Surface characteristics comparison between additively manufactured Ti6Al4V and wrought Ti6Al4V turned samples

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Abstract. This paper aims to contribute increasing the knowledge surrounding *Ti6Al4V* by making a comprehensive comparative analysis of surface characteristics between additively manufactured and conventionally wrought *Ti6Al4V* turned samples. The tests were carried out by varying the process parameters such as cutting speed and lubricant conditions (dry and cryogenic), and by keeping fixed the feed rate and the depth of cut. The comparison of these two manufacturing methods allows to explore how the different surface properties, such as roughness, microstructure and hardness, can change.

Introduction

Ti6Al4V Titanium alloy, is known for its remarkable mechanical properties and biocompatibility, it has garnered widespread attention in various engineering applications, particularly in the aerospace and biomedical fields [1]. With the advent of advanced manufacturing techniques, additive manufacturing (AM) has emerged as a promising method for fabricating components with improved design flexibility. However, the surface characteristics of additively manufactured *Ti6Al4V* components have been the subject of many studies due to the inherent complexities associated with layer-wise deposition [2, 3].

The decision to use *Ti6Al4V* samples, in this study, was made because this particular kind of material is employed to make different components in many fields and it can be produced by conventional techniques (i.e. casting, extrusion, etc.) or AM technologies [4].

The differences between wrought and additively manufactured Ti6Al4V arise mainly due to their distinct manufacturing processes, leading to variations in microstructure, mechanical properties, and potential applications [5].

Wrought *Ti6Al4V* is widely used in applications requiring high strength and toughness, such as in aerospace components and biomedical implants. Its application is somewhat limited by the geometric complexity that can be achieved through conventional manufacturing techniques [6].

AM *Ti6Al4V* offers design flexibility, allowing the production of complex geometries that would be difficult or impossible to achieve with traditional manufacturing methods. This makes AM particularly attractive for custom implants in the biomedical field, lightweight structures in aerospace, and components requiring intricate internal features [7].

Thus, while wrought *Ti6Al4V* has a long history of use in demanding applications due to its reliable and well-known properties, additively manufactured *Ti6Al4V* opens new possibilities in design and functionality, even if with better knowledge on their microstructure, mechanical properties, and the demand for post-processing to achieve optimal performance is still needed.

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Usually, turning process represents a traditional subtractive manufacturing method commonly employed for achieving high precision in components and for improving the surface state [8]. The comparison between wrought and additively manufactured samples, which have undergone turning process, provides valuable insights into the trade-offs and advantages associated with each manufacturing approach, offering a holistic understanding of surface quality and performance [9, 10].

In this study, a deeper investigation into the methodologies employed for both manufacturing processes will be performed, explaining which factors have more impact on the surface characteristics. Moreover, an analysis of the influence of surface features on the mechanical properties of the *Ti6Al4V* alloy was carried out, considering the implications for applications in demanding environments.

By highlighting the surface characteristics of additively manufactured *Ti6Al4V* in comparison to its wrought samples, this research aims to evaluate the strengths and limitations of each manufacturing technique. Such insights are crucial for optimizing material performance and focus on the selection of manufacturing processes based on specific application requirements.

Material and Methods

The workpiece material used for the experiments was the grade 5 titanium alloy in a shape of cylindrical bars with 30 mm of diameter. The experimental machining tests were performed under dry and cryogenic conditions on the additively manufactured and wrought specimens. The material was supplied in the as-built condition (as produced by the metal 3D printer). In detail, the material was used without any post-processing or heat treatment according to the industrial standard. Moreover, to compare and understand the difference regarding the machinability between the additively manufactured materials and the conventionally produced, some cylindrical bars of *Ti6Al4V* alloys produced via standard processes (the wrought bars were produced by extrusion process) were machined using the same cutting parameters and set-up.

Turning tests have been carried out on a high speed CNC turning centre (Mazak Quick Turn II.) using the turning parameters reported in Table 1.

Table 2. Experimental plan for turning.

Turning	Value
Cutting speed v (m/min)	60 – 75 - 90
Feed f (mm/rev)	0.15
Depth of cut (mm)	0.05
Cooling conditions	DRY - CRYO

A fresh cutting tool has been used at each test to avoid undesired effects of wear. Three repetitions for each parameter set have been executed. Two different lubricant conditions have been considered for the tests namely, dry (DRY) and cryogenic (CRYO). While dry conditions were used without the use of lubricant, the cryogenic setup involved the use of LN2 coolant applied at the pressure of 12 bar through two nozzles with a diameter of 2 mm to the cutting region. PVD coated TiAlN (Sandvik N123H2-0400-RO 1105) inserts with a clearence angle of 7◦ and a rake angle of 12◦ have been used.

The overall machining setup for both dry (a) and cryogenic (b) systems is reported in Fig. 1.

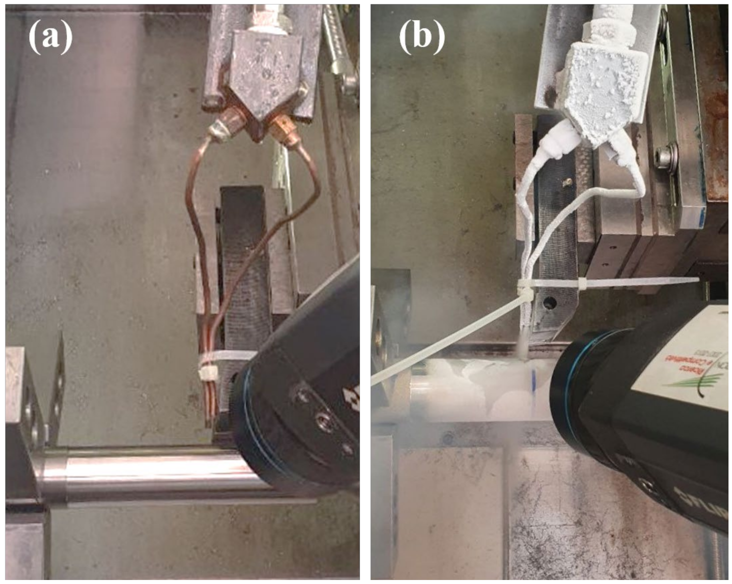

Figure - 1. Set up for dry (a) and cryogenic (b) turning tests.

The mean surface roughness Ra, was measured using a non-contact 3D confocal profilometer. Five measurements for each sample were acquired at different area of the turned surface in order to have statistically accurate dataset. Preliminarily, roughness measurements on the as produced AM and wrought samples were performed, finding a values of 9.97±0.78 µm and 1.20±0.50 µm, respectively.

Afterwards, samples have been sectioned in the cross section direction, mechanically polished up to 1 µm and etched using the Kroll's reagent to reveal microstructure. Then, the obtained specimens have been analysed under an optical microscope (Leica©DFC320 1000×) to verify the microstructure and evaluate the grain size. The grain size was measured using ImagePro commercial software able to identify the single grains from boundaries. It was used to calculate the reference equivalent circle diameter of each single grain on the turned surface, in accordance with ASTM E112–12 standard, leading with sufficient approximation, to an equiaxed grain equivalent configuration. Preliminarily, grain size measurements on the as produced AM and wrought samples were performed, finding a mean values of 5 µm for both.

The polished samples have been also used to test the changes in micro-hardness due to the severe plastic deformation process and the recrystallization phenomena. The $HV_{0.1}$ through the section has been tested by an instrumented micro indenter equipped with a Berkovich tip (Anton Paar micro-indenter MHT). Three matrix spots composed by twenty indentations were sampled for each test piece. Preliminarily, the micro-hardness values referred to the as produced AM and wrought samples are, 420 HV and 390 HV were measured respectively.

Results

Wrought *Ti6Al4V* typically has a more uniform and predictable microstructure. The manufacturing process involves melting, forging, and rolling, which results in a material with well-defined grain structures, as shown in Fig. 2(a). Typically, it has lower porosity and fewer defects, due to the nature of its manufacturing process, which involves melting, casting, and deformation under controlled conditions. This process allows for the control of microstructural features such as grain size and orientation, which can be optimized for specific applications.

Additively Manufactured *Ti6Al4V*, on the other hand, has a more varied microstructure that is strongly influenced by the specific AM process used. These processes involve layer-by-layer melting and solidification of titanium powder, which can lead to rapid cooling rates and the formation of fine, columnar grains and martensitic microstructures. The microstructure can vary significantly over small distances due to localized thermal gradients and cooling rates, as shown in Fig. 2(b). Also, AM *Ti6Al4V* can have higher levels of porosity and may contain defects such as lack of fusion or gas entrapment. These defects are intrinsic to the powder bed fusion processes and can affect mechanical properties such as fatigue life. Efforts in process optimization and post-processing are ongoing to minimize these defects.

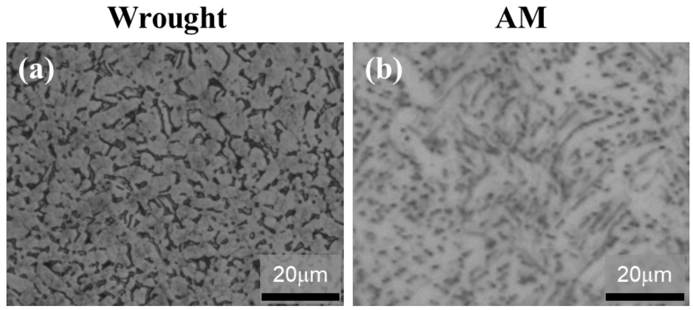

Figure - 2. Optical micrograph of Ti6Al4V microstructure, (a) wrought and (b) AM samples before turning tests.

After turning tests, as shown in Fig. 3, based on the different cooling conditions (dry or cryo) and considering the manufactured process (conventional or AM) the microstructure presented some significant modifications. In both cases, it exhibits a significant grain refinements especially near the surface and the subsurface. Concerning the AM samples, the properties can be more anisotropic, meaning they vary with direction relative to the build orientation. This is due to the layer-wise manufacturing process and the resultant microstructural differences. Post-processing heat treatments are often necessary to relieve residual stresses and improve ductility.

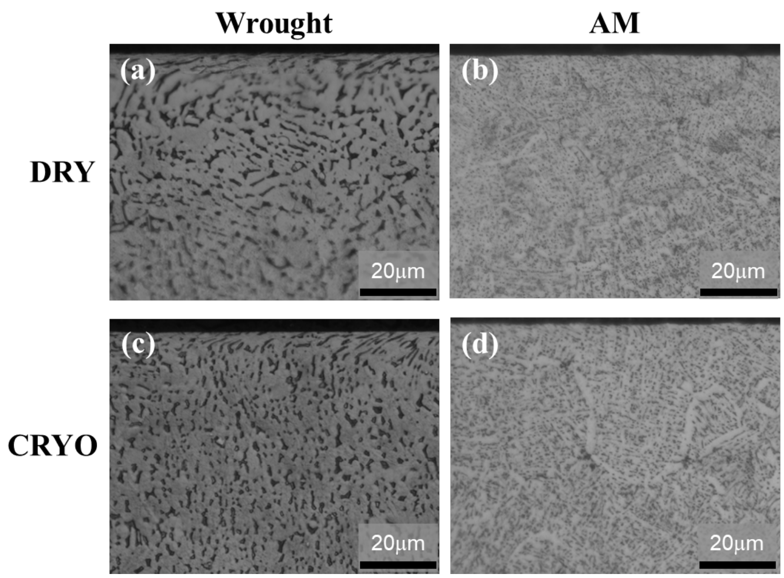

Figure - 3. Optical micrograph of Ti6Al4V microstructure after turning tests at 90 m/min of cutting speed, (a) wrought and dry, (b) AM and dry, (c) wrought and cryogenic, (d) AM and cryogenic.

Moreover, after the optical analysis the grain size was measured. The results are shown in Fig. 4, where at increasing cutting speed the grain size decreases in particular in cryogenic conditions compare to dry either in the case of wrought material as well as in the case of AM. This grain refinement is often the outcome of improvements in wear and corrosion resistance, generating compressive residual stresses enabling fatigue life enhancement.

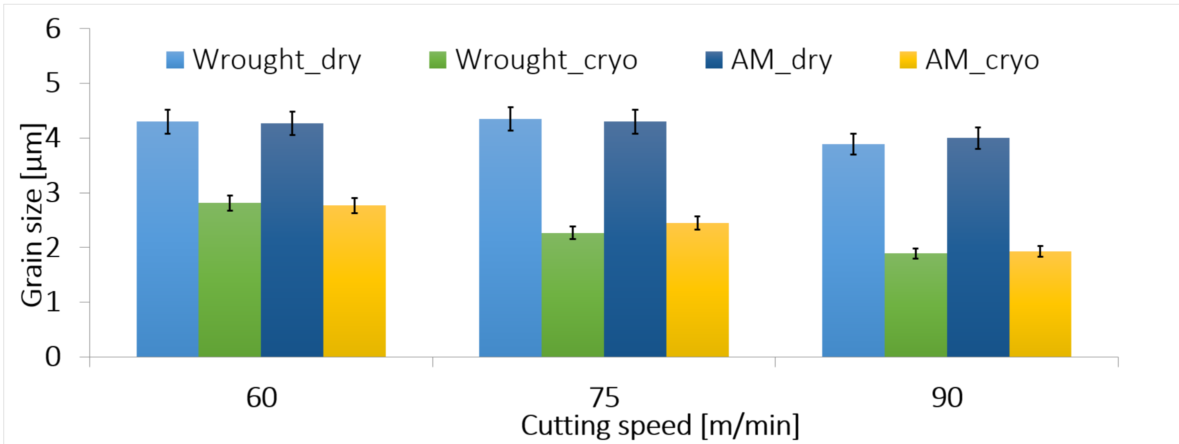

Figure - 4. Grain size evolution at varying turning speed, cooling conditions and manufacturing process.

Concerning the mean surface roughness Ra, turning process significantly improved the surface quality up to a mean value of about 0.30 µm for Ra. Therefore, as shown in Fig. 2, by varying turning process parameters and cooling conditions, the machined surface roughness was significantly improved. In particular, the roughness reduced at increasing of cutting speed. With approximately the same general trend, Ra decrease more when using cryogenic cooling compared to the same process parameters in dry conditions.

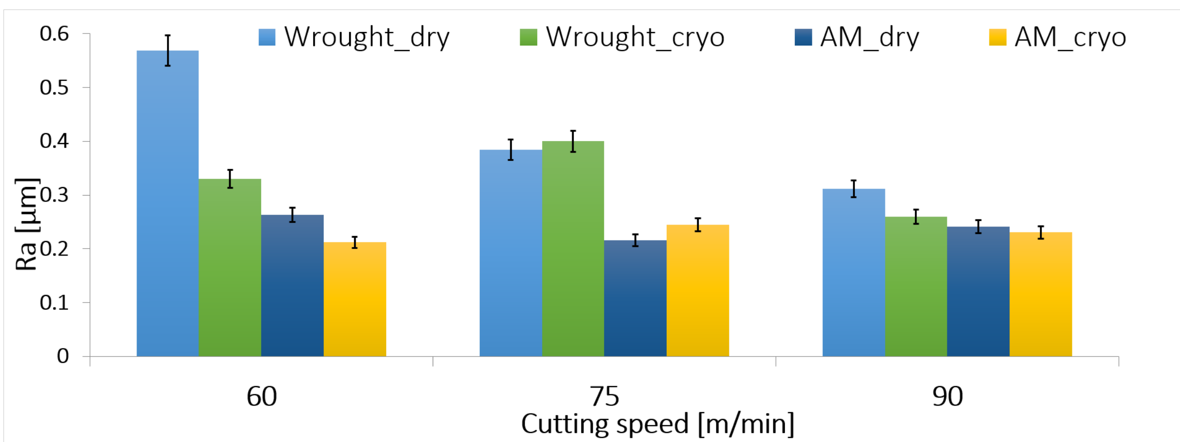

Figure - 5. Mean roughness Ra evolution at varying turning speed, cooling conditions and manufacturing process.

Finally, in terms of surface micro-hardness, as Fig. 6 shows, for the overall experimental campaign turning process leading a slight change in the surface hardness, by increasing the hardness at stronger process conditions namely by increasing the cutting speed and under cryogenic conditions. Furthermore, the deformed layer was deeper after turning, which proves an increased work hardening on the turned surface and sub surface. As can be observed cryogenic conditions lead to an increase in hardness higher with respect of dry conditions for both wrought and AM samples.

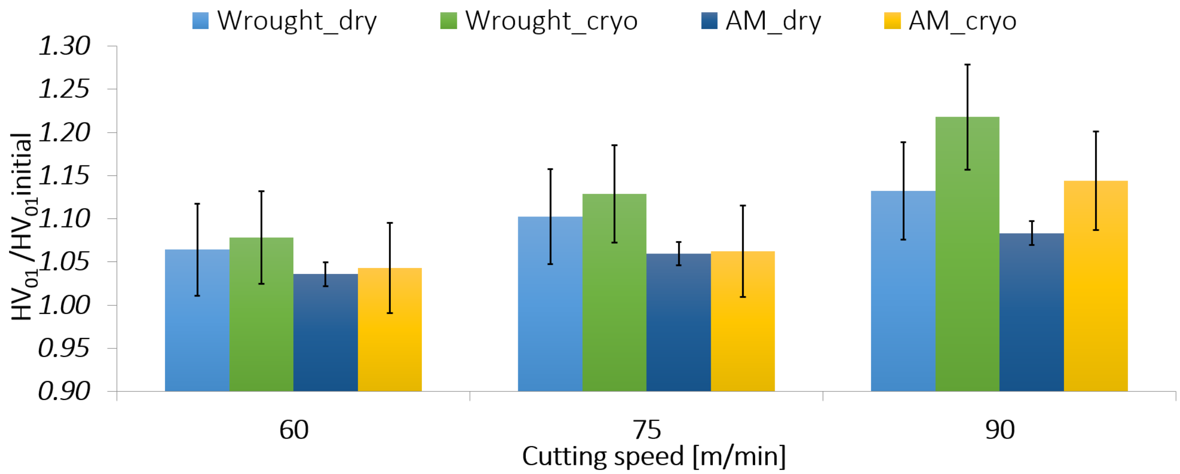

Figure - 6. Micro-hardness below the turned surface at varying turning speed, cooling conditions and manufacturing process.

Conclusions

In this study, we have comprehensively explored the behavior of wrought and AM *Ti6Al4V* alloy under both dry and cryogenic conditions through an extensive experimental campaign. The findings reveal significant distinctions in characteristics and properties between the two material types and the environmental conditions applied. Under dry conditions, both wrought and AM *Ti6Al4V* samples demonstrated expected wear behavior, with wrought samples exhibiting superior wear resistance attributed to their denser and more homogeneous microstructure. However, the introduction of cryogenic conditions altered the performance landscape. Cryogenic treatment enhanced the wear resistance of both samples significantly. This improvement is primarily due to the transformation of microstructural features and induced residual stresses.

Moreover, changes also in grain size, roughness and hardness were observed for both types of material and conditions.

Overall, this study not only underscores the importance of processing conditions on the performance of *Ti6Al4V* alloys but also highlights the potential of cryogenic treatment as a method to enhance the properties of AM materials. This could have significant implications for the aerospace, automotive, and biomedical sectors, where the demand for high-performance titanium alloys is continuously growing. Future work will focus on the long-term effects of cryogenic treatment on the microstructure and properties of these materials to further understand the mechanisms behind the observed enhancements.

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