite design approach of the response surface methodology is used for the design of experiments in order to find the effects and the combination of the parameters. The flow rates for the MQL used are 36 ml/hour, 72 ml/hour and 144 ml/hour. The MQL coolants used a hybrid nanofluid with a 0.1 concentration. Table 1 shows the chemical composition of the workpiece used for the experiment which is aluminium alloys A6061. Table 2 shows the design of the experiment matrix for this study. Three levels of machining variables are selected.

Table 1. Chemical composition of the Aluminium Alloy A6061.

Component	Amount (%wt)
Aluminium	Balance
Magnesium	0.8-1.2
Silicon	0.4-0.8
Iron	Maz 0.7
Copper	0.15-0.40
Zinc	Max 0.25
Titanium	Maz 0.15
Manganese	0.04-0.35
Others	0.05

The surface roughness and material removal rate are the two conflicting responses of the experiments. The surface roughness is measured using a perthometer (MarSurf XR 20 (Mahr)) while the material removal rate is calculated by weighing the workpiece after every single cut. The surface roughness (Ra) is measured in μm. The tool wear is measured in µm with a FESEM. The specimen workpiece material used is an AA6061T6 aluminium alloy with wide-ranging applications in the industry on account of its good machinability and continuous chips. The workpiece has the dimension of 100 mm × 100 mm × 20 mm. The density of the alloy used for calculating the material removal rate is 0.0027g/mm^3. A coated tungsten carbide end mill with two flutes is selected for the machining. An analysis of variance (ANOVA) is utilised to verify the adequacy of the experimental data. A commercial non-toxic type of renewable vegetable oil-based cutting fluid (Coolube 2210, UNIST, Inc.) is used. Experiments are performed using a vertical CNC milling centre, the HAAS VF6.

Table 2. Design of experiments.

Factors	Levels		
	1	2	3
Spindle speed (rev/min)	3000	4800	6800
Federate (mm^3/min)	610	975	1382
Depth of cut (mm)	0.35	0.95	1.3

RESULTS AND DISCUSSION

The optimal cutting parameters were obtained using the objectives as to minimise the surface roughness and simultaneously maximise the material removal rate, within the specified limits of the parameters as maximum and minimum boundary conditions for optimisation. A response surface is developed to predict the surface roughness (Ra) and material removal rate (mm^3/min) and the set of cutting parameters is selected for a given range of material removal rate until the tool wear reaches 0.3 µm, by which the surface roughness is not affected. The significance of the input parameters is determined based on the difference in the mean of the two groups of experimental design at high and low levels. The relative importance and rankings of the main parameters and their interactions with respect to response variables are evaluated by determining the parameters effect size using RSM. Figure 3 presents the effect of the spindle speed on the depth of cut in the material removal rate. Figure 3 shows the optimum result for surface roughness when the speed is 5718 rev/min and the feed rate is 1047 mm^3/min. Figure 4 shows the optimum result for the material removal rate. It shows that the best speed is 5124 rev/min and the feed rate is 600 mm^3/min and the material removal rate is 67597 mm/min.

One of the typical techniques to accurately quantify surface integrity is the surface finish measurement. It is considered as an indicator for the surface quality of the turned part, reporting that the wiper geometry provides the ability to duplicate the feed value and achieve the same surface finish with a conventional tool. It is suggested that the surface roughness values in finish machining are expected to be in the range of 0.5- 1.5 µm [41]. Figures 5-6 show the comparison between dry, MQL and hybrid nanofluids in terms of surface roughness and material removal rate at different cutting speed, depth of cut and feed rate values**.** Hybrid nanofluids show a slight improvement in enhancing surface roughness compared to the dry and MQL technique due to the lesser effect of the cooling function of the cutting fluid, which is significantly effective as a lubricant more than its function as a coolant [20]. The surface roughness value is increasing at a high speed and feed for dry and lubricated surfaces and the improvement in surface roughness can be attributed to the reduction in the material transfer onto the machined surface [42]. However, applying the MQL was also reported to result in some improvement in surface roughness [43]. Hybrid nanofluids indicated a slightly lower surface roughness than using the MQL technique and dry cutting. This can be due to the temperature reduction in the cutting zone [27, 44, 45]. A lower surface roughness was obtained at a low cutting speed and low feed rate. Surface roughness values tend to be higher at the end of tool life and the highest value was obtained at a high cutting speed and high feed rate.

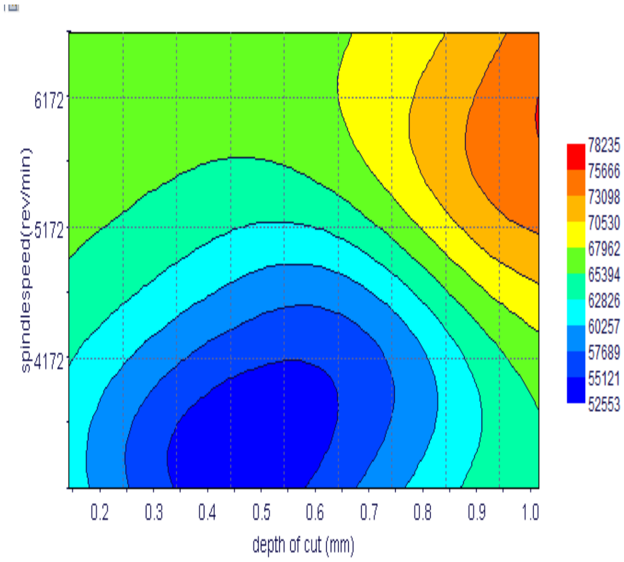


Figure 3. Effect of the spindle speed on the depth of cut in the material removal rate.

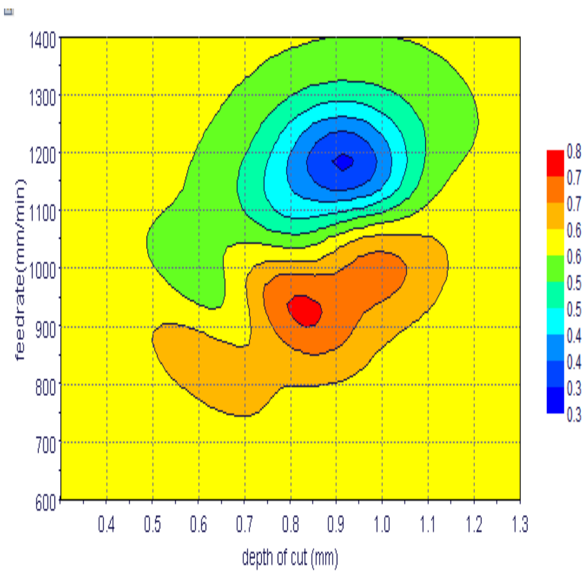


Figure 0. RSM for surface roughness.

In order to study the wear mechanisms, the cutting edges used in the experiments were taken to a Scanning Electronic Microscope (SEM) equipped with an EDX system. Figure 7 shows the flank wear lands of the carbide cutting edges used to cut with a spindle speed of 3000 rpm. The rough appearance of the wear land and the results of the EDS analysis showed that the wear lands of the edges used to cut the three alloys were full of the workpiece material adhered. The explanations for the occurrence of such adhesions on the tool flank are the favourable conditions developed during the cutting between the tool flank face and the workpiece [21, 46]. For the adhesion of the workpiece/chip material on the tool flank face to occur, some chip material has to be extruded in such a way to be able to pass between the edge and the workpiece and to adhere on the flank wear land. For a seizure (adherence) zone to occur on the flank wear land and start the attrition mechanism "attrition", some wear had to have already occurred, generated by some other wear mechanism, such as abrasion[47, 48]. In the presence of vibration during the cutting, the metal flow past the tool may be very uneven, causing small fragments of the tool to be removed. This mechanism was called attrition by them.

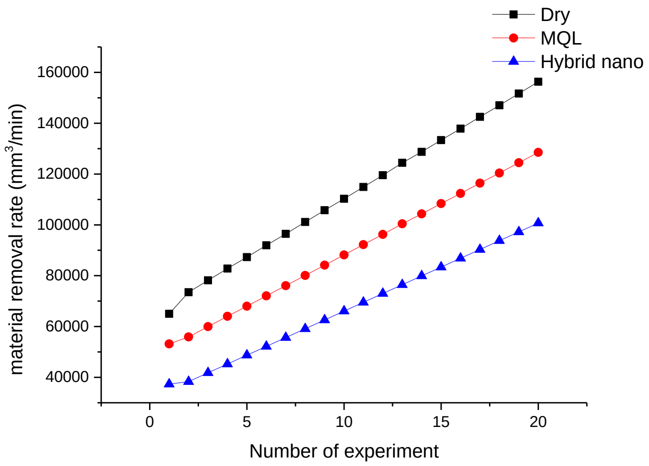


Figure 5. Material removal rate comparison for dry, MQL and hybrid nanofluids

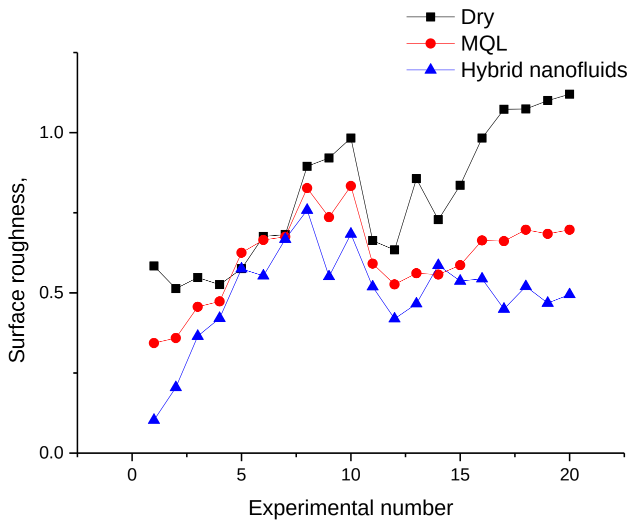
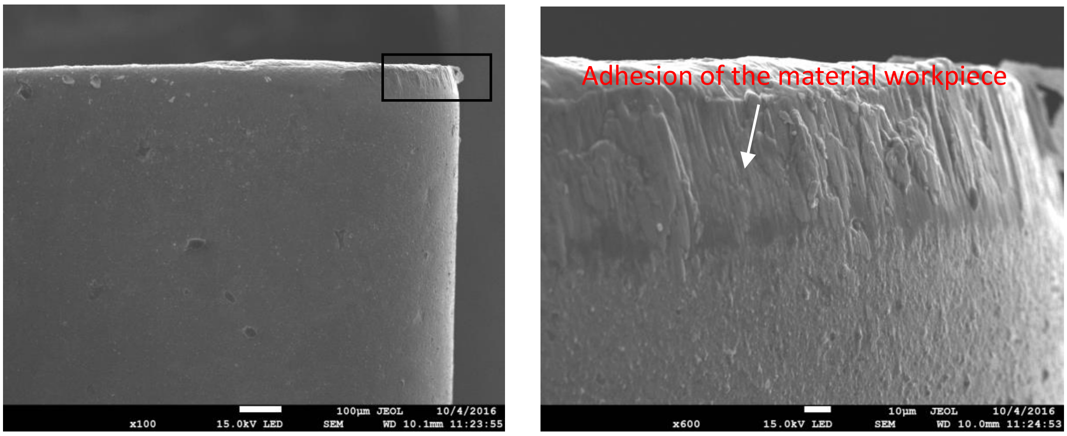
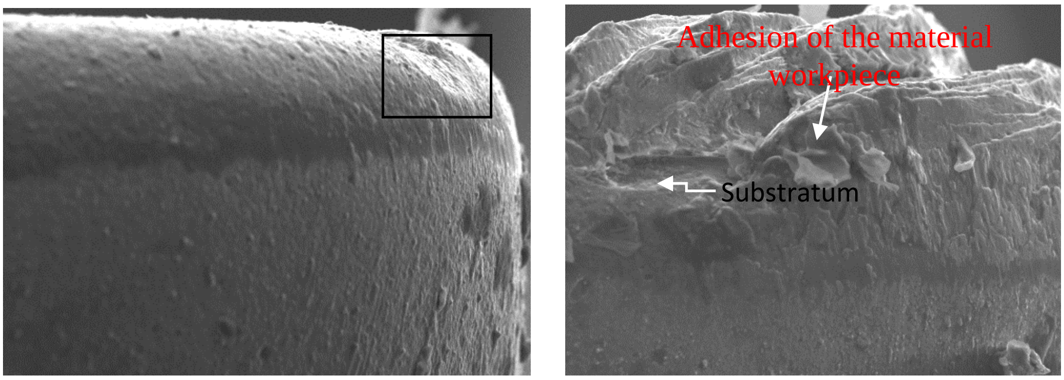


Figure 6. Surface roughness rate comparison for dry, MQL and hybrid nanofluids

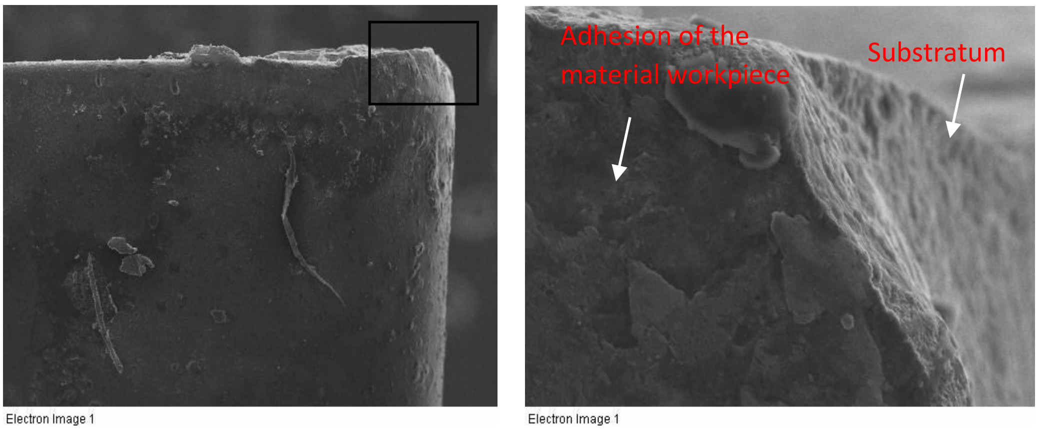
With a cutting speed of 3000 rpm adhesion was also present, as can be seen in Figure 7(a), the flank wear lands of the tools used to cut with 4400 rpm were also full of the workpiece/chip material adhered on it, indicating that attrition was also present at this cutting speed. However, in Figure 7(c), related to the tool, which cuts the aluminium alloy, it can be seen that a large portion of the edge was removed. Probably, the higher amount of heat generated by the process, due to the higher cutting speed, caused the softening of the edge and facilitated the removal of large particles of the tool [49].



(a) Spindle speed 3000 rpm, feed rate = 610 mm/min and depth of cut = 0.35mm



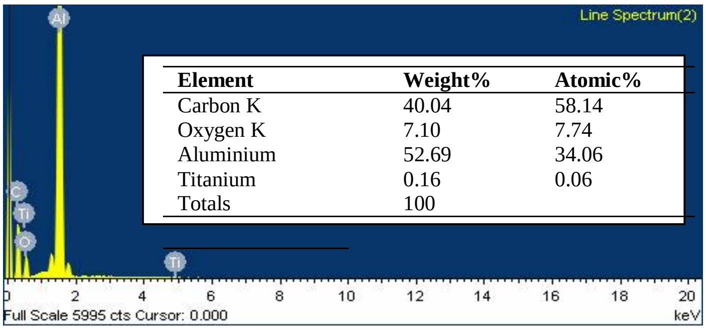
(b) Spindle speed = 4400 rpm feed rate = 894 mm/min and depth of cut = 0.70mm.



(c) Spindle speed = 6000 rpm feed rate = 1219 mm/min and depth of cut = 1.10mm.

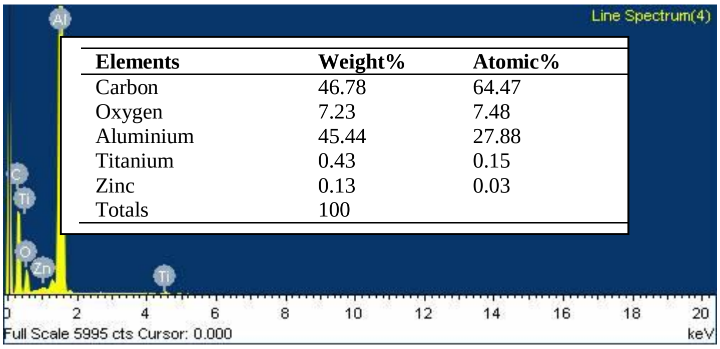
Figure 7. Flank wear of the cutting edge used to cut the aluminium alloy at the end of the tool life.

When using a lower and medium spindle speed, the aluminium alloys were cut and there was no removal of such large portion of the tool because due to the shorter tool lives, the cutting edge did not reach the temperature necessary to cause such a removal. Moreover, as the life of the tool which cut the aluminium alloy was longer, any vibration inherent to the machining process which stimulates the attrition mechanism could generate a higher number of shocks between the workpiece and the tool, thus leading to mechanical fatigue and, consequently, the chipping of the edge [50]. In this study, the EDX technique was used to analyse the deposits on the surface of the tool. The EDX analysis shows the areas of aluminium deposits and eroded areas on the tool rake face. Figure 8 shows the zones at the rake face in the case of finishing machining at a spindle speed of 3000 – 6000 rpm, respectively. The chemical analysis showed that all analysed elements are almost homogeneously distributed on the whole worn tool's surface. However, a bigger amount of aluminium in the above part signalises a destruction of the coating and a creation of the built-up edge.



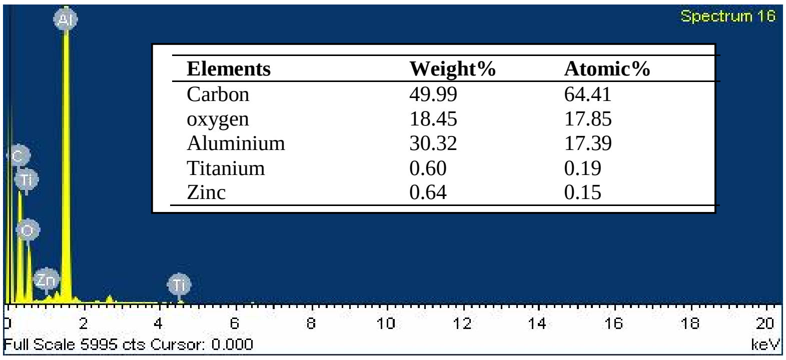
Element	Weight%	Atomic%
Carbon K	40.04	58.14
Oxygen K	7.10	7.74
Aluminium	52.69	34.06
Titanium	0.16	0.06
Totals	100	

(a) Feed rate 3000mm/min and depth of cut 0.35µm



Elements	Weight%	Atomic%
Carbon	46.78	64.47
Oxygen	7.23	7.48
Aluminium	45.44	27.88
Titanium	0.43	0.15
Zinc	0.13	0.03
Totals	100	

(b) Feed rate 4400mm/min and depth of cut 0.7µm

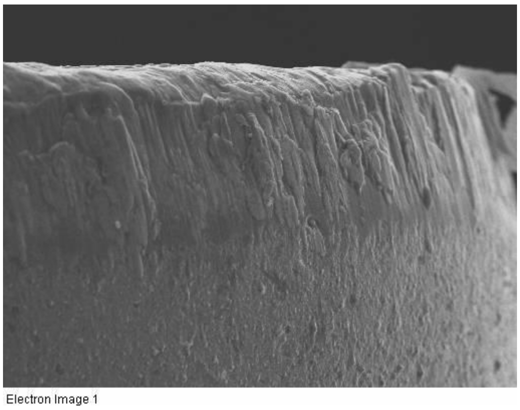


Elements	Weight%	Atomic%
Carbon	49.99	64.41
oxygen	18.45	17.85
Aluminium	30.32	17.39
Titanium	0.60	0.19
Zinc	0.64	0.15

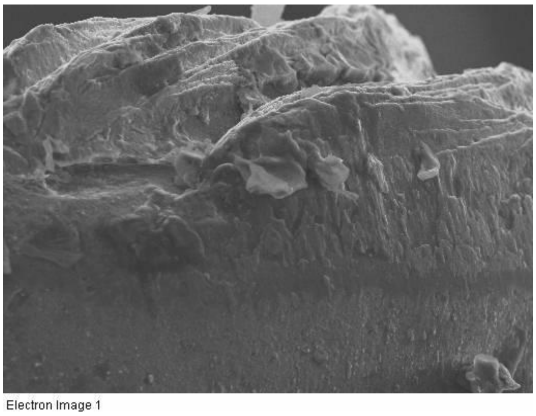
(c) Feed rate 6000mm/min and depth of cut 1.10µm

Figure 8. Micro area selected on the cutting edge

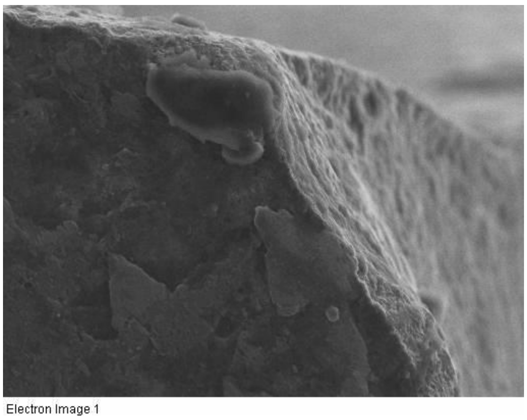
The distribution of tungsten indicated areas of heavy tool wear (areas where surface coating was removed) because tungsten (WC) is representing the tool body material. In Figure 8(a), the point analysis confirmed that no built-up edge formation was observed. The chemical analysis shows that all elements are almost homogenously distributed on the whole worn tool surface, therefore, the zinc elements disappeared. It can be observed that the zinc elements completely mix with the hybrid nanofluids. The wear mechanisms identified during the course of study are micro-attrition, abrasion, adhesion, and edge chipping. Micro attrition wear is characterised by the dull surfaces on the flank face due to the smearing of aluminium on the flank face while the abrasion flank wear is identified by the appearance of small flats surrounded by protruding carbide grains [51, 52].



(a) At spindle speed 3000 rpm



(b) At spindle speed 4400 rpm



(c) At spindle speed 6000 rpm

Figure 9. SEM analysis.

The flank wear is the main mode of wear, with abrasive wear as the baseline wear mechanism. Figure 9(a) shows the SEM micrographs for the cutting edge of the tool at machining conditions with a cutting speed of 3000 rpm, a depth of cut at 0.35mm, a feed rate of 610 mm/min and an MQL flow rate at 0.74 ml/min. Micro-abrasion and micro-attrition are clearly seen on the flank wear-land. The selected micro-area shows the zinc disappeared on the cutting edge, proving the nanoparticle of zinc completely homogenous transfer to material. Figures 9 (b-c) show fractures on the cutting edge. The fracture is caused by work material adhesion on the tool. The EDX spectra for the selected micro-area observed the presence of high concentrations of carbon and oxygen. The selected micro-area shows the presence of titanium and zinc on the cutting edge, proving the transfer of hybrid nano-material during the machining. For the combination of parameters with a speed of 6000 rpm, a feed rate of 1219 mm/min, a depth of cut of 1.10 mm, and an MQL flow rate set at 0.42 ml/min, the SEM images are shown in Figure 9(c). A fracture is seen at one location only in Figure 9(c). Micro-attrition followed by micro-abrasion is seen on the cutting edge. Very little chip adhesion is seen. Micro-attrition and abrasion seem to be major wear processes.

CONCLUSIONS

The tool wear was increased with the increasing cutting speeds and cutting depths for both materials investigated as expected. The SEM analyses of the worn tools after the machining of the aluminium alloy showed the formation of built-up edges. In wear, increases speed, feed rate and depth of cut, wear grow but speed produces the major influence. A hybrid nanocoolant using a minimum quantity lubrication technology seems to be a suitable alternative for an economically and environmentally compatible production. It is concluded that the cutting parameters and the MQL-hybrid nanocoolant play an important role in determining surface roughness, the material removal rate and tool wear. In roughness, a reduced feet rate gives better value and increases speed.

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