Characterization of Prepreg Tack for Composite Manufacturing by Automated Fiber Placement

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Introduction

Automated fiber placement (AFP) has become the industry standard for large-scale production of carbon fiber reinforced plastics (CFRP) to improve rate and reduce defects associated with manual layup.[1] Still, defects generated during AFP processes require manual, painstaking inspection by technicians and rework of the part when substantial defects are found. Prepreg (carbon fiber infused with uncured epoxy resin) tack is one of the primary factors that influences the generation of defects that arise during automated fiber placement (AFP).[2] Tack, as it relates to AFP processes and defect formation, can be understood as a combination of two stages, cohesion and decohesion.[3] During the cohesion phase, two pieces of prepreg are brought into contact under elevated temperature and pressure. Compaction of the resin within the contact area will result in a degree of intimate contact, *I*, between the mating prepreg surfaces. Defect formation, as a result of decohesion between prepreg surfaces, occurs after the cohesion phase and arises due to stress from events such as fiber placement over an existing defect, on a contoured path, etc. (Figure 1). Tack strength resists the displacement of prepreg on a surface due to stresses developed during deposition.

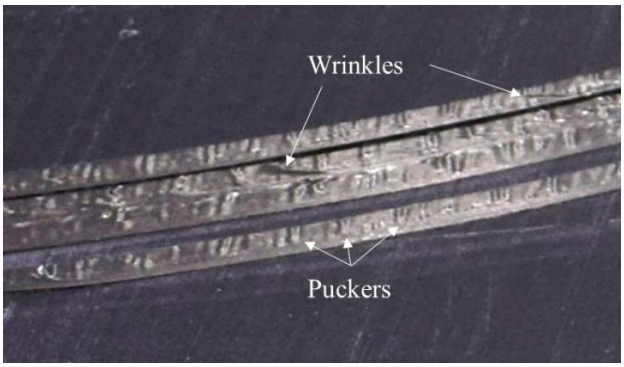

Figure 1. Defects observed during AFP using NASA Langley's Integrated Structural Assembly of Advanced Composites (ISAAC) over a 56 cm (22") radius, in-plane travel path using Hexcel® IM7/8552-1 slit-tape.

A major effort of NASA's Advanced Composites Project is to develop models that predict the occurrence of AFP defects. Characterization of prepreg tack is critical to establish model accuracy. Two techniques are utilized in this work to characterize tack force of Hexcel® IM7/8552-1 slit-tape, probe tack testing and micropeel testing (Figure 2).[4-5] Probe tack testing inseparably combines the cohesion and decohesion phases of characterization and, in the work described here, evaluates the tack force between the probe (a stainless steel surface) and a prepreg sample. Micropeel characterization was performed on a modified Sentmenant extensional rheometry (SER) fixture and enabled cohesion and decohesion phases to be performed independently. The relatively small sample size imposed by the SER fixture limited the collection of stable crack growth regions, and was a major contributor to noise. The details and results from both techniques will be presented here.

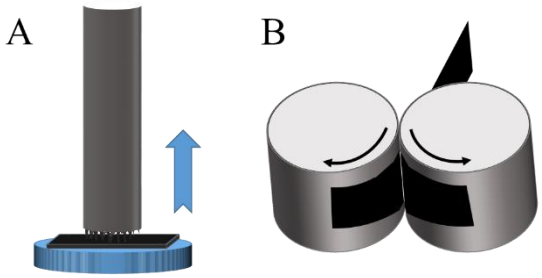

Figure 2. Two methods utilized in this work to characterize prepreg tack were (A) probe tack testing and (B) micropeel testing. The method by which decohesion was imparted on the test specimens is indicated by arrows.

Experimental

The prepreg used for tack characterization was Hexcel® IM7/8552-1 0.25" slit-tape tow. Prior to testing, the prepreg material was held in a freezer at -8 °C unless removed for sample cutting and preparation, which was conducted under ambient conditions (~ 20 °C). The samples were exposed to ambient conditions prior to testing for approximately 24 h as a result of removal of the material from the freezer and generation of sample specimens. The length of time at ambient temperature was held nearly constant for all samples to minimize the uncertainty in results that would be related to advancing of the epoxy resin. All tack characterization was performed on an Anton Paar USA Inc. MCR 520 TwinDrive™ Modular Rheometer equipped with an environmental controller (MHG 100 Humidty Generator).

Probe Tack Testing

Details regarding sample preparation, environmental conditioning, and test methodology were reported previ-

ously.[6] Briefly, prepreg samples were adhered to a rheometer lower plate using a custom-built sample preparation fixture that enabled pressure to be applied to the prepreg sample excluding the interrogation area. This minimized the influence that cohesion between the substrate and the prepreg had on the tack force determined during probe surface retraction. The probe surface (4 mm diameter circle) was held 5 mm from the prepreg surface during an environmental conditioning step that consisted of a stepwise change in temperature and relative humidity (RH) to the desired conditions followed by a 60 min. hold at those conditions. Next, the probe was brought into contact with the prepreg surface, held at that position using force control, where the probe position changed to retain the same force and account for resin flow from the contact area. Finally, the probe was retracted from the surface and the force-displacement curve was recorded to calculate the tack force. Since the probe contact and dwell time were necessarily connected to the probe retrieval steps, processes that influences the degree of intimate contact (cohesion) and decohesion were inseparably linked.

Micropeel Tack Testing

Unlike probe tack testing, micropeel testing was performed in such a manner that the cohesion and decohesion processes could be separated. For these experiments, two pieces of prepreg (~ 3.8 cm in length) were placed on a 50 mm lower plate and conditioned at a target temperature and RH for 60 min. After which, both of the exposed prepreg surfaces (i.e., not the side in contact with the backing film) were mated to each other with a piece of backing paper at one end oriented perpendicular to the fiber direction to act as a crack starter. This assembled microcrack specimen was placed on the lower plate, with the portion containing the crack starter positioned beyond the plate surface, while a 50 mm upper plate was lowered. The upper plate displacement was reduced until a target normal force (15-30 N) was applied. This was maintained for 5 seconds followed by upper plate retraction. The micropeel sample was attached to a modified SER fixture (Figure 2) with a drum diameter of 1.28 cm and a drum separation (gap) distance of 0.356 mm. This gap distance was determined to be sufficient to secure the micropeel sample without applying additional compressive force. The system was held in this configuration for approximately 8 minutes while the environmental conditions were adjusted to 40 °C and 40% RH. The counter-rotating drums were subsequently turned to peel the prepreg surfaces apart. The tack force was determined from the resultant force-displacement curve by taking the average force value at extensions between 5 and 20 mm where the most stable crack growth was observed. Each series of conditions was measured a minimum of three times.

To account for fiber bending during these experiments, prepreg micropeel specimens were prepared according to the previously described procedure with the exception that the backing film crack starter was positioned along the entire contact area such that there was no prepreg-prepreg contact. The force measured during the "stable crack growth" was the force required to bend the prepreg around the drums and the tack force between the prepreg and the backing film was considered negligible.

Results and Discussion

A series of experiments were performed to determine prepreg tack strength using both probe tack and micropeel tack procedures. Several experimental variables were considered in each experiment and are displayed in Table 1. These studies yielded several interesting outcomes and only a few salient results will be discussed here. A complete analysis will be provided in future publications.

Table 1. Experimental variables.

Probe Tack	Upper-Lower Bound
Temperature	40-60 °C
Relative Humidity	40-70%
Compaction Force	5-30 N
Dwell Time	5-300 s
Retraction Rate	1 mm/min
Micropeel Tack	**Upper-Lower Bound**
Temperature	40-65 °C
Relative Humidity	40%
Compaction Force	30 N
Dwell Time	5 s
Peel Rate	50-500 mm/min

Probe tack measurements were conducted at a constant retraction rate with all other experimental parameters varied. Thus, several relationships were identified including a decrease in tack force with increasing temperature and humidity and an increase in tack with an increase in dwell time. One particularly relevant relationship that probe tack testing revealed was the influence that contact force had on tack force (Figure 3). Along with dwell time, the contact force is one of the most influential conditions on the degree of intimate contact, *I*. Although tack force did increase with increasing contact force, the nonlinear dependence suggested that increasing contact force would result in a diminishing return on increased tack.

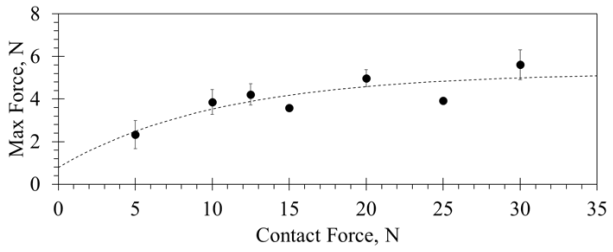

Figure 3. Tack force increased as the probe compaction force increased. Temperature, humidity, and dwell time were all constant at 40 °C, 40%, and 5 s, respectively.

Based on the results from the probe tack testing, a series of micropeel tests were conducted at a constant compaction force of 30 N. With a slit-tape width of 6.4 mm (1/4") and a sample length of 2.54 cm (1"), the pressure on the prepreg

was determined to be 186 kPa. The compaction force utilized for generation of the samples from ISAAC in Figure 1 was 115 kPa. Tack force was determined for a series of different peel rates and conditioning temperatures. The Williams-Landel-Ferry (WLF) equation (Eq. 1) was utilized to generate a time-temperature superposition graph (Figure 4).[7] This was first reported by Crossley as a way to translate processing conditions from the laboratory to those that would be more consistent with AFP production.[8] T is temperature and T_0 is the temperature the generated curve is specified for. C_1 and C_2 are constants dependent on the viscosity-temperature behavior of the tested material and were 9.781 °C and 50.101 °C, respectively.[9] T_0 was set to 20 °C. As can be seen, the tack force increased with increasing shifted peel rate. It should be noted that no maximum was observed as has been seen in other studies which could be due to the elevated temperatures that this study was conducted at.[10] Future work will probe lower temperatures to see if a maximum is observed.

$$log_{10}a_T = -\frac{C_1(T - T_0)}{C_2 + T - T_0} \quad (1)$$

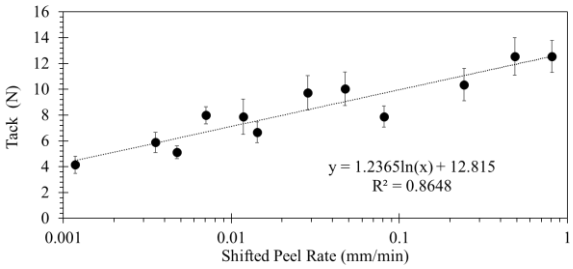

Figure 4. Time-temperature superposition of micropeel data showed an increase in tack relative to peel rate.

Comparison of the relationship between environmental conditions and tack force was of particular interest due to the differences between tack characterization techniques, namely that the probe tack test experiments measured tack between prepreg and metal, not between two prepreg surfaces. Interestingly, probe tack testing was determined to be more sensitive, relatively, to changes in temperature than the micropeel testing (Figure 5). This could be related to the fact that the peeling step of the micropeel testing was conducted under the same conditions (40 C and 40 % RH) for all specimens, while the probe retraction step of the probe-tack test was conducted under the same environmental parameters as the conditioning phase. Further testing at different micropeel environmental conditions will be performed to ascertain the influence these conditions have on tack force.

Conclusion

In this work both probe tack and micropeel test procedures were utilized to determine the tack force of Hexcel® IM7/8552-1 0.25" slit-tape tow. Based on these results, the degree of intimate contact, dependent on the resin flow index, was determined to dramatically influence tack force. Probe data was determined to be more sensitive to environmental conditions while micropeel data was determined to be more applicable to manufacturing conditions. Collectively, these techniques bring further elucidation of how processing conditions influence tack properties which will enable validation of models being developed to predict defect formation during AFP processes.

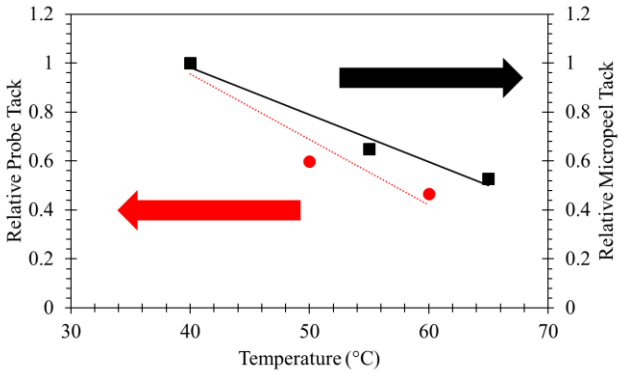

Figure 5. Relative tack force determined by probe (red, left axis) and micropeel (black, right axis) techniques.

References

1. J.A. Lukaszewicz, et al., *Composites: Part B* **2012,** 43, pp 997-1009.
2. O. Dubois, et al., *Experimental Mechanics* **2010,** 50, pp 599-606.
3. A. Forghani, et al. In *A Physics-Based Modelling Framework for Simulation of Prepreg Tack in AFP Process*, SAMPE Technical Conference, Seattle, WA United States of America, May 22-25, 2017; Society for the Advancement of Material and Process Engineering: Seattle, WA United States of America, 2017.
4. A.M. Gillanders, et al., *Internation Journal of Adhesion and Adhesives* **1981,** 1, pp 125-134.
5. R.J. Crossley, et al., *Composites: Part A* **2013,** 52, pp 126-133.
6. C.J. Wohl, et al., Tack Measurements of Prepreg Tape at Variable Temperature and Humidity. In *CAMX*, Orlando, FL, 2017.
7. A. Rudin and P. Choi, Mechanical Properties of Polymer Solids and Liquids. In *The Elements of Polymer Science and Engineering*, Third Edition ed.; Elsevier: San Diego, CA USA, 2013; pp 149-229.
8. R.J. Crossley. Characterization of Tack for Automated Tape Laying. University of Nottingham, Nottingham, 2011.
9. S. Ghose, et al., Slit Tape Buckling and AFP Defect Prediction. In *SAMPE Spring Meeting*, Long Beach, CA, United States of America, 2018.
10. A. Endruweit, et al., *Composites : Part A* **2018,** 114, pp 295-306.