



Article

Experimental Characterization of Cure-State-Dependent Tool–Prepreg Friction in a Carbon Fiber/Bismaleimide System

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Abstract

Tool–prepreg friction contributes to process-induced residual stress and distortion in thermoset composite manufacturing, but its variation with the resin cure state remains insufficiently characterized. This study experimentally characterizes the friction response of untreated and post-gel pretreated T800/bismaleimide prepregs using a pull-out apparatus. The effects of slip velocity, temperature, and normal pressure are evaluated, and the measured trends are interpreted using Coulomb-type contact, viscous film shearing, and mixed-lubrication concepts. The friction coefficient of the untreated prepreg increases with the slip velocity and decreases with temperature and pressure, indicating a substantial contribution from viscous resin-film shearing. In contrast, the post-gel pretreated prepreg is nearly insensitive to the slip velocity and pressure, while its friction coefficient increases with temperature, consistent with a predominantly solid-like interfacial response. During a cure cycle, the friction increases slowly at low cure levels and more rapidly during the later stages of curing. The results provide experimental friction data for a high-temperature bismaleimide prepreg system and suggest that the gelation state may serve as a useful reference for distinguishing early- and later-stage interfacial behavior.

Keywords: tool–prepreg friction; bismaleimide prepreg; cure state; mixed lubrication; composite manufacturing

1. Introduction

Carbon fiber–reinforced polymer (CFRP) composites are widely used in aerospace structures because of their high specific strength and stiffness, good fatigue resistance, and excellent corrosion resistance. During composite manufacturing, temperature gradients, resin chemical shrinkage, thermal-expansion mismatch, and the evolution of the viscoelastic properties of the resin can generate residual stresses, resulting in dimensional distortion and degradation of structural performance [1–5]. In addition to these thermochemical effects, mechanical interactions between the composite and the metallic tool can considerably influence the final stress and deformation state.

During curing and cooling, the chemical shrinkage of the resin and the difference in thermal expansion between the composite and the tool generate a tendency for relative in-plane deformation. Friction at the tool–part interface restricts this relative movement and transfers shear stresses between the tool and the composite. Twigg et al. [6] developed an



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experimental method for quantifying the tool–part shear interaction and demonstrated that the application of a release agent altered the strain evolution during processing. Kaushik and Raghavan [7] subsequently measured the static and dynamic tool–prepreg friction coefficients throughout an autoclave cure cycle and showed that the measured coefficients varied with process time, degree of cure, and heating rate. Using these cure-dependent friction data, Zeng and Raghavan [8] established a three-dimensional process model and demonstrated that a frictional tool–part interface was required to accurately predict the warpage of a large composite structure. More recent numerical and experimental studies have similarly shown that the assumed tool–part interaction condition can substantially affect the predicted curing-induced deformation [9,10]. These findings highlight the importance of obtaining physically representative tool–prepreg friction data for process simulation.

The frictional behavior of composite prepregs under different processing conditions has been extensively investigated. Martin et al. [11] studied the frictional resistance of thermoset prepregs and demonstrated its influence on honeycomb composite manufacturing. Ersoy et al. [12] developed a pull-out-type method for examining friction during composite processing and showed that the measured resistance was affected by temperature, sliding velocity, normal pressure, and the surface state of the prepreg. Sun et al. [13] investigated the inter-ply friction of carbon fiber/epoxy prepreg stacks under different processing conditions and related the observed differences to the resin distribution and surface morphology. Rashidi et al. [14] compared dry woven fabrics with thermoset prepreg fabrics and found that dry fabrics exhibited a predominantly Coulomb-type behavior, whereas the presence of resin in the prepregs resulted in a mixed-lubrication behavior. Liu et al. [15] developed a friction model for thermoset-based fiber–metal laminates and further demonstrated that slip velocity, temperature, and normal pressure can exert different effects on interfacial friction. For thermoplastic composite forming, ten Thije et al. [16,17] and Akkerman et al. [18] employed lubrication-based and Stribeck-type approaches to describe the transitions among direct solid-contact, mixed-lubrication, and viscous-film-dominated friction. These studies have established that fiber architecture, resin characteristics, surface conditions, and cure state are important intrinsic factors, whereas velocity, temperature, and normal pressure are major processing variables governing prepreg friction.

Most previous investigations have focused on uncured prepregs during forming or on the tool–part interaction throughout an imposed cure cycle. Kaushik and Raghavan [7] demonstrated that tool–prepreg friction evolves with process time and degree of cure, but their work was intended to quantify the overall tool–part interaction during autoclave processing rather than to isolate the changes in the processing-parameter sensitivity across gelation. In addition, Zeng and Raghavan [8] primarily used cure-dependent friction data to improve warpage prediction rather than to investigate the underlying friction regimes. More recently, Zhang et al. [19] systematically examined the effects of room-temperature aging, forming temperature, and ply orientation on the inter-ply friction and formability of thermoset unidirectional prepregs. They characterized the cure kinetics, the gel point, the glass-transition temperature, and the viscosity of aged prepregs and reported that aging reduced the room-temperature inter-ply friction resistance by 26.47%. Aveiga et al. [20] further investigated the friction resistance of uncured carbon/epoxy prepregs under thermoforming conditions and confirmed the strong sensitivity of the prepreg friction to the processing conditions. However, aging-induced inter-ply friction during compression molding is not fully equivalent to the metallic tool–prepreg interaction encountered during autoclave curing. In particular, systematic comparisons of how slip velocity, temperature, and normal pressure affect untreated and post-gel pretreated prepregs remain limited for high-temperature carbon fiber/bismaleimide systems. Surface observations supporting the corresponding changes in interfacial behavior are also relatively scarce.

In this study, a pull-out-type apparatus was used to characterize the friction between an aluminum tool and untreated or post-gel pretreated carbon fiber/bismaleimide preregs. The effects of slip velocity, temperature, and normal pressure were systematically evaluated for the two prepreg states. The measured trends were interpreted using Coulomb-type, hydrodynamic, and mixed-lubrication concepts. Microscopic observations and an elemental analysis were used to further support the interpretation of the interfacial behavior. In addition, the friction evolution was monitored during a complete curing cycle to examine whether the gelation could provide a useful reference for describing the evolution of the tool–prepreg interaction.

2. Materials and Methods

2.1. Materials

The material used in this study was a unidirectional T800 carbon fiber prepreg with an 802 bismaleimide (BMI) resin matrix. The preregs and the viscosity data for BMI were supplied by the Aerospace Research Institute of Materials & Processing Technology (Beijing, China) and the original manufacturer information cannot be disclosed due to confidentiality requirements. To prepare a post-gel comparison state, the prepreg was preheated in an oven at 140 °C for 2 h. Differential scanning calorimetry (DSC) was performed using STA449F3 differential scanning calorimeter (NETZSCH Scientific Instruments Trading (Shanghai) Ltd., Shanghai, China) from 40 °C to 400 °C, as shown in Figure 1. Four material states were examined by DSC: untreated prepreg, untreated prepreg after the 20–120 °C friction-test thermal history, pretreated prepreg, and pretreated prepreg after the same thermal history. The degree of cure was evaluated from the residual reaction enthalpy relative to the reference total reaction enthalpy. The detailed DSC thermograms and cure-state calculations are provided in the Supporting Information.

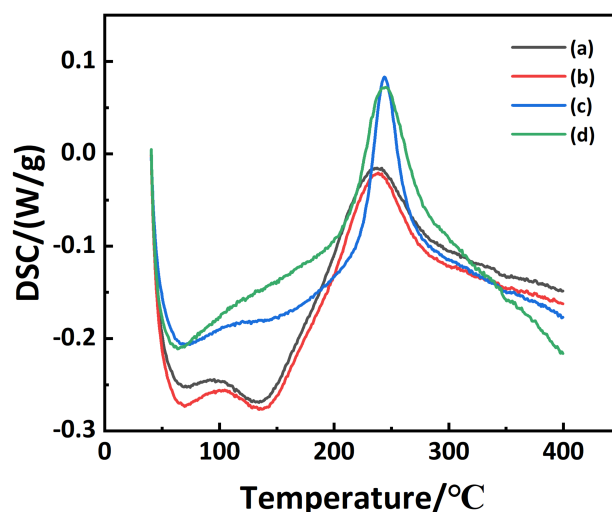


Figure 1. DSC results of four material states: (a) untreated prepreg; (b) untreated prepreg after temperature-related test; (c) pretreated prepreg; and (d) pretreated prepreg after temperature-related test.

Based on the residual reaction enthalpy, the degree of cure after the 140 °C/2 h pretreatment was approximately 0.45, confirming substantial cure advancement relative to the untreated material. The two conditions are therefore referred to as untreated prepreg and post-gel pretreated prepreg. Electron microscope observations were performed using a RISE-CLARA (TESCAN (Brno, Czech) and WITec (Ulm, Germany)) on untreated and pretreated preregs, as shown in Figure 2. The two prepreg states show clear differences in surface resin distribution. More resin is present on the untreated prepreg surface, where it forms a relatively continuous film. In contrast, less resin remains on the pretreated surface

and appears mainly as discrete granular regions. These two different surface topographies cause them to exhibit different friction behaviors.

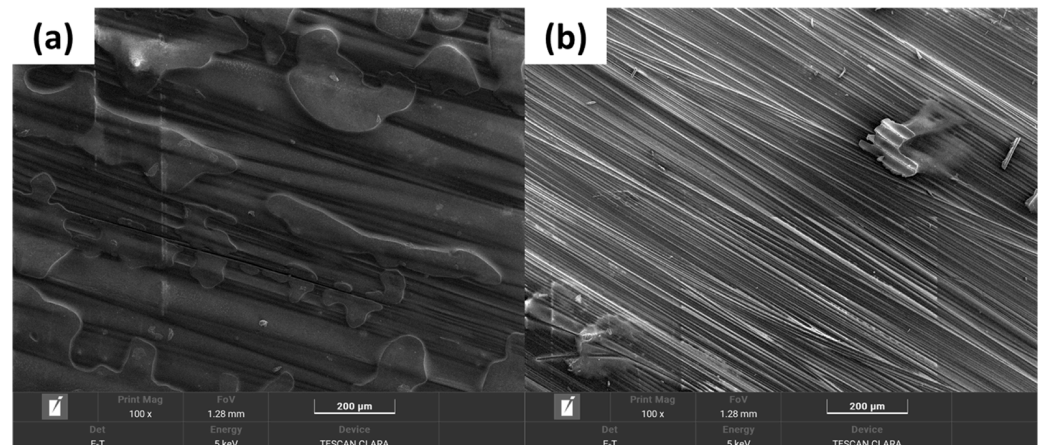


Figure 2. Electron microscope observations: (a) untreated prepreg; and (b) pretreated prepreg.

2.2. Test System

Figure 3a shows the friction test system, which consists of a base plate, pressing plate, heating plate, aluminum tool plate, mid plate, and auxiliary components. The system allows slip velocity, temperature, and normal pressure to be controlled. The fixtures are connected to a C45.105EY universal testing machine (MTS Systems (China) Co., Ltd., Shanghai, China). The prepreg is wrapped around the mid plate, while the base plate is fixed to the lower grip. The mid plate is then pulled by the upper grip, causing the prepreg to slide relative to the aluminum tool surface.

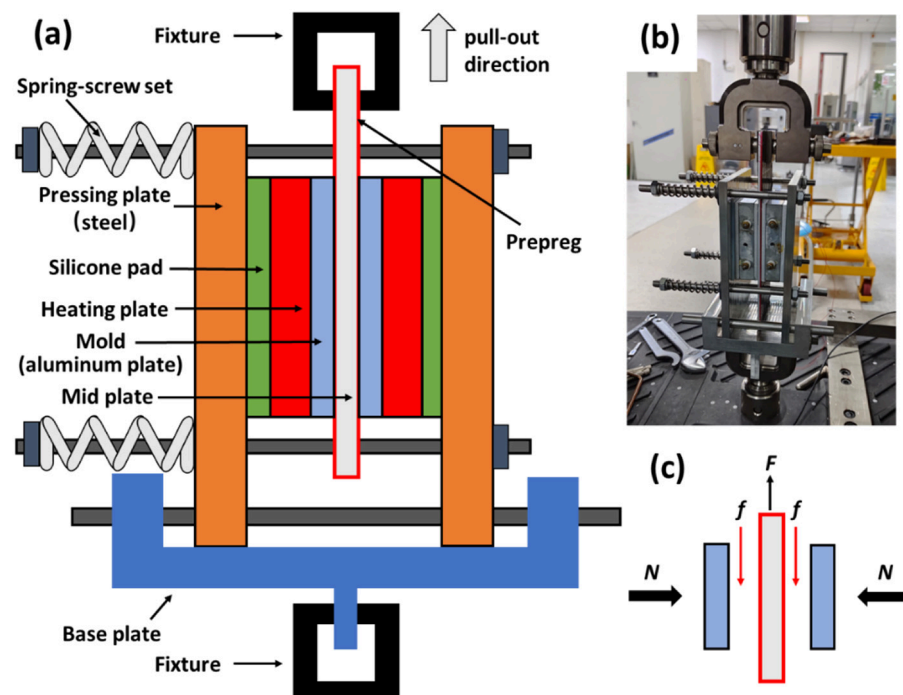


Figure 3. Friction test system: (a) schematic; (b) photograph; and (c) test configuration.

Figure 3c illustrates the force balance during the pull-out test. Since friction acts on both sides of the prepreg, the measured pull-out force F can be expressed as follows:

$$F = 2f \quad (1)$$

where F is the measured pull-out force and f is the friction force acting on one interface. For comparison among test conditions, an apparent friction coefficient is defined using a Coulomb-type normalization:

$$f = \mu N \quad (2)$$

$$\mu = F / (2N) \quad (3)$$

where N is the applied normal force on one interface and μ is the apparent friction coefficient. The term “apparent” is used because the untreated prepreg may exhibit mixed lubrication, for which the friction force is not necessarily proportional to the normal force.

In the test, the prepreg is heated by a heating plate to the predefined temperature. The heating plate is connected to a proportional–integral–derivative (PID) controller via a type-J thermocouple. The temperature can be increased at a constant rate or maintained at a constant value by feedback control of the thermocouple.

The normal pressure is applied by four springs and calibrated by the load–displacement relation of the springs. The prepreg width was strictly controlled at 100 mm, while the aluminum tool plates (105 mm) were slightly wider than the prepreg; therefore, the nominal geometric contact region remained approximately 100 mm × 100 mm during the pull-out process. No macroscopic jamming or abrupt interruption of sliding was observed in the steady-state region used for friction evaluation.

The stability of the applied normal load during heating was independently verified using a capacitive pressure sensor. The corresponding calibration and pressure-sensor data are provided in the Supporting Information and show only small load fluctuations under the validation conditions. The nominal geometric contact area remained unchanged during testing.

2.3. Experimental Conditions

This study investigates the effects of slip velocity, temperature, and normal pressure on the frictional behavior of the two prepreg states. The experimental conditions are summarized in Table 1. Each condition was independently tested three times. Representative evolution curves are presented to illustrate the transition from the initial pull-out stage to steady sliding. During the temperature-dependent experiments, the test system was heated from 20 °C to the specified temperature at a rate of 2 °C/min, and the aluminum plate was then pulled at that temperature until the displacement reached 1 mm. The system was subsequently heated to the next specified temperature at the same rate, and the procedure was repeated until all designated temperatures had been tested.

Table 1. Test conditions.

	Prepreg	Slip Velocity (mm/min)	Temperature (°C)	Pressure (MPa)
1	untreated	0.1, 0.2, 0.5, 1, 2	20	0.05
2	untreated	0.1, 0.2, 0.5, 1, 2	20	0.1
3	untreated	1	20, 40, 60, 80, 100, 120	0.05
4	untreated	1	20, 40, 60, 80, 100, 120	0.1
5	untreated	1	20, 40, 60, 80, 100, 120	0.15
6	pretreated	0.1, 0.2, 0.5, 1, 2	20	0.05
7	pretreated	0.1, 0.2, 0.5, 1, 2	20	0.1
8	pretreated	1	20, 40, 60, 80, 100, 120	0.05
9	pretreated	1	20, 40, 60, 80, 100, 120	0.1

The maximum temperature of the parameter-dependent friction tests was limited to 120 °C. This upper limit was not intended to reproduce the complete cure temperature range of the BMI system; rather, it was selected to investigate the effect of temperature while limiting additional cure advancement during measurement. At higher temperatures,

the BMI curing reaction would proceed more rapidly, making it more difficult to separate the effects of temperature and cure state. Additional DSC measurements were performed before and after reproducing the 20–120 °C thermal history (Figure 1). The corresponding changes in degree of cure $\Delta\alpha$ were 0.05 for the untreated prepreg and 0.02 for the pretreated prepreg (see Supporting Information).

2.4. Friction Models

In an ideal Coulomb friction model, the contact is treated as solid–solid interaction and the friction coefficient is independent of slip velocity. For an uncured prepreg, however, mobile resin may be squeezed into the interface and form a lubricating film. If resistance is governed primarily by viscous shearing of this film, the hydrodynamic contribution can be expressed as follows [15]:

$$f_v = \eta v A / d \quad (4)$$

where f_v is the viscous friction force, η is the resin viscosity, v is the slip velocity, A is the nominal contact area, and d is the film thickness. This idealized expression shows that the viscous contribution increases with resin viscosity and sliding velocity, while the actual prepreg interface may also contain direct fiber, resin, and tool contact.

When direct-contact and resin-film contributions coexist, the response is commonly described as mixed lubrication [16]. Figure 4 illustrates the idealized Coulomb, hydrodynamic, and mixed regimes. Direct contact between fibers or solid-like resin and the tool contributes a comparatively velocity-insensitive component, whereas a resin-rich interfacial film can contribute viscous shear resistance. Equation (4) is used only to illustrate the expected dependence of viscous resistance on resin viscosity and sliding velocity; it is not used as a constitutive fit to the measured interface.

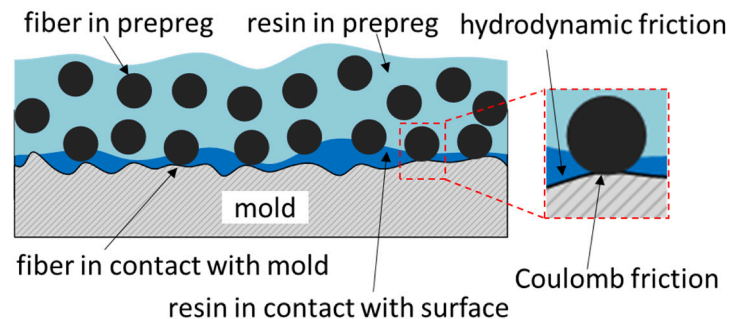


Figure 4. Idealized Coulomb, hydrodynamic, and mixed regimes.

3. Results and Discussion

This section examines the effects of slip velocity, temperature, and normal pressure on the tool–prepreg friction for the untreated and post-gel pretreated prepreps. The parameter sensitivities are interpreted using the idealized solid-contact, viscous-film, and mixed-lubrication concepts.

3.1. Parametric Effects on Friction

3.1.1. Slip Velocity

During pull-out, the measured tensile force increased and then approached a steady level. The present study focuses on this steady-state sliding response; the initial peak associated with the onset of motion was not separately analyzed as a static friction coefficient. The steady-state value was used to calculate the friction coefficient. Figure 5 shows representative evolution curves at 20 °C and 0.1 MPa. For the untreated prepreg, the friction coefficient increases with the slip velocity, indicating a velocity-dependent contribution

consistent with viscous resin-film shearing. For the post-gel pretreated prepreg, the effect of the slip velocity is small, which is consistent with a predominantly Coulomb-type response.

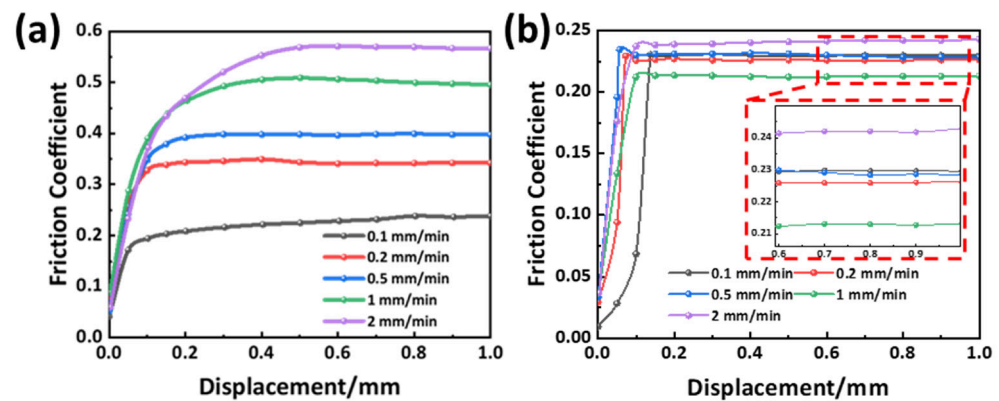


Figure 5. Friction coefficient at different slip velocities: (a) untreated prepreg; and (b) post-gel pretreated prepreg.

3.1.2. Temperature

Temperature is an important parameter influencing the friction coefficient. Figure 6 shows representative temperature-dependent responses of the two prepreg states. For the untreated prepreg, the friction coefficient gradually decreases with increasing temperature, with only minor differences observed between 80 °C and 120 °C.

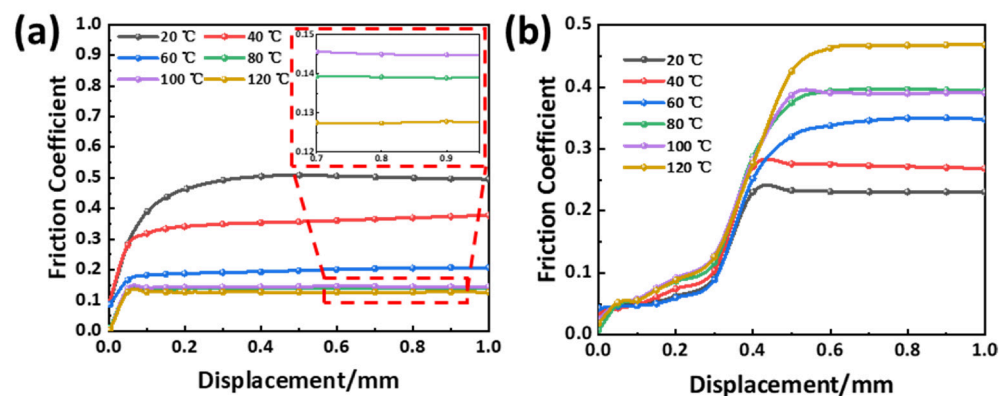


Figure 6. Friction coefficient at different temperatures: (a) untreated prepreg; and (b) post-gel pretreated prepreg.

The post-gel pretreated prepreg shows the opposite temperature trend: its friction coefficient increases with temperature. Although thermal softening generally reduces the bulk modulus and shear resistance of polymers, the quantity measured here is an interfacial response rather than a purely bulk property. After pretreatment, the viscous resin flow is strongly restricted. Heating may increase the conformity of the partially cured surface to the aluminum asperities. The resulting increase in local contact and mechanical interlocking may contribute to the higher friction coefficient.

3.1.3. Normal Pressure

To examine the influence of normal pressure, the velocity- and temperature-dependent tests were repeated at different pressure levels. Figure 7 presents the resulting friction coefficients with error bars from three independent tests. For the untreated prepreps, the friction coefficient decreased with increasing normal pressure, as shown in Figure 7. Moreover, as the slip velocity increased, the differences in the friction coefficients at different

normal pressures became smaller. However, with increasing temperature, the differences in the friction coefficients at the different normal pressures did not exhibit an obvious trend of either increasing or decreasing.

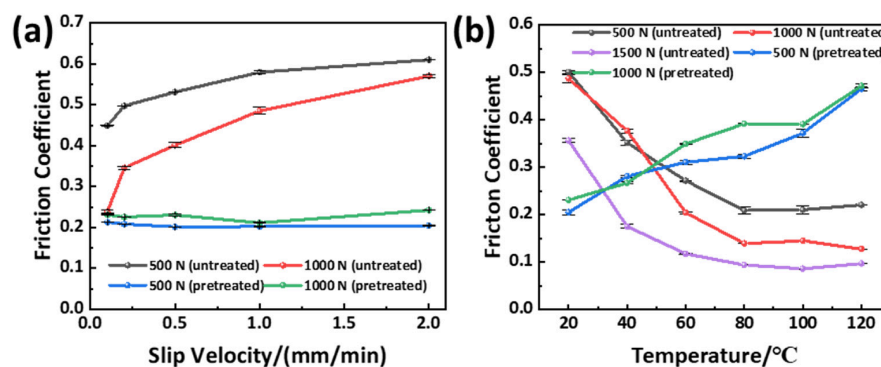


Figure 7. Effect of normal pressure on the friction coefficient: (a) velocity-dependent tests; and (b) temperature-dependent tests.

For the pretreated prepregs, the trend of the friction coefficient with the normal pressure was different. As the normal pressure increased, the friction coefficient increased slightly, although the difference remained small. At low temperatures, the friction coefficient under 0.1 MPa was slightly lower than that under 0.05 MPa but gradually reversed with increasing temperature. The difference reached its maximum at 80 °C and then decreased to a small value at higher temperatures.

3.2. Interpretation of the Friction Response

3.2.1. Untreated Prepreg

For an ideal viscous film, the friction resistance increases with the relative slip velocity. The velocity dependence measured for the untreated prepreg in Figure 5a therefore indicates a substantial viscous contribution. However, the response does not follow a purely linear hydrodynamic trend and retains a nonzero velocity-insensitive component. Figure 8 compares the measurements with the idealized Coulomb and hydrodynamic trends. The comparison is intended to illustrate the friction regime rather than to provide a constitutive-model fit. The results are consistent with a mixed-lubrication response in which direct-contact and viscous-film contributions coexist.

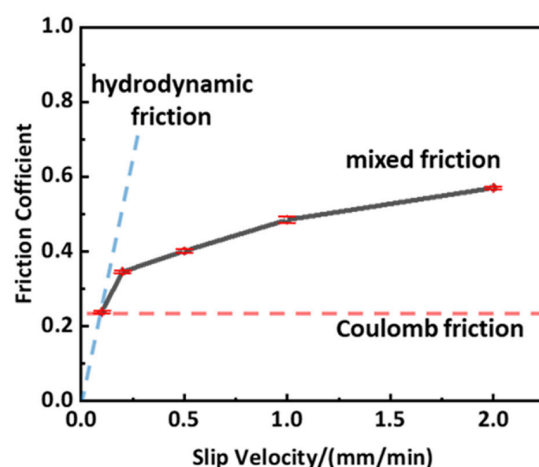


Figure 8. Comparison of the measured velocity dependence with idealized velocity-independent and viscous-film trends for the untreated prepreg.

An ultra-depth optical microscope (EasyZoom5 3D, MOTIC CHINA GROUP CO., LTD., Xiamen, China) was used to observe the prepreg and tool contact surfaces. Figure 9a,b shows the untreated prepreg before and after testing, and Figure 9c shows the corresponding aluminum surface. Resin-rich regions remain on part of the tool surface, whereas other regions show little visible resin transfer.

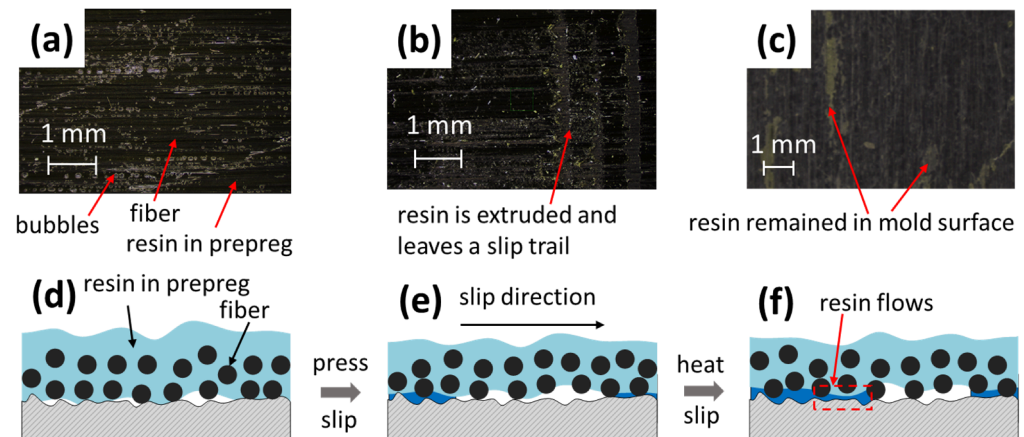


Figure 9. Schematics and surface observations for the untreated prepreg: (a) prepreg before testing; (b) prepreg after testing; (c) tool surface after testing; (d) interface before contact; (e) interface after compaction; and (f) interface during sliding.

The fibers on the surface of the prepreg, as well as the resin and the air bubbles between the fibers, could be clearly distinguished. The gaps between the fibers were not completely filled by the resin (Figure 9a), and the mold (aluminum plate) exhibited a rough surface, resulting in an uneven contact interface (Figure 9d). When the untreated prepreg came into contact with the mold, some of the resin between the fibers was extruded and filled part of the uneven surface (Figure 9e).

The resin film can reduce direct interactions with the rough aluminum surface, but it can also generate substantial viscous resistance when the resin viscosity is high. This explains why the untreated prepreg retains a comparatively high friction coefficient at 20 °C and higher sliding velocities. The measured response therefore reflects the balance between lubrication through surface separation and resistance from viscous shearing.

Increasing the temperature promotes resin softening and mobility, whereas increasing the pressure promotes resin redistribution within the interface. Both effects can alter the extent of the resin-rich interfacial regions. The viscous-film contribution consequently becomes more pronounced. Resin extrusion and stretching along the fiber direction are visible in Figure 9b, supporting resin mobility during compaction and sliding. Nevertheless, regions without obvious resin transfer remain, indicating that the interface cannot be treated as purely hydrodynamic.

As shown in Figure 10, the resin viscosity decreases sharply with temperature and approaches a lower, more stable level above approximately 80 °C. The friction coefficient follows a broadly similar trend. This correlation supports the importance of viscous resin-film shearing. The small discrepancy below 60 °C may arise because the high-viscosity resin flows less readily and a larger fraction of the load is carried by the direct-contact regions.

Figure 11 compares the aluminum surfaces after contact with the untreated prepreg at different normal pressures. In addition to the color optical observations, elemental analysis was performed on the aluminum surface after friction testing. The relative amount of transferred resin was estimated from the measured carbon signal (see Supporting Information). The results provide a semi-quantitative measure of the resin redistribution and transfer with the pressure. As the pressure increases, the amount of resin remaining

on the aluminum sheet also increases. The resin-rich regions may smooth local surface asperities and reduce the friction coefficient, while higher compaction can simultaneously increase the direct fiber–tool contact. This competition may explain why the coefficients at 2 mm/min are similar at 0.05 and 0.1 MPa. At 0.15 MPa, the separation becomes more difficult and some fibers remain attached to the aluminum surface.

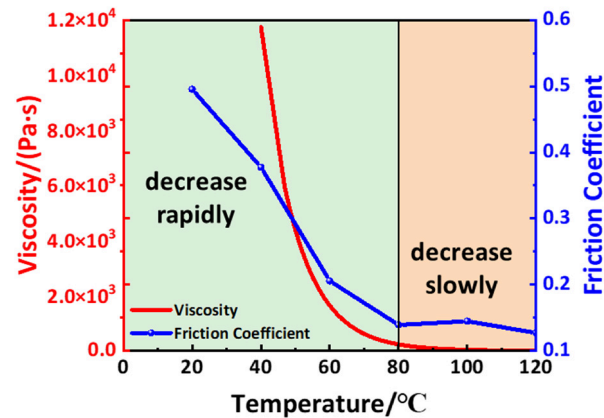


Figure 10. Variations in resin viscosity and friction coefficient with temperature (The green and orange shaded regions indicate the temperature ranges in which the resin viscosity decreases rapidly and slowly, respectively).

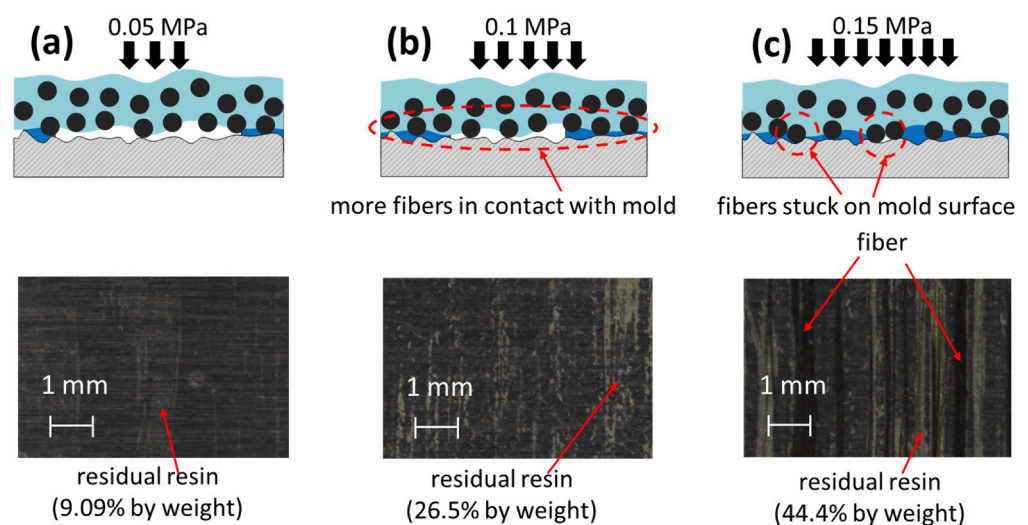


Figure 11. Schematics and surface observations of the aluminum tool after contact with the untreated prepreg at (a) 0.05 MPa, (b) 0.10 MPa, and (c) 0.15 MPa.

3.2.2. Post-Gel Pretreated Prepreg

The slip velocity and the normal pressure have relatively small effects on the friction coefficient of the post-gel pretreated prepreg, consistent with a predominantly Coulomb-type response. Figure 12 shows the schematics and the color optical observations of the interface. Compared with the untreated condition, visibly less mobile resin transfer is observed on the aluminum surface of the pretreated sample, and the difference is further evaluated by the elemental analysis provided in the Supporting Information. This result supports a reduced contribution from mobile resin-film shearing after pretreatment.

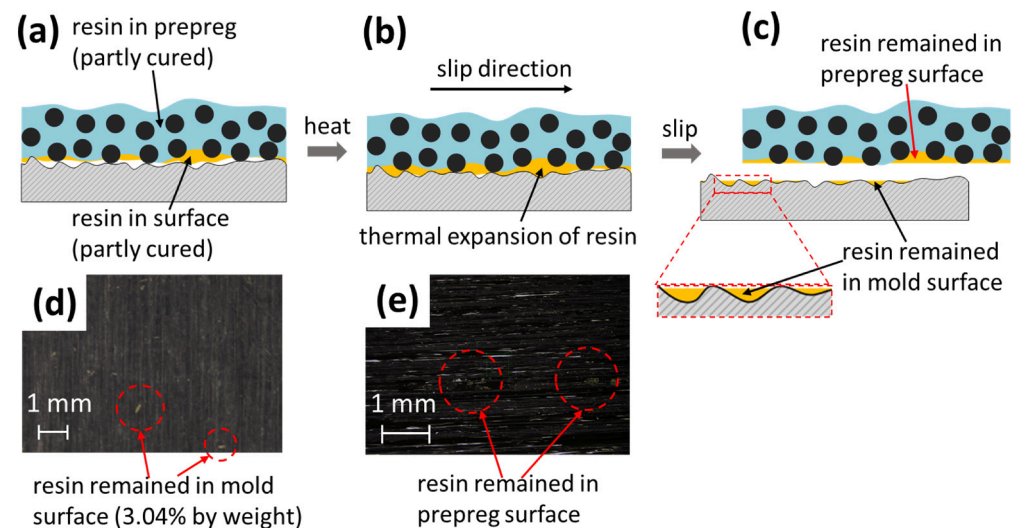


Figure 12. Schematics and surface observations of the post-gel pretreated prepreg: (a) interface before testing; (b) interface during loading; (c) interface after sliding; (d) tool surface after testing; and (e) prepreg surface after testing.

For the untreated prepreg, increasing the temperature reduces the resin viscosity and generally lowers the friction coefficient. In the post-gel pretreated material, the crosslinked resin cannot flow in the same manner and behaves more similar to a compliant solid. Heating can alter its modulus, thermal expansion, and conformity to the tool asperities. Greater conformity and local mechanical interlocking may increase the shear resistance required for sliding.

The untreated and post-gel pretreated prepreps therefore exhibit distinctly different sensitivities to velocity, temperature, and pressure. To examine friction evolution under a complete curing schedule, an additional test was conducted at a slip velocity of 0.01 mm/min and a normal pressure of 0.1 MPa. Figure 13a presents the temperature history, the calculated degree of cure, and the friction coefficient. The degree of cure was obtained from the resin cure-kinetics model, and the value corresponding to the adopted DMA gelation reference was approximately 0.21. The friction increases relatively slowly at low cure levels and more rapidly during the later stages of curing. A noticeable change in the friction-growth rate occurs near the DMA-defined gelation state. Before gelation, increasing temperature alone would be expected to reduce friction. However, the measured friction coefficient continued to increase during this stage.

To separate the effect of cure progression from that of increasing temperature, an additional friction test was conducted under isothermal conditions at 180 °C (Figure 13b). The friction coefficient showed a more pronounced increase near the gel point even under isothermal conditions. These results indicate that friction increases with advancing curing under the tested conditions. The observed cure-state dependence is qualitatively consistent with the previous reports that showed that tool-part or inter-ply friction in thermoset prepreps evolves with the cure progression and the thermal history [7,19,20]. Gelation may therefore provide a practical reference point for describing the cure-dependent evolution of tool-prepreg friction.

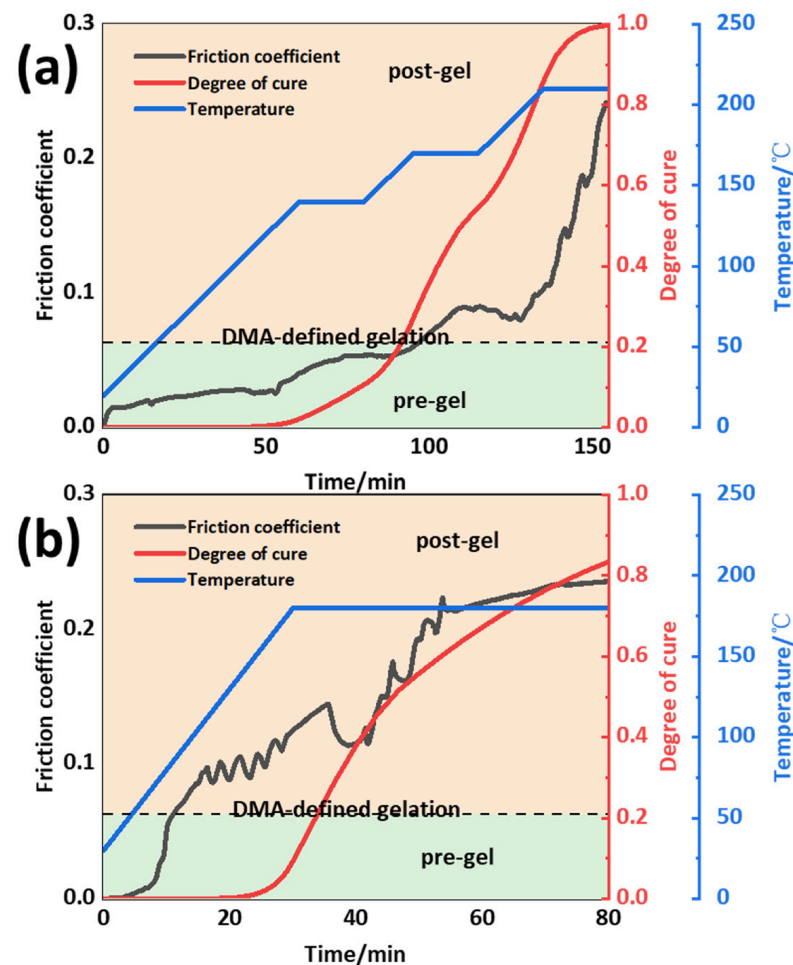


Figure 13. Tool-prepreg friction coefficient (a) during the complete cure cycle and (b) under isothermal curing at 180 °C (The dashed line indicates the DMA-defined gelation reference (α is about 0.21); the green and orange shaded regions denote the pre-gel and post-gel stages, respectively).

4. Conclusions

A custom pull-out apparatus was used to characterize the tool-prepreg friction for untreated and post-gel pretreated T800/bismaleimide prepreps. The experiments examined the effects of slip velocity, temperature, and normal pressure and provided the following conclusions.

- (1) The two cure states exhibit different parameter sensitivities. For the untreated prepreg, the friction coefficient increases with the slip velocity and decreases with increasing temperature and normal pressure. For the post-gel pretreated prepreg, the friction coefficient is comparatively insensitive to the slip velocity and pressure and increases with temperature.
- (2) The untreated prepreg response is consistent with a mixed lubrication involving both direct-contact and viscous resin-film contributions. The post-gel pretreated prepreg exhibits a predominantly Coulomb-type response with a reduced contribution from mobile resin-film shearing. The quantitative elemental analysis of resin transfer provides additional support for the different surface states.
- (3) During a complete cure cycle, the friction increases slowly at low cure levels and more rapidly during the later stages of curing, with an apparent change occurring in the vicinity of the DMA-defined gelation reference. The experimental data may serve as a basis for the future implementation and validation of cure-dependent tool-part interaction models in process simulations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jcs10090481/s1>, Figure S1: DSC curves for the four material states (black) and the corresponding integration baselines (red): (a) untreated prepreg; (b) untreated prepreg after the friction-test thermal history; (c) pretreated prepreg; and (d) pretreated prepreg after the friction-test thermal history; Figure S2: Capacitive-sensor calibration curve (red) and capacitance signals recorded during friction tests at three nominal loads (20 °C; slip velocity 0.1 mm/min); Table S1: Capacitive pressure-sensor calibration data; Table S2: Capacitive pressure-sensor monitoring data (pF); Table S3: Cure-kinetic parameters; Figure S3: DMA response of the prepreg at 140 °C; Figure S4: EDS spectra of the aluminum tool surfaces after friction testing: (a) untreated prepreg, 0.05 MPa; (b) untreated prepreg, 0.10 MPa; (c) untreated prepreg, 0.15 MPa; and (d) pretreated prepreg, 0.10 MPa; Table S4: Elemental analysis results.

Author Contributions: Conceptualization, Z.N. and H.Z. (Helezi Zhou); methodology, Z.N. and H.Z. (Helezi Zhou); investigation, Z.N., Z.L., X.L. and Y.M.; validation, Z.N., C.L. and H.Z. (Helezi Zhou); formal analysis, Z.N.; data curation, Z.N. and Z.L.; visualization, Z.N.; writing—original draft preparation, Z.N.; writing—review and editing, H.Z. (Helezi Zhou) and H.Z. (Huamin Zhou); supervision, H.Z. (Helezi Zhou) and H.Z. (Huamin Zhou); project administration, H.Z. (Helezi Zhou); funding acquisition, H.Z. (Helezi Zhou) and H.Z. (Huamin Zhou). All authors have read and agreed to the published version of the manuscript.

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