Analysis of the turning efficiency of the Cu-Ni 70/30 ASTM B122 alloy under minimum quantity of lubricant conditions

E García1,2, V Miguel1,2*, A Martínez2, M C Manjabacas1,2 and J Coello1,2

1 High Technical School of Industrial Engineers of Albacete, University of Castilla-La Mancha, 02071 Albacete, Spain
2 Regional Development Institute, Science and Engineering of Materials, University of Castilla-La Mancha, 02071 Albacete, Spain

*Corresponding author: valentin.miguel@uclm.es

Abstract: Traditional flood lubrication on machining processes involves a severe environmental risk due to the high quantity of contaminant that is deposited on the atmosphere. For this reason, the search of more sustainable lubrication methods is necessary. This paper analyses the minimum quantity of lubricant (MQL) procedure on the turning of copper-nickel ASTM B122 alloy in terms of cutting forces and surface integrity in comparison to dry cutting, using two different cutting oils: a synthetic vegetable oil and a synthetic mineral one. The aim is to find out the lower limit of cutting oil flow rate needed to improve the cutting condition. The results show that MQL conditions improve the efficiency of the turning process of this alloy, being effective in cutting force reduction and limiting the surface adhesions and defects. Besides, vegetable oil performance is better than mineral one. It has been found that flow rate needed depends on the depth of cut.

Keywords: Turning, Sustainable machining, MQL, Copper-nickel alloys, Cutting forces.

1. Introduction
In recent years, concerns about environmental problems and pollution have promoted the search for new sustainable lubrication and cooling solutions for traditional machining processes [1]. The use of high quantities of cutting oil in traditional flood lubrication poses a risk to human’s health due to the chemical components that are thrown into the atmosphere. Besides, coolants represent up to 17% of machining costs [2] and they are not completely efficient in the reduction of tool wear or heat generation [3].

Dry machining has been introduced as an environmentally friendly option, by avoiding the use of lubricants and oils. Nevertheless, for some materials and machining conditions, dry cutting cannot be considered as a solution due to the lack of effective lubrication and cooling. It is known that cutting temperature is one of the most determinant factors in tool wear [4] control and in material adhesion processes. The cutting temperature should be maintained below the thermal softening temperature of tool material, decreasing thermally-induced tool wear mechanisms and diffusion process [5]. Besides, high cutting temperatures can promote the appearance of residual stresses in the machining part. For those reasons, dry machining does not show good performance when machining difficult-to-cut materials.

Different solutions have been proposed in order to improve the efficiency of the machining processes without the use of abundant quantities of cutting oils. Cryogenic lubrication with liquid nitrogen, LN2,
or gaseous CO2 focuses on providing an effective cooling action. The objective of this approach is to reduce the cutting temperature to decrease the tool wear. However, the efficiency of this technique is not clear yet and its use in industry is limited. It requires specific equipment, and the high cost of liquid nitrogen reduces the applicability in industrial field [6].

Minimum quantity of lubricant, MQL, offers a new different approach. The aim of this technique is the reduction of friction during the turning process by providing an effective lubrication with a very low quantity of oil, therefore, this process is not focused on the cooling action [7], i.e., the reduction of friction between tool and chip can diminish considerably the cutting temperature, what means an important advantage. The mixture of cutting oil and air is bombarded directly to the rake face of the tool, ensuring that the lubricant achieves the cutting zone. As several liters of oil per hour are used in flooded lubrication, only a few milliliters are used in MQL. It supposes a high reduction in the environmental impact. Besides, vegetal biodegradable oils are commonly used for this purpose [8,9]. MQL systems are finding their place in the industry because of their low cost. Besides, it can be assured that only an initial investment is needed for the equipment.

However, more research must be done to improve the applicability and efficiency of these sustainable techniques for different materials under different cutting conditions [10].

In this paper, MQL technique is evaluated for the turning process of copper-nickel 70/30 ASTM B122 alloy in terms of cutting forces and surface integrity of the machined parts in comparison to dry cutting. Cu-Ni 70/30 alloy is widely used in marine and naval applications, such as ship piping and pump bodies due to its excellent corrosion resistance [11]. Nevertheless, it is known that there is a lack of information in order to analyze the efficient machining process of this alloy.

The high thermal conductivity of copper facilitates the heating of the machined part during the cutting process, increasing the thermal softening of the alloy, what results in increasing the coefficient of friction between tool and chip, and promoting the adhesions on the part surface [12], mostly when the cutting speed is higher. Dry cutting is enough to perform the turning process at 40 m/min of cutting speed, but when it is doubled to 80 m/min, several adhesions and defects take place in the machined part surface.

This study pretends to analyze the effectiveness of MQL at 80 m/min of cutting speed, comparing a synthetic vegetal oil and a synthetic mineral one for some combinations of pulse frequency and volume of oil per pulse, and establishing the minimum flow rate needed to perform the machining process in a stable way.

**Figure 1.** Nozzle position for MQL tests.
2. Experimental setup

Cu-Ni 70/30 ASTM B122 alloy, table 1, was turned under cutting speed of 80 m/min, 0.5 mm of depth of cut and 0.1 mm/rev of feed rate. The cutting speed has been established according to previous studies [13]. Dry and MQL were selected as environmental conditions and two cutting oils were tested, whose characteristics are shown in table 2. The degradation temperature of the oils was obtained by a thermal analysis. MQL tests were carried out by using the specific equipment Lubrimat L60 with an air pressure of 4 bar, atomizing the cutting oil directly to the rake face of the tool, figure 1. To analyse the MQL flow rate influence, different combinations of pulse frequency and an atomized oil volume per pulse were selected as shown in table 3, obtaining a range of flow rate from 6.5 ml/h to 64 ml/h, what includes the industrial application typical range.

| Table 1. Composition of Cu-Ni 70/30 ASTM B122 alloy (wt%). |
| Cu | Ni | Fe | Mn | Zn | Pb |
| 70% | 29-30% | 0.4-1% | max 1% | max 1% | max 0.05% |

To carry out the experimental tests, a semi-automatic Microcut H-2160 lathe of 10 kW with maximum spindle speed of 2000 rpm was used. A variable frequency drive was installed to keep the cutting speed constant for any diameter of the cylinder. TNMG 160408-MM2025 with MTJNR 2525M from Sandvik Coromant were chosen as cutting insert and tool holder. The cutting insert consisted of a 0.8 mm nose radius cemented carbide tool coated by TiCN + Al₂O₃+ TiN CVD.

| Oil Type | Density (g/cm³) | Viscosity (cSt) | Degradation Temperature (ºC) |
|----------|----------------|----------------|-------------------------------|
| Lubrimax Edel C Synthetic vegetable | 0.93 | 43 | 200 |
| Wd-40 Specialist Synthetic mineral | 0.81 | 22 | 150 |

| Table 3. MQL flow rate for different settings combination, Q = F · V (ml/h). |
| Frequency, F (pulse/min) | Oil volume per pulse, V (ml/pulse) |
|--------------------------|----------------------------------|
|                           | 0.004 | 0.016 | 0.028 |
| 27                       | 6.5   | 26    | 45    |
| 38                       | 10    | 36.5  | 64    |

The cutting forces were registered by using a three-axes dynamometer built by the research team, equipped with four strain-gages load cells and statically calibrated. To evaluate the surface integrity a three-dimensional roughness profilometer FormTalysurf50 by Taylor-Hobson was used. The arithmetic average roughness for a 5 x 4 mm² area of the machined part was obtained. This result was carried out after the application of a 0.8 mm Gaussian filter to remove the waviness component from the measured profile. Besides, to obtain a completed view of the cylinder, Talyrond 131C roundness machine was utilized.

With the aim of analyzing the effect of the cutting depth on the tested results, some additional experiments were developed with a cutting depth of 0.25 mm under dry and MQL with vegetal oil.

3. Results and discussion

Figure 2(a) shows the cutting forces evolution with regard to the flow rate of vegetal oil when turning at 80 m/min of cutting speed, 0.1 mm/rev of feed rate and 0.50 mm of depth of cut. Dry cutting is described by a flow rate of 0 ml/h. It is observed that the tangential force is the most important component, reaching the greatest values, three times higher than axial and radial components.
The application of low quantities of vegetal oil seems to be effective in the reduction of the cutting forces in comparison with dry machining. The reduction of the coefficient of friction, CoF, in the cutting zone and in the interface tool-chip diminishes the friction forces contribution to the total cutting forces. The experimental results throw that the increment of oil flow rate allows the cutting forces to be reduced. This could be explained according to the highest number of drops that reach the cutting zone. There is a directly proportional relationship between the tangential and axial components of the cutting force and the flow rate. Besides, the radial component experiments a noticeable reduction under MQL condition with only a flow rate of 6.5 ml/h. Greater MQL flow rates hardly reduce the radial force.

It is remarkable that, with a flow rate of only 6.5 ml/h, the tangential and axial forces are reduced by a 6% and radial force by a 30%, while for the maximum flow rate of 64 ml/h experimented herein, the tangential, axial and radial components decrease by a 20%, 32% and 40%, respectively. Although the most important change occurs in the range from 0 to 6.5 ml/h, no intermediate values could be considered because 6.5 ml/h is the minimum flow rate that can be obtained with the MQL device under controlled conditions.

Figure 2. Cutting forces evolution against flow rate of (a) vegetal oil and (b) mineral oil at 0.50 mm depth of cut.

Figure 2(b) shows the cutting forces evolution under MQL tests with synthetic mineral oil in comparison with dry machining (flow rate of 0 ml/h). In this case, the cutting forces do not follow a linear tendency with the flow rate, although they are reduced compared to dry cutting. The minimum value for the 110 N tangential forces is reached with a flow rate of 36.5 ml/h and not with the maximum flow rate experimented. The same statement can be applied to the axial and radial components, what means that the increase of the amount of oil does not always improve the cutting conditions.

Comparatively, synthetic vegetal oil shows a better efficiency than mineral one in the reduction of cutting forces. Besides, during the experimental tests it was observed that the mineral oil was degraded. Probably, the lubrication effect of the mineral oil is not effective enough in the reduction of friction coefficient and the heating phenomenon is augmented. Thus, the cutting temperature achieved during the process is high enough to reach the degradation temperature of the mineral oil losing its lubrication properties, resulting in a worsening of the cutting process.

Figure 3 shows the cutting forces vs MQL flow rate for 0.25 mm depth of cut with vegetal oil. An appreciable drop of the forces values is observed from dry machining (0 ml/h) to the flow rate of 6.5 ml/h. The tangential force decreases about 13% and the axial component about 42%. The cutting forces remain stable with the increment of the oil flow rate, which means that a low flow rate is enough to ensure the best machining conditions.
The previous observation could be explained according to the cutting temperature. It was observed that the temperature increment for 0.25 mm depth of cut was not as high as for 0.50 mm. It means that the CoF does not rise in the same ratio as for 0.50 mm and the flow rate of 6.5 ml/h is enough to provide an effective lubrication action between the chip and the tool, reducing the cutting forces.

Besides, the chip section for a 0.25 mm depth of cut is smaller and the contact between chip and tool is minor, making easier for the oil droplets to reach the cutting zone and form an effective oil film.

**Figure 3.** Cutting forces for MQL tests with vegetal oil and 0.25 mm depth of cut.

**Figure 4.** Surface detail of the machined cylinders under: (a) dry and (b) MQL with vegetal oil.

Figure 4 shows the cylinders surface measured by a roundness machine and a detail of the roughness registered by a contact profilometer under dry and MQL conditions. The surface finish is improved with a little quantity of oil and the number of surface defects and adhesions is dramatically reduced. When machining at 80 m/min, the high cutting temperature and the softening of the material produce a strong increase of the CoF without lubrication, increasing the adhesion phenomenon and the material dragging on the machined surface. MQL is efficient in the CoF reduction, avoiding the adhesions and allowing the chip to be easily removed.
Besides, the CoF decrease leads to a reduction on the vibration phenomena and the cutting process is more stable and uniform. This can be appreciated according to the cylindricity tolerance, CT, of the machined parts, figure 4. The CT value for dry machining is 213 µm, so much higher than the average value of 44 µm for MQL tests. The CT is non-flow rate dependent.

![Figure 5. Surface roughness parameters against flow rate of (a) vegetal oil and (b) mineral oil at 0.50 mm depth of cut.](image)

Figure 5 shows the experimental results for Ra and Rz under dry and MQL conditions. It is observed that the surface roughness of the machined parts improves with MQL technique, and the results are independent on the flow rate. Particularly, Ra value undergoes an improvement of 50% with respect to dry machining if MQL is used, no matter the type of oil considered. On the other hand, Rz values are reduced by 65% under MQL conditions.

![Figure 6. Surface roughness parameters against flow rate of vegetal oil at 0.25 mm depth of cut.](image)

From the experimental results, it is concluded that a quantity of lubricant of 6.5 ml/h, that corresponds to the minimum flow rate experimented, is enough to achieve the lowest values of Ra and Rz, leading to a surface integrity similar to that obtained for 64 ml/h. Thus, it represents an oil saving of 90%.
Similar results are found for 0.25 mm depth of cut tests, figure 6. The minimum flow rate of 6.5 ml/h is enough to drastically improve the surface roughness of the machined parts. Ra and Rz parameters decrease above 70%.

4. Conclusions
Minimum quantity of lubrication technique has been tested on the turning process of Cu-Ni 70/30 alloy at a cutting speed of 80 m/min. Surface integrity and cutting forces have been evaluated in order to find the most stable and efficient cutting conditions. The following conclusions can be drawn from the experimental tests:

- MQL conditions always enhances the machining performance of the Cu-Ni alloy, reducing the cutting forces and improving the surface integrity of the machined parts in comparison with dry cutting. Nevertheless, it has been found that the flow rate needed to get the best performance depends on the depth of cut.
- The synthetic vegetal oil tested shows better results than the mineral one. The cutting temperatures reached in the cutting zone are higher than the degradation temperature of the mineral oil losing its lubricant properties.
- Under MQL with vegetal oil, the cutting forces decrease with the increment of the oil flow rate, reaching the minimum for 64 ml/h. In this condition a reduction of 20% is found for the tangential component.
- MQL strongly enhances the surface integrity of the machined parts, avoiding adhesions and dragging material, always observed under dry condition. The 6.5 ml/h rate is enough to get a reduction of 50% on arithmetic average roughness values when machining with a 0.50 mm cutting depth.
- The reduction of the depth of cut to 0.25 mm, decreases the cutting temperature and a 6.5 ml/h flow rate is enough to obtain the lowest values of cutting forces along with the surface roughness.

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