中國機械工程學刊第四十六卷第三期第 271~277 頁(民國一百一十四年)
Journal of the Chinese Society of Mechanical Engineers, Vol.46, No.3, pp 271~277 (2025)

Tribology of 3D Printing Polylactic Acid Elements Sliding on the Synthetic Resins

Yuh-Ping Chang*, Chien-Te Liu*, Li-Ming Chu** and Huann-Ming Chou*

Keywords： Tribology, 3d Printing, polylactic acid, synthetic resins

ABSTRACT

Since advanced processes often require high dust-free levels, it is necessary for the machinery industry to develop low-friction, anti-wear and low-dust technologies for drive elements that can be quickly printed and formed. Polylactic acid is often used in rapid printing components, and synthetic resin has a wide range of industrial applications, the two materials are often paired with each other to form driven elements. In order to achieve "smooth driving", the adhesive wear under dry friction conditions should be reduced. To achieve "high dust-free grade", the grease conditions of mating elements should be improved to reduce the generation of wear dust. Therefore, wear of the 3D printed polylactic acid elements sliding against the synthetic resins are investigated in this study under dry friction and grease conditions, respectively. The changes of the friction coefficient are dynamic measured during the friction experiment, and after the friction experiment, the wear surface is observed with micrographs. The experimental results are analyzed both qualitatively and quantitatively to develop rapidly printed transmission components that meet high dust-free levels and can be used for a long time.

INTRODUCTION

"Sustainable development" has gradually become a policy jointly promoted by the world. Promoting industrial sustainability, improving energy- or resource-consuming manufacturing models, and promoting green technology will help achieve the goal of sustainable development [1-2]. According to the "12 Principles of Green ": It is found that material science and tribology technology must play an important role in effectively saving energy and resources: low friction and specific energy saving, anti-wear and reduction of resource consumption. Moreover, designing products that will not last long after their functions are terminated. It exists in the environment and can be decomposed into harmless substances to effectively reduce the burden on the environment.

Since the application market of polylactic acid and resin materials is huge, and the application forms of various polylactic acid and resin materials are very diverse. Therefore, it is necessary to explore various properties of basic materials based on the application characteristics of possible recessive markets. The improvement of the tribology performance of polylactic acid and resin materials is a new idea. There are still few relevant documents. The researches on various applications of resin materials are described as follows:

For various applications of resin materials, various mechanical properties must be considered, such as heat distortion temperature, elongation, tensile strength, impact strength, etc. Hence, it is necessary to add other materials that enhance mechanical properties [3-4]. As to the superiority of carbon fiber reinforced resin, the engineers can easily design a frame with an optimized mechanical structure, and it has the advantages of high rigidity, light weight, fatigue resistance and riding conformance [5-9].

Special resins are a high molecular photopolymer hardened by ultraviolet light. Since the strength of the material can be improved, they are widely used in various industrial projects. After being irradiated by ultraviolet light, the reaction rate of resin hardening becomes obviously faster [10]. Not only the toughness of the material but also the maximum elongation and tensile strength increase [11-13]. So far, although the printed products of polylactic acid and photosensitive resin have fast curing speed, their rigidity and electrical conductivity are not as good as metal products. Hence, how to improve their mechanical properties (such as tribology properties) will become the focus of research.

When resin materials are used in 3D printing components, they are suitable for complex parts with precision modeling, and usually use the support

Paper Received May, 2024. Revised December, 2024. Accepted January, 2025. Author for Correspondence: Yuh-Ping Chang.
** Department of Mechanical Engineering, Kun Shan University, Tainan City 710303, Taiwan, R.O.C.*
*** Department of Green Energy and Information Technology, National Taitung University, Taitung City 950309, Taiwan, R.O.C.*

structures. If powdered polymers are used as the printing material, the powder must be poured into the machines, and a thin layer of powder is reciprocally spread on the printing area, and then the materials are fused with laser light, and through slight height changes, gradually stack to complete the work pieces [14]. Since the printing material will fill the entire internal space, it is not necessary to use a support structure to assist molding, and the unused powder can be sieved through a special equipment before being mixed with the new powders [15].

Therefore, these can be confirmed that through the novel manufacturing process of resin materials, the processing technology of composite molding and the appropriate selection of matching materials, various new industrial products that can be applied to drive elements by 3D printing can be practiced. The wear mechanisms of polymer materials are quite complex, involving various influencing factors of the contact interfaces, including tribo-physics and tribo-chemicals. There are two research objectives: small frictional energy consumption can save energy; the proper material property is to improve the anti-wear performance to reduce the consumption of resources and achieve a longer operating life. Based on the above description, a reciprocating friction tester and the measuring system is used to study the wear characteristics of polylactic acid on commonly used synthetic resins. The experimental results are of reference value for the future application of rapid printing and forming transmission components.

Experimental equipment and procedure

Main experimental equipment

The mechanical gripper created by using a 3D printer had been independently developed by our laboratory as shown in Figure 1. Inside the red box in Fig.1 is a transmission gear set made of 3D printed polylactic acids. Therefore, it is necessary to improve the service life of the set. However, there are few literatures exploring the wear-resistant properties of 3D printed polylactic acid elements. In order to investigate the wear of 3D printed polylactic acid elements sliding against the synthetic resins, the reciprocating friction tester is used to conduct the experiments as shown in Figure 2. The pin is driven by a crank-slider mechanism and the length of the crank is adjusted to as the stroke of 12 mm. The plate is directly connected to the load cell. In order to meet to the load situation of the actual transmission of the robot arm, the normal load of 20N is relative to the pin through the plate and disposed along the level rule. The soft springs and oil damping are added to the load system to avoid vibration and impact during the friction process and maintain complete contact between the sliding specimens. The voltage signals of friction coefficient are input to the data acquisition system and fed to the personal computer for the data analysis.

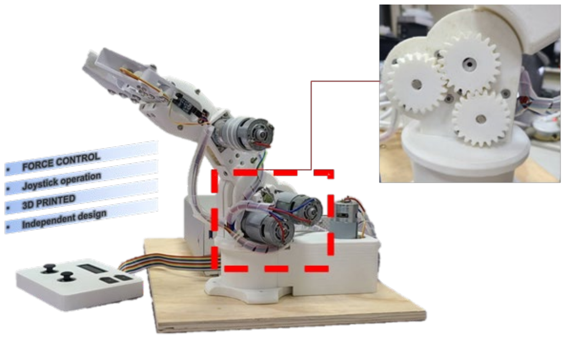

Fig. 1 Photo of the self-developed 3D printed drive elements.

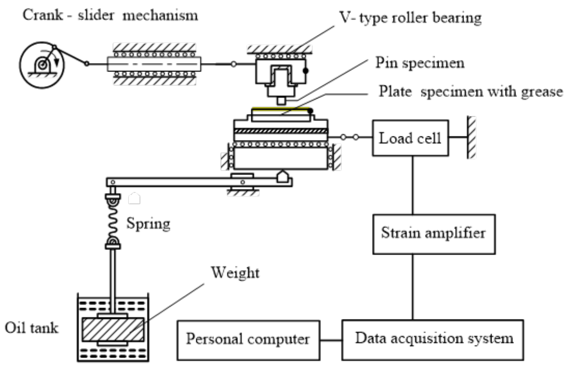

Fig. 2 Schematic diagram of the reciprocating friction tester

Geometry and physical properties of the experimental specimens

The 3D printed polylactic acids are used as the pin specimen. Moreover, the physical properties of polylactic acid are shown in Table 1. The size and diagram of the pin is shown in Figure 3, and the physical photo is shown in Figure 4 (a). The three types of synthetic resins are composed with base materials to form the plates respectively. The physical properties of the synthetic resins are shown in Table 2. The size and diagram of the plate is shown in Fig. 3, and the physical photo is shown in Fig.4 (b).

Table 1 Physical property of the pin specimens

3D printed polylactic acids	PLA 101	PLA 202	PLA 205
Density (g/cm^3)	1.42	1.24	1.23
Tensile strength (MPa)	45-65	55-65	40-60
Elongation at break (%)	2-4	3-6	6-13

Table 2 Physical property of the plate specimens

Synthetic resins	CM-211	PM-600	PN-107
Density (g/cm^3)	1.19	1.12	1.06
Tensile strength (MPa)	68	69	65
Elongation at break (%)	7	5	4

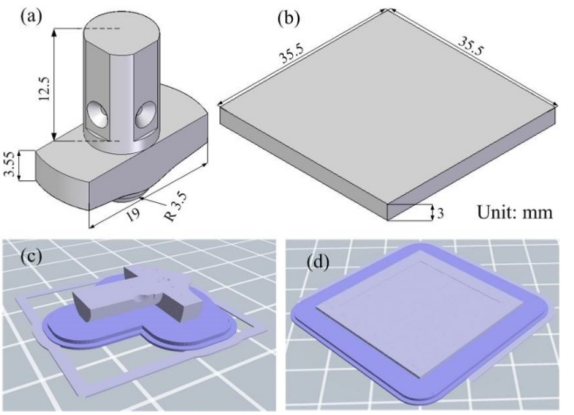

Fig. 3 Schematic diagram of the pin and plate specimens

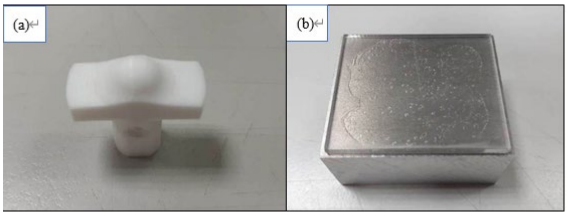

Fig. 4 Photo of the pin and plate: (a) 3D printed polylactic acids, (b) Synthetic resins

Experimental procedure

In order to explore the wear characteristics of three commonly used synthetic resins, dry friction and grease are planned as the experimental conditions respectively. The experimental parameters are set as follows: the reciprocating speed is 50 and 150cpm, the vertical load is 20N, the friction test time is 30sec, the ambient room temperature is 25 ± 2°C, and the relative humidity is 65 ± 5%.

Experimental results and discussion

Synthetic resin of CM-211

Typical response of friction coefficient for 3D printed polylactic acid elements sliding against the CM-211 under 50cpm and dry friction is shown in Figure 5. It is seen from the figure that the friction coefficient gradually increases from about 0.4 to 0.8, and the running-in period is not obvious. Figure 6. is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 5. It can be seen from Fig. 6 that the wear is very slight, the amount of wear debris peeling off on the pin is relatively small, and the adhesion transfer of materials between the pin and the plate is not obvious.

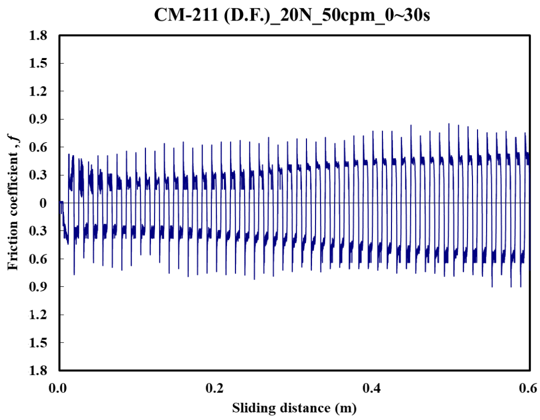

Fig. 5 Typical responses of friction coefficient of CM-211 under 50cpm and dry friction

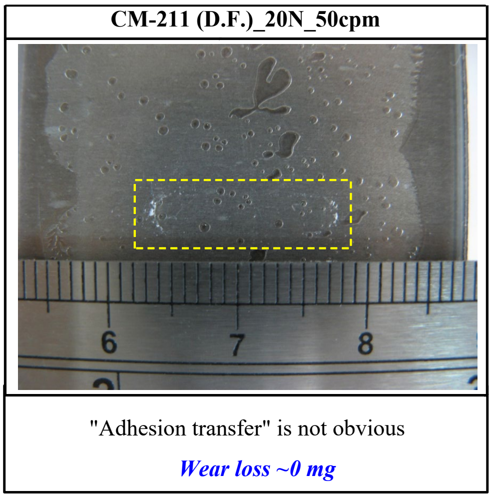

Fig. 6 Worn surface of the plate of CM-211 under 50cpm and dry friction

When the reciprocating rate is increased to 150cpm, the typical response of friction coefficient for 3D printed polylactic acid elements sliding against the CM-211 under dry friction is shown in Figure 7. It is seen from the figure that the friction coefficient gradually increases from about 0.5 to 1.5, and the running-in period is between the friction distances of 0 to 0.9m. Figure 8. is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 7. It is seen from Fig. 8 that the wear is serious, and the adhesion transfer is obvious. Moreover, it can be judged that 2.9mg of polylactic acid has transferred to the synthetic resin CM-211 from the change in the mass of the specimen and the color of the transfer layer.

The above results show that the friction coefficient of the general-grade PMMA synthetic resin CM-211 is still small and the wear is extremely insignificant under the condition of a low reciprocating speed of 50cpm. When reaching a high reciprocating speed of 150cpm, the friction coefficient increases significantly and shows severe wear.

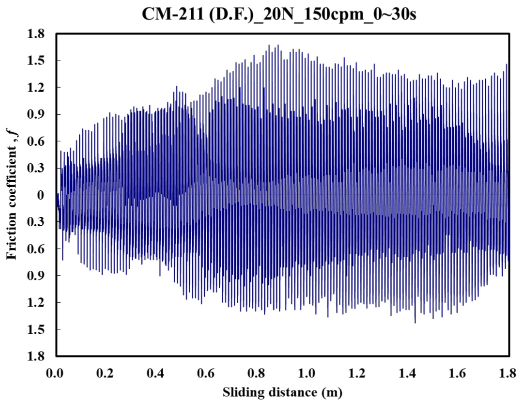

Fig. 7 Typical responses of friction coefficient of CM-211 under 150cpm and dry friction

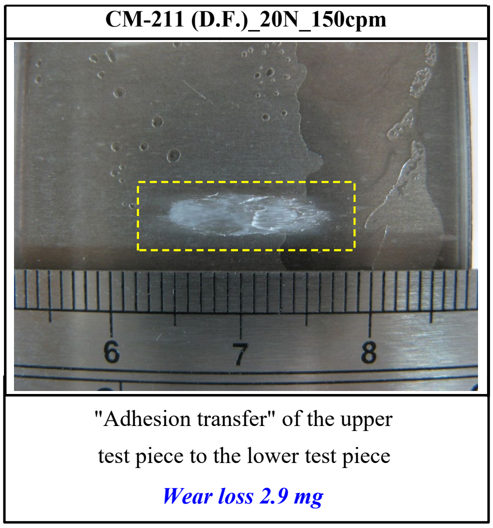

Fig. 8 Worn surface of the plate of CM-211 under 150cpm and dry friction

Synthetic resin of PM-600

Typical response of friction coefficient for 3D printed polylactic acid elements sliding against the PM-600 under 50cpm and dry friction is shown in Figure 9. It is seen from the figure that the friction coefficient gradually increases from about 0.2 to 0.8 during the friction distances of 0 to 0.1m, and the running-in period is quite obvious. Fig. 10 is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 9. It can be seen from Figure 10 that the wear is very slight, the amount of wear debris peeling off on the pin is relatively small, and the adhesion transfer of materials between the pin and the plate is not significantly.

When the reciprocating rate is increased to 150cpm, the typical response of friction coefficient for 3D printed polylactic acid elements sliding against the PM-600 under dry friction is shown in Figure 11. It is seen from the figure that the friction coefficient gradually increases from about 0.5 to 1.7, and the running-in period is between the friction distances of 0 to 0.6m. Figure 12 is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 11. It is seen from Fig. 12 that the wear is more serious, and the adhesion transfer is obvious. Similar, it can be determined that 3.1mg of polylactic acid has transferred to the synthetic resin PM-600 from the change in the mass of the specimen and the color of the transfer layer.

These results indicate that the friction coefficient of MS resin PM-600 has increased slightly at a low reciprocating speed of 50cpm, even though the wear is very slight. When reaching a high reciprocating speed of 150cpm, the friction coefficient increases significantly and shows severe wear.

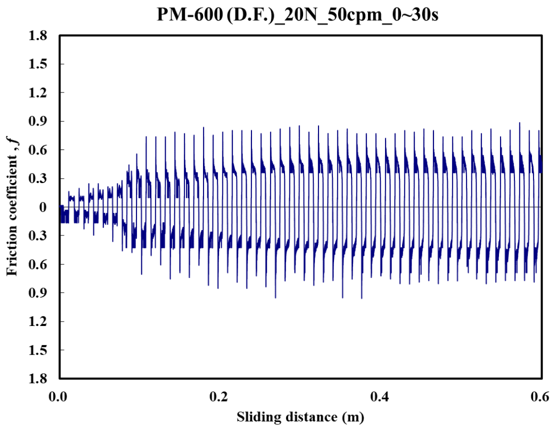

Fig. 9 Typical responses of friction coefficient of PM-600 under 50cpm and dry friction

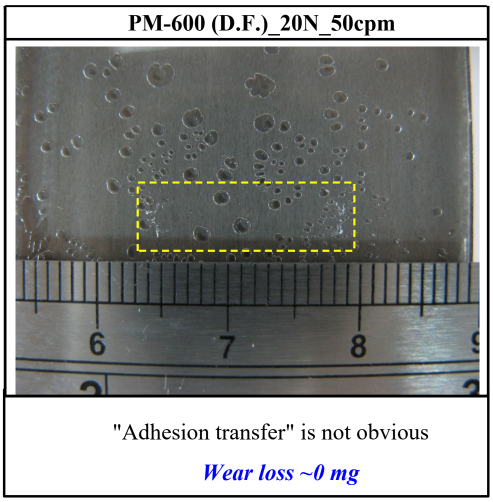

Fig. 10 Worn surface of the plate of PM-600 under 50cpm and dry friction

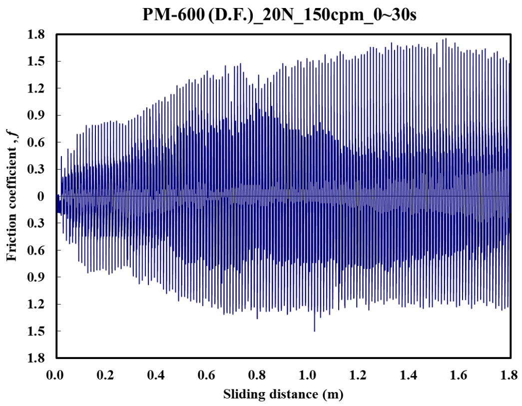

Fig. 11 Typical responses of friction coefficient of PM-600 under 150cpm and dry friction

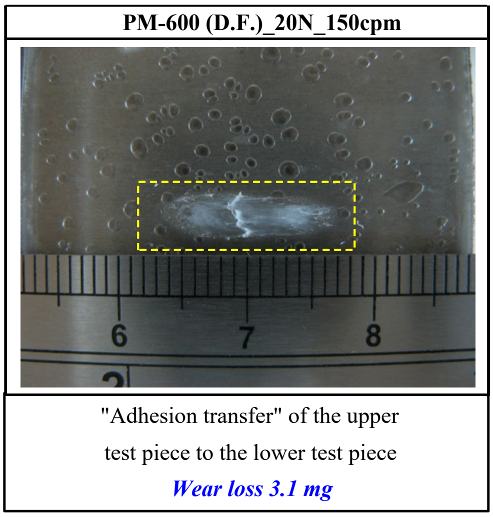

Fig. 12 Worn surface of the plate of PM-600 under 150cpm and dry friction

Synthetic resin of PN-107

Typical response of friction coefficient for 3D printed polylactic acid elements sliding against the PN-107 L125FG under 50cpm and dry friction is shown in Figure 13. It is seen from the figure that the friction coefficient gradually increases from about 0.2 to 1.0 during the friction distances of 0 to 0.45m, and the running-in period is very significantly. Figure 14 is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 13. It can be seen from Fig. 14 that the wear is quite slight, the amount of wear debris peeling off on the pin is relatively small, and the adhesion transfer of materials between the pin and the plate is not obviously.

When the reciprocating rate is increased to 150cpm, the typical response of friction coefficient for 3D printed polylactic acid elements sliding against the PN-107 L125FG under dry friction is shown in Figure15. It is seen from this figure that the friction coefficient significantly increases from about 0.3 to 1.5, and the running-in period is only during the friction distances of 0 to 0.1m. Figure 16 is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 15. It is seen from Fig. 16 that the severe wear occurs, and the adhesion transfer is significantly. Furthermore, it can be observed that 4.2mg of polylactic acid has transferred to the synthetic resin PN-107 L125FG from the change in the mass of the specimen and the color of the transfer layer.

The above results show that the friction coefficient of the SAN synthetic resin PN-107 L125FG has increased slightly at a low reciprocating speed of 50cpm, even though the wear still shows slight. When reaching a high reciprocating speed of 150cpm, the friction coefficient increases significantly and the running-in period is very short. Moreover, the result shows severe wear.

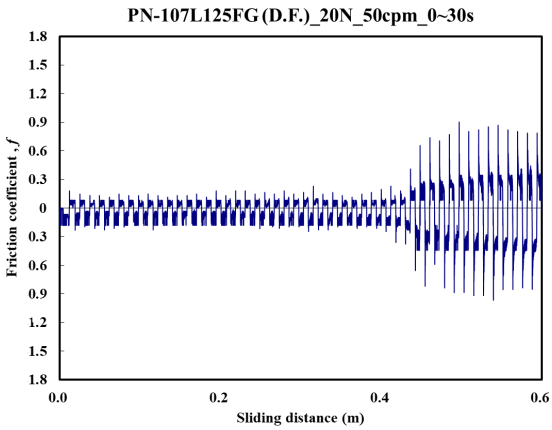

Fig. 13 Typical responses of friction coefficient of PN-107 under 50cpm and dry friction

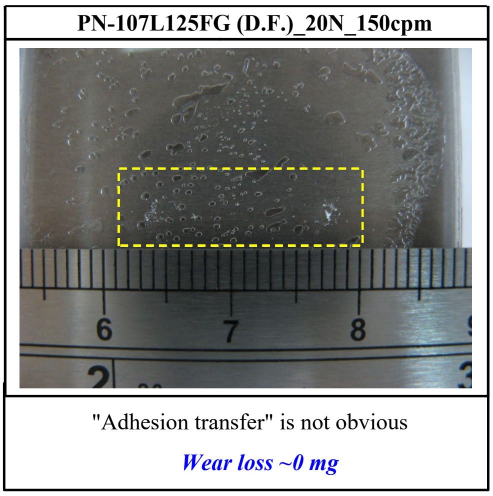

Fig. 14 Worn surface of the plate of PN-107 under 50cpm and dry friction

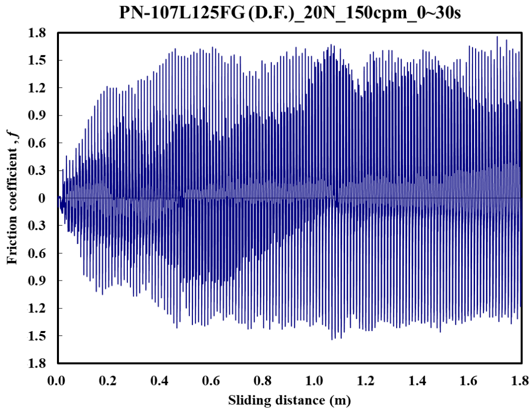

Fig. 15 Typical responses of friction coefficient of PN-107 under 150cpm and dry friction

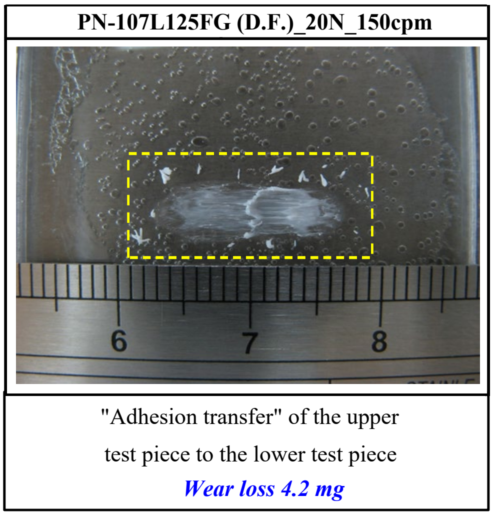

Fig. 16 Worn surface of the plate of PN-107 under 150cpm and dry friction

Effects of grease on the wear of PN-107

The three synthetic resins are sequentially CM-211, PM-600, PN-107 L125FG: the friction is very small and the wear is not obvious at a low speed of 50cpm. However, the friction coefficient gradually increases at a high speed of 150cpm, and the running-in period is more obvious. Wear also becomes serious in turn, and the amount of adhesion transfer is also more increasing. Since physical properties of the these three resin materials, such as density, tensile strength and elongation at break, bending strength, heat distortion temperature, etc., all happen to decrease sequentially. Therefore, physical properties of the resin materials do obviously affect the tribology performance, which can be provided to the engineers on the application side for the design, so as to boost the selections of appropriate materials.

Furthermore, this article also conducts additional research on the impact of grease on 3D printing polylactic acid elements sliding against the synthetic resins. Typical response of friction coefficient for 3D printed polylactic acid elements sliding against the PN-107 L125FG under grease lubrication is shown in Figure 17. It is seen from this figure that the friction coefficient is small and stable, with a value of about 0.1 to 0.2 and a slight change. Figure 18 is the observation of the worn surface after the friction test is completed under the experimental conditions corresponding to Fig. 17. It is seen from Fig. 18 that there is almost no wear and adhesion transfer.

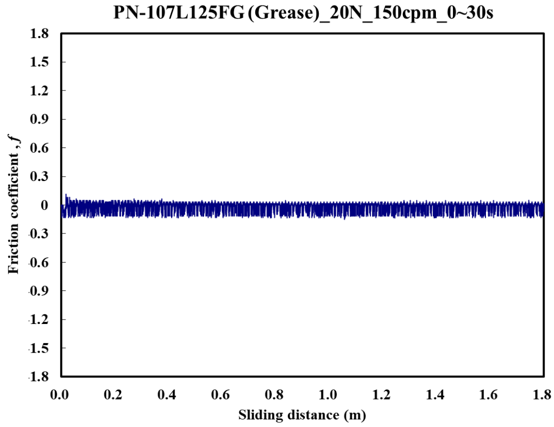

Fig. 17 Typical responses of friction coefficient of PN-107 under 150cpm and grease lubrication

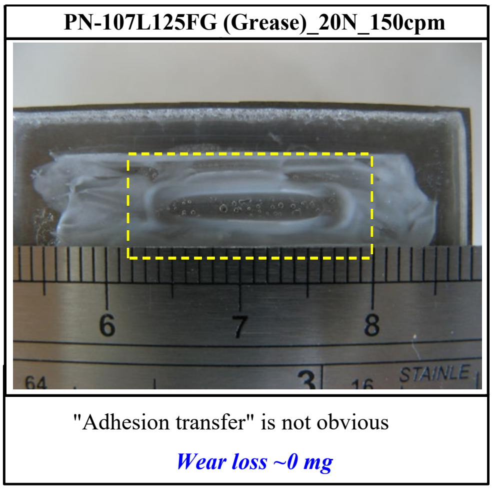

Fig. 18 Worn surface of the plate of PN-107 under 150cpm and grease lubrication

Conclusions and application suggestions

This study is to investigate the tribology characteristics of 3D printed transmission components sliding against the synthetic resins. The experiments were conducted under dry friction and grease conditions respectively. From the experimental results, the following conclusions are drawn:

(1) The physical properties of the resin materials will indeed significantly affect the tribology performance. The resin materials with higher tensile strength and higher heat deflection

temperature have better wear resistance, especially at the relatively high reciprocating speed.

(2) When the interface has the effect of grease, even at the high reciprocating speed conditions, there is almost no wear and adhesion transfer between the specimens.

(3) Since the 3D printed elements will have textures in a specific direction, the lubricating oil may be easily lost due to the effect of the texture. In order to achieve the purpose of prolonging the service life, the comparison experiment can be carried out to optimize the printing texture and lubrication conditions.

ACKNOWLEDGEMENTS

The authors express their appreciation to the National Science and Technology Council (NSTC 112-2221-E-168 -011) in Taiwan, R.O.C. for financial support. We declare no conflict of interests regarding the publication of this article.

REFERENCES

Anastas, PT, Bickart, PH, Kirchhoff, MM. Designing Safer Polymers, Wiley-Interscience, New York, 2000.

Anastas, PT, Warner, JC. Green Chemistry: Theory and Practice, Oxford University Press, New York, 1998:30.

Crivello JV, Advanced curing technologies using photo and electron beam induced cationic polymerization, Radiation Physics and Chemistry, 2002; 63.

Crivello JV, The Discovery and Development of Onium Salt Cationic Photoinitiator, J. Appl. Polym. Sci., 1999; 37:4244-4247.

Cosmi F, Maso AD, A mechanical characterization of SLA 3D-printed specimens for low-budget applications, materials today: proceedings, 2020; 32(2):194-201.

Dave RS, Mallow A, Kardos JL, Dudukovic' MP, Science-Based Guidelines for the Autoclave Process for Composites Manufacturing, SAMPE Journal, 1990; 26(3):31.

Jin L, Zhang K, Xu T, Zeng T, Cheng S, The fabrication and mechanical properties of SiC/SiC composites prepared by SLS combined with PIP, Ceram. Int., 2018; 44: 20992-20999.

Kou H, Asif A, Shi W, Photo polymerization Kinetics of Hyperbranched Acrylated Aromatic Polyester, Journal of Applied Polymer Science, 2003; 89:1500-1504.

Lecamp L, Lebaudy P, Youssef B, Bunel C, Influence of UV radiation wavelength on conversion and temperature distribution profiles within dimethacrylate thick material during photopolymerization, Polymer., 2001; 42:8544.

Lu, LH, Study on Hardening Process of Carbon Fiber/Epoxy Resin Composite, master's thesis, Institute of Polymer Research, Tsinghua University, 1985.

Sarrazin H, Kim B, Ann SH, Springer GS, Effects of Processing Temperature and Layup on Springback, Journal of Composite Material, 1995; 29:10.

Thoughts on the Application of Carbon Fiber Composite Technology in the Automotive Industry in Taiwan, Advanced Materials Technology Association, Seventh Edition, 2010; (21).

White SR, Hahn HT, Process Molding of Composite Material: residual Stresses Development During Cure. Part Ⅱ.Experimental Validation, Journal of Composite Materials, 1992; 26:16.

Yang SY, Huang CK, Influence of Processing on Accuracy of Advanced Composite Tools for Flat Plates, Composites Part A ： Applied Science and Manufacturing, 1997.

Yang SY, Huang CK, Wu CB, Influence of Processing on Quality of Advanced Composite Tools, Journal of Advanced Materials, 1996; 27:3