7 (2): 190-195 (2023)

Journal of Aviation

https://dergipark.org.tr/en/pub/jav

e-ISSN 2587-1676

Investigation of Dry Sliding Wear Behavior of CFRP Composite Used in New Generation Aircraft Wings

M. Sabri Gök[1], Yılmaz Küçük[1], Murat Pehlivanlı[2] and Azmi Erdoğan[3*]

[1] Bartın University, Faculty of Engineering, Architecture and Design, Mechanical Engineering, Bartın, Türkiye. (msabrigok@bartin.edu.tr, ykucuk@bartin.edu.tr).
[2] Bartın University, Graduate School of Education, Department of Mechanical Engineering, Bartın, Türkiye (mpehlivanli@tai.com.tr).
[3*] Bartın University, Faculty of Engineering, Architecture and Design, Metallurgical and Materials Engineering, Bartın, Türkiye. (aerdogan@bartin.edu.tr).

Article Info

Received: 29 April 2023
Revised: 30 May 2023
Accepted: 06 June 2023
Published Online: 30 June 2023

Keywords:
CFRP
Dry-sliding wear
Laying angle
Composite

Corresponding Author: *Azmi Erdoğan*

RESEARCH ARTICLE

https://doi.org/10.30518/jav.1253901

Abstract

In this study, it is aimed to examine the effect of reinforcement laying angle on wear resistance of CFRP composites used in the automotive and aerospace industries. Experiments were carried out on Ball-On-Disc wear device under 1, 3 and 5 N loads at room temperature. 3D optical microscope was used to determine the volume losses in the samples. The worn surface morphology of the samples was examined with the help of SEM (Scanning Electron Microscopy). In the test results, the volume losses of the samples increased depending on the increasing loads and shear rate. It has been understood that the change of the laying angle is important in the dry-sliding resistance of the samples. The wear resistance of the samples produced with 45 degree laying was better at both sliding speeds and all loads. It has also been understood that the laying angle is also effective in the coefficient of friction. Delamination, plastic deformation type dominant wear mechanisms have occurred.

1. Introduction

Researchers are constantly working to make human life more comfortable and to extend the life of the materials used. Therefore, existing materials are constantly being improved and replaced with smart and innovative materials. Due to their low cost, ease of manufacture and lightness, polymeric composites replace traditional materials such as metals and ceramics. In this way, innovative materials are created by taking advantage of the synergistic effect in the content of the composite material (Hamamcı et al., 2018; Kursuncu et al., 2020). A polymer is a large molecule (macromolecules) made up of repeating structural units. These subunits are typically linked by covalent chemical bonds (Kulkarni et al., 2012). Polymers and their composites may exhibit some properties that cannot be obtained or are difficult to obtain in metal and ceramic materials (Boztoprak and Kartal, 2019; Erdogan et al., 2021). Polymers and polymer composites are widely used in various tribological applications such as rollers, gears and dry plain bearings due to their inherent advantages such as high specific strength, corrosion resistance and self-lubricating behavior. It is widely accepted that the tribological performance of polymeric materials can be improved by using various fillers or reinforcing fibers (Man et al., 2021). Polymer matrix composites can be used in oil-free dry sliding applications due to their low friction, high durability and good solvent resistance properties (Erdogan et al., 2021).

Generally, the mechanical properties of polymers are insufficient for many structural purposes. Since their hardness and strength are low compared to metals and ceramics, their usage areas are limited. These disadvantages can be eliminated by adding additives to polymers (Karthik et al., 2020; Polanec et al., 2021). It is possible to produce polymer matrix composites using different types of reinforcing materials. The nature of the reinforcement directly affects the final physical and mechanical properties of the composite. With reinforcements, properties such as hardness, strength and thermal expansion of the polymer matrix can be improved. In addition, thanks to the superior tribological properties of the polymer matrix such as high wear resistance, self-lubrication, vibration and corrosion resistance, the use of composite materials in wear parts is constantly expanding. In addition to these features, they are preferred due to their recyclability, ease of production and low cost (Erdoğan et al., 2019; Kursuncu et al., 2020).

Since polymer composite materials exhibit high specific strength and hardness compared to monolithic metal alloys, they have attracted wide attention in various engineering fields, especially in aerospace applications (Çakır and Berberoğlu, 2018; Kessler, 2012; Sari and Sinmazçelik, 2007). Typically, composites consist of a matrix and a reinforcing element. While the reinforcing element serves to carry the load, the matrix serves as a load transfer tool between the reinforcements (Ateş and Aztekin, 2011; Jesson and Watts, 2012; Koç and Demirel, 2019). The matrix is more ductile than the reinforcing elements and therefore the reinforcing agent is often used as a strength enhancer. When the matrix and the reinforcement are combined efficiently, the resulting material can show very high strengths. In addition to their structural properties, composites are used in electrical, thermal and environmental applications (Karthik et al., 2020). In addition, the equipment required for the production of polymer matrix composites is simpler. Therefore, polymer matrix composites developed gradually and soon became popular for structural applications (Karthik et al., 2020).

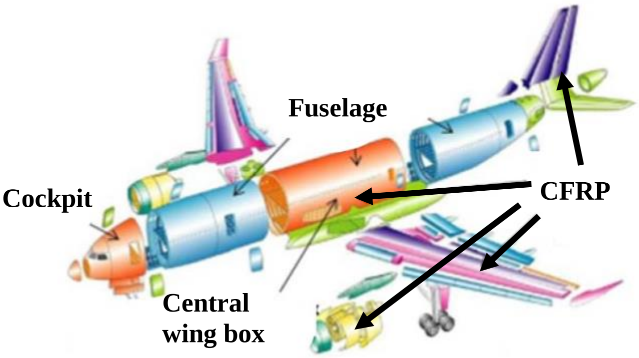

Figure 1. CFRP and other composite parts used in an aircraft (Mohamed, 2013).

Polymer matrix composites are the most widely used composite type on the market, and the two main application sectors (by value) are the automotive industry (over 30%) and the aerospace industry (over 20%) (Thomas et al., 2014). An example of a CFRP composite used in any aircraft is given in Figure 1. Apart from this, it is possible to see CFRP composite in many parts used in assembly (Mohamed, 2013). Carbon fiber reinforced polymers (CFRP) are characterized by exceptional specific strength and stiffness properties that make them particularly suitable for lightweight structures in the aerospace industry (Kumar et al., 2021; Kuo et al., 2018; Seeholzer et al., 2021). In this study, the dry-sliding wear behavior of CFRP composite material produced at different laying angles was investigated. It has been tried to understand how the laying angle has an effect on the wear behavior of the sample.

2. Materials and Methods

Composite materials were produced in the form of plates by hand-laying method. The production process was carried out using two different laying angles, “45” degrees and “0” degrees. CFRP composite specimens were produced with a width of 25 mm and a thickness of 5 mm. Reciprocating type dry-sliding wear tests were performed at room temperature using a 6 mm diameter Al_2O_3 ball using a Ball-on-disc tribometer device (TURKYUS POD). The hardness of Al_2O_3 balls used in the experiments is 15 GPa. Wear tests were carried out under loads of 1, 3 and 5 N. Another variable used in the tests is the sliding speed and it was applied as 0.02 m/sec and 0.04 m/sec for a total of 15 minutes. Total sliding distance is 18-36 m and wear stroke length is 5.5 mm. In order to increase the accuracy and validity of the results obtained from the experiments, each experiment was performed 3 times and average values were taken. After the wear tests, the volume losses of the samples were determined by taking a 3D profilometer image from the formed wear trace section. Cross-sectional images were taken from at least 4 parts of the groove formed by the abrasive ball on the sample, and their average value was used in the volume loss calculation. The images of the worn surfaces of the samples were taken on the TESCAN MAIA3 XMU brand SEM device.

3. Result and Discussion

Composites produced as polymeric materials and polymer matrix are used successfully in many applications. As in metallic materials, important parameters emerge in wear resistance depending on the material, counter surface, environment and operating conditions in polymer-based materials. In Figure 2, the volume loss values occurring in the sample produced with "0" degree laying angle, which was subjected to wear test at different sliding speeds and under three different loads, are given. There is an increase in the volume losses of the samples depending on both the load and the sliding speed. However, it is seen that this increase is not directly proportional in terms of applied wear load. It is possible to explain the increase in volume loss in the sample due to the increasing load simply by using the term hardness. Hardness can be defined as the resistance of a material against another material trying to sink from its surface.

If the force applied on a sample with the same hardness is increased, the rate of penetration of the object to the opposite surface will increase. Therefore, it will penetrate the opposite surface more. This sinking rate will create a compressive force on the sample and a deformation will occur depending on the yield strength of the material. The deformation will increase with the increase of the applied load. In this case, more material will be accumulated in front of the penetrating tip due to its relative motion. In other words, the amount of material that resists the cutting force of the ball will be more. Due to the ongoing relative movement, material transfer will start from the surface and there will be a change in the profile of the wear trace on the sample surface. As a result, if the shear force is sufficient, the increase in the load will be effective in increasing the volume loss of the material.

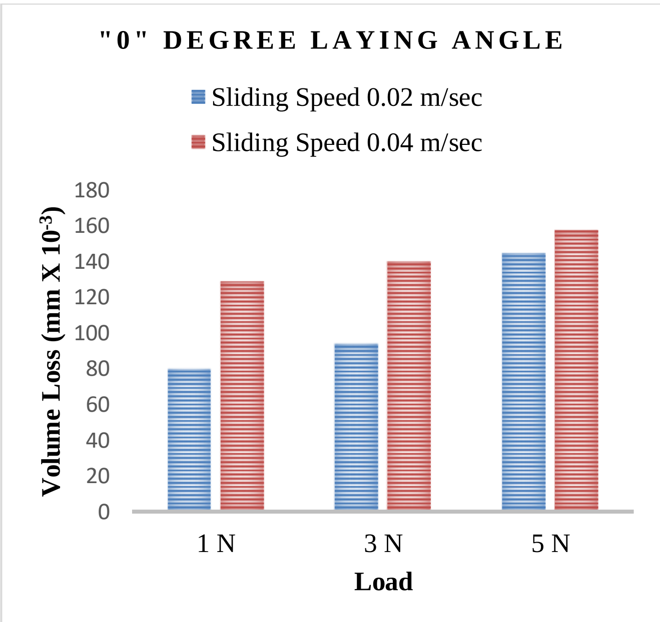

Figure 2. Volume losses in composites produced with “0” degree laying angle depending on shear rate and load.

As can be seen from the wear loss (Figure 1) graph, another parameter that affects the volume losses in the samples is the shear rate. It is seen that the volume losses increase with the increase of the sliding speed. It should not be forgotten that the increase in the applied sliding speed will increase the wear losses. Apart from this, two different possibilities can be presented for the variation in wear losses that can be caused by the sliding speed. The first of these is the sudden increase in heat that occurs during friction. The thermal increase that occurs during the mutual friction of two objects may have different effects depending on the material properties. For example, in a metallic material, the oxidation that occurs due to the increase in temperature can reduce friction and even material loss. However, the effect on a polymeric matrix will be different. In polymeric materials, the temperature increase due to friction causes the matrix to soften. For this reason, the matrix deforms more easily. This, in turn, increases material loss, resulting in a decrease in wear resistance. Another effect of the increase in the sliding speed is the increase in the impact effect. As the sliding speed increases, the abrasive ball moving on the material will create a more dynamic effect on the part accumulated behind it. This will create a higher impact effect with high sliding speed and will increase the wear losses.

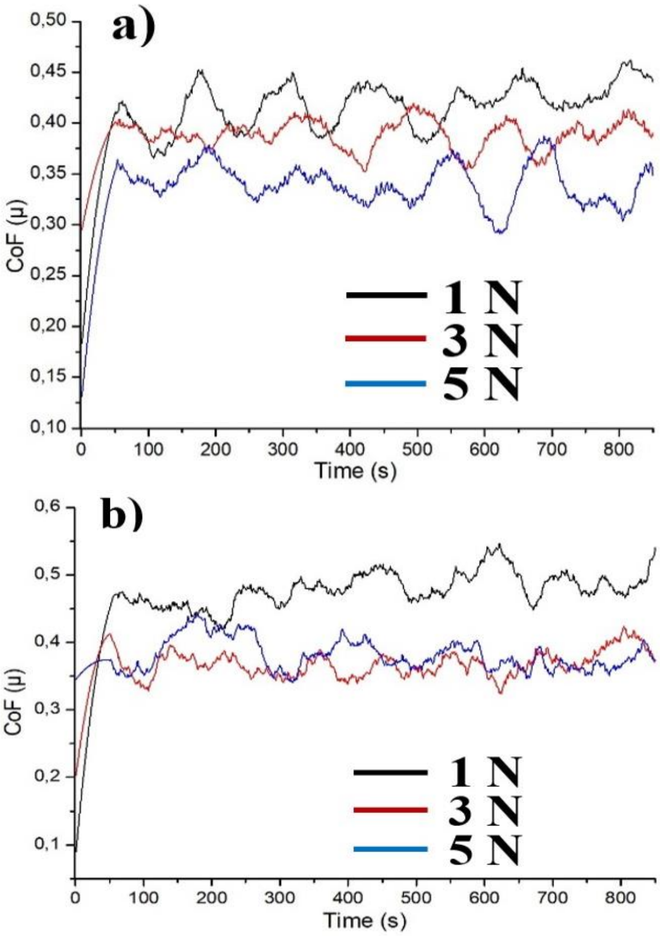

Figure 3. Depending on the sliding speed and load, the COF values occurring in composites produced with a "0" degree laying angle are a) 0.02 m/sec, b) 0.04 m/sec.

The coefficient of friction (COF) values of the samples obtained at different sliding speeds are given in Figure 3a-b. Although the COF values of the samples were close to each other, the increasing shear rate had an effect on the COF value. This effect is the change in peaks and valleys after steady-state wear, rather than an increase in the COF value. While the peaks that occurred as a result of the increase and decrease of COF at low shear rate showed a triangular formation (Figure 3a), these peaks were blunted with increasing shear speed (Figure 3b). This situation can be seen much more clearly, especially at increasing loads. It is possible to say that the flash heating caused by the increasing load and sliding speed on the material surface causes this situation. The high COF value, which is seen at the beginning and called run-in, is attributed to the cleaning of the surface roughness. With the start of the wear process, the abrasive tip makes contact with the opposite surface only above the roughness. At this point, a high contact pressure occurs because the contact area is very small. Due to the high contact pressure, the friction coefficient increases rapidly. As the roughness peaks flatten over time and wear marks begin to form, the contact area between the abrasive ball and the sample expands and the friction coefficient reaches average values.

SEM wear trace photographs of the samples produced with a “0” degree laying angle and subjected to the wear test at a sliding speed of 0.02 m/sec under three different loads are given in Figures 4a-c. Although the increased shear rate was effective in the wear losses of the samples, there was no critical change in the wear mechanisms. As a result of the wear process carried out under low load (1 N) (Figure 4a), micro-fatigues on the sample surface and adhesion related ruptures occurring perpendicular and angular to the wear path caused by these fatigues are observed. As a result, there was material separation from the surface by the union of these tears. It is seen that the effect of micro-fatigue increases with the increase of the load of 3 N, thus the micro-cracks become more prominent, and then the cracks that come to the macro-size form wider. It is understood that with the increase of the load 5 N, besides the abrasion damage mentioned above, the carbon fibers begin to appear with the severity of the abrasion. It is noteworthy that the polymer, which acts as a matrix between the abrasive ball and carbon fibers, creates slight elongations in the form of extrusion.

In Figure 5, the volume loss values of the samples, which were subjected to abrasion test under different sliding speeds and loads after being produced with a "45" degree laying angle, are given. Although similar volume losses are observed with “0” degree laying angle in the experiments carried out under 1 N load at a sliding speed of 0.02 m/sec, it is seen that the volume loss is relatively reduced at 3 N load. It can be seen from the graph that this situation becomes more evident under a load of 5 N. Similar volume losses under 1 N load are due to the fact that the abrasive works on the polymer matrix rather than the carbon fiber reinforcements at this load. Therefore, neither the effect of carbon fiber carbons nor their laying angles could be observed in this region. However, the change in volume losses between the two layings is striking with the increase of the load of 3 N. While a ratio difference of approximately 2% occurred between two pavings at 1 N load due to volume loss, this ratio increased to 8-9% at 3 N load and up to 12% at 5 N load. The increase in the reinforcing ratio of the carbon fibers on the bottom surface with the polymer matrix at 3 N load, and the operation of a mechanism that prevents the polymer matrix from flowing with the reinforcement under 5 N load, played a role in the decrease in volume losses. Although a noticeable volume loss is observed at 1 and 3 N loads with the increase in sliding speed, it is understood that this value is similar to the value obtained at 0.02 m/sec sliding speed at 5 N load.

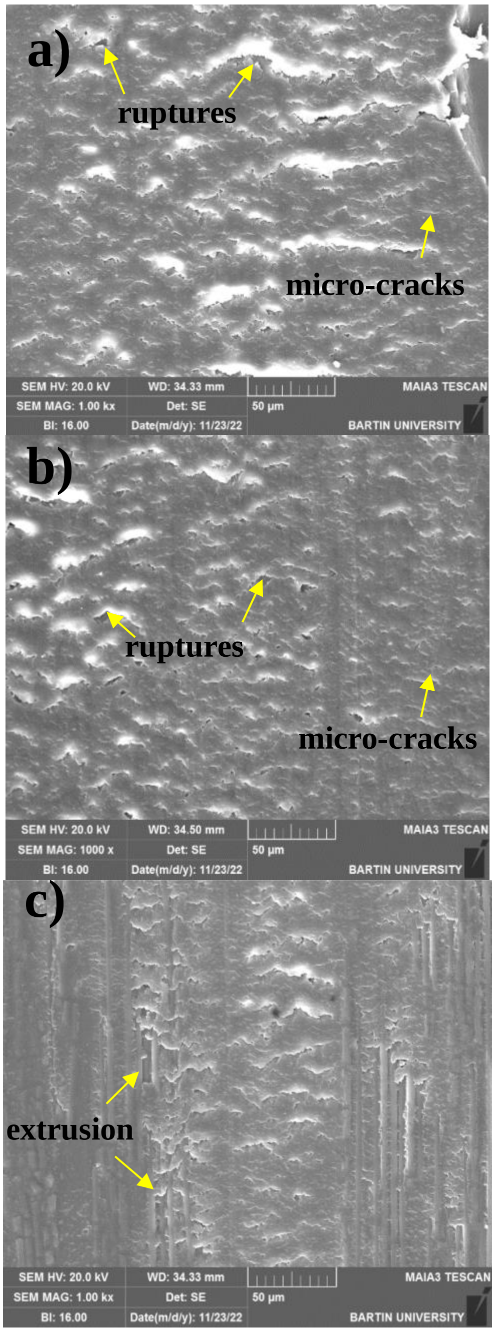

Figure 4. SEM images of worn surfaces due to load in composites produced with a "0" laying angle at a shear rate of 0.02 m/sec: a)1 N, b) 3 N, c) 5 N.

The COF values obtained at different shear rates of the samples produced with a "45" degree laying angle are given in Figure 6 a-b. A striking situation in both graphs is the decrease in COF values with increasing load. It is understood that the samples exit the run-in mechanism and show a stable COF value after approximately 100 s of sliding time at low shear speed. As the reason why the COF value decreases with the increase in the load is interpreted in the previous graphs, it will not be mentioned again here. However, it can be seen that peak and valley formations are much more severe, especially at loads of 3 and 5 N, with an increase in shear speed. Here, the heat caused by friction may play a role in the decrease of the COF value, as well as an increase in the COF value due to adhesions that occur due to sudden cooling or adhesions.

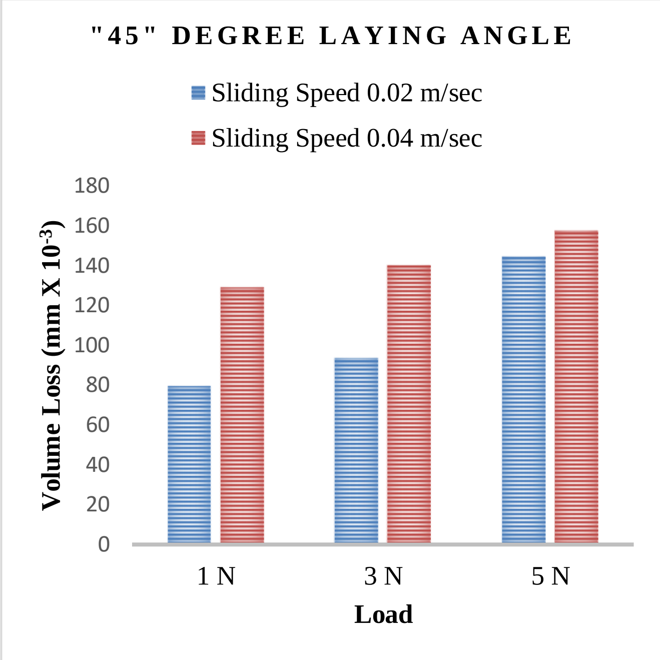

Figure 5. Volume losses in composites produced with "45" degree laying angle depending on shear rate and load.

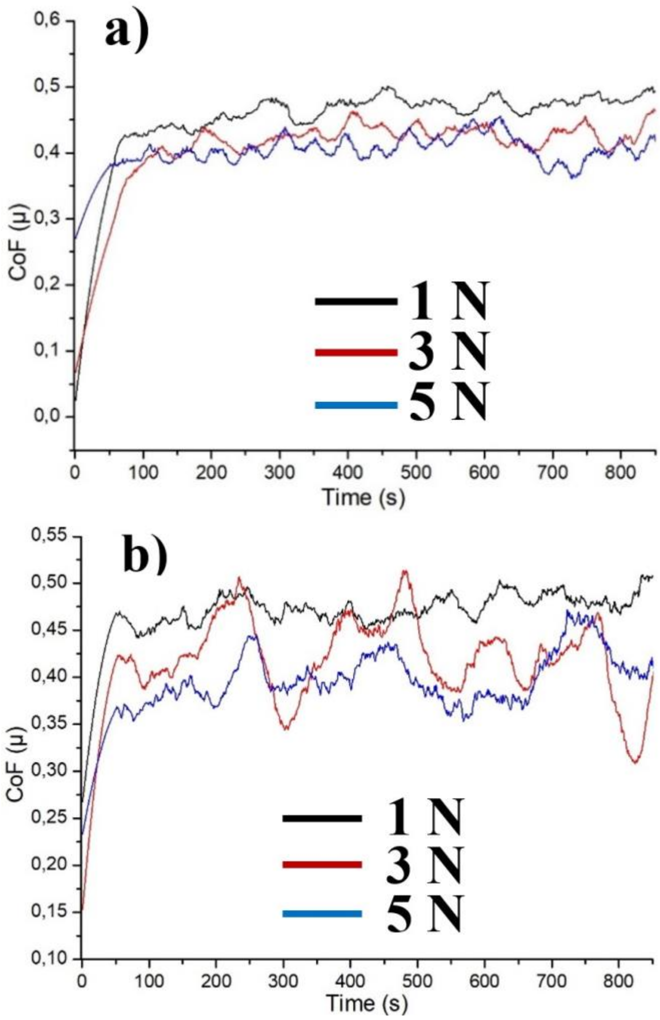

Figure 6. Depending on the sliding speed and load, the COF values occurring in composites produced with a "45" degree laying angle are a) 0.02 m/sec, b) 0.04 m/sec.

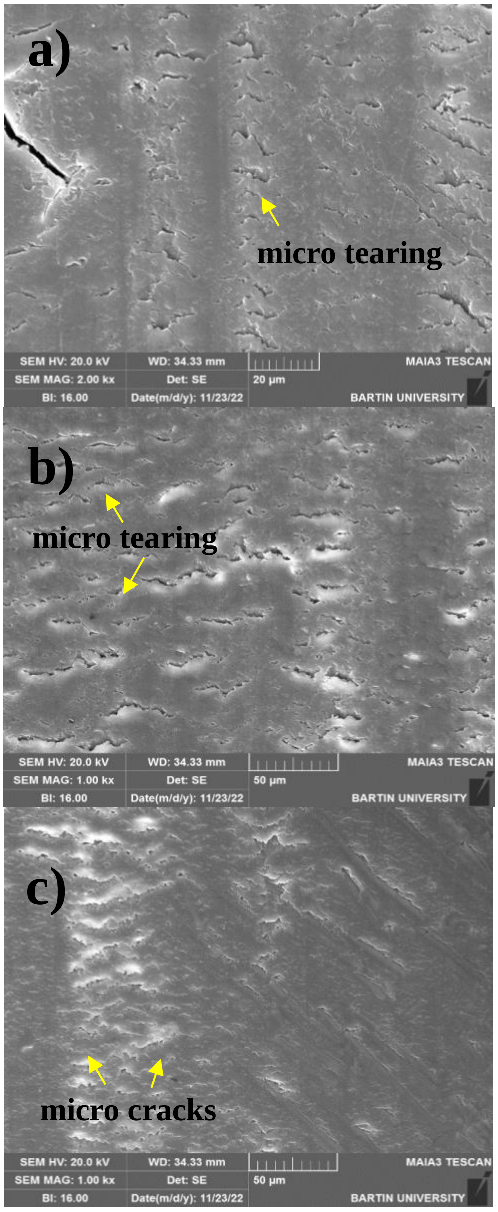

Figure 7. SEM images of the worn surfaces due to the load in composites produced with a “45” degree laying angle at a shear rate of 0.02 m/sec: a)1 N, b) 3 N, c) 5 N.

The SEM wear trace photographs of the samples produced with a "45" laying angle and subjected to the wear test at a sliding speed of 0.02 m/sec under three different loads are given in Figure 7a-c. It is seen that micro and macro cracks are formed in the direction perpendicular to the wear trace of the matrix surface, which is under the compressive and tensile stresses, as in the sample produced with a "0" degree laying angle. However, it is seen that the width of the traces perpendicular to the wear direction is less and the damage to the surface is lower when compared to the sample whose cracks were produced with zero degree laying and subjected to the wear test. When the SEM (Figure 7b) wear trace photograph of the sample, which was subjected to the test at a sliding speed of 0.02 m/s under 3 N load, is examined, it is seen that the damage caused on the surface by the forces resulting from friction has increased. Because it can be clearly seen that the width of the cracks that occur and perpendicular to the wear mark increase and the gap between them increases. The SEM wear trace photograph of the sample, which was produced with a "45" degree laying angle and subjected to wear treatment at a 5 N load, 0.02 m/sec sliding speed, is given in Figure 7c. Especially on the left side of the SEM image, the silhouette of the carbon fibers embedded under the polymer matrix can be seen with a 45 degree lay angle. However, when the degree of damage is compared to the damage of the samples produced with zero degree paving, it is seen that 45 degree paving is more resistant in all three loads.

4. Conclusion

In this study, the effect of laying angle on the wear resistance of CFRP (Carbon fiber reinforced plastic) composites produced with different laying angles was investigated. In addition, these parameters were also tested as variables to determine the possible effects of load and sliding speed. In the tests performed with the ball-on-disc method, it was observed that the laying angle, the applied load and the sliding speed had different effects on the wear resistance of the composites.

- The increase in load facilitated material loss due to increased compressive forces and reduced wear resistance. The increase in shear rate also caused an increase in volume losses.
- It was determined that the wear resistance of the composites produced with the "45" degree laying angle was higher. The effect of the laying angle became more evident with the increase in the load.
- It has also been understood that the laying angle is also effective in the coefficient of friction.
- Micro and macro cracks and extrusion type wear mechanisms were observed on the SEM wear surfaces of the samples.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Cite this article: Gok, M.S, Kucuk, Y., Pehlivanlı, M., Erdogan, A. (2023). Investigation of Dry Sliding Wear Behavior of CFRP Composite Used in New Generation Aircraft Wings. Journal of Aviation, 7(2), 190-195.