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PERFORMANCE OF AN INDIRECT COOLING SYSTEM DURING ABNT 1045 STEEL MILLING MACHINING

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Abstract. *This study aimed to compare two ambient, dry machining and a novel Indirect Cooling System – ICS that fixes the workpiece. The temperature was taken as a response variable, and it was made in a sequence of two passes given in the specimen. The input variables were ambient (dry or cryo) and rotation (670, 1 180, and 1 970 rpm), while the depth of cut (0,5 mm), were kept constant. The inserted thermocouple method showed that the temperature measurement significantly reduced using the indirect cooling system for all rotation conditions. For instance, at 670 rpm, there was a difference of ~24 °C less, for 1 180 rpm, it was ~20° C, and at 1 970 rpm, it was ~ 38 °C. Therefore, the indirect cryogenic cooling system demonstrated its ability to remove and keep the piece cooled during the cutting process.*

Keywords: *Indirect Cooling System - ICS, sustainable, 1045 steel, milling, eco-friendly machining, cryogenic machining*

1. INTRODUCTION

Machining is a nonlinear, complex process, which involves high frictional heat generation between two surfaces (tool/part) in a reduced contact area with high localized temperatures. It is estimated that almost all of the energy consumed in the process is transformed into heat (Abukhshim et al., 2006; Klocke, 2011; Luchesi & Coelho, 2012; Machado et al., 2011; Trent & Wright, 2000). Among the machining cooling techniques, cryogenic fluids can be considered one of the most efficient in temperature control (Gill et al., 2010; Yildiz & Nalbant, 2008).

According to Shokrani et al. (2013), the term cryogenics was introduced to the scientific world by Heike Kamerlingh Onnes, in 1894, in the article known "*On the cryogenic laboratory Leiden and the production of very low temperatures."* Cryogenics (cryo) is a term that refers to the study of shallow temperatures. Although there is no literary consensus, some authors argue that cryo temperatures are below the boiling point of atmospheric air (T = -153 °C) (Timmerhaus & Reed, 2007). The chemical elements that reach this point are nitrogen (LN_2), oxygen (O_2), helium (LHe), methane, ethane, argon. Inside the machining field, values below (T = -50 °C) are already considered cryogenic, such as using carbon dioxide (LCO_2), currently used commercially in CNC machines. Among the cryogenic fluids, the most used is liquid nitrogen (LN_2), obtained from the fractional distillation of atmospheric air in a liquid state. LN_2 vaporizes at -198.79 °C and is the most abundant gas in atmospheric air, ~ 78.00%.

Studies and methods of applying cryogenic fluid have been developed and are currently being tested in different industries such as medical, energy, aerospace, oil, gas, and automotive. The machined material determines the application. The focus is to increase tool life and productivity, besides avoiding cutting fluids, reducing costs, and environmental injuries. It has been successfully applied in many machining operations with different materials, from easy-to-cut to difficult-to-cut metals (Dhar & Kamruzzaman, 2007; Kale & Khanna, 2017; Pusavec et al., 2011; Shokrani et al., 2013).

In cryogenic machining, liquefied gases, mostly LN_2 and CO_2, are injected during the cutting process. High temperatures play an ambiguous role. On the one hand, high heat generation favors wear mechanisms being harmful to the tool, affecting its service life, dimensional tolerance, surface integrity, productivity, etc. On the other hand, they tend to cause the softening of the part's material, reducing its shear strength and facilitating the cutting. Therefore, the way liquefied gases are injected is crucial for good process performance.

The main cryogenic fluids are hydrogen, helium, nitrogen, argon, and methane. Among these, nitrogen stands out because it has excellent efficiency in producing low temperatures and is abundant in the atmosphere, besides not being harmful to the environment and chemically inert. Nitrogen exists in nature in the form of two isotopes. The distillation of liquid air produces it. Another way to produce it is to the selective absorption in the coal cradle. It is color and odorless. Another cryo gas is argon, which is an inert gas present in the air in the proportion of 0.934% volume. Argon boiling point is between oxygen and nitrogen. The oxygen has a blue color and is the only cryogenic fluid with a slightly magnetic characteristic. It exists in nature in the form of three isotopes. It is the second constituent of the air, where it is removed by distillation of liquid air. It is highly reactive with hydrocarbon, highly flammable. Finally, hydrogen is the lightest of cryogenic fluids with density in 1/14 of the water density.

Nitrogen is an environmentally friendly alternative since there is no cutting fluid to dispose of, as nitrogen evaporates harmlessly into the air. Moreover, the chip generated by this technique is free of contaminants and can be recycled. Experiments reveal the excellent performance of this technique at low cutting speeds obtaining reduced flank wear and increased tool life. However, regulating the flow and pressure of liquid nitrogen is a critical factor in avoiding the workpiece's overcooling and, consequently, an increase in cutting force (LISBOA et al., 2013).

According to Secco (2015), there are three ways of applying cryogenic fluid: pre-cooling, direct (or by spray), and indirect (Fig. 1). In the first one nozzle injects the cryogenic fluid into the part in a process before machining, in the second, the fluid is directed in one or more cutting zones, and in the third, the fluid circulates internally in channels or is kept in a chamber near the heat generation, cutting edge. Its efficiency is linked to the tool's material thermal conductivity and the distance where the LN_2 is confined (Oliveira, 2014; Secco, 2015).

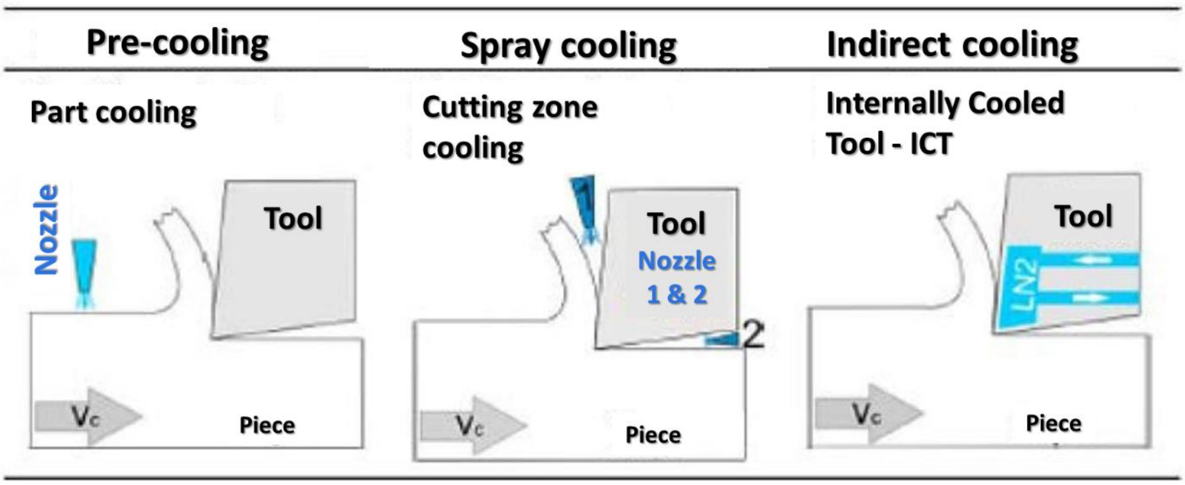

Figure 1. Cryogenic fluid application methods (Secco, 2015).

Steels are iron and carbon metal alloys, with carbon percentages ranging from 0.008 to 2.11%. Due to the excellent ductility, steels are easily deformable by forging, lamination, and extrusion. According to international AISI (American Iron and Steel Institute) and Society of Automotive Engineers (SAE) and Brazilian national standards ABNT (*Associação Brasileira de Normas Técnicas*), steels classification system is based on their chemical composition (González Santos, 2008). Following the standard NBR NM 87/2000, which establishes the chemical compositions of steels for mechanical construction, ABNT 1045 steel, or AISI 1045, must present chemical composition.

This work aims to design, manufacture, and test an indirect cooling piece fixing system, a drill/bench milling machine to minimize impacts on the tool due to increased temperature, avoiding the use of cutting fluids to improve the ambient conditions for the operator by reducing toxic pollutants.

2. MATERIALS AND METHODS

2.1 Cooling System Design

It was used indirect cooling of the workpiece fixing system. Cryogenic LN_2 was applied inside two aluminum supports, responsible for fixing the workpiece and removing heat in the cutting process through heat conduction.

Aluminum was adopted for fixing material as it has excellent thermal conductivity and because it has good oxidation resistance compared to steel, for instance. Figure 3 represents the fixing aluminum parts where the LN_2 reservoir was put above the entire system to use gravitational force and promote its circulation.

2.2 ABNT 1045 Steel preparation

A hole was drilled on one of the steel faces, Fig. 2, using an 8mm drill. In this hole, the thermocouple resolution of 0.25°C and a measuring range up to +1024°C was coupled to collect data from the temperature present in steel both in dry machining and the indirect cooling system proposed.

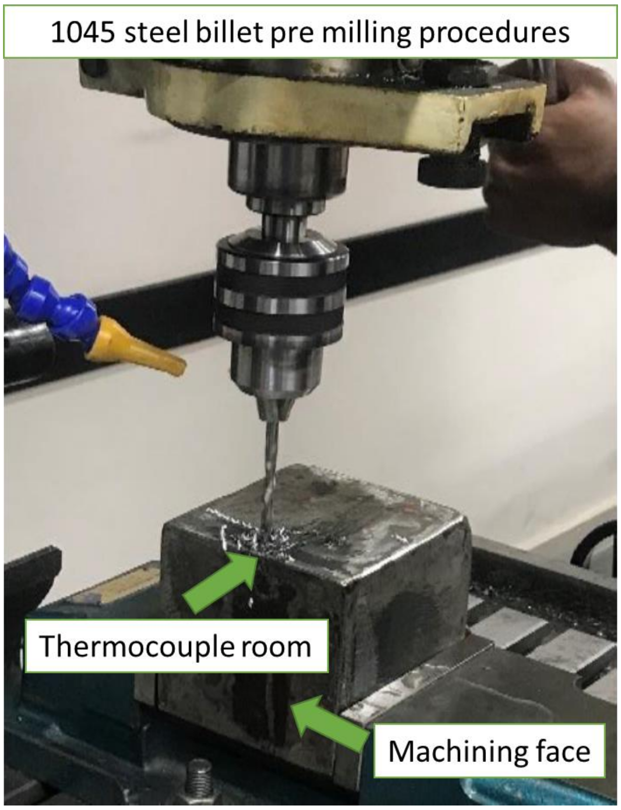

Figure 2. ABNT 1045 steel procedures to insert thermocouple near (2 mm) from the machining face.

The steel billets ABNT 1045 were standardized in the measurements 100 x 100 x 100 mm for the procedure performed. Three samples were used. Table 1 contains the mechanical properties and chemical composition of 1045 ABNT steel used (NBR, 2000 apud Azevedo, 2002).

Table 1. Chemical composition of ABNT 1045 steel (% by mass) (NBR, 2000)

Mechanical properties				
Yield strength [GPa]	**Yield Limit [MPa]**	**Tensile strength limit [MPa]**		**% stretching**
250	310	560		17%
Chemical composition				
C	**Mn**	**P_{max}**	**S_{max}**	**Si**
0.43 ~ 0.50	0.60 ~ 0.90	0.04	0.05	0.10 ~ 0.60

2.3 Aluminum fixing parts preparation

The novel proposed fixing parts were drilled with holes for the passage of cryogenic fluid and were prepared through two detailed aluminum blocks 125 x 110 x 75 mm, Fig. 3.

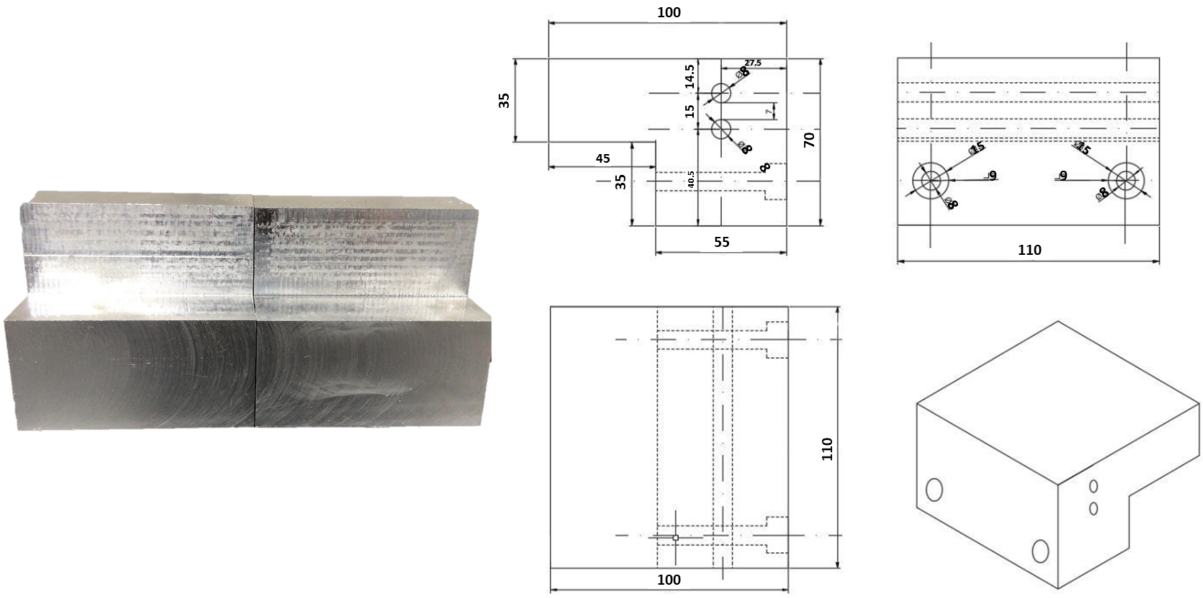

Figure 3. Designed fixing aluminum parts, real picture (left), and mechanical drawing (right)

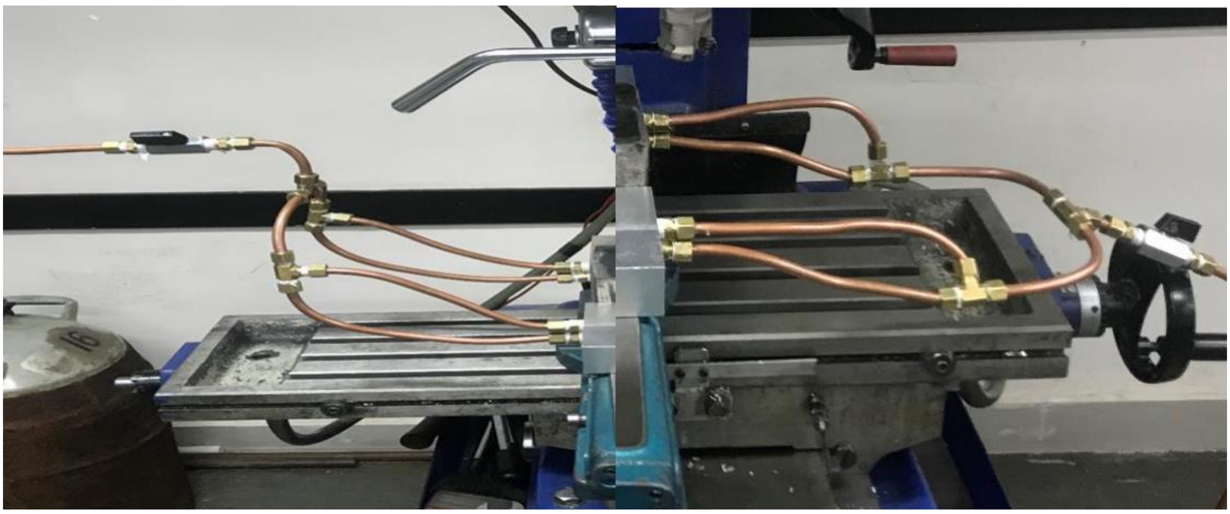

Figure 4. Front view of the assembled indirect cooling fixing system with cooper ducts for LN_2 passage

2.4 Measurement procedures

The thermocouple terminals were connected to an Arduino plate via a specific component (MODULE MAX6675) to perform measurements during testing and verify the cooling system's effectiveness. The thermocouple component could perform temperature monitoring when associated with an external microcontroller or other thermostatic intelligence. This converter has a resolution of 0.25°C and a measuring range of up to +1 024°C.

Two different ambient were tried dry and cryogenically cooled machining. It was used three rotations (670, 1 180, 1 970 rpm), with a 0.50 mm depth of cut and two passes for each rotation.

3. RESULTS & DISCUSSIONS

3.1 Dry machning temperature analisys

In the temperature tests, each rotation's first and second steps were compared through the tables with the collected data, thus generating a graph for each rotation analyzed in dry milling, Fig. 5.

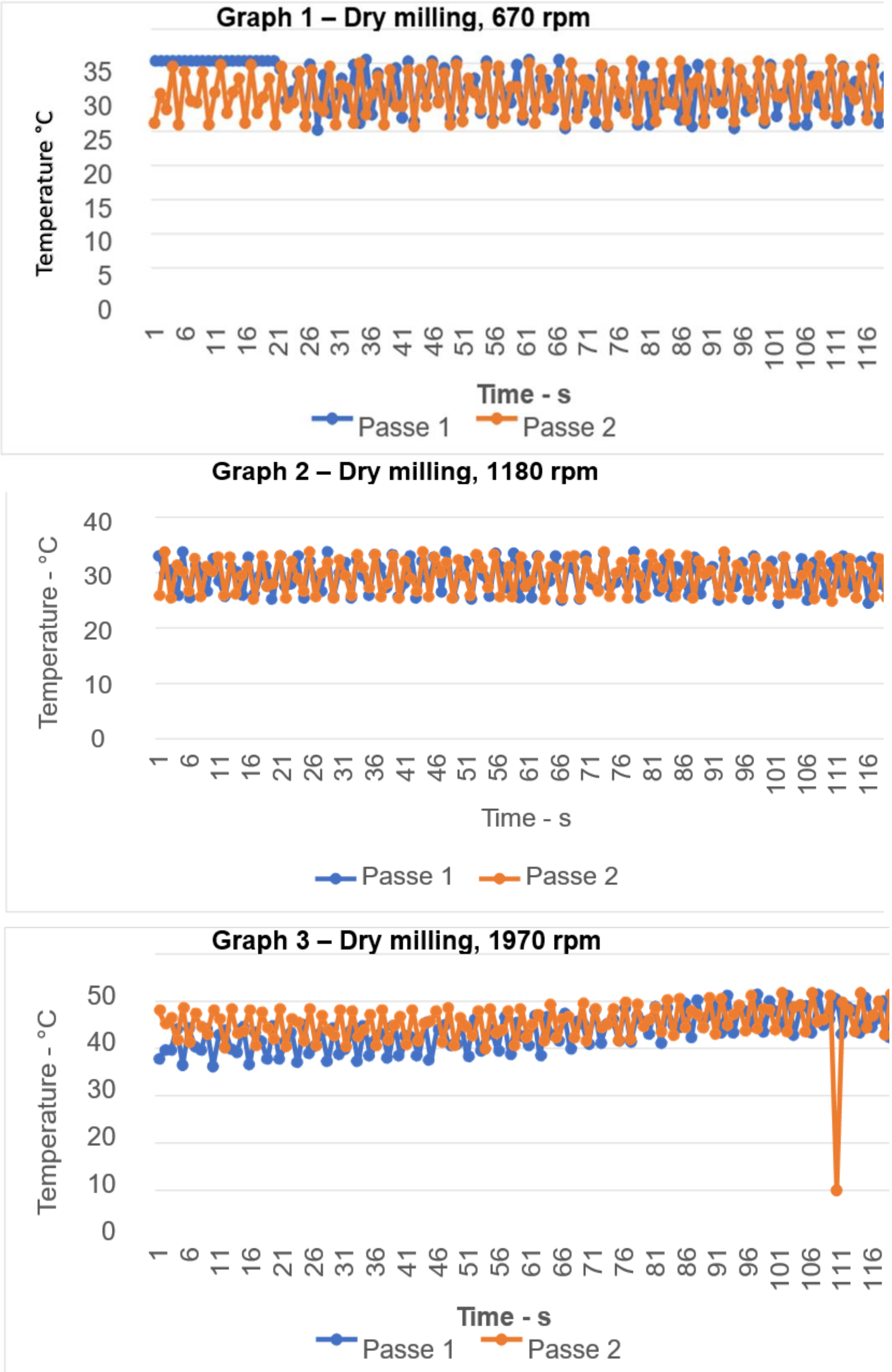

Figure 5. Temperature measurements in dry milling for 670, 1 180, 1 970 rpm

It can be observed, Fig. 5, graph 1, 670 rpm, a variation between 20 and 31°C in the lowest measured temperature of the procedure. This variation is due to the temperature gradient of the part, and then give the second pass, the piece already a little heated due to the previous pass, there was a slightly higher peak at the maximum temperature. Figure 5, graph 2, 1 180 rpm, shows a temperature increase compared to the previous rotation, which is expected since the higher the cutting speed, the higher the temperature. Finally, in Fig. 5, graph 3, 1 970 rpm, the maximum temperature measurement was observed, varying from ~40 to 50 °C.

3.2 Indirect cryogenic cooling machining

In the indirect cryogenic cooling milling, temperature measurements were made following the same conditions of dry machining to compare both processes. Figure 6 contains the graphs with temperatures for 670, 1 180, and 1 970 rpm.

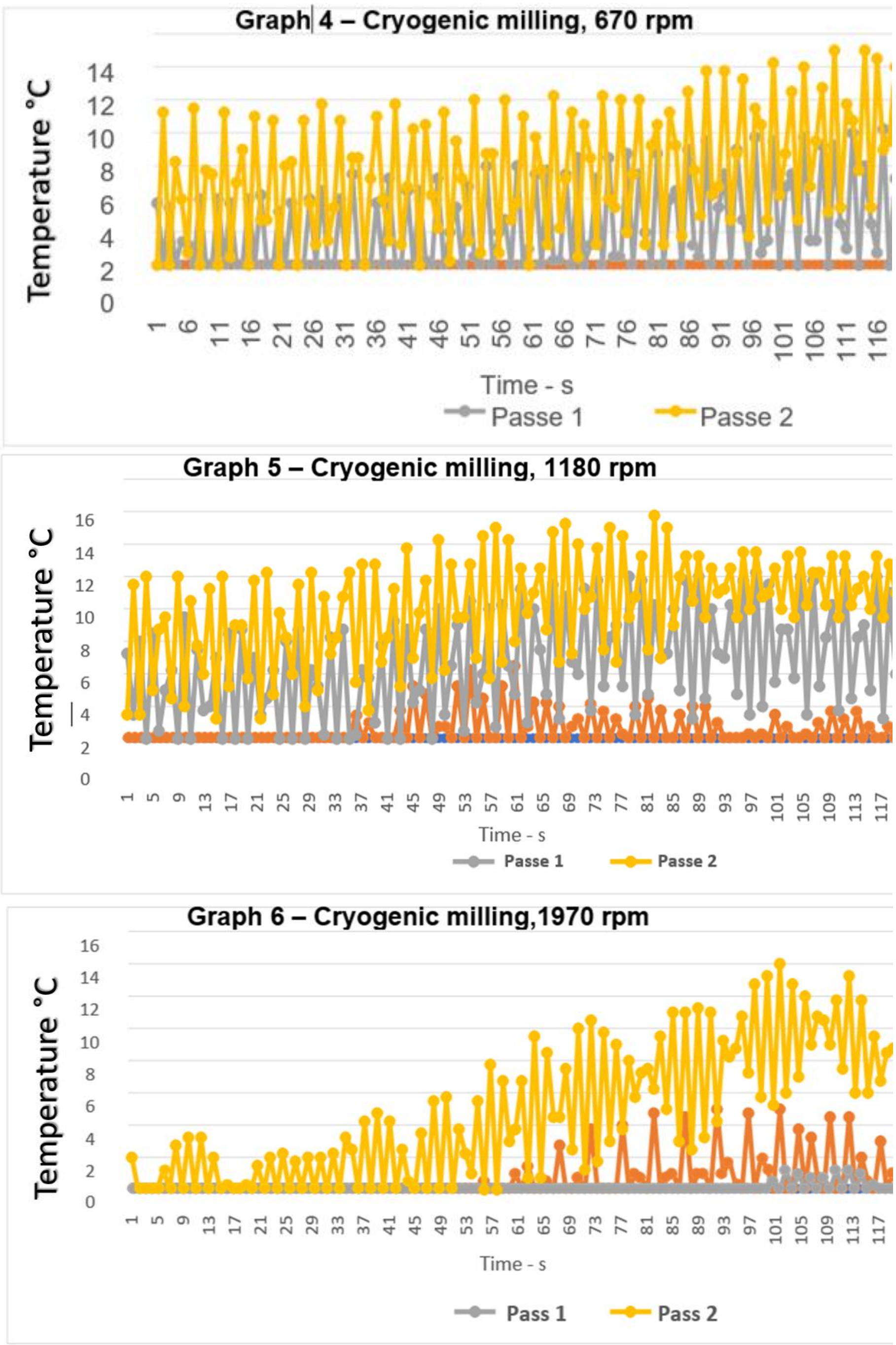

Figure 6. Temperature measurements in indirect cryogenic milling for 670, 1 180, 1 970 rpm

The results for indirect cryogenic machining had the same behavior of dry, i.e., as higher was the cutting speed, higher temperatures were found, as expected. It can be observed an average lower temperature in comparison to the dry machining process. For 670 rpm, there was a difference of ~24 °C less, for 1 180 rpm it was ~20° C, and for 1970 rpm, it was ~38 °C. Therefore, the indirect cryogenic cooling system demonstrated its ability to remove and keep the piece cooled during the cutting process.

4. CONCLUSIONS

This study aimed to compared two ambient, dry machining and a design cooling system for the workpiece system. The temperature was taken as the response variable, and it was made in a sequence of two passes given in the specimen. The input variables were ambient (dry or cryo) and rotation (670, 1 180, and 1 970 rpm), while the depth of cut (0,5 mm), were kept constant. The main conclusions indicate that:

- *Temperature measurement showed a significant reduction using the indirect cooling system for all rotation conditions used. For 670 rpm, there was a difference of ~24 °C less. For 1 180 rpm, it was ~20° C, and for 1970, it was ~38 °C. Therefore, the indirect cryogenic cooling system demonstrated its ability to remove and keep the piece cooled during the cutting process.*

- *Finally, an indirect cooling fixing system is a promising eco-friendly technique that keeps the temperature low during the cutting process, avoiding its harmful effects. More studies are necessary, especially comparing it with CFA, also circumvent the lubricating lack.*

5. ACKNOWLEDGEMENTS

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