

COB-2023-1710

BEYOND TRADITIONAL MACHINING: AN ECO-FRIENDLY ASSESSMENT OF ABNT 1045 STEEL SURFACE INTEGRITY USING ENVIRONMENTALLY SUSTAINABLE CUTTING FLUIDS

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Abstract. Several attempts to find sustainable manufacturing methods led us to study the performance of vegetable-based oils as cutting fluids in machining processes. Vegetable-based oils, despite having lower lubricating potential compared to mineral oils, tend to be less harmful to the operator's health and are more biodegradable. The roughness generated by the tool during chip removal significantly affects friction properties, surface wear, heat transmission, mechanical strength, fatigue, and fluid transport. Cutting speed, feed rate, depth of cut, cutting forces, workpiece material characteristics, and tool properties directly affect the resulting surface integrity of the produced part. Thus, the aim of this study is to investigate the performance of sunflower-based vegetable oil applied as Minimum Quantity Lubrication (MQL) during face milling of ABNT 1045 steel in terms of roughness. The results obtained were compared with the performance of the commercial lubricant LB 2000, also applied in MQL form. Despite the commercial fluid showing better results in reducing roughness signals R_y and R_a , at a speed of 210 m/min, a feed rate of 0.15 mm/tooth, and a cutting depth of 1 mm, it was found that sunflower oil yielded similar results to LB2000, with a 0.13% reduction in R_y roughness.

Keywords: Roughness, Sunflower oil, Minimum Quantity Lubrication, ABNT 1045 steel

1. INTRODUCTION

With the growing concern for the environment and human health in the metal-mechanical industry, the development of techniques and products that offer higher productivity and product quality while maintaining the sustainability of their processes has become essential. It is a fact that in order to maintain high product quality, it is necessary to reduce both the average and maximum roughness, aiming for improved surface characteristics of machined parts (Ferraresi, 2018).

Roughness is the result of irregularities and errors inherent in the cutting process. It can be measured using various parameters, but ISO 3685 (1977) recommends the use of the R_a parameter for final operation analysis. R_a , defined as the average roughness, is calculated by taking the arithmetic mean of the absolute values of the coordinates over the sampling length. R_y , on the other hand, is obtained by measuring the maximum height of the irregularities. Therefore, R_a highlights the overall surface quality of the part, while R_y ensures that there are no elevated peaks that could compromise the functionality of the component (Machado et al., 2018).

Milling is one of the primary machining operations, as characterized by Diniz et al. (2001), involving a tool with cutting edges distributed around a central axis. Material removal is achieved by rotating the tool around its own axis, while the feed motion (both longitudinal and transverse) is generated by the workpiece itself, which is secured on the machine table.

Cutting fluids are used when there is an intention to extend the tool's lifespan, decrease machining forces and power, enhance the finish of the workpiece, facilitate chip removal, and reduce the risk of workpiece distortions (Machado et al., 2018).

Currently, the use of cutting fluids is widely spread in machining processes. This is because the use of these fluids enables achieving higher cutting speeds, prolonging tool life, obtaining greater cutting precision, and improving surface finish. Additionally, machining with cutting fluids generates lower cutting forces compared to dry machining. Up until now, these cutting fluids were predominantly petroleum-based and known for their superior performance. However, it is important to note that these products are highly harmful to the environment and human health. As a result, they contribute to groundwater contamination and the emergence of cancer and skin diseases, leading to a range of environmental consequences (Grzesik, 2008).

Given this issue, researchers have initiated investigations in search of sustainable solutions that could match the performance of mineral-based synthetic fluids. However, achieving such performance with a vegetable-based fluid has proven to be a challenge due to its distinct properties. The choice of the fluid requires the consideration of various factors, such as the type of material to be used, cutting tool speed and material, as well as the type of machine used in the process, ensuring proper machining and resulting in increased tool and equipment durability. Furthermore, this choice should encompass impacts beyond the machining process (Seifert, 2021).

There are three categories of fluids: oil-based (mineral oils, animal oils, and vegetable oils), water-based, and gas-based. Water-based fluids, although widely used in the industry and having good cooling properties, suffer from the problem of corrosives, whereas mineral-based fluids stand out for their high corrosion protection. Due to environmental considerations related to these oils, vegetable-based oils emerge as the most promising alternative. They are known for their high viscosity, flash point, and lubricating capability, as well as being biodegradable (Seifert, 2021).

The main methods of applying cutting fluid in machining are presented in Figure 1, which correspond to 1-a low-pressure jet, 1-b high-pressure application (up to 163 bar), and 1-c atomization, commonly known as Minimum Quantity Lubrication (MQL) (Machado et al., 2018). In addition to the mentioned application methods, there is also dripping, which involves applying the fluid in drops to the area of interest (Silva, 2014).

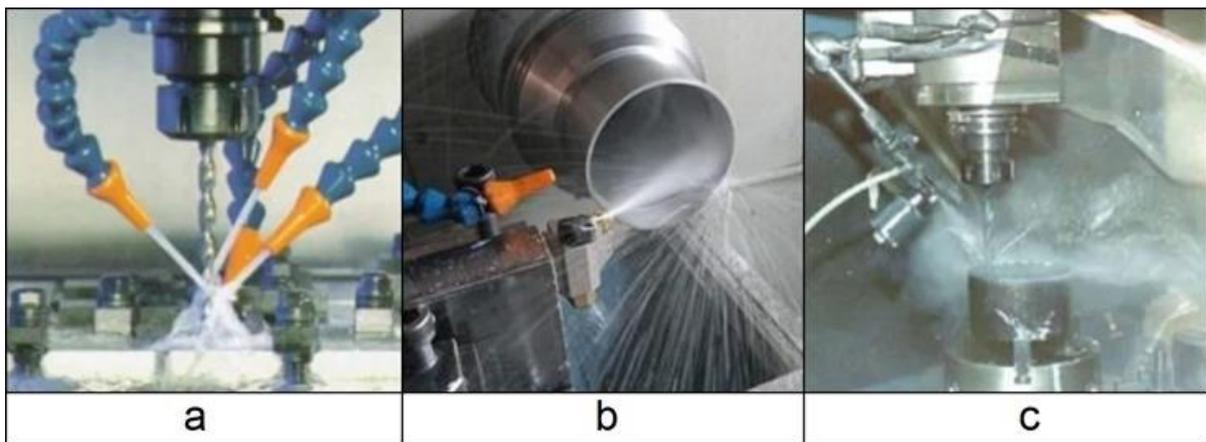


Figure 1. Main Cutting Fluid Application Methods: a) Jet (Souza et al., 2011), b) High Pressure (Santos et al., 2020), c) Minimum Quantity Lubrication (MQL) (Souza et al., 2011).

Per to Ross et al. (2021), the cooling produced by the MQL method has the potential to extend the tool's lifespan and reduce friction in the cutting region. The way it operates involves conveying a small amount of lubricant through a compressed air stream directed to the cutting area. This transport process results in the atomization of the lubricant, ensuring its uniform distribution in the cutting area (Correia, 2006).

According to Wickramasinghe et al. (2020), mineral oil-based fluids can cause skin irritation, respiratory diseases, and cancer in operators. These oils are also less biodegradable and pose difficulties for disposal due to their potential environmental harm. Therefore, vegetable-based oils emerge as a viable alternative to these issues, as they do not carry a high potential for harm to the operator's health or the environment.

As per the research of Wickramasinghe et al. (2020), vegetable oils, particularly when emulsified with water, provide an improved lubrication layer at the workpiece-tool interface. Additionally, the employment of Minimum Quantity Lubrication (MQL) can be regarded as a sustainable fluid application technique.

According to Saleem and Mehmood (2022), vegetable-based oils applied through the MQL method prove to be significant due to their biodegradability, lower toxicity, higher viscosity index, higher flash point, reduced disposal costs, and decreased health risks, all combined with their minimal usage.

The primary objective of this research is to examine the performance of sunflower-based vegetable oil, applied via Minimum Quantity Lubrication (MQL), on the surface integrity of ABNT 1045 steel during face milling. The results were subsequently compared with the performance of the commercial cutting oil, LB 2000, also administered using the MQL method. A flow rate of 50 ml/h was selected as it demonstrated superior cost-effectiveness and efficacy in pre-testing.

2. EXPERIMENTAL METHOD

The carbon steel ABNT 1045 (205 HB) was selected for the experiments due to its high hardness, a parameter that provides a more distinct evidence of roughness in the machined piece. This steel has the following chemical composition: carbon from 0.43 to 0.50%, manganese from 0.60 to 0.90%, phosphorus from 0 to 0.040%, and sulfur from 0 to 0.050% (NBR NM 87:2000).

According to the manufacturer, LB 2000 cutting oil is commonly used with the Minimum Quantity Lubrication (MQL) process and in general machining operations such as drilling and tapping with small diameter threads (less than 15,87 mm), solid saw cutting up to 152,4 mm in diameter, boring operations, and profile rolling. The physical characteristics of the LB 2000 cutting oil and sunflower oil are include at the table 1:

Table 1. Statistical comparison of roughness Ra of sunflower oil in relation to LB 2000 oil (ITW Polymers and Fluids; Moretto and Fett, 1998).

| Oil Type | Density (g/cm ³) | Viscosity (mm ² /s) | Flash Point (°C) |
|---------------|------------------------------|--------------------------------|------------------|
| Sunflower oil | 0.918 | 29.1 | 322 |
| LB2000 | 0.93 | 39 | 204 |

Both fluids were applied at a flow rate of 50 ml/h, a flow rate chosen for its superior performance in pre-tests. For the MQL application, a micro-lubrication device manufactured by ITW chemical, model ACCU-LUBE, was used. The device was configured to operate with a continuous flow of compressed air set at around 6 kg/cm² and intermittent fluid spraying at a frequency of 1 pulse/s.

The machine tool used was the Romi/Bridgeport vertical machining center, model Discovery 560, with GE Siemens 21i-MB CNC control. The spindle has a maximum speed of 7500 rpm, a maximum power of 9193.73 W, and a tool-fixing interface in the machine spindle of the ISO-40 taper type.

The tool employed was a Sandvik Coromant milling cutter with the code 345-08027-13M. The tool diameter is 80 mm and can accommodate six inserts. The insert used has a coating of TiCN + Al₂O₃ + TiN, a square shape, and double-sided inserts with eight cutting edges, code 345R-1305M-PM.

The test involved face milling of test specimens, with dimensions as shown in Figure 2-a. The cutting parameters used were: cutting speed (vc) of 165 and 210 m/min; feed per tooth (fz) of 0.15 and 0.30 mm/tooth; depth of cut (ap) of 1.0 and 2.0 mm; while the tool overhang and cutting penetration (ae) remained constant at 62 mm. Therefore, for each cutting oil, four tests were conducted at a cutting speed of 165m/min and another four tests at a cutting speed of 210m/min.

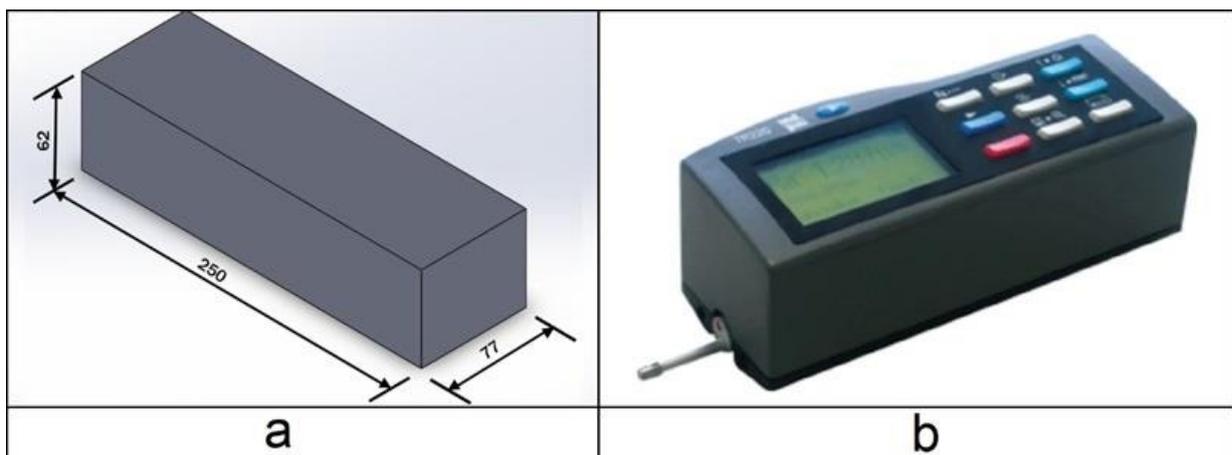


Figure 2. a) Test Specimen with Dimensions 250 x 77 x 62 mm, b) Digital Rugosimeter Model TR 220.

To measure the surface roughness of the test specimen after the test, a digital rugosimeter, model TR 220, manufactured by Time Group Inc., was used. This equipment has a resolution of 0.01 μ m and a cut-off sampling length of 0.8 mm. Roughness was measured five times at different positions on the machined surface, and the device is shown in Figure 2-b.

3. RESULTS AND DISCUSSIONS

Figure 3 illustrates the surface roughness behavior (R_y) when machining with sunflower oil and LB-2000 at a cutting speed of 165 m/min. It is evident that the best result was achieved with sunflower oil compared to the commercial oil under the condition of a 2 mm cutting depth and 0.3 mm/rot feed rate. Under these conditions, the vibration measured was 5.29 mm/s². For the remaining parameters, the commercial oil LB-2000 exhibited lower roughness and superior performance.

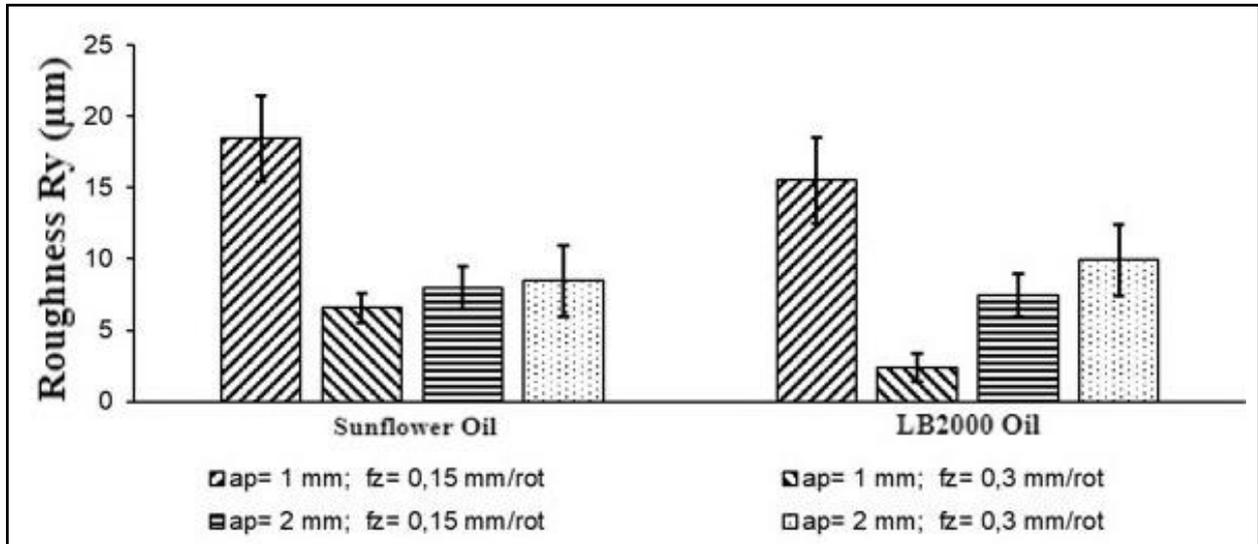


Figure 3. Bar chart with standard deviation for R_y roughness at $v_c = 165$ m/min.

Figure 4 depicts the performance of sunflower oil and LB-2000 concerning surface roughness (R_a) at a cutting speed of 210 m/min. At this cutting speed, the commercial oil LB-2000 demonstrated superior performance, except when used under the condition of a 2 mm cutting depth and cutting feed rates of 0.3 and 0.15 mm/rot.

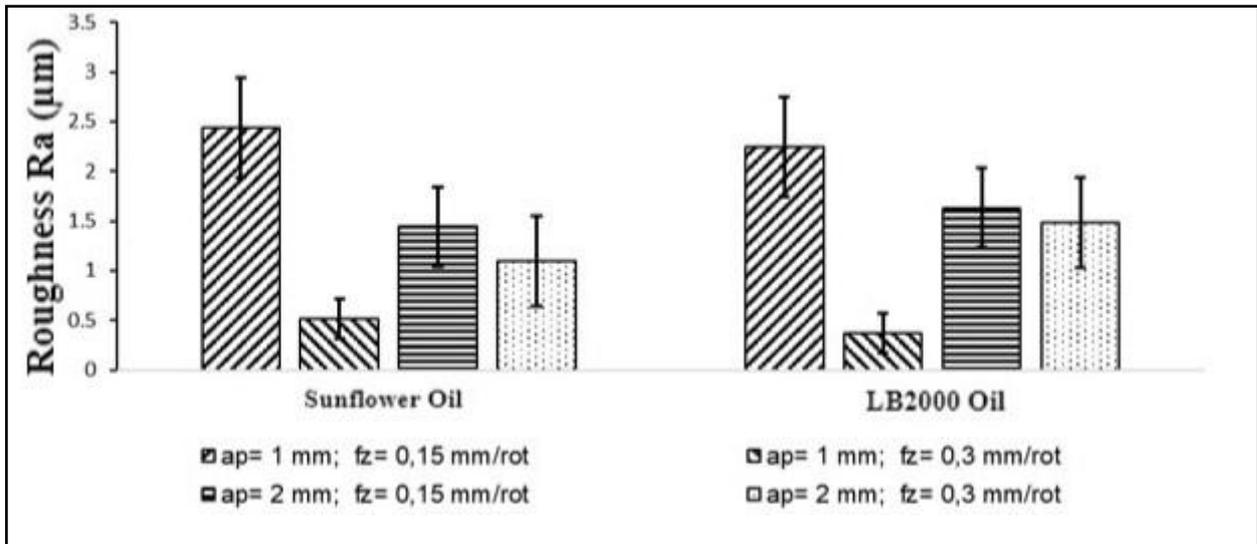


Figure 4. Bar chart with standard deviation for R_a roughness at $v_c = 165$ m/min.

It can be observed in Figure 3 that the lowest roughness values of sunflower oil and LB2000 OIL, both R_y and R_a , occur at a cutting speed of 165 m/min with a feed rate of 0.3 mm/rev and a depth of cut of 1 mm. This is due to the fact that a lower cutting speed, along with a smaller cutting depth, reduces friction, tool wear, and the amount of material removed. Increasing the feed rate leads to more heat dissipation, resulting in an improvement in the surface quality of the machined part.

Figures 5 and 6 also indicate the behavior of roughness R_y and R_a , but now at a cutting speed of 210 m/min.

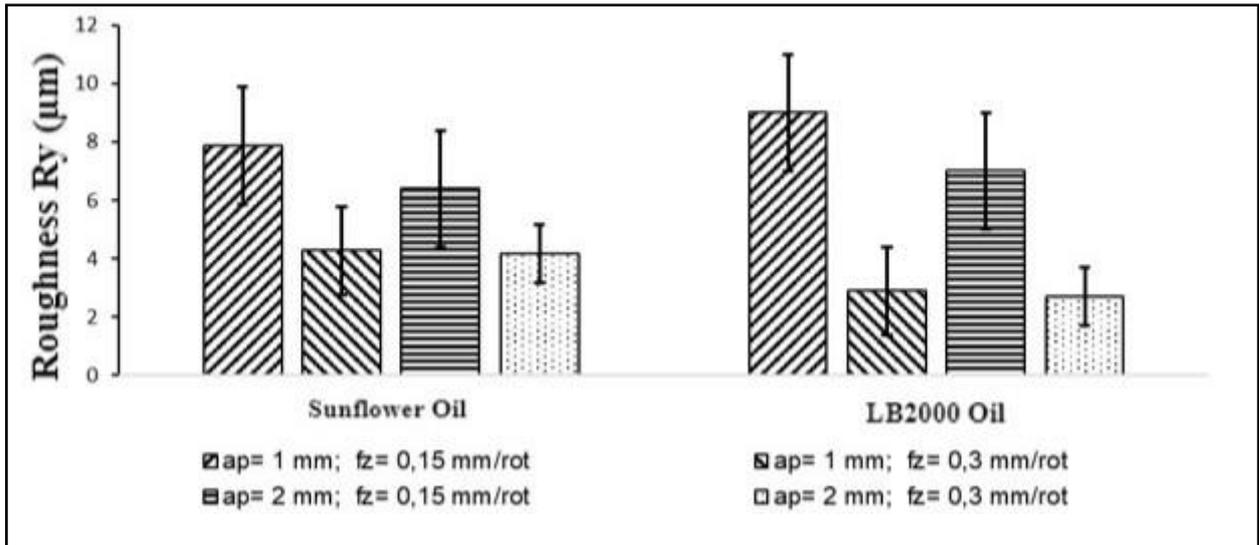


Figure 5. Bar chart with standard deviation for Ry roughness at $vc = 210$ m/min.

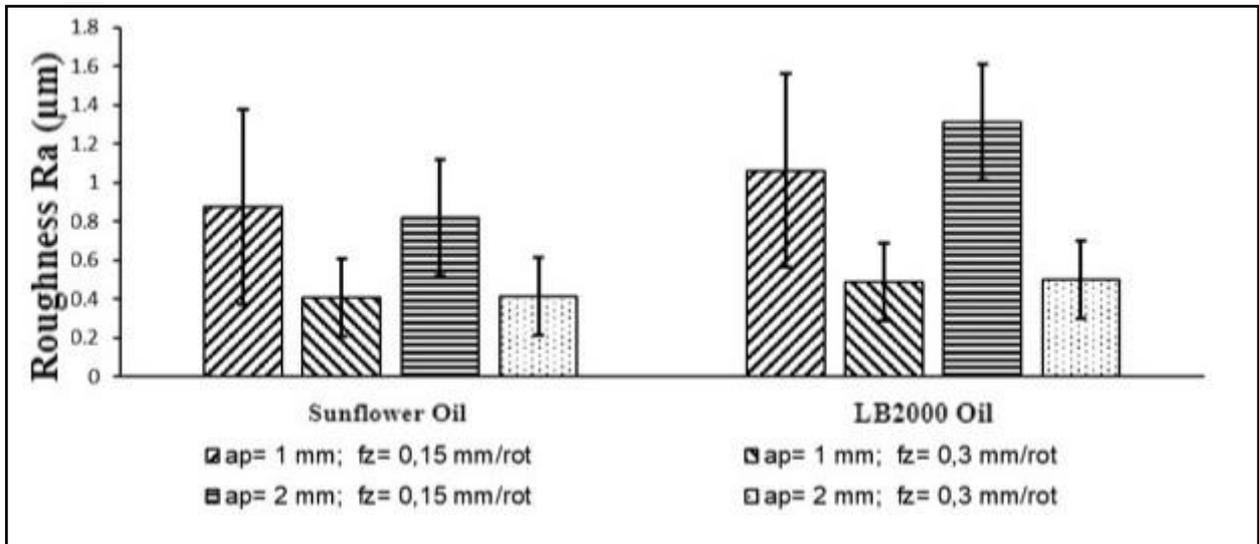


Figure 6. Bar chart with standard deviation for Ra roughness at $vc = 210$ m/min.

In Figures 5 and 6, it is evident that increasing the cutting speed significantly led to higher roughness values. This is primarily due to the increased heat generated during the machining process, which results in more tool wear and greater thermal deformation in the workpiece. It is also observed that at a cutting speed of 210 m/min, a feed rate of 0.15 mm/rev, and a cutting depth of 1 mm, sunflower oil yielded lower Ry and Ra roughness results, demonstrating superior performance compared to LB2000 oil.

The T-Student test was applied to compare the average between sunflower oil and LB 2000, then it was verified that the difference was significant in terms of p-value with an α of 5%. Table 2 presents the results of the values and the comparison between the values for the Ra roughness. The positive values in this table indicate a reduction in the Ry and Ra surface roughness from the heavy cutting process in favor of sunflower oil.

Table 2. Statistical comparison of roughness Ra of sunflower oil in relation to LB 2000 oil.

| vc (m/min) | ap = 1 mm | | | | ap = 2 mm | | | |
|---------------|-----------------------|---------|--------------------|---------|--------------------|---------|--------------------|---------|
| | fz = 0,15 mm/tooth | | fz = 0,30 mm/tooth | | fz = 0,15 mm/tooth | | fz = 0,30 mm/tooth | |
| | Difference | p-value | Difference | p-value | Difference | p-value | Difference | p-value |
| 165 | -0,09 % | 0,5921 | -0,40 % | 0,3297 | 0,12 % | 0,5267 | 0,26 % | 0,2775 |
| 210 | 0,18 % | 0,0879 | 0,17 % | 0,5921 | 0,37 % | 0,0603 | 0,17 % | 0,5921 |

Table 3 presents the results of the values and the comparison between the values for the Ry roughness.

Table 3. Statistical comparison of Ry roughness of sunflower oil in relation to LB 2000 oil.

| vc (m/min) | ap = 1 mm | | | | ap = 2 mm | | | |
|---------------|-----------------------|---------|-----------------------|---------|--------------------|---------|--------------------|---------|
| | fz = 0,15 mm/tooth | | fz = 0,30 mm/tooth | | fz = 0,15 mm/tooth | | fz = 0,30 mm/tooth | |
| | Difference | p-value | Difference | p-value | Difference | p-value | Difference | p-value |
| 165 | -0,19 % | 0,2165 | -1,73 % | 0,0011 | -0,07 % | 0,6540 | 0,15 % | 0,4316 |
| 210 | 0,13 % | 0,0002 | -0,48 % | 0,2410 | 0,09 % | 0,6862 | -0,54 % | 0,0845 |

Analyzing the average percentage differences where statistical differences were observed, it is evident that there was a significant increase in Ra roughness from sunflower oil compared to LB2000 oil. For values with a p-value greater than the significance level, corresponding to 0.5, it can be concluded that there was no statistical difference. However, at a feed rate of 0.15 mm/tooth, cutting depths of 1 and 2 mm, and a cutting speed of 210 m/min, there is a significant tendency towards reducing Ra roughness when using sunflower oil instead of commercial oil. This is due to better heat dissipation in the process due to a higher cutting speed, which consequently results in less tool wear and lower surface roughness.

As for the Ry roughness values, it is concluded that there was also a significant increase from sunflower oil to LB2000 oil. Regarding the data obtained with a p-value greater than the significance level, it is statistically concluded that there was no difference. However, with a feed rate of 0.15 mm/tooth, a cutting depth of 1 mm, and a cutting speed of 210 m/min, the Ry roughness values showed a reduction of 0.13% when using sunflower oil. It is also observed that when reducing the cutting speed to 165 m/min and increasing the feed rate to 0.3 mm/tooth, while maintaining a constant cutting depth of 1 mm, the oil that showed better performance was LB2000 oil, with a reduction of 1.73% compared to sunflower oil. This occurs due to its superior density and viscosity properties compared to sunflower oil, where there is better lubricating capacity, resulting in less tool wear and reduced surface roughness.

4. CONCLUSION

The results obtained in this study have led to the following conclusions:

- For face milling of 1045 steel using cutting fluids at a flow rate of 50 ml/h, the results indicate that the combination of cutting parameters with the fluid used determines the surface roughness of the workpiece, and none of the oils demonstrated superior performance for all cutting parameters when compared.
- When analyzing the results for sunflower oil, there is a trend towards reducing the Ra surface roughness compared to LB 2000 oil with cutting depths of $a_p = 1$ mm and $a_p = 2$ mm at feed rates of $f_z = 0.15$ and $f_z = 0.30$ mm/tooth at a cutting speed of $v_c = 210$ m/min.
- LB 2000 oil proved to be more efficient in reducing the Ra surface roughness with a cutting depth of $a_p = 1$ mm and feed rates of $f_z = 0.15$ mm/tooth and $f_z = 0.30$ mm/tooth at a cutting speed of $v_c = 165$ m/min.
- For a cutting depth of $a_p = 2$ mm with feed rates of $f_z = 0.15$ and $f_z = 0.30$ mm/tooth at cutting speeds of $v_c = 165$ m/min and $v_c = 210$ m/min, sunflower oil yielded better results in reducing the Ra roughness when compared to LB 2000 oil.
- Regarding Ry roughness, it is observed that LB 2000 oil was more efficient in reducing surface roughness for a cutting depth of $a_p = 1$ mm with feed rates of $f_z = 0.15$ mm/tooth and $f_z = 0.30$ mm/tooth at a cutting speed of $v_c = 165$ m/min.
- Sunflower oil showed a favorable statistical difference in reducing the Ry surface roughness for a cutting depth of $a_p = 1$ mm with a feed rate of $f_z = 0.15$ mm/tooth at a cutting speed of $v_c = 210$ m/min.
- Therefore, it is concluded that sunflower oil proved to be efficient in reducing roughness when using appropriate cutting parameters, also showing better performance than the commercial oil.

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