ISSN 2063-5346

Section A-Research paper

Effect of Carbon Fiber Composition and Lubrication on Tooth Wear Rate of 3D Printed Worm Gears

Prof. Syamsul Hadi, Ph.D.[1]*

[1]*Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: syampol2003@yahoo.com syamsul.hadi@polinema.ac.id

Wirawan[2]

[2]Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: wirawan@polinema.ac.id

Satworo Adiwidodo[3]

[2]Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: satworo.adiwidodo@polinema.ac.id

Hangga Wicaksono[4]

[2]Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: wicaksonohangga@gmail.com

Bima Cahya Maula Dana[5]

[2]Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: mauladanac@gmail.com

***Corresponding Author:** Prof. Syamsul Hadi, Ph.D.

*Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65141, Indonesia. Email: syampol2003@yahoo.com

ABSTRACT

The problem lies in the unknown wear level of the teeth on the 3D-printed worm gear ring and if it is worn, spare parts are not available without buying 1 complete unit of reduction gear. The aim of the study was to determine the level of wear and to obtain an alternative use of 3D printed worm gear rings which allow them to be used with the same function as a substitute for worm gear rings which were originally made of brass. The research method included scanning brass worm gear rings, modifying image dimensions for improvement, 3D printing with Onyx-Carbon Fiber composite materials, trials with torsion tests with variations of lubrication, and measurement of wear results with the help of Scanning Electron Microscopy (SEM) photos. The wear results show that with no lubrication and with lubrication using SAE 10W 30 Oil, and Grease is worth 72.3 μm, 33 μm, and 62 μm or experiencing wear compared to the thickness of the teeth before using the torsion test of 30 low carbon steel specimens with a torque of 23.5 Nm were 3.67%, 5.05%, and 2.53%.

Keywords: lubrication, Onyx-Carbon Fiber composite materials, reduction gear, 3D-printed worm gear ring

1.0 INTRODUCTION

Previous studies have tested a pair of worm wheels made of bronze alloys and worm gears made of plastic [1]. It is possible to pair different types of materials of a pair of worm wheels and worm gears. Testing the friction of a pair of worm wheels made of bronze alloy and worm gears made of plastic using TP-30 lubricating oil and 75W 90 multigrade oil showed the results of using power (W) and torque (T) [1]. The test results show that using TP-30 oil requires lower power (W) and torque (T) than using 75W 90 multigrade oil because the viscosity of the lubricant is lower. The use of the hardest and most wear-resistant materials in the manufacture of worm wheels and worm gears can increase the life of the gear box [1]. Hard gear material provides better wear resistance. Analysis of the torsional strength of two samples of used low carbon steel showed an 8.6% reduction in the modulus of elasticity than newly purchased low carbon steel [2]. In the torsion test, a new low carbon steel is used so that the torsional strength is not reduced.

Worm gear and worm gear box efficiencies were up to 96%, despite increased pitting damage, no significant effect on efficiency was noted. With the use of low viscosity lubricants (ISO VG 220), the efficiency achieved is 1 % lower compared to lubrication with oil and a viscosity of ISO VG 460. Mineral oil with a comparable viscosity produces a lower value of around 3 % [3]. The lower the viscosity of the lubricant, the lower the efficiency will be.

The carrying capacity of plastic worm gears and worm gear transmission from steel increased by 24 % and 12.86 % respectively for m (cutter module) = 0.8 which proves that the theory of spacing between teeth is not the same [4]. The carrying capacity of plastic worm gears and steel worm gear transmissions can be increased if the distance between the teeth is not the same.

The cost and time of making reverse duplication engineering through a 3D Scanner from a certain object in the form of a cloud into a data that can be converted into working drawings and 3D Printers for its embodiment are less than conventional methods [5]. Conventional methods still require design, calculation, drawing, and programming/engineering in its manufacture.

With 3D scanning and reverse duplication engineering associated with rapid prototyping technology, the data from the geometric components can be easily and quickly measured and analyzed [6]. The ease of the manufacturing process can be increased by the application of 3D scanning and reverse duplication engineering in making a product prototype.

Reverse duplication engineering aims to be able to create other objects based on physical form where existing objects are not available in 3D images [7]. Documentation of 3D images that were not owned before can be extracted or obtained from scanning the work piece.

The type and viscosity of the lubricant can reduce the power loss to the maximum. Selection of the worm wheel shaft rotational speed and worm gear shaft drive according to the torque achieved, the type and viscosity of the lubricant used can reduce power loss and increase efficiency [8]. The rotational speed of the worm wheel shaft that rotates the worm gear made of composite materials and which drives the worm wheel shaft made of steel and composite worm gears at the appropriate torque, as well as the right viscosity of the lubricant can reduce power and increase efficiency.

A good relationship was obtained between the temperature profiles at 35.0 °C, 35.7 °C and 39.3 °C for each lubricant VG100, VG460 and VG680 which revealed that lubricants with higher viscosity resulted in less amplitude of vibration. At 1150 rpm, a higher vibration amplitude was obtained compared to other motor speeds at 900 rpm and 1400 rpm, so it can be concluded that there is a correlation between lubrication viscosity, vibration level, temperature profile and worm gear speed [9]. Different lubricant viscosity can lower different vibrations.

Prediction of gearbox performance from worm gears and worm gears related to tribology and geometry factors has been obtained for a gear pair [10]. The performance of the gear box of the worm wheel and worm gear pairs is greatly influenced by tribological factors and their geometry.

The simple optical scanning procedure, the high data density obtained in a single scan, and the possibility of reverse-engineered duplication and integrated inspection are the advantages of such optical scanning compared to conventional measurement methods whereby due to the acquisition of three-dimensional measurement data, optical scanners are often considered as an alternative to coordinate measuring machine [11]. Optical scanning as an alternative to coordinate measuring machines.

The condition of the three worm wheels and worm gears of a gear box has identified pitting on the surface of the gears of the gear box A which indicates surface pitting of the teeth, while the gear boxes B and C do not show significant damage or can be said to be smooth [12]. The condition of the gears in the gear box under study may result in pitting on the surface of the teeth of the gears due to wear or erosion.

There are 4 important parameters in the 3D printing process, namely printing temperature, printing speed, printing base temperature, and filling percentage [13]. The printing temperature is affected by the temperature of the polymer material, the print speed is affected by the flow rate of the polymer melt, the temperature of the printing bed affects the adherence of the melted polymer material, and the filling percentage is affected by the type of 3D printed material. These four parameters are interrelated to produce good quality 3D prints.

Each component in a 3D printer is made with a different filling pattern with different strength results and material costs. In optimizing the use of the most economical filling pattern in 3D printing that meets all aspects, it is necessary to develop components with the lowest material consumption through optimization method validation of comparing physical properties, time consumption, costs of traditional manufacturing methods and additive manufacturing methods [14]. The physical properties of the product, processing time, minimization of material use and lowest cost are the main considerations in 3D printing.

Nylon spur gears 3D printed with filaments of Nylon 618, Nylon 645, alloy 910, along with Onyx and Nylon Markforged materials were tested for wear levels showing that Nylon 618 performed the best wear performance among the other 5 3D printed materials tested. The test results show that 3D gears imprinted with Nylon 618 perform better than injection molded nylon 66 gears at low to moderate torque [15]. Different types of Nylon material in 3D printed gears provide different wear resistance.

Injection molded gears made of Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene (HDPE) and Polyoxymethylene (POM) materials were tested for wear at different torque levels of 0.8, 1.2, 1.6 and 2.0 Nm and speed different 600, 800, 1000, and 1200 rpm. Testing at a torque of 1.4 Nm and a speed of 900 rpm to measure gear reduction, durability and failure modes that occur in the gear. ABS teeth are damaged by excessive wear and HDPE teeth are damaged by cracks in their tooth roots. ABS and HDPE gears can be tested for up to 0.5 and 1.1 million cycles respectively before failure whereas POM gears are tested for up to 2 million cycles without any sign of failure [16]. Comparison of damage to gears injection molded from POM materials shows the strongest resistance than ABS and HDPE.

2.0 EXPERIMENTATION

2.1 MATERIALS & METHODOLOGY

Reduction gear is a tool used to slow down a shaft rotation for a specific purpose, generally from a higher electric motor rotation around 1500 rpm to be slowed down to a certain rotational speed. Because the deceleration is high and a compact construction is required, which means it is efficient in decelerating rotation, a pair of worm wheel and worm gear types of gears is chosen while other gear pairs require several levels of deceleration, for example straight gears or oblique gears.

The reduction gear is chosen with the first deceleration ratio of 1:100 and the second 1:60 of its initial speed because the reduction gear installed on the torsion testing machine has the same ratio value, so that the worm gear ring does not change the position of the two shafts which are perpendicular to each other. The shape of the selected reduction gear is shown in Fig. 1.

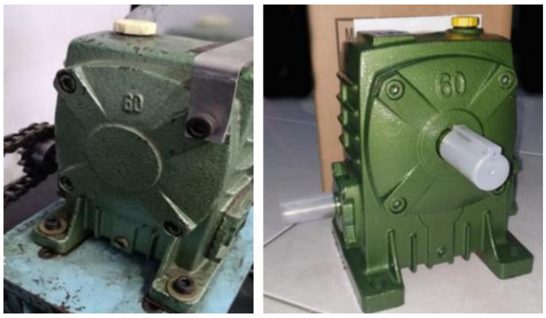

Fig. 1 Reduction gear: (left) Installed on torsion testing machine, and (right) New [17]

The rotational speed of the torsion test specimen is the alternating current (AC) motor rotational speed of 1400 rpm, decelerated through the first reduction gear with a deceleration ratio of 1 turn compared to 100 revolutions (1:100), so that the speed of the first reduction gear is 1400:100 = 14 rpm, then in the second stage reduction gear a speed ratio of 1 rotation is used compared to 60 revolutions (1:60), so that finally the rotation on the torsion test specimen is 14:60 = 0.233 rpm.

After disassembling the new reduction gear, the worm gear ring made of brass material is shown in Fig. 2.

Fig. 2 Worm gear ring made of Brass material

The 3D Scanner and 3D printed result of the worm gear ring is shown in Fig.3 for the Onyx composite material. worm gear rings made of Onyx material are intended to replace worm gear rings made of Brass material (Fig. 2) as an alternative material for the development of components from other materials that can replace it as a second quality material. Worm gear rings made of Brass material from the purchase of a new reduction gear were disassembled and immediately replaced with worm gear rings made of Onyx material as an alternative material thereof to observe the level of wear by operating it in a torsion test. In addition to the 3D printed worm gear ring material from Onyx material, it is also printed from Onyx material which is added 10% carbon fiber as a comparison of wear results.

Fig. 3 Three D Scanner (left) and 3D printout of worm gear rings for Onyx composite materials (right)

The installation of the worm gear ring on the worm wheel inside the reduction gear is shown in Fig. 4.

Fig. 4 Installation of the worm gear ring on the worm wheel in the reduction gear

The wear test using the Torsion Testing Machine is shown in Fig. 5, but the reduction gear was replaced with a new reduction gear in which the worm gear ring which was originally made of Brass material was replaced with Onyx material as a result of 3D printing, and the condition of the specimen during torsion testing is shown in Fig. 5. Figure 6 with low carbon steel specimens (ASTM E143-13) of 30 specimens measuring 6 mm x 6 mm x 160 mm until all specimens are twisted. The test conditions were treated with 3 conditions, namely conditions without lubrication or dry conditions, conditions with SAE 10W 30 oil lubrication between the contact surfaces of the teeth of the worm wheel and worm gears, and conditions with grease.

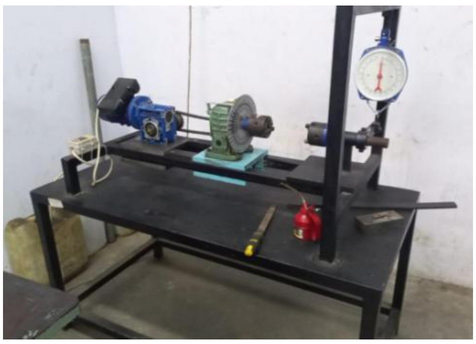

Fig. 5 Torsion Test Machine

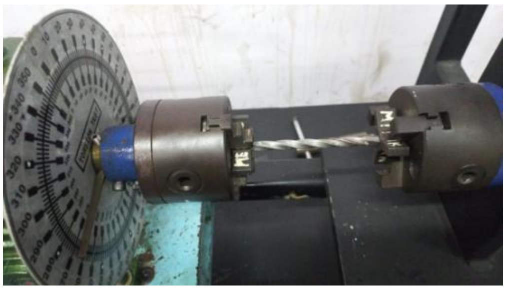

Fig. 6 Torsion test of low carbon steel specimens

Testing the torsion of the specimen from a rectangular bar of low carbon steel measuring 6 mm x 6 mm x 160 mm produces torsional force and torsional angle which is then calculated for the torsional stress value related to the torsional force measuring arm and the achieved torsional angle which is plotted in torsional stress against the angle twisted.

Twisting stress or referred to as shear stress is obtained by formula (1).

$$\tau = T.c/J \tag{1}$$

where T: torsional moment measured during torsion test, T = force x torsion arm = F . l; c: distance to the outermost fibers of the specimen/radius of the circle if the specimen has a circular cross-section. The force, F is read from the Spring Scales when testing torsion and the length of the arm, l on the Torsion Testing Machine is 145 mm or 0.145 m.

The polar moment of inertia, J for the rectangular specimen cross-section in the torsion test is calculated by formula (2).

$$J = (bh^3 + b^3h)/12 \tag{2}$$

where b: width, and h: height of the rectangular section.

After torsion testing was carried out with specimens from low carbon steel for each treatment with worm ring material from Onyx only and Onyx + 10 % Carbon Fiber with treatment in dry conditions, conditions with oil lubricants, conditions with grease lubricants, all from worm gear rings cut for observation by Scanning Electron Microscopy (SEM) for tooth thickness before and after torsion testing and tooth contact surfaces on worm gear and worm wheels pairs.

2.2 RESULT AND DISCUSSION

SEM photo results for tooth thickness of worm gear rings for Onyx and Onyx+Carbon Fiber materials are shown in Fig. 7 to Fig. 13.

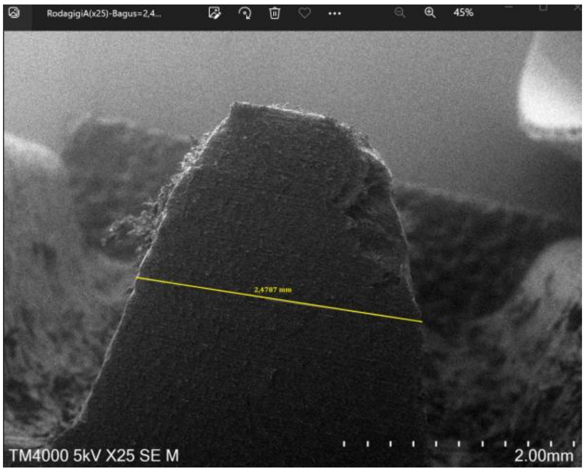

Fig. 7 SEM photo for tooth thickness of worm gear ring for Onyx dry condition (A code)

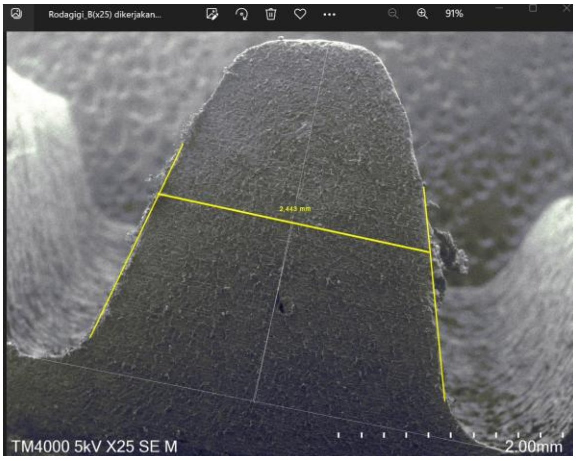

Fig.8 SEM photo for tooth thickness of worm gear ring for Onyx material with oil lubrication (B code)

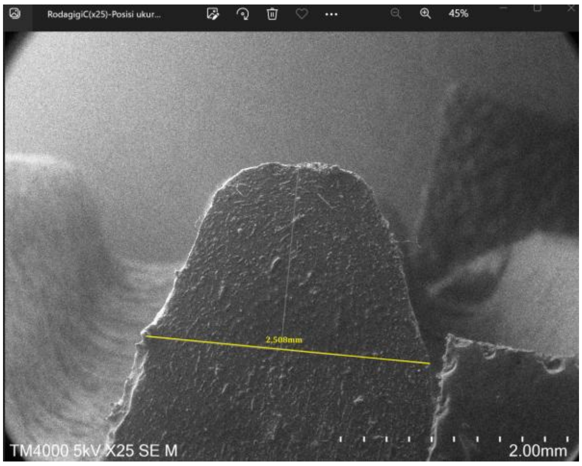

Fig. 9 SEM photo for tooth thickness of worm gear ring for Onyx material condition with lubricating grease (C code)

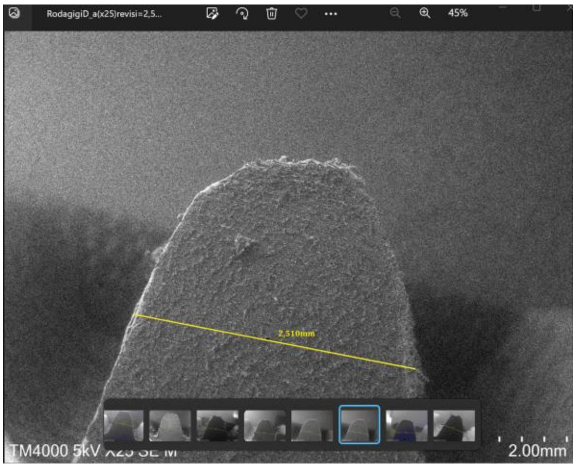

Fig. 10 SEM photo for tooth thickness of worm gear ring for dry condition Onyx+Carbon Fiber material (D code)

Fig. 11 SEM photo for tooth thickness of the worm gear ring for Onyx+Carbon Fiber material with oil lubrication (E code)

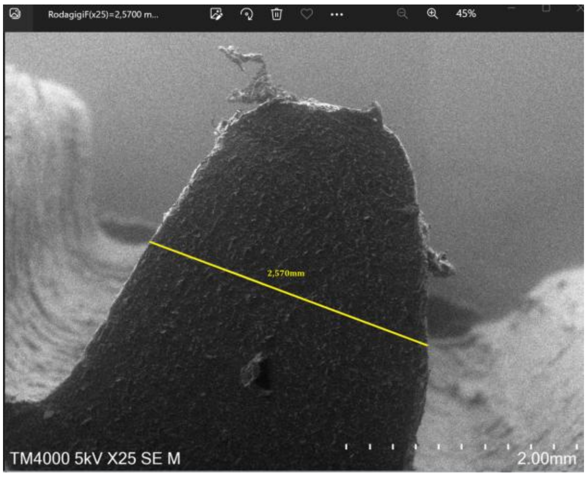

Fig. 12 SEM photo for tooth thickness of the worm gear ring for Onyx+Carbon Fiber materials with grease lubricating conditions (F code)

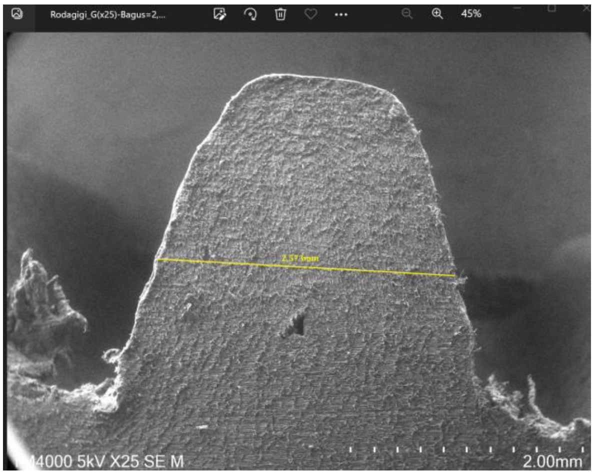

Fig. 13 SEM photo for tooth thickness of worm gear ring for 3D printed Onyx material without torsion testing as a comparison of tooth thickness (G code)

The results of measuring the tooth thickness of the worm gear ring through SEM photographs of Onyx only and Onyx+10% Carbon Fiber obtained the results shown in Table 1 and the graphical comparison is shown in Fig. 14.

Table: 1 Results of measuring tooth thickness from worm gear rings through SEM photographs

Code	Material and Lubricant	Teeth Thickness (mm)	Wear to original thickness (mm)
A	ONYX, DRY	2.4787	0.0943
B	ONYX, OIL	2.4430	0.1300
C	ONYX, GREASE	2.5080	0.0650
D	ONYX+10 % CARBON FIBER, DRY	2.5100	0.0220
E	ONYX+10 % CARBON FIBER, OIL	2.4760	0.0970
F	ONYX+10 % CARBON FIBER, GREASE	2.5700	0.0030
G	3D PRINTED ONLY, WITHOUT TORSION TEST	2.5730	0.0000

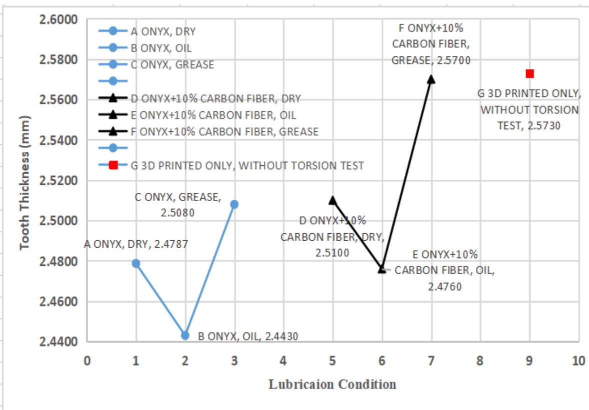

Fig. 14 Thickness of worm gear ring teeth measured using SEM photographs

In Fig. 14 it can be seen that the thickness of the 3D printed teeth without torsion test shows the highest thickness at 2.5730 mm as a comparison with the thickness of the other teeth. For the thickness of the teeth of the worm gear ring, the Onyx material alone shows a lower thickness than the Onyx material which is added with 10% Carbon Fiber. Torsion testing with 30 low carbon steel specimens with a rectangular cross-section with dimensions of 6 mm x 6 mm x 160 mm for specimens with oil lubricants showed a lower thickness than in dry conditions or conditions with grease lubricants, because it is possible for solubility to occur between the Onyx material and the Onyx material+10 % Carbon Fiber and SAE 10W 30 lubricant.

The wear due to torsion test with grease showed a lower value than the condition with oil lubrication and dry conditions and as the best result for torsion test conditions with minimal wear. The wear in the torsion test with grease lubricant on the worm ring material on the Onyx material is 0.0650 mm (65 μm) and on the Onyx+10 % Carbon Fiber material is 0.0030 mm (3 μm). The wear in the torsion test under dry conditions on the Onyx worm gear ring material was 0.0943 mm (94.3 μm) and on Onyx+10 % Carbon Fiber material was 0.0220 mm (22 μm). The wear in the torsion test with lubricating oil on the Onyx worm ring material was 0.1300 mm (130 μm) and on Onyx+10 % Carbon Fiber material was 0.0970 mm (97 μm).

The tooth surfaces and photographs due to contact between the teeth in dry conditions, conditions with oil lubrication, and conditions with grease lubrication are shown in Fig. 15 through Fig. 21.

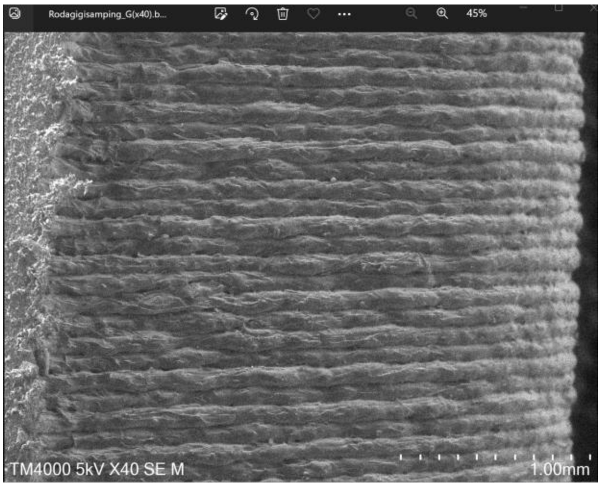

Fig. 15 Photo of the tooth surface before the torsion test on the Onyx material

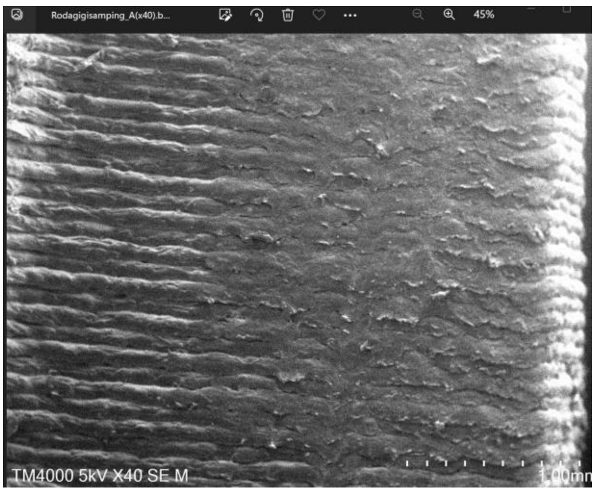

Fig. 16 Photo of the tooth surface after the torsion test was carried out in dry conditions on Onyx material

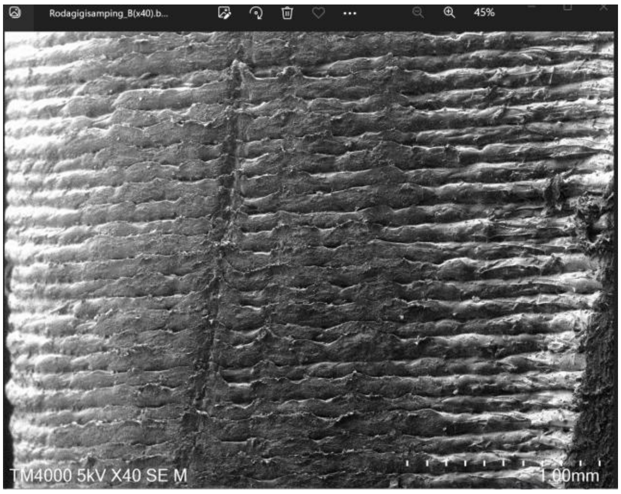

Fig. 17 Photo of the tooth surface after the torsion test was carried out under conditions with oil lubrication on the Onyx material

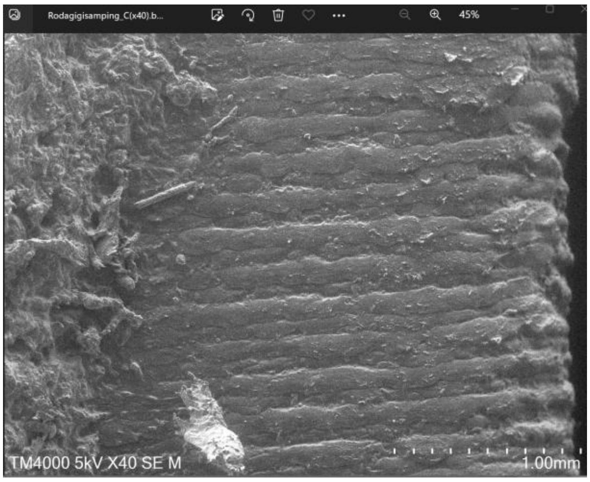

Fig. 18 Photo of the tooth surface after the torsion test was carried out under conditions with grease lubricants on the Onyx material

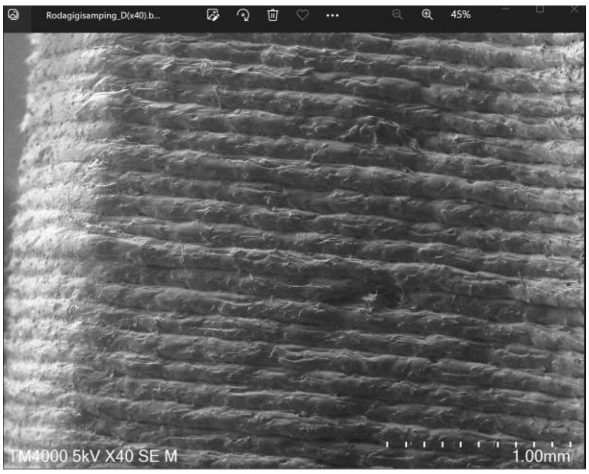

Fig. 19 Photo of the tooth surface after the torsion test in dry conditions on Onyx+10 % Carbon Fiber

Fig. 20 Photo of the tooth surface after the torsion test was carried out under conditions with oil lubrication on Onyx+10 % Carbon Fiber material

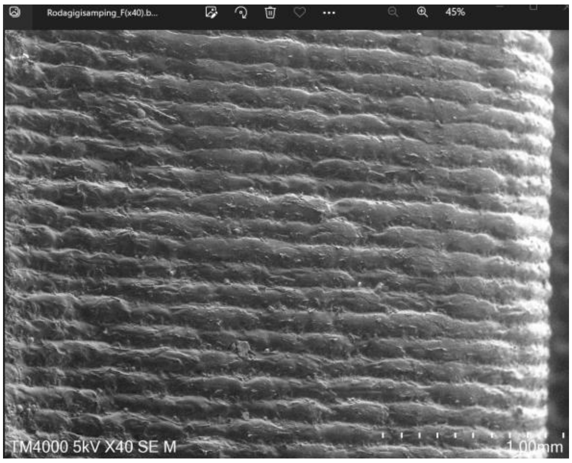

Fig. 21 Photo of the tooth surface after the torsion test was carried out under conditions with grease lubricants on Onyx+10% Carbon Fiber material

The change in the color of the oil before use which was bright brown in color (left) and after use which was more dark brown in color (right) in the reduction gear in the torsion test for 60 specimens or 117 rotations with a torque of 23.5 Nm is shown in Fig. 22.

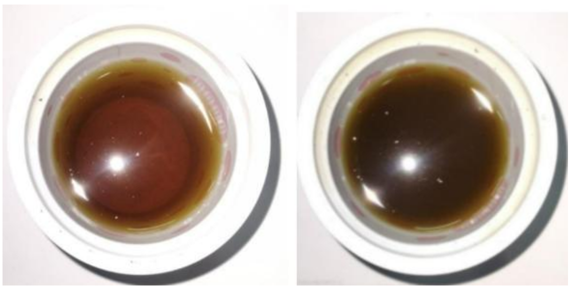

Fig. 22 Change in the color of the oil before use which is bright brown (left) and after use which is darker brown (right) in the reduction gear in the torsion test

3.0 CONCLUSIONS

The conclusion that can be drawn from research regarding the effect of carbon fiber composition and lubrication on tooth wear rate of 3D printed worm gears in torsion tests are:

1. The greatest wear rate occurs in Onyx materials with oil lubricating conditions of 130 μm followed by dry conditions of 94.3 μm and with the condition of lubricating grease worth 65 μm.
2. On the Onyx + 10 % Carbon Fiber material, the greatest wear was shown in conditions with 97 μm worth of oil lubrication, followed by 22 μm worth of dry conditions and 3 μm worth of grease lubricated conditions.

ACKNOWLEDGMENTS

The authors thank the State Polytechnic of Malang, Indonesia for research funding support from DIPA Number: SP DIPA-023.18.2.677606/2022 with Agreement Letter No. 10003/PL2.1/HK/2022.

References

1. Melnikov, P. & Schegoleva, S. (2019) Methods of increasing the efficiency of the worm gear, MATEC Web of Conferences, 298, 00001. https://doi.org/10.1051/matecconf/201929800001

2. Nwasuka, N. C. & Okoli, J. U. (2017) Design and performance evaluation of a low-cost torsion testing machine, International journal of scientific and technical research in engineering (IJSTRE), 2(2) 1-10. http://www.ijstre.com/Publish/222017/445350796.pdf

3. Mautner, E.-M., Sigmund, W., Stemplinger, J.-P. & Stahl, K. (2015) Efficiency of worm gearboxes, Proc IMechE Part C: J Mechanical Engineering Science, 0(0) 1-5. https://journals.sagepub.com/doi/10.1177/0954406215602286

4. Shi, J. R., Feng, Z. & Li, J. (2020) Key technology and experimental study of unequal pitches meshing between metal worm and plastic helical gears, Applied Sciences, 11(333), 1-17. https://doi.org/10.3390/app11010333

5. Chaudhary, K. & Govil, A. (2022) Application of 3D scanning for reverse manufacturing and inspection of mechanical components, Department of Mechanical Engineering, M.B.M. Engineering College, Jai Narain Vyas University, Jodhpur, India. https://doi.org/10.1007/978-3-030-73495-4_5

6. Yao, A. W. L. (2004) Applications of 3D scanning and reverse engineering techniques for quality control of quick response products, The Int. Journal of Advanced Manufacturing Technology, 26(11-12), 1284-1288. https://www.researchgate.net/publication/226456700_Applications_of_3D_scanning_and_reverse_engineering_techniques_for_quality_control_of_quick_response_products

7. Paulic, M., Irgolic, T., Balic, J., Cus, F., Cupar, A., Brajlih, T. & Drstvensek, I. (2014) Reverse Engineering of Parts with Optical Scanning and Additive Manufacturing, Procedia Engineering, 69, 795-803. https://doi.org/10.1016/j.proeng.2014.03.056

8. Radosavljević, S. Z., Stojanović, B. Ž. & Skulić, A. D. (2018) Determination of power losses in worm gear reducer, IOP Conference Series: Materials Science and Engineering, 393, 012050, 1-9. doi:10.1088/1757-899X/393/1/012050

9. Ismon, M., Zaman, I. & Ghazali, M. I. (2015) Condition monitoring of variable speed worm gearbox lubricated with different viscosity oils, Applied Mechanics and Materials, vol. 773-774, 178-182. doi:10.4028/www.scientific.net/AMM.773-774.178

10. Honkalas, R., Deshmukh, B. & Pawar, P. (2021) A review on design and efficiency improvement of worm and worm wheel of a gear motor, Journal of Physics: Conference Series 1969. doi:10.1088/1742-6596/1969/1/012023

11. Brajlih, T., Tasic, T., Drstvensek, I, Valentan, B., hadzistevic, M., Pogacar, V., Balic, J. & Acko, B. (2011) Possibilities of using three-dimensional optical scanning in complex geometrical inspection, Strojniški Vestnik-Journal of Mechanical Engineering, 57(11), 826-833. doi:10.5545/sv-jme.2010.152

12. Elasha, F., Mba, D., Cárcel. C. R., Kiat, G., Nze, I. & Yebra, G. (2014) Diagnostics of worm gears with vibration analysis, Cranfield Uni., Bedford, UK, MK43 0AL, 1-10. https://www.researchgate.net/publication/263651358

13. Zhang, Y., K. Mao, Leigh, S., Shah, A., Z. Chao & Ma, G. (2020) A parametric study of 3D printed polymer gears," The International Journal of Advanced Manufacturing Technology, 107, 4481-4492. https://doi.org/10.1007/s00170-020-05270-5

14. Kalavadiya, R. & Kalal, S. (2017) Optimization of infill patterns for spur gear in 3D printing using PLA, Conference Paper Gardi Vidyapith B. H. Gardi College of Engineering and Technology, 1-7. https://www.researchgate.net/publication/324475783

15. Zhang, Y., Purssell, C., Mao, K. & Leigh, S. (2019) A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears, Tribology International, 105953, 1-10. https://doi.org/10.1016/j.triboint.2019.105953

16. Singh, P. K., Siddhartha & Singh, A. K. (2017) An investigation on the thermal and wear behavior of polymer based spur gears, Tribology International, 118, 264-272. https://doi.org/10.1016/j.triboint.2017.10.007