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INFLUENCE OF COMPRESSED COLD AIR COOLING IN MILLING PROCESS WITH BARREL END MILL ON THE HARDENED STEEL

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Abstract. *Molds and dies are components used in various industrial sectors and are typically manufactured from hardened steels with highly complex geometries. Milling with ball nose end mills is one of the most commonly used machining processes for manufacturing parts with highly complex geometries. As an alternative, barrel mills can bring significant gains in terms of quality and productivity. Nevertheless, difficulties often arise in the machining process of these components, such as prolonged machining times, high heat at the chip-tool interface, and excessive tool wear. Based on this, the present work aims to analyze the influence of the use of cold air cooling on the quality of the machined surface, machining temperatures below the machined surface, and flank wear of the TiAlN+TiN coated barrel end mill in the milling of inclined surfaces of hardened AISI H13 steel. The cooling systems adopted were compressed air and cold air applied through a vortex tube. The results show that the cooling systems used did not interfere with the temperature below the machined surface or the chip shapes. However, with the cold air-cooling system, the best surface roughness values were achieved.*

Keywords: *Hard milling, Barrel end mill, Vortex tube, AISI H13.*

1. INTRODUCTION

The need to optimize machining processes has been explored by metal-mechanical industries to increase their productivity, as well as reduce manufacturing costs and environmental issues, in order to remain competitive in the market (Venturi et al., 2023). Among machining processes, milling is the most common and of great importance in industries due to its versatility and adaptability to various surfaces, especially those with high complexity (Galarza, 2018). Parts and tools with complex surfaces, such as molds and dies, which require machining processes with high quality and productivity, are common in different industrial sectors, such as automotive, aerospace, and energy generation. (Cao et al., 2016; Sai et al., 2018). In addition to the high complexity of mold and die profiles, they are usually made of hardened AISI H13 steel, which can have a hardness ranging from 45 to 64 HRC, making their machining challenging (Oliveira and Diniz, 2009; Davim, 2011).

Semi-finishing and finishing operations are usually the most time-consuming, as the material is highly hardened due to heat treatment, and small diameter tools are used (Dewes; Aspinwall, 1997). For machining complex geometries, the most commonly used tools are ball nose end mills. Additionally, barrel cutters have recently been developed as an alternative for 5-axis machining of these geometries (Herraz et al., 2020; Olvera et al., 2020). Barrel cutters have recently entered the market with innovative solutions for milling complex surfaces in high-value-added parts. With these tools, the number of passes and the machining cycle are reduced compared to ball nose end mills, Figure 1 shows the comparison between these tools (Artetxe et al., 2015; Pelayo et al., 2021). Due to the presence of a large radius at the tool's end, the reduction in finishing machining time can reach up to 90% (Levine, 2016).

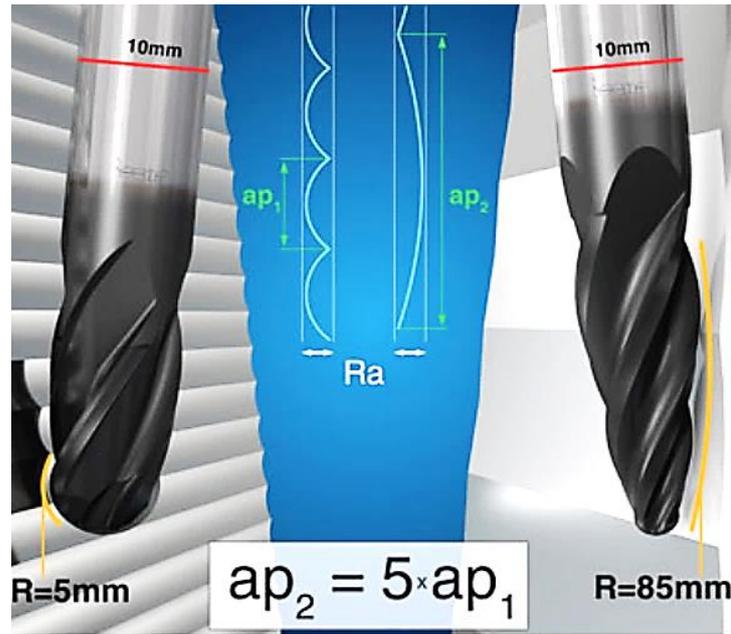


Figure 1. Comparison between ball nose end mills and barrel end mill (Iscar, 2023).

Cutting fluids are widely used in machining processes, and among the various types available, the most commonly used are those applied by jet (Singh, 2022). In the composition of a large portion of these cutting fluids, they may contain mineral oil, soap, synthetic detergent, active or neutral solid fillers, and other chemical additives (Gürkan et al., 2020). However, these substances pose health hazards to those who handle them and also contribute to environmental pollution (Singh, 2020). Furthermore, the concept of sustainability has gradually progressed, gaining global interest and becoming essential with significant trends in modern research for reducing the use of lubricants (Sen et al., 2019). According to Çakır et al. (2015), the impact on the environment and human health is directly related to a successful manufacturing process. The application of cold air for heat dissipation at the chip-tool interface corresponds to a more economical and environmentally friendly alternative, which can be achieved through the use of a vortex tube. This device is simple but capable of producing cold air, thereby reducing manufacturing costs and environmental impacts when compared to traditional cooling methods (Gupta, 2013; Singh, 2022).

Vortex tubes are classified based on the cold air outlet and their flow patterns. According to Sharma et al. (2016), the counter-flow vortex tube is the most common type. In this case, the air enters tangentially to the tube and passes through a chamber where the vortex is formed. Then, this primary vortex passes through a parallel wall that leads to a conical flow control valve, where the air is divided. The hot air exits through the exhaust end, while another portion of the air forms a secondary vortex and exits as cold air through the main end, as shown in Figure 2. (Vortec, 2022). These are the most commonly used for cooling the chip-tool interface in machining processes (Emuge Franken, 2023).

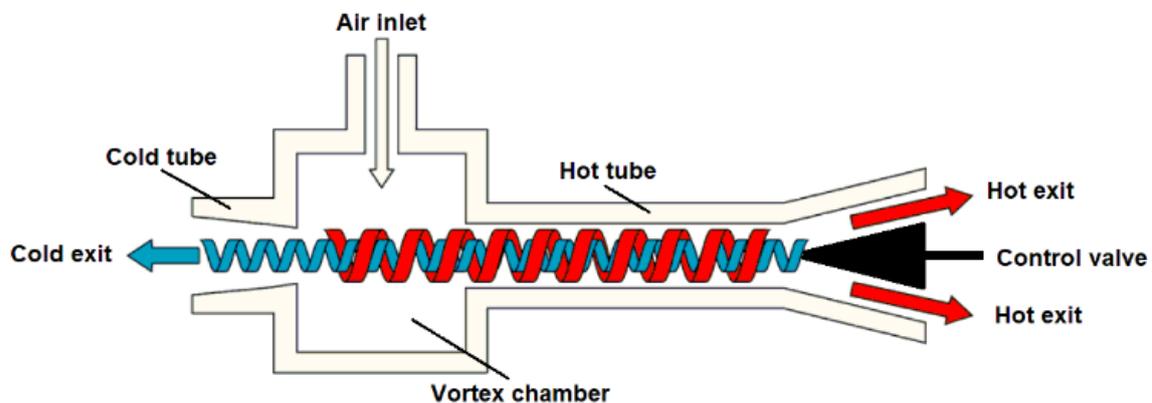


Figure 2. Schematic diagram of a vortex tube in counter-flow (Silva; Rocha; Clemente, 2017).

Considering the need to make the milling process of hardened materials less harmful to the environment, the importance of promoting good productivity and reducing process costs without compromising the quality of the machined

surface, the presented study aims to analyze the influence of using cooled air through a vortex tube on the surface quality of TiAlN+ TiN -coated barrel cutters in the milling process of hardened AISI H13 steel.

2. MATERIALS AND METHODS

2.1 Materials

The material used for the machining tests was heat-treated AISI H13 steel. Table 1 presents the nominal chemical composition of the material used. The material's hardness was measured after its heat treatment using the VEB HP200 hardness tester with a straight diamond cone indenter with a vertex angle of 150° and a testing force of 150 Kgf. Two hardness measurements were taken in each quadrant of the specimen, resulting in a hardness of 48 HRC.

Table 1. Chemical composition (Villares Metals, 2023)

C	Si	Mn	Cr	Mo	V
0.40	1.10	0.35	5.20	1.50	0.90

The specimen geometry is shown in Figure 3. The specimen was divided into four quadrants, allowing for one test per quadrant. Type T thermocouples were inserted into 3 mm diameter holes to measure the temperature beneath the machined surface during the machining process. These holes were drilled only after heat treatment to prevent cracking and stress concentration.

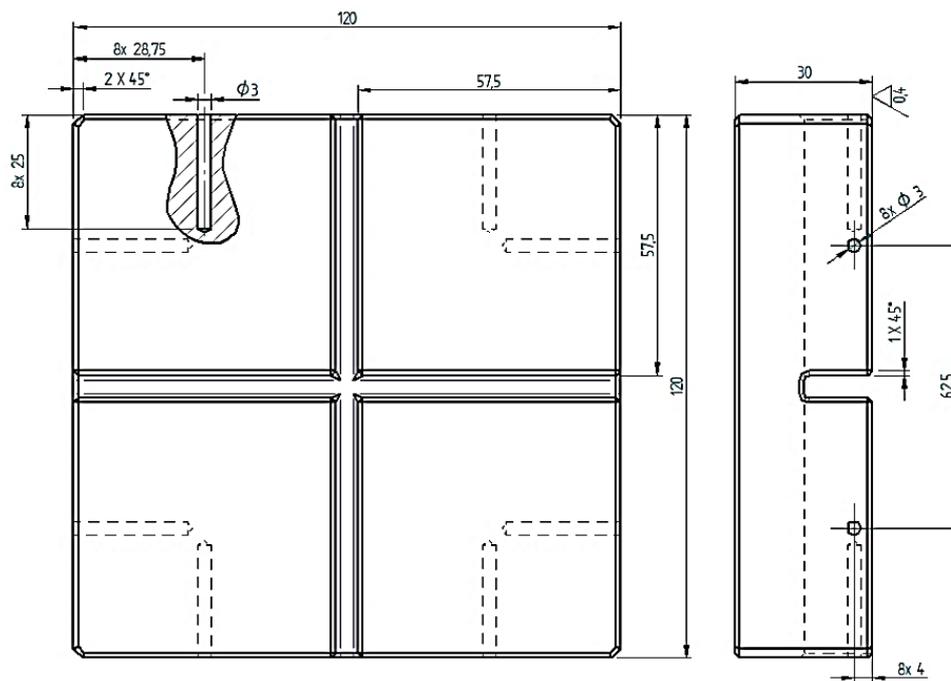


Figure 3. Geometry and dimensions of the test specimens.

2.2 Cutting tools

For milling the test specimens, a carbide barrel end mill from Iscar with four cutting edges and coated with TiAlN+ TiN using the PVD process was selected. The end mill has 10 mm radius. The tool designation classes are for carbon and alloy steels (ISO P), stainless steels (ISO M), cast irons (ISO K), non-ferrous metals (ISO N), superalloys (ISO S), and hardened steels (ISO H). The manufacturer provides recommended cutting conditions for each material to be machined. Figure 4. presents the dimensions of the tool used. The interchangeable inserts of the barrel end mills will be mounted on the MM S-B-L095/40-C20T06 shank, with its main dimensions indicated in Figure 5.

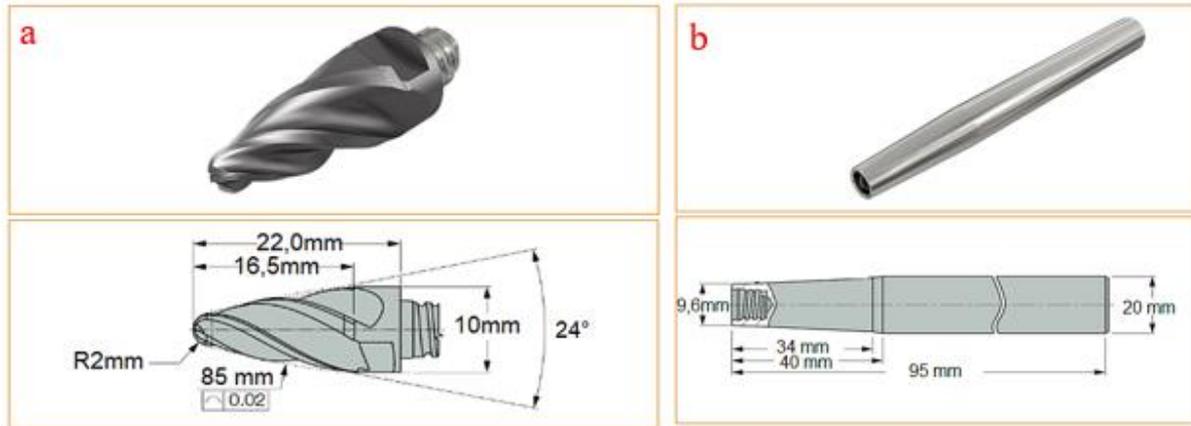


Figure 4. Barrel end mill: (a) Dimensions. (b) Conical shanks for interchangeable milling heads (Adapted Iscar, 2023).

2.3 Device for cold air application

The cold air for cooling the machining was applied through the vortex tube, whose device used to secure the tube is shown in Figure 6. The compressed air, which has passed through a dehumidification system with a dew point of 5°C, enters the device at a pressure of 6 bar through the inlet "a". At "b" is the outlet for the cold air to be used in the test, and at "c" is the outlet for the hot air. The outlet nozzle for the cold air is positioned 70 mm away from the cutting edge to avoid collision with any part of the machine, tool, or test specimen during machining.



Figure 6. Device for cold air application.

2.4 Methods

For the machining of the test specimens, the Hermle C40 5-axis machining center was used. The coolant media employed were compressed air and compressed cold air cooling by a vortex tube at a pressure of 6 bar. The vortex tube was regulated using a digital contact thermometer, which measured a temperature of 0 to -2°C at the outlet nozzle. The ambient temperature during the tests was 25.7°C. One test was conducted for each machining condition. The tests were performed in a concordant position with cutting and the depth of cut increments were from top to bottom. The cutting time for each test was 24 minutes. Table 2 presents the test number and the milling conditions used, and Figure 7

schematically illustrates the milling inclination angles, cutting direction, and cutting depth. Figure 7 was generated using a CAD system, which aided in identifying the effective cutting diameter ($\text{Ø}5,59$) under the given conditions.

Table 2. Milling conditions

Test	Cooling medium	cutting speed (m/min)	Feed (mm/flute)	Radial cutting depth (a_e)	Axial cutting depth (a_p)	Lead angle	Tilt angle	rpm
1	cold air-colling	60	0.03	0.2 mm	1 mm	4°	15°	3413
2	air	60	0.03	0.2 mm	1 mm	4°	15°	3413

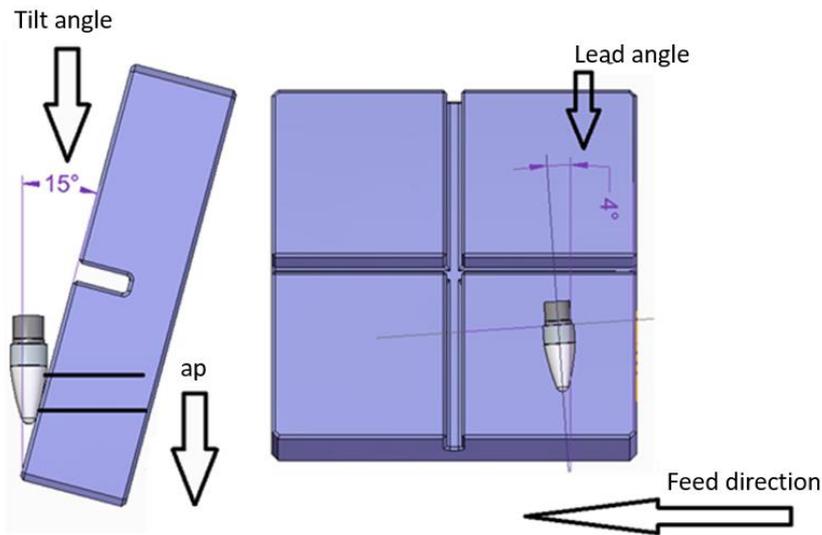


Figure 5. Schematic figure of the milling test

During the machining of the test specimens, samples of the chips were collected, and the temperature below the machined surface was observed using type T thermocouples. Data collection of the temperatures was carried out with the assistance of a 20-channel Yokogawa GP10 recorder. After the machining tests, surface roughness measurements were taken in the direction of cutting depth. The parameter used was Ra (arithmetic mean deviation) using the Perthometer S2 roughness tester. The roughness tester was configured according to ISO 3274 standard, with a cutoff of $0.25 \mu\text{m}$. Three measurements were taken for each conducted trial, and an analysis of variance (ANOVA) was performed. Additionally, chip samples were taken to analyze their shape. For the tool wear analysis, a KOZ-004 optical microscope and the Zeiss manufacturer's Stemi 2000-C stereoscope were used, equipped with an Axio Cam ER 5s camera.

3. RESULTS AND DISCUSSIONS

3.1 Temperature analysis

The temperature values obtained during machining were low because the thermocouples were located below the machined surface, thus, the highest temperature values obtained during each test were adopted. The maximum values of the temperatures obtained by the thermocouples below the machined surface are presented in the Table 3. There was no significant difference in temperatures, considering that the thermocouple limits of error are $\pm 1^\circ\text{C}$.

Coolant media	Temperature
Air	26.7 °C
Cold Air	24.4 °C

3.2 Tool analysis

The average flank wear values for both conditions were relatively low, 0.017mm for air and 0.011mm for cold air, indicating that there was no significant wear under the tested conditions. Through analyses conducted with the assistance of a microscope, it was possible to detect protrusions on the tool, as can be seen in Figure 6a, in comparison to Figure 6c, which depicts a new tool. There is a high likelihood that these protrusions are material from the workpiece adhered to the tool, however this assertion can only be confirmed through the use of EDX (Energy Dispersive X-ray) analysis.

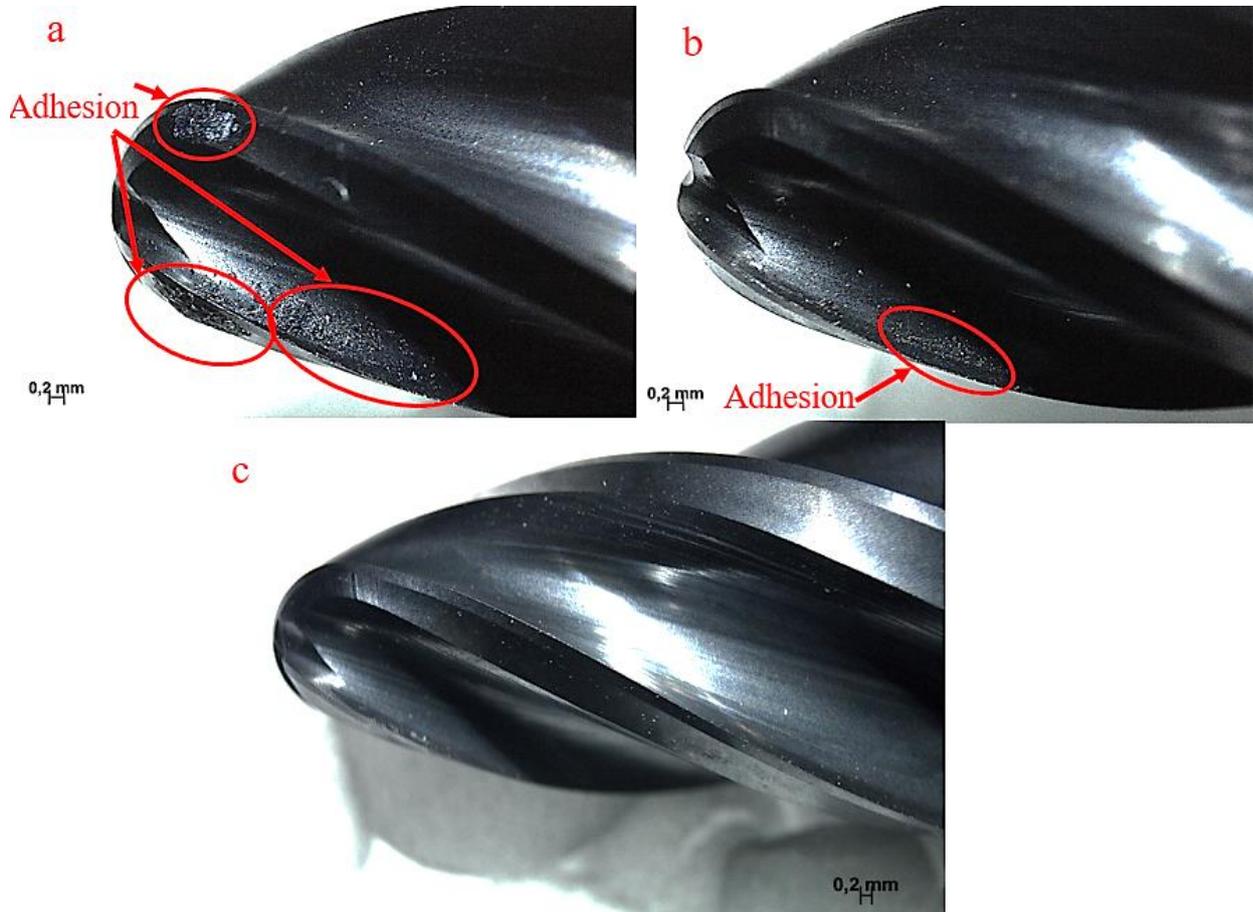


Figure 6 Tool images a) cold air-cooling b) air cooling c) new tool.

3.3 Surface roughness analysis

It was decided to evaluate the average surface roughness (R_a) as it is the most commonly used parameter in machining. With the surface roughness data, an analysis of variance (ANOVA) was performed, and a confidence interval plot of height was generated, whose results are presented in Table 4 and Figure 9.

As can be seen in Table 4, the "p" value for the coolant medium was below 0.05. This result indicates with 95% confidence that there are significant differences in surface roughness when the coolant medium is changed. The average surface roughness values with the cold air-cooling system were $0.217 \mu\text{m}$, while with the cooled air, the average obtained was $0.330 \mu\text{m}$, indicating that using the air coolant medium results in an approximately 52% increase in surface roughness compared to the cooled air coolant medium. The cold air has the potential to reduce the temperature at the tool-chip interface. The small molecular structure of air helps in this task. Therefore, the reduction of cutting temperature and shortening of the tool chip contact length may produce a better surface finishing. Furthermore, the barrel end mill proved to be an excellent alternative to ball nose end mills, as demonstrated in a study conducted by Venturi et al., (2023). In this study, they used ball nose end mills and machining conditions similar to those in the present work, achieving surface roughness values of $R_a 0.3 \mu\text{m}$ with cold air cooling and $0.524 \mu\text{m}$ in the air condition.

SOURCE OF VARIATION	SS	df	MS	F	P-value	F crit
Coolant medium	0.019041	1	0.019041	8.240335	0.045441	7.708647
within groups	0.009243	4	0.002311			
Total	0.028283	5				

Table 3 ANOVA – 95% Confidence.

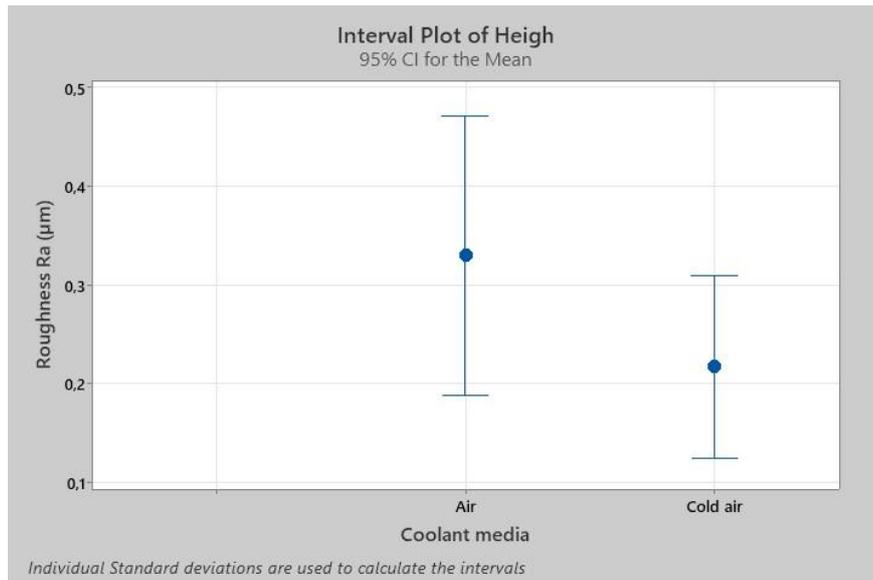


Figure 7 Confidence interval plot of height.

3.4 Chip analysis

According to ISO 3685:1993 standard, the observed form of the chips was needle chips. No color, size, or shape differences were identified among the chips under the tested conditions. Figure 10 (a) shows the chips using the air-cooling system, while Figure 10 (b) shows them with cold air. It was expected a more pronounced chip breakage in the cold air condition due to the material's embrittlement at low temperatures, as the toughness of metallic materials decreases at lower temperatures (Lin; Zhang; Wang, 2011). Considering what was expected and the obtained result, it is possible that the temperature used in cold air cutting was not low enough to cause a significant embrittlement of the material.

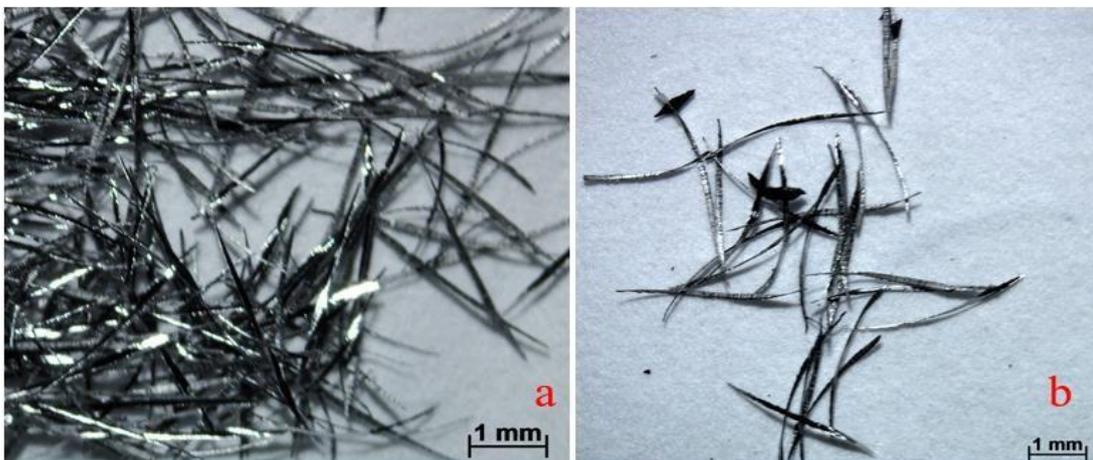


Figure 8 Chips.

4. CONCLUSION

After conducting this study, it is possible to affirm that:

- (a) There was no significant difference below the machined temperature under the conditions used;
- (b) Protrusions on the tool were identified in the cold air-cooling condition;
- (c) Surface roughness was lower in the cold air-cooling condition.
- (d) The cooling methods employed did not influence the chip shape.
- (e) The barrel end mill can be a good alternative to ball end mills.

5. ACKNOWLEDGEMENTS

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