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## **ASSESSMENT OF LUBRICOOLING METHODS ON TOOL LIFE AND SURFACE ROUGHNESS IN ASTM A182 F55 SUPER DUPLEX STAINLESS STEEL TURNING**

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**Abstract.** *Excellent mechanical properties combined with high temperature and corrosion resistance make the super duplex stainless steel appropriate for applications in the oil & gas industry, components and equipment implanted in corrosive environments, and other critical operating conditions. However, the properties that, on the one hand, make the use of this material attractive, on the other hand, make the machining of its components difficult, requiring further studies. Due to the growing trend towards environmentally friendly machining, alternative lubrication-cooling techniques have been employed. Thus, this work aims to investigate the effect of applying minimal quantity lubrication (MQL) and dry cutting, compared to the wet machining, on the PVD-TiAlSiN coated carbide tool life during the semi-finishing turning of the ASTM A182 F55 super duplex stainless steel. For this, two levels of cutting speed were used (80 and 120 m/min), while the feed rate (0.1 mm/rev) and depth of cut (1.0 mm) were kept constant. The behavior of the average roughness (Ra) of the machined surface was also evaluated during the tool life tests. A longer tool life was noted for all lubricooling methods for the lowest cutting speed (80 m/min). However, this improvement in tool life was not enough to increase the volume of material removed under DRY and MQL conditions. Thus, for these lubricooling conditions, the highest cutting speed (120 m/min) can result in higher productivity. Despite presenting intermediate performance in tool life for both cutting speeds (which is positive from an environmental point of view), the highest Ra values were produced in dry turning, which can be explained by the absence of lubrication. For both cutting speeds, wet machining resulted in an intermediate surface finish but generated a lower tool life due to the greater work hardening of the material in this condition. The MQL promoted higher tool life and lower Ra values compared to other addressed lubricooling techniques, regardless of the cutting speed level used, thus guaranteeing advantages from the environmental and productivity points of view.*

**Keywords:** *Turning, Minimum Quantity of Lubrication, Super Duplex Stainless Steel, Tool Life, Average Roughness*

### **1. INTRODUCTION**

Super duplex stainless steel (SDSS) can be characterized by the presence of alloy elements such as chromium, nickel and molybdenum, and by the two-phase microstructure composed of approximately 50% ferrite and 50% austenite. This composition ensures excellent mechanical strength, high ductility, good corrosion and temperature resistance (Gamarra and Diniz, 2018; Oliveira Jr. et al., 2014). Consequently, SDSS performs well in components and equipment subjected to corrosive environments, high temperatures, pressures, contact with aggressive chemicals and other critical operating conditions (Gamarra and Diniz, 2018). Such situations are typical in the oil & gas industry, and an example of the application of SDSS is in the manufacture of internal and external components of valves inserted in fluids with critical corrosive effects (Teles et al., 2022).

However, the properties that, on the one hand, make this material attractive, on the other hand, hinder the machining of the components (Gamarra and Diniz, 2018; Parsi et al., 2020). The presence of austenite and alloying elements, especially nitrogen in high percentages, decreases the machinability of the material that presents, in addition to low thermal conductivity, high ductility and tendency to work hardening (Ahmed et al., 2017; Gamarra and Diniz, 2018; Oliveira Jr. et al., 2014; Parsi et al., 2020).

Materials that tend to work hardening demand more energy for chip formation, promote very hard burrs, and reduce tool life, because they cause the removal of the coating and, consequently, increase the tendency of tool notch wear. The high ductility increases the contact region between the chip and tool, generating friction and abrasion wear mainly at high cutting speeds and built-up edge (BUE) formation at low cutting speeds (Machado et al., 2015). Consequently, the cutting tools used in machining SDSS have a reduced lifetime. Although the cost of cutting tools used in machining (compared

to other expenses) is low significant, a short tool life causes more stops for exchange and, consequently, a loss of productivity (Machado et al., 2015).

One of the main criteria used for determining the end of tool life in the turning process is the width of flank wear (VB), mainly because of the ease of quantitative evaluation. Flank wear is caused by friction generated by contact between the tool clearance surface and the workpiece (Astakhov and Davim, 2008). The cutting speed is the more significant parameter over the tool wear because the higher its level, the higher the temperature in the cutting zone, accelerating the wear mechanisms (abrasion, diffusion, oxidation) (Machado et al., 2015).

Cutting fluids are primarily used to lubricate the tool-part interface, reduce the temperature in the cutting zone, and assist the chip removal. Applying cutting fluids in machining difficult-to-cut materials is critical to improving process performance (Mia et al., 2018). For these reasons, using cutting fluids at high flow rates (WET condition) is widely used in industry. However, this system is inefficient, generating too much waste and low penetration in the cutting zone due to blocking by long chips (Dixit et al., 2012). In such circumstances, considerable efforts have been made to eliminate or minimize the consumption of cutting fluid while maintaining its benefits in improving machinability.

Considering the economic, environmental and occupational health points of view, machining without lubricooling methods (DRY condition) is the best solution because it does not generate disposal problems, does not pollute and does not pose risks to the operator's health. However, this alternative also does not guarantee the desired lubricooling properties. Alternatively, a technique widely used to reduce cutting fluids is the application of minimum quantity lubrication (MQL), which involves oil droplets sprayed in the cutting zone (nebulization) with the aid of compressed air in the contact zone chip-tool-workpiece (Dixit et al., 2012; Masoudi et al., 2018). Thus, MQL reduces the negative points related to WET, causing lubricooling effects on the process not achieved by DRY machining (Kang et al., 2008).

Surface roughness, often used as an output parameter of the machining process, is defined by microgeometric irregularities that make up the topography of the surface. Such irregularities can be assessed through roughness profiles and parameters. The average roughness "Ra" is the most used finish evaluation parameter for machining control because, in addition to being stable, it indicates changes in the process, such as tool wear. However, some essential characteristics of the process are not only identified by using Ra (Petropoulos et al., 2010). Therefore, other parameters are used together, and the roughness profile analyzes the irregularities graphically.

Studies related to the machining of SDSS have become relevant, primarily due to the increased demand in the oil & gas exploration industry (Gamarra and Diniz, 2018; Teles et al., 2022). Oliveira Jr. et al. (2014) showed that using high-pressure cutting fluid on SDSS turning resulted in longer tool life, good surface quality, and high corrosion resistance after the process. Subhash et al. (2019) observed lower surface roughness values and tool wear rate during the WET turning than DRY machining of SDSS. Rajaguru and Arunachalam (2020) conducted studies regarding the influence of lubricooling techniques in SDSS turning. They noted the advantages of using MQL and WET over DRY, especially for tool wear performance. Maruda et al. (2015) also showed that MQL positively affected the surface roughness after turning X10CrNi18-8 stainless steel. Finally, Parsi et al. (2020) compared coated and uncoated carbide tools in SDSS turning and noted that coated inserts have a service life of almost twice as long as uncoated inserts.

Thus, this work aims to assess the variation of cutting speed and MQL and DRY conditions compared to WET in the surface roughness and tool life of the coating carbide inserts during the semi-finish turning of SDSS.

## 2. MATERIALS AND METHODS

Turning experiments were performed at a CNC Mazak QTN 100-II lathe (maximum power of 23.6 kVA and maximum spindle of 6000 rpm) in an ASTM A182 F55 super duplex stainless steel workpiece bar with 243 mm length and 68 mm diameter. A PVD-TiAlSiN coated carbide insert Sumitomo type TNMG 160408 N-GU with a nose radius of 0.8 mm fixed in a Sandvik tool holder type DTJNL 2020 K16 with side cutting edge angle  $\kappa_r = -3^\circ$  and rake angles  $\gamma_o = \lambda_s = -6^\circ$ . According to the manufacturer, this carbide tool is recommended for machining stainless steel (first option) and heat-resistant super alloys (second option), ensuring high tool life stability even in unstable conditions. The suggested cutting speed and feed rate ranges are 80 to 140 m/min and 0.15 to 0.50 mm/rev, respectively (Sumitomo, 2023). The experiments used two carbide tools, and a new cutting edge was used for each machining condition.

Three lubricooling methods were tested for further comparative analyses between their effects: dry cutting (DRY), traditional condition (WET) and minimum quantity lubrication (MQL). The WET method applied the oil-free synthetic cutting fluid Blaser Swissslube Synergy 905, mixed in water, with a flow rate of 720 l/h. The MQL used the synthetic nanofluid Bondmann Way45-V with spherical nanoparticles of metallic silver; according to the manufacturer, these nanoparticles penetrate the microscopic peaks and valleys, reducing friction by nano-lubrication (Bondmann, 2023). The Tapmatic Nebulizer IV has applied this nanofluid at a flow rate of 200 ml/h and a pressure of 400 kPa.

The experimental procedure consisted of two tool-life tests for each lubricooling condition previously described, considering two cutting speeds ( $v_{c1} = 120$  m/min and  $v_{c2} = 80$  m/min) with feed rate ( $f = 0.1$  mm/rev) and depth of cut ( $a_p = 1.0$  mm) kept constant in all tests. Thus, six tool-life tests were performed, and at each run, the roughness and flank wear values were measured. The run sequence was planned for material removal in three sections with equal machining lengths (81 mm) to ensure shorter cutting times for each run and allow a higher evaluation frequency of the output

conditions between runs. Machining was done considering the stagger of the workpiece to minimize vibrations caused by unbalance, as shown in Figure 1.

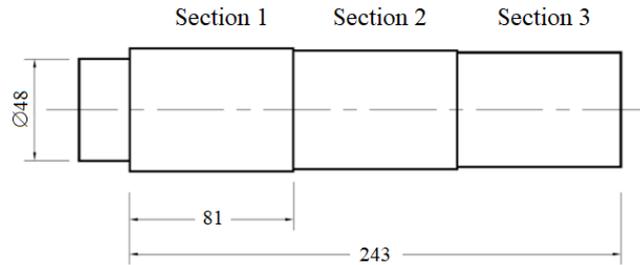


Figure 1. Workpiece representation after the 18 runs.

Due to the limited workpiece material and as the tool-life tests consisted of semi-finishing operations, the first criterion established to determine the end-of-life of the tool was the flank wear at  $VB \geq 200 \mu\text{m}$ . A second criterion was based on the maximum cutting time " $T_{\text{máx}}$ " and the maximum number of runs, ensuring sufficient material for all six conditions. Thus, the  $T_{\text{máx}} \leq 14$  min per test was established, and this situation was translated into the maximum number of runs (MNR), presented in Table 1.

Table 1. Maximum time and number of runs calculated for each condition.

Test	C1: DRY	C2: WET	C3: MQL	C4: DRY	C5: WET	C6: MQL
$v_c$ [m/min]	120 (insert 1)			80 (insert 2)		
$T_{\text{máx}}$ [min]	13.23	13.10	13.18	12.87	13.70	13.57
MNR	10	11	13	10	13	19

It is noticed that the MNR varies for each test. Such variation occurs for two factors: (i) reduction of workpiece diameter ( $d$ ) over time, which decreases cutting time per run ( $t_c$ ) (Eq. 1); (ii) variation of cutting speed ( $v_c$ ) (80 and 120 m/min), which also influences the cutting time per run ( $t_c$ ).

$$t_c = \frac{81 \cdot \pi \cdot d}{100 \cdot v_c} = 2.55 \left( \frac{d}{v_c} \right) \text{ [min]} \quad (1)$$

It should be noted that the values in Table 1 were determined considering the end tests by machining time, resulting in a total of 76 runs. Thus, for each test with a lower tool life ( $T$ ) at the specified maximum cutting time ( $T_{\text{máx}}$ ), the MNR was recalculated, and the total volume of material removed ( $V$ ) was obtained by Eq. (2):

$$V = a_p \cdot f \cdot v_c \cdot T = 0.1 \cdot v_c \cdot T \text{ [cm}^3\text{]} \quad (2)$$

The tool images (rake face, clearance face and corner) were acquired through the Dino-Lite AM-413ZT USB digital microscope, with a resolution of  $1024 \times 728$  and magnification up to 200x. The dedicated Dino Capture software assisted in measuring the  $VB$  values on the tool clearance face.

The measurement of the average roughness ( $R_a$ ) values of the samples was performed with a Mitutoyo SJ-201P portable rugosimeter (resolution of  $0.01 \mu\text{m}$ ). The data were acquired at each run without removing the workpiece from the CNC lathe. A sampling length of  $l_e = 0.8$  mm and an evaluation length of  $l_m = 5l_e = 4.0$  mm were adopted.

### 3. RESULTS AND DISCUSSIONS

#### 3.1. Tool Life

Figure 2 illustrates graphically the width of the flank wear ( $VB$ ) as a function of the cutting time for the three lubricooling methods considering  $v_{c1} = 120$  m/min, and Fig. 3 the  $VB$  values versus cutting time for  $v_{c2} = 80$  m/min.

The MQL (C3) resulted in better tool performance, being the only lubricooling condition for SDSS turning with  $v_{c1} = 120$  m/min that withstood the maximum cutting time of 829 s or 13.82 min with  $VB = 112 \mu\text{m}$ . The lifetime difference can be explained by the high penetration efficiency of the oil droplets in the cutting zone due to the pressurization of the fluid (400 kPa). On the other hand, this penetration happens on a smaller magnitude in the WET

(Varadarajan et al., 2002). Thus, MQL increased lubrication in the cutting zone, reduced friction in the workpiece interface, preserved the tool's coating layer and slowed the failures. However, this phenomenon does not explain the intermediate performance of DRY (C1), which exceeded the defined flank wear limit ( $VB \geq 200 \mu\text{m}$ ) during the 8<sup>th</sup> run of the nine performed, with a cutting time of 641 s or 10.68 min, higher than WET (C2). SDSS has a high degree of work hardening, which is accentuated by the temperature reduction. Thus, the tool, which probably has low toughness, tends to fail more quickly during the WET turning, mainly in the coating layer. According to Dillon et al. (1990) and Sun et al. (2010), the work hardening tends to decrease with increasing temperature. Thus, in dry machining, the work hardening occurs to a lesser extent due to the high temperature in the cutting zone, preserving the tool, which has good hot hardness. This hypothesis, observed by Oschelski (2020), also explains the best performance with MQL: the weak cooling effect of this method causes less work hardening of the material, while the suitable lubrication effect favors the tool life due to the reduction of friction that DRY does not provide.

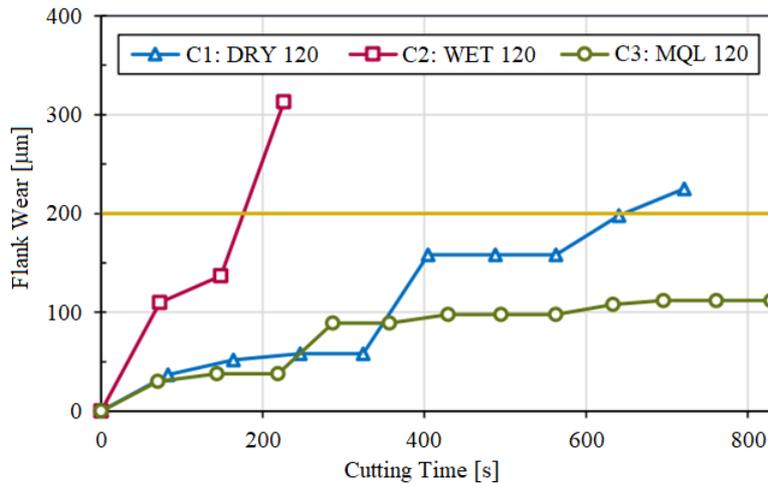


Figure 2. Flank wear versus cutting time for different lubricooling methods in turning with  $v_{c1} = 120$  m/min.

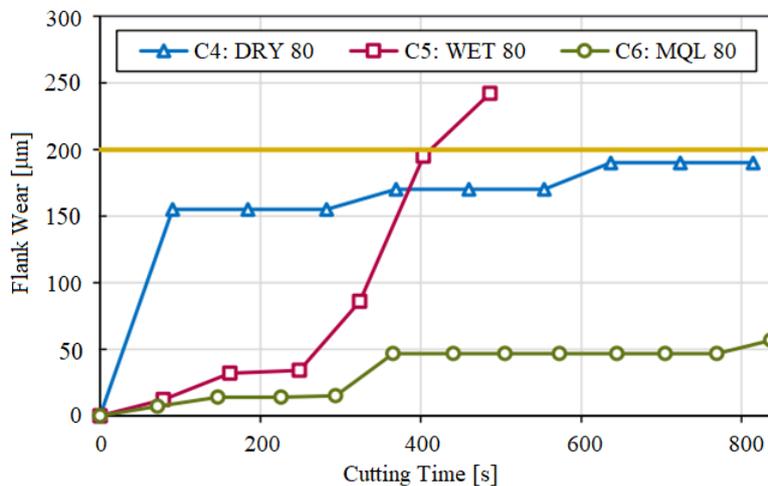


Figure 3. Flank wear versus cutting time for different lubricooling conditions in turning with  $v_{c2} = 80$  m/min.

The WET (C5) provided a short lifetime (403 s or 6.72 min), showing the low performance of this method in the semi-finishing turning of SDSS with  $v_{c2} = 80$  m/min. The cutting edges used in DRY (C4) and MQL (C6) completed the tool-life tests before reaching the flank wear limit. Again, the best result was observed with MQL turning, in which the tool presented  $VB = 56.7 \mu\text{m}$  after 837 s (13.95 min). In contrast,  $VB = 190 \mu\text{m}$  was noted in 814 s (13.57 min) on the tool when applied DRY cutting. Rajaguru and Arunachalam (2020) also attested to the advantages of using MQL to extend the tool life in SDSS turning.

Considering the lubricooling performance with the variation of cutting speed, in WET machining, the increase in the tool life with the decrease of the cutting speed is due to the better fluid penetration in the cutting zone. What differentiates C1 from C4 in DRY cutting is that the lower heat generated in the second condition increases the tool life. Regardless of

cutting speed, DRY produced higher tool life than WET, showing to be an economically and environmentally advantageous alternative.

During the tool-life test C4, there was a tool material pullout in the first run, causing  $VB = 155 \mu\text{m}$ . This phenomenon was repeated in the following runs, with small increments in the flank wear width until the end of the stipulated time. This behavior was not observed in the other tests. According to Astakhov and Davim (2011), a suitable lubricooling method ensures that the tool-wear curve does not express a rapid increase of  $VB$  at the beginning of tests. The friction reduction generated in the tool-part interface, caused by the lubricating effect of the cutting fluid, prevents premature degradation of the tool coating layer. For the MQL, the cutting edge showed gradual and uniform tool wear throughout the life test. However, in the tool-life test C5, the tool material pullout by adhesive wear was accompanied by successive failures that led to the premature end of the tool life.

Figure 4 compares the total volume of material removed ( $V$ ), calculated by Eq. 2, and tool life ( $T$ ) between the lubricooling conditions for the two cutting speeds. It is observed that for the higher cutting speeds, the performance differences between the cutting fluids were more substantial.

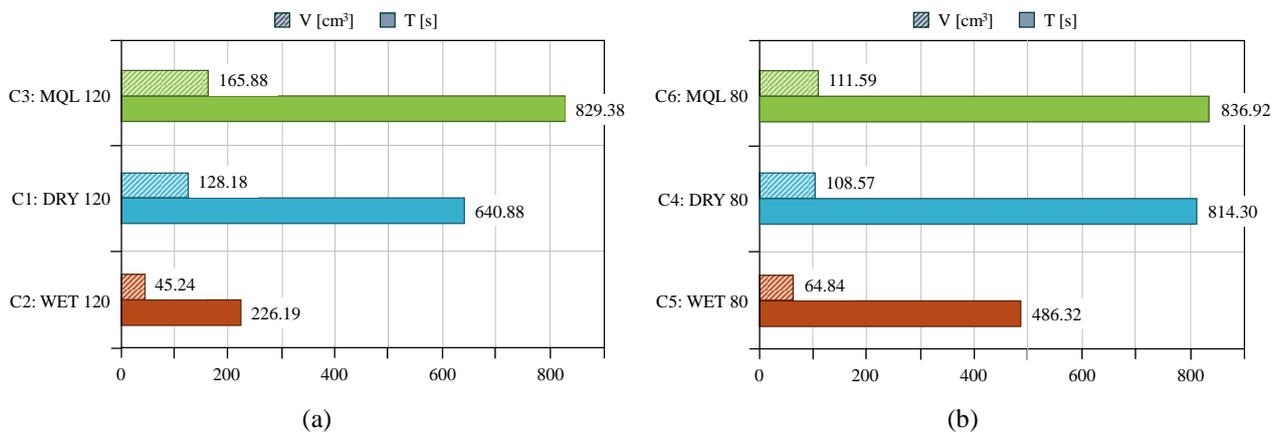


Figure 4. Volume of material removed [ $\text{cm}^3$ ] for each tool life [s] under different lubricooling conditions considering: (a)  $v_{c1} = 120$  m/min; (b)  $v_{c2} = 80$  m/min.

The percentage variations in tool life ( $T$ ) between MQL and WET (best and worst results) for cutting speeds  $v_{c1}$  and  $v_{c2}$  were 267.7% and 72.1%, respectively. This difference can be explained by the increased temperature in the cutting zone, which follows the increase in cutting speed. Thus, the physicochemical phenomena and thermally activated wear mechanisms, such as diffusion and oxidation (Cantero et al., 2013), became more evident for the higher cutting speed. When the cutting speed increased by 50% (from  $v_{c2}$  to  $v_{c1}$ ), both tool life ( $T$ ) and volume of material removed ( $V$ ) decreased in WET machining (53.5% and 30.2%, respectively); for MQL condition,  $V$  increased by 48.7% and  $T$  decreased about 1%; in DRY cutting,  $T$  reduced by 21.3% and  $V$  increased by 18.1%.

A simple performance analysis of the process shows that a larger volume of material is removed in a shorter time with a higher cutting speed. This information is valuable for industrial production lines. The cutting speed  $v_{c1} = 120$  m/min produces more parts before the end of tool life and in a shorter time, thus increasing productivity; in other words, the cutting process has a time-saving economy. In addition, better tool utilization reduces the costs related to these two situations.

### 3.2. Tool Wear

Figure 5 shows images of the rake face (exit), clearance face (flank), and corner (nose) of the inserts collected through digital optical microscopy at the end of tool-life tests with  $v_{c1} = 120$  m/min, and Fig. 6 the images acquired after the end-of-life tools with  $v_{c2} = 80$  m/min. Vertical marks of mechanical abrasion are observed in the worn regions, especially in the DRY condition, for both cutting speeds. With the lubricating effect of WET and, particularly, MQL, these marks became less evident due to friction reduction. Predominant flank wear is observed in all conditions. However, for WET and MQL, the formation of notch wear is observed, possibly due to friction between the long-serrated chip and cutting tool, as well as the presence of oxidation mechanisms (Machado et al., 2015). Additionally, a significant adhesion of material is observed, especially over the wear marks in the DRY cutting. Possibly, the adhered material covered the notch wear in this condition.

For  $v_{c2} = 80$  m/min, large amounts of adhered material were observed in all three lubricooling methods, as expected in ductile materials with a low cutting speed (Machado et al., 2015). Notch wear was possibly generated in all these three methods; however, in MQL and DRY, the adhered material covered the wear. An apparent cracking at the tool nose and a substantial material adhesion are noted in the DRY machining. The high tendency for adhesion of the material on the

cutting tool is an intrinsic characteristic in SDSS turning mainly due to the high ductility of the material. However, the amount of adhered material strongly depends on the process conditions, such as cutting speed and lubricooling method, and it strongly influences the output parameters investigated. The microscopy images show that the adhered material was removed in each run during the WET tests, causing material removal from the tool through adhesive wear (Machado et al., 2015), as represented by the significant increases in the VB width over the machining time (Fig. 3).

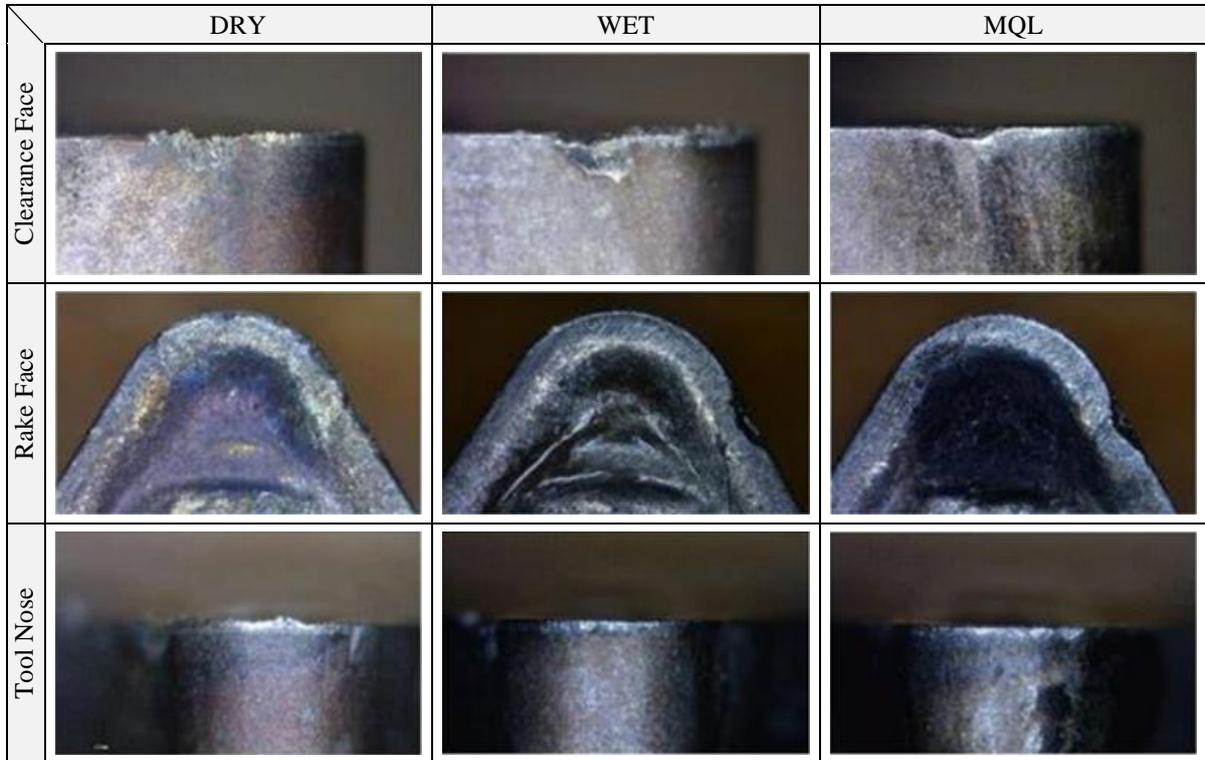


Figure 5. Carbides at the end of tests in the three lubricooling conditions with  $v_{c1} = 120$  m/min.

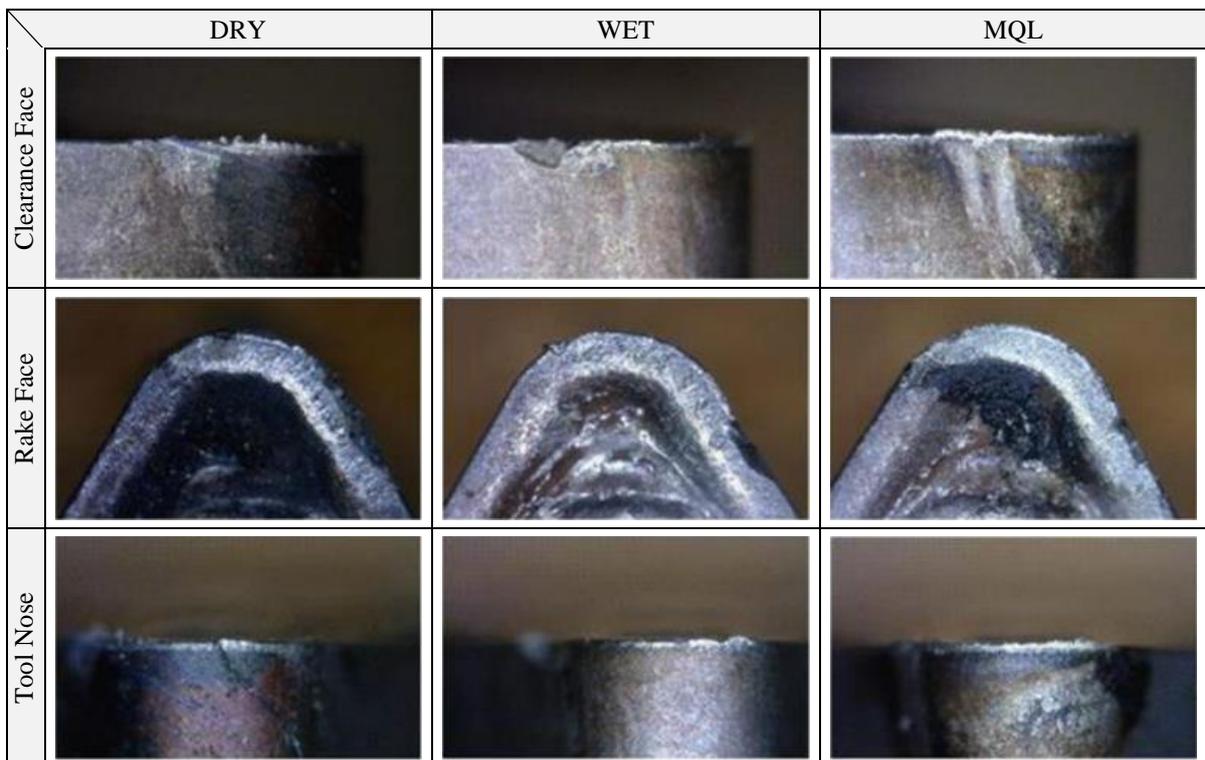


Figure 6. Carbide at the end of tests in the three lubricooling conditions with  $v_{c2} = 80$  m/min.

The adhered material remained on the wear mark for a long time, acting as a protective layer on the tool surface. Thus, there were no significant increases in the VB value when MQL and DRY machining. The temperature in the cutting zone explains this distinction. In WET, increased heat removal reduces the temperature in the cutting zone, as cited by Subhash et al. (2019). This decrease in temperature increases the hardness of the adhered material, resulting in a more rigid and, consequently, more brittle material that tends to break and be pulled out along with a portion of the cutting tool. In contrast, high temperatures provide some malleability in SDSS, reducing the occurrence of pullouts on cutting tools and ensuring a longer tool life in the MQL and DRY conditions. For example, DRY cutting with  $v_{c2} = 80$  m/min resulted in accelerated wear in the first run. However, the tool endured until the end of the tool-life test without further similar occurrences due to the adhered material not being wholly pulled out of the cavity generated by chipping on the tool. There were crater wear and oxidation marks in the DRY (more pronounced) and MQL (less prominent) conditions, as well as chipping after notch wear in the WET machining. However, the variation in cutting speed did not generate significant differences in wear types. The predominant wear type was flank wear, and the region where the notch wear occurred coincides with the depth of cut value ( $a_p = 1.0$  mm), which was expected since the chip width is nearly equal to  $a_p$ .

### 3.3. Surface Roughness

Figure 7 represents the variation of the average surface roughness  $R_a$  [ $\mu\text{m}$ ] generated on the semi-finished surface of ASTM A182 F55 super duplex steel during the tool-life tests, and Fig. 8 the percentage of points collected in each roughness class according to the ABNT NBR 8404 standard (1984).

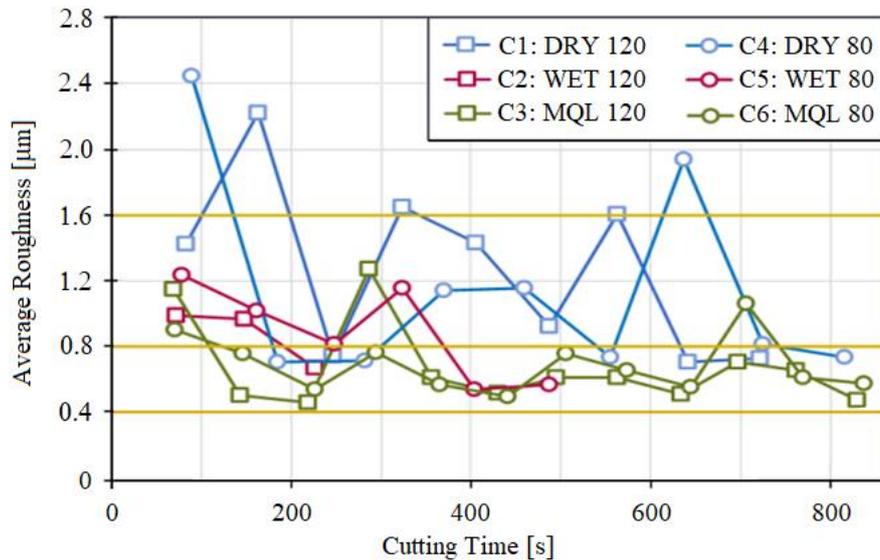


Figure 7. Average roughness values varying with the cutting time

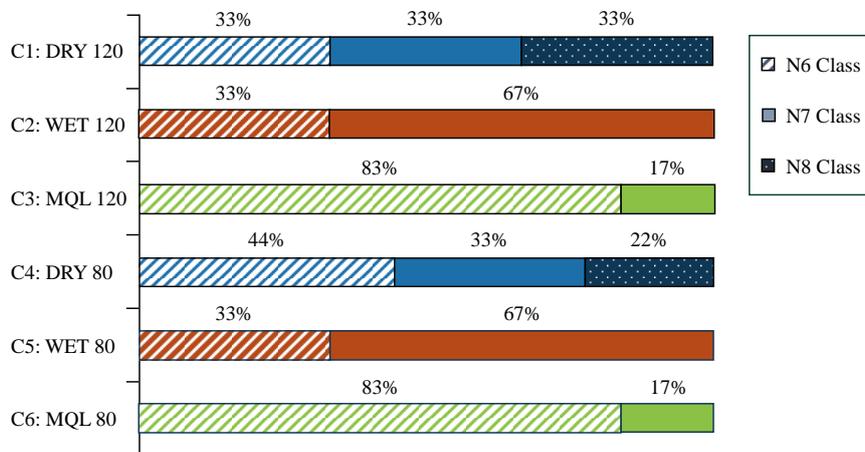


Figure 8. Percentage of  $R_a$  values in each roughness class for each cutting condition.

The best results were observed with the MQL turning, with 83% of the evaluated points in the N6 roughness class (from 0.4 to 0.8  $\mu\text{m}$ ) and no value in the N8 class (from 1.6 to 3.2  $\mu\text{m}$ ). Additionally, the N7 class (from 0.8 to 1.6  $\mu\text{m}$ ) was predominant when WET machining, with 67% of the measured points in this class. Maruda et al. (2015) also confirmed the positive effects on the surface finish of super duplex stainless steels in MQL turning. DRY cutting presented the worst performance, i.e., the only condition with values in the N8 class. The reduction of friction at the tool-workpiece interface, caused by the lubricating effect of the fluid (WET and MQL), facilitates the tool penetration into the workpiece with lower effort and also reduces the material adhesion, thus promoting a better quality of the machined surface (Stephenson and Agapiou, 2016). Another hypothesis is the higher temperature in the cutting zone resulting from the DRY machining generates higher plastic deformation rates on the workpiece surface near the chip formation region. With the cooling effect of the fluid, there is significant heat removal and, consequently, lower temperatures, resulting in fewer defects (Oliveira Jr. et al., 2014). Finally, the difference in cutting speed did not alter the percentage distribution of Ra values in the roughness classes for the WET and MQL conditions.

Figure 9 shows the difference between the average roughness generated by the new ( $VB < 100 \mu\text{m}$ ) and the worn cutting tool ( $VB > 100 \mu\text{m}$ ) in each lubricooling method. A mean of the Ra values was calculated without distinguishing between cutting speeds. The results indicated lower Ra values as the tool becomes worn. As observed by Shahabi and Ratnam (2009), this may be related to the flattening of the tool nose as wear occurs, increasing the effective tool nose radius and reducing the height of roughness peaks.

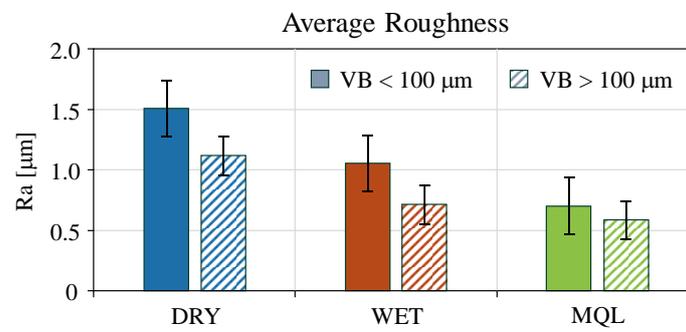


Figure 9. Difference between Ra values generated by the new and worn cutting tool in each lubricooling method.

#### 4. CONCLUSION

The study presented the influence of lubricooling techniques (DRY, WET and MQL) and cutting speeds ( $v_{c1} = 120 \text{ m/min}$  and  $v_{c2} = 80 \text{ m/min}$ ) on the tool life of PVD-TiAlSiN coated carbide tool during the semi-finishing turning of ASTM A182 F55 super duplex stainless steel. The main conclusions are pointed out as follows.

- A higher tool life (T) was observed for all lubricooling methods with  $v_{c2} = 80 \text{ m/min}$ . However, this extension in tool life did not suitably increase the total volume of material removed (V). Therefore,  $v_{c1} = 120 \text{ m/min}$  resulted in higher productivity.
- DRY cutting showed intermediate tool life performance for both cutting speeds, which is positive from the environmental perspective. Nevertheless, it exhibited higher flank wear (VB) at the beginning of the test compared to the other conditions, specifically for  $v_{c2} = 80 \text{ m/min}$ . On the other hand, DRY resulted in higher roughness values due to the lack of lubrication, mainly with  $v_{c1} = 120 \text{ m/min}$ .
- For both cutting speeds, the WET condition showed an intermediate surface finish. However, it had a shorter tool life, reaching prematurely the established criterion ( $VB \geq 200 \mu\text{m}$ ) due to higher work hardening of the material that was encouraged by the cooling effect of the fluid.
- MQL machining showed higher performance in tool life and machined surface roughness compared to DRY and WET conditions, regardless of the cutting speed employed. Then, for the cutting conditions analyzed, the MQL provides advantages from the environmental and productivity perspectives.
- The increasing flank wear flattens the tool nose area, raises the nose radius, and reduces the average roughness values due to decreased height of roughness peaks for all lubricooling conditions.

#### 5. ACKNOWLEDGMENTS

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