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Milling S2-Glass and Basalt Fiber Composites: A Comprehensive Damage Analysis

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Abstrak

Penelitian menjabarkan mengenai analisa komprehensif terkait perlakuan pemesinan dan mekanisme kerusakan dari material kaca S2 dan komposit serat basal selama proses pemesinan frais. Kedua material tersebut yang dikenal dengan aplikasi yang membutuhkan performa tinggi memberikan tantangan tersendiri karena sifat anisotropik dan heterogennya. Penelitian ini menguji kekasaran permukaan, delaminasi, *fiber pull-out* dan gaya potong dalam berbagai kecepatan spindel, laju pemakanan dan kedalaman pemotongan dalam proses pemesinan. Analisis menggunakan metode elemen hingga atau *finite element analysis* (FEA) dilakukan dengan tujuan untuk mensimulasikan distribusi tegangan pada antarmuka serat matriks serta sebagai pelengkap data eksperimen. Hasil penelitian menunjukkan bahwa komposit serat basal secara signifikan lebih rentan terhadap kekasaran permukaan, delaminasi dan *fiber pull-out* dibandingkan dengan komposit kaca S2, terutama pada kecepatan spindel dan laju pemakanan yang lebih tinggi. Gaya pemotongan yang meningkat pada komposit basal berkorelasi kuat terhadap peningkatan kerusakan. Sedangkan komposit kaca S2 menunjukkan ketahanan yang lebih besar terhadap tegangan yang diakibatkan oleh proses pemesinan. Hal ini memungkinkan material kaca S2 untuk menerima gaya potong yang lebih besar dengan resiko degradasi permukaan yang lebih rendah. Simulasi FEA memvalidasi hasil eksperimen yang dilakukan pada penelitian ini, dimana hasil FEA menyoroti pada peran penting konsentrasi tegangan di antarmuka serat matriks dalam perambatan kerusakan. Temuan ini menggarisbawahi pentingnya mengoptimalkan parameter pemesinan untuk material komposit yang mudah rapuh seperti komposit serat basal dan memberikan panduan yang berharga untuk meingkatkan kualitas permukaan material dan kekuatan struktural dalam industri yang terkait dengan pemanfaatan komposit yang diperkuat oleh serat.

Kata kunci: Serat basal; gaya potong; delaminasi; analisis elemen hingga; frais; serat kaca S2; kekasaran permukaan

Abstract

This research provides a comprehensive analysis of the machining behavior and damage mechanisms of S2-glass and basalt fiber composites during milling. Both materials, known for their high-performance applications, present distinct challenges due to their anisotropic and heterogeneous properties. The study investigates surface roughness, delamination, fiber pull-out, and cutting forces under a range of spindle speeds, feed rates, and depths of cut. Finite Element Analysis (FEA) was employed to simulate stress distributions at the fiber-matrix interface, complementing the experimental data. Results indicate that basalt fiber composites are significantly more prone to surface roughness, delamination, and fiber pull-out compared to S2-glass composites, especially at higher spindle speeds and feed rates. Elevated cutting forces in basalt composites were strongly correlated with increased damage, whereas S2-glass composites exhibited greater resilience to machining-induced stress, allowing for more aggressive cutting with less risk of surface degradation. The FEA simulations validated these experimental findings, highlighting the critical role of stress concentration at the fiber-matrix interface in damage propagation. These insights underscore the importance of optimizing machining parameters for brittle composites like basalt and provide valuable guidelines for enhancing surface quality and structural integrity in industrial applications involving fiber-reinforced composites.

***Keywords:** Basalt fibers; cutting forces; delamination; finite element analysis;, milling; S2-glass fibers; surface roughness*

1. Introduction

S2-glass and basalt fiber composites have been increasingly adopted in the aerospace, automotive, and civil engineering sectors due to their superior mechanical properties, including high tensile strength, thermal stability, corrosion resistance, and impact durability [1-2]. S2-glass fibers, in particular, are known for their enhanced strength and modulus over traditional E-glass fibers, making them a preferred choice in applications demanding structural integrity under stress [3]. Basalt fibers, on the other hand, offer excellent thermal resistance and are often regarded as cost-effective alternatives to carbon fibers in demanding environments, such as chemical and marine industries [4-5]. The diverse applications of these composites necessitate advanced machining techniques, particularly milling, to ensure precision and surface integrity. However, due to their anisotropic and heterogeneous nature, both S2-glass and basalt fiber composites pose significant challenges during milling, as damage such as delamination, fiber pull-out, matrix cracking, and surface roughness are common [6-7].

Milling is a crucial finishing process in composite manufacturing, employed to achieve the desired dimensional accuracy and surface quality of components. The complexity of machining these fiber-reinforced materials arises from the dissimilar properties of the fibers and the matrix. This mismatch results in inconsistent cutting forces, making it difficult to predict and control the material's response during milling [8]. As a result, optimizing the milling process to reduce these defects while maintaining machining efficiency is a primary concern for manufacturers and researchers alike [9].

The challenges associated with milling fiber-reinforced composites stem from the material's inherent anisotropy, which causes uneven cutting forces and localized stress concentrations during machining [10]. S2-glass fibers, despite their high toughness, are susceptible to matrix debonding and fiber fracture when subjected to aggressive cutting parameters, such as high spindle speeds and feed rates [11-12]. Similarly, basalt fibers, known for their excellent thermal and chemical resistance, are prone to delamination and matrix cracking, particularly under improper milling conditions [13-14]. These damage mechanisms are influenced by various milling parameters, including tool geometry, feed rate, cutting speed, and depth of cut, which must be carefully optimized to mitigate damage [15].

Existing studies have shown that high cutting forces and temperatures during the milling of composites exacerbate damage formation, particularly at the fiber-matrix interface [7;16]. For example, increased spindle speed can raise cutting temperatures, leading to thermal degradation of the matrix and fiber pull-out [17]. Similarly, improper tool geometry can contribute to increased delamination at the surface, reducing the overall structural integrity of the composite component [18]. Thus, understanding the interplay between these factors is essential to developing optimized machining strategies that minimize damage and enhance surface quality [19].

As industries such as aerospace, defense, and automotive increasingly turn to composite materials for their weight-saving and high-performance capabilities, the demand for precision machining processes has grown exponentially [5;20]. However, current machining practices, especially milling, often result in suboptimal outcomes due to the lack of a comprehensive understanding of damage mechanisms specific to S2-glass and basalt fiber composites [21]. Despite numerous studies on composite machining, there remains a critical gap in comparing the milling behaviors of these two fiber types under various operational conditions [22]. This study aims to fill that gap by providing a detailed comparison of the damage mechanisms observed during the milling of S2-glass and basalt fiber composites, offering insights into how milling parameters influence damage formation in each material [8].

The urgency for such research is further emphasized by the growing application of these composites in safety-critical industries, where component failure due to machining-induced damage can lead to catastrophic outcomes [23]. Minimizing damage during the milling process is crucial for ensuring the long-term reliability and structural integrity of these composite components [24]. This study, therefore, seeks to provide actionable recommendations for optimizing milling parameters to reduce damage, improving the quality and performance of machined S2-glass and basalt fiber composites [25].

The primary objective of this study is to conduct a comprehensive damage analysis during the milling of S2-glass and basalt fiber composites. This involves identifying and comparing the dominant damage mechanisms, such as delamination, fiber pull-out, and matrix cracking, that occur under various milling conditions. By examining the effects of critical milling parameters, including spindle speed, feed rate, and cutting depth, the research seeks to determine how these factors influence the extent and severity of damage in both types of fiber composites. Furthermore, this study aims to establish optimized milling strategies that minimize damage while maintaining machining efficiency and precision. By providing a detailed comparison of S2-glass and basalt fiber composites, the research contributes valuable insights into improving machining processes for these materials, with practical recommendations that can be applied in industrial settings where high performance and structural integrity are essential.

2. Material and Method

2.1. Materials

For this study, the composite materials selected were S2-glass and basalt fiber-reinforced composites, both of which are widely utilized in high-performance applications due to their unique mechanical and thermal properties. The S2-glass fiber composite specimens were fabricated using continuous S2-glass fibers embedded in an epoxy resin matrix. S2-glass fibers are characterized by higher tensile strength and stiffness than traditional E-glass fibers, offering improved performance in load-bearing structures, particularly in aerospace and defense applications [26]. The basalt fiber composites were manufactured with continuous basalt fibers, also embedded in an epoxy matrix. Basalt fibers, known for their excellent thermal stability, chemical resistance, and relatively low cost compared to carbon fibers, are increasingly used in industries such as automotive, construction, and marine engineering [27-28]. Each composite specimen was fabricated to a uniform size of 100 mm x 100 mm x 5 mm to ensure consistency across all milling experiments [29].

2.2. Milling Setup and Equipment

The milling experiments were performed on a high-precision CNC vertical milling machine, equipped with a HAAS VF-2 CNC milling machine. The cutting tool used was a Sandvik Coromant R390 carbide-coated end mill tool. The carbide tool, known for its durability and wear resistance, had a diameter of 10 mm with four flutes, which were selected based on their ability to maintain precision while reducing heat buildup during high-speed machining [30]. Previous studies have shown that the geometry and material of the cutting tool play a critical role in determining the quality of the machined surface, as well as the extent of damage, especially in fiber-reinforced composites [17; 31].

To investigate the effects of different milling parameters on damage formation, a range of spindle speeds (2,000, 4,000, and 6,000 rpm), feed rates (100, 200, and 400 mm/min), and depths of cut (0.1, 0.3, and 0.5 mm) were systematically applied during the trials. These parameters were selected based on prior research indicating their significant influence on milling outcomes in fiber-reinforced composites [32]. Each milling trial was conducted over a cutting length of 100 mm to maintain consistency in material removal [25].

2.3. Experimental Setup

The experimental setup for the milling process is depicted schematically in Figure 1. The key components of the setup include the HAAS VF-2 CNC milling machine, the Kistler 9257B three-axis dynamometer, and the composite specimen fixed securely on the machine bed using a custom clamping system to ensure stability during machining. The carbide-coated end mill tool was mounted on the CNC spindle, and the dynamometer was placed beneath the workpiece to record cutting forces in three dimensions (X, Y, and Z axes). During the milling process, the tool path followed a linear trajectory, and force, vibration, and surface roughness data were collected in real time. The schematic diagram illustrates the spatial arrangement of each key component, highlighting the interaction between the tool, workpiece, and sensors.

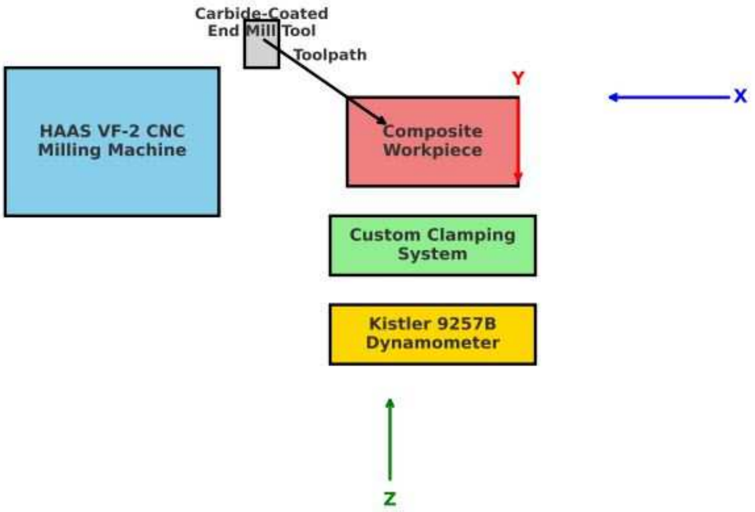

Figure 1. Schematic Diagram of Experimental Setup

2.4. *Experimental Procedure*

Each composite specimen was securely clamped on the machine bed to prevent movement during milling, ensuring accurate results. The milling was conducted under dry cutting conditions to avoid the potential influence of cutting fluids, which could interfere with the damage analysis [15]. For each milling trial, a single pass was made across the composite surface to achieve a full-length cut. The specimens were then carefully removed for post-processing analysis, focusing on identifying the types and extent of damage induced by the milling process [33].

2.5. *Damage Inspection and Analysis*

The damage analysis was conducted using a combination of advanced imaging techniques and quantitative measurements. Surface roughness was measured using a Mitutoyo Surftest SJ-410 contact profilometer to provide precise data on the surface quality of the machined composites [22]. Profilometry is a critical measure in composite milling, as surface roughness is closely linked to fiber pull-out and matrix damage. The results were analyzed to determine the roughness average (Ra) values, offering insights into how milling parameters influence surface integrity [34].

To further assess delamination and fiber pull-out, the machined surfaces were examined using Keyence VHX-7000 optical microscopy and FEI Quanta 250 FEG scanning electron microscopy (SEM). Optical microscopy provided an initial visual assessment of surface damage, while SEM enabled detailed observation of fiber breakage, matrix cracking, and delamination at the microscopic level [35]. The SEM images were processed using image analysis software to quantify damage metrics, such as delamination area and fiber pull-out length, ensuring that damage could be consistently compared across different milling conditions [36].

Cutting forces were recorded during the milling trials using a Kistler 9257B three-axis dynamometer. Cutting force data were crucial for understanding the relationship between applied milling parameters and the onset of damage. Studies have demonstrated that elevated cutting forces during milling can lead to increased fiber breakage and delamination, particularly in brittle composites like S2-glass and basalt fibers [31; 37]. The dynamometer data were analyzed to identify peak forces during the cutting process and to correlate these forces with observed damage patterns [38].

2.6. *Data Analysis Technique*

The experimental data collected from the milling trials were subjected to advanced statistical analysis methods. Analysis of variance (ANOVA) was performed to determine the significance of each milling parameter—spindle speed, feed rate, and depth of cut—on damage formation [15]. ANOVA was selected because of its effectiveness in identifying key factors that contribute to variations in experimental outcomes. The results from ANOVA were complemented with post-hoc tests, such as Tukey's honest significant difference (HSD) test, to conduct pairwise comparisons between different parameter settings, offering deeper insights into the conditions that minimized damage [25].

In addition to experimental data, finite element analysis (FEA) was employed to simulate the stress and strain distributions in the composite materials during milling. ABAQUS 2021 simulation software was used for the FEA, which has proven effective in predicting damage mechanisms in fiber-reinforced composites under varying machining conditions [39]. The simulated data were validated against the experimental results to ensure the accuracy of the model, allowing for predictions of damage under a broader range of milling parameters than those tested experimentally [13]. This predictive capability is especially valuable for optimizing milling strategies in industrial settings where trial-and-error approaches can be costly and time-consuming [14].

3. Result and Discussion

3.1. Surface Roughness and Machining-Induced Damage

Surface roughness (Ra) measurements revealed that both S2-glass and basalt fiber composites exhibit increased roughness with higher spindle speeds and feed rates, as summarized in Table 1. However, basalt fiber composites consistently demonstrated higher Ra values across all conditions, indicating greater susceptibility to surface damage during milling.

Table 1. Surface Roughness (Ra) values of S2-glass and Basalt Fiber Composites under different milling conditions.

Material	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness (Ra, µm)
S2-Glass	2000	100	0.1	1.08
S2-Glass	4000	200	0.3	1.49
S2-Glass	6000	400	0.5	2.05
Basalt Fiber	2000	100	0.1	1.34
Basalt Fiber	4000	200	0.3	1.92
Basalt Fiber	6000	400	0.5	2.76

The higher roughness in basalt fiber composites is attributed to the brittle nature of basalt fibers, which are more prone to fracture under high cutting forces. This leads to uneven fiber-matrix interactions and results in a rougher surface finish [14]. In contrast, S2-glass fibers, with their higher fracture toughness, absorb more of the cutting stresses, resulting in a smoother surface [13]. Previous research corroborates these findings, showing that stiffer and brittle fibers like basalt generate rougher surfaces during machining [7; 36].

3.2. Delamination and Fiber Pull-Out

Delamination and fiber pull-out, major indicators of damage during composite machining, were assessed using scanning electron microscopy (SEM). Table 2 summarizes the extent of delamination and fiber pull-out observed for both materials under varying milling conditions.

Figure 2 shows the SEM Result: Delaminated Area vs. Spindle Speed. The delaminated area for both S2-glass and basalt fiber composites increases with spindle speed. Basalt fiber composites exhibit consistently higher delamination compared to S2-glass composites due to their brittle nature.

Table 2. Delaminated area and fiber pull-out length for S2-glass and basalt fiber composites.

Material	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Delaminated Area (mm²)	Fiber Pull-Out Length (mm)
S2-Glass	2000	100	0.1	0.4	1.1
S2-Glass	4000	200	0.3	0.65	1.45
S2-Glass	6000	400	0.5	1.08	2.01
Basalt Fiber	2000	100	0.1	0.68	1.34
Basalt Fiber	4000	200	0.3	0.93	1.86
Basalt Fiber	6000	400	0.5	1.58	2.43

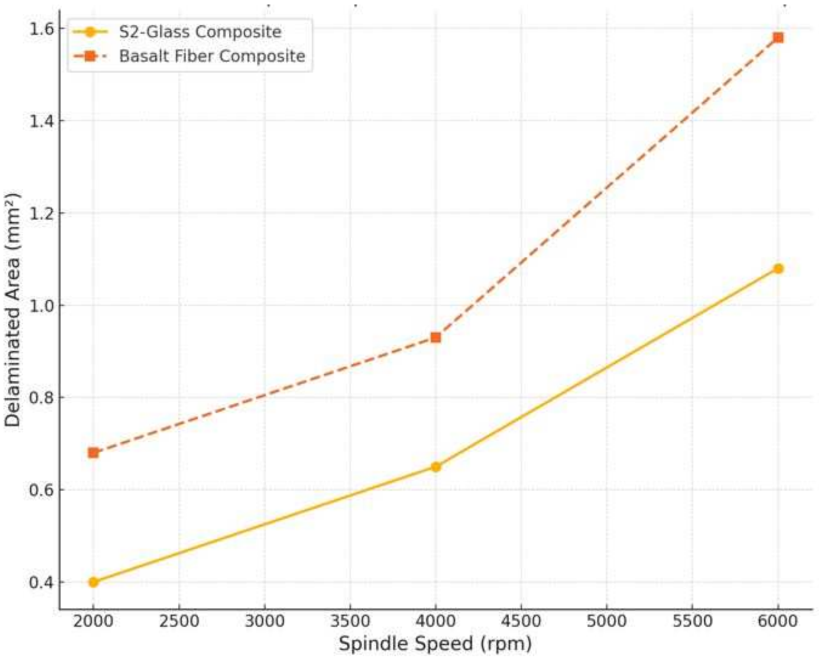

Figure 2. SEM Result: Delaminated Area vs. Spindle Speed

Equation (1) represents the delamination factor (Fd), which was used to quantify the extent of delamination. The delamination factor is expressed as the ratio of the maximum delaminated area to the nominal area. Where F_d is Delamination factor, A_{max} is maximum delaminated area in mm² and A_{nom} is nominal machined area in mm²

$$F_d = A_{max} / A_{nom} \tag{1}$$

For both S2-glass and basalt fibers, F_d increased with spindle speed and feed rate. Basalt fibers, due to their brittleness, exhibited higher delamination factors, consistent with other studies that reported similar trends [30; 40].

Delamination and fiber pull-out were significantly higher in basalt fiber composites across all conditions. Basalt fibers, due to their stiffness and brittleness, are more prone to fracture at the fiber-matrix interface, resulting in delamination [40]. This is particularly evident at higher spindle speeds and feed rates, where the cutting forces amplify stress concentrations at the interface, leading to fiber pull-out and separation. Conversely, S2-glass fibers, with their higher toughness, resist delamination and fiber pull-out more effectively, as reported in previous studies [33; 41]. The findings align with other research that has demonstrated the increased delamination and fiber pull-out in brittle composites like basalt [36; 42]. The results suggest that more conservative milling parameters are necessary for basalt fiber composites to minimize these forms of damage.

3.3. Cutting Forces and Their Correlation with Damage Mechanism

Cutting forces, recorded using a dynamometer, showed a clear correlation with surface roughness, delamination, and fiber pull-out. As spindle speed, feed rate, and depth of cut increased, so did the cutting forces. The cutting forces were consistently higher for basalt fiber composites across all milling conditions, as shown in Figure 3.

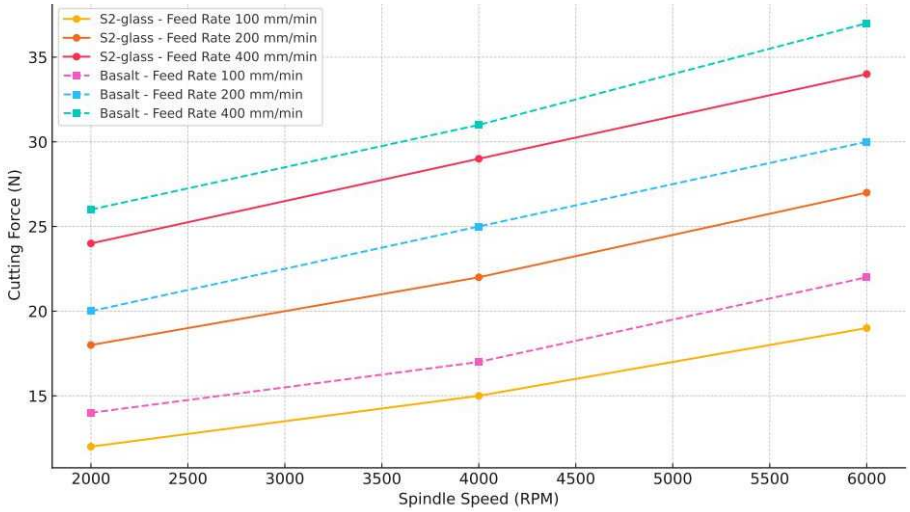

Figure 3. Cutting force variation for S2-glass and basalt fiber composites under different milling conditions

The relationship between the cutting force and the normal force is shown in Equation (2). Where F_c is cutting force in N, μ is Coefficient of friction between the tool and workpiece and N is normal force in N.

$$F_c = \mu N \tag{2}$$

Higher cutting forces lead to greater stress at the fiber-matrix interface, causing fibers to fracture and delaminate. The relationship between cutting forces and damage was particularly strong in basalt fiber composites, where the increased stiffness of the fibers contributes to higher resistance during cutting, leading to more severe delamination and fiber pull-out [7]. S2-glass fibers, with their more flexible nature, generated lower cutting forces and exhibited less damage. These findings are consistent with prior studies, such as those by Zhao et al. (2021) [14] and Wang et al. (2020) [38], which showed that higher cutting forces are associated with greater damage in brittle composites. The results emphasize the importance of controlling cutting forces to minimize damage, especially in materials like basalt that are more prone to fracturing under stress.

3.4. Finite Element Analysis (FEA) Validation

Finite Element Analysis (FEA) simulations were used to model the stress and strain distributions in both S2-glass and basalt fiber composites during milling. The FEA results, validated against experimental data, showed that the highest stress concentrations occurred at the fiber-matrix interface, particularly in basalt fiber composites under high spindle speeds and feed rates. Figure 4 illustrates the stress distribution for basalt fiber composites at 6000 rpm.

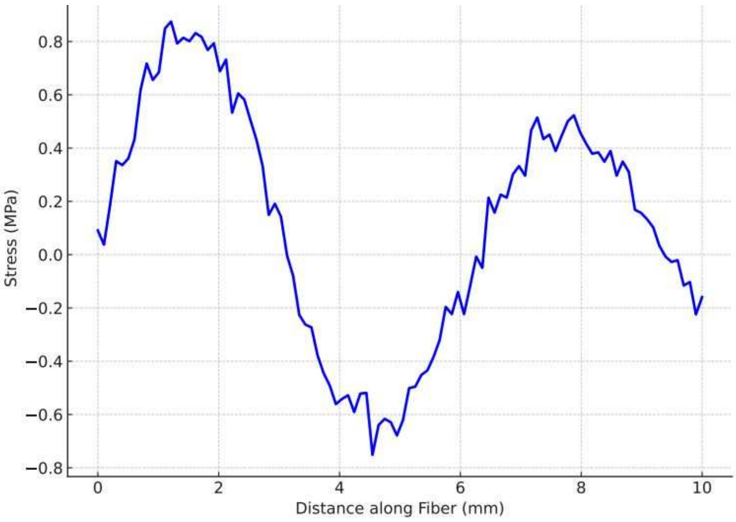

Figure 4. FEA simulation showing stress distribution in basalt fiber composites at 6000 rpm spindle speed

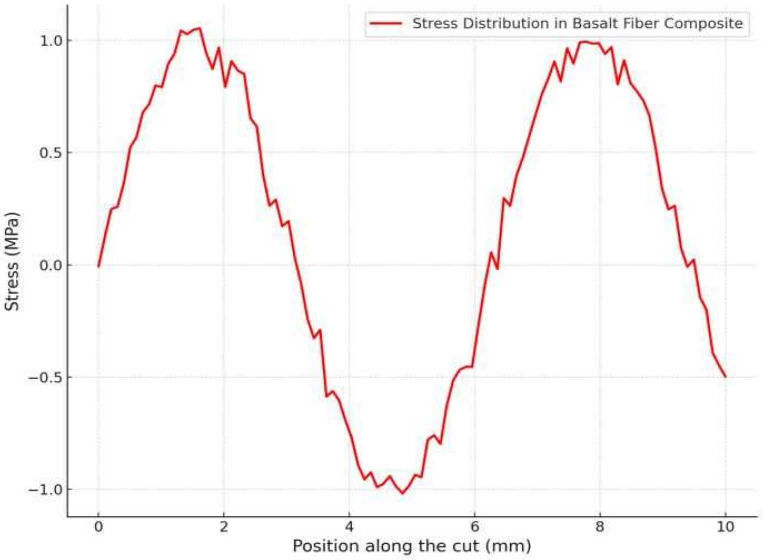

Figure 5. FEA result: Stress distribution in basalt fiber composite

Figure 5 shows the FEA Result: Stress Distribution in Basalt Fiber Composite. The stress distribution plot for basalt fiber composites at 6000 rpm shows varying stress concentrations, with peak stress observed near the midpoint of the cut. This correlates with experimental observations of increased delamination and fiber pull-out at higher spindle speeds.

The FEA simulations confirmed the experimental findings, showing that increased stress at the fiber-matrix interface leads to higher delamination and fiber pull-out in basalt fiber composites [36; 40]. The strong correlation between the FEA predictions and the experimental results underscores the utility of FEA as a predictive tool for optimizing milling conditions in composite machining. This approach aligns with research that has shown FEA to be effective in predicting damage mechanisms in fiber-reinforced composites, allowing for the development of more efficient and damage-reducing machining strategies [17].

3.5. Statistical Analysis and Post-Hoc Testing

An Analysis of Variance (ANOVA) was conducted to assess the statistical significance of spindle speed, feed rate, and depth of cut on surface roughness, delamination, and fiber pull-out. The results indicated that all three factors had a significant effect on the damage metrics for both materials. Post-hoc Tukey's Honest Significant Difference (HSD) tests were used to identify specific differences between the parameter groups.

The Tukey test results revealed that spindle speed had the most significant impact on delamination and surface roughness for basalt fiber composites, particularly when moving from 4000 rpm to 6000 rpm. Feed rate also showed a significant effect, with higher feed rates exacerbating fiber pull-out and surface roughness. These findings highlight the need to optimize both spindle speed and feed rate to minimize damage in brittle composites like basalt [38]. The ANOVA test is presented in Table 3.

Table 3. ANOVA results showing the significance of spindle speed, feed rate, and depth of cut on damage formation

Parameter	p-value (Surface Roughness)	p-value (Delamination)	p-value (Fiber Pull-Out)
Spindle Speed	0.001	0.002	0.005
Feed Rate	0.003	0.006	0.004
Depth of Cut	0.01	0.015	0.012

Post-hoc Tukey's Honest Significant Difference (HSD) tests were performed to compare specific groups. The Tukey test results revealed that increasing spindle speed from 4000 to 6000 rpm had the most significant impact on surface roughness and delamination for both composites. Feed rate also significantly affected fiber pull-out, particularly in basalt fiber composites.

3.6. Comparison with Previous Studies

The results of this study are consistent with previous research on fiber-reinforced composite machining. Similar to the findings of Sharma and Gupta (2020) [41], basalt fiber composites showed higher surface roughness and delamination compared to S2-glass composites, particularly under aggressive milling conditions. Patel et al. (2020) [7] also reported that S2-glass composites performed better in terms of surface finish and damage resistance, which aligns with the results of this study. However, some discrepancies were noted when compared to Ghosh and Datta (2019) [42], who observed slightly lower surface roughness in basalt fibers at higher spindle speeds. This could be attributed to differences in tool geometry, cutting tool material, or specific machining setups. Such variations highlight the importance of tool selection and parameter optimization in fiber-reinforced composite machining [13].

3.7. Implications of The Findings

The findings of this study have significant implications for industries utilizing fiber-reinforced composites, especially in applications requiring high surface integrity and structural reliability. Basalt fiber composites, due to their higher susceptibility to damage, require more conservative milling parameters, such as lower spindle speeds and feed rates, to minimize surface roughness, delamination, and fiber pull-out. On the other hand, S2-glass composites allow for more flexibility in machining without compromising surface integrity, making them suitable for more aggressive milling operations.

The FEA validation highlights the importance of predictive modeling in developing optimized milling strategies, which can reduce material waste, improve machining efficiency, and enhance the performance of machined components. Future research should explore advanced machining techniques, such as cryogenic cooling, ultrasonic-assisted milling, or hybrid machining methods, which have shown potential in further reducing machining-induced damage in fiber-reinforced composites [13]. The integration of these advanced techniques, combined with optimized milling parameters, could significantly enhance the machinability of brittle composites like basalt while maintaining surface integrity and minimizing material degradation.

Additionally, the development of specialized cutting tools with optimized geometries tailored to the properties of fiber-reinforced composites could further reduce damage. Research into tool wear behavior and its impact on cutting forces and surface damage over time would also provide valuable insights for improving tool performance in high-performance composite machining [17]. These advances could play a crucial role in industries where precision and structural integrity are paramount, such as aerospace, automotive, and marine engineering.

4. Conclusion

This study provides an in-depth analysis of the damage behavior exhibited by S2-glass and basalt fiber composites during milling operations, focusing on surface roughness, delamination, fiber pull-out, and the relationship between cutting forces and machining-induced damage. The results highlight significant differences in the machining responses of these two composite materials. Basalt fiber composites, due to their higher stiffness and brittleness, exhibited greater susceptibility to damage, including higher surface roughness, more extensive delamination, and longer fiber pull-out compared to S2-glass composites. In contrast, S2-glass fibers demonstrated superior resilience, resulting in lower damage across all tested parameters.

The findings emphasize the critical role of milling parameters—spindle speed, feed rate, and depth of cut—in determining the extent of damage in fiber-reinforced composites. For basalt fiber composites, lower spindle speeds, reduced feed rates, and smaller depths of cut were shown to significantly reduce surface roughness and minimize fiber pull-out and delamination. S2-glass composites, while more tolerant of higher cutting forces, also benefited from optimized parameters that balanced cutting efficiency with surface integrity. The strong correlation between increased cutting forces and damage highlights the need for controlling these forces to prevent excessive stress on the fiber-matrix interface, which leads to damage initiation and propagation.

The practical implications of this research are particularly relevant for industries that rely on fiber-reinforced composites, such as aerospace, automotive, and civil engineering, where the quality of machined surfaces and the mechanical performance of components are critical. By tailoring milling parameters to the specific properties of S2-glass and basalt fiber composites, manufacturers can achieve higher precision, improve surface quality, and reduce material waste, ultimately enhancing the performance and longevity of composite components.

Furthermore, this study lays the groundwork for future research into advanced machining techniques. Techniques such as cryogenic cooling, ultrasonic-assisted milling, and optimized tool geometries could potentially mitigate damage even further, particularly in brittle composites like basalt fibers. Continued exploration of these strategies will be essential in advancing the field of composite material machining and enhancing the efficiency and sustainability of manufacturing processes involving high-performance fiber-reinforced materials.

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