The Effect of Build Orientation on Liquid Absorption and Wear of 3D-Printed Denture Materials

Muhammad Ikhlas[a], Sukmaji Indro Cahyono[a], Benidiktus Tulung Prayoga[b,c], Rini Dharmastiti[a,c,d], Budi Arifvianto[a,c], Muslim Mahardika[a,c]*

[a]*Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl Grafika 2 Yogyakarta 55281, Indonesia*

[b]*Department of Mechanical Engineering, Vocational School, Universitas Gadjah Mada, Jl. Yacaranda Sekip Unit IV Yogyakarta 55281, Indonesia*

[c]*Center for Innovation of Medical Equipment and Devices (CIMEDs), Faculty of Engineering, Universitas Gadjah Mada, Jl. Teknika Utara Yogyakarta 55281, Indonesia*

[d]*Biomedical Engineering Program, The Graduate School, Universitas Gadjah Mada, Jl. Teknika Utara, Pogung, Sinduadi, Mlati, Sleman, Yogyakarta 55284, Indonesia*

Corresponding author: muslim_mahardika@ugm.ac.id

Abstract

Up till now, denture has been widely used for resolving dental problems, especially those due to attrition. The attrition of tooth enamel could lead to wear and lowering the functions of normal teeth. So far, denture is made conventionally by using heat curing method in a mold. However, the complex geometries of teeth and oral cavity has led to the use of the more advanced techniques, such as additive manufacturing. In this research, the denture material fabricated by using digital light processing (DLP) additive manufacturing was studied in term of their liquid absorption capability and wear behavior. The specimen was printed with three build orientations, namely 0°/180°, 90°/90°, and 45°/135°. These are the degree between printing direction against sliding direction. An immersion and wear test were carried out in artificial saliva liquid. The result showed the lowest weight gain and dimensional change in the specimens printed with 90°/90° and 45°/135°. Meanwhile, the specimens prepared with build orientation of 0°/180° or printed with layer parallel to sliding direction demonstrated the smallest value of wear factor, indicating a better wear resistance compared to the others. A visual examination of the worn surface indicated delamination, abrasion and cracking as the possible wear mechanisms of the printed denture materials.

Keywords: Build orientation; Denture materials; Digital light processing; Liquid absorption, Wear

1. Introduction

Nomenclature

α	Degree between printing direction and sliding direction (°)
W_L	Weight loss (%)
W_o	Initial weight (kg)
W_t	Final weight (kg)
WF	Wear factor (m^3/Nm)
V_W	Wear volume (m^3)
N	Normal applied (N)
s	Sliding distance (m)

Currently, additive manufacturing (AM) has become an alternative choice for manufacturing of solid parts with complex geometries and customized design. In principle, this technique creates a solid 3-dimensional (3D) object by printing a stack of layers based on a model that has been previously designed with computer aided design (CAD) software. Several AM techniques have so far been developed and applied for product manufacturing, i.e., (1) binder jetting, (2) directed energy deposition, (3) material extrusion, (4) material jetting, (5) powder bed fusion, (6) sheet lamination and (7) vat polymerization [1]–[4]. Among these techniques, the AM processes based on the vat polymerization such as stereolithography (SLA) and digital light processing (DLP) have been widely used for preparing biomedical devices such as microneedles [5], drug-loaded ear implants [6], scaffolds [7] and dentures [8][9]. With DLP technique, a solid 3D product could be realized by curing layers of material from a polymeric resin with a laser beam [10].

Dentures is known as a device for aiding the restoration of oral cavity, with which artificial teeth are used for replacing the missing ones [11]. It is noted in the literature that the people with ages over 50 years have begun to experience lowering functional teeth; leading to the need for denture [12]. Up to recently, most dentures are prepared conventionally by using heat curing method. With this method, there are some limitations, for instance, it requires long period for preparation and discomfort feeling of patients [13]. The AM have some potential to solve those weaknesses. With the AM, the procedures for preparing dentures would be faster without compromising the accuracy with the geometries of the oral cavity. Basically, a denture could be prepared with AM with the following steps, i.e., scanning, designing, and printing of this device prior to its application to the patients [14–16].

Several article of denture fabrication with DLP has been published. The mechanical properties of those additively manufactured denture depend on its fabrication parameters , such as layer thickness, build orientation, normal exposure time, post washing time, and post curing time [17–19]. The work by [20] reported that the hardness of a denture was higher once prepared by with post curing time of 120 min. The flexural strength of a denture made with AM could be enhanced by applying various layer thicknesses [18]. In their work, it is shown that a higher layer thickness led to a greater flexural strength, indicating that a higher thickness could withstand greater loads. Meanwhile, the work of [21] has the opposite results, in which a thinner layer being printed led to a greater flexural strength. This phenomenon was attributed by a stronger bonding between each layer of material due to multiple curing process at each printed layer. Although there have been many studies showing successful preparation of denture with AM, it is still not known the wear resistance of the denture material prepared with DLP. In earlier work, the research by [22] studied the wear resistance of polymeric material prepared with fused filament fabrication (FFF) with pin-on-plate tribometer in bovine serum. The result of their work showed that the wear resistance of such additively manufacture polymer was affected by the raster or build orientation of the printed material.

2. Materials and Method

2.1. Material Preparations

In this research, the material for denture made of polymethyl methacrylate (PMMA) were printed in cylindrical form with diameter and height of 8 mm and 20 mm, respectively, by using DLP based 3D printer (Shenzen Anycubic Technology Co., Ltd. China). Three build orientations were prepared in the specimen, i.e., 0°/180°, 90°/90°, and 45°/135° such as shown in Figure 1. In this figure, α was defined as the degree between printing direction and sliding direction. For instace, tribology with the sliding reciprocating concept for specimen with α = 45°/135°, 45° represented of friction in the + direction and 135° represented of friction in the – direction. The parameters used for printing specimen were listed in Table 1.

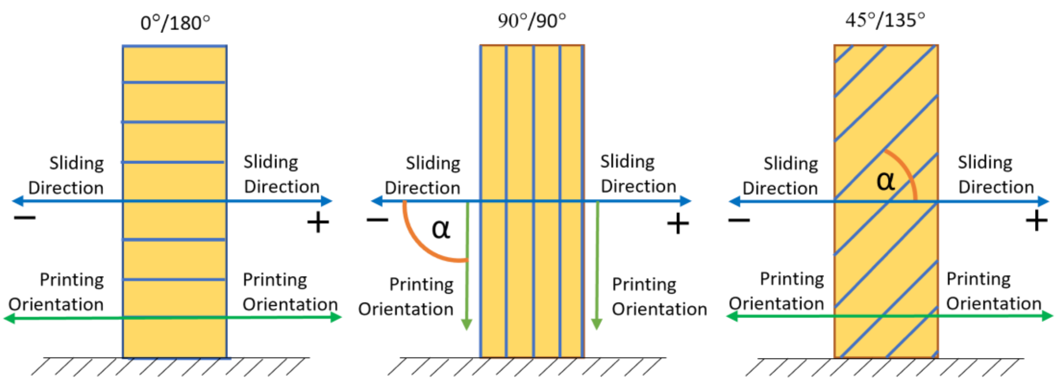

Figure 1. Build orientation of the materials.

Table 1. Parameter fabrication specimen.

Parameter fabrication	
Layer thickness (mm)	0.025
Exposure time (s)	2.3
Build orientation (°)	0°/180°, 90°/90°, and 45°/135°
Off time (s)	0.5
Bottom exposure time (s)	28
Z lift distance (mm)	8
Z lift speed (mm/s)	8
Z retract speed (mm/s)	2
Wash time (s)	5
Curing time (s)	30

A plate made of 316L stainless steel having a dimension of 55 mm × 14 mm × 4 mm was used as the countersurface in wear test in this research. The roughness of this plate (Ra) was 0.039±0.007 µm as measured by using roughnes tester (Mitutoyo SURFTEST SJ-210).

2.2. *Absorption of artificial saliva*

An absorption test was conducted to assess the changes in the mass and volume of the specimen during immersion in an artificial saliva with pH ±7 (netral). Water absorption testing was conducted by first recording the initial dry weight of each specimen. The specimens were then immersed in artificial saliva for 24 hours, subsequently removed, gently cleaned to eliminate surface residues, and weighed again to determine the mass change. This test was carried out in artificial saliva at room temperature for 8 days and for each type of specimen with four repeated measurements were conducted on identical samples to ensure reliability, reproducibility, and enhance the accuracy of the results. The specimen weight change in this test was calculated by using Equation 1.

$$W_L = \frac{W_t - W_o}{W_o} \cdot 100\% \tag{1}$$

where W_o dan W_t are the initial and the final weight of the specimen, respectively.

2.3. *Tribological Test*

The tribology test in this study was carried out in a sliding reciprocating pin-on-plate tribometer with a normal load of 49 N at room temperature, a travelling distance of 25 mm, a sliding speed of 50mm/s, a frequency of 1 Hz and contact pressure of 0.97 MPa. The testing was performed for 84 min which was equivalent to one years of the artificial tooth aplication [23]. During the test, all the sliding contact surfaces of the specimens were kept immersed in artificial saliva as the lubricant and reduced the wear [24]. In this research, artificial saliva was selected as the lubricant and composed of NaCl 0.4g, KCl 0.4g, $CaCl_2.2H_2O$ 0.795g, $NaH_2PO_4.2H_2O$ 0.78g, $Na_2S.9H_2O$ 0.005g, urea 1g, and distilled water 1000ml [11][25].

2.4. *Wear Factor and The Worn Surface Morphology*

The wear factor of the specimen after tribological test was calculated by using Equation 2.

$$WF = \frac{V_W}{N \cdot s} \tag{2}$$

where V_W is wear volume of pin (mm^3), N is the normal load applied (N), and s is total of sliding distance travelled over the plate (m). This process of tribology also measured of weight loss was carried out using an Ohaus scale with an accuracy of 0.0001g, adopting the procedure from material weight reduction after immersion [26][27]. The surface roughness of the pin were observed by using roughnes tester (Mitutoyo SURFTEST SJ-210) and for the worn surface morphologies of the pin and plate sliding surface were observed by using an Olympus SZX16 microscope.

3. Results and Discussion

3.1. Absorption of artificial saliva

Basically, saliva have several functions, i.e., preventing enamel dentin from microbial adhesion [28], lubrication, and moisturization of oral cavity [29]. It is important to note that the use of saliva is averagely 1-1.5 L/day in a healthy oral cavity [30]. In this research, the specimen was first tested in terms of its absorbability to artificial saliva in order to mimic the actual condition of denture in the oral cavity.

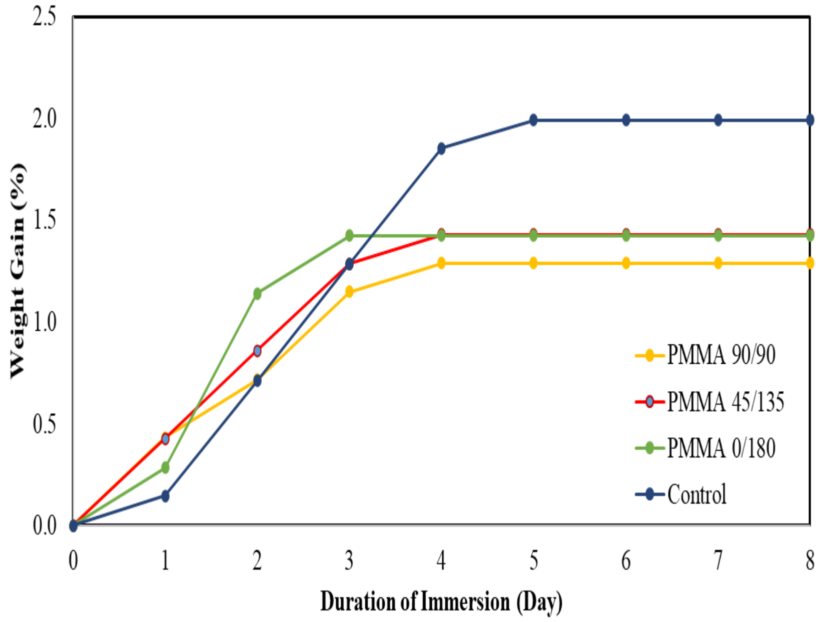

Figure 2. The weight gain of the 3D printed specimen during the immersion in artificial saliva.

According to Figure 2. It is evident that the differences in the absorption capability of 3D-printed denture material were significant [31–33]. Generally, the denture material printed with $\alpha = 90°/90°$ had the lowest weight gain, possibly due to its lower porosity compared to the others. After 4 days of immersion, the material reached a saturated state, indicating the maximum water absorption capacity had been achieved. This condition occurred due to the absence of remaining accessible pores or voids within the material structure. As a result, no further weight gain was observed, and the material's mass remained constant through to the final day of measurement. This phenomenon can be attributed to the tightly packed and strongly bonded polymer chains, which result in reduced porosity within the material. In addition, although the methods used to measure weight gain due to water absorption vary, a positive correlation was observed between material porosity and water absorption capacity. Higher porosity leads to greater water uptake, primarily due to the presence of voids within the particle structure that facilitate water penetration [34]. This phenomenon was also mentioned earlier [35], where the water absorption of the 3D-printed materials were greatly influenced by their porosity, where the more porous material would absorb more liquid. They also mentioned that the material with a smoother surface would lead to a lower absorption to a liquid. Specimens with smoother surface morphology exhibited more uniform, dense, and tightly bonded microstructures, which limited the penetration of liquid into the material. In contrast, rougher surfaces were associated with irregular bonding patterns and larger intermolecular gaps, facilitating greater fluid absorption into the specimen. As can be seen in Figure 2. The percentage weight gain of the printed material saturated after 4 days of immersion in the artificial saliva in this research. This finding was confirmed by the previous work [36], which showed the saturation of material weight after several time of immersion in liquid.

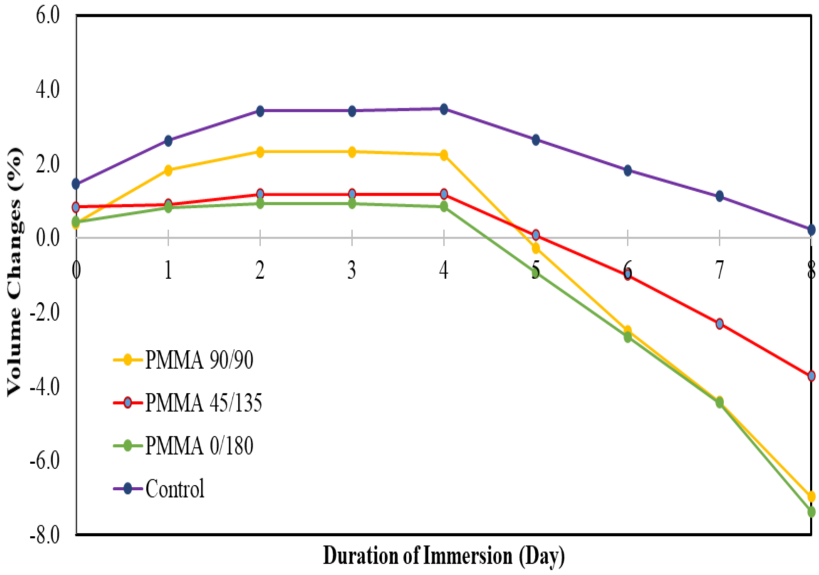

Figure 3. Volume changes of printed during the immersion.

As also demonstrated earlier [37], solid materials basically experienced swelling or increased size shortly after immersion in artificial saliva and prolonged immersion may lead to the disruption of polymer chain structures and intermolecular bonds, thereby facilitating water ingress and resulting in an increase in specimen volume. However, their dimensions would decrease after several days of immersion in this liquid, such as shown in Figure 3. This might be due to chemical reaction that affect the polymer structures and finally caused shrinkage of the specimen after 4 days of immersion. This may also be related to post-curing during specimen fabrication, where the duration of post-curing affected to the volume changes during water absorption, as found by [38]. Their study indicated that dimensional changes in the material also depend on the duration of post-curing. They varied the post-curing time from 0 minutes to 60 minutes, with the largest dimensional change occurred at 60 minutes. Hence, the smallest volume changes were observed in the case of specimen printed with a = 45°/135°.

3.2. Wear Factor and The Worn Surface Morphology

According to the Figure 4, the lowest value of wear factor (WF) of the 3D-printed pin was seen in those prepared with α = 0°/180°, i.e., WF = 0.041×10^{-11}m^3/Nm. Meanwhile, the pin with the highest WF can be seen in those printed with α = 90°/90°, i.e., WF = 0.097×10^{-11}m^3/Nm. This phenomenon was possibly attributed by the interlayer region of the specimen with α = 0°/180° that was parallel to the sliding direction during the tribological test, which was more resistant to wear. The improved surface quality of the specimen printed with α = 0°/180° also generated the lowest of WF value than in the specimen with other printing orientations. Nevertheless, it is noted from Figure 4. That the WF value of all the printed specimens were lower to the control one, which was prepared conventionally in a mold with heat curing process. In the case of the steel plate used as the countersurface in the tribological test, the WF value of all the plates showed similar trend to that of the 3D-printed pin.

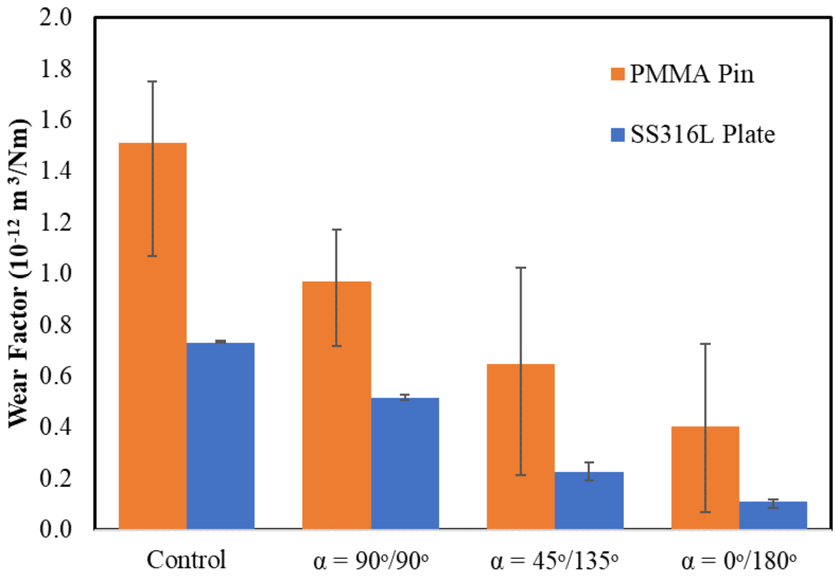

Figure 4. Wear factor of the PMMA pin and its steel plate countersurface.

The result of visual inspection on the sliding surface of both the 3D-printed pin and its countersurface steel plate can be seen in Figure 5. The pin surface shown in Figure 5(a) indicated the presence of steel debris as a result of their sliding contact movement. Meanwhile, scratches along the sliding direction could also be seen on the pin surface, such as shown in Figure 5(b) and the steel plates in Figure 5(c) and (d). Besides, several phenomena were also identified over the surfaces of these materials, such as adhesion, delamination, and crack, such as shown in Figure 5(c) and 5(d). Adhesion occurred corresponding to the transfer of the pin material to the plate surface during the sliding movement [39]. Delamination occurred as the sliding movement between the two surfaces continued, causing the adhered polymer to detach from the surface of the steel plate [40]. In some cases, the pin material could suffer plastic deformation during this event.

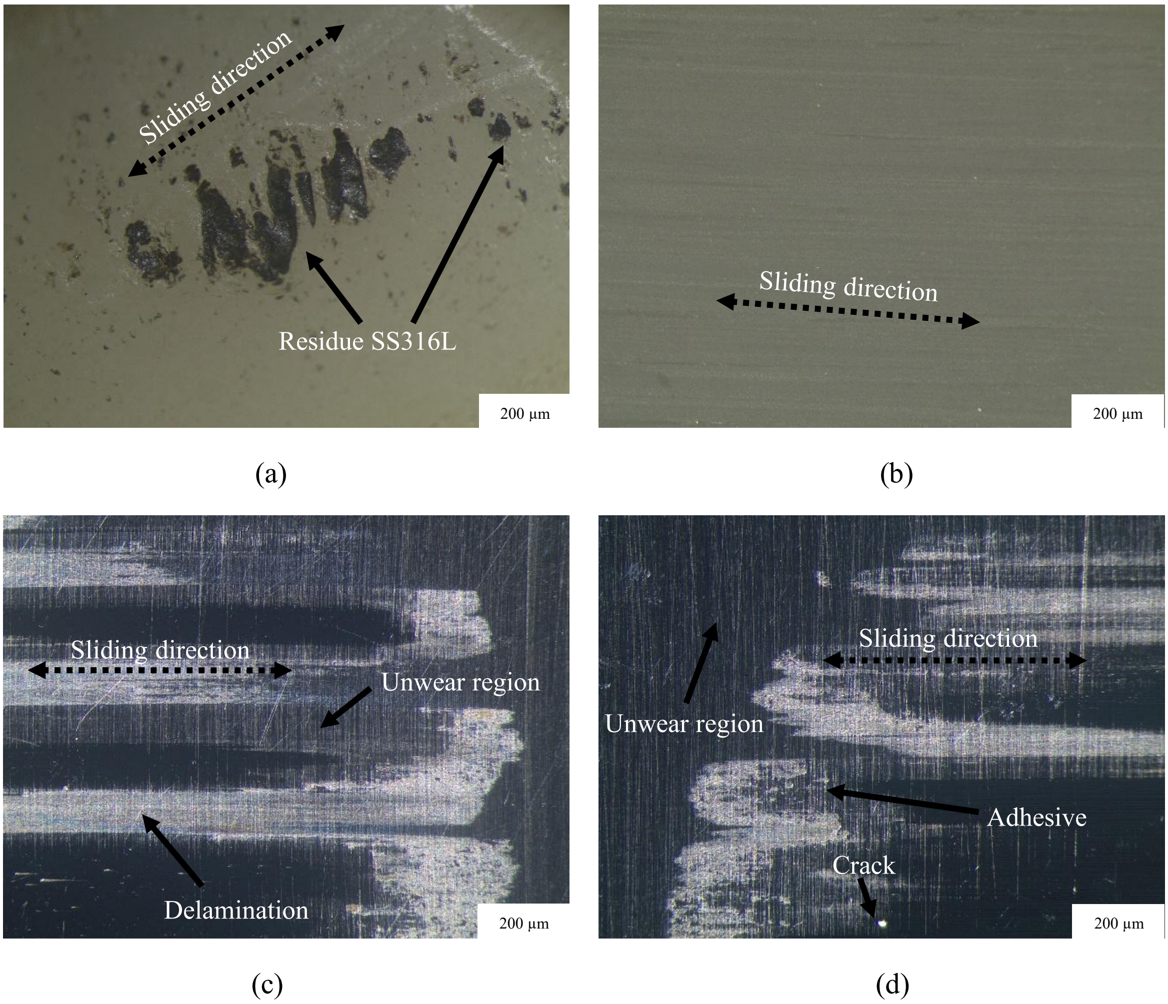

Figure 5. Worn surface morphologies of the (a) control; (b) PMMA pin; and (c and d) steel plate surfaces.

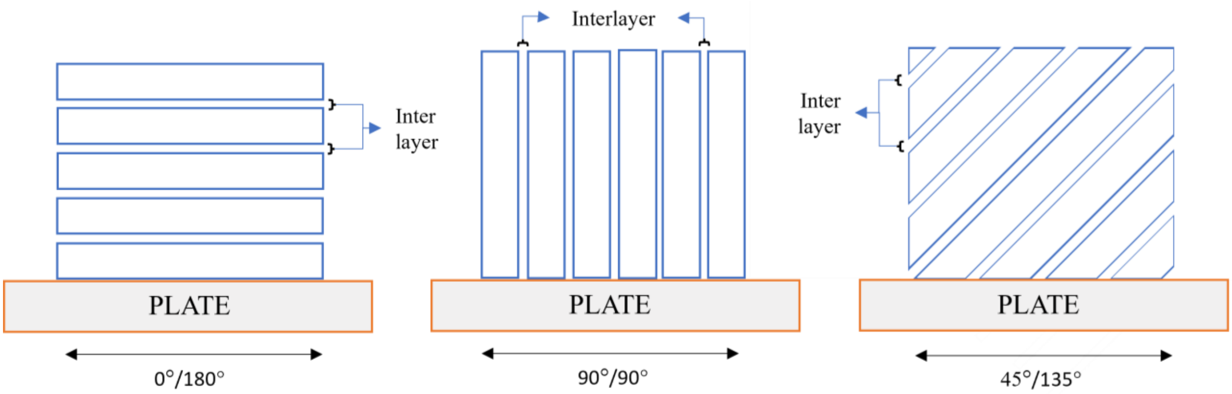

Figure 6. Interlayer based on orientation.

According to the result of this research presented above, it can be summarized that the interlayer region in the 3D-printed material plays an important role in determining its wear resistance during the sliding friction process. The interlayer region is where the bonding between two layers produced 3D-printing process. This region constitutes the weakest part of a 3D-printed material [41]. Once friction took place in this interlayer region, the more severe wear would occur. In this research, the orientation of printing would determine the direction of such weak interlayer region relative to the sliding direction. In this case, a printed pin having interlayer region parallel to sliding direction such as shown in Figure 6, such as in that with a = 0°/180° resulted in a less WF value. Beside the orientation of the interlayer region, the surface quality of the 3D-printed material was also recognized to contribute to its wear resistance. A printed material with a better surface quality or smoother surface would lead to a greater the wear resistance. An example of 3D-printed material with poor surface conditions is shown in the Figure 7 and the result of the experiment is shown in Figure 8.

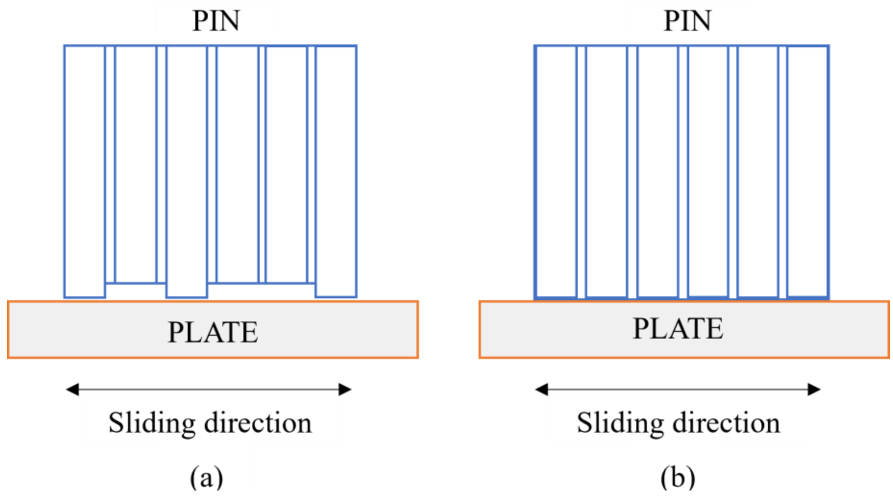

Figure 7. Quality of surface pin: (a) bad surface; and (b) good surface.

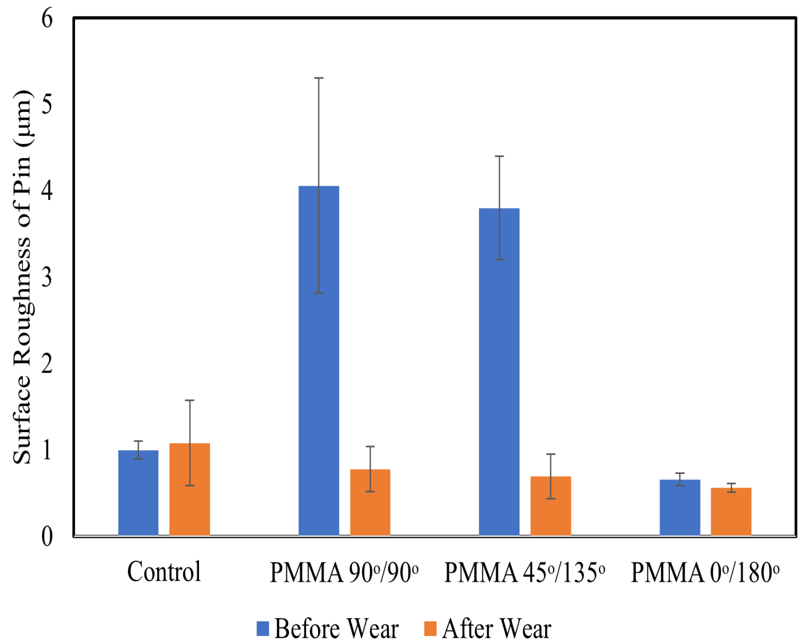

Figure 8. Surface roughness before and after wear test of pin.

4. Conclusions

Based on the experimental work in this research, it can be concluded that the printing orientation determined the absorbability of 3D-printed materials to artificial saliva dan wear resistance. It is also concluded in this research that the 3D-printed material prepared with DLP based printing was a good candidate for dentures, as it has higher resistance to wear than that of the polymer prepared conventionally with heat curing process.

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