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**EFFECT OF CUTTING FLUID ON SURFACE FINISH OF 316L DURING  
MILLING FROM PIECES OBTAINED FROM ADDITIVE  
MANUFACTURING AND ROLLING PROCESS**

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**Abstract.** *The use of additive manufacturing (AM) has increased significantly in recent years, mainly for small components and pieces with complex geometry that cannot be manufactured through conventional processes. One of the problems of this technology is the poor surface roughness. The application of a secondary process, such as machining, improves the surface finish and it's necessary in most cases. The objective of this study was to investigate the effect of cutting fluid and dry cutting on the machined surface roughness of components produced through AM and conventional rolling processes of AISI 316L. A carbide tool was used during the milling process in a machining center. The surface roughness was measured using a laser interferometer microscope and the surfaces were analyzed through scanning electron microscopy (SEM). The best results for surface roughness were achieved with the use of dry cutting instead cutting fluid. The smaller roughness was 1.267 when dry cutting and rolling pieces were used. The higher was 1.665 when cutting fluid and rolling pieces were used, 31% higher then the best result. The SEM analysis didn't show significant differences between the surfaces analyzed, considering the machining condition*

**Keywords:** *surface roughness, cutting fluid, AISI 316L steel, additive manufacturing*

## 1. INTRODUCTION

Our societal world has been restructuring by new and innovative technologies. In this advanced manufacturing era, the academia and industry have been studying and focusing on additive manufacturing (AM) in their arena of research and manufacturing (Majeed et al., 2020). The current manufacturing industry is characterized by high quality, low cost, and faster delivery and advanced manufacturing systems are targeted for outstanding performance, best stability, and higher repeatability. AM is an evolving technology for today's manufacturing enterprises and it has been established about thirty-five years ago, commonly known as rapid prototyping (RP). American Society of Testing and Materials (ASTM) defines the AM as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies” (Majeed et al., 2020). Additive manufacturing (AM) is becoming more and more established in industrial applications. The extended freedom of design of additively manufactured components is combined with a tool-less and near-net-shape production, producing components without the need for specific tools enables cost efficient production of small quantities down to batch size one. AM techniques exhibit significant potential in reducing the high production cost of conventional components made from relatively expensive materials in aerospace, automobile, and medical applications (Bae et al., 2020). Metallic additive manufacturing (MAM) is a rapidly expanding manufacturing process whose advantages are plentiful. Namely, AM is able to deliver complexity for free, which translates to the ability of producing complex components in approximately the same time frame as a simple component of the same volume and this contrasts with conventional subtractive processes such as machining, where the time-to-build scales with the number of necessary operations. Additionally, it is a versatile process, relinquishing the need for different tools or cast dies every time a distinct geometry is to be produced and easily automated (Gil et al., 2021). AM also can be used to manufacture intricate shapes for biomedical applications such as human implants. (Guo et al., 2017) also cite that parts manufactures by AM can be widely used in various industries, such as automobile, aerospace and medicine. Near net shape parts can be generated in a timely manner, at a reduced production

cycle with minimum waste of material. AM also offers a particularly high economic advantage for producing high-value-added components using high-performance alloys able to withstand high temperatures, corrosive environments, and intense mechanical stresses (Lizzul et al., 2021). Hence, AM has been considered a very promising production process in many sectors such as healthcare, mold tooling, automotive, and aerospace (Moheimani et al., 2022). One of the most used processes for AM of metal parts is selective laser melting (SLM), in which a component is built layer by layer in a powder bed; a layer of new material and defined thickness is applied from a powder supply by a scraper. The cross section of the later workpiece is then exposed by a laser, which melts the powder material and creates the material cohesion. These steps are repeated until the completion of the component (Greco et al., 2021). AM is a technique used for fabricating a wide range of structures and complex geometries using three-dimensional (3D) model data. However, most of the parts produced by AM processes cannot be used directly. This is because the surface integrity of additively manufactured (AMed) parts is unpredictable, specifically, the roughness, hardness and residual stress on the surface of the printed parts are considerably higher than the wrought material. Therefore, finish machining on the AMed parts is one of the critical post-processing steps that is required to be carried out, in order to obtain the smooth surface finish for part assembly (Li et al., 2022). (Danish et al., 2023) et al. also cite that AM method can manufacture parts with complicated structures, the surface of the part may not have a fine quality, needing further machining to achieve the requirements for a successful application. The surface quality of such parts is determined by a series of interconnected input variables associated with the type of AM technology, process parameters, part design, and material feedstock. This leads to surface roughness values ranging from 4  $\mu\text{m}$  to 60  $\mu\text{m}$ , or even higher (Lizzul et al., 2021). AMed components for high-end applications, such as for the automotive and aerospace industries, require high geometrical precision and surface quality, making it necessary post processing operations such as machining, grinding, chemical polishing, shot peening to obtain a functional form and finish and post-processing after conventional and innovative manufacturing technologies is a major task in industry (Amon et al., 2022). For obtaining high integrity, the surface roughness index should be minimum level. The work material surface roughness is greatly impressed by actual cutting parameters, i.e., “feed rate, cutting speed, and radial and axial depth of cut”, besides the noncontrolled agents, namely non-uniformity of work material and the cutting insert (Yasir et al., 2021)

Milling is one of the most common post-processing technologies to finish the surface of components, and is frequently employed in the processing of complex parts thanks to digital control systems. Because of its flexibility, ball end milling is widely used to obtain optimal surface finishing of curved and multifaceted surfaces, such as those of the AMed components (Lizzul et al., 2021). During conventional machining processes, high-temperatures can cause tool wear and damage to the machined face. Dry machining, while potentially useful for reducing the number of cleaning processes, drastically reduces machinability, degrades the integrity of the machined face, and shortens the tool life because of the induced cutting forces and temperature increase. Dry machining leads to more friction and adhesive action between the chip-tool and work-tool junction thereby leading to higher wear on the tool and reducing the tool life. Since dry machining may lead to negative characteristics on the work material such as high surface roughness, and also reduced tool life, different coolant techniques have been used to address this problem. To maximize the machinability of any material, suitable cutting fluids (CFs) have been employed historically, such as mineral oils that contain typically highly harmful chemical additives that serve as coolants, lubricating agents and chip flow assistants, so it is crucial to employ cutting fluids during machining to reduce the effects of high feed rates and deep cuts. Also, it prevents the work hardening effects due to low thermal conductivity exhibited by some hard materials by preventing the heat flow away from surfaces machined. Overheating can also give rise to distortion, which is challenging to tackle of or to correct. The cutting fluids provide lubrication and help reduce tool wear by washing away all the possible machining swarf (Jeevan et al., 2021).

Stainless steel materials have been preferred in various fields such as food, medical, aerospace, and automotive industries due to their high ductility, high creep rupture strength, high temperature, etc. properties, however, they are classified as difficult-to-machine owing to the low thermal conductivity, work hardening tendency, and high built up edge (BUE) formation (Touggui et al., 2021). Yasir et al. (2021) also cite that AISI 316L is often considered as a “difficult-to-machine” material. The reason behind this could be elevated “ductility”, higher “tensile strength”, and poor “thermal conductivity”. All these things collectively produce an unacceptable surface finish and also shortened the tool life due to rapid tool wear. Apart from that, high fracture toughness of AISI 316L increases the temperature in the primary cutting zone which deteriorates the surface finish and the ability of the chip to break. Moreover, the “built-up-edge” (BUE) generation is also significantly found at high cutting speeds which also deteriorate the surface quality which in turn increases the cutting forces during machining process. AISI 316L (SS316L) is widely used in aerospace, automobile, and medical applications owing to its corrosion resistance and high ductility. In particular, SS316L products manufactured by the SLM process are fully dense and defect-free and can be used immediately without post-heat treatment (Bae et al., 2020). Moheimani et al. (2022) also cite that AISI 316L as austenitic stainless steel has frequently been used in different sectors such as the medical, nuclear, aerospace, petroleum, and marine industries, and this wide range of applications for AISI 316L is because of its high corrosion resistance, strength, and biocompatibility characteristics. However, these days, advanced manufacturing technologies such as additive manufacturing (AM) are considered promising alternatives to the traditional production processes of the small to medium batch manufacturing of AISI 316L parts (Moheimani et al., 2022). Due to the increasing complexity of the AM process itself and the increasing demands on the powder properties when additively producing microstructured components in a single process step, SLM and subsequent micromilling are also a

suitable process splitting for structuring surfaces of individually shaped parts in the micrometer range (Greco et al., 2021). Stainless steel (SS) 316L is a material that is regularly used in many engineering and medical applications because of its outstanding resistance to oxidation and corrosion. It also possesses strong mechanical properties that make it suitable for high-strength applications. In the medical field, it is used as an implant material since it possesses excellent biocompatibility. In general, conventionally produced stainless steel is used for several purposes, but new methods should be developed for manufacturing intricate shapes with great precision (Danish et al., 2023). With the realization of the requirements that pertain to bioimplant technology, the selection of appropriate materials and a compatible machining method has become a prime point of concern. A good strength-to-weight ratio, excellent mechanical and corrosion resistance properties, non-toxicity, and osseointegration with the human body are the general requirements for a material to be considered biocompatible. In the context, titanium (and its alloys), magnesium alloys, and stainless steels are the most preferable materials for the aforementioned reasons. Specifically, AISI 316L is a SS grade that is relatively more favored for bio-applications due to its certain attributes such as relatively high modulus (compared with human bones), good mechanical properties, excellent toughness and corrosion resistance, and economic processing. Additionally, the machinability of AISI 316L is relatively better than other SS grades as it allows less severe formation of martensite during cutting operations which facilitates its processing via available conventional means (Zahoor et al., 2019).

The objective of this work is to study the influence of milling process on the surface roughness of AISI 316L stainless steel, manufactured by AM and rolling process, using cutting fluid and dry cutting.

## 2. METHODS AND MATERIALS

The “as built material” for the specimens was AISI 316L with three conditions:

- Rolling plate of 1”, cut and machined to 20 mm x 20 mm x 20 mm;
- AM parts manufactured by EOSINT, model M280 with the DMLS (direct metal laser sintering) process, applying LPBF (laser powder bed fusion), were used and they were separated by the EDM-wire process with the equipment V650G of Excetek. The input parameters for the AM process were as follows: laser power: 160 and 190 W; laser speed: 1000 mm/s; thickness: 20  $\mu$ m; laser efficiency: 100%; laser focus: 72  $\mu$ m; laser width: 5 mm; ground temperature: 81°C; laser direction rotation after each layer: 67°. The properties for specimens after AM were as follows: roughness: Ra = (13  $\pm$  5)  $\mu$ m; Rz = (80  $\pm$  20)  $\mu$ m; ultimate tensile strength XY direction: = (640  $\pm$  50) MPa; Z direction = (540  $\pm$  55) MPa; yield stress XY direction: = (530  $\pm$  60) MPa ; Z direction = (470  $\pm$  90) MPa; elastic modulus: XY direction= 185 GPa; Z direction: = 180 GPa; elongation XY direction = (40  $\pm$  15)%; Z direction = (50  $\pm$  20)%; hardness: 89 HRB. The final dimensions of the workpieces were 20 x 20 x 15 mm.

For the machining process, an end mill, solid carbide mill  $\varnothing$ 25, 4 cutters, produced by Dormer Pramet, was used with the following cutting parameters:

- Cutting speed (vc): 85 m/min; feed rate (fz): 0.078 mm/rev; cutting depth (ap): 0.5 mm;
- Cutting fluid: a) no cutting fluid (dry cutting); b) flooded cutting fluid with Boreal BL from YPF, mineral oil, emulsion pH: 8.5 – 10; density (20°C): 0,9144, pour point (max): -30, proportion of 1/19 in water, directly on the contact tool/piece;

The milling experiments were carried out in a Romi Discovery 560 machine center.

“Figure 1” shows an example of a machined surface. The AM process started from the bottom up to the machined surface illustrated at the upper face.

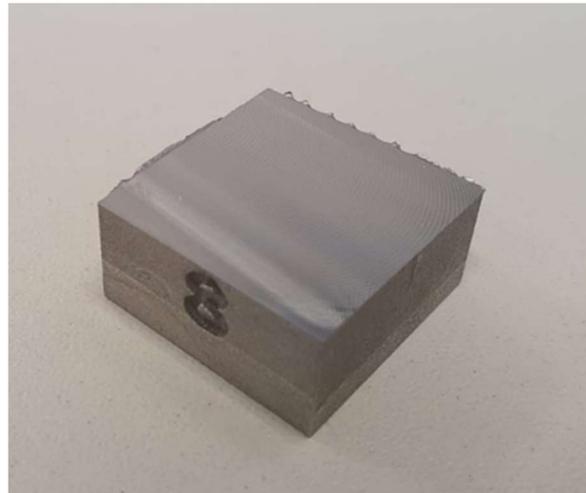


Figure 1. Example of machined piece.

The surface analysis was made using SEM, with a Tescan Vega 4 at Instituto Maua de Tecnologia. An Alicona Infinite Focus by interferometry was used for the surface roughness measurements at Dormer Pramet.

### 3. RESULTS AND DISCUSSION

After machining with cutting fluid the following results (Table 1) were obtained for the surface roughness.

Table 1. Median roughness machined with cutting fluid

Sample	Roughness $R_a$ ( $\mu\text{m}$ )
Rolling	1.665
AM - 160 W	1.579
AM - 190 W	1.502

For a better visualization, the Figure 2 shows with great evidence that there is an improvement in the finish in the machining of parts produced by additive manufacturing, and that they get even better with the increase in laser power in the production of the part. In this case, probably the greater cohesion of the microstructure of the rolling piece made it difficult to remove the material, causing higher roughness. Probably the same justification can be used for the variation used in the laser power, since it has a direct influence on the fusion of the layers of the parts manufactured by AM.

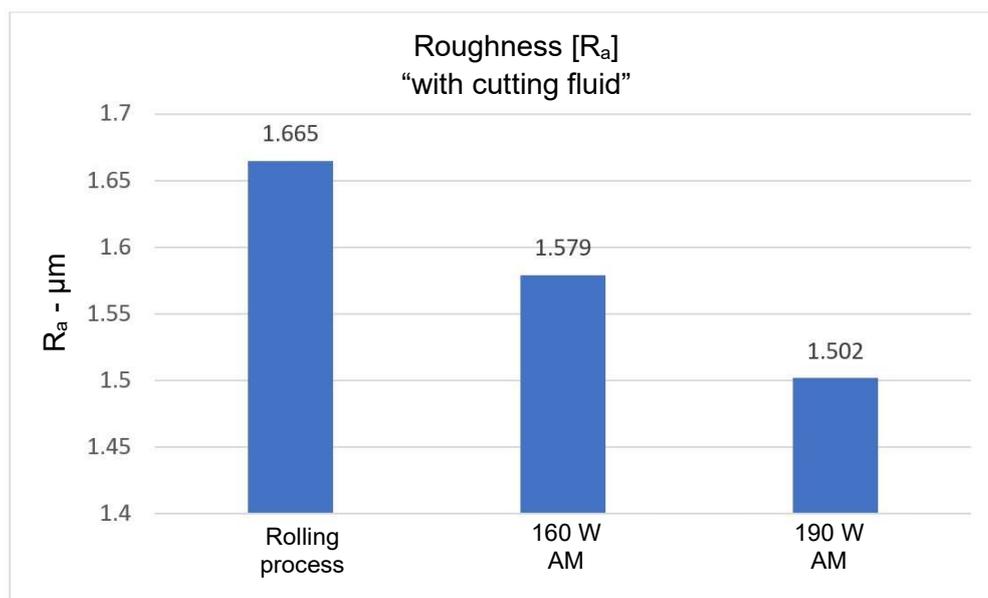


Figure 2. Median roughness machined with fluid

Figure 3 shows the graphs obtained from the 3d surface roughness measurements for the pieces machined with cutting fluid. There are no major differences between the results of the images. In Figure 3c, a smaller scale can be seen between the tool feed rate marks, evidencing the lower roughness found. It is important to emphasize that the difference between the surface roughness was around 5%.

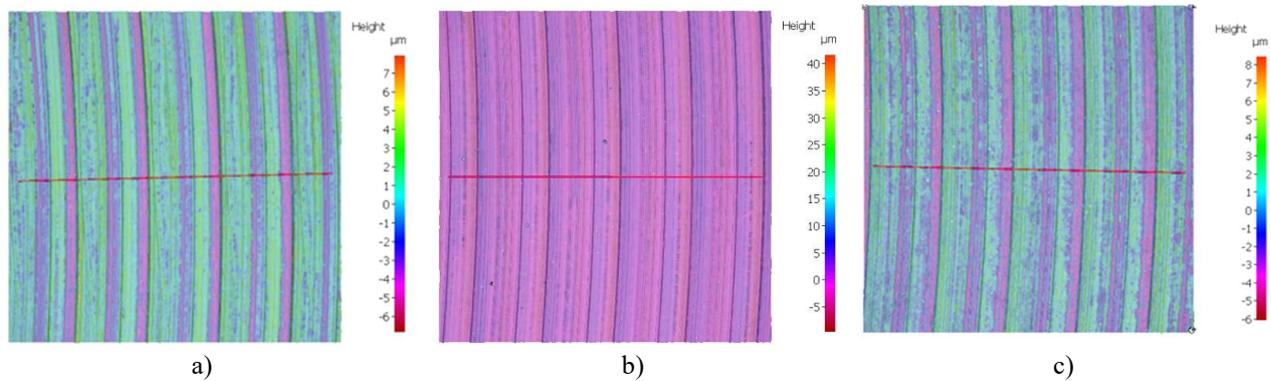


Figure 3. Surface roughness a) Rolling; b) AM – 160 W; c) AM – 190 W

Table 2 and Figure 4, shows the results for the dry machining and Figure 5 the images acquired during the surface roughness measurements.

Table 2. Median roughness dry machining

Sample	Roughness $R_a$ ( $\mu\text{m}$ )
Rolling	1.267
AM - 160 W	1.35
AM - 190 W	1.374

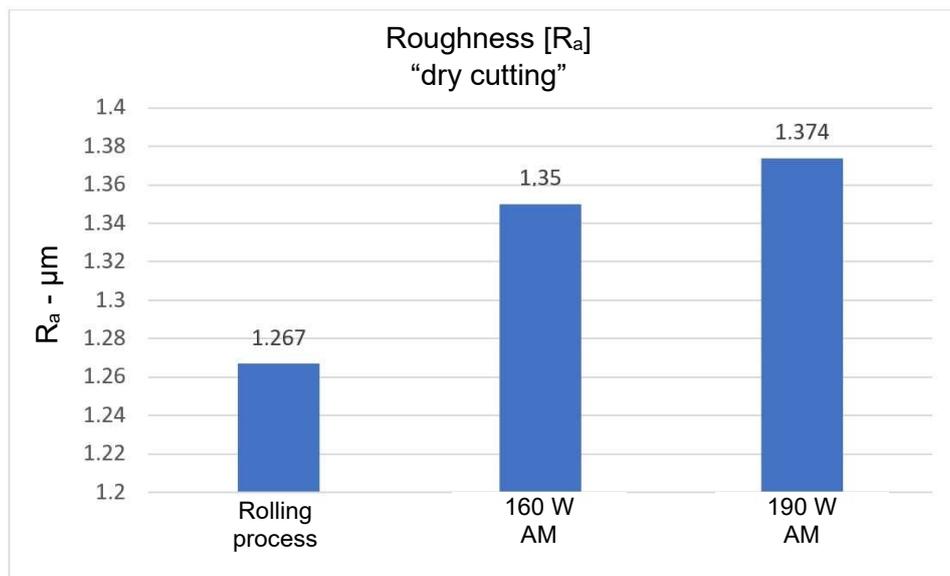


Figure 4. Median roughness machined by dry cutting

It is possible to observe the feed rate marks of the tool in the images. The images of the parts milled with fluid (Figure 3) show these marks less pronounced than the images in Figure 5. It was not possible to observe considerable differences between the parts obtained by AM with the two laser power, and the rolling process.

When the cutting fluid in abundance was replaced by dry machining, the surface roughness behavior was reversed. In this case, the characteristic altered in the process was the temperature, which considerably reduced the roughness of the laminated piece around 30% and certainly facilitated the removal of the material, since its shear stress decreases with higher temperature. For the additive manufacturing parts generated by 160 W and 190 W there were also a reduction in roughness, around 16% and 9% respectively. The surface roughness varied from 1.267 Ra (rolling process and milling using dry cutting), to 1.665 (rolling process and milling using cutting fluid). For machining without fluid, higher surface roughness was obtained for parts manufactured by additive manufacturing, around 8.5% and for machining with cutting fluid, higher surface roughness was obtained for parts manufactured by rolling process, around 11%.

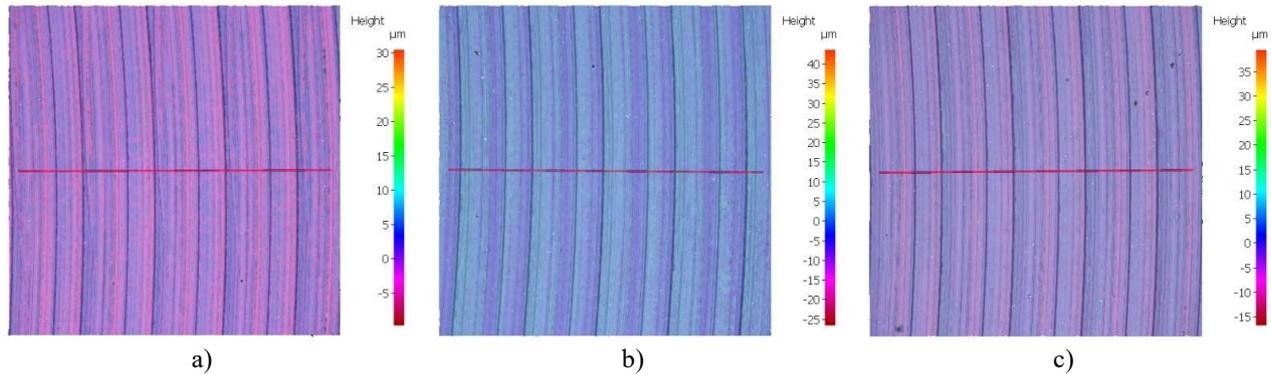


Figure 5. a) Rolling; b) AM – 160 W; c) AM – 190 W

Figures 6 to 8 show the analyzes performed with SEM. There are some defects common to machining process. Feed marks (ridges and grooves) were formed by cutting residues between adjacent tool paths, and were generated by the relative movement of tool and workpiece and distributed in parallel lines. The width between tool paths was related to the feed rate. Another defects like side flow and tearing were also found. In general, tearing surface existed on the machined surface, which was related to the extrusion and friction of BUE and material particles. The Figure 9 shows tearing with 3000x of magnification. The tearing and small voids were present in all surfaces but they were more pronounced in parts obtained by additive manufacturing, probably by the small cohesion between the surface layers and not melted points.

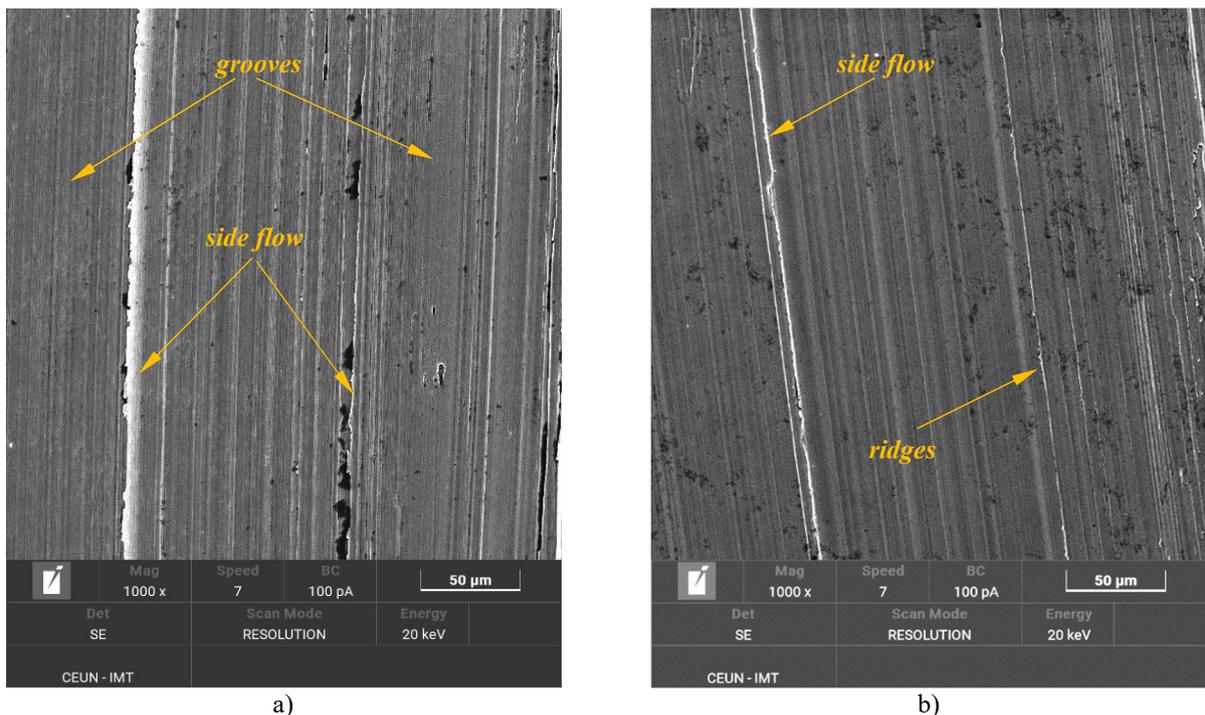
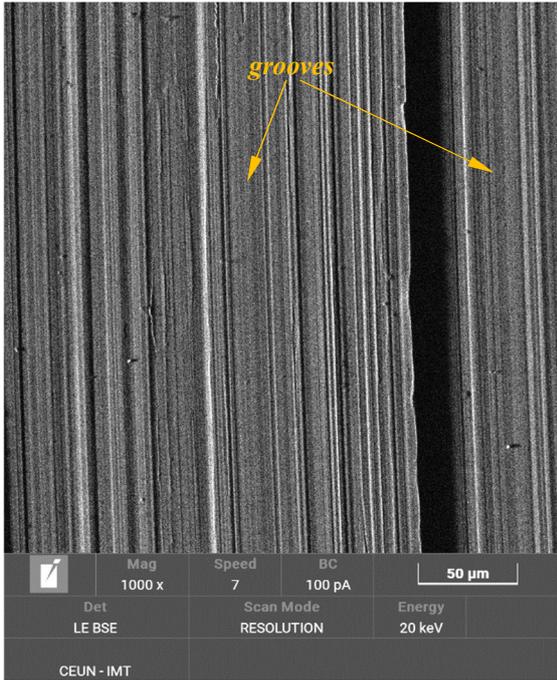
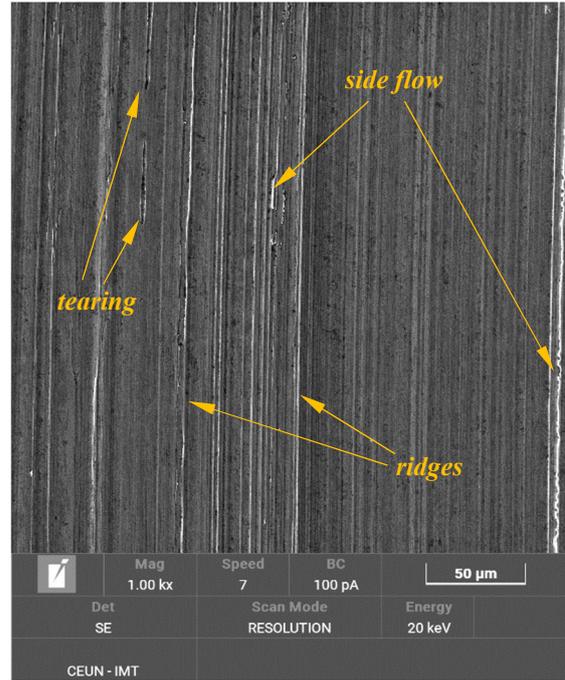


Figure 6. Rolling pieces surfaces. a) with cutting fluid; b) dry cutting; (magnification 1000X)

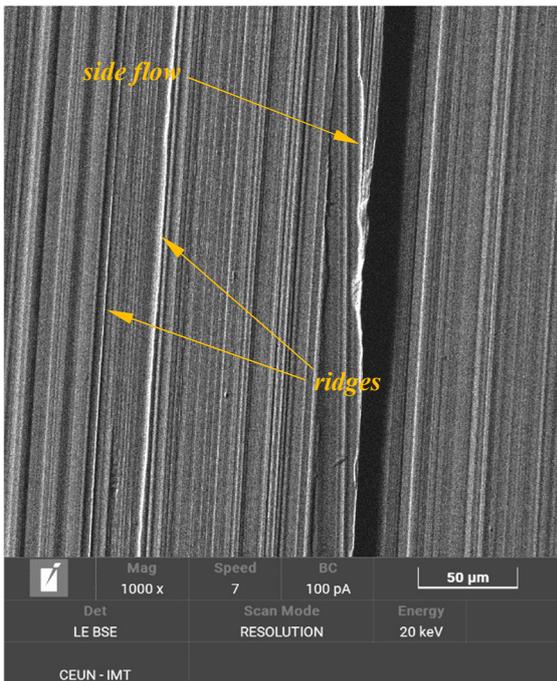


a)

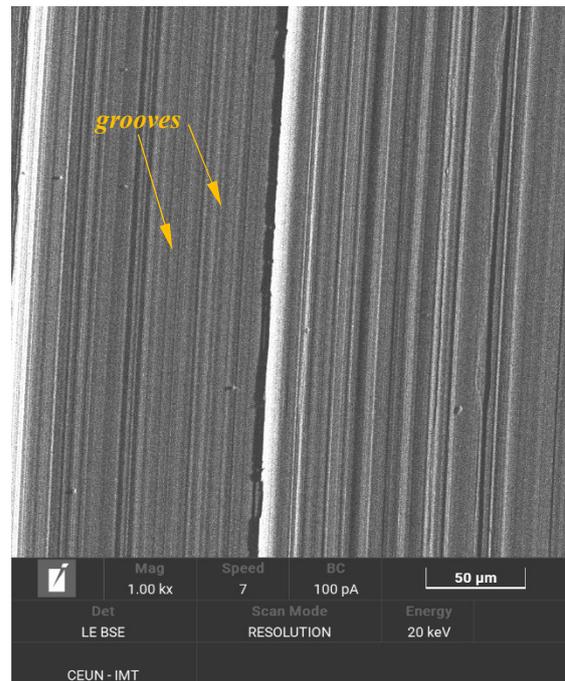


b)

Figure 7. AM – 190 W - a) with cutting fluid; b) dry cutting; (magnification 1000X)



a)



b)

Figure 8. AM – 160 W - a) with cutting fluid; b) dry cutting; (magnification 1000X)

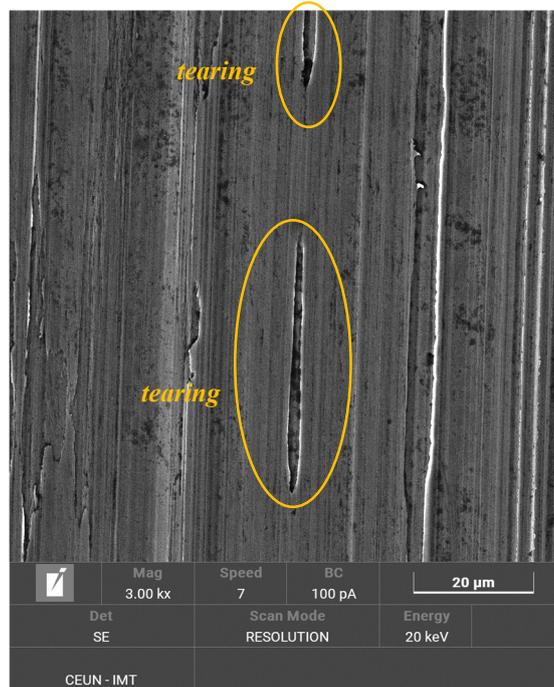


Figure 9 – Defects on the surface (tearing) - AM – 190 W - dry cutting; (magnification 3000X)

#### 4. CONCLUSION

After the analyzes made with the use of fluid and without and parts manufactured from the additive and laminated manufacturing process, the following conclusions can be obtained:

- The surface roughness varied from 1.267 Ra (rolling process and milling using dry cutting), to 1.665 (rolling process and milling using cutting fluid);
- For machining without fluid, higher surface roughness was obtained for parts manufactured by additive manufacturing, around 8.5%;
- For machining with cutting fluid, higher surface roughness was obtained for parts manufactured by rolling process, around 11%;
- In the visual inspection of the images, obtained by SEM, the parts obtained by additive manufacturing had more voids and tearing on the surface, when compared to the rolling parts;

#### 5. ACKNOWLEDGMENTS

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