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TRIBOLOGICAL CHARACTERISTICS OF ADDITIVE MANUFACTURED COMPONENTS BY DIGITAL LIGHT PROCESSING, SUBJECTED TO LINEAR RECIPROCATING MOTION

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Abstract: *In the field of additive manufacturing, digital light processing (DLP) technology has emerged as a practical and inexpensive solution for the manufacturing of mechanical components based on photocurable resins, which are used in various areas of industry. Often these components are in motion, relative to the counterpart, and in contact with metal components, and subjected to friction and wear. This study presents the influence of UV treatment on tribological characteristics, applied to a set of samples fabricated by digital light processing, for the case where they are subjected to reciprocating linear motion. Anycubic Mono 4K printer was used to fabricate the samples. Samples were cured for 3 (s), 4 (s), 5 (s) and 20 (s). A separate set of samples, manufactured and cured under the same parameters, is naturally aged for six months. The tests were performed on the CETR-UMT2 micro tribometer, for which the metal counterpart is a bearing ball with a diameter of 6.35 (mm). The applied load for the friction tests is 10 (N), with a contact speed of 5 (mm/s), for a sliding distance of 10 (mm), over a period of time of 600 (s). The scratching tests has been performed under a normal force of 5 (N), at a speed of 0.167 (mm/s) and a scratching time of 60 (s), for a distance of 10 (mm). The denting tests has been performed using a Rockwell diamond tip, with a force applied in five different steps up to 5 (N). Tribological tests showed that the friction coefficient exhibits two stages. In the running-in phase, the value of the friction coefficient increases drastically, followed by a stabilization phase at a very small value, with a small tendency of growing. The scratching test showed that the UV curing time has no significant impact in the scratching depth. Also, the applied load varies proportional with the scratching depth.*

Key words: *additive manufacturing, digital light processing, tribology, friction, scratching, denting.*

1. INTRODUCTION

In the world of additive manufacturing, resin photopolymerization is used in various 3D printing methods, including digital light processing (DLP) [1].

This technology is based on the principle that the final component is built up by successive polymerization of the resin in different layers, where the shape of the layer is defined by a digital system and projected on the bottom of a vat, filled with UV sensible resin, using an optical system. The mechanical system is mainly responsible for controlling the thickness of the layer [2].

According to Pagac et al. [3], due to the versatility of the manufacturing method with regard to the design and material possibilities, the technology has gained popularity in various fields of the industry and engineering, such as smart composites, soft robotics, flexible electronics, superhydrophobic 3D objects, medical and biomedical appliances, prosthetics and orthotics, sports equipment, jewelry, etc.

Many applications of DLP manufactured components are in contact and in relative motion with other elements, the counterpart in most cases being made of metal, e.g., linear guiders.

Even if, in many cases, the load is low and worthy to be ignored, the tribological behavior of the 3D printed components is not well known.

Hanon et al. [4] has tested a similar type of resin (Wanhao UV resin), on pin-on-plate set-up, with a load of 150 N. The samples were heat treated at 60°C, for 30 minutes and UV cured for 30 minutes. The tests have shown that the dynamic friction coefficient varies between 0.72 and 0.79.

It has been observed in the literature that the tribological study with reciprocating movement in dry conditions of DLP printed specimens, on ball-on-plate set-up and under low load, is not studied.

For a better understanding on the tribological characterization of the DLP printed specimens, this study aims to present the influence of the UV post treatment. The article aims to show the results from friction, scratch and denting tests, and to present a comparation between continuous circular testing and linear reciprocating testing.

2. MATERIALS AND EQUIPMENT

2.1 Materials

The material used to make the specimens is a white resin manufactured by Anycubic.

The white resin is composed of a liquid polymer that is photosensitive, meaning it solidifies and hardens when exposed to specific wavelengths of light. The parameters of the resin are presented in Table 1.

Table 1

Parameters of Anycubic White resin [5]

Parameter	Value	Parameter	Value
Viscosity (mPa×s) 25°C	150-200	Density g/cm^3	1.05-1.25
Wavelength (nm)	405	Hardness (Shore D)	80D
Tensile strength (MPa)	36-45	Elongation (%)	8-12
Flexural strength (MPa)	50-65	Flexural modulus (MPa)	1200-1600
Volumetric shrinkage (%)	4.5-5.5	Notched impact strength (J/m)	25
Heat deflection temperature (°C)	65-70	Shelf life (year)	1

The dimensions of the samples are presented in Fig.1

The specimens were designed as a disc with a hole in the center to facilitate the fixation on the testing table (Figure 2).

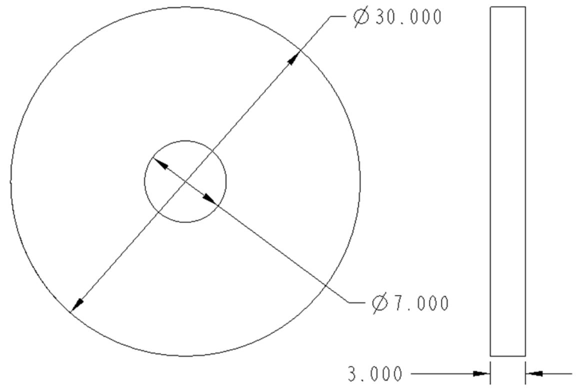

Fig.1 Mechanical dimensions of the tested specimens (all dimensions in millimeters).

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 first tribological test).

2.2 Equipment

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

The 3D printing system used to fabricate the samples is Anycubic Mono 4K.

The main element of the Anycubic Mono 4K is the monochrome LCD screen with a resolution of 3840 x 2400 pixels. This high-resolution display allows the printer to achieve incredibly fine detail, and smooth surfaces, resulting in precise and visually stunning prints.

The printer uses a powerful UV LED light source of 405 nm, with a power density of 3.5-4 mW/cm^2, that ensures uniform and precise curing of the resin, guaranteeing consistent and reliable print results. UV LED technology not only improves the curing process, but also provides energy efficiency, extending the life of the light source and reducing operational costs.

With a building volume of 192mm x 120mm x 200mm, the Anycubic Mono 4K offers ample space for producing specimens of various sizes. Whether for small, intricate models or larger prototypes, the printer offers enough space to accommodate a wide range of applications.

The curing system is the WANHO BOXMAN-1 UV curing chamber specifically designed for further processing of DLP printed specimens.

With its high-intensity UV light source of 120 W, at 405 nm wavelength, ensures efficient and uniform curing of DLP printed specimens.

The chamber design ensures an even distribution of UV light across the curing surface, minimizing the risk of uneven curing and resulting in consistent mechanical strength and dimensional accuracy.

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

The UMT CETR 2 offers a versatile range of test modes, allowing researchers to accurately simulate various tribological conditions. These modes include disc pin, piston and linear tribological tests, allowing investigation of material behavior under different sliding, rolling or reciprocating motions.

The configuration used for this study is ball-on-plate. The general view of the system is presented in Figure 3.

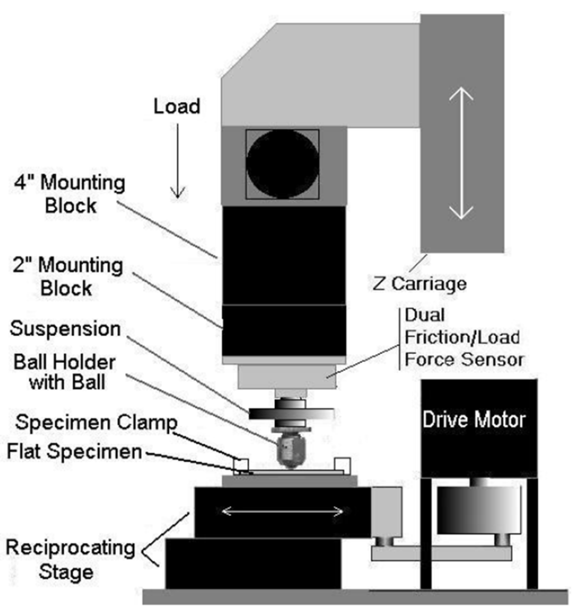

Fig.3 Simplified view of the testing system [6]

The UMT CETR 2 is equipped with sophisticated software that provides a user-friendly interface for setting test parameters, monitoring data in real time during experiments and generating comprehensive reports.

With a wide range of sensors and measuring instruments such as friction force sensors, displacement sensors and wear measuring devices, UMT CETR 2 provides accurate and detailed data on critical tribological parameters.

These measurements include friction forces, contact pressures, wear rates and other key characteristics of the materials under test. UMT CETR 2's comprehensive measurement capabilities allow researchers to gain a thorough understanding of material behavior and performance under specific test conditions

The tribometer UMT CETR 2 is used also for denting and for scratch tests. The test parameters are specified in the next chapter.

3. PRINTING, CURING AND TESTING PARAMETERS

3.1 Printing parameters

The printing parameters used for sample fabrication are presented in Figure 4.

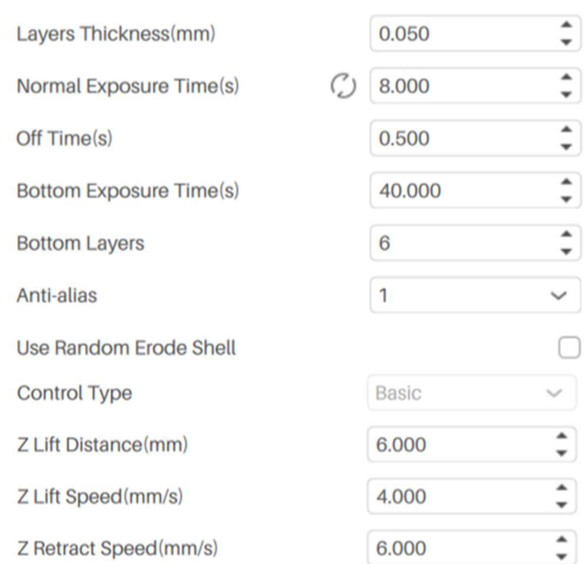

Fig.4 Printing parameters of the specimens.

The most important parameters of interest for our study are the layer thickness, which is 50 μm, and the normal layer exposure time, which, for our study, is 8 seconds.

Two sets of five samples are fabricated and cured under the same parameters. One of the sets is naturally aged for 6 months in a dark room.

3.2 Curing parameters

The curing of the samples is performed under different times, to highlight the impact over the tribological properties.
The samples (S1÷S5) were cured according to the Table 2.

Table 2

The curing plan of the tested samples.

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

3.3 Testing parameters

All samples were subjected to the same testing parameters, and each test was repeated three times. The reciprocating sliding distance of the ball is 10 (mm), with a speed of 5 (mm/s), the mobile part being the specimen. The normal load is 10 (N). The time applied for each test is 600 (s), resulting in 150 cycles or, 3000 (mm) of reciprocating sliding distance, or a reciprocating frequency of 0.25 (cycles/s).

The scratch test has been performed under a normal force of 5 (N) at a speed of 0.167 (mm/s), for a duration of 60 (s), over a distance of 10 (mm).

The denting test was performed following the profile described in Figure 5 using a Rockwell diamond tip with a radius of 200 (μm).

Fig.5 The profile of the normal load applied for the denting test

4. RESULTS

4.1 Friction test

The testing output is summarized in the next three graphs. In the graph presented in Figure 6 is shown the cyclic behavior of the test, where we can observe the variation of the friction coefficient for the whole length of the wear track.

As expected, the friction coefficient is close to zero at the both ends of the wear track.

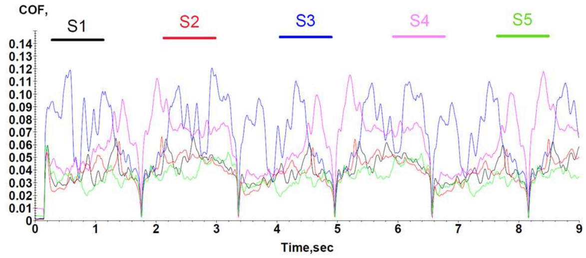

Fig.6 The variation of the coefficient of friction and the cyclic behavior at the beginning of the test.

The variation of the coefficient of friction (COF), for the unaged samples, is presented in the Figure 7. Unlike the graph presented in Figure 6, the data for the Figure 7 and 8 has been filtered in UMT Viewer, with a filter size of 5000, applied once, to display the average value and to preserve the reciprocated characteristic of the test.

In Figure 7 can be observed that, at the beginning of the test, the friction coefficient rises drastically after which is followed by a stabilization phase. At the first sight, one noticeable aspect is the growing tendency of the coefficient of friction for each specimen.

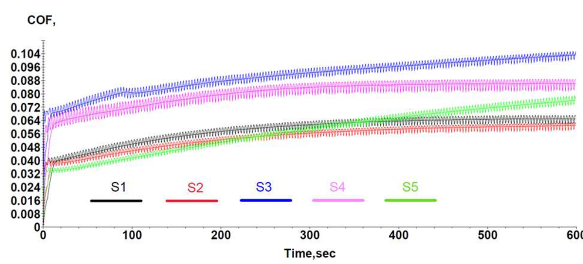

Fig.7 The variation of the coefficient of friction for the entire testing duration.

To check the evolution of the COF in time, another test was performed on a set of samples, which are naturally aged for six months. These samples are fabricated, cured and tested under the same parameters as the unaged samples. The COF graph is presented in Figure 8.

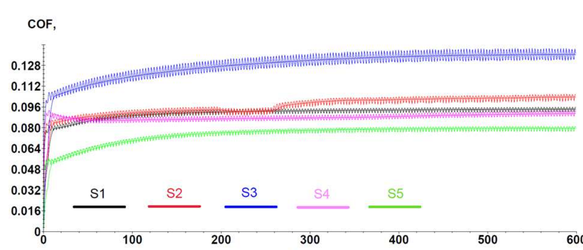

Fig.8 The variation of the coefficient of friction for the entire testing duration, for the samples aged 6 months.

The second test showed less intense undulatory characteristic, with slightly higher COF. This can be attributed to the hardening of the samples. The undulatory characteristic represents the variation of the coefficient of friction along the wear trace, or in other words, due to the reciprocating behavior of the test.

In Table 3 is shown the average COF, during stabilization phase. COF_1 is the friction coefficient for the first set and COF_2 is the friction coefficient for the naturally aged samples.

Table 3

The average value of the COF in the stabilization phase, for the first set of samples

	S1	S2	S3	S4	S5
COF_1	0.061	0.056	0.092	0.083	0.058
COF_2	0.092	0.1	0.13	0.087	0.078

Analyzing Table 2, we can observe that the friction coefficient is slightly higher for the samples aged for six months. This can be attributed to the ageing of the specimens.

Also, the low COF values can be linked to the roughness of the surface of the samples, being measured a value of Rz ≈ 0.64 µm.

One important aspect of the friction tests is the fact that the graph of the aged samples shows a smaller slope. This means that the coefficient of friction is much more stable in time.

Macovei et al. [7] showed that for identical samples, subjected to continuous circular friction test at higher contact speeds (1000 mm/s instead of 5 mm/s), exhibited much higher COF, having the stabilization phase at ~0.44.

In contrast to the samples tested at higher speeds, the sample post-cured for 20 seconds also showed the lowest COF of approximately 0.39, confirming that a longer curing time correlates with a lower COF. Another important aspect is that the growing tendency is also visible at higher contact speeds.

4.2 Scratching test

Even though the UMT tribometer can apply loads up to 20 (N), the scratch test had to be limited to 5 (N), due to the fact that, for higher values, the load exceeded the maximum allowable value for short periods of time. Both tests were performed for 60 seconds.

The scratching test for variable load, applied linear, is presented in Figure 9, and for constant load is presented in Figure 10. The curves marked S1, S2, S3, S4, S5, also known as parameter Z, represents the scratching depth for each sample (named S1, S2, S3, S4, S5)

It can be noticed from the Figure 9 that for the sample S2, the scratching depth (Z) follows an almost proportional dependency with the load, presenting a very small change of slope after 10 seconds, while the rest of the samples follows the proportionality up to a specific point, where the slope rise drastically.

This can be attributed to the fact that the chips accumulate in front of the scratching tool. And, combined with the increasing scratching depth, the force rises drastically in that point.

We can conclude that when a specific amount of material is accumulated, it breaks, resulting in a release of tension, and therefore, a drop on the graph, followed by a fast increase when the tool enters again in contact with the base material.

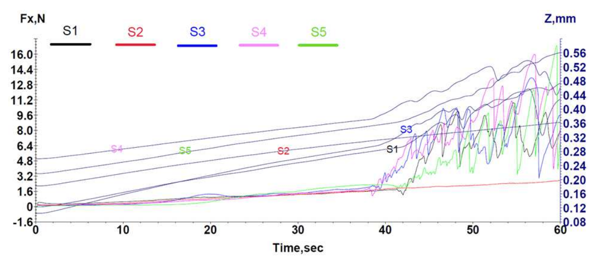

Fig.9 The variation of Fx during the scratching test for variable load, applied linear.

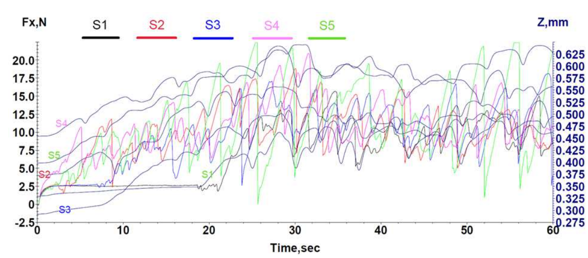

Fig.10 The variation of Fx during the scratching test for constant load

The aged samples were also tested to scratching, under variable load applied linear (Figure 12), and constant load (Figure 13).

Comparing the graphs presented in Figure 9 and Figure 10, we can conclude that when the scratching depth reaches a specific value, the material breaks. These limits are presented in Table 4 and are based on Figure 10.

Table 4

The depth limits to which the material breaks an generate chips during scratching

	S1	S2	S3	S4	S5
Depth [mm]	0.29	-	0.29	0.37	0.35
Fx [N]	1.8	-	2.1	1.9	1.9

The sample S2 has no value in the table due to the fact that Fx (the tangential force) and Z has no sharp change of the slope, Z being the scratching depth.

The aged samples were also tested to scratching, under variable load (Figure 11) and constant load (Figure 12).

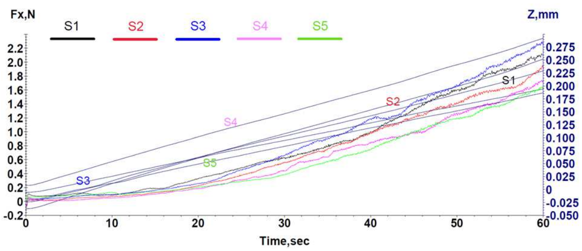

Fig.11 The variation of Fx during the scratching test, for constant load, measured on naturally aged samples.

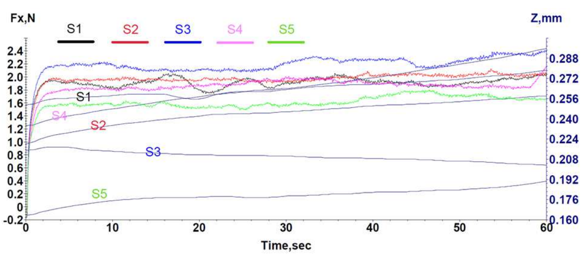

Fig.12 The variation of Fx during the scratching test for constant load, measured on naturally aged samples.

It can be noticed that the aged samples have no sharp variation in the scratching depth or scratching force. This can be attributed to the fact that the material is soft and it doesn't break with glassy chips. This softness of the material can be attributed to change of proprieties at molecular level over time.

4.3 Denting test

The denting results show the influence of the UV curing time over the hardness of the samples. Can be observed that the sample cured for 20 seconds has the highest hardness.

Another important aspect that can be noticed is the elastic behavior of the material, dependent of the UV curing time and aging time, which can be observed when the force decreases, through the unilinear dependency with the applied load.

The results of the denting test are presented in Figure 13 for the unaged samples and Figure 14 for the aged samples.

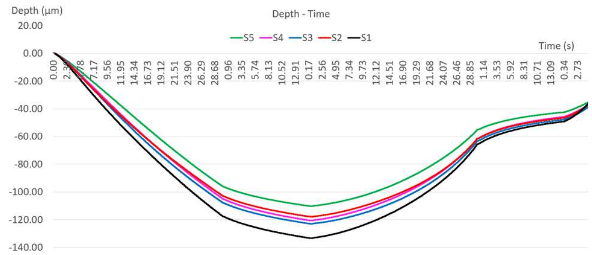

Fig.13 The variation of the denting depth during testing for the unaged set of samples

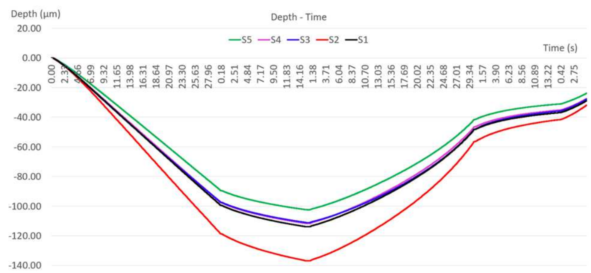

Fig.14 The variation of the denting depth during testing for the naturally aged samples

After testing, the samples show a permanent denting, which for almost all samples has a depth of approximatively 0.38µm.

The values of hardness and Young modulus are shown in the Table 5 for the unaged samples, and in Table 6 for the aged samples.

Table 5

The Rockwell hardness and the Young modulus of the unaged samples.

	S1	S2	S3	S4	S5
Hardness [GPa]	0.025	0.029	0.027	0.028	0.033
Young Modulus [GPa]	0.222	0.309	0.289	0.288	0.32

Table 6

The Rockwell hardness and the Young modulus for the naturally aged samples.

	S1	S2	S3	S4	S5
Hardness [GPa]	0.036	0.028	0.036	0.038	0.043
Young Modulus [GPa]	0.237	0.168	0.259	0.241	0.273

5. DISCUSSIONS

In the case of a type of contact metal-to-metal, the friction is a well-known phenomenon, as long as the temperature does not get close to the point to which the proprieties of the material start to change.

In contrast with the mechanic components made of plastic, with a quite low melting point and which are very different than
metal, the friction phenomenon is much more complex.

According to Quaglini et al. [8], two main mechanisms are recognized as contributing to the frictional force between a polymer pad and a metal surface: the shearing of the junctions formed by adhesion between the asperities of the contact surfaces and energy dissipation due to plastic deformation and abrasion.

Quaglini et al., [8] has presented in his work a mathematical model for the calculation of the friction coefficient, for a polymer-metal contact, for sliding contact. The relation between the relevant parameters is presented in equation (1).

$$\mu = k \times \tau_s \times (F_N)^{m-1} \quad (1)$$

where:

- k is the factor of proportionality and depends on several factors including the shape and distribution of the asperities and the bulk properties of the polymer,
- τ_s is the shear stress required to produce sliding between the surfaces,
- F_N is the normal load,
- m is a coefficient between 0 and 1 which depends of material and the load. For example, $m = 1$ for metals. For polymeric materials m varies between 0.74 and 0.96 [8].

However, this model cannot be used in our case due to the lack of data with regard to material proprieties.

Myshkin et. al., [9] concluded that for the polymers, the friction force is affected considerably by the load, sliding velocity and temperature of the environment and the contact.

6. CONCLUSIONS

In this article, a detailed examination of the tribological characteristics of DLP fabricated specimens, tested at low loads and speeds, is provided.

Friction tests showed that the coefficient of friction increases drastically at the beginning of the test, followed by a stabilization phase with a small tendency of growing.

It has been observed that low exposure times (3, 4, and 5 seconds) has no consistent impact over friction coefficient, scratching depth and denting, and it is comparable with the uncured sample, demonstrating that it has no significant impact.

The UV curing time has a significant impact for sample S5, which is cured for 20 seconds, demonstrating that a longer curing time increases the hardness and therefore decreases the COF.

Also, the tests showed that the effect of low UV curing times tends to diminish in time, effect visible on samples S1÷S4. The sample S5 still presenting the lowest COF, the lowest scratching depth and the lowest indentation depth. Further studies are required to understand how the effect of UV treatment changes in time.

The denting test showed that the specimens have an elastic behavior, which depends on the UV curing time, this can be noticed through the nonlinear dependency with the applied force, when the force is decreased linearly.

It was observed that the naturally ageing specimens showed a slightly higher coefficient of friction, but with a lower growing tendency.

Ageing has an impact on the scratching depth. It has been observed that the aged samples do not produce glassy chips during scratching.

It has been observed that the ageing increases the hardness and decreases the Young modulus.

Friction is a complex phenomenon with DLP printed components due to the fact that the material properties depend on many factors, such as UV curing time, humidity, age from time of manufacture, temperature and load, therefore it is difficult to establish a mathematical model.

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Caracteristicile tribologice ale componentelor fabricate prin aditivare prin prelucrare digitală a luminii, supuse unei mișcări liniare alternative

În domeniul fabricării aditive, tehnologia de prelucrare digitală a luminii (DLP) a apărut ca o soluție practică și ieftină pentru fabricarea de componente mecanice pe bază de rășini fotocurabile, care sunt utilizate în diverse domenii industriale. Adesea, aceste componente sunt în mișcare, în raport cu piesa pereche, și în contact cu componente metalice, fiind supuse la frecare și uzură. Acest studiu prezintă influența tratamentului UV asupra caracteristicilor tribologice, aplicată unui set de piese fabricate prin procesare digitală a luminii, pentru cazul în care acestea sunt supuse unei mișcări liniare alternative. Pentru fabricarea probelor a fost utilizată imprimanta Anycubic Mono 4K. Probele au fost tratate timp de 3 (s), 4 (s), 5 (s) și 20 (s). Un set separat de eșantioane, fabricate și tratate cu aceiași parametri, este îmbătrânit natural timp de șase luni. Testele au fost efectuate pe microtribometrul CETR-UMT2, pentru care piesa metalică este o bilă de rulment cu un diametru de 6,35 (mm). Sarcina aplicată pentru testele de frecare este de 10 (N), cu o viteză de contact de 5 (mm/s), pentru o distanță de alunecare de 10 (mm), pe o perioadă de timp de 600 (s). Testele de zgâriere au fost efectuate cu o forță normală de 5 (N), la o viteză de 0,167 (mm/s) și un timp de zgâriere de 60 (s), pentru o distanță de 10 (mm). Testele de indentare au fost efectuate cu ajutorul unui vârf de diamant Rockwell, cu o forță aplicată în cinci trepte diferite de până la 5 (N). Testele tribologice au arătat că coeficientul de frecare prezintă două etape. În faza de rodaj, valoarea coeficientului de frecare crește drastic, urmată de o fază de stabilizare la o valoare foarte mică, cu o mică tendință de creștere. Testul de zgâriere a arătat că timpul de polimerizare UV nu are un impact semnificativ asupra adâncimii de zgâriere. De asemenea, sarcina aplicată variază proporțional cu adâncimea de zgâriere.

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