ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

Turning of Medium Carbon Steel with Vegetable-Based Oil delivered by MQL

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Abstract. *It is known that various problems in machining are connected with incorrect use of cutting fluids. The effectiveness of cutting fluids affects tool wear rate and failure modes during machining as well as surface integrity of machined parts. Correct selection of fluids is mainly to minimize tool wear and provide machined parts within the tolerances required, thus ensuring a higher production rate. Most recent works about fluids in machining have been focused on the ecological and economical aspects of using cutting fluid, i.e. whenever possible going for green machining. Simultaneously, it has been reported in the literature various benefits of using minimum quantity lubrication (MQL) in machining compared to conventional flood-cooling technique. Vegetable based cutting fluids have been increasingly used in machining operations due to several reasons such as: less harmful to the operator and environment and also because of ability to minimize tool wear rate. This work aims to investigate the performance of a vegetable-based oil on turning of a medium carbon steel with cemented carbide insert with two cutting speeds (200 and 350 m/min) and feed rates of 0.20 mm/rev and 0.32 mm/rev. Comparative trails with under dry condition were also performed. Machining trials were carried out at a low wear stage up to* VB_{Bmax} *= 0.20mm. Tool wear and surface roughness of machined parts were used to access the performance of vegetable-based oil. SEM images of the worn tools to identify the wear mechanisms. Results showed that machining with vegetable based fluid delivered by the MQL technique outperformed dry cutting in terms of tool wear rate. Also, it was observed that tools employed under dry condition experienced intense plastic deformation, unlike the tools using vegetable-based oil that experienced a adhesive wear under the conditions investigated. Surface roughness values recorded were below 6* μm*. Negligible effects of cooling environment in finishing were observed.*

Keywords: *turning, vegetable-based oil, MQL technique, tool wear, surface roughness*

1. INTRODUCTION

During machining process cutting tool experiences high stress and high temperatures at the cutting point what generate heat and wear, so it is necessary constant changes in their cutting edges. Simultaneously, there is the heating generated that is transferred to most machined parts, which can lead to alterations in design dimensions and structural properties that can compromise the use of the part. Into this context, there are many possibilities to minimize tool wear rate and to avoid negative effects of heating flowing to workpiece. One of these possibilities is a correct selection of a cutting fluid.

In 1894 F. W. Taylor observed that the application of a water jet directed at the cutting site allowed the increase of 33% of the cutting speed, with no harm to the cutting tool. Later, crude oil derivatives were incorporated into this process, and their use has become widespread thanks to their good lubricating capacity and anticorrosive action. The association of these two elements – water and oil derivatives – resulted in a system with a wide range of applications, offering the advantages of cooling by water and of lubrication by oil derivatives (Trent and Wright, 2000).

Cutting fluids help to cool the cutting area by removing generated heat during machining, especially at high cutting speeds, and lubricate the cutting area at low speeds by reducing friction process, as well as acting in reducing cutting forces, improve tool life, surface finish and the dimensional accuracy of workpiece. Cutting fluids also help to break the chip, provide transport of chips and protect the machine tool and machined surface against oxidation (Bianchi *et al*., 2009; Sales *et al*., 2001). Da Silva et al. (2011) reported that cutting fluid efficiency in machining will depend on tribological interactions existing at the workpiece-tool-chip interfaces for each combination of cutting speed, feed rate and lubrication/cooling system employed.

However, the benefits obtained with cutting fluids in machining have been questioned in the last two decades due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment (Dhar *et al*., 2007). Consequently, ecological regulations and economical consideration have emphasized the need for more dry machining or environmentally clean metal cutting processes. Additionally, the conventional flood supply system demands more resources for operation, maintenance, and disposal.

Among the various methods and environments to minimize or even avoid the use of petroleum-based metalworking fluids (MWFs) cutting fluid in machining operations, the Minimal quantity lubrication (MQL) poses as an effective method of supplying lubrication in machining to achieve both environmental and economical benefits. A MQL technique usually supplies 10 - 110 ml/h of a cutting fluid with pressurized air or other supplemental gases, whereas a conventional coolant system supplies about several thousand ml/h of cutting fluid. Da Silva et al. (2011) carried out their experiments in milling of medium carbon steel with using different machining lubrication/cooling systems. The authors used MQL technique and flooding with fluid delivery at a flow rate of 60 ml/h and 276,000 ml/h, respectively.

It has been reported that vegetable-based oil possess good lubricity properties compared to mineral oil and lubrication function of fluids are required when machining at severe conditions (De Paula and Abrão, 1999). Petroleum-based metalworking fluids (MWFs) can cause some undesirable effects, such as allergies or others health problems to the operators by the skin contact or the inhalation of its mists, the deterioration caused by fungi and bacteria acquired during their lifecycle, and it has to be careful recycled, since it cannot be disposed in the soil or in sewers. Belluco and De Chiffre (2004) studied the efficiency of several cutting oils when drilling AISI 316L austenitic stainless steel with HSS-Co tools and reported that all vegetable-based oils outperformed mineral-based oils in terms of tool life. In some cases, up to 177% tool life increase was obtained when a blend of rapeseed oil and ester oil was employed in relation to the mineral based-oil used as a reference fluid in the investigation. De Paula and Abrão (1999) observed a slight improvement in the roughness of machined surfaces when vegetable-based oil and castor oil were employed in comparison with mineral oil and dry machining due to good lubrication ability of such oil that acted minimizing friction at tool-chip-workpiece interfaces.

The present work deals with experimental investigation of performance of vegetable based cutting fluid delivered by MQL in turning of SAE 1050 steel with cemented carbide inserts. Dry cutting were also tested for comparison. Tool wear, failure modes and surface roughness of machined surfaces were monitored and used to assess the performance of the vegetable-based oil.

2. EXPERIMENTAL PROCEDURE

A comprehensive testing procedure was carried out to evaluate the performance of vegetable based oil when turning SAE 1050 modified steel grade (Gerdau S.A.) with CVD coated cemented carbide inserts with designation ISO SNMG120408 DM T9035 (with chipbreaker).

All the machining trials were carried out using a Multiplic 35D lathe with 11kW motor drive, made by Romi Industries Inc., and speed range from 3 to 3.000 rpm. The workpiece material had a length of 500mm and initially a diameter of 50.8mm. Some physical properties of this material are shown in Tab. 1. Common applications of such steel are in the manufacturing of components for the automotive, naval and building industries.

Table 1. Physical properties of SAE 1050 steel alloy.

Elastic Modulus (GPa)	Tensile strength (MPa)	Elongation (%)	Average Measured Hardness (HV)	Density (g cm^{-3})	Thermal conductivity at 20ºC (W/m.K)
210	340	15	216	7.86	11.7

Vegetable-based cutting fluid was applied by MQL technique through one nose at a flow rate of 60 ml/h and at a pressure of 0.8MPa, with a concentration of 7% in water. This cutting fluid is commercially available as Syntilo 916 (Castrol, 2011). It is a soluble ester based fluid free of mineral oil, boron, chlorine and nitrite free with a density of 1.071 g/cm^3 at 20ºC. These fluids are recommended for machining of carbon steels, alloyed steels and stainless steel. They have good anti-corrosion properties to protect machine tools and parts. Vegetable-based oil possess high biodegradability characteristics (reference of measurement of the environmental compatibility of lubricants), what explains current use of such oils in MQL applications (Belluco and De Chiffre, 2004; McCabe and Ostaraff, 2001).

MQL device is manufactured by Accu-Lube®. More detailed information about MQL device and their components can be found in the work of Da Silva et al., 2011. Tests in dry condition were carried out to compare the results with the other conditions.

The cutting parameters employed were cutting speed, Vc, of 200 and 350 m/min and feed rate, f, of 0.20 and 0.32 mm/rev. A constant depth of cut of 2.0 mm was employed throughout the machining trials. The output variables monitored and analyzed in this investigation were: tool wear, surface roughness and images of worn tools.

Although tool rejection criterion recommend by roughing operation is maximum flank wear, VBmax $\geq$ 0.6 mm (ISO 3685, 1993), in this work it was adopted flank wear value of VBmax $\geq$ 0.20 mm due to limited quantity of

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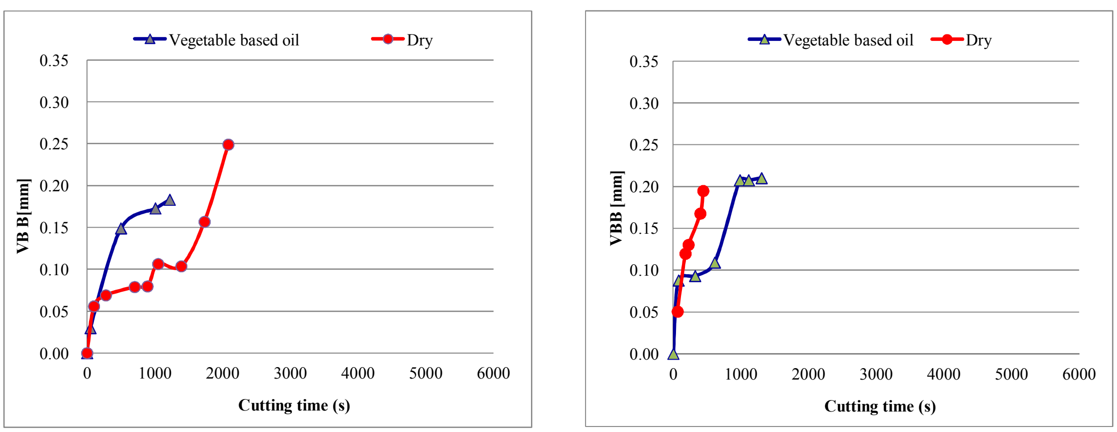
available workpiece material from the same batch. Tool wear measurements were carried out at various machining intervals using an optical microscope (Olympus, Evolution LC Color SZ6145TR model) – with digital camera and image analysis software (Image-Pro Express 5.1) at the end of each machining pass with a magnification of x45. Also, some relevant images of the worn inserts were selected and captured with the aid of a computer connected to the scanning electron microscopy (SEM).

Surface roughness (Ra parameter) of the machined surfaces were recorded after each pass using portable stylus type instrument (Surftest Mitutoyo, model SJ 201) with sampling length of 0.8 mm and evaluation length of 5 mm. Measurements were carried out in three different regions (beginning of machining pass, in the middle of machining pass; end of pass) of the workpiece. Three measurements were realized on each region (equally distributed along the circle of the bar) and the average of three readings represents the surface roughness value of the machined surface for each region. When a machining trial exceed five machined passes, then the methodology for measuring and recording the output variables was performed after every five passes.

3. RESULTS

Figs. 1 and 2 show the evolution of flank wear land with cutting time when turning SAE 1050 steel under different cooling environments and at different cutting speeds of 200 m/min and 350 m/min, respectively, and feed rates. It can be observed that tool wear increased with prolong machining time under the conditions investigated and that curves have different slopes. As expected, shorter cutting time was recorded when machining at higher speed and feed conditions due to the more severe thermal/frictional actions taking place at cutting zone. As a consequence, thermal gradient is increased which affects the yield strength of the tool material that drops rapidly, thus accelerating wear at the cutting edge during machining (Trent and Wright, 2000; Ezugwu, 2005).



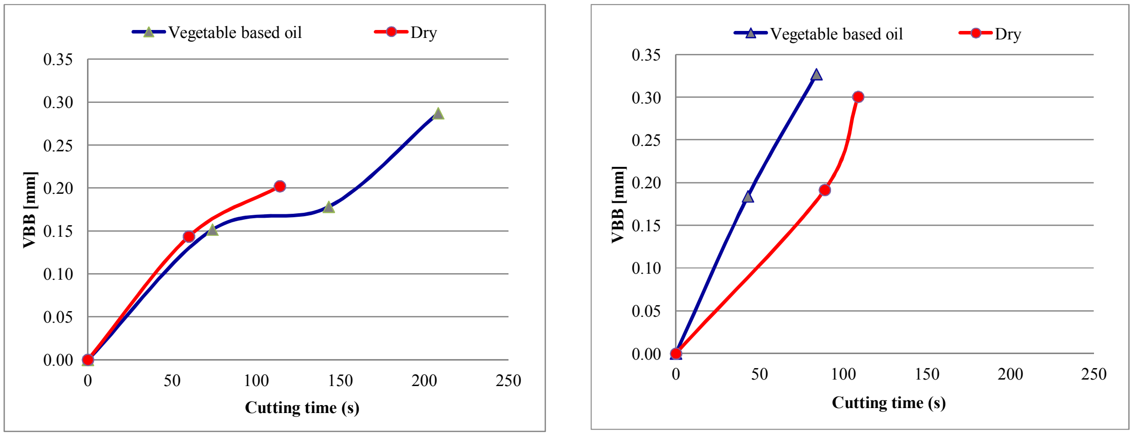
(a) (b)

Figure 1. Flank Wear vs. cutting time during machining with vegetable based fluid and under dry condition at a speed of 200 m/min: (a) f=0.20 mm/rev, (b) f=0.32 mm/rev.

In general, from Fig. 1 and Fig. 2 can be seen that increase in feed rate from 0.20 to 0.32 mm/rev resulted in shorter tool life. Machining with vegetable based oil provided superior performance in terms of tool wear rate compared to dry condition, except when machining at more severe conditions, Vc=350 m/min and f=0.32 mm/rev (Fig. 2 (b)).

The expected superior lubricity of vegetable-based oil was noticed when machining in combination of Vc=200 m/min and f=0.32 mm/rev in presence of fluid, MQL technique (Fig. 1(a)). Superior performance of MQL with vegetable oil also was observed when machining at the highest speed of Vc=350 m/min and f=0.20 mm/rev (Fig. 2 (a)). Dhar et al. (2006) also used MQL technique in turning process of medium carbon steel and concluded that, in some cases, a mixture of air and soluble oil has been shown to be better than the overhead flooding application of soluble oil. The minimization of cutting fluid also leads to economical benefits by saving lubricant costs and workpiece/tool/machine cleaning cycle time. Also, Diniz and Micaroni (2002) carried out an experimental trials in turning of AISI 1045 steel with TiC-Al_2O_3 -TiN coated carbide inserts and varied cutting speed (430 and 540 m/min), feed rate (0.1 and 0.14 mm/rev) and tool nose radius (0.4 and 0.8 mm) in presence of fluid (synthetic oil with concentration of 6%) and under dry. They concluded that finish turning under dry condition was possible (without harming tool life and cutting time and improving surface roughness and power consumed) for the following combination parameters: lower cutting speed, higher feed rate and larger tool nose radius.

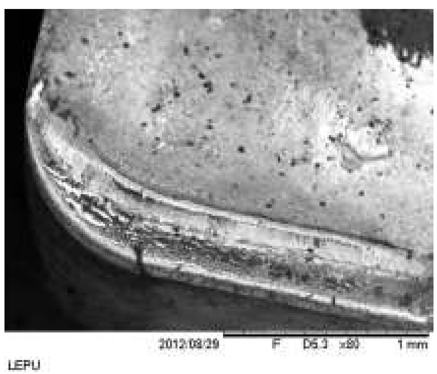
ISSN 2176-5480



(a) (b)

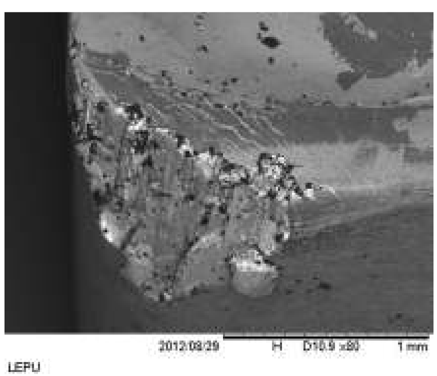
Figure 2. Flank Wear vs. cutting time during machining with vegetable based fluid and under dry condition at a speed of 350 m/min: (a) f=0.20 mm/rev, (b) f=0.32 mm/rev.

Figs. 3 and 4 show worn cutting inserts images captured after turning SAE 1050 steel under the various cutting conditions using MQL technique and under dry machining, respectively.

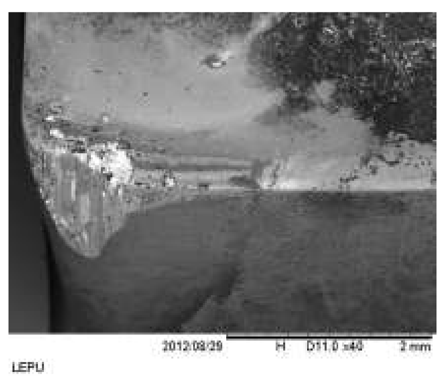


(a) Vc=200 m/min, f=0.20 mm/rev

(b) Vc=200 m/min, f=0.32 mm/rev



(c) Vc=350 m/min, f=0.20 mm/rev



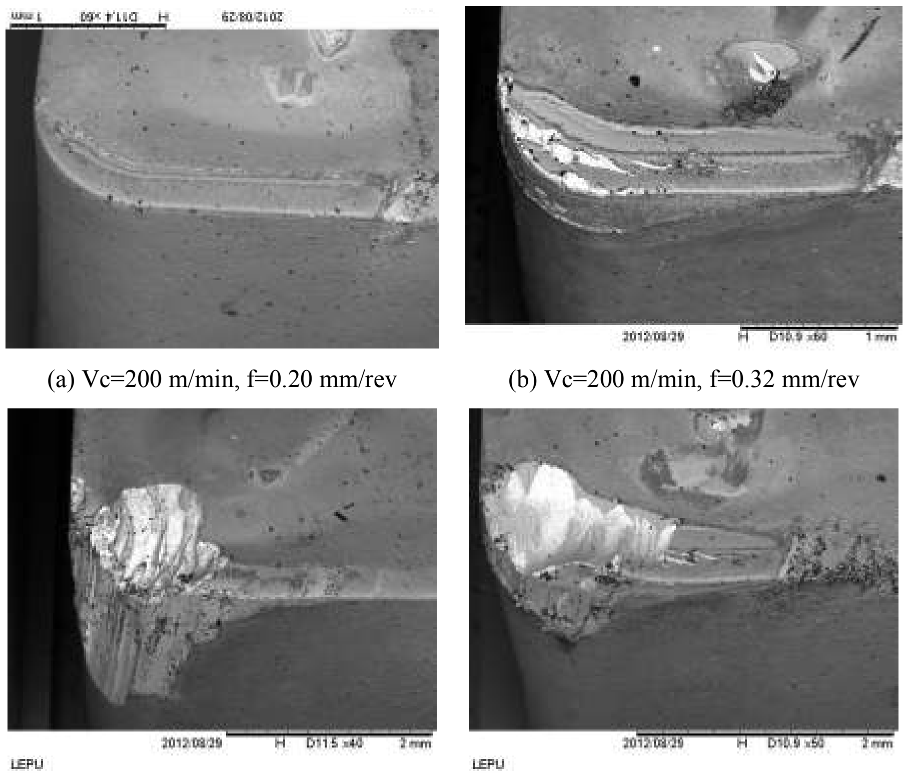
(d) Vc=350 m/min, f=0.32 mm/rev

Figure 3. SEM worn inserts images after machining with vegetable based oil at different cutting conditions.

Figures 3 (a)-(d) show cemented carbide worn inserts after machining SAE 1050 steel with vegetable based fluid at different speeds and feed rates. It can be seen that, machining at lower speed and feed rate (Fig. 6(a)), an uniform wear was spread along the both nose and flank faces, unlike those wear modes observed when machining at the same speed, but at the highest feed rate of 0.32 mm/rev (Fig. 3(b)), and also at higher cutting speeds (Fig. 3(c) and (d)). These facts suggest that wear modes and mechanisms are very sensitive to changes in either speed and feed rate parameters when

ISSN 2176-5480

machining with vegetable-based oil under the conditions investigated. From the figures presented when machining at the highest speeds, there is the evidence of adhesion of work material onto the tool nose as result of the continuous contact between the tool and the work material during machining, in particularly in worn insert shown in Fig. 3(c), that experienced more severe nose and flank wears under the conditions investigated.



(a) Vc=200 m/min, f=0.20 mm/rev (b) Vc=200 m/min, f=0.32 mm/rev

(c) Vc=350 m/min, f=0.20 mm/rev (d) Vc=350 m/min, f=0.32 mm/rev

Figure 4. SEM worn inserts images after dry machining under at different cutting conditions.

Figs 4(a) and (b) show smoothly worn inserts with flank wear spreading along the flank face after machining under dry condition at lower cutting speed of 200 m/min, independently of feed rate. However, at the highest speed of 350m/min inserts experienced intense plastic deformation. In addition, From Fig. 4(c) chipping of cutting edge is observed as result of higher temperatures generated in the cutting zone, thereby indicating that non favorable tribological conditions (in terms of tool wear) can not be reached when machining under dry condition.

Fig. 5 shows results of average surface roughness (Ra parameter) values recorded during machining of SAE 1050 steel with coated cemented carbide inserts at various cutting conditions. It can be seen, as expected, better surface finish was obtained when machining at the lowest feed rate of 0.20 mm/rev, irrespective of speed employed. An increase in feed rate will increase the surface roughness values, hence deteriorating the machined surfaces (Xavior and Adithan, 2009). Reddy et al. (2011) carried out a work to evaluate the effect of feed rate on the generation of surface roughness in turning of mild steel and they reported that increase in roughness is generally considered to be a function of square of the feed rate, but in some conditions, in practice, it is more likely directly related to the feed rate due to the effect of swelling and side flow. On the other hand, Bonifácio and Diniz (1994) reported that the effect of cutting fluids on surface finish generated during machining is not clearly defined. This effect may be dependent on the combination of the cutting conditions employed and also on the machining time. Surface roughness is related to the vibration system which is dependent on the cutting conditions selected too.

By comparing the MQL technique and dry environment, surface finishing values recorded when machining with vegetable based fluid was, in general, slight higher than those values recorded under dry machining. The highest Ra value of 5.70 µm was obtained after machining with vegetable-based fluid applied by MQL technique under a combination of the lowest cutting speed (Vc=200 m/min) and the highest feed rate (f=0.32mm/rev). From Fig. 5 can also be seen that increase in feed rate resulted in poor surface finishing under the conditions investigated. An increase in any of the machining parameter generally leads to increase in cutting temperature. An increase in feed rate directly increases the primary and secondary shear zones, tool-chip contact length and, consequently, increase in heat generation, then contributing to easy shearing of the work material (Da Silva et al., 2012). On the other hand, with the increase in heat generation the yield strength of the tool material drops rapidly (Trent and Wright, 2000), thus accelerating wear at the cutting edge during machining. Vegetable-based oils typically posses good lubricity properties compared to mineral oil and lubrication function of fluids are required when machining at less severe conditions.

These results indicate that machining SAE 1050 at the cutting conditions investigated will require the correct choice of cutting fluid and its application system in order to ensure that the required surface quality is achieved. An increase in feed rate will increase the surface roughness values, hence deteriorating the machined surfaces.

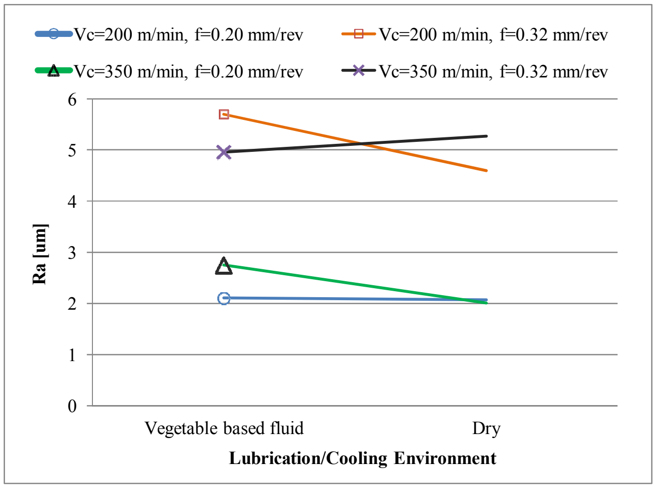


Figure 5. Surface finish recorded after turning SAE 1050 steel in different lubrication/cooling environments.

4. CONCLUSIONS

The following conclusions can be drawn from this study:

- Machining SAE 1050 steel with coated cemented carbides in presence of vegetable-based fluid (Boron, Chlorine and Nitrite free) delivered by MQL technique exhibited at least, if not superior to, equal performance in terms of tool life and failure modes, compared to dry machining, mainly at heavy machining conditions, probably to the optimal tribological conditions combination between lubricity of such oils and overall performance of MQL technique under the conditions investigated.
- Wear modes and mechanisms are very sensitive to changes in either speed and feed rate parameters when machining with vegetable-based oil under the conditions investigated.
- Inserts after machining under dry condition at the highest speed of 350m/min experienced intense plastic deformation. Chipping of cutting edge was observed in some tools as result of higher temperatures generated in the cutting zone, indicating that dry condition can not be recommendable, in terms of wear mode, for such workpiece material under the conditions investigated.
- Lower surface finish results were obtained after machining at the lowest feed rates. Negligible effects of cooling environment in finishing were observed.

5. ACKNOWLEDGEMENTS

The authors are grateful to the Brazilian foundations CAPES, CNPq and FAPEMIG for sponsoring this work. Authors also thank the CAPES-PROEX of Post-Graduate Program of Mechanical Engineering of UFU for financial support.

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