Eco-sustainable Improvement of Super Duplex Stainless Steel Turning Trough CryoMQL Technique

O. Pereira[1], N. Villarrazo[1], A. Rodríguez[1], L. N. López de Lacalle[1](✉), and D. Martínez-Krahmer[2]

[1] CFAA—Aeronautics Advanced Manufacturing Center, University of The Basque Country, Biscay Science and Technology Park, Ed. 202, 48170 Zamudio, Spain
norberto.lzlacalle@ehu.eus

[2] INTI—National Institute of Industrial Technology, Avenida General Paz 5445, 1650 Miguelete, Provincia de Buenos Aires, Argentina

Abstract. In machining processes, the environmental footprint reduction is a fact that is been addressed in recent years. In this line, the use of recycled CO_2 as cryogenic cutting fluid in those processes is taking advantage in comparison with other lubricooling alternatives to replace oil emulsions in workshops. This technique is characterized by its high cooling capability and its cleaning efficiency. Besides, it is environmentally innocuous due to the CO_2 is captured form a primary process to be used as cutting fluid. However, the CO_2 has low lubricant properties what implies a challenge to be used in heat resistant alloys because combine both high hardness and low thermal conductivity. Therefore, in this work is explored the use of CO_2 combined with biodegradable oil spray under CryoMQL technique for dealing with super duplex stainless steel during turning operations. In particular, the CryoMQL technology was optimized for achieving a successful process through tool life improvement. The results shown that the optimization carried out implies that the use of CryoMQL technique extend tool life a 45% in comparison with the use of conventional oil emulsions, obtaining in this way not only an environmental improvement but also a technical one in this kind of alloys.

Keywords: CryoMQL · Eco-sustainable machining · Difficult to cut alloy

1 Introduction

In the current industry dealing with environmental issues with the aim of reducing their impact processes and being more ecofriendly is mandatory due to not only more restrictive laws but also society's greater environmental awareness [1]. In this line, from machining industry the reduction or suppression of cutting fluids is the path to answer those requirements because they are the major source of contamination. In particular, in machining processes, such as turning and milling operations, traditionally oil emulsions are used as cutting fluids. However, despite from a technical point of view those oil emulsions works and assist machining processes lubricating and cooling the cutting zone,

H. Kohl et al. (Eds.): GCSM 2023, LNME, pp. 641–649, 2025.
https://doi.org/10.1007/978-3-031-77429-4_71

from a environmental and health point of view have several disadvantages that cause damages in the environment and workers' health. In one hand, regarding environmental issues, oils emulsions are petroleum derivatives in which 30% are lost through leaks and workpieces cleaning processes, etc. [2]. This implies that these emulsions reach the food chain through the drain that led to the rivers and these in turn to the sea in an uncontrolled way [3]. On the other hand, in relation to workers' health it is know that continuous exposure to these emulsions by workers means that in the short term they may present skin and respiratory irritation and in the long term even lung cancer [4, 5]. Therefore, as was mentioned above, its elimination implies achieving processes that are not only safer for workers but also more environmentally friendly.

In this line, in the literature several alternatives were proposed with the aim of suppressing oil emulsions from machining processes, being the alternatives most efficient the Minimum Quantity Lubrication (MQL) and Cryogenic cooling. MQL consists of using an biodegradable oil spray as cutting fluid, which has excellent lubricating properties [6]. In the case of Cryogenic cooling, nitrogen or carbon dioxide liquified is used as cutting fluid, presenting both gases a high cooling capacity [7]. These techniques were widely analyzed in several materials such as aluminum and Ti6Al4V alloys obtaining satisfactory results [8, 9]. However, in difficult-to-cut alloys such as nickel alloys and super duplex stainless steels where cooling and lubricating is needed at the same time to deal with their high hardness and ductility MQL and Cryogenic cooling need to be combined under CryoMQL technology where lubricating and cooling properties are achieved at the same time due to the cryogenized biodegradable oil particles that are sprayed in the cutting zone [10]. For example, CryoMQL technique was successfully applied to turning AISI 52100 bearing steel. In particular, in this case the biodegradable oil spray was injected through the toolholder and the CO_2 was used to cool the workpiece. The results showed that in comparison with the use of oil emulsions the tool wear was similar, being therefore an alternative to be applied in this kind of alloys [11]. Other research deals with Inconel 625 in turning operations in which also CryoMQL in comparison with MQL and cryogenics "stand-alone" mode obtained and improvement in tool life of 80% [12]. Other recent research combined CryoMQL lubricooling technique with nanoparticles to turning Haynes 25 superalloy obtaining among the ecofriendly alternatives the longest tool life [13].

In summary, the utilization of CryoMQL technology proves to be a viable option for difficult to cut alloys. Nevertheless, to implement it in an industrial setting, it is imperative to optimize the consumption of liquefied gas in order to effectively manage the associated costs and it is here where there is lake of information in the researches. Therefore, this work steams from the idea of applying an optimized cryogenized biodegradable oil spray under CryoMQL conditions to turning AISI 440C super duplex stainless steel to be applied in industrial processes. Besides, once CryoMQL was optimized the results obtained were compared with the use of oil emulsion and CO_2 in "stand alone mode". The results shown that optimization is mandatory, as the injection of additional CO_2 does not yield improved outcomes. Thus, achieving the appropriate flow rate emerges as a critical parameter for attaining a reliable and effective CryoMQL technique suitable for practical implementation.

2 Experimental Setup

Experimental tests were carried out in a CMZ TC25BTY lathe with 35 kW of power. The alloy employed was AISI 440C super duplex stainless steel with 100 mm of initial diameter and length of 400 mm. This steel is characterized by presenting a high chromium content (≈ 25%) followed by nickel (≈ 5%). Additionally, its microstructure consists of a roughly equal proportion of austenite and ferrite, making it challenging to machine.

The lubricooling technologies tested in these experiments were CryoMQL, CO_2 and oil emulsions, respectively. In particular, for the application of CryoMQL and CO_2 as cutting fluid, the BeCold® system was used. The system injects CO_2 at a pressure of 12 bar, and the flowrate of biodegradable oil was 100 ml/h. Finally, Houghton® Horocut 4260 oil emulsion with a concentration of 9% was used as a reference.

The utilized inserts were Sandvik® CNMG120408 MM 2025 (TiN-coated carbide) with cutting conditions of a cutting speed of 100 m/min, a feed rate of 0.15 mm/rev, a depth of cut of 1.5 mm, and an initial cutting length of 300 mm. The employed tool holder was an Iscar® PCLNR 2525M-12X-JHP which during the tests to optimize the process its nozzle outlet diameter was modified. Cutting forces were measured during the experiments using a Kistler® dynamometer equipped with piezoelectric sensors. Additionally, after each pass, the cutting edge was examined using a PCE-200 microscope. The test stop criterion was established according to ISO 3685, which specifies that the test should be stopped upon reaching a flank wear of 0.3 mm, severe chipping, or general chipping. Figure 1 illustrates the experimental setup and summarizes the employed cutting conditions.

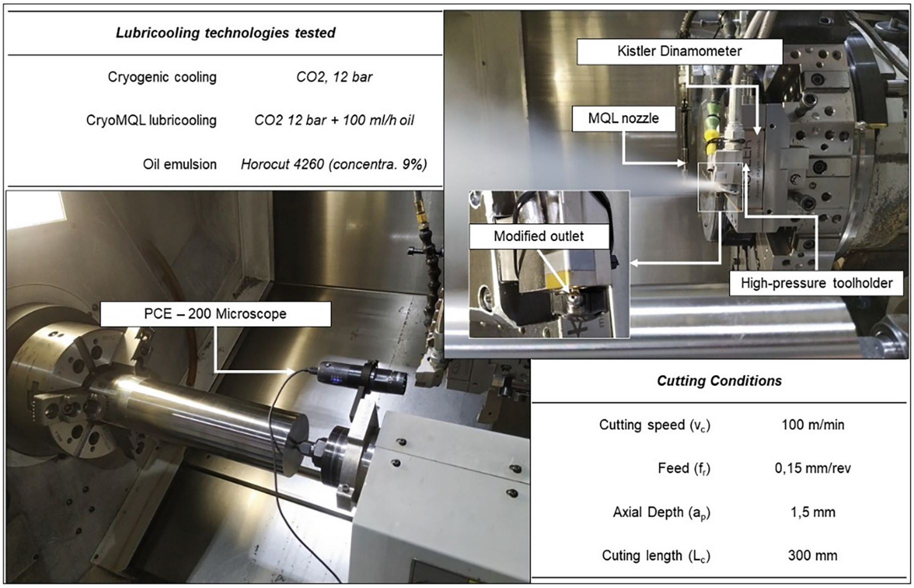

Fig. 1. Experimental setup and cutting conditions used.

3 CryoMQL Optimization and Validation.

3.1 CryoMQL Optimization Process

The optimization began by applying cryogenic cooling using the commercially available high-pressure tool holder (without modifying the outlet), with CO_2 directed towards the chip and rake face, at a flow rate of 5 kg per 8 min of machining. In this case, the insert successfully machined a length of 458 mm but experienced catastrophic failure, as depicted in Fig. 2.

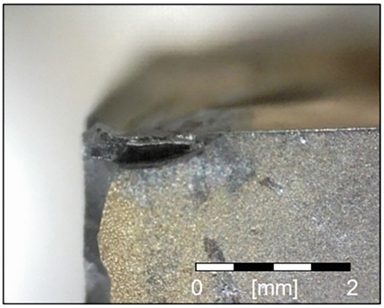

Fig. 2. Insert once CO_2 test was finished.

As can be observed in the figure, the failure was due to mechanical causes due to lack of lubrication. In this case the insert did not show any wear due to thermal causes, which indicates that CO_2 is able to solve this problem but not the mechanical stress to which the insert is subjected. Therefore, subsequently it was proceeded to combine cryogenic cooling with CO_2 combined with biodegradable oil aerosol under CryoMQL technology as cutting fluid. In this second test, the nozzle was placed on the rake face parallel to the CO_2 nozzle as is shown in Fig. 3.

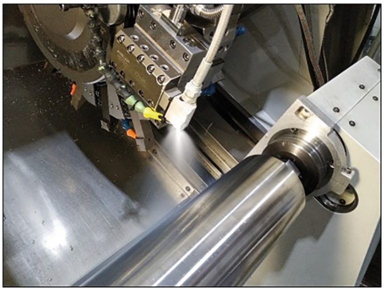

Fig. 3. Initial CryoMQL setup.

In this case, the biodegradable oil particles were absorbed by the Venturi effect due to the CO_2 flow. In this test, the CO_2 flank face outlet of the tool holder was also closed to reduce the CO_2 consumption. However, this test was aborted for several reasons. Firstly, the chips were getting entangled in the MQL system nozzle, causing movement. Additionally, the CO_2 consumption remained substantial. Finally, the insert exhibited premature wear due to thermal and mechanical effects after a single pass, as depicted in Fig. 4.

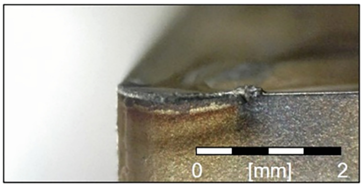

Fig. 4. Insert tool wear once CryoMQL test without optimization was finished.

In this case, the wear due to mechanical effects on the rake face is significant, along with the high CO_2 consumption. This prompted a reconsideration of how CryoMQL technology should be applied. Consequently, the MQL nozzle was repositioned on the flank face of the insert, and an external CO_2 nozzle was used on the rake face. However, in this case, the issue arose with chip entanglement in the nozzles, rendering their use ineffective based on the proposed setup (Fig. 5).

Then, based on this result, the commercial high-pressure tool holder was modified so that the CO_2 outlet diameter was suitable for this application. Specifically, the rake face outlet diameter was reduced to 1.5 mm. The use of this diameter was based on previous experiences carried out by the authors [14]. The optimized CryoMQL setup was as shown in Fig. 6.

Fig. 5. Optimized CryoMQL setup

With this optimized assembly it was possible to reduce the CO_2 consumption up to 1 kg of CO_2 every minute and forty seconds, that is, the CO_2 flow rate was reduced 40%. In this case, the aerosol injected by the MQL nozzle at 6 bar travels by Coanda effect through the wall of the tool holder and once it reaches the CO_2 flow, it is absorbed by it and injected much more efficiently into the cutting zone.

In this case, it was able to machine 1.570 mm of cutting length, stopping the test due to the formation of a ridge around the workpiece due to the loss of cutting edge of the tool.

3.2 Validation of CryoMQL Optimization

Once CryoMQL was optimized, other tests were conducted using oil emulsions as cutting fluid with the aim of obtain reference values and analyze the feasibility of employing the optimized CryoMQL technology in this kind of alloys. The cutting length achieved in this test before insert failure was 1.540 mm.

Afterwards, once these tests were finished, an analysis and comparison were conducted between the different lubricooling techniques were carried out taking into account the machined lengths (number of passes), machining time, volume of chips removed and cutting forces obtained. Figure 6 presents the obtained results related with the process productivity, as well as the condition of the inserts used with coolant and CryoMQL in their final stages of useful life.

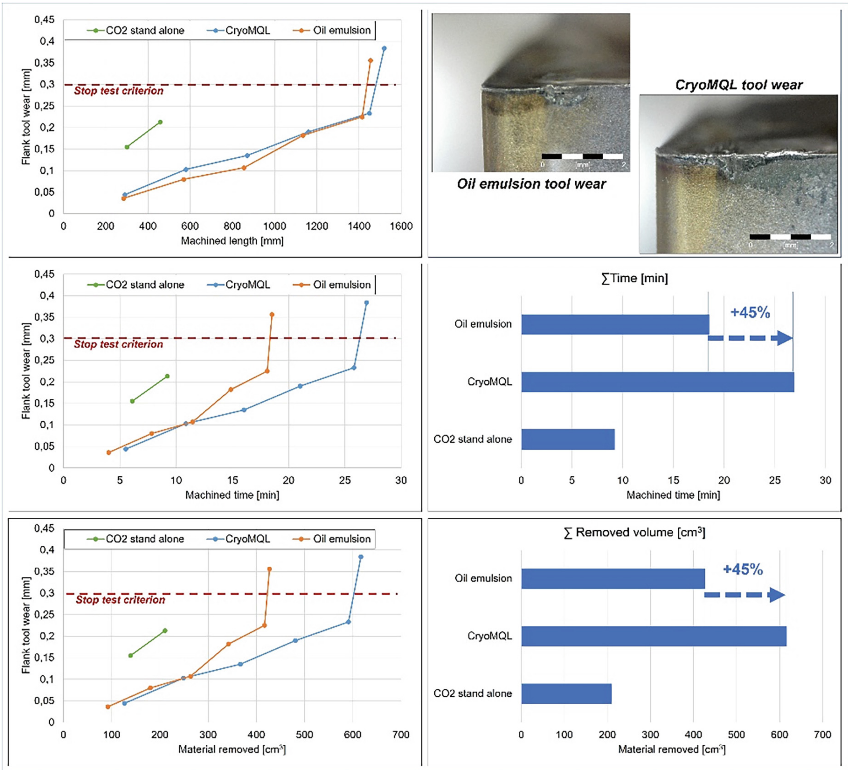

Fig. 6. Productivity results obtained with the different lubricooling technologies.

From the analyzed results, it can be deduced that the use of cryogenic cooling with CO_2 is not viable compared to the use of cutting fluid or CryoMQL, ruling out the use of CO_2 in "stand alone" mode. Taking the oil emulsion results as a reference, in the case of the linear length machined by CryoMQL, the tool life is comparable for both technologies. However, it should be noted that as the diameter of the AISI 440C steel workpiece decreases, the machining time per pass and the volume of chips removed also decrease, as the cutting speed remains constant during machining. Therefore, when analyzing the feasibility of CryoMQL technology, these two parameters should be taken into account.

Observing the machining time, which is the actual tool durability parameter, using oil emulsion as cutting fluid, the technology achieves 18.52 min of machining. However, utilizing CryoMQL as cutting fluid results in a 45% increase in this value, allowing for 26.93 min of machining before the insert reaches the end of its useful life. Regarding the volume of chips removed, the result is analogous, with CryoMQL evacuating 45% more chip volume (616.62 cm^3) compared to cutting fluid (427.05 cm^3).

Furthermore, upon analyzing the images of the insert's edge condition at the end of its useful life, it can be observed that the wear morphology in both cases is similar, exhibiting the typical notch characteristic of materials with austenite in their microstructure. This notch is caused by the hardening of the surface layer generated during machining due to the compression exerted by the insert tip on the material surface. Consequently, this is the area where the insert experiences the most stress, resulting in the formation of the aforementioned notch on the edge (Fig. 7).

Finally, regarding cutting forces, Fig. 7 shows the average cutting force modulus. In this figure it can be observed that in all technologies the values and the trends are analogous and that the value of the average force increases linearly without presenting values that indicate destabilization of the machining and could cause the breakage of the insert in an uncontrolled manner.

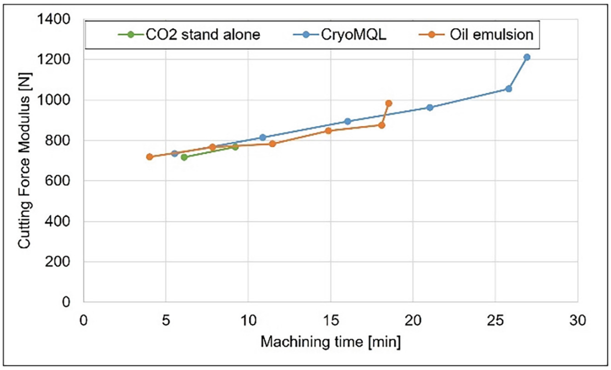

Fig. 7. Average cutting force modulus obtained.

4 Conclusions

In this work a CryoMQL optimization was carried out with the aim of obtaining a feasible technology to be applied to super duplex stainless steels industrially. Besides, several tests were carried out to validate the optimization in comparison with the use of conventional oil emulsions and CO_2 in "stand alone" mode. The conclusions obtained are listed below:

- The optimization of CO_2 flowrate to apply CryoMQL technology is mandatory. In this case, the reduction of the initial flowrate used was a 40%, being this the optimum point to deal with super duplex stainless steel.
- The use of CO_2 in "stand alone" mode does not sufficiently reduce the mechanical wear effects on the insert, resulting in premature wear of the insert.
- The use of CryoMQL as lubricooling technology implies an increase of tool life compared to oil emulsions of 45% and therefore a similar increase in the volume of chips dislodged.
- The cutting forces do not reveal unstable machining for any of the three technologies analyzed.

References

1. Pereira O, Rodríguez A, Fernández-Abia AI, Barreiro J, López de Lacalle LN (2016) Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304. J Clean Prod 139:440–449
2. Lawal S, Choudhury I, Nukman Y (2012) Application of vegetable oil-based metalworking fluids in machining ferrous metals: a review. Int J Machine Tools Manufact 52:1–12
3. Byrne G, Dornfield D, Denkena B (2003) Advancing cutting technology. CIRP Ann – Manuf Technol 52(2):483–507
4. Cetin MH, Ozcelik B, Kuram E, Demirbas E (2011) Evaluation of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by Taguchi Method. J Clean Prod 19:2049–2056
5. Park KH, Olortegui-Yume J, Yoon MC, Kwon P (2010) A study on droplets and their distribution for minimum quantity lubrication (MQL). Int J Mach Tools Manuf 50:824–833
6. Sharma VS, Dogra M, Suri N (2009) Cooling techniques for improved productivity in turning. Int J Mach Tools Manuf 49(6):435–453
7. Pereira O, Rodríguez A, Calleja-Ochoa A, Celaya A, López de Lacalle LN, Fernández-Valdivielso A, González H (2022) Simulation of Cryo-cooling to improve superalloys cutting tools. Int J Precis Eng Manuf-Green Techn 9:73–82
8. López de Lacalle LN, Angulo C, Lamikiz A, Sánchez JA (2006) Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. J Mater Process Technol 172(1):11–15
9. Khanna N, Shah P, López de Lacalle LN, Rodríguez A, Pereira O (2021) In pursuit of sustainable cutting fluid strategy for machining Ti-6Al-4V using life cycle analysis. Sustain Mater Technol 29:e00301
10. Pereira O, Celaya A, Urbikaín G, Rodríguez A, Fernández-Valdivielso, A, López de Lacalle LN (2020) CO_2 cryogenic milling of Inconel 718: cutting forces and tool wear. J Mater Res Technol 9:8459–8468
11. Çetindağ HA, Çiçek A, Uçak N (2020) The effects of CryoMQL conditions on tool wear and surface integrity in hard turning of AISI 52100 bearing steel. J Manuf Process 56:463–476
12. Yildirim ÇV, Kivak T, Sarikaya M, Sirin S (2020) Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL. J Mater Res Technol 9(2):2079–2092
13. Sirin S (2022) Investigation of the performance of cermet tools in the turning of Haynes 25 superalloy under gaseous N_2 and hybrid nanofluid cutting environments. J Manuf Processes 76:428–443