Green manufacturing by using organic cooling-lubrication fluids

B Arsene¹, G Pasca Pascariu¹*, F A Sarbu¹, M Barbu¹ and G Calefariu¹

¹ Department of Engineering and Industrial Management, Transilvania University of Brasov, Brasov, 500174, Romania

*E-mail: arsene.bogdan@unitbv.ro

Abstract. The global competition and trends force the manufacturing industry players to permanently innovate, reduce costs and become more environmentally friendly, thus the pressure for eco-friendly, sustainable and more reliable products is rising. The environmental concerns have begun to be increasingly included in sustainable development strategies of the companies since the effects of worldwide pollution have become more and more visible. In manufacturing industry, in machining units, the cutting fluids are an important source of expenses and they can also be a threat for environment and employee’s health. This paper presents a study regarding the possibility of replacing the traditional flood cooling in hard turning with minimal quantity lubrication using vegetable biodegradable oils since the scientific community has brought many contributions to the phenomenon of replacing grinding with hard turning. The capability of hard turning to replace grinding in many industrial applications is proved and thus the elimination of harmful coolant and transition to biodegradable cutting fluids seems to be the way of the future in machining.

1. Introduction

The environmental concerns have begun to be increasingly included in sustainable development strategies of the companies. Nowadays, machining processes constantly meet cost pressure and high quality expectations [1], thus to minimize the environmental hazards due to industries a new approach in manufacturing is necessary i.e. green manufacturing, which is a key element under the overarching umbrella of sustainability [2, 3]. According to Maruthi&Rashmi “Green Manufacturing is a philosophy rather than a standard or a process” which aims “to minimize waste and pollution through product and process design” having as main goal the sustainability [4].

In the effort to achieve and implement sustainable manufacturing, the companies understand that sustainability is an important strategy for business environment i.e. saving resources (energy, raw material etc.), alignment with legal regulations and customer demands, and obtaining competitive advantage, which may lead to innovation in manufacturing [5]. Thus, the transition to green manufacturing is not only helpful for environment, it is helpful also for business [2].

Green manufacturing refers to methods and techniques to reduce the costs and environmental impact [6], to create safe and clean work-places [1], to reduce harmful emissions, to minimize or eliminate wasteful resources consumption and to recycle as much as possible [2, 4]. In manufacturing, the machining process is a major resource consumer, thus, the concerns and future research in green manufacturing regarding machining processes shall be focused on the main elements which lead to
green and sustainable machining e.g. energy-efficient machine-tool, recyclable cutting tools and biodegradable cutting fluids, to achieve green production and eco-innovation, as they are presented in figure 1.

**Figure 1. Green resources for green & sustainable machining.**

For many years, manufactures are using different green machining strategies to respond to high pressures for sustainability, which include process time minimizing, optimizing the energy consumption and different actions to save oil, water, raw material and energy [7]. Green machining is an approach which doesn’t use traditional cooling system, since the coolants have some unhealthy and dangerous chemical substances e.g. biocide to control the microbial growth [8]. The traditional method used in machining for cooling, i.e. flood cooling, has some important disadvantages e.g. it is harmful both for environment and workers due to chemical content of MWF such as chlorine, sulfur and phosphorus which are harmful and cause environmental pollution [9], it can cause serious ecological damage, it requires proper infrastructure (e.g. for storing, pumping, transport, reclamation, filtration and waste-water treatment) [1, 6], it demands continuous monitoring and treatment of the coolant to avoid fungal and bacterial growth [6] and it represents over 10% of the machining cost [1, 2, 6, 10]. Sivarajan&Padmanabhan [1] reported that 16 – 20 % of the manufacturing costs in metal cutting industries are represented by CF and lubricants, while Xiao&Zhang [9] stated that 15 –30% of the machining cost, for a manufacturer from the automotive industry, consists in the use of grinding fluid. On the other hand, Tai et.al. [6] claimed that within powertrain operations, the cost of MWF is about 10-17% of the total manufacturing cost and Elmunafi et.al.[10] indicated that the cost for coolant use and handling can be about 17% of the overall production costs. These issues led to new approaches in machining e.g. nearly dry machining (NDM), cryogenic machining and dry machining. All these approaches are in agreement with the green machining requirements. The nearly dry machining methods consist in minimal quantity lubrication (MQL) and minimal fluid application (MFA). An overview of approaches for cooling in machining, i.e. in turning, is presented in figure 2 [11, 12].

**Figure 2. Cooling approaches in turning [11, 12].**
2. Traditional cooling vs. MQL

In many machining units, the conventional coolant is still considered an essential factor in machining, "a necessary evil" [1], since it helps reduce friction, cutting temperature, thermal expansion of workpiece, fixture, and machine, remove chips [1, 6] and prevent adhesion between tool and chip, with impact in obtaining a stable machining process, a high-quality surface and a longer tool life [1]. Nevertheless, the elimination of harmful coolant, i.e. transition to biodegradable and environmental friendly CF and the wide implementation of MQL is the future in machining.

According to [13] the MQL technique was proposed a decade ago “as a mean for addressing the issues of environmental intrusiveness and occupational hazard associated with airborne cutting fluid particles”. MQL is an ecological alternative to traditional cooling systems (e.g. flooding the work-piece) [2, 6] used in machining to acquire cooling and lubrication during processes, which consists in spraying directly into the cutting zone through nozzles of a small amount of oil or metal working fluid (MWF) based on compressed air [2, 6], at a low rate of 10 – 200 mL/h [6, 10, 14]. This method has shown in the last 10-15 years numerous advantages in comparison with flood cooling, e.g. significant savings in CF, energy and equipment costs, it consumes less energy, it offers a high flexibility to relocate the machines, it reduces ecological hazards, it provides a healthier and cleaner work-place, it reduces greenhouse gas emission, and ensures better quality of products and higher productivity [2, 6], with effects in cost optimization and competitiveness increase.

One of the first applications of MQL in hard turning was designed by Ko et.al. [15] that developed an air-oil mix cooling system to provide cooling and lubrication effects concurrently when hard turning AISI 52100 (62-64 HRC) steel. They have used several types of inserts e.g. coated tungsten carbides inserts, cermet-based inserts and CBN inserts. First, they have found that the coolant should be ejected on the rake and clearance faces, since the higher temperature was located in these zones rather than in other zones. The highest temperature was observed on the rake face. Second, they have found that this system provides better results in terms of Ra roughness, radial force and tool wear comparative to dry, flood and air-jet cooling when turning hard material with TIN coated carbide inserts due to the simultaneous reduction of temperature and friction by the mist coolant. Obviously, the carbide inserted tool life was shorter than cermet and CBN inserts, but the most important conclusion of the study is that the proposed method i.e. air-oil mix cooling is superior and more suitable than the rest of methods.

This technique was studied in machining by various authors on different types of oils. The most environment friendly oils used in experiments are vegetable oils e.g. castor oil [16, 17], coconut oil [18-23], sunflower oil [16, 22, 24-27], soya bean oil [22, 27-29], palm oil [19, 30-32] and canola oil [16, 20, 21, 25, 26]. The outcomes have shown improvements in terms of tool wear, tool life, cutting and feed forces and surface roughness (Ra) compared to dry machining or flood cooling and according to [22] the performance of the vegetable oil which is superior to mineral-based oils. Vegetable oils have the status of environmental friendliness regarding biodegradability, resource renewability and cutting process efficiency [10], they are less toxic and decrease the waste treatment cost due to their great biodegradability [25] and according to [33] they are considered “as viable alternative to petroleum-based fluids“ due to the following reasons:

- the nature and structure of the molecules create a strong and dense homogeneous lubricating film with high capacity to absorb pressure [33, 34];
- the vegetable oil lubricating film is intrinsically strong and lubricious and improves quality of the products, it reduces frictions and reduces heat generation [25, 33, 34];
- the high boiling point and major molecular weight ensure less losses from vaporization and misting [33];
- vegetable oils have a high flash point, thus the risk of fire hazards is lower and of smoke formation is reduced [33-35];
- vegetable oils are environmentally friendly, they do not cause health issues [33] and they have high biodegradability [35];
- vegetable oils are compatibility with additives [35];
• vegetable oils have a high viscosity index which provides a stable lubricity [34, 35];

Another technique named Minimal Fluid Application (MFA) or Minimal Cutting Fluid Application (MFCA) was developed by Varadarajan et.al [36]. The proposed solution contains in a fuel pump coupled to an infinitely variable electric drive which generates and sends high velocity pulsing jet of cutting fluid on tool-part interface. The main advantage of this system is that it facilitates the independent variation of the injection pressure, frequency of pulsing and the rate of application of cutting fluid [36-38]. Also, the system can deliver fluid at a flow rate of 0.5 ml/min (i.e. 30 ml/h) through six nozzles simultaneously [36]. Some pieces of research [38, 39] have shown that MCFA technique provides better results than MQL in terms of surface roughness and cutting temperature at soft turning of steel with 45 HRC hardness.

3. Current researches in MQL machining on vegetable oils

3.1. Soft machining on vegetable oils as cooling-lubrication fluids

In soft machining there are several papers which aim at the use of vegetable oil as cooling-lubrication fluid. Belluco & De Chiffre [40] studied the drilling AISI 316L austenitic stainless with high speed steel (HSS) having as CF a mineral oil-based and a mixture based on rapeseed oil with an amount of sulfur and phosphor containing additives. The experiments indicated that the vegetable-based oils produced better results than mineral oil (MO) regarding tool life (177% increase) and thrust force (7% reduction). On the other hand, Rahim & Sasahara [30] describe the drilling of titanium alloy Ti–6Al–4V with an indexable carbide drill. The palm oil and synthetic ester was selected as CF. MQL on palm oil produced lower thrust force, torque, workpiece temperatures, flank wear and corner wear compared with MQL on synthetic ester and flood cooling. Similar results were obtained in another study of the same authors [31] when drilling Inconel 718. Kuram et.al. [24] presented the end milling of AISI 304 on vegetable CF as sunflower and canola oils with 8% lubricating additive (sulphur based additive) and commercial semi-synthetic CF. The outcomes have shown better results regarding specific energy (J/mm3) and surface roughness for canola oils. From the experiments of Pereira et. al. [16] who studied the end milling of heat resistant super-alloy (HRSA) Inconel 718 using different types of vegetable lubricating fluids e.g. sunflower oils, castor oil, canola oil and a recycled oil, we know that the highest tool life was achieved by using canola oil and recycled oil and the lower friction coefficient was obtained when on castor oil.

Regarding the turning of materials, Elmunafì et.al [17] studied the turning of AISI 420 stainless steel (47-48 HRC) on castor oil at a flow rate of 50 mL/h and 5 bar air pressure, to observe the influence of cutting parameters on tool life, surface roughness and cutting forces. Their observations revealed that vegetable oil is superior to dry hard turning since the tool life was much higher due to reduction in friction and temperature in cutting zone, and the surface roughness and cutting forces enhanced slightly. Raj et. al. [28] conducted experiments on turning (MFA) of AISI 4340 (45 HRC) using soya bean and MO as lubrication fluid in order to identify the dynamic of cutting force. The cooling parameters were set on three levels and for oil pressure, oil quantity and frequency of pulsating the values were 50 bar, 75 bar and 100 bar, 3ml/min, 6ml/min and 9ml/min, respectively 250, 500 şi 750 pulses/min. The result have shown that the use of MFA technique on soya bean oil provided the minimum value of cutting force compared to flood cooling (soya bean or MO) and dry cutting, regarding MFA, the highest oil rate and pressure provided the lowest cutting force. Xavior & Adithan [18] evaluated the influence of cutting fluids on tool wear and surface roughness, using coconut oil, soluble oil and straight cutting oil, in turning of AISI 304. In general, coconut oil was found to be a better cutting fluid than the conventional mineral oils and according to ANOVA it is the second influencing factor after feed rate on surface roughness. Some authors dealt with turning of AISI 1040 (32 HRC) using conventional CF and vegetable oil based nano cutting fluids, at a flow rate of 10 mL/min [19-21]. Vamsi Krishna et.al. [19] studied the machining on coconut oil and synthetic oil prepared with solid nanoboric acid particles (50 nm) in different percentage (0.25%, 0.5% and 1%). Thermal conductivity increased and specific heat decreased with percentage increase in nanoboric acid.
in base oil. The coconut oil showed better performance compared to synthetic oil in terms of cutting temperatures, tool flank wear and surface roughness and in all cases the palm oil with 0.5% suspensions was superior. On the other hand, Padmini et.al. [20, 21] investigated the machining on canola, sesame and coconut oil prepared by dispersing nano-suspensions of molybdenum disulphide (MoS2) with the same nano-particle inclusion (NPI-%) i.e. 0.25, 0.5 and 1. The coconut oil with 0.5% MoS2 leads to lowest cutting force, lowest cutting temperatures, lowest tool wear and best surface roughness compared to all other lubricating conditions.

Cetin et.al. [25] and Ozcelik et.al. [26] investigated the turning of AISI 304L (32 HRC) stainless steel on two types of vegetable oil (canola and sunflower), a commercial mineral based CF and a commercial semi-synthetic CF. The vegetable oils were prepared with 8% and 12% extreme pressure (EP) chemical additives, whose functions refer to corrosion prevention, pH regulation, anti-foaming and improving the flash point. In [25] polysorbate (Tween 85 and Tween 20) was used as additive and in [26] sulfur based EP additive (Polartech XP 9018) was used. From [25] we know that higher rate (12%) of EP additives provide better performance in terms of forces (cutting and feed) and affects negatively the surface roughness due to chemical interaction with the machined surface. Anyway, the vegetable oils are superior to mineral and semi-synthetic CF. Ozcelik et.al. [26] indicated that canola oil with 8% and 12% extreme pressure chemical additives gave the best performance regarding surface roughness, feed forces and tool wears. Ghuge & Mahalle [22] investigated the soft turning of AISI 4130 dry, flood and MQL (50mL/h) using 5 types of oils, one mineral and four vegetable (soya beam, coconut, sunflower and groundnut). The cutting temperature was reduced by 18% in case of MQL compared with dry and 5% compared to flood. Regarding the oils, soya beam oil provides better results than the others in terms of cutting forces and roughness. In another study, [27], the same authors evaluated the cutting force and power consumption at turning of the same steel, using soya beam, sunflower and MO. As in the previous study, soya beam oil provided the best result i.e. 9% reduction in cutting force and power consumed compared with MO and an average of 7% compared to sunflower oil.

A summary of the parts considered in the research, performed in soft machining by replacing flood cooling with vegetable oils is presented in table 1.

| Machining operation | Type of oil | Materials | References |
|---------------------|-------------|-----------|------------|
| Drilling            | Palm and rapeseed /canola | AISI 316L, Ti–6Al–4V, Inconel 718 | [30,31,40] |
| Milling             | Sunflower, castor and canola | Inconel 718, AISI 304 | [16,24] |
| Turning             | Castor, soya bean, coconut, canola, palm, sesame, sunflower, groundnut | AISI 420, AISI 4340, AISI 304, AISI 1040, AISI 304L, AISI 431 | [17-22, 25-27, 28, 32] |

3.2. Hard machining on vegetable oils as cooling-lubrication fluids

Since the scientific community has brought many contributions to the phenomenon of replacing grinding with hard turning and the capability is proved, the elimination of flood cooling and the transition to MQL or MFA on vegetable oil is the next step for hard turning. Even if, the literature presents lots of papers regarding soft machining (e.g. soft turning) on vegetable oils as cooling-lubrication fluids, there is a lack of papers regarding hard turning of materials with hardness higher than 55 HRC.

Chinchanikaret.al. [23] studied the hard turning of AISI 52100 (60-62 HRC) under dry condition and on two different types of coolant, a milky emulsion (composed of water and soluble cutting oil) and vegetable oil (coconut oil). The outcomes have shown that at high speed rate (over 160 m/min) and high depth of cut (over 0.35 mm) the coconut oil has provided better surface finish in terms of roughness compared to the other two. This result indicates that using vegetable oil is the most suitable
way in order to increase the productivity. Even if the tool wear and cutting force were not considered, the perspective for coconut oil as coolant is real. Gajrani et.al. [41] presented the hard turning of AISI H13 (56 HRC) on a mineral oil-based and a vegetable-based eco-friendly bio-cutting fluid. The techniques chosen were flood cooling and MQL at an air pressure of 0.5 MPa (5 bar) and oil flow rate of 35 mL/h. Compared to flood cooling, MQL produced better results in terms of feed and cutting forces, surface roughness and friction coefficient and regarding MQL CF, the biodegradable fluid performed better than mineral oil-based fluid taking into account the same features and it has shown higher thermal conductivity and better ability to penetrate the chip-tool interface.

Gunjal & Patil [29] conducted experiments on hard turning of AISI 4340 with coated carbide inserts under MQL and dry conditions, on three types of vegetable based oil, namely canola, soya bean and coconut, at a flow rate of 50mL/h and 5 bar pressure. The best results in terms of tool life, tool wear and surface roughness were obtained by the machining on canola oil. Last but not least, Mia et.al. [14] investigated the hard turning of AISI 1060 with hardness 56-60 HRC using olive oil and coated carbide inserts, under MQL at a flow rate of 150 ml/h. Their study focused on the influence of cutting parameters on surface finish characteristics e.g. average surface roughness (Ra), root mean square surface roughness (Rq) and maximum height of surface roughness (Rz) and tool wear e.g. average principal flank wear (VB) and auxiliary principal flank wear (VS). The outcomes indicated that the lowest level of roughness was obtained with the highest cutting parameters, which means that olive oil may be a viable alternative to increase the productivity and reduce costs. Even if the experiments have not indicated the difference between flood or dry hard turning and MQL on olive oil, this study may be the starting point for future research with regard to MQL hard turning on olive oil, due to superior lubrication property.

A summary of the parts considered in the research, performed in hard turning of hardened steels (> 55 HRC) using vegetable oils is presented in table 2:

Table 2. Parts considered in research, performed in hard turning using vegetable oils.

| Reference | Material | Hardness (HRC) | Tool material | Lubricant | Discussion |
|-----------|----------|---------------|---------------|-----------|------------|
| [14]      | C60 (AISI 1060) | 55-60         | • Coated carbide inserts | • olive oil | • olive oil was used in order to identify the effect of cutting parameters on tool wear and surface roughness |
| [23]      | 100Cr6 (AISI 52100) | 60-62         | • PVD TiSiN®-TiAlN® coated carbide inserts | • coconut oil | • coconut oil provided better surface roughness |
| [29]      | 40NiCrMo6 (AISI 4340) | 52-54         | • PVD AlTiN® coated carbide inserts | • coconut oil • canola oil • soyabean | • canola oil performed better than soya bean and coconut oils in terms of tool life, tool wear and surface roughness |
| [41]      | X40CrMoV5 (AISI H13) | 56            | • TiN® coated carbide insert | • vegetable-based eco-friendly bio-CF | • biodegradable CF performed better than mineral oil-based in terms of feed and cutting forces, surface roughness, friction coefficient and thermal conductivity |

*pPhysical Vapor Deposition;  
*TiSiN - Titanium Silicon Nitride;  
*Titanium Aluminium Nitride;  
*Aluminium Titan Nitride;  
*Titanium Nitride.
As it can be seen, there is a lack of research regarding MQL hard turning on vegetable oil. Whether the outcomes of future work are similar or better than the result from soft machining e.g. reduction in cutting force, thus the perspective of HT forecast reduction or productivity increase seems to be real. From the fundamentals of machining we know that the cutting power (Pc - kW) depends largely on the cutting speed (Vc) and on the main cutting force (Fc). Thus, the energy consumed (kWh) depends mainly on these two parameters. As well, the tool wear (flank and crater) is influenced by Vc and Fc. In this way, the perspective for HT on vegetable oil as cooling-lubrication fluid is presented in table 3.

Table 3. Perspectives of HT on vegetable oil as BCF using MQL technique.

| Reduction in Fc & Constant Vc | Decrease of energy consumption i.e. lower energy cost, lower tool wear, higher tool life and lower tool cost |
|-------------------------------|----------------------------------------------------------------------------------|
| Reduction in Fc & Increase of Vc | Constant energy consumption & increase of productivity |

4. Conclusions and further work
The transition to eco-friendly CF is necessary to ensure a sustainable and greener manufacturing and machining, more safety and cleaner workplaces, in order to enhance the competitiveness and to gain the technology competitive advantage.

The vegetable oils seem to be a real, viable and cheap option to replace traditional flood cooling in many industrial application, since the outcomes proved that this types of cooling-lubricating fluids yield better performance in terms of roughness, cutting force, power consumption, tool wear and specific energy. Even if, the literature presents lots of paper regarding soft machining (e.g. soft turning, drilling and milling) on vegetable oils as cooling-lubrication fluids, there is a lack of papers regarding hard turning of materials with hardness higher than 55 HRC, in order to replace grinding in an eco-efficient way. Thus, further research shall be focused in this direction, using ceramic and CBN inserts with wider geometry and different types of vegetable oils, applying MQL, in order to investigate the surface characteristics (e.g. micro-hardness, white layers, residual stress and surface roughness), tool wear, power consumption and process costs.

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