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Influence of vegetable based cutting fluids on cutting force and vibration signature during milling of aluminium metal matrix composites

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HIGHLIGHTS

- *Influence of cutting fluids were analyzed during milling.*
- *Four vegetable based cutting fluids were considered.*
- *Palm oil results with minimum cutting force and vibration.*

ABSTRACT

Due to the environmental and health issues, there is an enormous requirement for developing the novel cutting fluids (CFs). The vegetable based cutting fluid (VBCFs) doesn't affect the environment, diminish the harmful effects to the operator and also enhance the machining performances such as surface roughness, tool life, minimum vibration and cutting forces. In this work, the performances of four different VBCFs like palm, coconut, sunflower, soya bean oils, and a commercial type of CFs were considered to analyze the influence of cutting fluids while measuring the cutting force and vibration signatures during milling of 7075–T6 hybrid aluminium metal matrix composite with carbide insert tool. The experiments were conducted in CNC L-MILL 55 vertical machining center, with milling tool dynamometer to measure the cutting force and a tri-axial accelerometer to measure the vibration signals. The flow rate of the VBCFs were maintained at a constant rate and the results were compared with a commercial cutting fluid. The obtained result shows that palm oil suits better than the other vegetable based cutting fluids in terms of minimum cutting force requirement and minimum vibration. Also, the experimental result shows that the cutting fluid was one of the important parameter needs to be considered which influences the cutting force and vibration signals.

Keywords:
| Metal matrix composite | Keyway milling | Vegetable-based cutting fluids | Cutting force | Vibration |

1.0 INTRODUCTION

Metal Matrix Composites (MMC) finds its applications in the places where elevated operating temperatures is required, mainly it can be achieved using Powder metallurgy route. Most of these composites were developed for the aerospace and automotive industries where the temperature was abnormal (Teti, 2002). While machining of MMC, cutting force and tool wear increases with increase in cutting speed due to the presence of hard particles in the Al alloy (Kannan and Kishawy, 2008). Sometimes during machining, the adhesion of workpiece material to the tool cutting surface was also found. This problem can be reduced by the application of minimum quantity of lubrication or oil-jet lubrication (Sreejith, 2008). Also, several other details of machinability of aluminium alloys were discussed in the recent literature (Santos et al., 2016). Cutting fluids (CFs) was one among the other important machining parameter in the manufacturing industry, because of its lubricant effect, cooling and chip removal properties (Cetin et al., 2011). The essential functions such as enhancing the tool life, machining process efficiency, improving the surface integrity and dimensional accuracy of the part, minimizing the cutting forces and vibrations were obtained using better CFs. A better surface finish was not only preferred for the visual appearance of any manufactured goods, also for better tribological properties, fatigue strength, and corrosion resistance. Thus, the surface quality was exceptionally essential in evaluating the efficiency of machine tools and mechanical parts which mainly depends on the cutting conditions and cutting fluids (Davim et al., 2008). In 2005, the quantity of lubricants utilized in manufacturing industries was reported about 38 Mt with an anticipated rise of 1.2 % more than the succeeding decade. Almost 85 % of the mineral based cutting fluids were used around the world; on the other hand, the impacts of cutting fluids on the healthiness and the environment had been questioned in recent times. Due to the extensive use of mineral - based cutting fluids, it caused considerable environmental pollutions throughout their life cycle (Debnath et al., 2014). The recent developments in bio-based CFs by using various vegetable oils and their performances in machining was reviewed and concluded that these bio-based CFs significantly reduces the ecological problems caused by mineral-based CFs (Debnath et al., 2014). The oxidation process of the vegetable based lubricants was briefly reviewed and discussed (Fox and Stachowiak, 2007).

Mineral, synthetic and semi-synthetic CFs fit into a place of the ecological cycle with air, soil and water and their toxicity affect ecosystems (Birova et al., 2002). Particularly when CFs diminish and dispense as a vapor and microparticles, they cause severe health issues such as respiratory diseases, lung cancer, dermatological and genetic diseases (Bennett, 1983). Vegetable based cutting fluids (VBCFs), minimum quantity lubrication (MQL) and near dry cutting had the prominent potential consumption under these restrictions. In MQL, utilization of the CFs was very less and the MQL had been used widely in the literature (Fratila, 2009; Fratila and Caizar, 2011; Marksberry, 2007; Sanchez et al., 2010). VBCFs were environmental friendly, renewable and non-toxic as like mineral based CFs and they reduced the waste treatment cost owing to their essentially superior biodegradability. In order to make a manufacturing process as a clean process, the harmful effects of the coolant should be avoided, for that the development of biodegradable cutting fluid was required (Alves and de Oliveira, 2006). Therefore, there arises a necessity to discover eco-friendly and user-friendly alternatives to the conventional cutting fluids. The introduction of solid lubricants in machining process enhanced the tribological performance by means of reducing the coefficient of friction, cutting forces and tool wear. The reduction in cutting force leads to the requirement of lower specific cutting energy which reduced the production cost (Krishna et al., 2011). When using various solid lubricants in turning process, the performance of boric acid was better than graphite in terms of significant improvement in reducing the cutting forces, the coefficient of friction between chip and tool interface, average tool flank wear and the surface roughness of the machined surface (Krishna et al., 2010). An extensive attempt had been made to study the role of emulsifier in the efficiency of the cutting fluid on cutting forces, cutting temperatures, tool wear and surface roughness (Srikant et al., 2009). Graphite had better lubricating and cooling properties, so the addition of graphite nano - particles in cutting fluid could help in formulating an enhanced coolant in a machining operation. This reduced the average chip - tool interface temperature, tool wear and cutting forces during turning of AISI 1040 steel (Amrita et al., 2013). The preparation process and characterization of the basic properties of nano-cutting fluid were discussed recently (Amrita et al., 2014). The cutting performance of minimum quantity lubricant (MQL) with vegetable oil-based cutting fluid on AISI 9310 steel was studied (Dhar and Khan, 2009), and the results were better than dry and wet cutting conditions. The tribological performance of castor oil was compared with 20W-50 high-quality crankcase oil and the palm oil performed better than crankcase oil in terms of wear and coefficient of friction (Bongfa et al., 2015).

In turning of AISI 304L, the performance of the various vegetable-based cutting fluids was evaluated with extreme pressure and different cutting parameters, the results were compared with commercial types of CFs. The result shows that the sunflower and canola based CFs performed better than the others in terms of minimum cutting force and surface roughness (Cetin et al., 2011). The effect of the machining parameters and vegetable based cutting fluids were experimentally studied while milling the stainless steel substrate. The results recommended that CCF-II provided the minimum specific energy, CCF-II or SCF-II could be selected for minimizing the surface roughness and proportion of the cost of consumed energy and CCF-II performed globally better than the others (Kuram, Ozcelik, Bayramoglu, et al., 2013). The influence of CFs on tool wear along with surface roughness through turning the process of AISI 304 austenitic stainless steel with carbide tool by considering the three different types of CFs (coconut oil, soluble oil and straight cutting oil) were experimentally investigated (Xavior and Adithan, 2009). The results indicated that the coconut oil had performed better than other CFs in terms of minimum tool wear and better surface quality. The effects of four vegetable based CFs (groundnut, palm kernel, coconut, and shear butter oils) on cutting force in turning of three different materials (mild steel, copper, and aluminum) by means of tungsten carbide tool was examined (Ojolo et al., 2008). They found that the decreasing trend of cutting force by 51 % with groundnut oil when compared to palm kernel oil. The result shows that the groundnut and palm kernel oils were efficient for reducing the cutting force during turning of the three workpieces.

The performance of four CFs, two different vegetable-based CFs prepared from refined sunflower oil and two commercial types CFs, was explored for surface roughness during drilling of AISI 304 austenitic stainless steel with HSSE (high-speed steel with cobalt) tool. The results indicated that the vegetable-based CFs was performed better than commercial CFs and the better surface roughness values were obtained with vegetable based cutting oil (Ozcelik, Kuram, Demirbas, et al., 2011). The formulation and application of vegetable oil based metal working fluids during turning process was focused (Lawal et al., 2013) and the results suggested that between 13 and 15% of improvement in surface roughness and between 1.5 and 2.2 times reduction in tool wear with coconut oil compared with soluble oil, during the turning process of AISI 304 austenitic stainless steel with carbide tool. The evaluation of new vegetable based cutting fluids (VBCFs) on thrust force and surface roughness in the drilling of AISI 304 using Taguchi method was studied (Kuram et al., 2011). Five types of CFs (three VBCFs developed from crude and refined sunflower oils and two commercial types) were considered. The experimental result shows that SCF-I (sunflower cutting fluid-I) resulted with lower surface roughness values than CSCF-I (crude sunflower cutting fluid). But CSCF-I gave lower thrust force values than that of SCF-I (Kuram et al., 2012). In turning of FCD700 ductile cast iron, palm oil based lubricant produced better surface roughness due to the excellent adhesion of palm oil compound to the metal surface and oxygen content that created a stronger bonded layer of lubricant on the metal surface (Ghani et al., 2015). Further the effects of the various CFs and machining parameters on the turning of AISI 304L were also studied. The results concluded that VBCFs were better substituted for mineral and semi-synthetic CFs in the turning process. The sunflower based CF with 8% of extreme pressure additives (EP) and commercial semi-synthetic CF performed better than the rest of the CFs in terms of reducing the surface roughness, cutting and feed forces (Kuram, Ozcelik, Tolga Simsek, et al., 2013). The performances of VBCFs during turning of Al 7075-T6 were better than that of the commercial mineral cutting fluid (CMCF). A better enhancement in performances with respect to percentage increment of EP additive in CFs was noticed. In general, the tool wear for VBCFs was less as compared with CMCF due to the high viscosity values (induced BUE in the tool) of VBCFs (Kuram, Ozcelik, Huseyin Cetin, et al., 2013). The performance of cutting fluids on machining of Aluminium alloys was discussed (Mendes et al., 2006) and found that the cutting fluid contains chlorine as extreme pressure additive exhibited minimum cutting forces and better surface finish at high cutting speed and low feed rate and depth of cut. Additionally, the cutting force (Shankar and Mohanraj, 2015), sound pressure and vibration signals were used for monitoring the condition of the tool. The tribological properties of aluminum alloy materials lubricated with palm olein at various load conditions were studied using pin-on-disk. The palm olein had better performance in terms of friction reduction and wear resistance at different load conditions at high speeds (Nuraliza, 2016; Sapawe et al., 2014).

Most of the recent literature presented the experimental results based on the performance of vegetable based cutting fluids and process parameter optimization related to tribological performance (surface roughness, tool wear, the coefficient of friction and tool wear etc) during the machining process. However, no studies were found to relate the influence of the cutting fluids over the cutting force and vibration signatures measurements during milling. In this study, four VBCFs namely palm, coconut, sunflower and soya bean oils were used for machining. The results were compared with other commercial cutting fluid and dry cutting with respect to the performances in terms of cutting force and vibration values during milling of Al 7075 – T6 alloy.

2.0 EXPERIMENTAL PROCEDURE

2.1. Vegetable-Based Cutting Fluids

VBCFs were an oil-in-water suspension type which consists of base oil, surfactant(s) and additives to meet the required specifications such as resistance to bacterial growth, corrosion, foaming and wear (Dickinson, 1992). In this study, the additive elements were not considered. The VBCFs were prepared with pure base oil without any heat treatment process. The cutting fluids used in this work were palm, coconut, sunflower and soya bean oil and laboratory purpose commercial cutting fluid. The VBCFs contain nearly no destructive materials and environmentally friendly, better for operators and having a higher rate of biodegradability (>95%). The characterization of VBCFs was presented in Figure 1. The density for Palm oil is 840 kg/mm^3 and other VBCFs are 860 kg/mm$^{3.}$ The viscosity of a cutting fluid was one of the major parameters to conclude the effectiveness of cutting fluids. In the current study, viscosities of the cutting fluids were measured at 40°C using a Saybolt viscometer. The viscometer was calibrated with pure water. The viscosity results were presented as a function of temperature. The viscosity of cutting fluids decreases with increasing temperature.

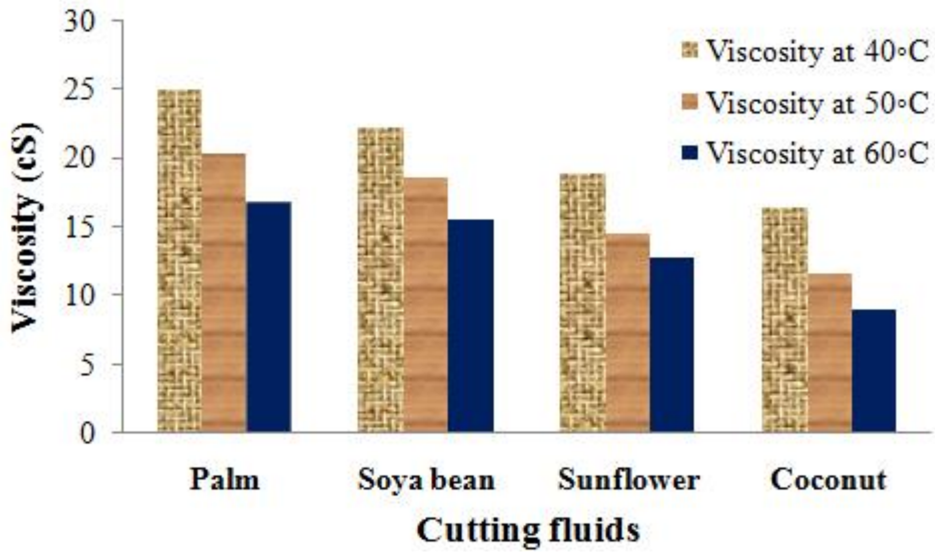

Figure 1: Characterizations of vegetable oil based cutting fluids

2.2. Experimentation

Al 7075-T6 hybrid composite alloy was used as a workpiece in this study. Aluminium alloy hybrid metal matrix composite was fabricated through two-step stir casting technique. Table 1 shows the physical and mechanical properties of Aluminium alloy hybrid composite. The milling experiments were carried out with the proposed VBCFs in order to acquire the cutting force and vibration signatures on L-Mill 55 Vertical Machining Center, which had a maximum spindle speed of 6000 rpm and a maximum spindle motor power of 11 kW. M680 tool holder of 25 mm diameter with three flutes was chosen and WIDIA XDHT-090308HX-PA120 grade inserts were used for the machining process. Its geometry was as follows: relief angle of 15°, tolerance of 0.025 mm and nose radius of 0.8 mm. The milling process was carried out with the optimal cutting parameters of 3930 m/min cutting speed, 0.08 mm/tooth feed rate, 1 mm axial depth of cut and 25 mm radial depth of cut. The entire experiments were carried out with the above-mentioned constant parameters. The flow rates of the coolant for VBCFs were maintained at a constant flowrate of 60 ml/h. Initially, the commercial cutting fluid (considered as the reference fluid) was used for the machining. The results of the proposed VBCFs and the performance of the dry cutting were compared with the commercial CF.

Table 1: Physical and mechanical properties of Aluminium alloy hybrid composite

Physical properties		**Mechanical properties**	
Materials	**Composition**	Tensile strength	232 MN/mm^2
Sic	7.5 wt.%	Vickers Micro Hardness	165 HV
TiC	7.5 wt.%	Density	2.85 g/cm^3
Zinc	5.6-6.1 wt.%		
Magnesium	2.1-2.5 wt.%		
Copper	1.2-1.6 wt.%		
Silicon, Iron, Manganese, Titanium, Chromium and other metals	< 0.5 wt.%		

2.3 Measurements

The cutting force and vibration signatures were acquired from the Milling tool dynamometer and Tri-axial accelerometer respectively. The workpiece material was mounted on the machine vice of the milling tool dynamometer, which was located on the table of the CNC machine (Figure 2). The tri-axial accelerometer was mounted on the workpiece with a proper adhesive solution. The orientation of the sensor location along with machine table feed direction was physically verified before mounting the vibration sensor. The milling tool dynamometer and tri-axial accelerometer were connected with BNC noise free cable and the raw signals were conditioned with a proper signal conditioning unit. The milling tool dynamometer had the accuracy of ±1% of full-scale voltage and force range of 0-5000 N. The tri-axial accelerometer (Dytran®) had the sensitivity of 10mV/g, the range of 500 g and the frequency range of 1.5 to 10,000 Hz. The cutting force and vibration signals were acquired from the cutting zone with the aid of NI USB 6221 DAQ card and stored in the computer. The electrical noise signals were eliminated with the proper filtering process. The signals were acquired with the sample rate of 1K samples per second. In this study, the resultant cutting force and vibration signatures were considered to evaluate the coolant effect.

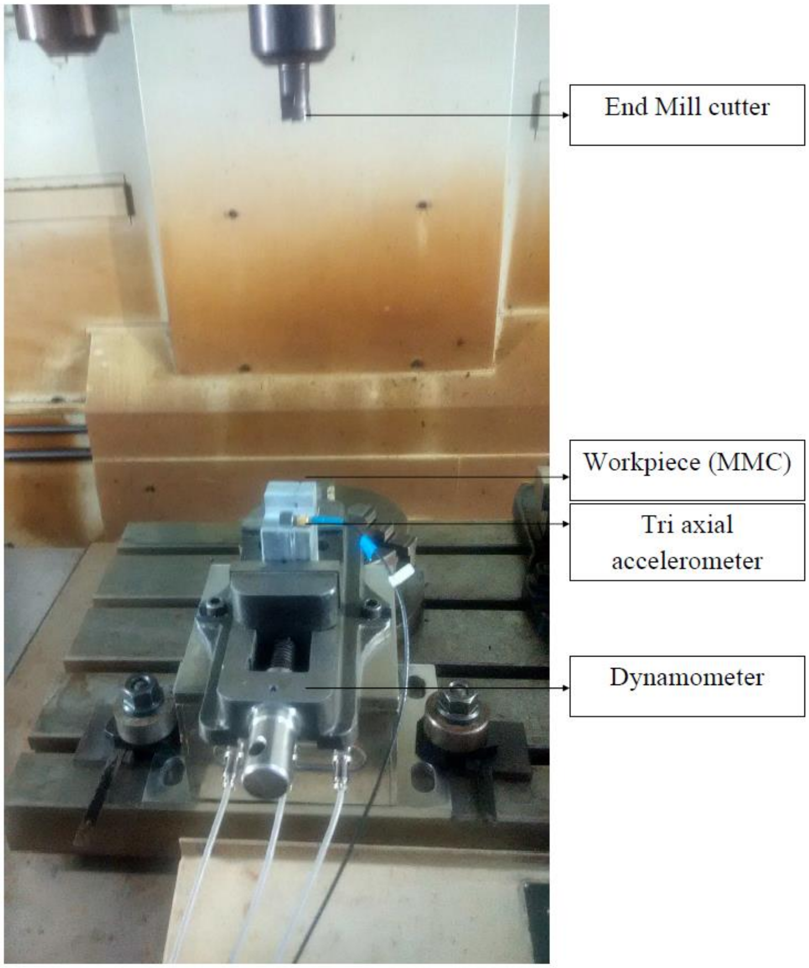

Figure 2: Experimental setup

3. RESULTS AND DISCUSSION

Cutting force (Feed force *Fx*, Thrust force *Fy*, and Cutting force *Fz*) and the vibration in three axes (*Vx*, *Vy* and *Vz*) were measured for both CFs including commercial cutting fluid and dry machining experiments during the milling of Al 7075-T6 hybrid alloy composite.

3.1 Cutting Forces

The dynamometer was capable of measuring primary cutting force (*Fz*), thrust force (*Fy*) and feed force (*Fx*) while machining process takes place. The resultant force (total cutting force) was computed using Equation (1).

$$\mathrm{Fr} = \sqrt{\mathrm{Fx}^2 + \mathrm{Fy}^2 + \mathrm{Fz}^2} \tag{1}$$

The performances of CFs on *Fy* and *Fr* during the milling process were evaluated and the results were shown in Figures 3 and 4. The average values of thrust forces and the resultant cutting forces were represented. The order of the performances from the maximum thrust force value to the minimum thrust force value was followed by coconut oil, sunflower oil, soya bean oil, dry cutting, palm oil and commercial cutting fluid. The thrust force values of the commercial CF (37.06 N) and palm oil CF (43.06 N) were very close to each other. The performance of the commercial fluid was better than other VBCFs due to the addition of mineral particles (Kuram et al., 2011). The palm oil CF had the minimum thrust force than the remaining VBCFs, also palm oil had the highest viscosity. The performance of the palm oil CF was better than the performance of dry cutting, since the coolant reduces the friction and temperature between the workpiece and tool contact area. The soya bean, sunflower oil, and coconut oil had the higher thrust force compared to other CFs which was due to the high viscosity of the cutting fluids. The palm oil had the minimum cutting force but the coconut oil produced the highest cutting force requirement, the same response also obtained from the literature while considered during turning of Aluminium material (Ojolo et al., 2008). The VBCFs results with a lesser cutting force value than that of CMCF (Belluco and De Chiffre, 2004). However, in this study, VBCFs except palm oil exhibited to some extent higher values of forces than that of dry cutting condition (705.41 N). But previous literature reported that the palm oil could be used as an alternative lubricant for the machining applications (Rahim and Sasahara, 2011). The cutting force exhibited during the milling of AISI 304 austenitic stainless steel with carbide tool material also higher for sunflower oil (Kuram, Ozcelik, Bayramoglu, et al., 2013). In previous literature, it was reported that the minimum quality cutting lubrication with biodegradable vegetable oil can effectively improve the machinability of Inconel 718 (Zhang et al., 2012).

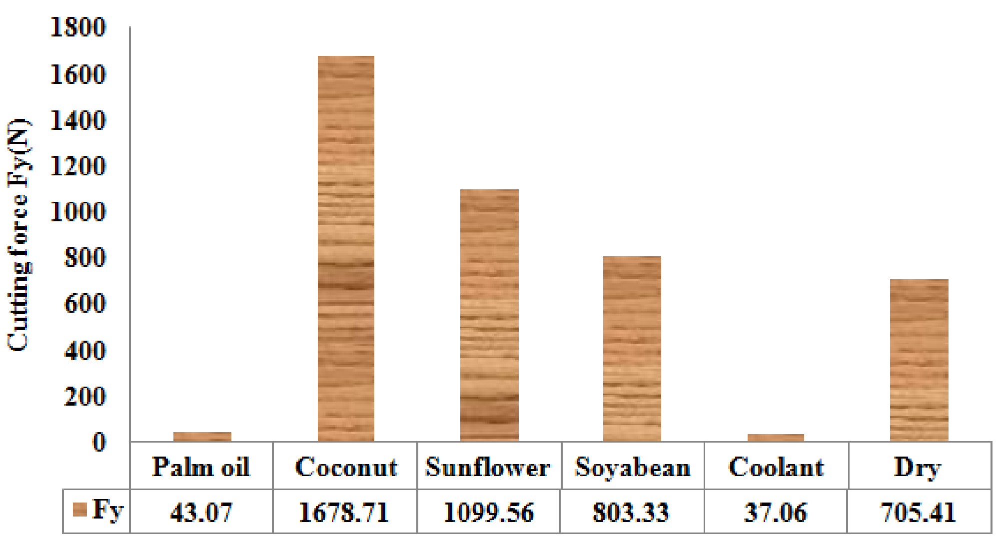

Figure 3: Effect of various cutting fluids on average feed forces (*Fy*)

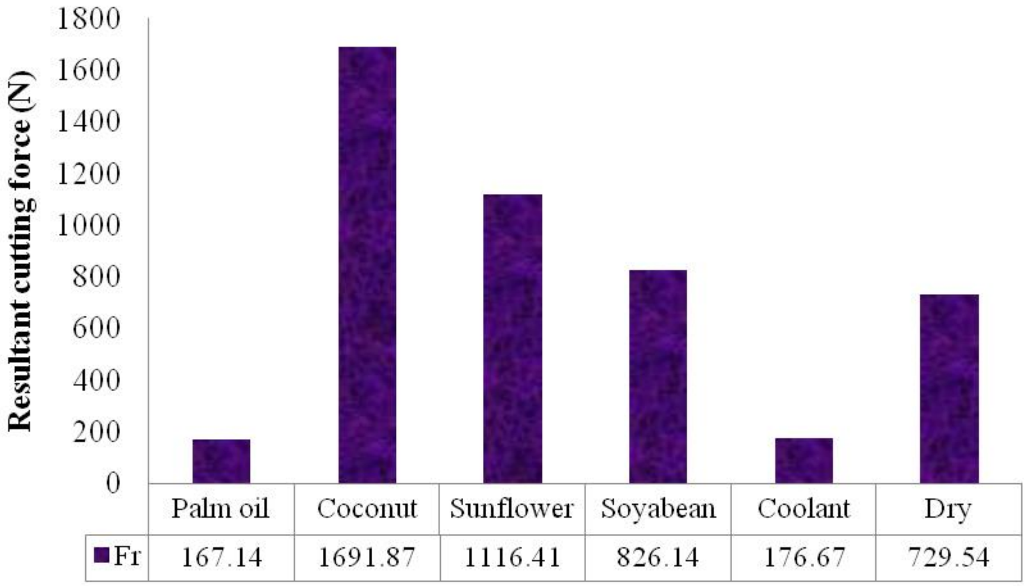

Figure 4: Effect of various cutting fluids on resultant cutting forces (*Fr*)

The resultant cutting force for the various VBCFs, commercial cutting fluid and dry cutting was presented in Figure 4. While using palm oil as a CF, the resultant cutting force was better than all other CFs. Palm oil exhibited the minimum resultant force. The cutting force produced by VBCFs (except coconut oil) varied nearly 5-10 times of the force produced by the palm oil. The same response was obtained from the previous work while turning mild steel (Lawal et al., 2007; Ojolo et al., 2008) and palm oil was also suitable for machining of titanium and super alloys (Rahim and Sasahara, 2011). The coconut oil had the significant influence on reducing the resultant cutting force followed by palm oil. The performance of the coconut oil and palm oil were nearly the same. During turning of AISI 304 material with carbide tool, the coconut oil out-performed the other CFs (Xavior and Adithan, 2010). The resultant force for dry cutting was around 730 N. The average resultant cutting force values for various VBCFs namely soya bean, sunflower, and coconut were 826.14 N, 1116.41 N and 1691.87 N respectively. Compared to other VBCFs, the coconut oil recorded the highest cutting force (*Fy*, *Fr*) as similar to previous observations. (Lawal et al., 2013; Ojolo et al., 2008).

A better performance of VBCFs with respect to commercial cutting fluid was explored using the higher viscosity of VBCFs. Due to the higher viscosity values of the VBCFs; they had more stable lubricity across the machining temperature range and held the cutting fluid in the machining zone. The viscosity of the commercial cutting fluid decreased faster than the VBCFs when the temperature was increased (Krahenbuhl and Goshen, 2005). This nature of the VBCFs reduces the friction between the tool and workpiece which leads to the small reduction of heat generated at the interface (Xavior and Adithan, 2009) which reduced the cutting force. The resultant force (167.14 N) for palm oil was very low compared to commercial cutting fluid and other VBCFs. On the other hand, the feed force and the resultant cutting force values for VBCFs were higher than the dry cutting condition. The same trend was found in turning of AISI 304 (Ozcelik, Kuram, Cetin, et al., 2011). The tool wear was reduced as well as nominal surface roughness values were produced. The friction between the tool and workpiece was the major parameter for cutting force and the cutting force components mainly depends on spindle speed (Shankar et al., 2016). Generally, the friction was reduced while using the cutting fluids. So using CFs become important due to their lubrication and cooling properties in the cutting zone, to reduce cutting forces (Kuram et al., 2012). Based on viscosity values of the different cutting fluids, an increase in viscosity leads to a reduction in cutting force can be achieved. Because cutting fluids with high viscosity has a huge quantity of unsaturated fatty acid which will create a high strength lubricant film and acts as a boundary lubricant (Nuraliza, 2016). Palm oil used in this work has the higher viscosity, hence exhibited the minimum cutting force compare to other VBCFs. But the commercial cutting fluid had the lowest viscosity which produced the minimum cutting force due to the addition of minerals and chemical particles.

3.2 Vibration signals

The cutting vibration in milling process mainly depends on the intermittent cutting force generated during machining process (Zhong et al., 2010). The vibration values from the three axes (*Vx*, *Vy*, and *Vz*) were measured from the tri-axial accelerometer which mounted on the workpiece. The resultant vibration value from the entire three axes was calculated by the equation 2. The average vibration signals produced in *X* and *Z* directions had the minimum effect. So, the vibration in *Y* direction (*Vy*) and the resultant vibration (*Vr*) were considered to analyze the influence of VBCFs.

$$V_r = \sqrt{V_x^{\,2} + V_y^2 + V_z^2} \tag{2}$$

The influence of the cutting fluids on the vibration signals (*Vy* and *Vr*) were presented in the Figures 5 and 6. The commercial cutting fluid exhibited the maximum vibration of 0.0041 g. In this process, the analysis was carried out with time domain features and the frequency domain analysis was not considered. The dry cutting process produced the minimum vibration (0.0017 g). The palm oil had the significant influence on the vibration signal which had the similar response (0.00177 g) of commercial cutting fluid. The palm oil performance in terms of vibration was very close to the dry cutting process. The vibration response for the sunflower and soya bean oil was similar to each other. The coconut oil exhibited slightly larger values of vibration to other two VBCFs. The influence of commercial cutting fluid was a negative impact on the vibration signature. Based on the viscosity of the fluids, an increase in viscosity reduced the vibration signatures. This trend was observed in the resultant vibration signatures (*Vr*).

The utilization of high viscosity cutting fluid could reduce the cutting vibration (Zhong et al., 2010). The coconut oil recorded the highest vibration signatures compared to other VBCFs. The vibration signature not only depends on the cutting fluids also depends on the process parameters and tool wear. The minimum vibration signature was obtained with a minimum flow of the cutting fluids. The flow rate of the VBCFs was lower than the flow rate of the commercial cutting fluids. The same response was obtained in turning of AISI 4340 steel (Paul et al., 2016). In general, the resultant vibration signal was higher with coolant than dry cutting. The same response also found in the high-speed turning of Ti-6Al-4V (Pai and D'Mello, 2015).

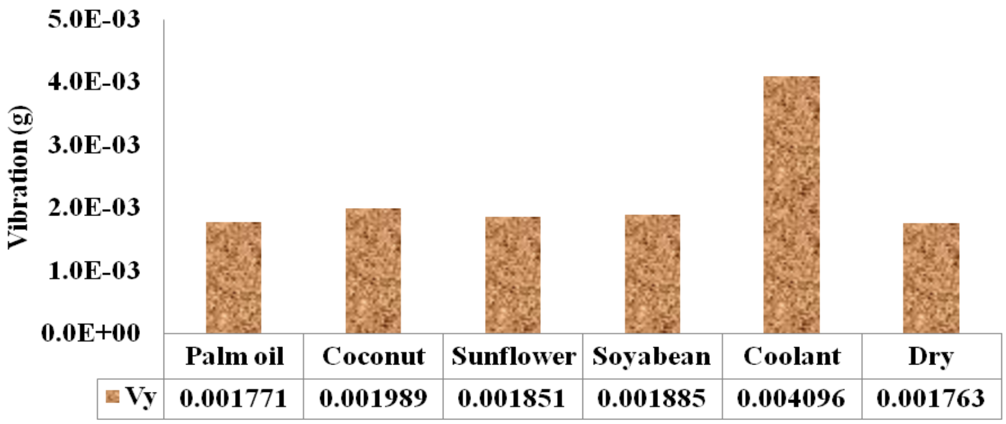

Figure 5: Effect of various cutting fluids on vibration (*Vy*)

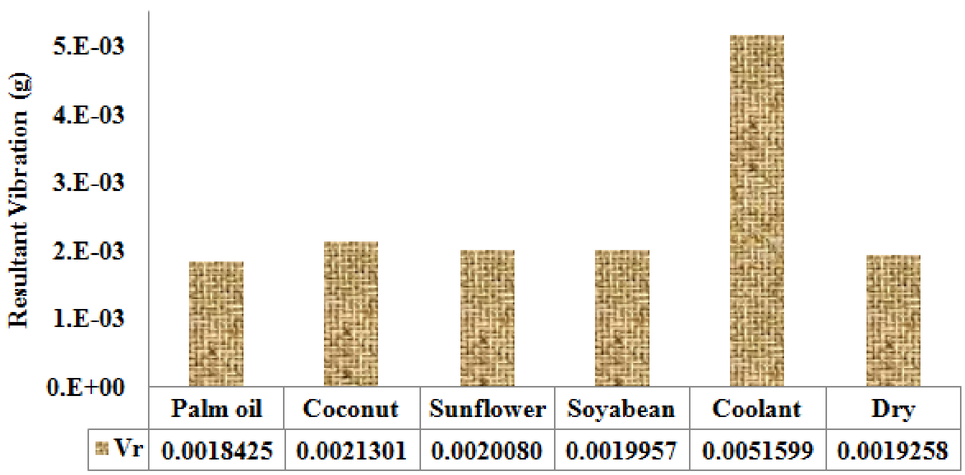

Figure 6: Effect of various cutting fluids on resultant vibration (*Vr*)

The influence of the resultant vibration signals was presented in Figure 6. The palm oil exhibited the minimum vibration (0.00184 g) compared to all other CFs. Similar to that of *Vy* response, the commercial cutting fluid had the maximum value of 0.00516 g which was the highest vibration produced during the machining process. The remaining CFs had the slight variation in their vibration values. The performance of dry cutting and the soya-bean cutting oil was similar to each other. The results of the palm oil recorded the lowest vibration signatures due to its highest viscosity values. An increase in the cutting fluid viscosity, the resultant vibration signature was significantly reduced. Further design of tool condition monitoring systems, the cutting fluids with high viscosity might be preferred than the commercial cutting fluids to reduce the vibration as well as the minimum cutting force requirements. In all the experiments, the tool wear was not considered.

CONCLUSIONS

In this study, the influence of the various CFs and dry cutting on the milling of 7075-T6 hybrid aluminium alloy composite was experimentally investigated. This study focused on the performances of VBCFs with respect to commercial cutting fluid in terms of cutting forces and vibration during the milling process. The experiments were conducted with constant process parameters. The following conclusions were drawn:

a) The minimum feed force and resultant cutting force was obtained with commercial cutting fluid (Fy = 37.06N) and palm oil (Fr = 166.6714 N). But there was a slight difference in the performance of commercial CF and Palm oil. The variation in resultant cutting force was around 5% only. Hence this variation can be ignored.
b) The cutting force (Fy and Fr) values for the coconut oil (1678 N and 1691 N) was very high compared to palm oil (43.06N and 167.14 N) and commercial cutting fluid. The soya bean and sunflower oil also generated higher cutting force than dry cutting but better than the coconut oil.
c) The palm oil exhibited a very minimum resultant vibration (Vr) signals. But the commercial cutting fluid exhibited the larger vibration values, while machining which was 2.6 times higher than dry cutting. There was no large variations in the vibration signals of sunflower, soya bean, and coconut oils.

The obtained result shows that the palm oil suits better than the other vegetable based cutting fluids in terms of minimum cutting force requirement and minimum vibration. Overall from the extensive study, it can be concluded that the influence of VBCFs will produce the significant impact on the design of tool condition monitoring systems.

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