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PLY-TOOL AND PLY-PLY FRICTION CHARACTERIZATION OF A BINDER STABILIZED UNIDIRECTIONAL NON-CRIMP FABRIC

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ABSTRACT

Recent advancements in high-pressure resin transfer molding (HP-RTM) have shown significant potential for efficiently producing small to medium-sized fiber-reinforced plastic (FRP) composite parts with geometric complexities, particularly in automotive applications. Use of unidirectional non-crimp fabrics (UD-NCFs) can further enhance the fabrication efficiency and lightweight potential of liquid molded FRP composite parts owing to more targeted tailoring of material anisotropy and part performance. Managing friction during the fabric preforming phase poses a considerable challenge for UD-NCFs due to interactions among fiber tows, yarns, and stitching. In this study, a series of Coulomb friction tests were conducted to characterize the friction behaviour of a binder-stabilized UD-NCF at both room and elevated temperatures. A custom-designed testing apparatus was used that allowed detailed observation of fabric-to-fabric (ply-ply) and fabric-to-tool (ply-tool) frictional interactions and measurement of static and dynamic friction coefficients. The results revealed a significant dependency of friction coefficients on temperature and fabric contact side. Notably, ply-ply interactions between the stitching side of the fabric showed a considerable increase in friction at elevated temperatures due to the activation of thermosetting polymer binders. The complex inter-ply and intra-ply interactions must be considered for optimizing preform tool design to enhance the quality and efficiency of FRP composite manufacturing.

1 INTRODUCTION

Recent advancements in liquid composite molding technologies, particularly high-pressure resin transfer molding (HP-RTM), and snap-cure resins have enabled the rapid manufacturing of geometrically complex, small to medium-sized fiber-reinforced plastic (FRP) composite parts for automotive applications. The use of unidirectional non-crimp fabrics (UD-NCFs) instead of traditional woven fabrics significantly enhances fabrication efficiency and lightweight capabilities due to more effective tailoring of the anisotropic properties of the parts [1]. However, the formability challenges associated with UD-NCFs are greater than those with woven fabrics, often leading to specific local draping defects such as intra-ply tow gapping and buckling, and out-of-plane wrinkling due to complex interactions between the main fiber tows and stitching [2]. Fabric preforming is a crucial step in the HP-RTM process, where binder-stabilized fabric layers are draped in a heated mold to produce a net-shaped dry preform. During the preforming phase, intricate ply-tool and ply-ply frictional behaviors emerge due to the interactions among the fabric constituents and the impedance to sliding caused by the activation of the binder. These interactions directly influence the quality of the final composite part, affecting the deformation mechanisms of the fabric, such as intra-ply shear and ply bending [3,4]. Understanding and accurately modeling these frictional behaviors are essential for predicting and mitigating potential defects during preforming to improve the performance and structural integrity of FRP composite parts [2]. Previous research has focused on characterizing the friction behaviors between different fabric interfaces for various types of fabric, which are pivotal for understanding the mechanisms involved in fabric forming and for simulating the preforming process. These studies have explored interactions between fabric layers (ply-ply) and between fabrics and tool surfaces (ply-tool), employing experimental methods such as the pull-out test and the Coulomb friction test to analyze the effects of variables such as normal pressure and temperature on frictional behavior [5].

Despite the important contributions of previous studies focused on characterizing the frictional behavior of various types of fabric, few studies have considered binder-stabilized UD-NCFs. The objective of this study is to characterize the ply-ply and ply-tool friction behavior for a binder-stabilized UD-NCF at both room and elevated temperatures.

2 METHOD

2.1 Material Description

In this study, the binder-stabilized heavy-tow unidirectional non-crimp fabric PX35-UD300 (Zoltek™) was characterized. The fabric consisted of parallel tows each comprising 50,000 PX35 carbon fibers, transversely oriented supporting glass fiber yarns positioned on one side of the fabric (i.e., glass side), a warp knitted polyester stitching in a tricot pattern (i.e., stitch side), and a thermosetting powder binder. The properties of the UD-NCF are provided in Table 1.

Table 1. PX35-UD300 (Zoltek™) unidirectional non-crimp fabric characteristics.

Parameter	**Value**
Total fabric areal density	333 g/m^2
Carbon fiber tow weight fraction	92.8 %
Glass fiber yarn weight fraction	3.0 %
Glass fiber yarn linear density	34 dtex
Polyester stitch weight fraction	1.8 %
Polyester stitch linear density	76 dtex
Binder resin powder weight fraction	2.4 %
Nominal Carbon fiber diameter	7.2 µm

2.2 Test Setup

Coulomb friction tests were performed to evaluate the ply-ply and ply-tool static and dynamic friction coefficients for the UD-NCF using a custom apparatus that was based partly on the standard ASTM D1894. The steel used in the test setup was representative of steel used in industrial forming tools, while the surfaces were sanded with 150-grit sandpaper to provide a comparable surface finish. The experimental protocol involved wrapping the UD-NCF sample around a precisely dimensioned 63.5 mm square steel sled (mass of 200 g), ensuring that the fabric adhered uniformly to the sled surface using double-sided tape. The test apparatus consisted of a robust supporting base that supported the sled, a pulley to guide the nylon wire that pulled the sled, and an upper attachment that secured the wire during testing (Figure 1-A). This setup ensured a controlled and repeatable testing environment. Temperature regulation was a crucial component of the test setup, which was managed using a digital two-channel thermometer connected to a heater device, ensuring that the UD-NCF was subjected to consistent thermal conditions throughout the testing process (Figure 1-B).

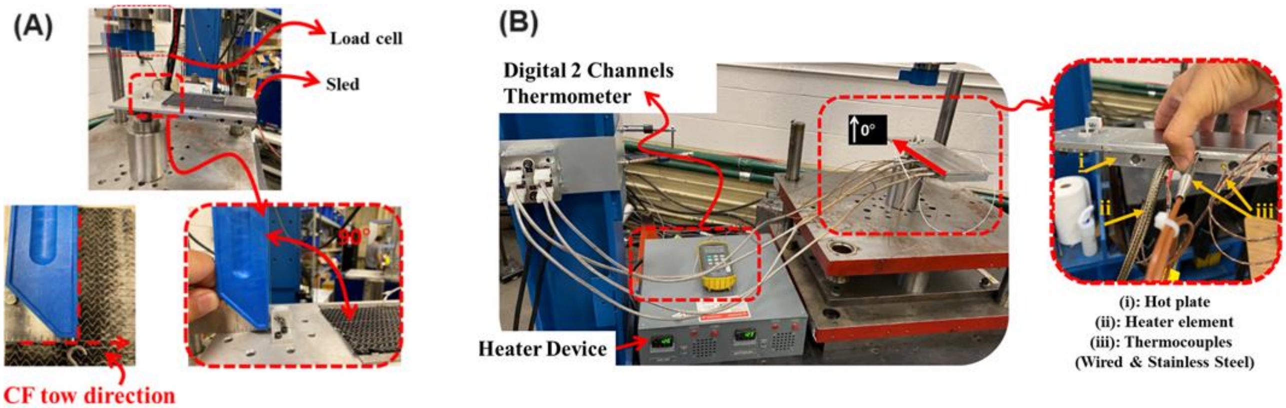
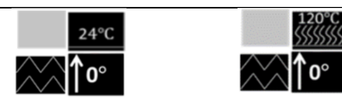
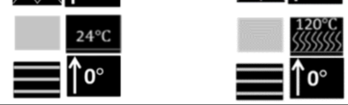
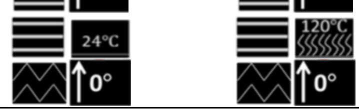


Figure 1. (A) Orientation and progression of the sled and monofilament during the Coulomb friction test, (B) Experimental setup for temperature control during friction testing.

Table 2. Test Configurations for UD-NCF Contact Pairings at Varied Temperatures

	Contact Surfaces	CF Direction	Temperatures	Symbols
Ply-Tool	Stitch Side/Steel	0°	24°C, 120°C	
	Glass Side/Steel	0°	24°C, 120°C	
Ply-Ply	Stitch Side/ Stitch Side	0°	24°C, 120°C	
	Glass Side/ Glass Side	0°	24°C, 120°C	
	Glass Side/ Stitch Side	0°	24°C, 120°C	

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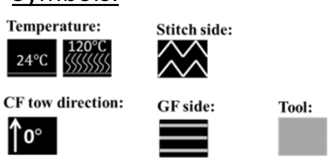

The sled bearing the UD-NCF specimen was drawn at a constant displacement rate of 1 mm/s using a servo-hydraulic test frame with a 445 N load cell, mimicking the closing speed of a forming tool during the actual preforming process. Frictional testing encompassed an array of ply-ply and ply-tool contact scenarios including steel-stitch, steel-glass, stitch-stitch, glass-glass, and glass-stitch, with the UD-NCF oriented to align parallel with the material's tow directions for each contact condition. To obtain a statistical data set, each configuration was tested at least three times to ascertain the consistency of the friction response. This methodology allowed for the calculation of the average static and dynamic friction coefficients from the measured force-displacement response using the following equation:

$$\mu = \frac{F}{W} \tag{1}$$

where μ represents the coefficient of friction, F is the frictional force (measured directly from the load cell), and W is the normal force exerted on the fabric (i.e., the weight of the sled). The testing conditions were specifically designed to investigate the role of temperature. Controlling temperature was crucial to replicate the high-temperature preforming process and to gain insight into the behavior of the UD-NCF under realistic manufacturing conditions. The different test configurations considered in this study are detailed in Table 2.

3 EXPERIMENTAL RESULTS

3.1 Fabric/Tool and Fabric/Fabric at Room Temperature

Figure 2 displays the typical force-displacement curves derived from the Fabric-Tool and Fabric-Fabric friction tests conducted at room temperature. For the Fabric-Tool tests, the captured peak static friction force (F_s) was approximately 0.9 N for both cases, which indicates that at room temperature the frictional properties of the fabric remained stable regardless of the contact side with the tool (Figures 2-A and 2-B). In contrast, the fabric-to-fabric friction test results reveal a slight change in both F_s and the steady state friction force (F_{std}) for different contact surfaces (Figures 2-C to 2-E). Despite these variations, the sides of the fabric that are in contact has minimal influence on the friction behavior at room temperature. This result highlights inherent stability in the behaviour of the UD-NCF fabric at room temperature, which is crucial for applications where the contact surface of the fabric cannot be precisely controlled.

3.2 Fabric/Tool and Fabric/Fabric at Elevated Temperature

Figure 3 presents the load-displacement curves for ply-tool and ply-ply friction tests at an elevated temperature of 120°C. An increase in temperature resulted in a noticeable rise in the friction force for both the static and dynamic stages for all cases when compared to the tests performed at room temperature. The increase in force is attributed to the activation of the binder at higher temperatures, creating a tacky layer on the fabric surface and increased resistance to sliding. During the static stage (F_s), a clear temperature dependency was observed. Specifically, the initial peak force observed in Figure 3-C showed an increase of 334% compared to baseline tests at room temperature (Figure 2-C), highlighting the significant impact of temperature on friction behavior. Similarly, Figures 3-D and 3-E demonstrated increases of 436% and 564%, respectively, for different fabric combinations under the same testing conditions. The subsequent force to sustain the sliding motion (F_{std}) was also observed to be influenced by temperature. These quantitative evaluations clearly illustrate how each fabric-to-fabric interface responds differently under the same elevated temperature conditions, providing crucial insights for optimizing manufacturing processes involving UD-NCFs. Further detailed observations in the stitch-stitch interactions reveal that the dynamic friction coefficient at 120°C is 315% higher than its counterpart at room temperature, underscoring the significant role of thermal activation of the thermosetting polymer binder, which becomes tacky and enhances the fabric's frictional properties. Across all tested temperatures, the friction force for fabric-to-fabric interactions remain distinctly higher than those for fabric-to-steel interactions, with the former amplifying frictional forces due to intrinsic fabric interactions. Notably, at 120°C, the dynamic friction coefficient for the stitch-stitch case is 13% higher than for the glass-glass case, further highlighting the critical influence of fabric architecture and binder activation in shaping both ply-to-tool and ply-to-ply friction characteristics.

3.3 Summary of Calculated Static and Dynamic Friction Coefficients

The measured friction coefficients for all test cases are summarized in Figure 4. These results not only reveal the dynamic changes in frictional behavior for different contact surfaces and temperature conditions, but also provide essential data that can be used to calibrate contact models in future forming simulations. Such simulations can help predict and optimize manufacturing processes, particularly by adjusting for the thermal effects observed at higher temperatures.

4 CONCLUSION AND FUTURE WORKS

This study aimed to characterize the ply-ply and ply-tool friction behavior for a binder-stabilized unidirectional non-crimp fabric (UD-NCF). Coulomb friction tests revealed the notable influence of ambient temperature and contact side on the static and dynamic friction coefficients, underscoring the pivotal role of the thermosetting polymer binder. Notably, activation of the binder at elevated temperatures increased the ply-to-ply friction coefficient, which is crucial for understanding and optimizing the manufacturing process.

Future research will expand on these findings by applying varying normal forces and exploring different fabric orientations. Such studies would enhance our understanding of their effects on ply-ply and ply-tool interactions and further refine the friction behavior characterization in manufacturing processes involving UD-NCFs.

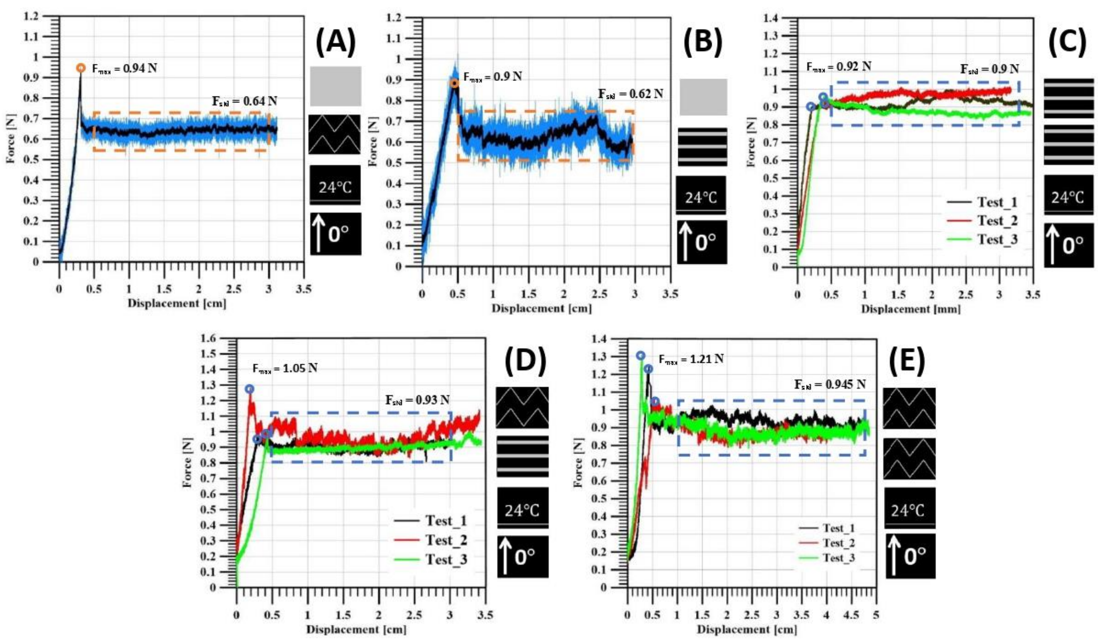

Figure 2. Force-displacement results for Coulomb friction tests performed at 24°C: (A) Stitch/Steel, (B) Glass/Steel, (C) Stitch/Stitch, (D) Glass/Glass, (E) Glass/Stitch interactions.

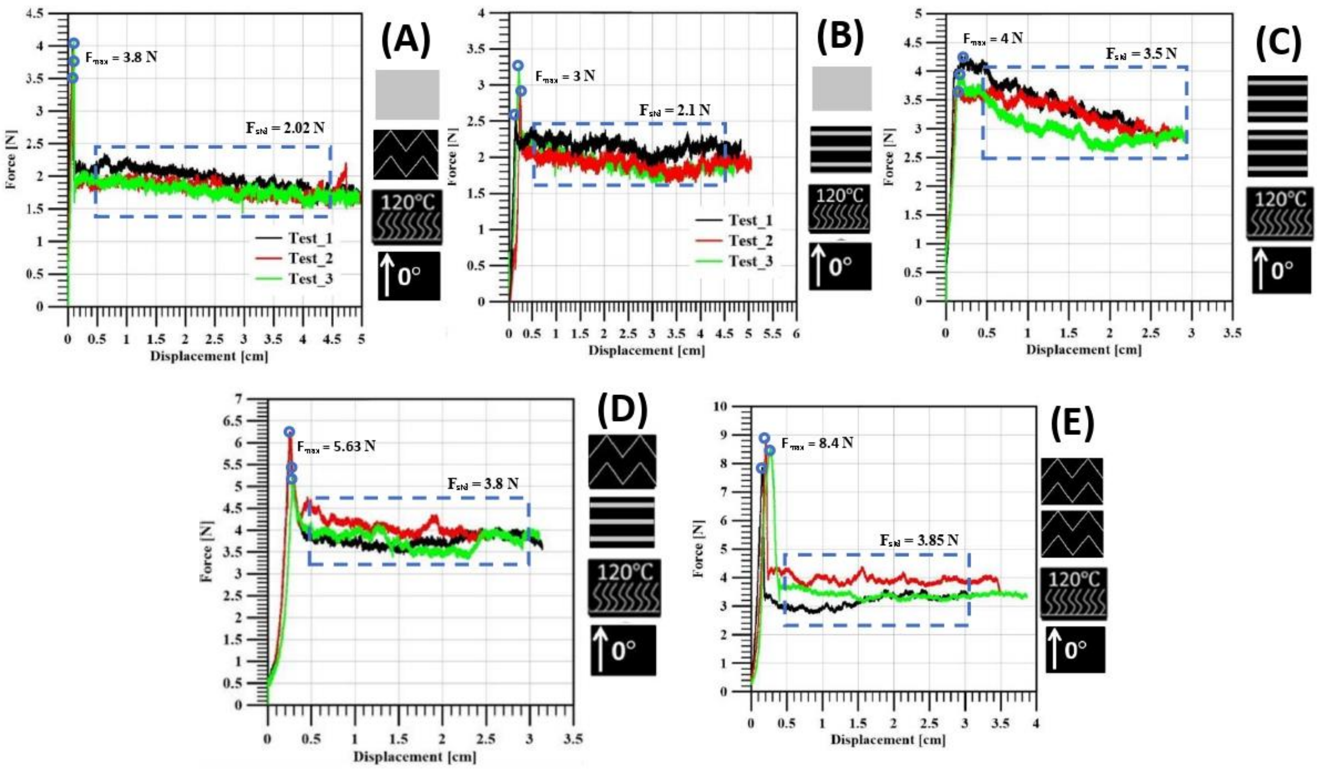

Figure 3. Force-displacement results for Coulomb friction tests performed at 120°C: (A) Stitch/Steel, (B) Stitch/Steel, (C) Stitch/Stitch, (D) Glass/Glass, (E) Glass/Stitch interactions.

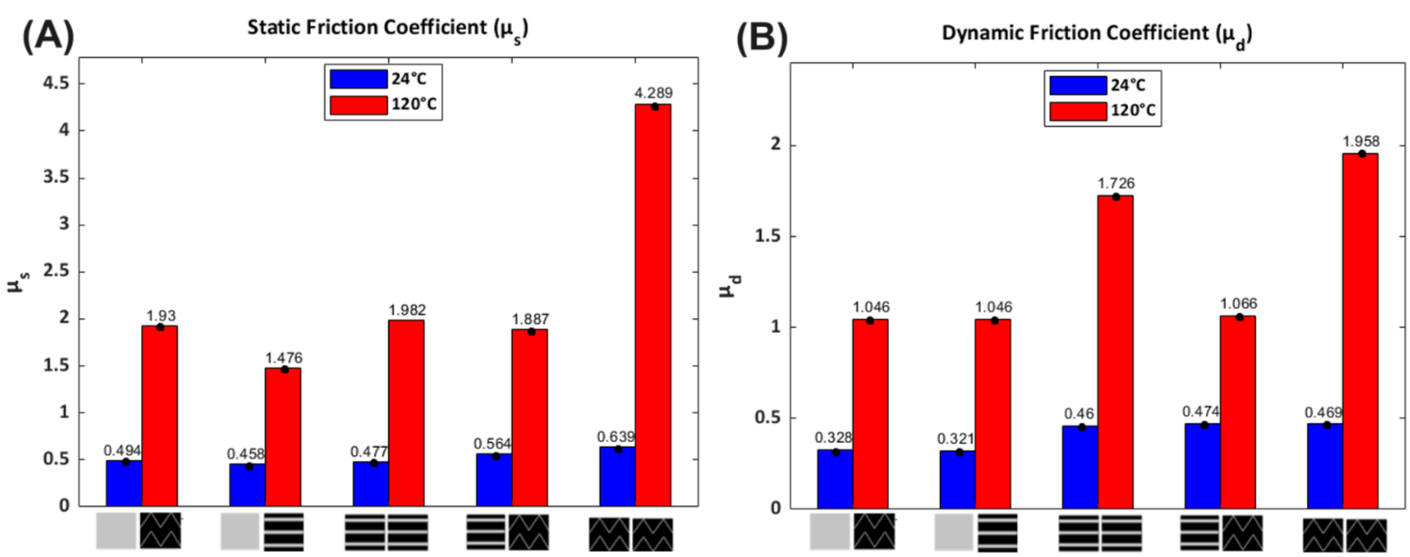

Figure 3. Comparative Analysis of (A) Static and (B) Dynamic Friction Coefficients at 24°C and 120°C for Different Fabric Contacts.

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