**Characterization of The Wear Resistance of 3D Printed Polylactic-Acid (PLA) in Water and Bovine Serum**

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**Abstract.** Three-dimensional (3D) printing has become an emerging technology for the fabrication of geometrically complex, patient-specific biomedical implants. However, several properties of the 3D printed material have not so far been fully understood. Among these properties, wear resistance is considered as the critical one for the 3D printed material that should be applied as a sliding component in an artificial joint prosthesis. In this research, the wear resistance of a 3D printed polylactic-acid (PLA) pin that slid over the surface of titanium plate was characterized in water and bovine serum by using a pin-on-plate tribometer. The result showed that the use of bovine serum could reduce the wear of the 3D printed PLA better than the use of the water as the lubricant. Based on the analysis of weight losses and worn surface morphology, polymer film transfer was proposed as the possible wear mechanism that occurred during the sliding of the 3D printed PLA pin over the surface of the Ti plate.

**Keywords:** 3D printing; polylactic-acid; titanium; wear; water; bovine serum

1. **Introduction**

Recently, three-dimensional (3D) printing has become potential technology that can be used to aid the fabrication of geometrically complex, patient-specific biomedical implants [1-3]. With this technology, a solid 3D material can be built by depositing multiple layers of fully or partially melted material. In order to meet the requirements of any specific applications, many studies have currently been carried out to investigate the properties of such 3D printed materials, such as their mechanical properties [4, 5], bioactivity [6] and wear resistance [7, 8]. Among these properties, wear resistance is considered of the critical one, particularly for the materials that should be able to withstand shear loads in their applications.

Up to now, the number of studies for investigating the tribological properties of 3D printed polymeric materials is still limited. The work of Sood et al. [7] briefly explained the mechanisms involved in the wearing process of a 3D printed material. They reported the following steps of the wear mechanism of the 3D printed polymeric material, i.e., (i) adhesion of the surface asperities, (ii) plastic shearing, and (iii) detachment of the tips of the softer material. Meanwhile, the work of Borges et al. [8] demonstrated the benefit of the porous
structure of the 3D printed material in lowering friction coefficient and wear of this material in a lubricated sliding system. Further studies are however still needed to unravel many other issues related to the tribological behaviors of the 3D printed polymeric materials.

In this research, a preliminary study was conducted to characterize the wear resistance of a 3D printed polylactic-acid (PLA) pin in a reciprocating pin-on-plate tribometer. Two types of lubricants were used in this study, i.e., distilled water and bovine blood serum. Water has long been utilized as a lubricant for many tribological tests owing to its simple preparation. However, the use of water as a lubricant for biotribology could result in a different wear mechanism from that in a periprosthetic joint [10]. Therefore, several bio-lubricants were utilized [11, 12], including bovine blood serum that had been reported to be able to mimic the properties of synovial fluid in the human body [11]. To determine possible wear mechanism in this research, characterizations of the weight losses and the worn surface morphologies and roughness of both the PLA pin and Ti plate were carried out.

2. Materials and Methods

In this research, polylactic-acid (PLA) and grade 2 titanium (Ti) were used as the materials for the cylindrical pin and the plate, respectively, in a unidirectional reciprocating pin-on-plate tribometer. The PLA pin was prepared by using 3D printing technique to obtain a cylindrical solid material with 8.1 mm and 20 mm in diameter and length, respectively. Meanwhile, the Ti plate was prepared with a dimension of 55 mm × 18 mm × 3 mm. Surface roughness of the sliding surfaces of both the PLA pin and the Ti plate were determined by using a contact stylus profilometer (Surfcom 120A, Advanced Metrology System, UK), with which the average $R_a$ values of three different locations on the material surface were obtained. Scanning of the stylus over the surface of the material was conducted in a direction perpendicular to the raster orientation and sliding direction of the PLA pin over the surface of Ti plate. All the samples were cleaned up by rinsing in ethanol and distilled water and then dried in air prior to and after the sliding test in tribometer.
Fig. 1. Unidirectional reciprocating pin-on-plate tribometer used in this research.

The sliding test of the PLA pin was performed in a six-station unidirectional reciprocating pin-on-plate tribometer at room temperature, such as shown in Fig. 1. The PLA pin was mounted on its holder while the Ti plate was positioned inside the sliding chamber. During the test, the sliding surfaces of both these materials were immersed into the lubricant. A solid weight was added so that a normal load of 120 N could be applied on each of the PLA pin. The sliding test of the PLA pin against the titanium plate was run with a sliding distance of 25 mm and velocity of 50 mm s\(^{-1}\), respectively, and with a sliding direction parallel to the raster orientation of the printed PLA pin. Two types of lubricants were used in this experiment, i.e., distilled water and bovine blood serum solution. The latter was prepared with a composition of 25% bovine serum and 75% of distilled water. In order to prevent the lubricant from bacterial contamination, sodium azide with volume fraction of 0.1% was added into the bovine serum lubricant. Detailed information about the experimental procedures of this research was described in the work of Prayoga et al. [9].

The weight losses of the PLA pin and Ti plate were determined in microbalance (Ohaus, Germany). Prior to weighing, all the PLA pins were cleaned up by using distilled water in an ultrasonic bath for 15 minutes and then dried at room temperature. The weight losses (\(w_L\)) of the PLA pin and the Ti plate were then calculated by using Eq. (1):

\[
w_L(\%) = \frac{w_0 - w_t}{w_0} \times 100\%
\]  

(1)

where \(w_0\) and \(w_t\) are the initial weight and the weight of material after being rubbed for certain sliding distance against its countersurface in tribometer, respectively. Surface morphology and the PLA pins and Ti plates were characterized by using an electron microscope (JSM-6510LV, JEOL Ltd., Japan).

3. Results and Discussion

In this research, a preliminary work had been carried out to investigate the wear resistance of a 3D printed PLA pin that slid over the surface of Ti plate in a reciprocating pin-on-plate tribometer. Fig. 2 shows the physical appearance of all the 3D printed polyactic-acid (PLA) pins after the sliding test in the tribometer. As seen in Fig. 2a, the sliding surface of the PLA pin melted after the sliding without any lubricants for a distance of approximately \(1 \times 10^3\) m over the surface of Ti plate. This finding might indicate that the local temperature at the sliding surface of the pin increased significantly during the test and exceeding the melting point of PLA material. The use of lubricant, either distilled water or bovine serum, seemed to be able to reduce local temperature rise at the contact and sliding surface between the PLA pin and the Ti plate. Therefore, all the PLA pins remained intact after the sliding test for \(4 \times 10^3\) m.
Fig. 2. The 3D printed PLA pin after sliding test (a) without lubricant, (b) with distilled water and (c) with bovine serum

Fig. 3a shows the changes in the percentage of weight losses of PLA pin due to wear that occurred during the sliding test. In general, the weight loss of the PLA pins increased with the sliding distance travelled by the pin. Interestingly, the rate of the weight loss of this material was apparently higher at a distance of less than $3 \times 10^3$ m, as indicated from the steeper slopes of the weight loss plots within the range of sliding distance from 0 to $3 \times 10^3$ m. This phenomenon occurred in both the sliding tests with water and bovine serum. Meanwhile, as seen in Fig. 3b, the plots of the weight losses of the Ti plate were also obviously influenced by the lubricant used in the test. Once tested with bovine serum lubricant, the plot of the weight losses of the Ti plate increased with the sliding distance. However, the weight of the Ti plate sliding in distilled water remained constant after a distance of $0.5 \times 10^3$ m had been reached. All these findings confirmed that the weight losses of the 3D printed PLA pin and its Ti countersurface due to wear were obviously dependent on the lubricant used in the test.

Fig. 3. Weight losses of (a) the 3D printed PLA pin and (b) Ti plate due to sliding wear

Fig. 4 shows the changes in surface roughness of the sliding surface of the 3D printed PLA pin after the test in tribometer with a sliding distance of $4 \times 10^3$ m. As demonstrated in this figure, the wear decreased the $R_a$ value of the sliding surface of the PLA pin. As also seen in Fig. 4a, the type of lubricant used in the sliding test apparently influenced final roughness of the sliding surface of the PLA pin. In this case, after sliding for $4 \times 10^3$ m in distilled water, the worn surface of the PLA pin was slightly smoother than that tested in bovine serum. In contrary, as seen in Fig. 4b, the sliding over the PLA pin surface resulted in the increased roughness of the Ti plate.
Fig. 4. The roughness of the sliding surface of (a) the 3D printed PLA pin and (b) Ti plate.

Fig. 5 shows a series of micrographs displaying the morphologies of the sliding surface of the 3D printed PLA pin and Ti plate prior to and after the sliding tests. In Figs. 5a and b, the initial surface morphology of the PLA pin and Ti plate could be recognized from their relatively flat and smooth surface. A linear defect was clearly seen in Fig 5a, indicating the boundary between two adjacent rasters of the PLA material that were formed with the 3D printing technique. Meanwhile, as shown in Fig. 5b, thin scratches could be seen at the surface of the Ti plate, as a result of mechanical grinding and polishing that were carried out in the preparation of the plate prior to the sliding test.

Fig. 5. Micrographs of the sliding surface of (a) the PLA pin and (b) Ti plate prior to the sliding test, (c) the PLA pin and (d) Ti plate after the sliding test in distilled water, and (e) the PLA pin and (f) Ti plate after the sliding test in bovine blood serum.
Figs. 5c - f displayed typical worn surfaces of the 3D printed PLA pin and Ti plate after the test in tribometer with a sliding distance of $4 \times 10^3$ m. A white arrow was added into Figs. 5c – f to indicate the sliding direction of the PLA pin over the surface of the Ti plate. As seen in Figs. 5c and e, the sliding of the PLA pin over the surface of Ti plate generally caused scratches and crevices at the sliding surface of the pin. In Fig. 5c, it is also clearly seen that cracks were formed at the crevice and then propagated to the surrounding of the defect at the sliding surface of PLA pin that was tested in distilled water. However, as seen in Fig. 5e, this phenomenon could not be clearly seen at the worn surface of the PLA after sliding in bovine serum. In addition, fragments of the PLA material were visible in both Figs. 5c and e. Meanwhile, Figs. 5d and f shows typical worn surface of the Ti plate after a sliding test for $4 \times 10^3$ against the 3D printed PLA pin. In general, both Figs. 5d and f demonstrated similar pattern of scratches. However, the tips of the scratches at the Ti surface that was tested in distilled water were apparently sharper than those at the Ti surface sliding in bovine serum lubricant. Furthermore, some dark spots could be recognized in Figs. 5d and f, which might correspond to the presence of carbon as a trace of the wear debris of the PLA material.

In a previous work, the influence of lubricant type on the wear resistance of polymeric material that slid against the surface of metallic material had been highlighted. In their review, Brown and Clarke [10] mentioned that the use of water as the lubricant in tribological testing of an implant material resulted in massive flake-like particles with several micrometers in sizes. Meanwhile, the particle wear debris retrieved from periprosthetic tissue in total hip replacement was round and elongated in shape and having submicron sizes. Accordingly, water was then considered of being inappropriate lubricant for the tribological testing of biomedical implant material [10]. Meanwhile, Wang et al. [11] reported that submicron size particle wear debris with round an elongated shape could be obtained once bovine serum was used as the lubricant in a tribological test of ultra-high molecular weight polyethylene (UHMWPE) in hip simulator. This might demonstrate that bovine serum could mimic the properties of synovial fluid that lubricates the surface of articular joint tissue.

Based on the results presented in Figs. 3 – 5, some important findings of this study could be summarized as follows:

1. the worn surface of the PLA pin could be recognized consisting of some grooves that stretched over the pin surface and parallel to the sliding direction against Ti plate;
2. the weight losses of the 3D printed PLA pin due to sliding wear against Ti plate could be reduced once bovine serum was preferred as the lubricant instead of distilled water;
3. the weight losses of Ti plate was higher once bovine serum was preferred as the lubricant rather than distilled water;
4. after tribological test with a sliding distance of $4 \times 10^3$ m, the surface of the Ti plate lubricated with distilled water was slightly smoother than that lubricated with bovine serum;
5. dark spots together with some deep scratches were observed at the sliding surface of the Ti plate and this might indicate the presence of carbon as a trace of the PLA material.

Considering all these findings, the wear mechanism of the 3D printed PLA pin that slid over the surface of Ti plate was possibly attributed by abrasion and polymer film transfer phenomenon. According to this mechanism, the wear debris of the polymeric pin were firstly sheared by the sharp metal asperities and detached from the sliding surface of the pin. The wear debris that trapped in the clearance between these two sliding materials then adhered, formed many small clumps and agglomerated at the surface of the Ti plate [13]. As a consequence, the presence of this transferred polymer film could add the weight of the Ti plate.
In this research, it is confirmed that the use of bovine serum could slightly reduce wear of the 3D printed PLA pin. As also inferred in Fig. 4a, the more asperity peaks of the PLA pin were removed when water was used as the lubricant, resulting in a smoother PLA pin surface. It is also reported by Cooper et al. [14] that protein containing lubricant such as bovine serum could reduce the amount of the polymer film transfer into the metallic countersurface. The plots in Fig. 3b might confirm the work of Cooper et al. [13], in which the weight loss of the Ti plate in distilled water was lower than that in bovine serum due to the more polymer film attached at the surface of this plate.

Although the current work might be able to explain possible wear mechanism of a 3D printed PLA pin that slid over the surface of Ti plate, further studies are still needed to ensure the presence of polymer traces at the worn surface of the Ti plate. Further analysis to determine friction coefficient and surface chemical composition of both the PLA pin and the Ti plate should also be carried out.

4. Conclusions

In this research, a preliminary study was carried out to characterize wear characteristics of 3D printed polylactic-acid (PLA) pin that sliding over the surface of Ti plate. Based on the results of this work, it can be concluded that the presence of lubricant could prevent the sliding surface of the PLA pin from excessive heat generation and in the end maintain the shape of the pin during the sliding test. Meanwhile, the use of bovine serum reduced the wear of the 3D printed PLA better than the use of water as the lubricant. Considering all the findings obtained in this research, the wear mechanism of the 3D printed PLA pin that slid over the Ti plate was possibly attributed by abrasion and polymer film transfer phenomenon.

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References

[1] Ventola CL 2014 P&T 39 704
[2] Mertz L IEEE Pulse 2013 4 15
[3] Thomas DJ J. Orthop. 2017 14 182
[4] Tymrak BM, Kreiger M and Pearce JM 2014 Mater. Des. 58 242
[5] Farzadi A, Solati-Hashjin M, Asadi-Eydivand M and Osman NAA 2014 Plos One 9 1
[6] Fielding GA, Bandyopadhyay A and Bose S 2012 Dental Mater. 28 113
[7] Sood AK, Equbal A, Toppo V, Ohdar RK and Mahapatra SS 2012 CIRP J. Manuf. Sci. Technol. 5 48
[8] Borges RA, Choudury D, and Zou M 2018 Tribol. Int. 122 1
[9] Prayoga BT, Suyitno S and Dharmastiti R 2016 Tribol. Industry 38 543
[10] Brown S and Clarke IC 2006 Tribol. Trans. 49 72
[11] Wang A, Essner A, Stark C and Dumbleton JH 1996 Biomaterials 17 865
[12] Guezmil M, Bensalah W and Mezlini S 2016 J Mech. Behav. Biomed. Mater. 63 375
[13] Bahadur S 2000 Wear 245 92
[14] Cooper JR, Dowson D and Fisher J 1993 Clin. Mater. 14 295