INVESTIGATION OF FIBER CONTENT, FIBER DIRECTION, AND SURFACE CHARATERISTICS OF DIFFERENT SURFACE ANGLE OF ADDITIVELY MANUFACTURED COMPOSITE RELATIVE TO THE PRINTING DIRECTION

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Abstract

Extrude Deposition Additive Manufacturing (EDAM) is a widely used additive manufacturing technology for fiber reinforced thermoplastic composite materials. Pelletized composite materials are melted in an extruder and deposited layer by layer onto a building plate through a printing nozzle. In the printing process, the majority of fibers align with the printing direction. One of the significant applications of additive manufactured composites is for building composite part manufacturing tools. The surface characteristics of the tool play an important role in determining its durability, the surface finish quality of composite parts, and the required demolding force for composite part manufacturing. The orientation of the fiber on the tool surface changes with the tool surface angle relative to the printing direction. The surface characteristics influenced by the fiber orientation can vary depending on the surface angle relative to the printing direction. Therefore, understanding the surface properties resulting from different surface angles is essential. In this study, an 20% by weight carbon fiber reinforced acrylonitrile butadiene styrene (ABS) composite block was printed using EDAM technology. Surface property test specimens were cut along different planes (the plane that is perpendicular to the stacking direction, the plane perpendicular to the traverse direction, and the plane perpendicular to the printing direction) and observed under a microscope for fiber content and orientation. The specimens were then finished using a computer numerical control (CNC) milling machine to achieve the desired testing surface. Surface characteristics critical for composite tooling applications, such as surface hardness, abrasion resistance, roughness, and friction, were evaluated.

Keywords: Additive manufacturing, thermoplastic, composite tooling, surface characteristic testing

Introduction

Fiber-reinforced composite materials have a wide range of practical applications in industries such as automotive, aerospace, and wind energy due to their weight reduction, high strength-to-weight ratio, and energy-saving potential [1]. In the composite part manufacturing process, composite part manufacturing tools are essential. The tools serve as the foundation upon which composite plies are laid, cured, and consolidated, ultimately shaping the final product. However, the fabrication of traditional composite part manufacturing tools, which are often made of traditional metal, composite laminates, and tooling board, has limitations in terms of production rate and cost, particularly when producing large-scale tools. Furthermore, traditional methods not only require weeks of lead time but may also result in inconsistent quality and dimensional accuracy of the mold, depending on the technician's skill level [2].

Along with the rapid development of additive manufacturing technologies, it has been found that additive manufacturing technology can be highly effective in the production of composite part molds [3]. Additive manufacturing technology, which is a key component of the latest industrial revolution, Industry 4.0, can fabricate highly complex parts with higher speed, efficiency, and accuracy than traditional tool manufacturing processes [4,5]. Additionally, additive manufacturing technology offers the potential for reduced material waste, lower production costs, and greater design flexibility, making it an attractive option for tool manufacturing operations [4–6].

Among various printing materials, fiber-reinforced composite additive manufacturing technology is frequently used for large-scale additive manufacturing due to its fast-printing speed and high cost-effectiveness. The composite additive manufacturing technology allows to produce larger tool in a single print run, reducing the need for assembly and potentially lowering large-scale tool production costs for industries such as aerospace and wind energy [7]. Extrude Deposition Additive Manufacturing (EDAM) is a widely used large-scale additive manufacturing technology for short fiber reinforced thermoplastic composite material to produce tools [8]. The process involves melting pelletized feedstock material through an extruder and dispositioning it layer by layer onto a building plate through a printing nozzle. The whole production process begins with a digital (CAD) geometry of the part; a slightly over dimensioned geometry is used for the printing process, and then the extra deposited material is required for the subsequent finishing step to obtain a smooth tooling surface using a Computer Numerical Control (CNC) mill, as shown in Figure 1. [9,10]

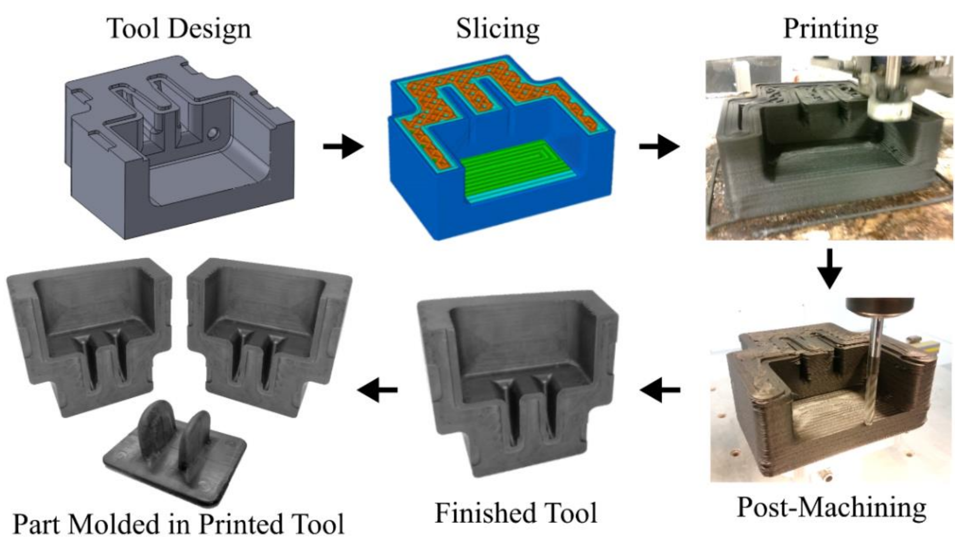

Figure 1. Extrude Deposition Additive Manufacturing (EDAM) fiber reinforced composite additive manufacturing technology for composite part manufacturing tooling application.

The utilization of additive manufacturing technology in tooling applications is a promising approach; however, certain limitations exist to achieve optimal tooling surface performance. The surface characteristics of the tool play an important role in determining its durability, the surface finish quality of composite parts, and the required demolding force for composite part manufacturing [11]. Surface durability of the composite part manufacturing tool is critical. The surface of additively manufactured fiber-reinforced composite tools is often less durable than the traditional metal tool. Therefore, the surface is more prone to damage such as scratches and dents during the composite part manufacturing process. Any defects on the mold surface are transferred to the part surface made from the tool, and they can shorten the life of the tool. The heterogeneous nature of fiber-reinforced composites causes challenges during the post-machining process. Surface defects, such as fiber pull-out and fiber breakage, can arise, and the elevated temperatures involved in machining can lead to the melting of polymer on the machined surface. As a result, these defects can lead to a rough surface, increased demolding force, and excessive surface friction caused by different surface angles during machining. Such excessive friction can affect the final surface quality of the part during removal, causing damage to both the tool and the part.

It is important to understand surface characteristics, such as surface durability and surface finish quality, in additively manufactured composites, especially for tooling applications. Fiber-reinforced composites show significant variations in mechanical and physical properties based on fiber content and orientation inside the composites. The surface characteristics may also be influenced by the fiber content on the surface and the orientation of the fibers, due to the different properties between the fiber and matrix. During the printing process, fibers predominantly align with the printing direction, leading to a locally diverse distribution of fiber orientation and content when the printed tool surface is finished at different angles relative to the printing direction. Therefore, surface characteristics influenced by fiber orientation may vary depending on the surface angle relative to the printing direction. The variations in fiber orientation and content on the machined surface can result in differences in local surface quality and varying demolding force for surfaces machined at different angles. Figure 2 shows stereoscope images of the additively manufactured fiber reinforced composite tool with different fiber orientations based on the cutting direction.

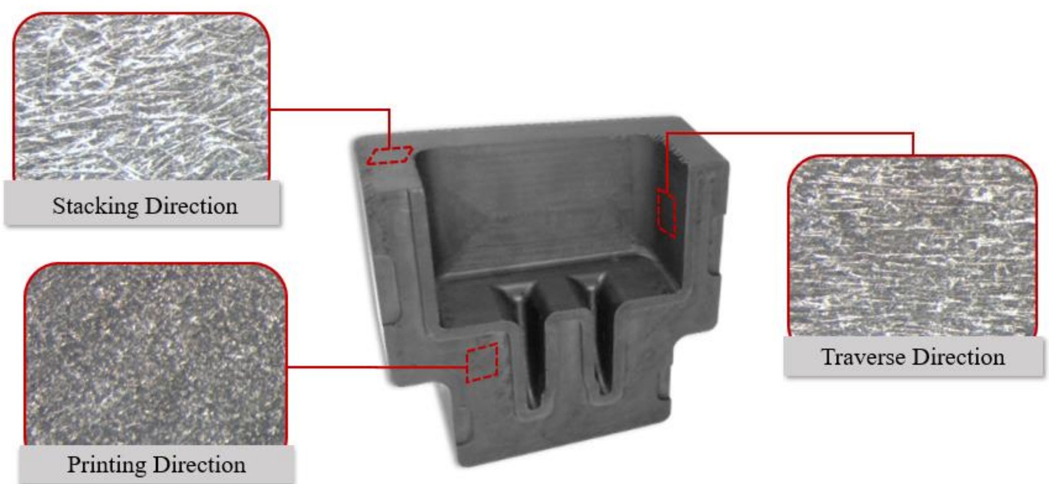

Figure 2. Stereoscopic images of additively manufactured fiber reinforced composite tool with different fiber orientations relative to cutting direction.

Therefore, understanding the surface properties of additively manufactured fiber-reinforced composite materials resulting from different surface angles is essential. In this study, the different surface characteristics of additively manufactured material at different surface angles were investigated. More specifically, the surface characteristics relevant to composite part manufacturing tooling applications, such as surface durability and surface finish quality, were studied. The acrylonitrile butadiene styrene (ABS) composite block filled with 20% carbon fiber by weight was printed using EDAM technology for the test specimens. Surface property test specimens were cut along different planes (the plane that is perpendicular to the stacking direction, the plane perpendicular to the traverse direction, and the plane perpendicular to the printing direction) and then finished using a CNC milling machine to achieve the desired testing surface. The microscopic image and stereoscope image have been taken for each test specimen to investigate different fiber orientations and content for different surface angles. Then, the surface properties, including hardness, surface abrasion resistance, roughness, and surface friction, were evaluated on test specimens with different surface angles, and the results were compared to identify any differences between them. The details of the testing process and test results for each test would be demonstrate.

Methodology

Test specimen manufacturing

To investigate the surface characteristics of additively manufactured fiber-reinforced composite for tooling application, test specimens were fabricated for different surface property tests including surface hardness test, abrasion resistance test, roughness test and surface friction test. The test block fabricated was produced through the EDAM process using Large Scale Additive Manufacturing (LSAM) of Thermwood. The EDAM process involves the extrusion of pelletized stock material using a single screw extruder. The pelletized feedstock enters the volumetric feeder and melts in the single screw extruder. The molten polymetric material passes through a convergence zone in the nozzle and is then deposited on a numerically controlled printed bed. The print bed is mounted on a 3-axis motion table, and it coordinates with the stationary extruder by adjusting its motion. The gear pump installed at the extruder's output regulates the trembling material flow. During the flow of polymetric material through the converging zone and extrusion nozzle, the fibers align predominantly with the deposition direction, which is the printing direction [12–14].

For this study, ABS reinforced with 20% by weight of carbon fiber was used. The pelletized carbon fiber-reinforced ABS composite was dried at 180 °C for 2 hours, according to material property data. The test block was printed with a 12.70 mm diameter nozzle, resulting in a printed bead with dimensions of 21.08 mm width and 5.08 mm height. A block with overall dimensions of 393.7 mm × 79.4 mm × 88.9 mm was printed with 4-bead across the width direction. For the surface characteristics test specimens, the printed ABS composite block was cut at three different angles and subjected to surface finishing using a CNC milling machine, as the condition of additively manufactured composite tools.

The printed test block was sectioned into three distinct orientations to be cut. The first cut was made in the plane that is perpendicular to the stacking direction, the second in the plane perpendicular to the traverse direction, and the third in the plane perpendicular to the printing direction. In this work, each cut was made in a different direction with a plane perpendicular to the stacking direction cut name as the stacking direction cut, a plane perpendicular to the traverse direction cut name as the traverse direction cut, and a plane perpendicular to the printing direction cut name as printing direction cut, as shown in Figure 3.

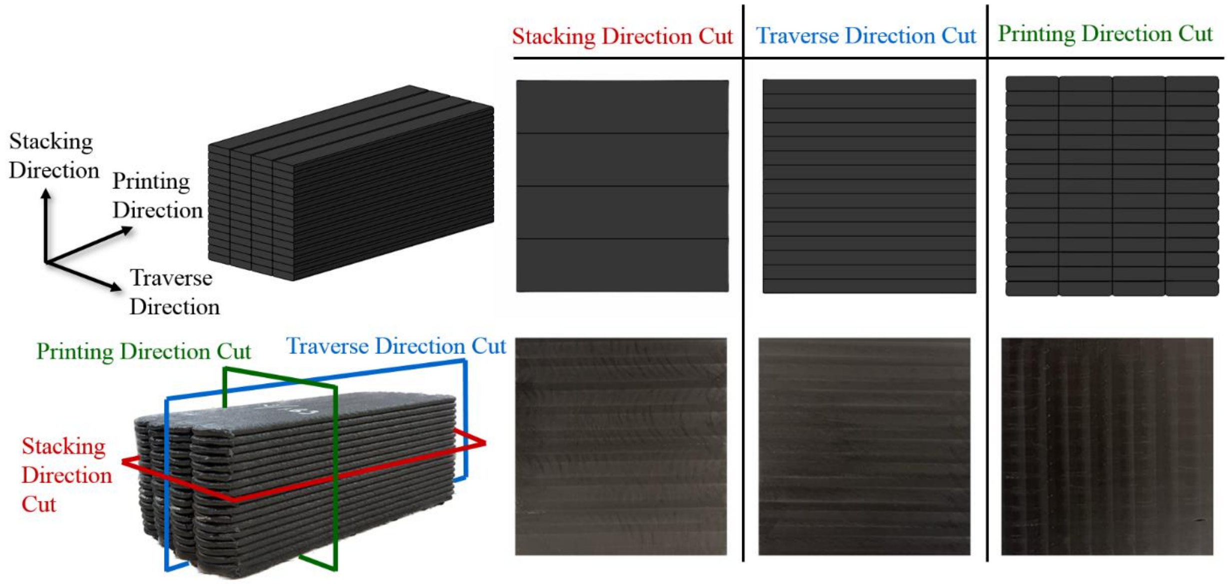

Figure 3. Schematic drawings and images of the additively manufactured fiber-reinforced composite test specimen that were cut at different angles from the printed block.

Following the cut, the top and bottom faces of each cut material were machined flat using a CNC milling machine, resulting in test specimens with a thickness of 6.35 mm. A 12.7 mm diameter, 4-flute solid carbide square end mill was used for the milling with 500 surface speed (SFM) and 0.005 inch per tooth (IPT) machining parameters. Then, the individual test specimens were cut from the face machined plate using an abrasive waterjet. For hardness, roughness, and surface abrasion resistance tests, the specimens were cut to dimensions of 101.6 mm by 101.6 mm, while the specimen for the surface friction test was cut to dimensions of 63.5 mm by 63.5 mm. The surface abrasion resistance test specimen had a 6.35 mm hole at the center of the test specimen to be able to mount on the abraser turntable of abrasion tester. All the test specimens were cleaned with compressed air and wiped with isopropyl alcohol to remove any grease or contamination on the surface. In order to investigate the fiber content and the fiber orientation on the test specimens cut with different angles, microscopic images of each test specimen were made.

Surface hardness test

Hardness of the material indicates the material's resistance to localized deformation, such as scratching, indentation, or penetration [11]. For tooling applications of additively manufactured composite material, hardness is essential for determining durability. During the composite part manufacturing process, particularly during the demolding process, the molds are prone to scratching and denting. This can result in surface damage to additively manufactured composite material tools, which are often softer than traditional metal tools. Surface damage not only affects the premature surface quality and accuracy of the final product, but it can also impact the service life and production run of the tool [15]. As a result, the hardness of the mold is critical to ensuring that the final product meets the desired standard of quality and accuracy, and that the tool can achieve the maximum number of production cycles. The surface hardness of additively manufactured carbon fiber-reinforced ABS composite test specimen was tested using a Barcol impresser in accordance with ASTM D283, the standard test method determining the indentation hardness of reinforced and nonreinforced rigid plastics. Qualitest GYZJ-934-1 was used for a Barcol impressor, as shown in Figure 5(a). The test method involved placing the Barcol impresser perpendicular to the surface of the material and applying constant pressure. The depth of penetration measured by the impresser's indenter was used as an indicator of a material's hardness, as shown in Figure 4(b). Three different composite test specimens cut along printing, traverse, and stacking directions were prepared. 50 different hardness measurements were collected from each test specimen.

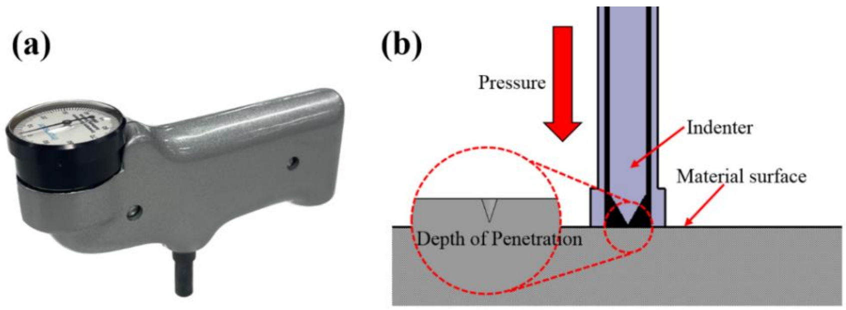

Figure 4. (a) Barcol hardness tester and (b) schematic drawing of hardness tester during the surface hardness test.

Surface abrasion resistance

Surface abrasion resistance refers to the ability of a material's surface to withstand friction wear. It measures how well a material can resist repeated contact with an abrasive surface without degrading. Surface abrasion resistance is an important property for composite materials that are used in tooling applications. Tool needs to be able to withstand friction wear from repeated contact, such as rubbing and scraping, during demolding process without losing its surface finish quality or dimensional accuracy. The surface abrasion resistance test was performed in accordance with ASTM D4060, the standard method for abrasion resistance of organic coatings, by the Taber Abraser. The Teledyne Taber abraser model 503 was used for this test, as shown in Figure 5(a). The abrasion resistance test specimen is mounted on the turntable of the tester and rotates at a constant speed. Two CS-10 Calibrase resilient wheels are pressed against the surface of the specimen with 500 g of load. The wheels rotate and rub the surface of the test specimen while the test specimen rotates on the turn table, as shown in Figure 5(b). Three different test specimens that cut along printing, traverse, and stacking directions were tested. The S-11 refacing disc is used to refacing the surface of the abrasion wheel every 1000 abrasion cycles. The weight of the test specimens was measured on every 200 abrasion cycles, and a total of 2000 abrasion cycles were tested for each test specimen. Any abraded residue on the test specimen have been removed before weighing the test specimens. Based on the weight change of the test specimen every 200-abrasion cycle, wear index for each test specimen was calculated with the following Equation:

$$I = \frac{(A-B)1000}{C}$$

Where I represent the wear index, A refers to initial weight of the test specimen, B refers to the final weight of the test specimen after wear has occurred, and C represents the number of abrasion cycles. The wear index quantifies the rate of material loss due to abrasion cycles and allows for comparison between specimens. A higher wear index value indicates increased material loss, whereas a lower wear index value indicates improved wear resistance.

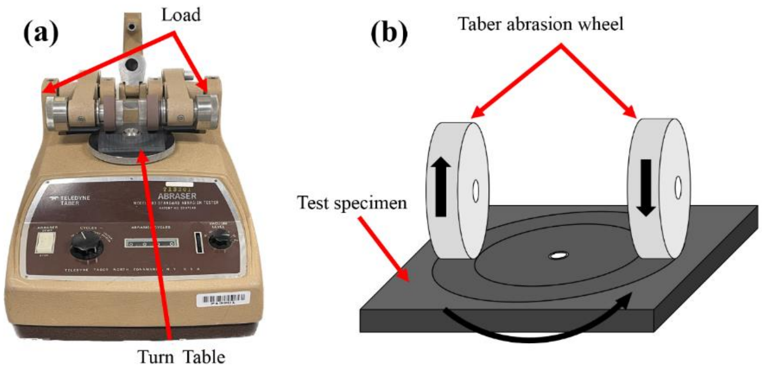

Figure 5. (a) Teledyne Taber abraser model 503. (b) Schematic drawing of the surface abrasion test.

Surface roughness test

Surface roughness indicates the texture and irregularity of a material's surface roughness, which is an important surface characteristic property of a composite part manufacturing tool. The surface roughness of the tool determines the surface finish quality of the final product. Moreover, the roughness of the mold surface affects the demolding force of the tool. A tool surface with high roughness can cause high required demolding force, which can eventually lead to part and tool defects. Furthermore, the high surface friction caused by high surface roughness can accelerate surface damage and erosion during repeated production cycles. As a result, low surface roughness is required for the tool surface to achieve high part surface finish quality and extended tool life. The surface roughness test was performed in accordance with ASTM D727, which is the standard method for measuring the surface roughness of abrasive blast cleaned metal surfaces with a portable stylus instrument. Mitutoyo SJ-210 surface tester was used as a surface roughness measuring tool as shown in Figure 6(a). The tester probe moved along the path, measuring deviations in the direction of the surface of the test specimen as shown in Figure 6(b). Arithmetic average roughness (R_a) was collected from each test specimen. The roughness tester was calibrated with a sampling length of 12.5 mm for the test. The roughness of all test specimens was measured in the same direction as the machining direction. Three different test specimens cut along printing, traverse and stacking directions were prepared. 30 surface roughness measurements were collected from each test specimen.

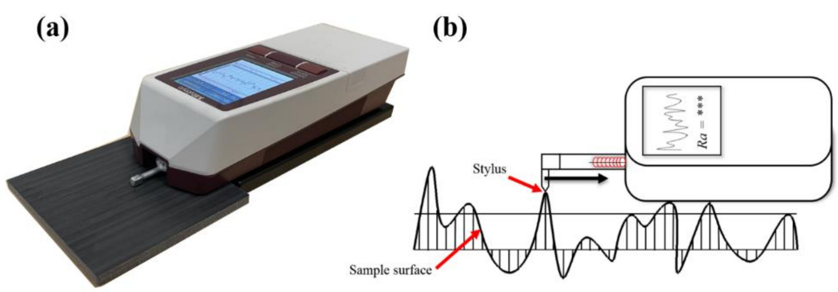

Figure 6. (a) Mitutoyo SJ-210 surface roughness tester and (b) schematic drawing of surface roughness measuring process using surface roughness tester.

Surface friction test

Surface friction indicates the resistance between two surfaces when they contact and slide or move relative to each other. During the composite part manufacturing process, a cured part needs to be removed from the composite part manufacturing tool, which requires low surface friction to prevent any damage to the tool and part. Moreover, because excessive friction between the tool and cured composite part can lead to premature surface wear and deformation of the shape of the final product, low surface friction between the mold and composite part is required.

The surface friction test was performed in accordance with ASTM D1894, the standard test method for the static and kinetic coefficients of friction of plastic film and sheeting. The surface friction test measures both the static coefficient of friction and the kinetic coefficient of friction. The static coefficient of friction represents the resistance to initial motion between the test plate and test specimens, and the kinetic coefficient of friction represents resistance when test specimen surfaces are already in motion. To investigate surface friction between additively manufactured composites with different angle cuts and composite parts, four printing direction cut, four stacking direction cut, and four traverse direction cut test specimens were prepared. The carbon fiber composite laminate was also installed onto the surface friction test plate to simulate a composite part that was manufactured on a tool. The test specimens were placed on the composite laminate surface and connected by string to a 22.68 kg capacity load cell. A string went through a pulley and connected to the loadcell. To apply the normal force to the test specimen, a weight block weighing 6.26 kg was placed on top of each test specimen. Figure 7 shows the surface friction test setup.

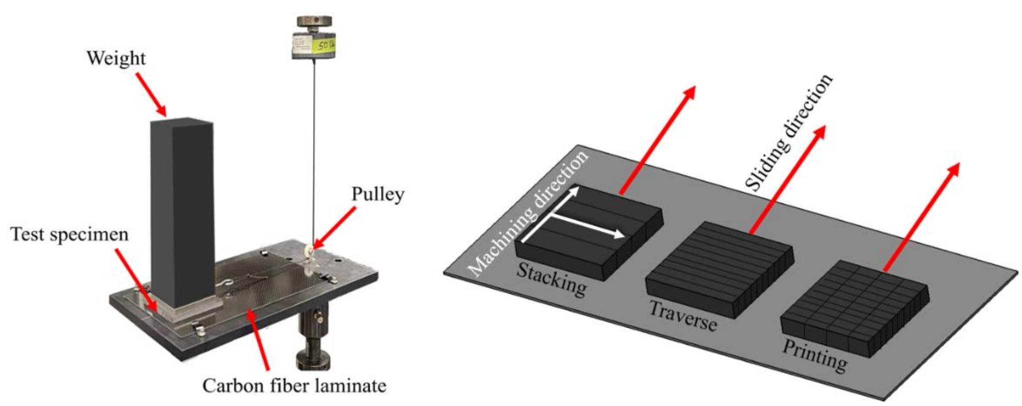

Figure 7. The surface friction test setup and schematic drawing showing tests specimens sliding direction relative to fiber direction.

The pulling rate of 50 mm/min was used. Three different cut angle specimens were placed on carbon fiber laminate and slid along the machining direction during the test. Additionally, test specimens were also placed and evaluated perpendicular to the machining direction in order to see the difference in surface friction of additively manufactured composites by direction of surface finishing. The static friction and kinetic friction between carbon fiber laminate and additively manufactured composite test specimens were calculated using the following equation:

$$F_s = \mu_s \mathrm{N}$$

$$F_k = \mu_k N$$

where F_s represents static friction force and F_k represent kinetic friction force. μ_s and μ_k represent static and kinetic friction coefficient. N represents the normal force applied to the test specimen.

Results

The microscopic images showed the variations in fiber content and orientation on the surfaces cut at different angles, as shown in Figure 8(a). The stacking direction microscopic image showed a significant presence of elongated fibers, indicating substantial in-plane oriented fibers on the surface. The varied orientations observed within the in-plane configuration suggest that during the process of compacting and printing, the fibers undergo flow, leading to localized changes in fiber orientation rather than a completely random distribution. In the traverse direction, both elongated fibers and dot-like fiber formations are observed. However, the presence of elongated ellipses aligned in a consistent direction suggests that the alignment can be attributed to the influence of the flow of the printing bead during the printing process, similar to the effect observed in the stacking direction. In the printing direction, the majority of the fibers appear in a dot-like pattern, indicating a substantial alignment of fibers in the normal direction, which corresponds to the direction of printing. Within the stacking direction cut test specimen, fiber content of 12.2% was measured. The traverse direction cut test specimen showed a slightly lower fiber content of 10.8%, while the printing direction cut test specimen had the lowest fiber content at 8.3%. Figure 8(b) shows the bar graph of average fiber content for each direction of cut.

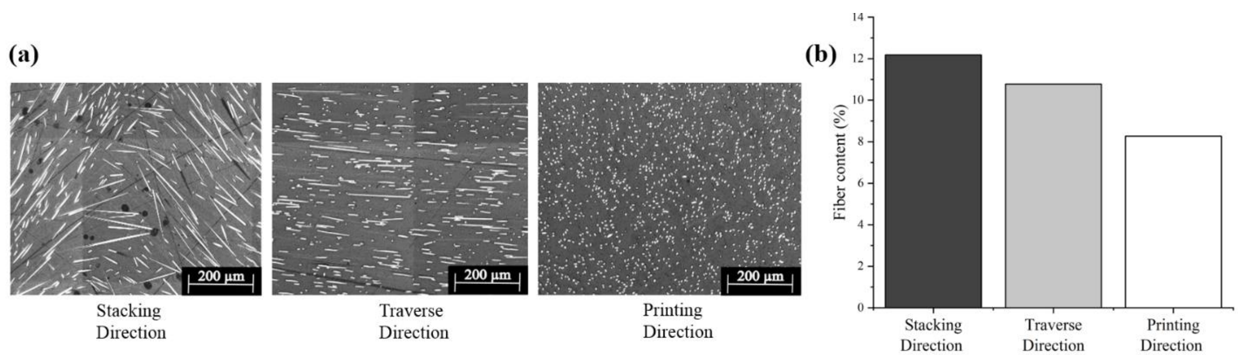

Figure 8. (a) Microscopic images corresponding to each direction cut direction of the test specimens and (b) the bar graph of fiber content of the test specimens cut with the stacking direction, traverse direction, and printing direction.

Surface Hardness Test

The surface hardness test findings revealed that the specimen cut along the stacking direction had the highest average Barcol hardness of 6.2, while the traverse direction had 0.62 average Barcol hardness and the stacking direction had 0.08 average Barcol hardness. According to the statistical analysis, there was a substantial difference in the average Barcol hardness between test specimens cut along the stacking direction and those cut along the traverse and printing directions. However, the average hardness did not differ considerably between test specimens cut along the traverse direction and the printing direction. Figure 9 shows a bar graph of the average Barcol hardness with a standard deviation bar for each test specimen.

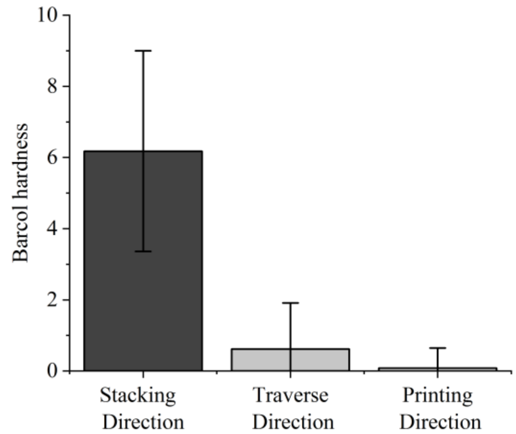

Figure 9. Bar graph of average Barcol hardness with standard deviation bar for each test specimens: cut with stacking direction, traverse direction, and printing direction.

Surface Abrasion Resistance Test

The evaluation of surface abrasion resistance among additively manufactured composite materials with different angle cuts did not show any significant differences. Figure 10(a) represents the weight change of each test specimen for every 200 abrasion cycles, and Figure 10(b) represents a bar graph of the average wear index of each test specimen, along with a standard deviation bar. The stacking direction had a wear index of 17.5, the traversal direction had a wear index of 17, and the printing direction had a wear value of 16. The test results indicated a consistent and linear decrease in weight change across all the test specimens. Moreover, from the statistical analysis, it was found that the average wear index exhibited no significant difference across all the test specimens, suggesting a comparable level of surface abrasion resistance.

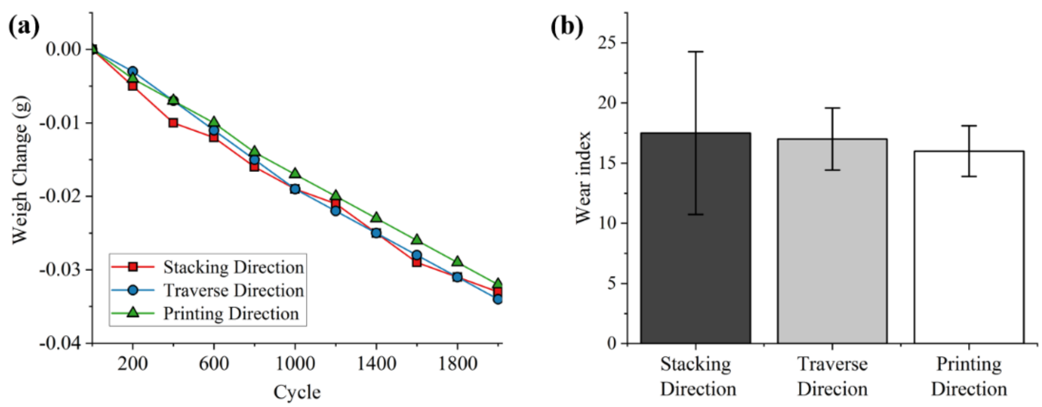

Figure 10. (a) The weight change of each test specimen for every 200 abrasion cycles during abrasion resistance test and (b) bar graph of the average wear index of each test specimens with standard deviation.

Surface Roughness Test

The investigation into surface quality, the roughness assessment, and the statistical analysis showed significant disparities in surface finish among different machining directions. The printing direction cut test specimen had an average R_a of 0.9, the traversing direction cut test specimen had an average R_a of 0.7, and the stacking direction cut test specimen had an average R_a of 0.7. The printing direction, in particular, had significantly greater roughness values than both the traverse direction (a difference of 28.37%) and the stacking direction (a difference of 13.8%). Figure. 11 shows a bar graph of average roughness with a standard deviation bar. The results show that the average R_a of test specimens cut along the printing direction was the highest, and test specimens cut along the traverse direction were the lowest. This can be attributed to the irregular dot-like pattern of fibers observed in the stacking direction of cut specimens during microscopic analysis. Such a fiber arrangement may contribute to increased roughness. Additionally, the stacking direction may have limited interlayer bonding compared to other directions, leading to the formation of surface defects and higher roughness.

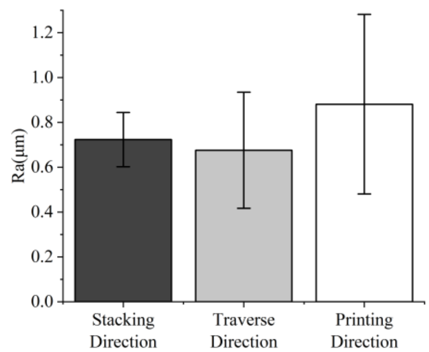

Figure 11. The bar graph of average R_a of the test specimens cut with stacking direction, traverse direction, and printing direction with standard deviation bar.

Surface Friction Test

In terms of surface friction, the static friction coefficient in the non-machining direction differed significantly from the stacking and printing directions. The average static friction coefficient for stacking direction cut was 0.35, traverse direction cut was 0.38, and printing direction cut was 0.40. The printing direction showed a static friction coefficient that was 15.05% higher than the stacking direction. This is most likely due to greater resistance caused by higher surface roughness and irregular distribution of short fibers in the printing direction. The static friction coefficient, on the other hand, did not significantly different between machining directions. The average static friction coefficient for the stacking direction was 0.40, the traversal direction cut was 0.41, and the printing direction cut was 0.39. This is attributable to the machining process, which results in a more uniform and consistent surface texture, which results in similar friction behavior.

There was no substantial variation in the kinetic friction coefficient between the various directions in the non-machining direction. The average kinetic friction coefficient for the stacking direction was 0.26, the traversal direction cut was 0.27, and the printing direction cut was 0.28. This is attributable to the fact that surface features like roughness and fiber pattern may not have a substantial impact on frictional behavior during sliding motion. However, a significant change in the kinetic friction coefficient was found within the machining direction. The average kinetic friction coefficient for the stacking direction was 0.33, the traversal direction cut was 0.34, and the printing direction cut was 0.31. The traverse direction was 8% higher than the printing direction. This difference could be attributable to differences in fiber orientation, as long fibers perpendicular to the sliding direction may provide more resistance than short fibers perpendicular to the stacking direction. Figure 12(a) shows a plot graph of the results for each test specimen, while Figures 12(b) and (c) show an average bar graph with standard deviations for the static and kinetic friction coefficients throughout the test specimens. These figures show the observed differences in friction characteristics across cut angles as well as machining and non-machining directions.

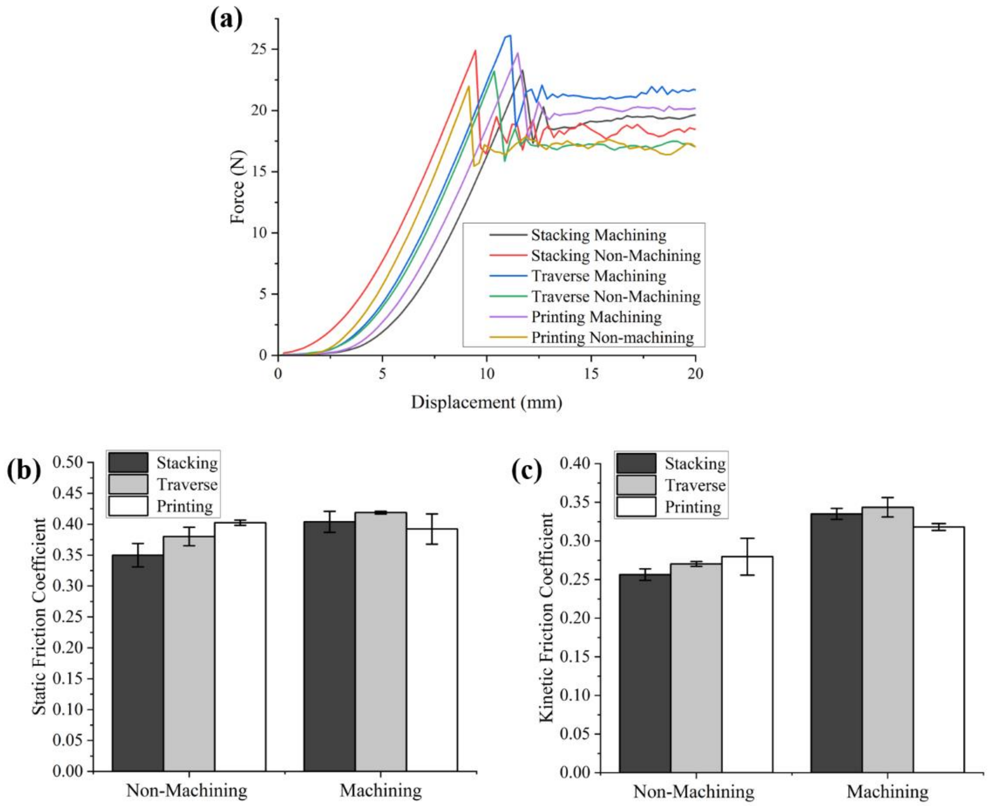

Figure 12. (a) Force versus displacement plot of surface friction test for each test specimens. Average (b) static and (c) kinetic friction coefficient of test specimen with standard deviation bar.

Discussion

The additively manufactured composite material showed a heterogeneous surface, comprising both fibers and matrix, with variations in fiber content and orientation depending on the cutting angle. The test results showed significant variations in hardness, roughness, and friction, not in surface abrasion resistance. Overall, the surface properties of the composite material showed some limitations for optimal tooling application. The abrasion resistance of the additively manufactured composite surface was lower than the traditional tooling metals, and both static and kinetic surface friction coefficient of the additively manufactured composite were high regardless of the cutting angle.

To address these issues, Kim et al. [16] investigated the application of an additional thermoset polymer coating with ceramic particles for additively manufactured composite tooling. Kim et al. [16] reported that the additional coating resulted in a more homogeneous surface for the tool, offering consistent surface characteristics regardless of the cutting angle as shown in Figure 13.

The coated surface simplified the overall surface characterization of the tool and enabled more accurate prediction of the required demolding force. Also, the additional coating with ceramic particles enhanced certain surface properties. Although the coating did not improve hardness and roughness, it significantly improved abrasion resistance and surface friction. Kim et al. [16] used additively manufactured 50% carbon fiber by weight Polyphenylene Sulfide (PPS) for the test specimens. The non-coated composite test specimen had an average wear index of 23.5, but it decreased to 2.5 (89% decrease). The additional coating with the ceramic particle provided abrasion resistance that was even higher than the traditional tooling metals (6061-T6 aluminum: 7.5 and 1020 steel: 7). Kim et al. [16] also reported that the additional coating on the additively manufactured composite material also reduced the average static friction coefficient by 40% and the average kinetic friction by 38%.

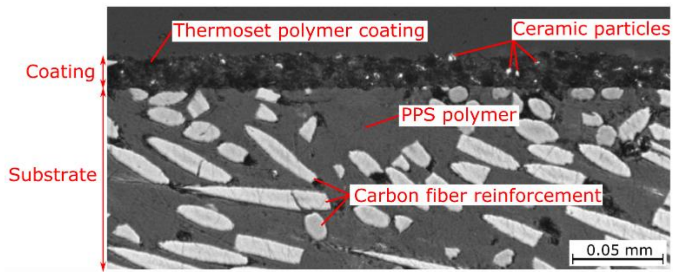

Figure 13. Microscopic image of cross-sectional area of the coating applied on the substrate.

Conclusion

The surface properties of a 20% carbon fiber-filled acrylonitrile butadiene styrene (ABS) composite block manufactured using additive manufacturing were investigated in this work. The composite block was printed with EDAM technology and cut in three directions: the printing direction, the traversal direction, and the stacking direction. The goal was to assess the composite material's surface characteristics for possible tooling applications. The test specimens were CNC machined to provide optimal surface quality for performing surface property tests such as hardness, surface abrasion resistance, roughness, and surface friction. Microscopic investigation was also carried out to assess the fiber content and pattern.

In terms of surface properties related to durability, hardness, and surface abrasion resistance, the test specimens cut along the stacking direction showed significantly higher hardness (6.2) compared to the traverse direction cut (0.62) and printing direction cut (0.08) test specimens. However, no significant difference in surface abrasion resistance was observed across test specimens cut along the stacking, traversing, and printing directions, which is critical for tool lifespan. The investigation of roughness and surface friction, which are critical for assessing the surface finishing quality of the final composite product, showed that the printing direction cut test specimen had the highest roughness, with a value 28.37% greater than the traverse direction and 13.8% greater than the stacking direction. The stacking direction and printing direction cut showed a difference in the static coefficient friction in the non-machining direction. On the other hand, it did not show significant difference in machining direction Also, there was no significant difference in kinetic friction coefficient in the non-machining direction. However, there was significant difference between traverse direction and stacking direction with traverse direction was 8% higher than stacking direction.

In this work, the difference in the surface characteristics of additively manufactured composite material due to the different angle of cut has been investigated. Although the application of composite additive manufacturing technology for tooling showed advantages over traditional metal tooling by reducing costs and manufacturing time, it has been found that it has some limitations in achieving optimal surface properties for tooling applications. Additional study on coating the surface of additively manufactured tools will be needed to achieve optimal surface characteristics for tooling and enhance the durability and surface quality of tool and the final product.

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