lubricants

Article

Investigation of Wear Behavior in Self-Lubricating ABS Polymer Composites Reinforced with Glass Fiber/ABS and Glass Fiber/Carbon Fiber/ABS Hybrid

Aravind Dhandapani [1,2], Senthilkumar Krishnasamy [3,*], Rajini Nagarajan [1,*], Anto Dilip Albert Selvaraj [3], Senthil Muthu Kumar Thiagamani [1], Chandrasekar Muthukumar [4], Faruq Mohammad [5], Hamad A. Al-Lohedan [5] and Sikiru Oluwarotimi Ismail [6]

[1] Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil 626126, India
[2] University Science Instrumentation Centre, Madurai Kamaraj University, Palkalai Nagar, Madurai 625021, India
[3] Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641062, India
[4] School of Aeronautical Sciences, Hindustan Institute of Technology & Science, Padur, Kelambakkam, Chennai 603103, India
[5] Department of Chemistry, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
[6] Department of Engineering, School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield AL10 9AB, UK
* Correspondence: kmsenthilkumar@gmail.com (S.K.); rajiniklu@gmail.com (R.N.)

Abstract: A new hybrid fabrication technique was introduced to manufacture composite laminates made of glass fiber, carbon fiber, and acrylonitrile butadiene styrene (ABS) as the matrix. The fabrication process utilized two different techniques: fused deposition modeling and hot press molding. The composite laminates were produced using five layers of glass fibers to form glass fiber-reinforced composites (GF/ABS) and five layers of glass fiber and carbon fiber to form glass fiber, carbon fiber-reinforced hybrid composites (GF/CF/ABS), with three layers of glass fibers and two layers of carbon fibers. The fabricated composite laminates were subjected to wear testing at velocities of 2 m/s, 3 m/s, and 4 m/s and under loads of 5 N and 10 N. The results indicated that GF/ABS samples had the lowest wear loss at 5 N and a velocity of 4 m/s. Additionally, the GF/CF/ABS hybrid samples had the lowest coefficient of friction (COF) of 0.28 at 4 m/s. The GF/ABS samples also exhibited the lowest friction force of 1.7 at 5 N and a velocity of 4 m/s. The worn samples were analyzed using a scanning electron microscope to examine the fiber-to-matrix adhesion behavior. GF/ABS and GF/CF/ABS composites are widely used in various applications due to their high strength-to-weight ratio and resistance to wear. These materials could be used in automotive parts, sporting goods, and marine applications.

Keywords: acrylonitrile butadiene styrene; glass fiber; carbon fiber; hybrid manufacturing; fused deposition modeling; hot press molding; wear

check for updates

Citation: Dhandapani, A.; Krishnasamy, S.; Nagarajan, R.; Selvaraj, A.D.A.; Thiagamani, S.M.K.; Muthukumar, C.; Mohammad, F.; Al-Lohedan, H.A.; Ismail, S.O. Investigation of Wear Behavior in Self-Lubricating ABS Polymer Composites Reinforced with Glass Fiber/ABS and Glass Fiber/Carbon Fiber/ABS Hybrid. *Lubricants* **2023**, *11*, 131. https://doi.org/10.3390/lubricants11030131

Received: 21 February 2023
Revised: 5 March 2023
Accepted: 8 March 2023
Published: 13 March 2023

1. Introduction

Fiber-reinforced thermoplastic composite laminates are extensively used in various industries, such as aerospace, automotive, wind energy, materials handling, and civil construction. The advantages of these laminates are their low weight and high relative strength, which make them attractive for applications that require high strength-to-weight ratios. Additionally, these composites offer resistance to wear, corrosion, abrasive chemicals, and weather; low friction; and sustainability. Therefore, they have potential for a broad range of applications from domestic to commercial use. In space applications, perfluoropolyether

(PFPE) lubricants have been recognized for their reliable stability under challenging conditions, as reported by Gleirscher et al. [1]. Keshavamurthy et al. investigated the fabrication of composites using acrylonitrile butadiene styrene (ABS) and graphite powder, which showed a decrease in wear loss [2].

In order to satisfy the burgeoning demand for lightweight reinforced composite materials as a substitute for traditional materials, it is necessary to combine different manufacturing techniques to achieve both quality and efficiency. One potential solution is to utilize a hybrid manufacturing process, which merges multiple fabrication techniques into a single process, thereby reaping the advantages of each while minimizing their respective drawbacks. Nevertheless, selecting a suitable manufacturing technique can prove to be a daunting task, as it greatly influences the properties of the composite material [3–5].

Amongst the fabrication techniques, additive manufacturing technology is a highly flexible technique for producing complex shapes with minimal material loss. The technique utilizes computer-aided design data as input and allows for a high degree of geometric freedom. As the name suggests, additive manufacturing involves adding material in successive layers to create three-dimensional shapes [6]. Notable additive manufacturing techniques include stereolithography, selective laser sintering, and FDM, with FDM being the most widely used [7–9]. Similarly, hot press molding is a method used to fabricate composite samples by applying heat and pressure to a preform, which can be made of fibers and resin. This process results in a dense, uniform, and high-quality composite material that is suitable for various applications, such as aerospace, automotive, and construction [10]. Therefore, in this current study, the FDM and hot press techniques were combined to fabricate composite laminates, which were subsequently analyzed.

Tribological studies are crucial for composite samples, as they examine the behavior of materials under friction, wear, and lubrication conditions. They help to understand the wear resistance properties of composite samples, which is important for applications where high wear resistance is needed, such as gears, bearings, and other mechanical components. Tribological studies also allow one to identify the wear mechanisms and predict the life of the composite material. This information is vital in the design and development of new composite materials for wear-sensitive applications [11,12]. Moreover, glass and carbon fiber composites are commonly used for wear applications due to their high strength and durability [13]. When combined with an ABS matrix, these composites can provide additional advantages such as increased impact resistance and improved thermal stability. Additionally, the use of glass or carbon fibers can improve the wear resistance properties of the composite material, making it well suited for applications such as industrial gears, bearings, and sporting equipment.

Synthetic fibers and polymers have recently gained popularity, as they are replacing conventional materials due to their physical properties, ease of fabrication and design, resistance to corrosion, and the superior strength-to-weight ratio [14–17]. The annual global production of synthetic fibers is around 68 million tons, or approximately 62% of the annual production of all fibers [18]. Glass and carbon fibers are in high demand, as they are versatile and widely used industrially. Glass fiber-reinforced composites (GFRPs) are widely utilized for their strength-enhancing properties in various fields, including aerospace, automotive, energy, marine, electronics, and defense industries. In the construction industry, they are proposed as an alternative to brittle materials due to their ability to address brittleness concerns. Hausberger et al. investigated the fabrication of composites using metal sulphides and polymer-based solid lubricants incorporated with glass fiber polyetheretherketone and glass fiber-filled polyphthalamide. The results showed a reduced wear rate, indicating the potential of these composites for tribological applications [19]. Glass fibers are relatively inexpensive and possess properties such as hardness, chemical resistance, transparency, stability, inertness, high strength-to-weight ratio, flexibility, and stiffness [20,21]. Carbon fiber-reinforced polymer (CFRP) composite materials are known for their high strength-to-weight ratios, making them ideal for use in a variety of applications, including space and aerospace industries, sail boats, modern bicycles and bikes, tool spindles, powertransmission shafts, and robot arms. To address the need for solid lubricants in unique and extreme environmental conditions or loads, Suarez et al. suggested the use of carbon nanomaterials for engineering applications that restrict the use of liquid lubricants [22]. Ujah et al. demonstrated improved wear resistance, reduced wear volume, and decreased coefficient of friction (COF) through the incorporation of carbon nanotubes in metal matrix composites, polymer matrix composites, and ceramic matrix composites [23]. Additionally, carbon nanotubes have been proposed as one of the best reinforcing materials for advanced structural, industrial, high strength, and wear-prone applications. On the other hand, carbon fibers are costlier but possess properties such as superior tensile strength, chemical resistance, resistance to high temperatures with a low coefficient of thermal expansion, and good stiffness. The mechanical strength of composites made from carbon fibers per unit weight is greater than steel and aluminum, reducing energy consumption during operation [24]. Thus, in this study, composite samples were produced using carbon fiber, glass fiber, and an ABS matrix and were subjected to wear analysis.

Minchenkov et al. identified pultrusion as a relatively under-researched technique for producing thermoplastic composites. However, this method was found to be effective for creating polymer composites with a constant cross-section, making it a popular choice for various applications in bridge construction, transportation, energy, civil and architectural engineering, and welded joints. Additionally, pultruded thermoplastic polymers offered advantages over thermosets, such as improved impact strength and the potential for recycling and long-term storage. These benefits made pultruded thermoplastics a promising alternative for various industries [25]. Vedernikov et al. fabricated an in-house pre-consolidated GF/polypropylene thermoplastic flat laminate using pultrusion and compared its performance with commercially available pre-consolidated tapes. The in-house flat laminate demonstrated superior flexural, tensile, and apparent interlaminar shear strength by 106%, 6.4%, and 27.6%, respectively, when compared to the commercially available pre-consolidated tapes. This improvement in mechanical performance was attributed to the restricted formation of matrix cracks within the center portion of the fiber bundles [26].

Rattan et al. fabricated reinforced fiber composites using hot compression at 385–390 °C. Three different weaves of carbon fabric, namely, plain, twill, and satin, were used as reinforcement and thermoplastic polyetherimide as the matrix. A constant fabric content of 55% was maintained. The friction and wear performance were analyzed using a pin-on-disc against a mild steel disc. The conditions were set to a dry adhesive wear mode, various loads between 100 and 500 N, and at room temperature and at a high temperature of 90 °C. The friction performance (μ) and the wear resistance of the composites followed the order of Twill > Plain > Satin at both room temperature and high temperature [27]. In another study, Jayashree et al. fabricated composites in the following combinations: (i) thermoplastic polyethersulphone (PTFE) as matrix and short glass fibers containing solid lubricants such as polytetrafluoroethylene and molybdenum disulfide (MoS_2) as reinforcement, and (ii) thermoplastic PTFE as matrix and short carbon fibers (30% and 40%) as reinforcement. These composites were subjected to adhesive wear study by sliding against a mild steel disc using a two-pin-on-disc set-up and abrasive wear performance using silicon carbide abrasive. The sliding wear investigation reported that the wear performance increased by an order of two for glass fiber-reinforced thermoplastic PTFE composites when compared to PTFE samples. Furthermore, in the combinations involving glass fibers, PTFE performed better than the MoS_2 combination, but carbon fiber thermoplastic PTFE composites performed better than the rest, with 40% carbon fiber incorporation producing a specific wear rate in the order of 10^{-16} m^3/Nm, which was the best. However, it was observed that there was a decrease in wear performance due to the incorporation of fibers or solid lubricants from abrasive wear results [28].

Mohit et al. fabricated composites with continuous carbon fibers as reinforcement and thermoplastic polyetherimide as the matrix. They maintained a constant fiber content of 80% and fabricated the composites under different fiber orientation angles of 0°, 30°, 45°, 60°, and 90° using the hand lay-up technique. The friction and wear performance were analyzed using a universal wear tester, with an abrasive wear mode in a single-pass condition, linear and unidirectional forward motion against SiC 800 grade abrasive paper. The conditions set were (i) sample fixed on a movable bed at a constant speed (2 m/min), and (ii) various loads of 10, 20, 30, and 40 N. The tribological evaluation, in terms of coefficient of friction (μ) and specific wear rate, indicated that a decrease with increasing load and a low specific wear rate of 0.71×10^{-9} m^3/Nm was obtained for composites with a 0° fiber orientation angle, which was three times lower than the specific wear rate obtained for composites with a 90° fiber orientation angle. The researchers also concluded that an overall fiber reinforcement with 0° fiber orientation enhanced tribological performance [29].

In a study conducted by Sudin et al., composites of carbon fiber/ABS were fabricated using the FDM technique and were subjected to wear testing under dry sliding conditions using the pin-on-disk method. The testing conditions included (i) room temperature (23 ± 5 °C), (ii) sliding speed of 286 rpm (0.63 m/s), (iii) loads of 5, 10, 15, and 20 N, (iv) running times of 3 and 5 min, and (v) relative humidity of 50 ± 10%. The results indicated improved wear performance for the ABS/CF-reinforced composites, with wear ranging from 100 to 1200 μm, frictional force ranging from 0.25 to 2.25 N, frictional coefficient ranging from 0.04 to 0.14, and temperature change ranging from 22 to 26 °C, compared to the pure ABS samples, which had wear ranging from 500 to 2000 μm, frictional force ranging from 0.25 to 3 N, frictional coefficient ranging from 0.06 to 0.13, and temperature change ranging from 22 to 38 °C. Additionally, the study revealed that the load applied and the duration of the load had an influence on the wear rate, friction force, and coefficient of friction [30]. Amrishraj et al. fabricated reinforced ABS composites with nano zirconia and PTFE using a melt compounding process with the aid of a twin screw extruder. The wear analysis was carried out using a pin-on-disc tribometer in accordance with ASTM G99 standards. The testing conditions included (i) a sliding distance of 500 m; (ii) loads of 10, 30, and 50 N; and (iii) sliding velocities of 0.5, 1.25, and 2 m/s. The results showed a linear decrease in the coefficient of friction (μ) up to a load of 30 N followed by a sudden decrease at a load of 50 N. The inclusion of both PTFE and zirconia resulted in a decrease in μ, but for ABS composites, μ decreased with an increase in PTFE content beyond 1.25% and decreased drastically with 3% zirconia. These results reported enhanced wear performance, and the optimized parameters were recorded as (i) 2.5% of PTFE, (ii) 3% of zirconia, (iii) a load of 50 N, and (iv) a sliding velocity of 2 m/s [31].

The focus of our research was the fabrication of fiber-reinforced composites using a hybrid manufacturing method that combines 3D fabrication techniques, specifically fused deposition modeling (FDM), and hot compression molding. This approach represented a unique combination, and to the best of our knowledge, there have been no previously reported studies utilizing this specific combination of techniques. Using FDM for 3D fabrication, followed by hot compression molding, allowed for the production of high-quality composite materials with improved strength and durability. Moreover, the fabricated composite samples were subjected to wear testing by varying the fiber layering sequences, such as carbon fiber/ABS, glass fiber/ABS, and glass fiber/carbon fiber/ABS. Morphological images were examined to comprehend the fiber–matrix adhesion characteristics.

2. Materials and Methods

2.1. Materials

A bi-directionally woven E-glass fiber mat (GF) and carbon fiber mat (CF) were obtained from Rakshana Agencies and M/s Vruksha Composites in India, respectively. ABS was procured from M/s Filament Wol3D in India. Figure 1a–c show the images of the ABS filament, GF mat, and CF mat used. The key details of the reinforcement and ABS are given in Tables 1 and 2.

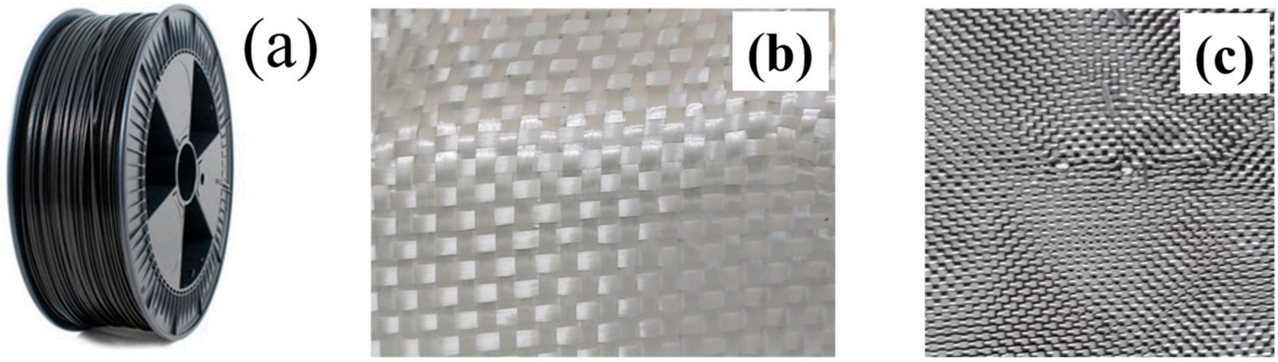

Figure 1. (**a**) ABS filament, (**b**) GF mat, and (**c**) CF mat.

Table 1. Key details of reinforcements.

Parameters	Glass Fiber	Carbon Fiber
Tensile strength (MPa)	3100–3800	4100
Young's modulus (GPa)	80–81	240
Elongation at break %	4.8	1.8
Density (g/cm^3)	2.62	1.77
Grams per square meter (GSM)	300	200

Table 2. Key details of ABS.

Parameters	ABS
Tensile strength	≥43 MPa
Flexural strength	≥70 MPa
Flexural modulus	≥2300 MPa
Impact strength (IZOD, 23 °C)	≥108 J/m (ASTM 256)
Elongation at break	≥30%

2.2. Composite Fabrication Using Hybrid Manufacturing Technique

The fabrication of CF/ABS, GF/ABS, and their hybrid combinations was carried out using two distinct processing methods: fused deposition modeling (FDM), and hot pressing. Figure 2a–e depict the sequential stages involved in the fabrication of the composite material.

FDM technique: ABS coating was applied to the GF and CF layers using a 3D printer (JB Technology, Coimbatore, India; model number: XL300) at JB Technology, 3D Printing Services, Coimbatore, India. For example, in the fabrication of GF/ABS composites, a total of five GF layers was utilized, with the ABS layer maintained at a thickness of 0.3 mm. Similarly, CF/ABS composite laminates were fabricated. The number of layers and filament thickness and fiber layering sequence for GF/ABS, CF/ABS, and GF/CF/ABS are presented in Tables 3 and 4. When applying the ABS coating over glass or carbon fiber layers using the FDM technique, it was important to maintain a printing speed of 35 mm/s and a nozzle temperature of 90 °C in order to ensure proper adhesion between the ABS coating and the fiber layers. The slower printing speed allowed for better control over the extrusion of the ABS, which could help to prevent over-extrusion and ensure a consistent layer thickness. A nozzle temperature of 235 °C was also maintained to ensure that the ABS was heated to the appropriate temperature for proper melting and extrusion, which could help to ensure good adhesion between the ABS and the fiber layers. These ABS-coated samples were subsequently subjected to a hot press technique.

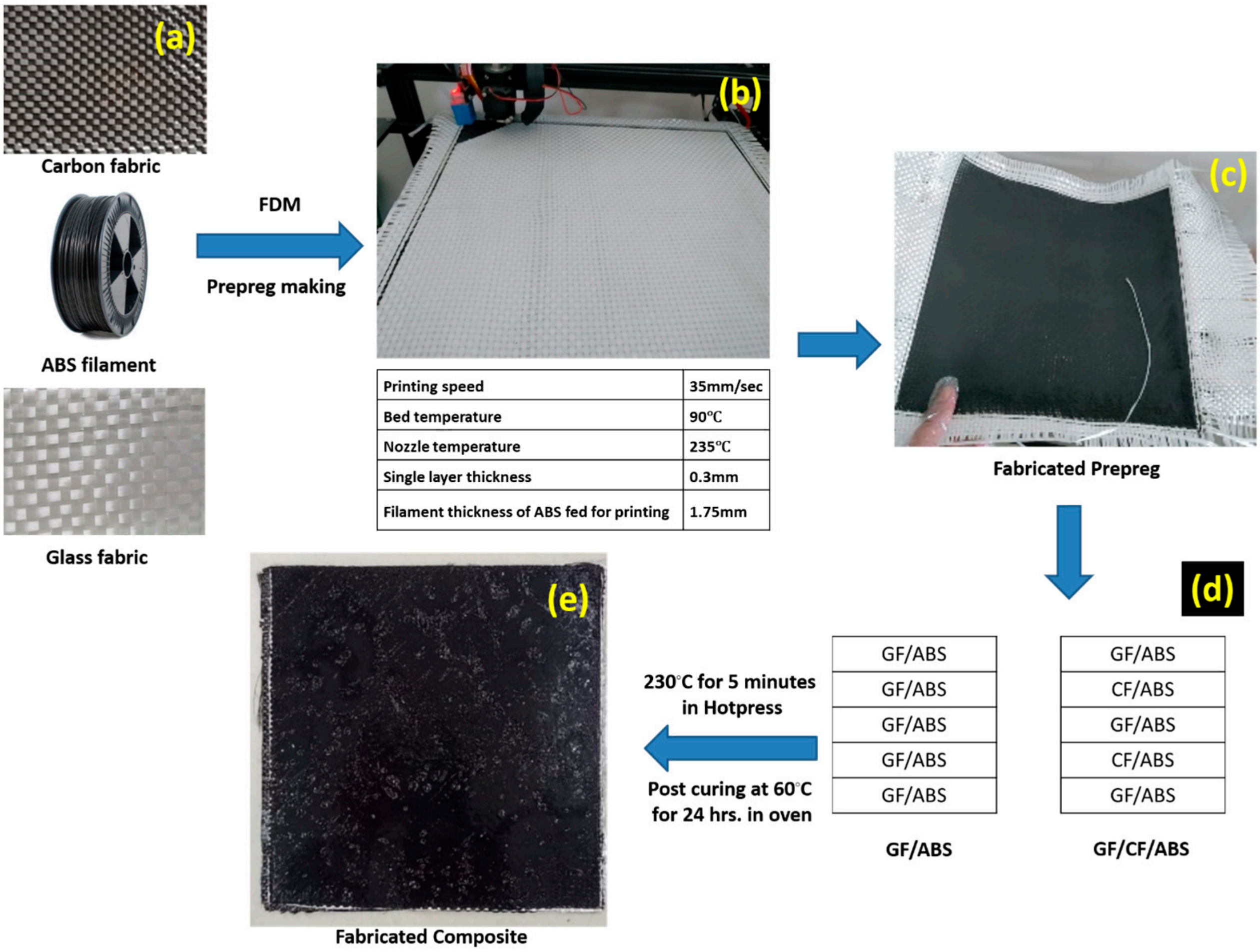

Figure 2. Two-step procedure of fabrication technique: (**a**) raw materials; (**b**) 3D printing of GF/ABS and CF/ABS prepreg; (**c**) fabricated prepreg; (**d**) composite stacking sequence; and (**e**) laminate after curing.

Table 3. Fabrication details of GF/ABS matrix composites.

Layer Details	Matrix and Fiber Details	Composite Configuration
1st layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	GF/ABS
2nd layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	
3rd layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	
4th layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	
5th layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)/3D printed ABS (0.3 mm)	

Hot press technique: The ABS-coated fiber layers such as GF, CF, and GF/CF were loaded separately into a hydraulic press machine (hydraulic compression molding press—30 tons, Modern Hydraulics, Maharashtra, India). After positioning the fiber layers in the press, the pressure and temperature were set to 1000 psi and 230 °C, respectively, for a period of five minutes to obtain a composite laminate of 200 mm × 200 mm. During this process, the ABS coating liquified and penetrated through each layer before curing. The composite laminate samples were removed from the press and underwent post-curing at 60 °C for 24 h. During post-curing, the heat can cause the ABS matrix to further crosslink and form stronger bonds between the GF, CF, and matrix. This process can result in improved strength and helps to remove any remaining volatiles that may have been trapped in the laminate during the initial curing process. It also ensures that the laminate has been fully cured and has reached the desired mechanical properties. Subsequently, the composite laminate was cut according to ASTM standards for further testing. The ratios of fiber and matrix, such as GF, CF, and ABS, are presented in Table 5.

Table 4. Fabrication details of GF/CF/ABS matrix composites.

Layer Details	Matrix and Fiber Details	Composite Configuration
1st layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	GF/CF/ABS
2nd layer	3D printed ABS (0.3 mm)/Carbon fiber (0.4 mm)	
3rd layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)	
4th layer	3D printed ABS (0.3 mm)/Carbon fiber (0.4 mm)	
5th layer	3D printed ABS (0.3 mm)/Glass fiber (0.4 mm)/3D printed ABS (0.3 mm)	

Table 5. Details of fiber and matrix weight reinforcement ratios.

Type of Composites	Weight (g)			Weight Fraction (%)		
	Wt_G	Wt_c	Wtm	WF_G	WF_c	WFm
Neat ABS	-	-	140	-	-	100
GF/ABS	136	-	84	61.84	-	38.18
GF/CF/ABS	81.6	65	84	35.34	28.19	36.43

G = glass fiber; C = carbon fiber; m = matrix; Wt_G = weight of glass fiber; Wt_C = weight of carbon fiber; WF_G = weight fraction of glass fiber; WF_C = weight fraction of carbon fiber.

2.3. Wear Test

The wear test was conducted utilizing a pin-on-disk apparatus (DUCOM: TR–20LE–CHM–400, shown in Figure 3) in accordance with ASTM standard G99 under dry sliding conditions. The test was performed under the following parameters: (i) ambient temperature; (ii) sliding velocities of 2, 3, and 4 cm/s; (iii) applied loads of 5 and 10 N; (iv) 50 ± 10% relative humidity; (v) sliding distance of 5000 m; and (vi) track diameter of 60 mm. Samples with dimensions of 3 mm × 3 mm × 32 mm (width × thickness × height) were utilized. Finally, the average values of the wear loss, coefficient of friction, and frictional force were reported.

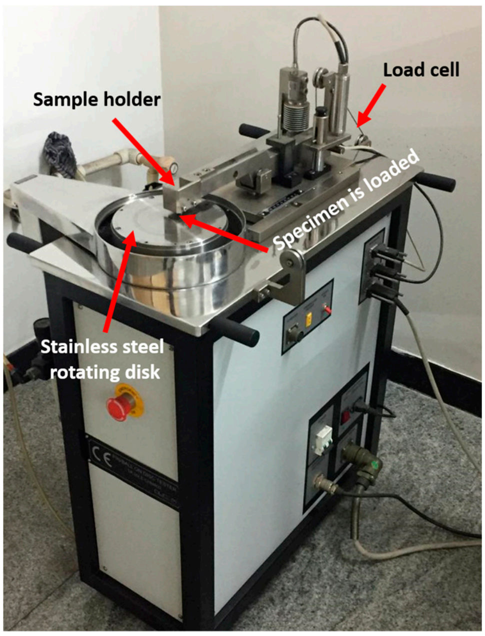

Figure 3. Pin-on-disc machine.

2.4. Scanning Electron Microscope

The worn surfaces of ABS, GF/ABS, and GF/CF/ABS samples were examined using a scanning electron microscope (ZEISS, Germany). To minimize charging effects and obtain high-quality images, the worn samples were coated with sputtered gold.

3. Results and Discussion

Wear Test

Figure 4a–c depict the wear loss results for ABS, GF/ABS, and GF/CF/ABS hybrid composite materials. The measurements were taken by varying the sliding velocities of 2 m/s, 3 m/s, and 4 m/s, and the loads applied were 5 N and 10 N. Figure 4a illustrates the impact of load variations on the wear loss of ABS samples. The results indicated that the wear loss of the sample subjected to a load of 5 N decreased as the velocity increased from 2 m/s to 3 m/s. However, when the velocity was further increased to 4 m/s, the wear loss increased. In contrast, the wear loss of the sample subjected to a load of 10 N increased with each increase in velocity from 2 m/s to 3 m/s, and from 3 m/s to 4 m/s. The observed difference in wear loss between the ABS samples subjected to 5 N and 10 N loads could likely be attributed to the varying levels of stress applied to the samples. The 5 N-loaded sample experienced a lower level of stress, which led to a decrease in wear loss when the velocity increased from 2 m/s to 3 m/s. However, when the velocity was further increased to 4 m/s, the increased stress caused the wear loss to rise. Conversely, the 10 N-loaded sample was subjected to a higher level of stress, which resulted in a continuous increase in wear loss with each increase in velocity, as the ABS material was unable to withstand the increased stress and resulted in greater wear.

When comparing Figure 4a,b it was observed that the ABS samples exhibited higher levels of wear loss compared to the GF/ABS and GF/CF/ABS hybrid materials. ABS, being a thermoplastic material, possesses relatively lower wear resistance compared to composites such as GF/ABS and GF/CF/ABS, which have reinforcement materials incorporated into the matrix material. The reinforcement materials (glass fiber, carbon fiber) enhanced the stiffness, strength, and hardness of the composites, resulting in reduced wear loss.

Figure 4b presents the wear loss of GF/ABS and GF/CF/ABS hybrid composites with respect to varying velocities and a constant load of 5 N. The wear loss of GF/ABS composites decreased as the velocity increased, while the wear loss of GF/CF/ABS hybrid composites increased. The behavior of wear loss in GF/ABS and GF/CF/ABS composites could be attributed to several factors, including the properties of the individual materials and the nature of the composite structure. Glass fiber reinforcement in the ABS matrix improved the mechanical properties, such as strength and toughness, of the composite material. The increased velocity applied to the composite material generated high levels of stress, which the reinforced glass fibers absorbed, thus reducing the overall wear loss of the composite. In contrast, the addition of carbon fibers to the ABS matrix resulted in a stiffer and stronger composite material, but it also led to increased brittleness and decreased toughness. As a result, the wear loss of the GF/CF/ABS composite may have increased as the velocity increased due to the high levels of stress and the composite's inability to absorb and distribute the stress effectively.

Furthermore, comparing Figure 4b,c, the loading conditions (increasing the load from 5 N to 10 N) may have caused the materials to experience higher levels of stress, leading to increased wear loss. The increased load may have also altered the contact conditions between the samples, which could have influenced the results. Similarly, Hasim and Nihat [32] examined the wear behavior of glass fiber (GF)-reinforced composite materials and polyester by varying the speed (500 RPM and 700 RPM) and loads (500 g and 1000 g). The results indicated that the weight loss of the samples increased as the speed and loads increased.

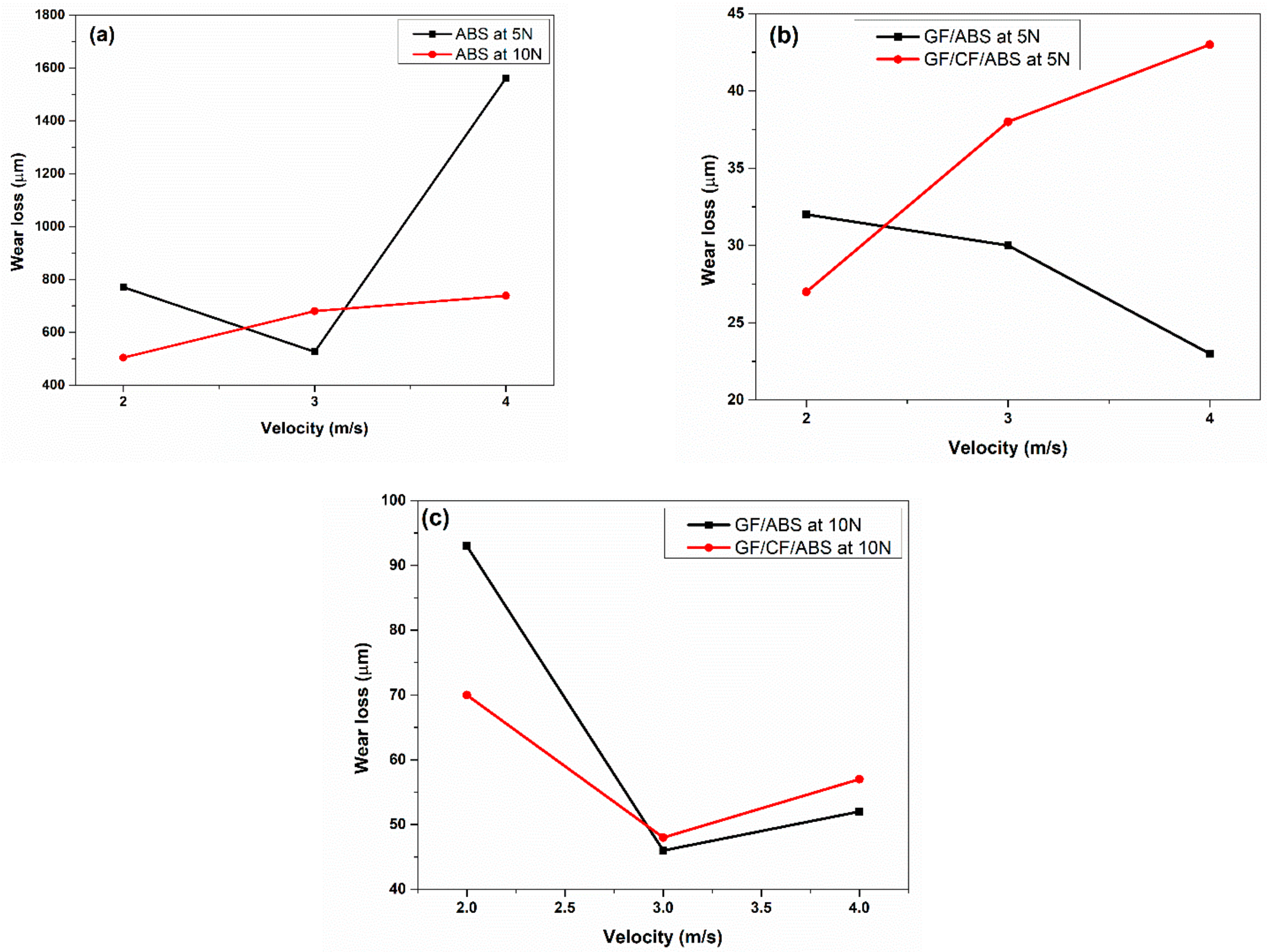

Figure 4. (**a**–**c**) Wear loss vs. sliding velocity of ABS, GF/ABS, and GF/CF/ABS composites. Test conditions: sliding velocity 2 m/s, 3 m/s, and 4 m/s; load 5 N and 10 N; sliding distance 5000 m; and track diameter 60 mm.

Figure 5a–c display the coefficient of friction of ABS, GF/ABS, and GF/CF/ABS hybrid materials. The measurements were taken at varying velocities of 2 m/s, 3 m/s, and 4 m/s under loads of 5 N and 10 N. The coefficients of friction for both ABS and composite materials were observed to decrease as the velocity increased.

Figure 5a shows the coefficient of friction results for ABS samples that were tested at loads of 5 N and 10 N. It was observed that the sample tested at a load of 5 N exhibited a lower coefficient of friction compared to the sample tested at a load of 10 N. The difference in coefficient of friction (COF) between 5 N and 10 N tested samples was attributed to the level of force applied to the surface of the ABS material. The COF is a measure of the force required to move an object along a surface and is influenced by several factors, including the roughness of the surface, the material properties of the objects in contact, and the nature of the contact between the objects.

When a lower force, such as 5 N, was applied to the ABS material, the surface roughness and the material properties played a more significant role in determining the COF. The COF was lower in this case because the surface was not as deformed or indented, allowing for a smoother movement of the object. However, when a higher force, such as 10 N, was applied to the ABS material, the nature of the contact between the objects became more important in determining the COF. The increased force caused the ABS surface to deform more, creating a rougher or uneven surface and a higher COF.

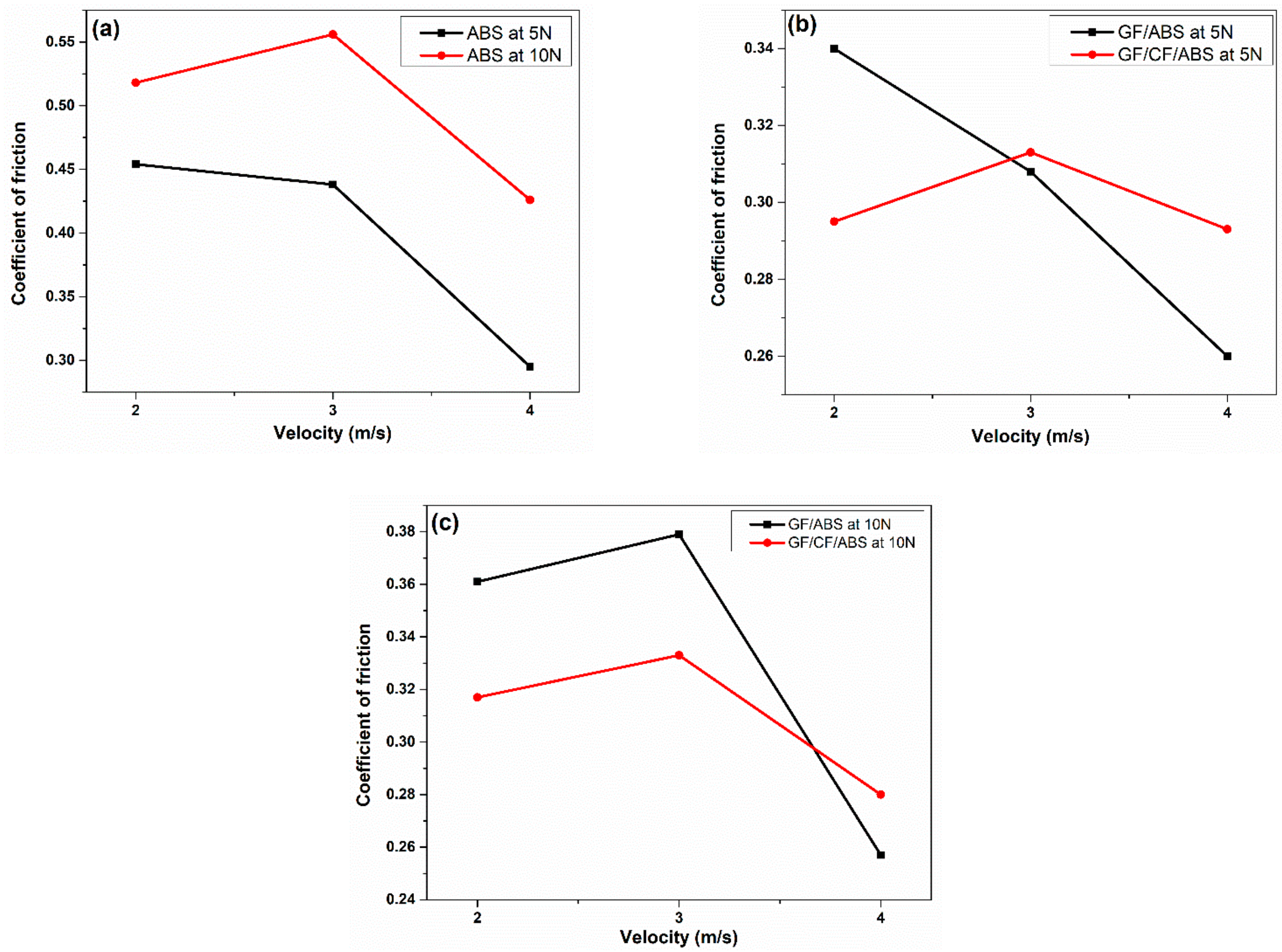

Figure 5. (**a**–**c**) Coefficient of friction vs. sliding velocity of ABS, GF/ABS, and GF/CF/ABS composites. Test conditions: sliding velocity 2 m/s, 3 m/s and 4 m/s; load 5 N and 10 N; sliding distance 5000 m; and track diameter 60 mm.

Upon examination of Figure 5a–c, it was observed that the coefficients of friction (COFs) of ABS samples were higher than those of GF/ABS and GF/CF/ABS samples. This could be attributed to several factors, including the properties of the ABS material alone, which could affect its COF through its surface roughness, chemical composition, and hardness. Additionally, the presence of glass fiber and carbon fiber reinforcements in the ABS matrix altered the surface properties and mechanical behavior of the composite, which in turn influenced its COF. The fiber layering sequence and distribution within the matrix, as well as the fiber–matrix interface, also played a role in determining the COF of the composite material.

Figure 5b depicts the results of the coefficient of friction tests performed on GF/ABS and GF/CF/ABS samples at a load of 5 N. The results indicated that the coefficients of friction of the samples were impacted by both the velocity and the composition of the materials. When the velocity was 2 m/s, the GF/ABS samples showed a higher COF compared to the GF/CF/ABS samples. This difference in COF can be attributed to the fact that the GF/ABS samples have a simpler composition, with only one type of fiber reinforcement, while the GF/CF/ABS samples have a more complex composition with two types of fiber reinforcement. The presence of the additional carbon fiber reinforcement in the latter samples may have improved their overall mechanical properties and reduced the COF compared to the GF/ABS samples. At the velocities of 3 m/s and 4 m/s, the GF/CF/ABS samples showed higher COFs compared to the GF/ABS samples. This difference in COF can be attributed to the fact that the increased velocity resulted in greater deformation and indentation of the ABS material, which in turn increased the roughness of the surface and raised the COF.

Figure 5c depicts the coefficient of friction (COF) results for GF/ABS and GF/CF/ABS samples that were tested at a normal load of 10 N. The increase in COF with increasing normal load (from 5 N to 10 N) can be due to several factors. One possible explanation was that higher normal loads increased the contact pressure between the sample and the counterface, resulting in an increase in friction. This was due to the fact that the contact area between the two materials increased with the normal load, causing the pressure between the surfaces to increase as well. Another possible factor was the deformation of the sample's surface. Ze-Kun Zhao et al. [33] conducted a study to evaluate the wear performance of glass fiber/polyethersulfone and carbon fiber/polyethersulfone composites. The results showed that the carbon fiber-reinforced composites exhibited a lower friction coefficient (~0.45 to 0.35) compared to the glass fiber-reinforced polyethersulfone composites (~0.45 to 0.65).

Figure 6a–c depict the friction forces of ABS, GF/ABS, and GF/CF/ABS samples under varying velocities, including 2 m/s, 3 m/s, and 4 m/s, with the application of 5 N and 10 N loads. Figure 6a illustrates the friction forces of ABS samples tested under 5 N and 10 N loads. It was noted that lower friction forces were recorded for ABS samples tested at 5 N in comparison to those tested at 10 N. This difference could have been caused by several factors. Firstly, the normal force applied, also known as the load, had a direct impact on the friction force. As the normal force increased, the friction force also increased due to the proportional relationship between the two. Secondly, the mechanical properties and surface roughness of the ABS material also played a role in determining the friction force. The hardness, yield strength, and modulus of elasticity of the ABS material affected its deformation behavior under an applied load, which in turn impacted the friction force. Additionally, the surface roughness of the material had an effect on the friction force, with a smoother surface leading to a lower friction force.

Upon comparing Figure 6a–c, it was observed that ABS exhibited a higher friction force compared to the GF/ABS and GF/CF/ABS samples. This could be attributed to the lower modulus of elasticity and lower tensile strength of ABS, which leads to easier deformation and ultimately higher friction. The wear behavior of ABS and carbon fiber/ABS composites was similarly studied by Sudin et al. [30]. The examination involved varying the applied loads from 5 N to 25 N. The results showed that the composite materials exhibited lower friction forces compared to the pure ABS samples.

Figure 6b,c illustrate the friction forces of GF/ABS and GF/CF/ABS composites at different velocities and under loads of 5 N and 10 N. The difference in friction forces between GF/ABS and GF/CF/ABS samples at 5 N and 10 N loads could be attributed to several factors. Firstly, the load or normal force applied had a direct impact on the friction force, with an increase in the normal force leading to an increase in the friction force. Secondly, the presence of glass fiber and carbon fiber reinforcements in the ABS matrix altered the mechanical behavior and surface properties of the composite, which in turn affected the friction force. The fiber distribution, layering sequence, and fiber–matrix interface in the composite also impacted the friction force. At a lower load of 5 N, the glass fiber reinforcement in the ABS matrix may have improved the mechanical properties, such as strength and toughness, of the composite material and reduced the friction force. At a higher load of 10 N, the increased normal force may have generated higher levels of stress, leading to an increase in the friction force for the GF/ABS composite. The stiffer and stronger GF/CF/ABS composite, resulting from the addition of carbon fibers to the ABS matrix, had a lower ability to absorb and distribute the high levels of stress effectively, leading to a lower friction force than the GF/ABS composite at 10 N.

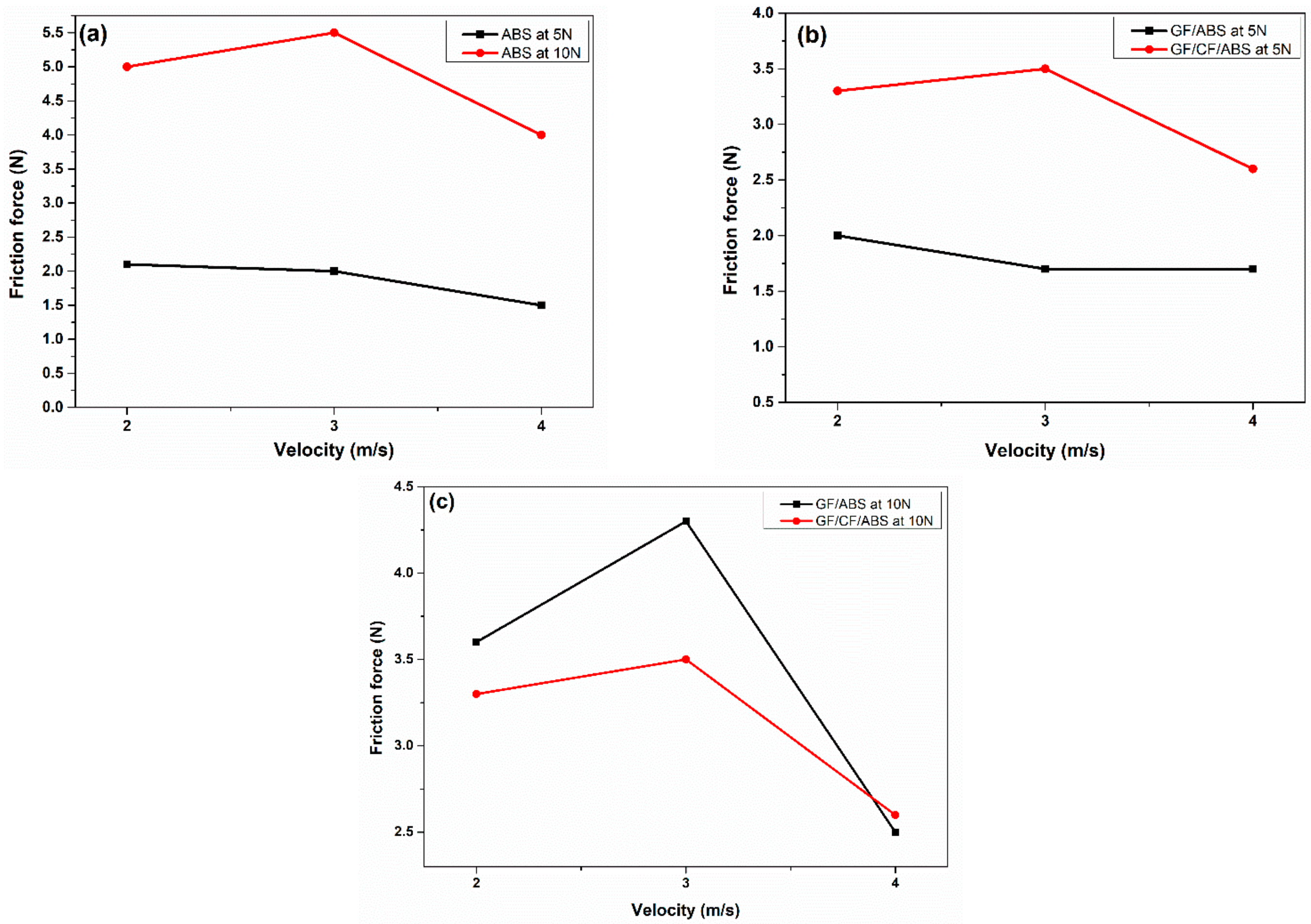

Figure 6. (**a**–**c**) Friction force vs. sliding velocity of ABS, GF/ABS, and GF/CF/ABS composites. Test conditions: sliding velocity 2 m/s, 3 m/s, and 4 m/s; load 5 N and 10 N; sliding distance 5000 m; and track diameter 60 mm.

The SEM micrographs of the ABS, GF/ABS, and GF/CF/ABS samples are presented in Figure 7a–c. The observation shows (Figure 7a) that the ABS sample achieved higher wear loss at 5 N with a velocity of 4 m/s, which was justified by examining the SEM micrograph. Specifically, Figure 7a illustrates the SEM image of the ABS sample at a sliding speed of 4 m/s and a load of 5 N, while Figure 7b presents the SEM image of the worn surface of the ABS sample that experienced lesser wear loss. By comparing these two images, the extent of material removal and changes in the surface morphology of the ABS sample under different sliding speeds and loads was assessed. This information provided insight into the relationship between the sliding speed and load and the wear behavior of the ABS sample.

Figure 7c shows that the SEM images of the GF/ABS composite (tested at 5 N and velocity of 4 m/s) revealed minimum matrix breakage, debonding, fiber fracture, and fiber pullout, which contributed to a decrease in wear loss compared to the GF/CF/ABS sample (Figure 7d). The presence of these features indicated that the GF/ABS composite had better resistance to wear and degradation than the hybrid sample and was less susceptible to mechanical failure during sliding.

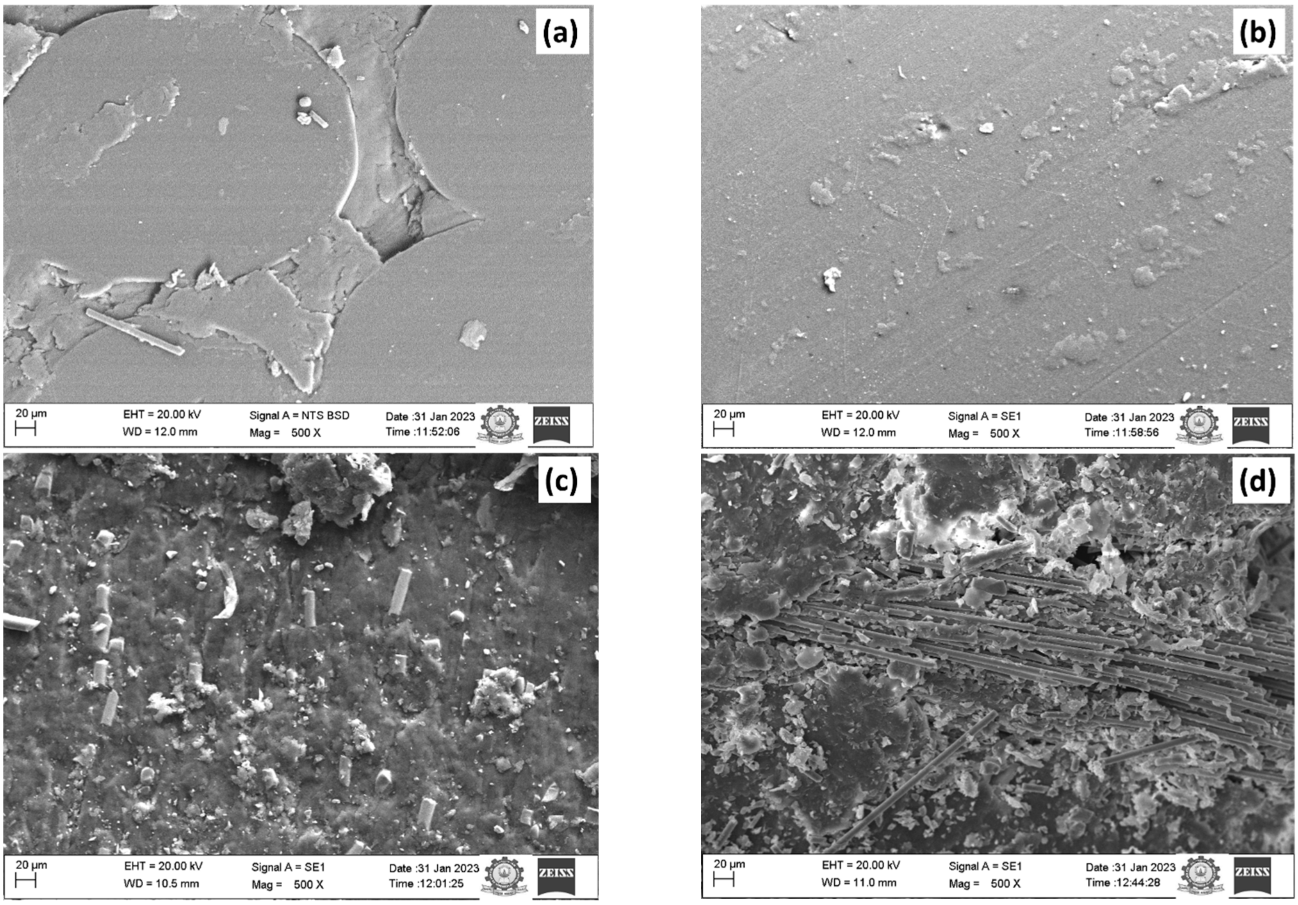

Figure 7. SEM micrographs of (**a**) ABS at 5 N and velocity of 4 m/s, (**b**) ABS at 5 N and velocity of 2 m/s, (**c**) GF/ABS at 5 N and velocity of 4 m/s, and (**d**) GF/CF/ABS at 10 N and velocity of 4 m/s.

4. General Discussion

The results of this study provide valuable insights into the tribological properties of thermoplastic composite materials, specifically ABS and hybrid composites of ABS with glass fiber and carbon fiber. The finding that the wear loss of composite laminates was lower than that of ABS samples suggests that these hybrid composites have potential applications in industries where wear resistance is a critical factor.

Furthermore, the finding that GF/ABS composite laminates exhibited the lowest wear loss among the tested samples indicates that this material has the highest potential for use in designing products where wear resistance is a primary concern.

The study also showed that the wear loss increased with an increase in load, which highlights the importance of considering load conditions in the design of products made of these materials. Overall, the results obtained can be applied in the engineering practice of designing products made of thermoplastic composites, particularly in industries where wear resistance is a critical factor.

The developed technology of combining fused deposition modeling and hot press technology for composite laminate fabrication offers several advantages compared to traditional technologies such as Resin Film Infusion.

Firstly, it allows for greater control over the final product as the technology enables the fabrication of laminates with precise dimensions and fiber alignment, resulting in improved wear resistance properties. Secondly, the technology is cost-effective and energy-efficient, as it does not require the use of expensive equipment or large amounts of energy.

Overall, the developed technology provides a viable alternative for the fabrication of thermoplastic composites with improved wear resistance properties and cost-effectiveness compared to traditional technologies such as resin film infusion.

The developed technology of combining fused deposition modeling and hot press technology can be used to manufacture a range of products made of thermoplastic composites. These products can include but are not limited to automobile components, aerospace parts, sailboats, and bicycles. The technology also has the potential to be applied in specialized fields such as defense and electronic items.

5. Conclusions

The present study investigated the wear and morphological characteristics of ABS, GF/ABS, and GF/CF/ABS hybrid composites. The composite laminates were fabricated using a novel technique that combined fused deposition modeling and hot press technology. Wear loss, coefficient of friction, and friction force were evaluated for the ABS, GF/ABS, and GF/CF/ABS hybrid samples by varying the velocities (2 m/s, 3 m/s, and 4 m/s) and loads (5 N and 10 N).

- The study found that the wear loss of the composite laminates was lower compared to that of the ABS samples. The GF/ABS composite laminates exhibited the lowest wear loss of 23 μm (5 N and 4 m/s) among all the tested samples. However, the wear loss increased as the load increased from 5 N to 10 N for both the GF/ABS and GF/CF/ABS samples. These findings indicate that the addition of glass and carbon fibers to the ABS matrix could improve the wear resistance of the resulting composites.
- The coefficient of friction of the ABS samples was lower, with a value of 0.295 at 4 m/s under a 5 N load. The composite laminates also showed a lower coefficient of friction at 4 m/s for both 5 N and 10 N loads. Among the different loaded samples, the GF/ABS samples showed the lowest coefficient of friction.
- The ABS samples showed lower friction force values at 2 m/s to 4 m/s under 5 N of load, with a friction force of 1.5 measured for ABS samples (5 N and 2 m/s). In the composite laminates, the GF/ABS exhibited a lower friction force under a 5 N load. When the load was increased from 5 N to 10 N, the friction force increased.

In summary, this study demonstrated that composite laminates produced via a novel fabrication method exhibited superior wear resistance and a lower coefficient of friction in comparison to ABS samples. Notably, the GF/ABS composite laminate displayed the lowest wear loss and coefficient of friction within the tested specimens. However, increasing the load from 5 N to 10 N resulted in an upsurge in wear loss and friction force.

Future research could explore the use of different tribo fillers and their effects on the performance of the composite systems. This would provide valuable insight into the optimal type and concentration of tribo fillers for the best performance. Examples of tribo fillers that could be used in GF/ABS and GF/CF/ABS composite systems include alumina (Al_2O_3) nanoparticles, silicon carbide (SiC) particles, boron nitride (BN) nanoparticles, tungsten carbide (WC) particles, and graphite particles. Future research in this direction could lead to the development of composite systems with enhanced performance for various applications.

Author Contributions: Conceptualization, investigation, A.D.; methodology, validation, writing—review and editing, S.K.; validation, writing—review and editing, supervision, R.N.; editing, A.D.A.S.; editing, S.M.K.T.; editing, C.M.; funding acquisition, F.M.; editing, H.A.A.-L.; editing, S.O.I. All authors have read and agreed to the published version of the manuscript.

Funding: Researchers Supporting Project (RSP2023R54), King Saud University, Saudi Arabia.

Data Availability Statement: The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Acknowledgments: The King Saud University authors acknowledge the funding from Researchers Supporting Project number (RSP2023R54), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Gleirscher, M.; Wolfberger, A.; Schlögl, S.; Hołyńska, M.; Hausberger, A. Accelerated Thermo-Catalytic Degradation of Perfluoropolyether (PFPE) Lubricants for Space Applications. *Lubricants* **2023**, *11*, 81. [CrossRef]
2. Keshavamurthy, R.; Tambrallimath, V.; Rajhi, A.A.; Ahmed, R.S.; Patil, A.Y.; Khan, T.M.Y.; Makannavar, R. Influence of Solid Lubricant Addition on Friction and Wear Response of 3D Printed Polymer Composites. *Polymers* **2021**, *13*, 2905. [CrossRef] [PubMed]
3. Dilberoglu, U.M.; Gharehpapagh, B.; Yaman, U.; Dolen, M. Current Trends and Research Opportunities in Hybrid Additive Manufacturing. *Int. J. Adv. Manuf. Technol.* **2021**, *113*, 623–648. [CrossRef]
4. Zhu, Z.; Dhokia, V.G.; Nassehi, A.; Newman, S.T. A Review of Hybrid Manufacturing Processes—State of the Art and Future Perspectives. *Int. J. Comput. Integr. Manuf.* **2013**, *26*, 596–615. [CrossRef]
5. Stavropoulos, P.; Foteinopoulos, P.; Papacharalampopoulos, A.; Bikas, H. Addressing the Challenges for the Industrial Application of Additive Manufacturing: Towards a Hybrid Solution. *Int. J. Lightweight Mater. Manuf.* **2018**, *1*, 157–168. [CrossRef]
6. Horn, T.J.; Harrysson, O.L.A. Overview of Current Additive Manufacturing Technologies and Selected Applications. *Sci. Prog.* **2012**, *95*, 255–282. [CrossRef] [PubMed]
7. Tamez, M.B.A.; Taha, I. A Review of Additive Manufacturing Technologies and Markets for Thermosetting Resins and Their Potential for Carbon Fiber Integration. *Addit. Manuf.* **2021**, *37*, 101748. [CrossRef]
8. Valvez, S.; Santos, P.; Parente, J.M.; Silva, M.P.; Reis, P.N.B. 3D Printed Continuous Carbon Fiber Reinforced PLA Composites: A Short Review. *Procedia Struct. Integr.* **2020**, *25*, 394–399. [CrossRef]
9. Dixit, N.; Jain, P.K. 3D Printed Carbon Fiber Reinforced Thermoplastic Composites: A Review. *Mater Today Proc.* **2020**, *43*, 678–681. [CrossRef]
10. Kim, H.H.; Lee, M.S.; Kang, C.G. The Fabrication of a Hybrid Material Using the Technique of Hot-Press Molding. *Mater. Manuf. Process.* **2013**, *28*, 892–898. [CrossRef]
11. Findik, F. Latest Progress on Tribological Properties of Industrial Materials. *Mater. Des.* **2014**, *57*, 218–244. [CrossRef]
12. Karthikeyan, S.; Rajini, N.; Jawaid, M.; Winowlin Jappes, J.; Thariq, M.; Siengchin, S.; Sukumaran, J. A Review on Tribological Properties of Natural Fiber Based Sustainable Hybrid Composite. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2017**, *231*, 1616–1634. [CrossRef]
13. Suresha, B.; Chandramohan, G.; Samapthkumaran, P.; Seetharamu, S.; Vynatheya, S. Friction and Wear Characteristics of Carbon-Epoxy and Glass-Epoxy Woven Roving Fiber Composites. *J. Reinf. Plast. Compos.* **2006**, *25*, 771–782. [CrossRef]
14. Kishi, H.; Nakao, N.; Kuwashiro, S.; Matsuda, S. Carbon Fiber Reinforced Thermoplastic Composites from Acrylic Polymer Matrices: Interfacial Adhesion and Physical Properties. *Express Polym. Lett.* **2017**, *11*, 334–342. [CrossRef]
15. Mittal, V. *High Performance Polymers and Engineering Plastics*; John Wiley & Sons: Hoboken, NJ, USA, 2011; ISBN 9781118016695.
16. Krishnasamy, S.; Thiagamani, S.M.K.; Muthu Kumar, C.; Nagarajan, R.; Shahroze, R.M.; Siengchin, S.; Ismail, S.O.; Indira, I.D. Recent Advances in Thermal Properties of Hybrid Cellulosic Fiber Reinforced Polymer Composites. *Int. J. Biol. Macromol.* **2019**, *141*, 1–13. [CrossRef] [PubMed]
17. Dhandapani, A.; Krishnasamy, S.; Muthukumar, C.; Thiagamani, S.M.K.; Nagarajan, R.; Siengchin, S. Plastics in Marine Engineering. *Ref. Modul. Mater. Sci. Mater. Eng.* **2020**, *4*, 225–236. [CrossRef]
18. Sophia, O.; Joyce, R.S.; SuetYin, S.; Evonne, T. *Preferred Fiber and Materials Market Report 2021*; Textile Exchange: London, UK, 2021.
19. Hausberger, A.; Stiller, T.; Kappl, C.; Hensgen, L.; Grün, F. Improving the Tribological Properties of Technical Polymers with Metal Sulphide Compounds. *Lubricants* **2021**, *9*, 91. [CrossRef]
20. Morampudi, P.; Namala, K.K.; Gajjela, Y.K.; Barath, M.; Prudhvi, G. Review on Glass Fiber Reinforced Polymer Composites. *Mater. Today Proc.* **2020**, *43*, 314–319. [CrossRef]
21. Thomason, J.L. *Glass Fibre Sizing: A Review*; Elsevier Ltd.: Amsterdam, The Netherlands, 2019; Volume 127, ISBN 0044141548.
22. Suarez, S.; Rosenkranz, A. Carbon Nanomaterials—Promising Solid Lubricants to Tailor Friction and Wear. *Lubricants* **2019**, *7*, 51. [CrossRef]
23. Ujah, C.O.; von Kallon, D.V.; Aigbodion, V.S. Tribological Properties of CNTs-Reinforced Nano Composite Materials. *Lubricants* **2023**, *11*, 95. [CrossRef]
24. Yao, S.-S.; Jin, F.-L.; Rhee, K.Y.; Hui, D.; Park, S.-J. Recent Advances in Carbon-Fiber-Reinforced Thermoplastic Composites: A Review. *Compos. B Eng.* **2018**, *142*, 241–250. [CrossRef]
25. Minchenkov, K.; Vedernikov, A.; Safonov, A.; Akhatov, I. Thermoplastic Pultrusion: A Review. *Polymers* **2021**, *13*, 180. [CrossRef] [PubMed]
26. Vedernikov, A.; Minchenkov, K.; Gusev, S.; Sulimov, A.; Zhou, P.; Li, C.; Xian, G.; Akhatov, I.; Safonov, A. Effects of the Pre-Consolidated Materials Manufacturing Method on the Mechanical Properties of Pultruded Thermoplastic Composites. *Polymers* **2022**, *14*, 2246. [CrossRef] [PubMed]
27. Rattan, R.; Bijwe, J.; Fahim, M. Optimization of Weave of Carbon Fabric for Best Combination of Strength and Tribo-Performance of Polyetherimide Composites in Adhesive Wear Mode. *Wear* **2008**, *264*, 96–105. [CrossRef]
28. Bijwe, J.; Rajesh, J.J.; Jeyakumar, A.; Ghosh, A.; Tewari, U.S. Influence of Solid Lubricants and Fibre Reinforcement on Wear Behaviour of Polyethersulphone. *Tribol. Int.* **2000**, *33*, 697–706. [CrossRef]
29. Sharma, M.; Mohan Rao, I.; Bijwe, J. Influence of Fiber Orientation on Abrasive Wear of Unidirectionally Reinforced Carbon Fiber-Polyetherimide Composites. *Tribol. Int.* **2010**, *43*, 959–964. [CrossRef]

30. Sudin, M.N.; Ramli, F.R.; Alkahari, M.R.; Abdullah, M.A. Comparison of Wear Behavior of ABS and ABS Composite Parts Fabricated via Fused Deposition Modelling. *Int. J. Adv. Appl. Sci.* **2018**, *5*, 164–169. [CrossRef]
31. Amrishraj, D.; Senthilvelan, T. Dry Sliding Wear Behavior of ABS Composites Reinforced with Nano Zirconia and PTFE. *Mater. Today Proc.* **2018**, *5*, 7068–7077. [CrossRef]
32. Pıhtılı, H.; Tosun, N. Investigation of the Wear Behaviour of a Glass-Fibre-Reinforced Composite and Plain Polyester Resin. *Compos. Sci. Technol.* **2002**, *62*, 367–370. [CrossRef]
33. Zhao, Z.-K.; Du, S.-S.; Li, F.; Xiao, H.-M.; Li, Y.-Q.; Zhang, W.-G.; Hu, N.; Fu, S.-Y. Mechanical and Tribological Properties of Short Glass Fiber and Short Carbon Fiber Reinforced Polyethersulfone Composites: A Comparative Study. *Compos. Commun.* **2018**, *8*, 1–6. [CrossRef]