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A COMPREHENSIVE REVIEW ON CUTTING FLUIDS ON MICROMACHINING OPERATIONS

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Abstract. *Micromachining does not have a single definition, it can be characterized by the uncut chip thickness, tool size and/or the size of the part that is being machined. However, the so called size effect is a characteristic of micromachining operation that is unanimity in the literature. This is characterized by a nonlinear increase in the specific energy, caused by the similar sizes of the tool cutting edge radius and the material microstructure. Differently from macro machining, the tool cutting edge radius is large, and the tool cannot be considered perfectly sharp. These characteristics lead the micro cut to have high plowing, excessive burr formation, adhered material in the cutting edge and high tool wear. The use of cutting fluids can hinder these difficulties, once it favors the chip formation and allows better surface finish and lower wear rates. In this sense, this work aims to present a literature review on the use of cutting fluids on micromachining operation. Different cooling-lubricant atmospheres will be compared, namely: dry, flood, cryogenic and minimum quantity of lubrication (MQL). After analyzing the literature, it could be observed that dry micromilling usually presented the worse results favoring BUE formation and slots poor finishing, however, regarding the tool wear, it can enhance or reduce the tool life if it is stable or non-stable, respectively. The use of flood, in general, presents results intermediate between dry and MQL. The MQL stands out demonstrating to be the best methodology for micromilling metals, resulting in better surface finishing, less adhered material, lower surface roughness values and smaller burrs. In some of the studies MQL could also increase tool life. Cryogenic methodologies, on the other hand, are usually applied in high ductility materials, highlighting the polymers. The method stands out for allowing good surface finishing, higher dimensional accuracy, and reduced burr formation.*

Keywords: *Micromachining; Flood; MQL; Cryogenic; Surface Finishing.*

1. INTRODUCTION

In general, micromachining differs from conventional machining due to the dimensions of the cutting tools used, as defined by Aramcharoen et al. (2008) and Câmara et al. (2012), who consider that the diameter of microtools ranges from 1 µm to 1000 µm. For Masuzawa (2000) the term “micro” is related to magnitudes ranging from 1 µm to 999 µm. Other researchers also define this process based on the slice thickness values used, such as Ng et al. (2006), who defined that the slice thickness ranges from 10 nm to 2 µm. Thus, there is still no consensus regarding the definition of micromilling. By considering only the cutting thickness limit values for a micromachining process, the considerable scale reductions present in micromachining processes cause specific phenomena that are explained by the size effect (Simoneau; Ng; Elestawi, 2006). Therefore, the size effect is a feature of the micromachining operation that is unanimous in the literature.

The size effect explains some peculiarities of micromachining, which is not a simple scale reduction of the conventional machining process. With the reductions made in the process, there is a significant increase in the specific cutting energy in micromachining, which changes the chip formation mechanism in relation to conventional milling (Chae, Park and Freiheit, 2006).

Due to the presence of the size effect, the uncut chip thickness becomes comparable to the radius of the cutting edge and the grains of the machined surface. Thus, the uncut chip thickness, the radius of the cutting edge, and the grain size of the machined material have great influences on the cutting process (Cheng and Huo, 2013).

In micromachining, due to the small dimensions involved, the reduction of wear on microtools is very important, as well as their deflection and the quality obtained on the machined surface (Gomes et al., 2021). Therefore, many studies are performed to optimize these parameters. One of the ways to obtain this optimization is to use optimal cutting conditions and/or cutting fluid (Nevala et al., 2012).

Cutting fluids can be used to reduce friction and heat generation in micromachining processes. In studies that evaluate the effect of its use in micromachining, are observed the reduction of cutting forces and tool wear, as well as an improvement in the finish of micromachined surfaces (Gajrani; Reddy; Sankar, 2016; Kieren-Ehses, 2018).

According to Machado et. al (2011), in operations with low cutting speeds, the refrigerant function of the fluid is neglected, since in these operations the temperatures generated during cutting are low. Also, the low speeds favor the penetration of the fluid in the cutting region, which will reduce the friction generated. While in high-speed operations, the fluid will act in reducing the heat generation, since the high speeds will not favor the penetration of the cutting fluid in the cut region. Therefore, the lubricating function of the cutting fluid will be impaired. In micromachining, this behavior will be influenced not only by the cutting conditions but also by the cooling/ lubricating technique used (Walker, 2015).

There are different cooling/ lubricating techniques such as dry cutting, flooding cutting, Minimum Quantity Lubrication (MQL), and cryogenic methods. The performance of each one will depend on the type and way they are applied during the process (Rezaei, 2017). Therefore, given the importance of using cutting fluid in micromachining and the differences in existing techniques for employing them, this article aims to review the literature on this subject, indicating the characteristics of each technique, in order to favor the selection for the best to use.

2. CUTTING FLUID APPLICATION METHODS

2.1 Cutting Fluid Applied by Flood

One of the cutting fluid application methods in machining operations is the flooding technique. In this method, cutting fluid is used at high rates of 240 to 18,000 l/h (Sanchez et al., 2010). However, this method is not very effective in micromachining due to the characteristics of its processes (Dornfeld et al., 2006).

In micromachining, cutting tools with small dimensions and with lower bending modules are used, thus, the high rate of cutting fluid used in the flood method can easily deflect the cutting tool, which will affect the quality of machining (Rezaei et al., 2017). In addition, high speeds are used in machining processes, typically in the range of 30,000 to 120,000 rpm, to compensate for the small dimensions of the cutting tools used, making it possible to obtain cutting speeds that guarantee high productivity (Chukewad, 2014). This high rotation creates a layer of air around the microtool, which prevents the fluid from penetrating its interface with the workpiece and the chip that is being formed (Hung et al., 2019), therefore, the fluid does not reach the zone cutting which leads to a reduced lubricating action.

Another issue is related to the amount of cutting fluid used by this technique, as it will be challenging to remove the excess fluid used, even more so when considering green machining, and this large amount of fluid must be discarded correctly, to avoid environmental problems with the contamination of soil and water resources (Zulkifli et al., 2016). There are still risks related to the health of the operator in the respiratory and digestive systems, as well as the skin, which will be further intensified due to a large amount of cutting fluid used in this method (Haider and Hashmi, 2014; Nee, 2015).

Due to the above, there are few works that investigate the effect of the application of cutting fluid by the flooding method in micromachining, we will see later that there is much research that analyzes the use of MQL (minimum quantity lubrication), due to its innumerable advantages in relation to the flood system (Zulkifli et al., 2016).

Kajaria et al. (2012) analyzed the micromilling of 316L stainless steel by investigating four different cutting conditions: dry, mist with 0.022cc/min 2210EP, flood cutting with Blasercut 2000 universal, 5: 1 mixture, and cutting conditions in spray (Blasercut mist) with Blasercut 2000 universal, 14cc/min and 0.8Mpa. In the tests performed under all these conditions, tungsten carbide microtools with a cutting diameter of 1.016 mm, chip load of 10μm/tooth, axial depth of 0.348mm, and radial depth of 0.558mm were used. When analyzing the life of the cutting tool used in the tests, it was observed that the mist-cutting condition improves the life performance of the microtool compared to the dry and flooding condition, as shown in Figure 1. The authors explain this result based on the failure mode of the microtool, and in the mist condition abrasive wear was found due to better cooling and low friction in the cutting region, while in the dry condition, the microtool failure occurred due to chipping and deformation plastic. This shows that in the mixed condition, the used cutting fluid has a greater lubricating and cooling action than in the flood condition.

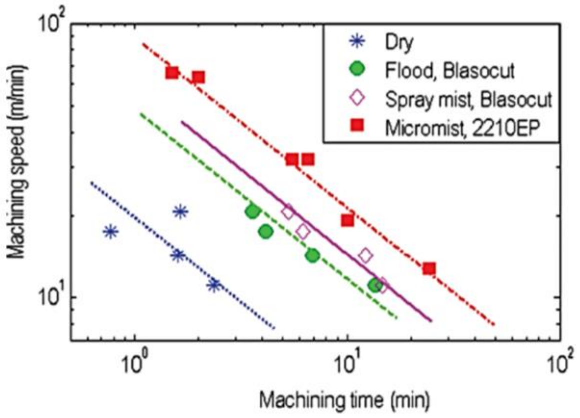
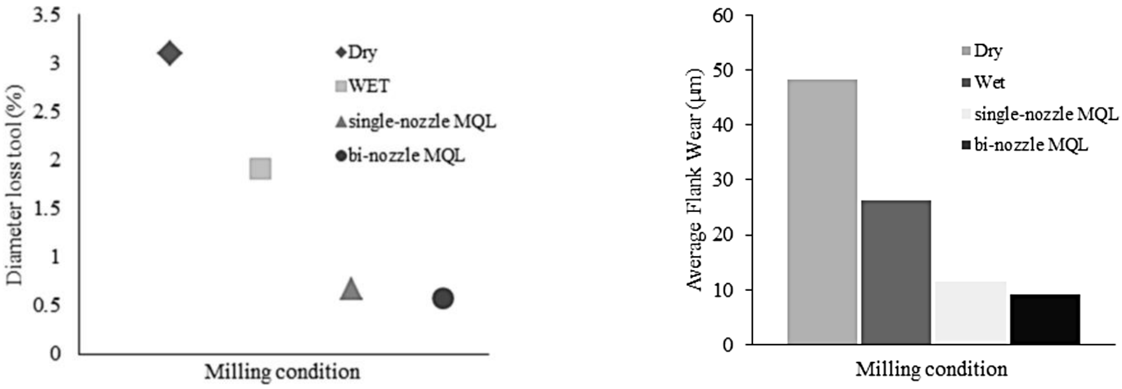


Figure 1 – Tungsten carbide microtools life when micro-milling 316L stainless steel (Kajaria et al., 2012).

Rezaei et al. (2017) investigated the effects of three different cooling and lubricating systems: dry cutting, wet condition, and minimum quantity lubrication (MQL) in the micromilling of titanium alloy Ti6Al4V. For this, they used microtools with a cutting diameter of 0.8 mm and the following conditions: a cutting speed of 60 m/min, a depth of cut of 150 µm, and a chip load of 6 µm/tooth. According to the authors, for the MQL system, two ways of spraying with one nozzle in the feed direction, and two nozzles in both feed and against feed direction were used. As result, it was observed that in the dry condition, the highest wear was obtained, while in the MQL condition with two nozzles the lowest wear was obtained, both in the measurement of wear by reducing the diameter of the tool, Figure 2-a, and in the measurement of wear of flank, Figure 2-b. They also noticed a reduction in surface roughness for the MQL condition, with the lowest values obtained for the two nozzle condition of 0.311 µm.



(a) (b)

Figure 2 - Wear measurement (a) by cutting diameter reduction and (b) by flank wear (Rezaei et al., 2017).

From a qualitative analysis, when observing the images obtained from the manufactured microchannels, Figure 3, Rezaei et al. (2017), concluded that the burrs were smaller for the MQL conditions and were higher for the dry condition. These authors also analyzed the temperature and cutting force obtained in each condition, obtaining results that were in accordance with expectations. Therefore, the lowest temperature was obtained for the MQL condition and the highest cutting force (6.77 N) was obtained for the dry condition, followed by the flood condition (4.028 N), the One-nozzle MQL (3.002 N), and from Two-nozzle MQL (2,736 N).

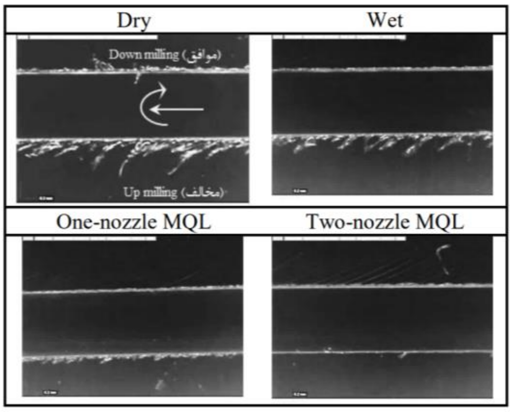


Figure 3 – Burrs formed under the analyzed conditions (Rezaei et al., 2017).

Aslantas and Çiçek (2018) investigated the influence of the application of minimum quantity lubrication (MQL), dry cutting, and flooding condition in the micromilling of Inconel 718. In the MQL system, a vegetable cutting fluid was used, DuALL Al 2100 a flow rate of 10 ml/h. In the flooding condition, a fluid soluble in water and ethanol was used at a pressure of 4 bar. To carry out the tests, carbide micromills with a cutting diameter of 0.6 mm and the following cutting conditions were used: cutting speed of 31.4 m/min, feed rate of 40 mm/min, and depth of cut of 0.1 mm. The results showed that the highest wear on the cutting tool was obtained in the cutting condition with ethanol, while the lowest wear was obtained with MQL, this is because in micromilling the ethanol has insufficient lubricating action, which does not prevent the occurrence of wear. abrasive on the microtool, while in the MQL condition, the lubrication effect will be higher. In addition, the authors analyzed the burrs formed under the analyzed conditions and concluded that for the conditions with the ethanol, wet and dry conditions there is bottom burr formation, while only for the condition with MQL this type of burr did not form, as it can be seen in Figure 4. The authors associated this result with microtool wear. Finally, the authors observed the average roughness of the micromachined surfaces under the analyzed conditions and concluded that the best surface finish was obtained in the MQL condition since it was the condition with the least wear on the microtool. They also observed that in the dry condition the surface quality was better, close to the MQL condition, but they did not explain this result.

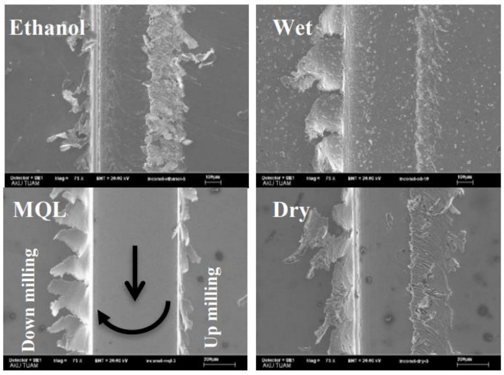


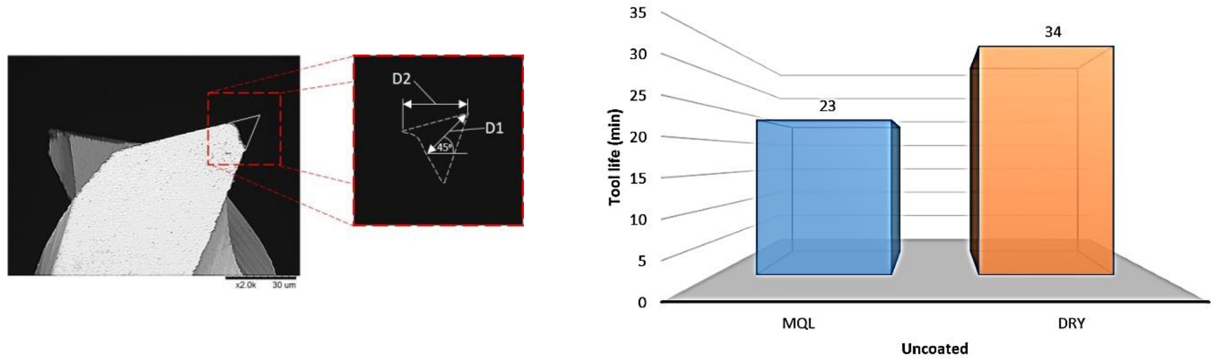
Figure 4 – Burrs formed under different cutting conditions (Aslantas and Çiçek, 2018).

2.2 Minimal Quantity Lubrication

As mentioned on Item 2.1, there are different methods to lubri-refrigerate during micromilling. Considering the usually high amount of cutting fluid that is used in the flood cooling, and the environmental damages it can cause it not handled correctly (Sanchez et al., 2010), the MQL methodology stands out as a good replacement alternative. In the MQL technique, a small flow rate of oil is normally delivered to the cutting zone with compressed air at the right pressure (Li et al, 2015) at a pressure of around 0.6 MPa, or higher as presented by different authors, to form an optimal aerosol mixture which ensures lubrication of the cutting area and at the same time cooling of the part. This method allows the formation of a thin layer of lubricant on the tool surface, before the with the workpiece (Marinescu et al., 2007).

This enhancement in the lubrication, due to the film formation, can allow a reduction in friction and consequently on tool wear, that in addition to being a problem in itself is associated with higher burrs and worse surface finishing. To evaluate this influence, Vasquez et al. (2015), studied micromilling Ti-6Al-4V, with 200 µm Mitsubishi tools, with ap = 20 µm, 30 000 rpm, and fz = 1.25 µm. Using a MAK KIT10 vegetable cutting fluid, with a 1:10 dilution in water, with MQL and flood techniques, the flow rates were not specified. The authors verified that when using cutting fluid with flood technique, the wear was greater than that presented when using MQL applied in the feed direction, the wear, measured as a reduction in the diameter of the micromilling cutter, were 6.15% and 1.60%, for flood and MQL, respectively.

On another study, Ziberov et al. (2016a) evaluated the wear of carbide micromills, with 152.4 µm in diameter, without coating, when micromilling Ti-6Al-4V, dry and with application of cutting fluid by the technique of minimum amount of lubricant (MQL), using a COOLUBE lubricant. The authors measured two types of wear, as shown in Figure 5 a). They adopted the strategy of measuring wear after each pass, to follow the evolution of wear on the microtool during the process. The authors mentioned that the behavior of tool wear followed the usual for macro tools: there is a first region of wear with accentuated rates due to the accommodation of the system, followed by a region with lower rates of wear and a third region in which wear is high and its rate increases again. Despite showing severe wear after 25.2 mm, Ziberov et al. (2016a) report that there is no tool breakage for the investigated conditions. The tool life for dry and cutting with MQL can be observed in Figure 5 b).

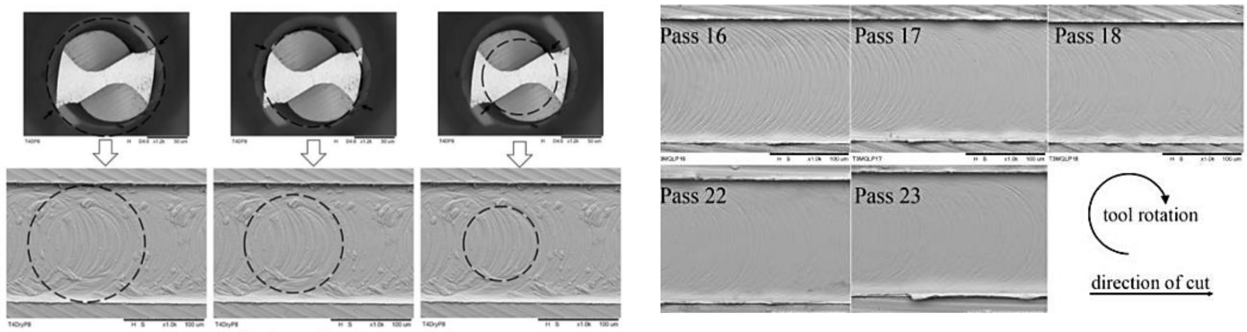


a) Wear measurement methodology
b) Tool life for different cooling-lubricant conditions

Figure 5 – Details of a) Tool wear measurement and b) tool life for different cooling-lubricant conditions (Ziberov et al. 2016a)

The study by Ziberov et al. (2016a) also considered the types of wear and flank wear was predominant for this type of operation. In some tools, wear was observed due to the adhesion mechanism, which is characteristic of low cutting speeds (10 m/min). Another observation was the formation of APC for machining without application of MQL cutting fluid, which reduces the wear rate of the microtool but produces a groove with an inadequate finish, this was associated with built up edge (BUE) formation, that presented the cutting edge but worsened the surface quality as one can note in Figure 6 a).

The authors highlighted that the surface quality with MQL was smoother, Figure 6 b), and burrs with smaller dimensions were generated (Ziberov et al. 2016a). To corroborate with those results, it is worth mention the study developed by Wang et al. (2016). The authors carried out a study in order to verify the influence of APC formation on the surface quality of 316L stainless steel slots when using MQL technique. For this, uncoated carbide micromills with a diameter of 406 µm were used. The authors varied the cutting speed 10 m/min, 27 m/min, 44 m/min, 60 m/min and the feed per tooth: 0.05 µm, 0.20 µm, 0.50 µm and 1.00 µm always with application of fluid via MQL technique. Wang et al. (2016) quantified the formation of APC through images of the surface of the channel, then correlated this data with the roughness results and obtained a statistical model that allows predicting the roughness of the channel from the quantization of the cutting edges. They also point out that the formation of APC is the main responsible for deteriorating the quality of the micro-milled surface.



a) Worsened surface finishing when dry micromilling Ti-6Al-4V (Ziberov et al. 2016a)
b) Smoother surfaces produced using MQL (adapted from Ziberov et al. 2016a).

Figure 6 – Comparison of dry and MQL micromilling in terms of surface quality.

The use of cutting fluid by MQL can be associated with tool coating, Ucun et al. (2013) studied the effect of coating on tool wear when micromilling Inconel 718. They used a micromill of 768 µm and cutting edge radius equal to 2 µm, with the following coatings: TiAlN+AlCrN, DLC, AlTiN, TiAlN+ WC/C and AlCrN. The adopted cutting speed was 48 m/min, the feed values of 1.25 µm, 2.50 µm, 3.75 µm and 5.00 µm and the cutting depths 100 µm, 150 µm and 200 µm, the authors also adopted as standard the machined length before analysis of 120 mm. Coolube 2210 vegetable oil, was applied via the MQL technique with a flow rate of 150 ml/h As a result of the study, the authors observed that flank wear, due to the abrasive wear mechanism, was the most frequent type of wear, in addition, local fractures were observed on the cutting edges and secondary edges as a result of fatigue and formation cutting edge.

Ucun et al. (2013) also observed a reduction in the wear rate for coated tools in relation to uncoated ones and likewise the coated ones showed a smaller reduction in diameter, which they attribute to the high hardness of the coatings, as well as to the low coefficients of friction. Among the coatings, the best ones were DLC and TiAlN+WC/C. Unlike the macro process, greater wear was observed for smaller feeds and small depths of cut. Regarding the use of lubricant, they concluded that lubrication significantly increased tool life and prevented chip adhesion, Figure 8.

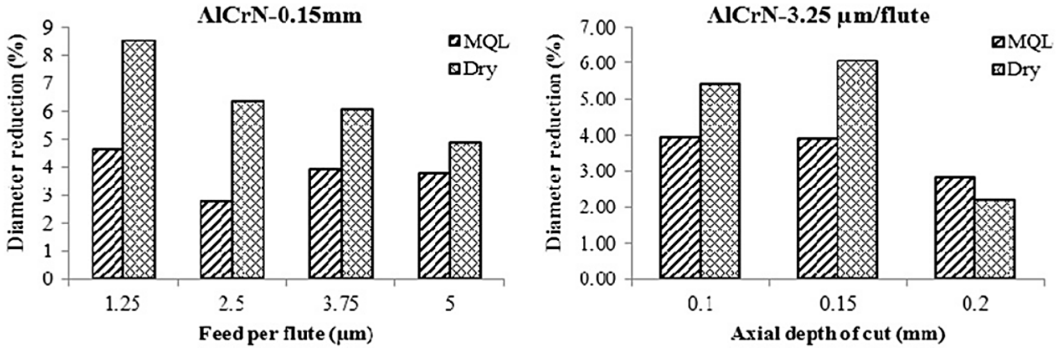


Figure 7 – Effect of MQL lubrication on tool diameter change (Ucun et al., 2013)

Besides the good results presented, it is necessary to properly adjust the flow rate and how the cutting fluid is delivered to the cutting zone. According to Li et al. (2015) it is important that the air pressure is sufficient to go through the air flow that is generated by the tool rotation. Also, De Oliveira et al. (2020) pointed out that when using pulse pumps to deliver the cutting fluid, the frequency of the cutting fluid application will determine the quality of the surface. On their study the author performed the micromilloing of Inconel 718 with 400µm diameter WC tools. The cutting fluid applied was the Coolube 2210EP-UNIST cutting fluid at 0.23 MPa and two flow rates: 40.7 and 270mL/h, equals to 30 and 200 pulses/min (0.5 and 3.33 Hz) respectively. The cutting parameters were 40µm depth of cut, of 25.1m/min cutting speed, and 5µm/tooth chip load. The surface roughness presented the following behavior: 0.23µm Ra in dry machining, lubricant at 0.5 Hz pulse, Ra of 0.16µm and at 3.33Hz Ra of 0.14µm. Qualitatively it was possible to observe more material adhered on the slot surface, for the lower frequency and higher burr formation, Figure 9.

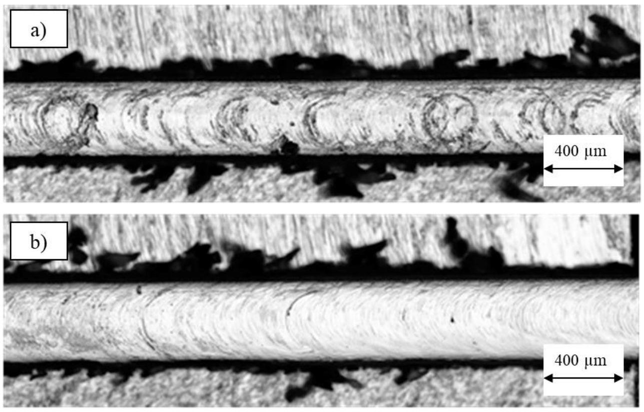
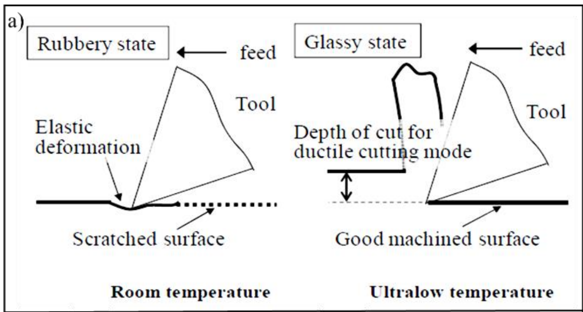


Figure 8 – Micromilled Inconel 718 slots: a) dry and b) MQL with 3.33Hz (adapted from Gomes et al. 2022).

2.3 Cryogenic Methods

Cryogenic machining is a method in which the workpiece, tool, or cutting zone is cooled by a cryogenic environment, such as air, liquid nitrogen, liquid CO2, or liquid helium, the temperature of which during cutting is less than -150°C. Liquid nitrogen (LN2) has been the most used medium due to its chemical inertness, abundant resources and low cost (Wang et al., 2020). In the micromachining process, this method has still been little explored and a large part of the study carried out has investigated cryogenic micromachining in difficult-to-machine materials, such as polydimethylsiloxane (PDMS), which has low elasticity and high adhesion.

In this sense, Mishima, Kakinuma and Aoyama (2010) emphasize the glass transition temperature (Tg) of soft polymer materials, which depends on the structure of the polymer main chain. Just below Tg, the polymer changes from rubbery state to glass state, and stiffness increases remarkably. Furthermore, since the movement of the molecules is suppressed, the polymer adhesion is expected to disappear. In this sense, the authors proposed a cryogenic micromachining model, assisted by liquid nitrogen cooling, to machine the elastic polymer below Tg, which for PDMS is 150 k. In Figure 9 a), the scheme can be seen illustrating the concept of cryogenic micromachining of a soft polymer proposed by the authors, in which the ductile mode cut is applied by adjusting the cutting depth. When experimentally evaluating the proposed model, as outlined in Fig. 1c, for the micromilling and microdrilling processes, and using the parameters shown in Figure 9 b), the authors found that below the glass transition temperature of 150 k, the stiffness of PDMS increased significantly, high adhesion did not occur, and the cutting performance improved. Therefore, it was concluded that cryogenic micromachining is efficient for both micro groove and micro hole fabrication.



b)

	(a)	(b)
Tool	Micro end mill (NS tool)	
Tool diameter mm	ϕ 0.5	ϕ 0.05
Rotational speed min^{-1}	15000	17500
Feed rate mm/min	3.0	3.0
Cutting space temperature K	110~220	77

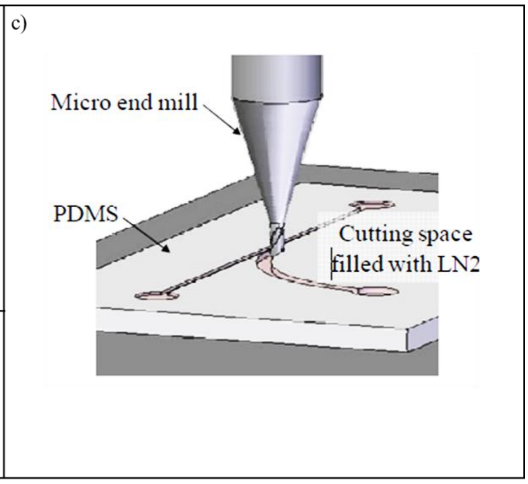


Figure 9 – a) Concept of cryogenic micromachining; b) Cutting condition; c) Experimental method of the proposed cryogenic micromachining (Mishima; Kakinuma, Aoyama, 2010)

With a similar objective, Kakinuma, Yasuda and Aoyama (2008) investigated freezing milling method using liquid nitrogen in PDMS micromilling. To this end, the authors designed a special jig with nitrogen chambers, as can be seen in Figure 10. The liquid nitrogen reservoir and the part support placed in the center of the reservoir were made of aluminum due to its high thermal conductivity. The PDMS plate was placed on the stage and fixed with an aluminum clamp. The other flamed made of bakelite had the function of insulating the heat transfer and suppressing the change from liquid nitrogen to gas. To keep the temperature on the bottom face of the jig constant and to avoid generating heat bypass from the dynamometer, a water circulation system was incorporated between the jig and the dynamometer. The results showed that microchannels can be easily and accurately molded in PDMS by the proposed method.

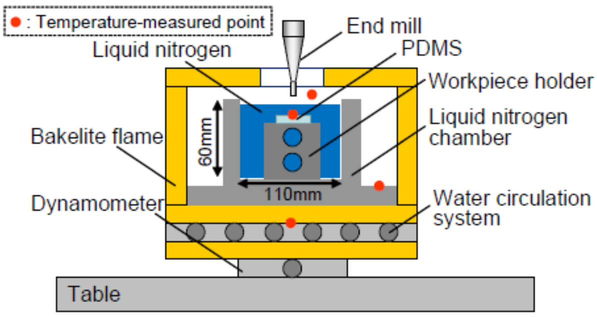


Figure 10 – Structure of Cryogenic Liquid (Kakinuma; Yasuda; Aoyama, 2008)

Getu, Spet and Papini (2011) investigated the cryogenic abrasive jet micromachining of polymers (CAJM) to optimize the process in order to determine the rate and extent of cooling for a given configuration, and to determine the effect of thermal strain on the final room temperature shapes of micromachined features. The analysis showed that the material (polydimethylsiloxane – PDMS) was over-cooled and that the CAJM process could be further optimized to conserve LN2 by decreasing its flow rate, or by pulsing the LN2 jet so that the surface was only cooled periodically. It was also observed that the temperature reduced with decreasing speed and that the ability to machine PDMS at a temperature of -67 °C suggests the possibility of using another medium other than LN2, such as dry ice, to effectively cool the substrate of PDMS.

Kakinuma, Kidani and Aoyama (2012) also evaluated cryogenic micromachining of viscoelastic polymers, such as PDMS, with the aid of external supply cooling. It was found that the external supply of cooling to the tool forces the direction of heat flow to be kept towards the tool. This allows the PDMS to be machined in the glassy state to obtain a fine quality machined surface, as well as enabling cryogenic micromilling. Thus, the authors concluded that cryogenic micromilling is an effective process for manufacturing 3D microfluidic chips with submicron to millimeter scale channels.

Evaluating cryogenic micromachining on a material other than PDMS, Ucun, Aslantas and Bedir (2015) analyzed the effect of minimum quantity lubrication and cryogenic pre-cooling on cutting performance in the micromilling of Inconel 718. Therefore, dry cutting, minimum quantity lubrication and cryogenic pre-cooling were considered as the cutting conditions. To carry out the process using the MQL, a vegetable liquid lubricant was sprayed in the cutting region with a consumption amount of 150 ml/h. To perform pre-cooling under cryogenic conditions on the surface of the part, liquid nitrogen was sprayed into the cutting zone at low pressure (<1 bar), as can be seen in Figure 11. With this process, local freezing and embrittlement of the part surface were sought. The results showed that the cutting tool performance was better in the MQL processOn the other hand, when using the cutting process with cryogenic pre-cooling, the tool wear was maximum. As for surface roughness, the cutting process with cryogenic pre-cooling provided lower values for this variable. In addition, a small difference between dry cutting and MQL cutting was observed. The most pronounced effect of cryogenic pre-cooling was observed on burr formation. Burr formation was prominently reduced in the cryogenic pre-cooling cutting process. In the dry cut and in the cut with MQL, it could be observed that there was no significant difference between them regarding the formation of burrs.

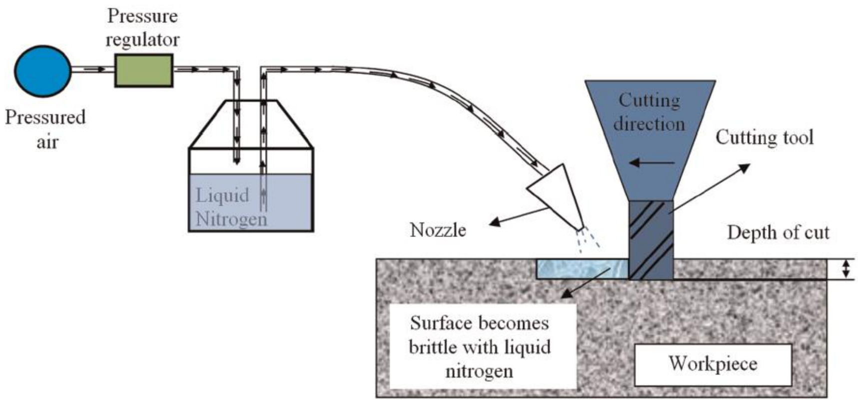


Figure 11 – The schematic representation of the experimental setup para testes com cryogenic pre-cooling.

3. CONCLUSIONS

After performing the literature analyses of different cooling-lubrication applied in micromachining some tendencies could be identified as follows:

i. Dry micromilling is usually applied in researchers as compassion, presenting worsened machined surface and favoring BUE formation. Regarding the tool wear, it can enhance or reduce the tool life if it is stable or non-stable, respectively.
ii. The conventional methodology, flood, usually presents results intermediate between dry and MQL. It is recommended to use this method when MQL is not available.
iii. MQL demonstrated to be the best methodology for micromilling metals, resulting in better surface finishing, less adhered material, lower surface roughness values and smaller burrs. In some of the studies MQL could also increase tool life.
iv. Cryogenic methodologies are usually applied in high ductility materials, highlighting the polymers. The method stands out for allowing good surface finishing, higher dimensional accuracy and reduced burr formation.

4. ACKNOWLEDGEMENTS

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