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TRIBOLOGICAL CHARACTERISTICS OF ADDITIVE MANUFACTURED COMPONENTS BY DIGITAL LIGHT PROCESSING

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Abstract: *The additive manufacturing technology is able to produce different types of mechanic components with applicability in various fields of the industry. When these components are subjected to friction and wear, they require good characteristics. This study shows the influence of the UV treatment on the tribological characteristics, applied to samples manufactured by Digital Light Processing (DLP). The tests were performed on the micro-tribometer CETR-UMT2. The applied load was 10N, with a constant sliding speed of* $1m/s$*, on a ball-on-disk set-up. The samples were cured for 0s, 3s, 4s, 5s and 20s. The tests showed a noticeable decrease of the friction coefficient and a lower roughness of the wear trace, for the samples cured for a longer time.*

Key words: *additive manufacturing, 3D printing digital light processing, tribology, friction, wear.*

1. INTRODUCTION

In the field of additive manufacturing, Katal et al [1] observed that digital light processing (DLP) has emerged as a powerful technology capable of transforming digital designs into physical objects with remarkable accuracy.

Alzarrad et al., [2] concluded that the additive manufacturing (AM) technology has a huge impact in industry, on the way we used to manufacture components.

As this technology continues to advance, it becomes increasingly vital to understand the mechanical properties of the components manufactured through the DLP technique to ensure their performance and reliability.

One crucial aspect of component performance is the interaction between surfaces, specifically friction and wear characteristics. Friction, the resistance encountered when two surfaces slide or attempt to slide against each other, and wear, the gradual loss of material due to friction and other mechanical forces, play pivotal roles in determining the lifespan and efficiency of mechanical systems. Also, when the components are subjected to UV treatment, their mechanic characteristics change, with possible impact on the tribological behavior.

To capture the essence of real-world applications, our experimental setup simulates practical working conditions, taking into account factors such as load, speed, and UV treatment. By replicating these parameters, we strive to bridge the gap between laboratory tests and actual operational environments, enhancing the relevance and reliability of our findings.

The results of our study not only provide an in-depth understanding of the friction and wear performance of DLP-manufactured components but also serve as a foundation for optimizing their design and manufacturing processes.

Hanon et. al., [3] has performed a similar test on DLP printed components, but the treatment with UV light was for all specimens, and for a much longer time (30min) than what is proposed for this article, also the test set-up is cylinder-on-plate with reciprocating speed. He reported a value for the friction coefficient of approx. 0.72

In other article published two years later, Hanon et. al., [4] presented also the influence of the graphene presented in the UV cured polymer matrix. He observed that adding nanoparticles in the polymer matrix will result in a shattered UV light, resulting in an uneven cured resin. Therefore, the tribological proprieties became worse for more than 2% wt. graphene.

Kazemi et. al., [5] has studied the abrasion performance of DLP printed components on a pin-on-disk tribometer, where both components were DLP fabricated and not post-cured with UV light, with the difference that the pin was placed under various angles. The study reported that the most important factors in determining the abrasion rate was the load applied on the pin, with a percentage of 71,58% followed by the normal load measured relative to the surface with a percentage of 27,7%, the left percentage of 0,11% being represented by the layer thickness.

Slapnik et. al., [6] has studied the impact of solid lubricants such as PTFE, graphite and MoS2, added in various concentrations in the composition of a resin prepared from the oligomer CN964A85, the monomer SR605D in a ratio 7:3, and a photo initiator. The samples were also post cured with UV light for 900[s] and tested on pin-on-disk tribometer. The results showed that all samples containing PTFE presented a decrease of the COF (Coefficient Of Friction) from approx. 0.7 to approx.0.5. Similar effect was noticed for the wear rate. The addition of graphite and MoS2 showed almost no impact in the tribological behavior.

Huetting et al. [7] made a comparation between samples manufactured by conventional, additive and subtractive technologies, in terms of wear behavior, using PMMA as base material. The wear tests were performed in wet conditions at up to 5000 cycles and a normal force of 5[N] and a sliding gap of 10[mm]. The wear tests showed no significant difference between samples.

It was noted that there are no tribological studies that shows the effect of UV curing for short times (under 20s), with comparation to uncured samples. Therefore, this article presents a comprehensive analysis of the impact of UV treatment on the friction and wear characteristics of components fabricated by the DLP technique.

2. MATERIALS AND EQUIPMENT

2.1 Materials

The material used for the fabrication of the specimens is a white resin manufactured by Anycubic. The Anycubic white resin is a specially formulated material designed for use in Digital Light Processing (DLP) 3D printing technology. It is specifically engineered to provide high-quality results with exceptional accuracy and detail. The white resin is composed of a liquid polymer that is photosensitive, meaning it solidifies and hardens when exposed to specific wavelengths of light.

Anycubic's white resin offers several key characteristics that make it an attractive choice for various applications. Firstly, it boasts excellent flowability, allowing it to evenly distribute and fill intricate details of the printed object. This characteristic ensures precise replication of the digital design with minimal imperfections, resulting in smooth surfaces and sharp edges.

Furthermore, the white resin exhibits high stability during the printing process, minimizing the chances of warping or distortion. This stability contributes to the overall dimensional accuracy and consistency of the printed parts.

The specimens were designed as a disk with a hole at its center, with the purpose to optimize the amount of the resin required for the production (figure 2). The dimension of the samples is presented in fig.1

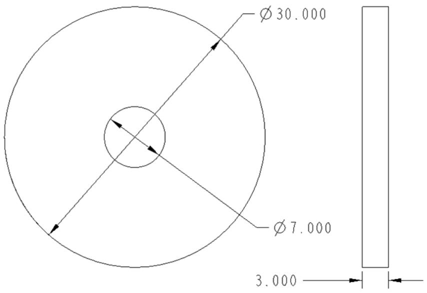


Fig.1. Mechanical dimension of the tested specimens

The counter-part used for all tribological tests is a bearing steel ball, with a diameter of 6.35mm.

Fig.2. View of the samples (photo taken after tribological testing)

2.2 Equipment

The equipment used for this study are the 3D printing system, the UV curing chamber, the roughness tester and the tribometer.

- The 3D printing system used for the fabrication of the samples is Anycubic Mono 4K (figure 3).

At the core of the Anycubic Mono 4K is its monochrome LCD screen with a resolution of 3840 x 2400 pixels. This high-resolution display enables the printer to achieve incredibly fine details and smooth surfaces, resulting in visually stunning and accurate prints.

The monochrome nature of the LCD screen also enhances the printing speed compared to color displays, enabling faster production of specimens without compromising on quality.

Fig.3. The 3D printed used for the fabrication of the samples

The printer utilizes a powerful UV LED light source that provides uniform and precise curing of the resin, ensuring consistent and reliable print outcomes. The UV LED technology not only enhances the curing process but also offers energy efficiency, prolonging the lifespan of the light source and reducing operational costs.

With its build volume of 192 x 120 x 200mm, the Anycubic Mono 4K offers ample space for producing specimens of various sizes. Whether it's small intricate models or larger prototypes, the printer provides sufficient room to accommodate a wide range of applications.

- The curing system is the WANHO BOXMAN-1 UV curing chamber specifically designed for the post-processing of DLP printed specimens. This advanced equipment plays a crucial role in the complete curing and solidification of resin-based materials, ensuring optimal mechanical properties and performance.

With its high-intensity UV light source, the WANHO BOXMAN-1 offers efficient and uniform curing of DLP printed specimens. The chamber's design ensures even distribution of UV light across the curing area, minimizing the risk of uneven curing and resulting in consistent mechanical strength and dimensional accuracy.

- The testing system is the UMT CETR 2 (Universal Mechanical Tester, CETR Inc.), is a highly advanced tribometer specifically designed for conducting comprehensive testing on various specimens in scientific research.

The UMT CETR 2 offers a versatile range of testing modes, allowing researchers to simulate different tribological conditions accurately. These modes include pin-on-disk, reciprocating, and linear tribology tests, enabling the investigation of material behavior under different sliding, rolling, or reciprocating motions. This versatility ensures that a wide array of tribological scenarios can be accurately reproduced and analyzed.

The configuration used for this study is ball-on-disk. The general view of the system is presented in figure 4.

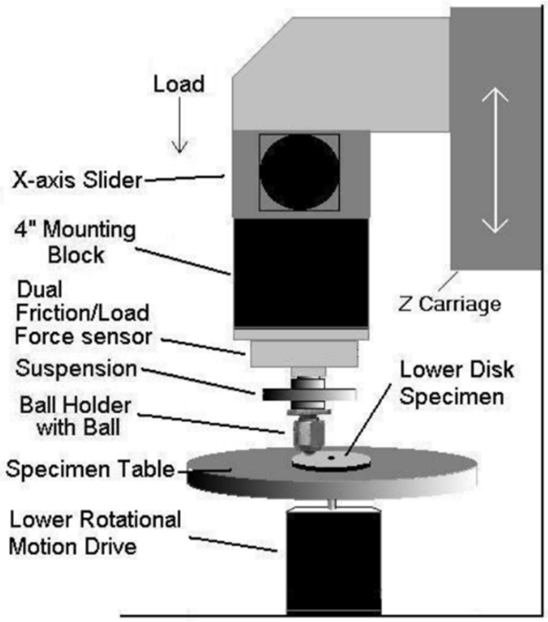


Fig.4. Simplified view of the testing system

One of the key strengths of the UMT CETR 2 lies in its precise control of load and displacement. The instrument incorporates advanced sensors and actuators that enable accurate measurement and control of these parameters. This level of precision ensures the reproducibility and consistency of test results, facilitating reliable data collection and analysis.

The UMT CETR 2 (figure 5) is equipped with sophisticated software, offering a user-friendly interface for configuring test parameters, monitoring real-time data during experiments, and generating comprehensive reports. The software allows researchers to customize test conditions, track measurements, and perform in-depth analysis of the acquired data. This streamlined process enhances efficiency in experimentation and simplifies the extraction of valuable insights from the test results.

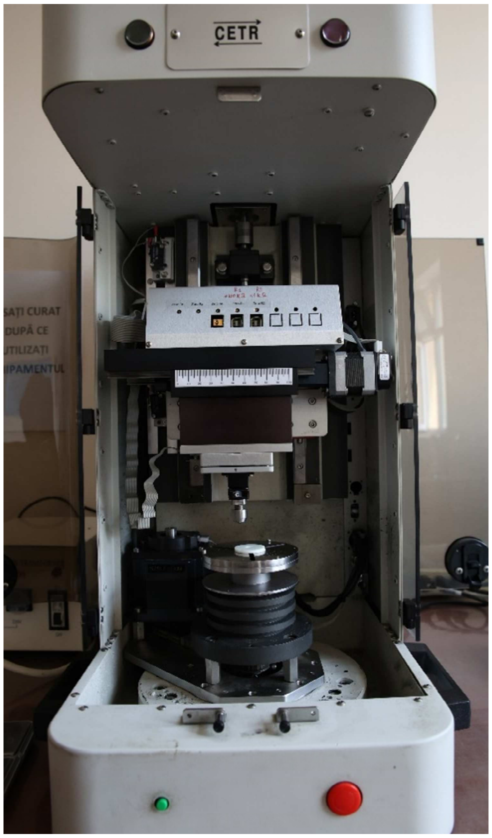


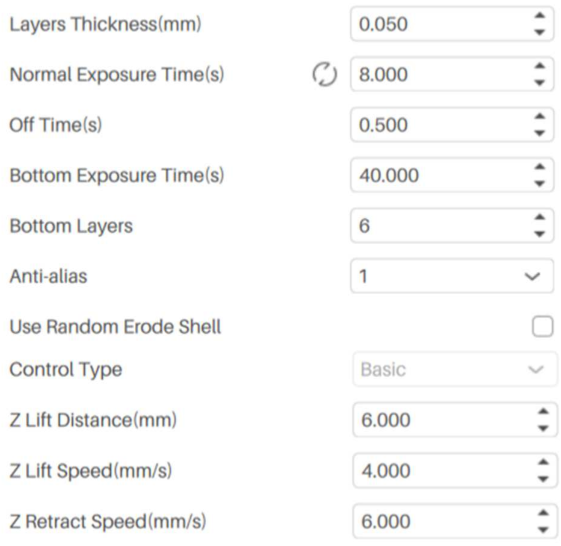
Fig.5. Front view of the tribometer UMT CETR-2.

With a wide array of sensors and measurement tools, such as friction force sensors, displacement sensors, and wear measurement devices, the UMT CETR 2 provides accurate and detailed data on critical tribological parameters. These measurements include frictional forces, contact pressures, wear rates, and other essential characteristics of the tested materials. The comprehensive measurement capabilities of the UMT CETR 2 enable researchers to gain a thorough understanding of material behavior and performance under specific test conditions.

3. PRINTING, CURING AND TESTING PARAMETERS

3.1 Printing parameters

The printing parameters used for the are the presented in the figure 6.



Layers Thickness(mm) 0.050
Normal Exposure Time(s) 8.000
Off Time(s) 0.500
Bottom Exposure Time(s) 40.000
Bottom Layers 6
Anti-alias 1
Use Random Erode Shell ☐
Control Type Basic
Z Lift Distance(mm) 6.000
Z Lift Speed(mm/s) 4.000
Z Retract Speed(mm/s) 6.000

Fig.6. Printing parameters of the specimens

The most important parameters which poses interest for our study is the layer thickness, which is selected to be 50μm, and the normal exposure time of the layer, which for our study is 8s.

3.2 Curing parameters

The curing of the samples is performed under different times, to highlight the impact over the tribological proprieties. The samples (S1÷S5) were cured according to the table 1.

Table 1

The curing plan of the tested samples.

	S1	S2	S3	S4	S5
Curing time [s]	0	3	4	5	20

3.3 Testing parameters

All samples were subjected to the same testing parameters. The sliding radius of the ball was 10mm, with a speed of 1000[rpm] for the disc sample. The normal load was 10[N]. The time applied for each test was 300[s]. The testing set-up is presented in figure 7.

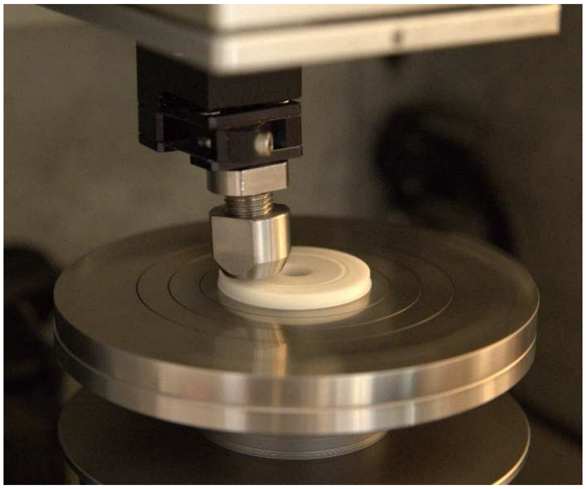


Fig.7. View of the testing set-up during testing

The tangential velocity of the sliding contact can be calculated with the formula (1):

$$v = r \times \frac{2\times\pi}{60} \times n \quad [m/s] \qquad (1)$$

Resulting a tangential velocity of:

$$v = 1\ [m/s]$$

An additional specimen was fabricated, which was not cured. The purpose of this uncured specimen is to show the wear mode when it is subjected to intense wear.

The fabrication steps and procedure of handling of this specimen are the same as for the sample S1. The specimen was tested under a constant load of 10N, but with variable sliding speeds, which was applied in steps, using a time of 60[s] for each step.

The mobile part was the specimen, to which the speed of the rotary table started from 100[rpm], then jumped to 250[rpm] followed by a successive incrementation with 250[rpm] until it reached 2500[rpm], resulting in 11 steps.

4. RESULTS

4.1 Roughness measurements

The roughness measurements after the friction tests are presented in the table 2. R_z represents the roughness in the tested area.

Table 2

Roughness measurements of new samples

	S1	S2	S3	S4	S5	S6
R_z[µm]	5.5	6.3	5.7	4.5	3.3	165

The profile of the surfaces in the tested area are presented in the figures 8, 9, 10, 11, 12, 13.

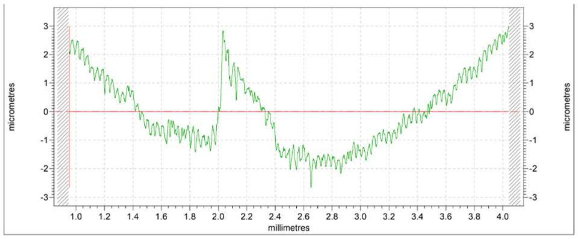


Fig.8. The surface profile of the uncured sample subjected to friction test

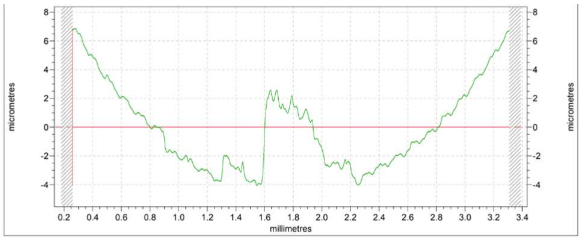


Fig.9. The surface profile of the cured sample for 3 [s] subjected to friction test

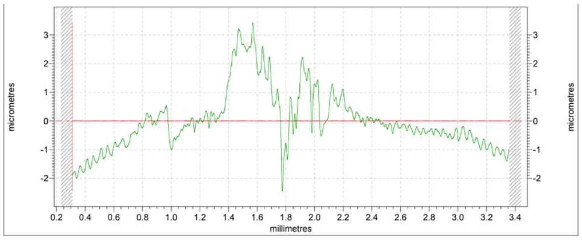


Fig.10. The surface profile of the cured sample for 4 [s] subjected to friction test

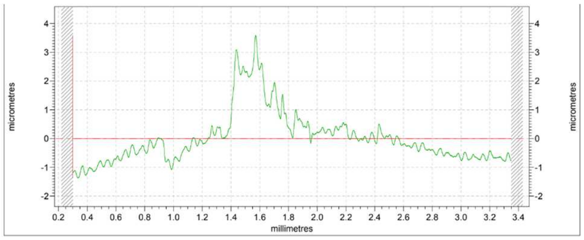


Fig.11. The surface profile of the cured sample for 5 [s] subjected to friction test

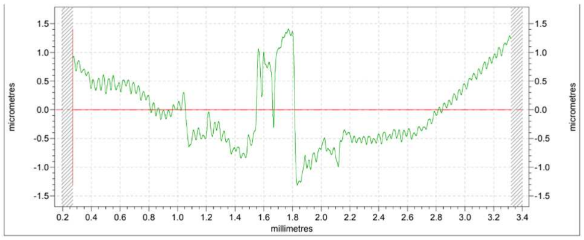


Fig.12. The surface profile of the cured sample for 20 [s] subjected to friction test

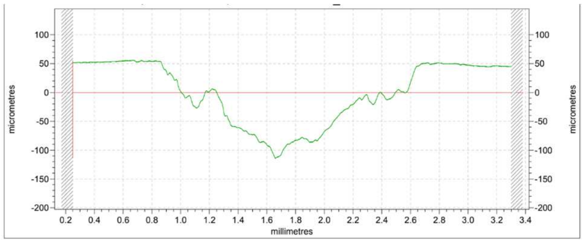


Fig.13. The surface profile of the uncured sample subjected to friction test at variable speed and constant load

It can be observed from the figures 8÷12 that the wear track is elevated from the normal surface, which presents a convex tendency for the specimens S1, S2, S4 and S5. In the figure 13 can be observed the profile of the intense wear of the uncured specimen.

4.2 Coefficient of friction

The friction coefficient varies across the testing duration. The figure 14 presents a comparation between COF for all samples, where T means the exposure time of the UV treatment.

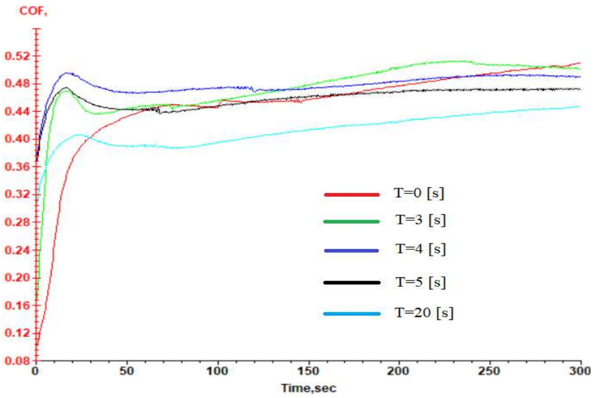


Fig.14. The variation of COF in time

In table 3 is presented the average COF for each sample, during the stabilization phase, right before it starts to manifest a growing tendency.

Table 3

The average value of the COF in the stabilization phase

	S1	S2	S3	S4	S5
COF	0.45	0.44	0.49	0.44	0.39

4.3 Wear modes

The analysis was made using optic microscope with electronic sensor for the storage of the image. The wearing modes are presented in the figures 15, 16, 17, 18, 19 ,20.

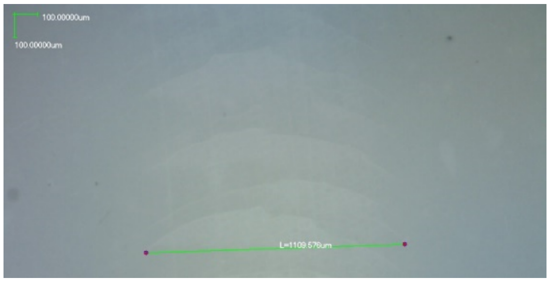


Fig.15. The wearing mode of the sample S1

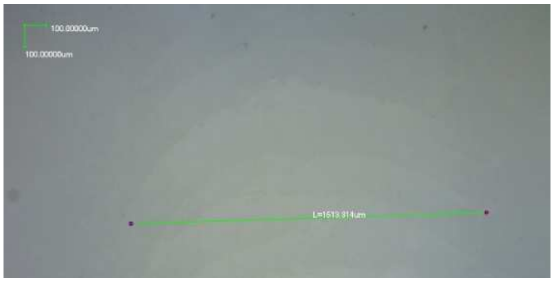


Fig.16. The wearing mode of the sample S2

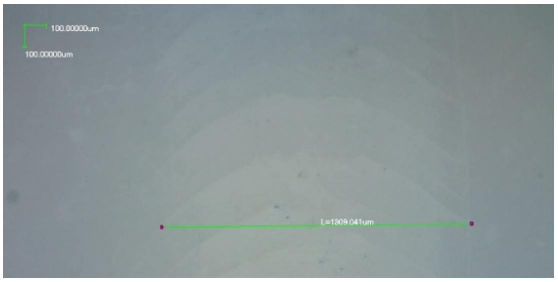


Fig.17. The wearing mode of the sample S3

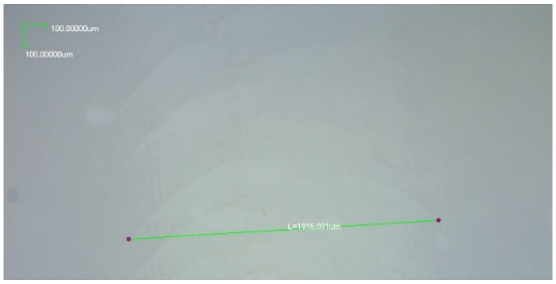


Fig.18. The wearing mode of the sample S4

Fig.19. The wearing mode of the sample S5

Fig.20. The wearing mode of the sample subjected to variable speed (S6)

The wear modes are mainly similar for all samples S1÷S5, and it can be observed from figures 15÷19 that the main wear mode is the adhesive wear. The material tends to adhere to the ball and when the polymeric bonding exceeds the adhesive bonding, the material is left behind, creating a wave. Fact that might explain why the wear trace has waves and why the friction coefficient decreases for the sample cured for a longer time, being known that the curing makes the DLP samples more brittle.

For the sample subjected to intense wear (figure 20), the main wear mode seems to be a combination between fatigue fracture and abrasive wear, since the wear track seems glassy and full of cracks.

5. DISCUSSIONS

The roughness measurements before testing have shown that the surface profile has a convex shape. This behavior might be only due to the changes of the shape during drying, since this behavior is presented also on the cured samples.

The heat generated by the friction process, caused the base material of the specimen to be softer, effect similar to the thermoplastics, even though the cured resin can be considered to be a thermoset. This effect has been observed at the end of the testing, during the replacement of the specimens from the testing platform.

The friction coefficient presents two stages. In the first stage, named the running-in stage, has been measured a very sharp increase of the COF, followed by a stabilization phase, in which the COF stops to a certain value, with a small tendency of growing.

It can be observed that the UV treatment has a significant impact in the tribological characteristics for the sample exposed for a time of 20[s], having the lowest value for the COF, the highest being measured on the sample cured for 4[s].It can be noticed that for all samples, the COF grows very fast, then it falls and stabilizes at an average value of 0.44, followed by a constant rising, with a exception for the sample S2, for which the COF starts to decrease after approx. 230[s].

The material removed from the worn area was like a very fine powder. This has been observed especially on the specimen tested up to 2500 [rpm]. For the samples tested at constant speed and load, the amount of material removed by wear was barely noticeable.

After the friction tests, the measurement of the roughness, showed that the wear trace has been elevated, compared to the rest of the surface. This effect might be due to the deterioration of the bonding between layers, caused by fatigue and possibly also due to the fact that the heat induced by the friction, has generated gases between the layers where the bonding was destroyed.

6. CONCLUSIONS

In this article, a thorough examination is provided regarding the influence of UV treatment on the friction and wear properties of components manufactured through Digital Light Processing.

Following the obtained profilometry results, the samples presented convex deviations from the designed shape on the top side.

The tribological testing showed that the COF presents two stages. In the running-in stage the COF rise drastically to an average value of 0.44. In the stabilization stage, the COF presents a small tendency of growing, which for the samples cured for 3[s] and 4[s] showed a small tendency of falling after approx. 230[s] of testing.

Under constant load and speed conditions, the tested samples exhibited an elevated surface roughness in the worn region. This was primarily attributed to the fatigue-induced deterioration of layer bonding, possibly compounded by the generation of gases between the layers due to friction-induced heat, resulting in the destruction of bonding.

The main wear mode for the samples S1÷S5 has been concluded to be the adhesive wear, while for the sample S6 has been concluded to be a combination between fatigue fracture and abrasive wear.

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Caracterizarea tribologică a componentelor fabricate aditiv prin procesare digitală a luminii

Tehnologia de fabricație aditivă este capabilă să producă diferite tipuri de componente mecanice cu aplicabilitate în diverse domenii ale industriei. Atunci când aceste componente sunt supuse la frecare și uzură, ele necesită caracteristici bune. Acest studiu arată influența tratamentului UV asupra caracteristicilor tribologice, aplicat pe probe fabricate prin procesare digitală a luminii (DLP). Testele au fost efectuate pe microtribometrul CETR-UMT2. Sarcina aplicată a fost de 10N, cu o viteză de alunecare constantă de 1m/s, pe un montaj cu bilă pe disc. Probele au fost tratate timp de 0s, 3s, 4s, 5s și 20s. Testele au arătat o scădere notabilă a coeficientului de frecare și o rugozitate mai mică a urmei de uzură, pentru probele tratate pentru o perioadă mai lungă de timp.

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