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An experimental investigation into tribological behaviour of additively manufactured biocompatible Ti-6Al-4V alloy

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Abstract. Additive manufacturing techniques are increasingly being utilized in industrial-level applications due to their flexibility and ability to produce customized parts, such as various types of biomedical implants. However, the conditions during additive manufacturing fabrication and the nature of these processes can lead to implications on the properties of the produced parts, potentially requiring appropriate post-processing before real applications. The tribological behavior of printed parts not only affects their performance but also their service life, making it crucial to investigate their wear rate and friction coefficient under different lubricant environments. In this study, an experimental investigation was conducted on as-printed Ti-6Al-4V specimens to determine the effect of various lubricant environments on wear rate and friction coefficient. The results demonstrated that the reduction in wear rate in liquid environments can be significantly hindered by the accumulation of debris from the worn specimen. However, the development of a thin film of an appropriate lubricant was shown to be favorable regarding the friction behavior of printed parts.

Introduction

Additive Manufacturing (AM) is a nonconventional, automated freeform fabrication manufacturing process that operates on the principle of layer-by-layer construction [1,2]. AM can offer several other advantages, including the elimination of the need for tools and fixtures, the capability for nesting and parallel processing, the reduction in scrap material or waste, and the ability to economically produce customized parts and components [3]. Moreover, AM can simultaneously define both the geometry and material properties of a part during the build process [4]. Laser Powder Bed Fusion (L-PBF) is among the first commercialized AM methods, wherein the power/energy source for bonding the raw material, which is in powder form, is provided by a focused laser beam. L-PBF began as a polymer-based method but has, over the years, expanded to include metals and ceramics [5]. Although LPBF processes provide significant advantages in metal processing, they are limited by uncertainties due to complex physical phenomena that occur on multiple spatial and temporal scales [6]. Consequently, extensive research focuses on understanding post-printing material properties and exploring methods to improve them. The combination of titanium/titanium alloys and L-PBF has proven to be a feasible technology, finding applicability in the aerospace, medical, and automotive sectors. This is a result of titanium's excellent properties and AM's inherent capability to produce complex and lightweight structures and components [7, 8]. However, the outcome of the LPBF process for titanium alloys such as the resulting microstructures and mechanical properties, and consequently, the properties of the final built part can be influenced by various factors [9]. The most common research topic regarding L-PBF processed materials involves studying their mechanical properties. However, considering the demanding operating conditions of titanium alloys and their applicability across a wide range of fields, it is also scientifically and practically valuable to investigate the tribological properties and wear behavior of L-PBF fabricated titanium alloys under various conditions.

The current research's feasibility is supported by two main factors. Firstly, the tribological and wear properties of a material are directly dependent on its microstructure [10]. Secondly, the wear environment significantly influences the development of friction, thereby affecting the tribological behavior and resultant wear. Inherent to L-PBF is the development of a unique microstructure, a consequence of thermal loading cycles involving rapid heating and cooling. Consequently, it is anticipated that materials processed through L-PBF will exhibit different properties compared to those manufactured by conventional methods. For instance, Attar et al. [11] conducted a comparison of the wear properties between cPTi (commercial pure titanium) parts produced by Selective Laser Melting (SLM) and their cast-produced counterparts. Based on SEM observations, they noted a martensitic microstructure in SLM-fabricated specimens, in contrast to a plate-like microstructure in cast specimens. Furthermore, although both SLM-fabricated and cast cPTi samples exhibited similar wear mechanisms, the SLM-fabricated samples demonstrated superior wear resistance compared to the cast versions. Liang et al. [12] linked the tribological properties of SLM-fabricated Ti6Al4V and the material's machinability, focusing specifically on its tribological behavior against cemented carbide under dry conditions. Among various notable findings, they highlighted that the relatively high friction coefficient and its wide fluctuation range during the friction between SLM titanium alloy and cemented carbide suggest intense wear under dry conditions. Additionally, they observed that the average friction coefficient was largely independent of the applied load, while the influence of temperature on tribological properties was more complex. In another notable study focusing on the tribological and wear behavior of L-PBF fabricated titanium alloys, Liu et al. [13] examine the anisotropy of wear and tribo-corrosion properties in L-PBF fabricated Ti6Al4V. They concluded that this anisotropy is linked to the material's microstructure. Consequently, they found that the horizontal plane, perpendicular to the building direction, exhibits superior wear and tribo-corrosion resistance compared to the vertical plane, which is parallel to the building direction.

Kaur et al. [14] and Mahamood et al. [15] have highlighted the significance of studying the wear and tribological behavior of titanium alloys, especially given their widespread use in demanding bioengineering applications. Consequently, it is reasonably deduced that the investigation of the tribological and wear properties of titanium alloys is a crucial and continuously developing area of research. Simultaneously, it is equally important to investigate the materials' tribological behavior under various environments and conditions that closely simulate their actual application scenarios. For instance, Pandey et al. [16] investigated the tribological performance of SS316L, and Ti6Al4V in various solutions, i.e., artificial saliva (AS), phosphate buffer solution (PBS), Ringer's solution (RS), and simulated body fluid (SBF), to simulate their use in biomedical applications. Their findings indicated that wear is a combination of abrasion, adhesion, oxidation, and delamination. Furthermore, they demonstrated that the wear characteristics of both cPTi and Ti6Al4V are significantly influenced by the different solutions, simulating varied environments. Sirin et al. [17] also considered different environments in their study, where they conducted a series of friction wear tests on titanium Grade 2 under various conditions. These conditions included dry environment, base fluid (vegetable-based oil), graphene nanoplatelets (GNPs), hexagonal boron nitride (hBN) nanofluids, and a hybrid nanofluid of GNPs and hBN. Their results indicated that the friction environment significantly impacts the material's wear characteristics.

In the current study tribological tests were conducted on as-printed Ti-6Al-4V specimens under different lubricant environments in order to determine their effect on the tribological behavior of the printed specimens by analyzing friction coefficient and wear rate. The tribological tests were carried out for two different sliding distances in order to further investigate the effect of environment on the progression of wear on the specimens.

Materials and Methods

In the present study, tribological properties of additively manufactured Ti-6Al-4V specimens under different conditions were evaluated, in order to determine the effect of lubricants on the friction and wear behavior of the printed specimens. At first, a small square shaped Ti-6Al-4V slab was printed by a L-PBF machine tool under the recommended optimum conditions. The tribological specimens were then cut to the required dimensions in a Wire-EDM machine tool in order to eliminate possible alterations to the specimens' microstructure due to heat-induced phenomena. Then, the tribological properties were tested by using a T-05 block-on-ring tribotester (Łukasiewicz – ITeE, Radom, Poland) at ambient temperature (21 °C) under technically dry and wet friction conditions. The wet sliding contact was conducted with two different liquids, namely distilled water and SUPRACUT MQL 45 is a synthetic neat cutting oil developed for machining involving chips removal of ferrous and non-ferrous metals. During the test, in order to ensure proper contact between the specimen and the steel ring (heat-treated steel 100Cr6, 53 HRC, Ø49.5×8 mm) rotating at a constant speed, a rectangular tribological sample (4x4x20 mm) was fixed in a holder containing a hemispherical insert. The surface of the specimen in contact with the friction was perpendicular to the direction of the load (L). A double lever system was used to push the specimen in the direction of the ring with an accuracy of the load of ± 1.5%. In total, six different conditions were employed for the tribological tests, as can be seen in Table 1, by conducting the tests under three different environments for 2 different sliding distances, which were supposed to be representative of the conditions occurring under real operating cases. The other testing parameters, such as rotational speed and load were kept constant. Each test was repeated three times and standard deviation of the measurements was also reported.

Table 1. The wear test parameters.

Sliding contact	Counter-specimen	Rotational speed	Load	Sliding distance
Technical dry	steel 100Cr6, heat-treated, with hardness 53 HRC	200 [rpm]	100 [N]	250 [m] 1000 [m]
Wet (water and oil)				

The loss of mass during the test and the average coefficient of friction both in wet and technically dry conditions were measured by dedicated software, whereas the wear rate was determined according to Eq.1:

$$W_r = \frac{\Delta m}{L \bullet Sd} \tag{1}$$

where Δm represents loss of mass in g, L represents load in N and Sd represents sliding distance in m.

Results and Discussion

Mass loss, average friction coefficient and wear rate. After the tribological tests were carried out, the results regarding mass loss, average coefficient of friction and wear rate were obtained.

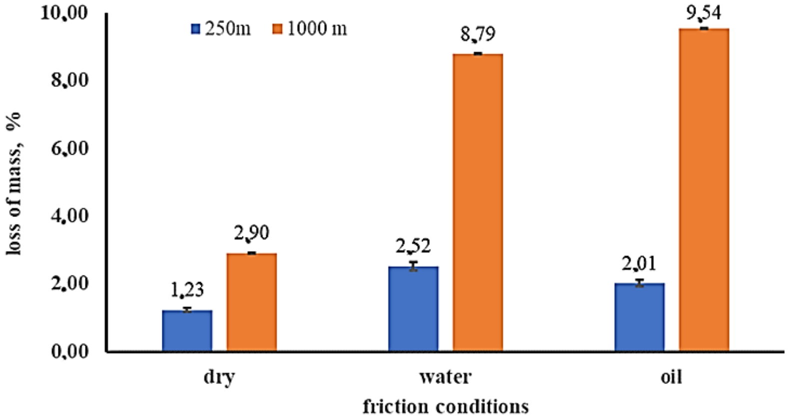

Fig. 1. Effect of tribological test parameters on mass loss.

At first, the wear resistance of the specimens was able to be studied based on mass loss measurements. It is anticipated that mass loss is strictly dependent on the friction conditions (dry or wet) and the friction distance. In Fig. 1, it can be seen that an increase in the friction distance results in an increase in weight loss, in every case, with the increase being more prominent in the case of wet environment. Moreover, the use of water and oil eventually leads to higher mass loss than the one occurring in dry environment in any case.

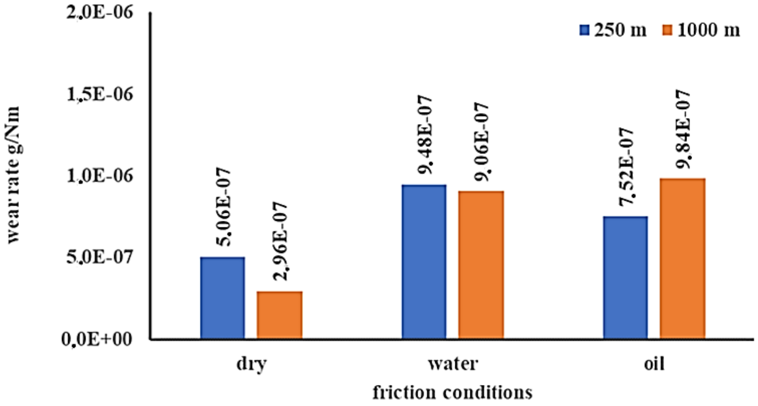

Fig. 2. Wear rate as a function of tribological test parameters.

However, based on the results of Fig. 2, it can be seen that the phenomena occurring during contact stabilize over time, as the rate of mass loss is gradually reduced along the imposed sliding distance, thus leading to a decrease in the wear rate, except for the tests conducted in oil environment, for which the rate of mass loss is assumed to be slightly increasing thus causing higher levels of wear rate.

Furthermore, the results of Fig. 2 suggest that, in the case of the titanium alloy tested, both water and oil do not reduce wear but significantly increase it. These observations can be directly attributed to the fact that both water and oil became contaminated with chipped sample fragments, turning into suspensions, which also influenced the test as they could contribute to increased material removal from the specimens. Moreover, the inherently porous nature of printed parts and their relatively high roughness may also be the reason for this phenomenon, as during the early stages of the wear, fragments from rough protrusions on the specimen surface could have probably been removed and remain in the liquid as debris, something that can also occur in real applications.

On the other hand, regarding coefficient of friction, the use of liquid environment is proven to achieve at least a comparable friction coefficient or a significantly lower one. Based on the results of Fig. 3, it can be seen that the use of water does not reduce the coefficient of friction, even over a distance of 250 m, showing similarity to dry friction conditions. However, as expected, the application of oil causes a significant reduction in the coefficient of friction compared to dry friction due to the development of a thin film between the two contacting surfaces during the tests, although this reduction did not correspond to a decrease in the wear rate.

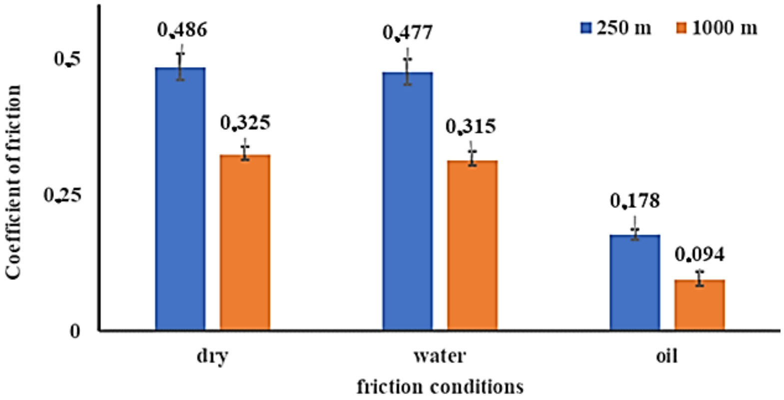

Fig. 3. Coefficient of friction as a function of tribological test parameters.

Especially, regarding friction coefficient, its progression can be directly observed in the friction force plots of Fig.4 and 5.

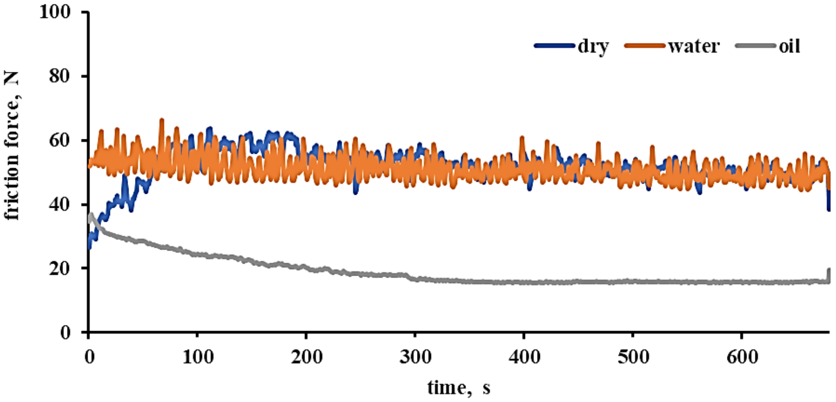

Fig. 4. Friction force of the investigated samples as a function of time and processing conditions, sliding distance: 250 m.

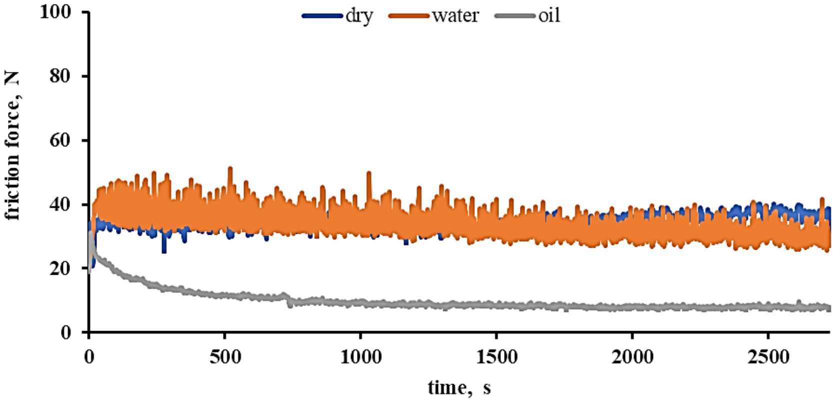

Fig. 5. Friction force of the investigated samples as a function of time and processing conditions, sliding distance:1000 m.

The changes in frictional force recorded over time illustrate the stability of the friction process. Analyzing the curves in Fig. 4 and 5, it can be concluded that the greatest fluctuations occur in the test performed with water. The use of oil stabilizes the friction path significantly; in the dry-start test, the force gradually decreases and stabilizes after approximately 500 s. No significant instantaneous changes in force are observed in the oil process curve, indicating the presence of an oil film between the test sample and the steel counter example.

Wear mechanisms. Apart from determining the fundamental tribological properties of the material under the applied test conditions, it is important to identify the phenomena taking place at the friction node. This identification is made possible by observing the surface morphology after friction, which, in turn, allows the recognition of the friction mechanisms that occurred during the test. Thus, Fig. 6 presents the surface prior to tribology tests, while Figs. 7 – 9 depict the surfaces after the tests, providing a comprehensive overview of typical examples of the post-friction surface morphology of the tested titanium alloy.

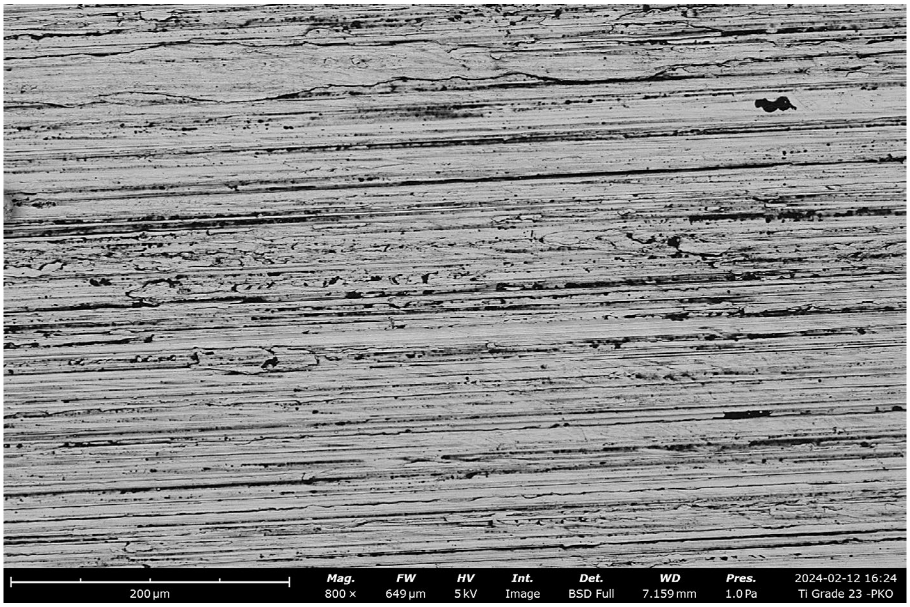

Fig. 6. Surface morphology prior to tribology experiments.

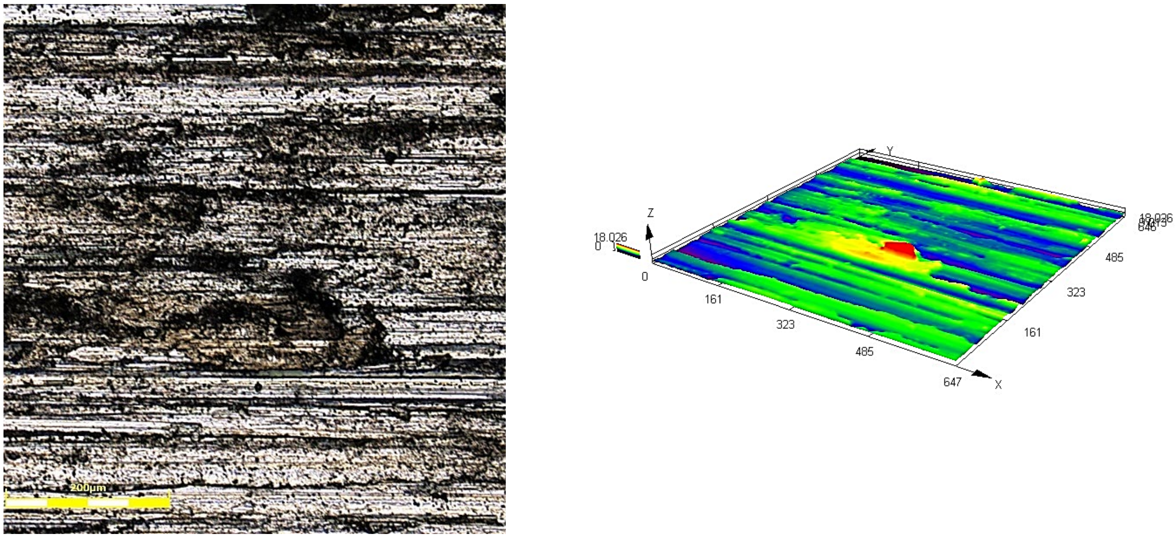

Fig. 7. Surface morphology after sliding contact under technically dry friction.

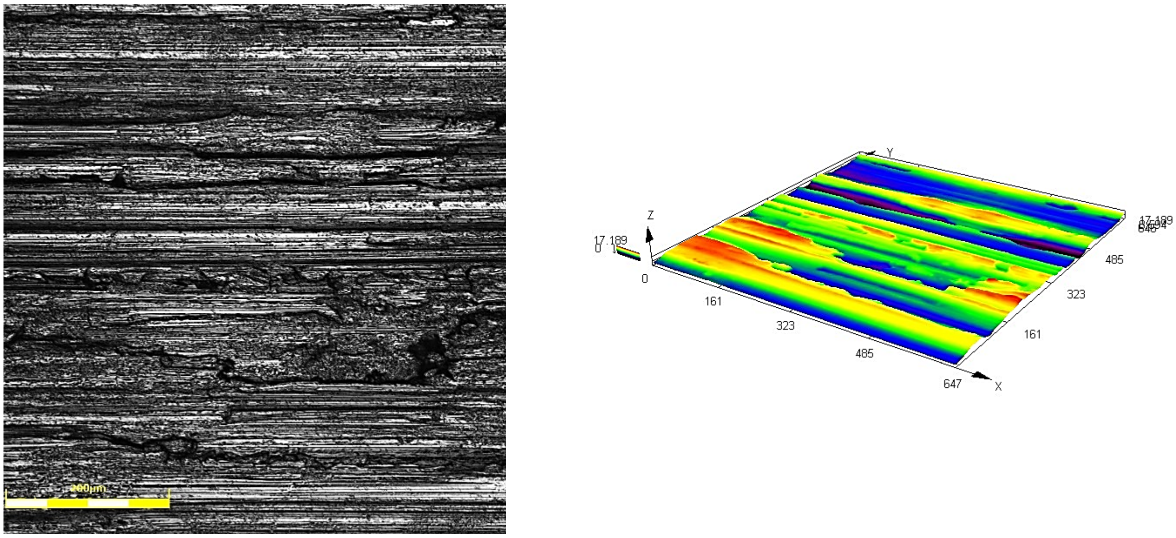

Fig. 8. Surface morphology after sliding contact under wet (water) friction.

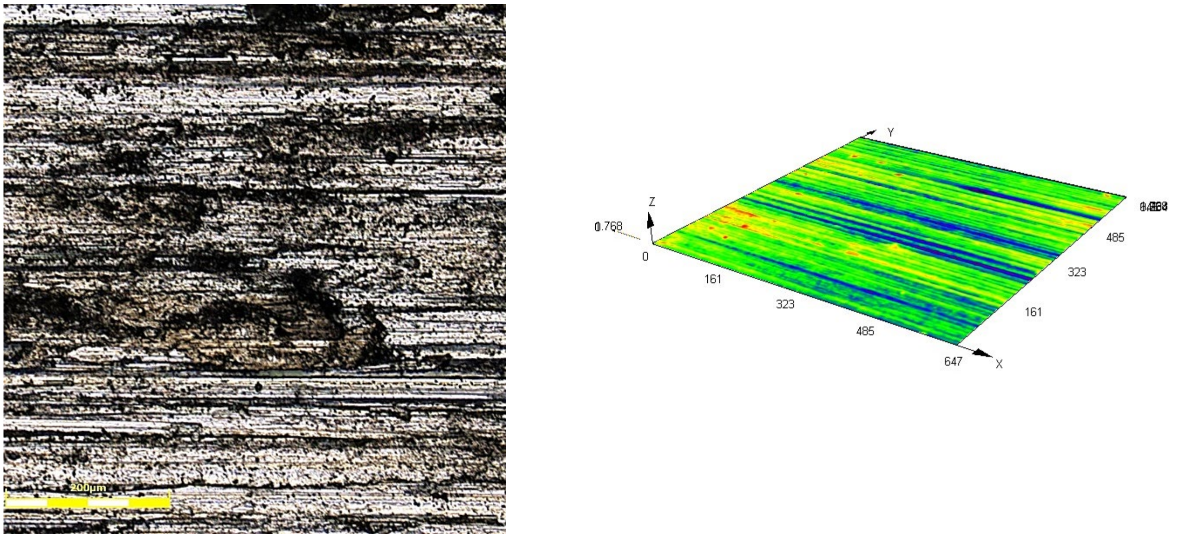

Fig. 9. Surface morphology after sliding contact under wet (oil) friction.

After analyzing the morphology of the worn surfaces depicted in Figs. 6 to 8, it can be concluded that the predominant friction mechanism is abrasive wear, characterized by scratching and furrowing. Additionally, chipping marks are visible on all observed surfaces, regardless of whether wet or dry friction was employed. As mentioned earlier, both oil and water became contaminated with wear products, indicating the intensity of the process despite the short test time. Analyzing the weight losses shown in Fig. 1 under different friction conditions, it is evident that chipping processes and the reaction of fluids with the resulting cracks are crucial in the friction process. Both oil and water, due to capillary forces, penetrate fatigue-induced cracks on the surface, causing rapid chipping. This phenomenon is not observed in dry friction and is described as pitting, typically occurring after an extended period of friction.

Furthermore, these observations suggest a weak particle bond easily broken by load-related frictional forces, leading to crack formation into which fluid infiltrates under high pressure. Unfortunately, in the case of oil, despite a significant reduction in the friction coefficient and the obvious stabilization of the friction force, there is no improvement in the wear resistance of the tested materials. These findings can be proven crucial for the potential applications of the printed specimens.

Conclusions

In this study, tribological tests were carried out on biomedical grade additively manufactured Ti-6Al-4V specimens under different lubricant conditions in order to evaluate the effect of lubrication environment on the friction and wear behavior of the printed specimens for two different sliding distances.

Wear rate calculations based on mass loss measurements showed that the mass loss rate is gradually reduced leading to lower wear rate for longer sliding distances for dry and water environment whereas a slight increase was observed in the oil environment, probably due to accumulation of debris in the liquid, resulting from the removal of protrusions from the porous surface of as-printed specimens. This phenomenon also caused the wear rate being larger in the case of wet friction tests, compared to the dry friction case.

Regarding friction coefficient, it was demonstrated that the friction coefficient can be efficiently reduced by using an appropriate lubricant such as oil, as a threefold reduction in friction coefficient was observed due to the development of a thin film of lubricant between the two contacting surfaces. However, the capability of distilled water as lubricant was proven insignificant in the present case.

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