TACK TESTING TO AID OPTIMISATION OF PROCESS PARAMETERS FOR AUTOMATED MATERIAL PLACEMENT IN AN INDUSTRIAL ENVIRONMENT

Andreas Endruweit[1], Sayata Ghose[2], Brice A. Johnson[2], Samuel Kelly[1], Davide S.A. De Focatiis[1] and Nicholas A. Warrior[1]

[1] Composites Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.
email: andreas.endruweit@nottingham.ac.uk, samuel.kelly@nottingham.ac.uk, davide.defocatiis@nottingham.ac.uk, nick.warrior@nottingham.ac.uk
website: http://www.nottingham.ac.uk
[2] The Boeing Company, Seattle, WA 98124, USA
email: sayata.ghose@boeing.com, brice.a.johnson@boeing.com
website: http://www.boeing.com

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ABSTRACT

A test fixture used in dynamic tack testing, where a prepreg is bonded to and peeled from a substrate in a single continuous motion using compaction and peel rollers, was modified to increase the ease of handling and to guarantee robustness of the test method. New features allow the compaction force bonding the prepreg to a substrate to be monitored, two types of peel roller (compliant/stiff) to be interchanged, the temperature at the interface between prepreg and substrate to be monitored with improved accuracy, and uncertainties due to specimen misalignment to be minimised. Guidelines for testing and data reduction were formulated. Results of different test series, exploring the effect of the surface pairing, prepreg out-time, ply angle, compaction force, and type of compaction roller on tack illustrate the potential to inform the choice of parameters for optimisation of automated material placement processes in industrial manufacture of composite components. The modified test fixture produces consistent results, facilitating the exchange of tack data between prepreg suppliers and end users.

1 INTRODUCTION

In the manufacture of aerospace composite components from prepreg tape employing automated material placement (AMP) processes (Fig. 1), the lay-up performance can be significantly affected by the quality of adhesion (tack) between the prepreg and the tool, between adjacent prepreg layers, and between the prepreg and rollers on the deposition head. A sufficient level of prepreg-tool and prepreg-prepreg tack is required to prevent the uncured lay-up from delaminating while subject to moderate shear and peel forces. On the other hand, prepreg-roller tack needs to be minimal to prevent resin from building up on the roller or prepreg wrapping around the roller leading to possible process failures.

Figure 1: Example of automated material placement technology employed in production of composite components for commercial airliners (reproduced from Lewis [1]).

To aid optimising AMP process parameters, Crossley designed a test fixture, originally for measurement of tack between a prepreg specimen and a rigid tool surface [2]. In the proposed method for tack measurement, rectangular prepreg specimens are laid up on rectangular substrates. Substrates with specimens are loaded into the test fixture, where they are clamped between a compaction roller and a peel roller pressing the substrate against the prepreg (at a defined compaction force). The fixture is mounted on the base of a universal testing machine. One end of the prepreg specimen is attached to the cross-head and load cell of the testing machine though a material clamp, such that the specimen is bent around the peel roller. In a tack test, the cross-head moves vertically at constant speed, which translates into a horizontal movement of specimen and substrate through the fixture. This results in the prepreg being bonded to and peeled from the substrate in a single continuous motion at a “feed rate” (or “peel rate”) which corresponds to the speed of the cross-head movement. The tack force is then derived from the tensile force at the load cell, which is recorded as a function of the cross-head displacement.

2 PREVIOUS EXPERIMENTS

2.1 General observations

In previous experiments on a commercially available aerospace grade uni-directional (UD) carbon fibre/epoxy prepreg tape [3], tack was measured on different surfaces at a range of temperatures and feed rates. The normal force applied through the compaction roller over a tape width of 75 mm was 100 N. At low temperatures, maxima in tack were found to occur at low feed rates. While the maxima move to higher feed rates as the temperature is increased, the maximum tack values are approximately constant.

Carrying out complementary oscillatory rheometry on the neat resin system used to produce the prepreg, and employing the principle of time-temperature superposition (TTS), i.e. shifting shear moduli measured at any temperature and frequency to other frequencies such that optimum overlap with data measured at a reference temperature is achieved, allows a rheological master curve to be obtained. In analogy, shifting the tack force measured at different temperatures and feed rates to new feed rates corresponding to a reference temperature (by multiplying the feed rates with the same temperature-dependent shift factors as for the rheology data) allows a tack master curve to be generated at any reference temperature, T_0 [4]. The resulting tack master curve has a bell shape (Fig. 2), where the rising flank (towards low feed rates) is dominated by cohesive failure in bonds formed between the prepreg and the substrate, the falling flank (towards high feed rates) by adhesive failure since there is not enough time for strong bonds to develop.

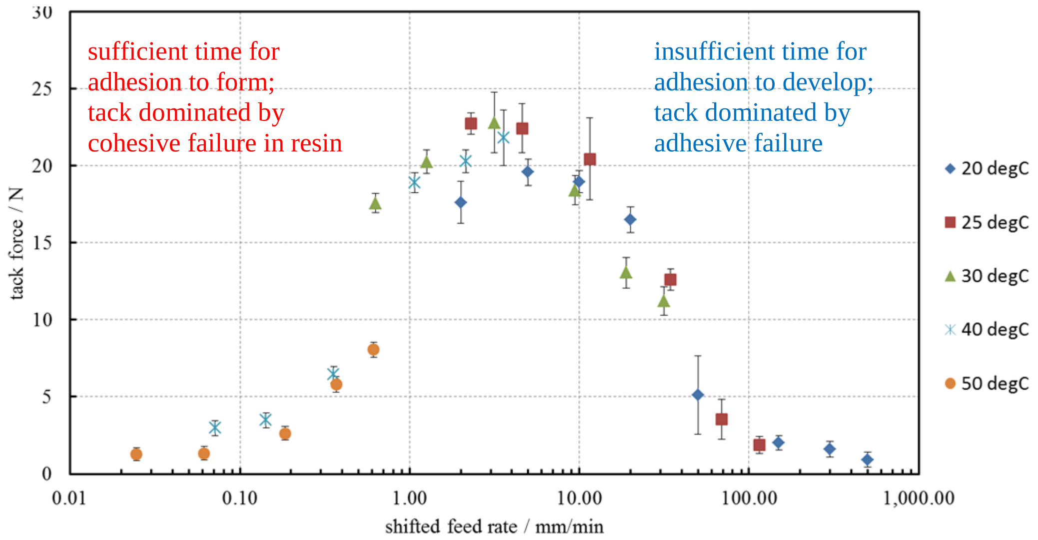


Figure 2: Example for a prepreg-prepreg tack master curve at a reference temperature $T_0 = 20$ °C; different markers indicate different temperatures at acquisition of shifted tack data.

TTS-shifting of tack data to predict the feed rate for maximum tack at any temperature is a particularly powerful tool for process optimisation, allowing process parameters to be selected to achieve maximum production rates and laminate lay-up quality in industrial composites processing. This is illustrated by the example in Fig. 3, where the black line indicates pairings of feed rate and temperature to obtain maximum tack.

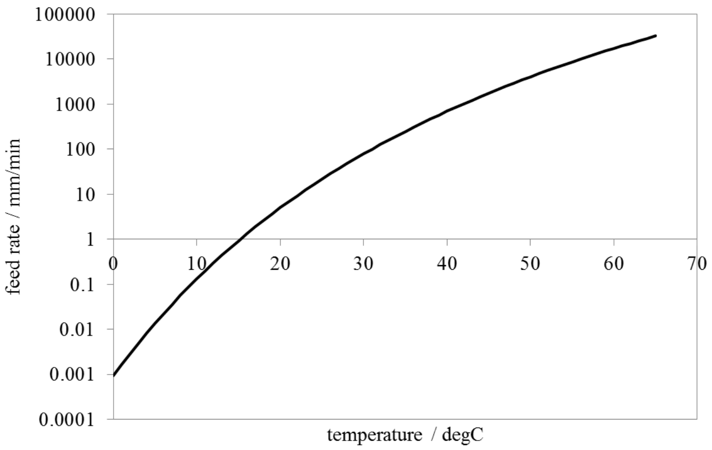


Figure 3: Feed rate-temperature space for prepreg-prepreg tack; the black line indicates pairings of feed rate and temperature to obtain maximum tack.

2.2 Effect of surface pairing

Tack was measured for the prepreg on different surfaces relevant to the actual lay-up process. It was also considered that the prepreg tape has two distinguishable faces (Fig. 4). The inner face (when on a roll), is covered with a protective backing paper. The outer face, with no protective paper, is normally the face to be applied to the substrate in an AMP process. The faces will be referred to as "paper" or "no paper" face. The resin distribution is suspected to be more uniform on the "paper" face.

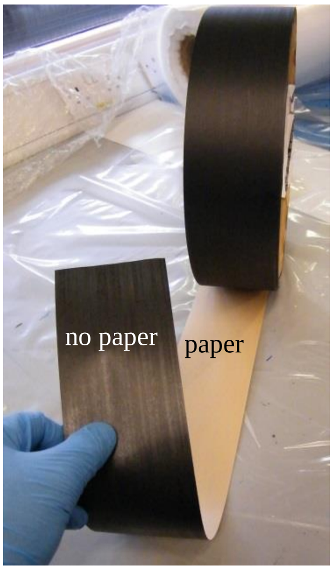


Figure 4: Different faces of prepreg tape.

The five surface combinations characterised here were:

- Prepreg on polished steel, representing a flat tool surface (neither release agent nor tackifier were applied); “paper” or “no paper” face of prepreg in contact with steel surface.
- Prepreg on prepreg, plies aligned; extending the original test method, the bottom ply was bonded onto a stiff steel substrate; “paper” or “no paper” face of top ply in contact with “paper” face of bottom ply.
- Fluorinated ethylene propylene (FEP) film, representing deposition equipment surfaces, on prepreg; prepreg ply bonded onto a stiff steel substrate; “paper” face of prepreg in contact with FEP.

For each combination, tack was measured at different temperatures and feed rates. The tack data were then TTS-shifted to a reference temperature (T_0 = 20 °C). Comparing results for different surface pairings at T_0 (Table 1), the observed maximum tack force for prepreg on prepreg was significantly higher than for prepreg on a steel substrate. In both cases, the maximum occurs at approximately the same shifted feed rate. Low-level tack was observed for FEP on prepreg. The maximum in FEP-prepreg tack, which was hard to identify, appears to occur at significantly lower shifted feed rates than for prepreg-steel and prepreg-prepreg tack.

material combination	max. tack force / N	feed rate / mm/min (at max.)
prepreg – steel (“paper” face)	8.6 ± 0.8	3.6
prepreg – steel (“no paper” face)	5.4 ± 0.7	3.6
prepreg – prepreg (“paper” face – “paper” face)	19.2 ± 1.4	3.1
prepreg – prepreg (“no paper” face – “paper” face)	22.8 ± 2.0	3.1
FEP – prepreg (“paper” face)	1.6 ± 0.5	0.6

Table 1: Measured maximum tack values for different material combinations (average values and standard deviations are given) and shifted feed rates at which the maxima occurred (at T_0 = 20 °C).

2.3 Effect of ply orientation

In aerospace applications, laminates are frequently produced from UD prepreg tapes at different orientation of the individual layers. The effect of the inter-ply angle on prepreg-prepreg tack was studied in a series of tests for the pairing "no paper" face on "paper" face, at a single temperature (T = 30 °C) and feed rate (50 mm/min) near maximum tack. The measured tack increased continuously with increasing inter-ply angle (Fig. 5). However, for ply angles greater than 60°, adhesion between the bottom prepreg layer and the substrate failed, while there was still adhesion between both prepreg layers. For these cases, the actual tack force was higher than the recorded value. Ignoring the affected values at ply angles of 75° and 90°, the maximum recorded tack value (at a ply angle of 60°) was found to be approx. 33 % higher than tack for aligned plies. For a ply angle of 45°, which seems particularly relevant since laminates frequently contain [0°, 45°, 90°] lay-up sequences, tack increased by 20 % compared to 0°. The underlying mechanism causing tack to increase with increasing inter-ply angle is currently still being studied by the authors.

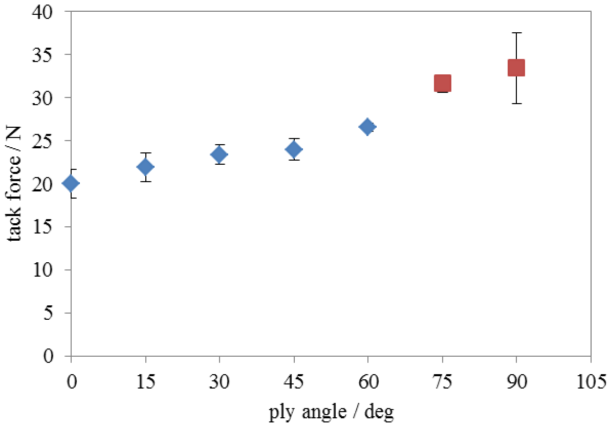


Figure 5: Effect of ply angle on measured prepreg-prepreg tack

2.4 Effect of out-time

While prepregs are normally stored in a freezer to delay heat-induced onset of resin cure, they are exposed to "workshop conditions" (i.e. ambient temperature and humidity) for a finite length of time ("out-time") during laminate lay-up and prior to the curing process. To study the effect of out-time on prepreg tack, specimens were conditioned for a maximum of 14 days at a temperature of (19.1 ± 0.3) °C and a relative humidity of (42.4 ± 2.2) %. At different out-times, prepreg-prepreg tack ("no paper" face on "paper" face) was measured at a range of temperatures and feed rates. It is to be noted that both plies in the lay-up were conditioned separately before the test. The measured data were TTS-shifted to a reference temperature T_0 = 20 °C. To obtain the appropriate shift factors, rheometry was carried out on resin samples with the same out-times as the prepreg specimens in the tack tests. For each out-time, a Gaussian curve was fitted to the shifted experimental data. Results characterising the tack behaviour, derived from the fitted Gaussian curves, are listed in Table 2. The data indicate that the feed rate at maximum tack decreases with increasing out-time of the prepreg specimens. This is consistent with an increase in the time required for adhesion to form, which is related to an increasing degree of cross-linking of the resin in the prepreg. There appears to be a trend for the maximum tack value to decrease slightly.

out-time / days	peak tack / N	feed rate at peak tack / mm/min
0	22.41	3.98
7	17.05	0.78
14	18.57	0.22

Table 2: Maximum tack values for different out-times and shifted feed rates at which the maxima occurred (at T_0 = 20 °C).

3 MODIFICATION OF TEST FIXTURE

To enable transfer of tack testing capabilities to an industrial environment, the original Crossley-designed test fixture was modified to facilitate handling and guarantee robustness of the test method. Several new features were included in the revised design of the test fixture (Fig. 6):

- The stiffness of all parts of the fixture was increased to allow for a wider range of compaction forces (up to 200 N) to be applied to the prepreg. Two miniature load cells were integrated into the fixture to continuously monitor the compaction force during a test.
- A compliant roller, the main body of which is from stainless steel coated in polyurethane (Shore 40A hardness), was newly designed to be used as peel roller. The ratio of diameters between stainless steel and polyurethane is consistent with that for rollers on actual AMP production equipment. Compliant and stiff (solid stainless steel) versions of the peel roller can be easily switched. At given compaction force, different stiffness of the peel rollers will result in different pressure distributions on the interface between prepreg and substrate.
- Fixation points are provided for instrumentation with thermocouples. Since the presence of the test fixture and specimen affects the air flow during convective heating, the temperature distribution in an environmental chamber was studied. An optimum position for placement of thermocouples was found to give a reading representative of the temperature at the interface between prepreg and substrate. It is also possible to attach a micro-camera to monitor the morphology of the interface in the peel zone. This can give a visual indication of the type of failure of the bond between prepreg and substrate, cohesive (indicated by the presence of long resin threads) or adhesive (smooth surfaces).
- Aids for improved alignment of the specimen are integrated in the test fixture to minimise uncertainties due to misalignment.

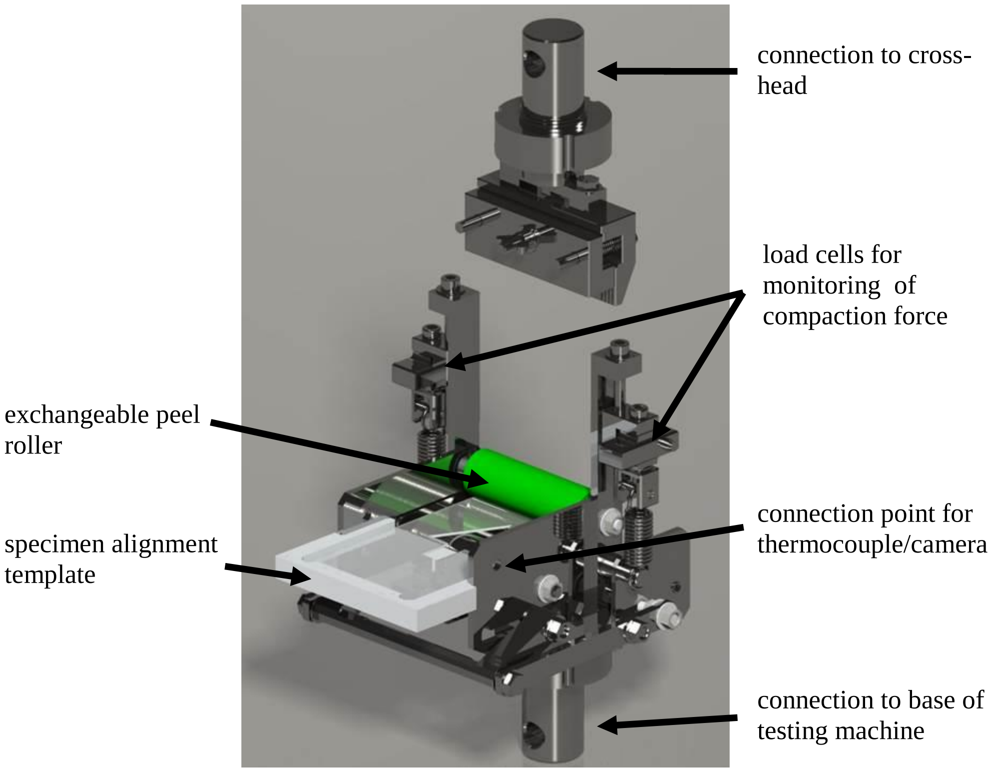
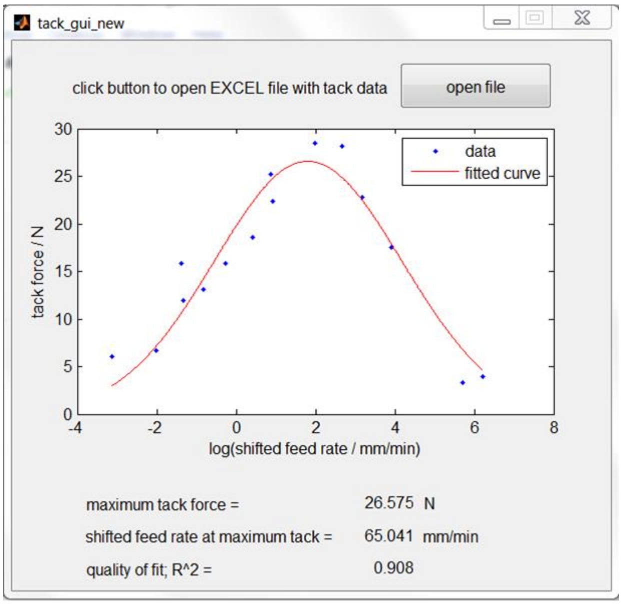


Figure 6: Modified fixture for measuring prepreg tack.

To minimise the influence of the operator on test results, guidelines on how to conduct the tests were formulated. In addition, a semi-automated data reduction scheme was implemented

- to obtain the tack force in each experiment from measured force-displacement raw data;
- to obtain the maximum tack force and the feed rate at maximum tack at a reference temperature by fitting a Gaussian curve to a series of TTS-shifted data (Fig. 7).



click button to open EXCEL file with tack data

maximum tack force = 26.575 N

shifted feed rate at maximum tack = 65.041 mm/min

quality of fit; R^2 = 0.908

Figure 7: Automated evaluation of a series of tack data to obtain the maximum tack force and the feed rate at maximum tack (at a reference temperature).

Validation tests were carried out on the new fixture, and a comparison of data showed very good agreement between results obtained with the new fixture and with Crossley's original design (Fig. 8). The data in Fig. 8 refer to prepreg-prepreg tack for a different tape than in Tables 1 and 2, hence the peak tack value is different.

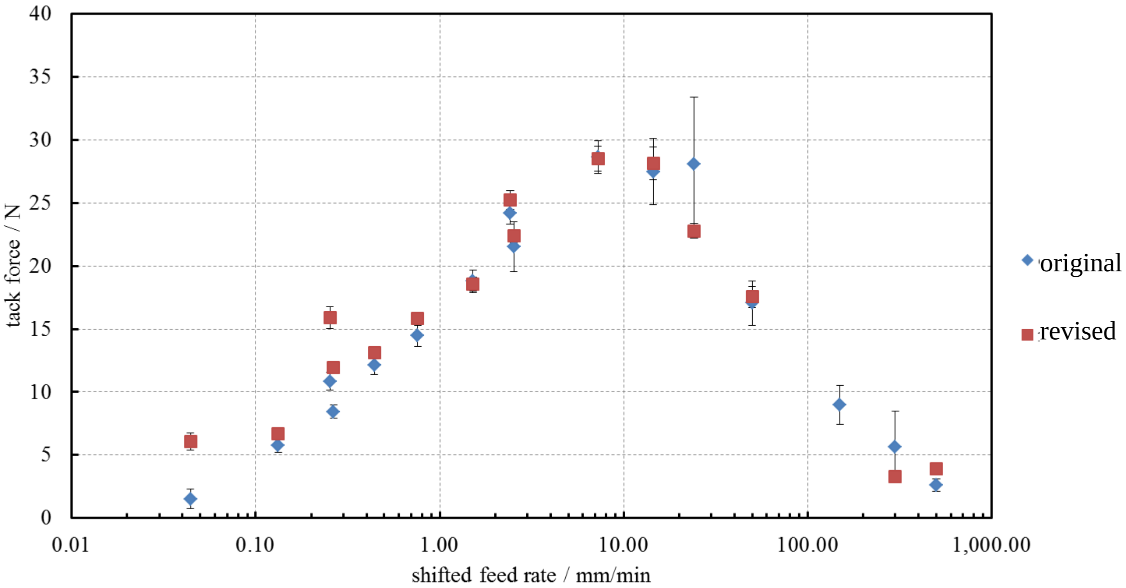


Figure 8: Comparison of tack data obtained using revised and original versions of test fixture.

4 ADDITIONAL EXPERIMENTS

Making use of new features in the revised design of the test fixture, the effect of additional controllable parameters on tack was explored. The effect of the compaction force and of the properties of the peel roller on prepreg-prepreg tack was studied in a series of tests for the pairing "no paper" face on "paper" face, at a single temperature (T = 30 °C) and feed rate (20 mm/min) near maximum tack.

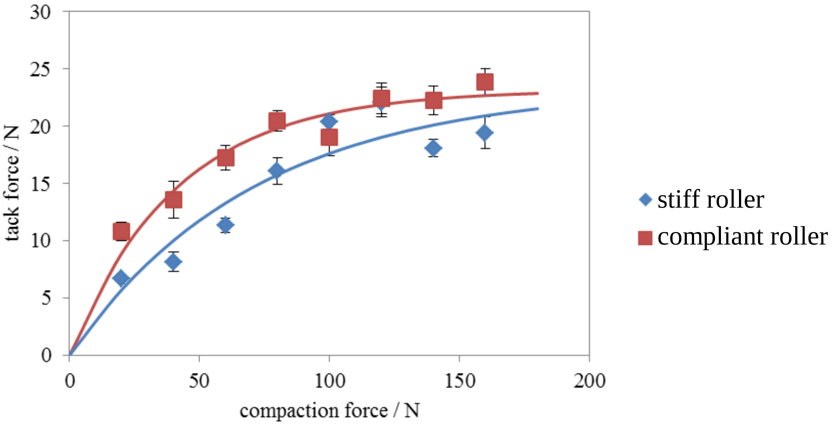


Figure 9: Effect of compaction force on prepreg-prepreg tack; experimental data and fit curves according to Eq. (1).

The miniature load cells integrated in the revised fixture allow the compaction force to be set accurately for tack measurement. Tack data measured at different compaction force using different peel rollers are plotted in Fig. 9. Here, the compaction force was defined as the force set when the steel substrate with the bottom prepreg layer (which is bonded onto it) was clamped between the compaction and peel roller. If the same values of the compaction force are set when the steel substrate with both prepreg layers is clamped between the rollers, the data in Fig. 9 are shifted along the abscissa.

Figure 9 indicates that the measured tack force converges with increasing compaction force. The dependence of the tack force, F_t, on the compaction force, F_c, can be expressed as

$$F_t = F_{t\infty}\,(1 - \exp(-F_c / F_c^*)) \quad , \tag{1}$$

where $F_{t\infty}$ is the limit value of the tack force, and the constant F_c^* is a measure for the rate of change in tack force with increasing compaction force. Fitting equations of this type to the experimental data indicates that results obtained using different peel rollers converge to the same tack force, and that convergence is faster for the compliant roller than for the stiff roller (Table 3).

roller	$F_{t\infty}$ / N	F_c^* / N
compliant	23.2	41.3
stiff	23.4	71.7

Table 3: Constants in Eq. (1) for prepreg-prepreg tack data obtained using different peel rollers.

The general behaviour shown in Fig. 9 for each peel roller is related to flattening of the slightly uneven prepreg surfaces in the compressed area when the compaction pressure is increased. This results in an increase in the true contact area between the prepreg layers, meaning that the number of bonds which can form between the layers increases. Hence, the tack force increases with increasing compaction pressure. At high compaction pressure, all asperities on the prepreg surfaces are flattened, and the true contact area does not change if the pressure is increased any further. Hence, the tack force converges to a limit value which depends on the resin properties only.

Comparing results obtained using the two different rollers, deformation of the compliant roller implies that a given compaction force results in a larger interface area (length of interface in feed direction) between the prepreg layers than for the stiff roller. Hence, the effective compaction pressure (which determines the true contact area) is smaller than for the stiff roller. On the other hand, the duration of pressing the prepreg faces together at a given feed rate is longer than for the stiff roller, i.e. there is more time for adhesion to form in the true contact area between the layers. For the material characterised here, superposition of these effects results in a greater tack force at given compaction force when the compliant roller is used than when the stiff roller is used. At small compaction force, the deformation of the compliant roller is small, and results obtained using both rollers converge.

5 CONCLUSIONS

A previously designed test fixture allows prepreg tack to be measured on different surfaces and at different temperatures and feed rates. Typical results show that, at low temperatures, maxima in tack occur at low feed rates. While the maxima move to higher feed rates as the temperature is increased, the maximum tack values are approximately constant. Employing the principle of TTS allows a tack master curve to be generated at any reference temperature. This has the potential to optimise the temperature and feed rate to achieve maximum production rates and laminate lay-up quality in industrial composites processing.

The original test fixture was modified to increase the ease of handling and to guarantee robustness of the test method. New features include

- integrated load cells allowing the compaction force to be monitored;
- a compliant peel roller which can be used as an alternative to the original stiff stainless steel roller;
- a thermocouple positioned to give a reading representative of the temperature at the interface between prepreg and substrate;
- an integrated alignment template to minimise uncertainties due to specimen misalignment.

In addition, guidelines for testing were formulated and a data reduction scheme was implemented.

The potential to inform the choice of parameters for optimisation of AMP processes was illustrated for the example of a uni-directional carbon fibre/epoxy prepreg tape. Tack data measured at different temperatures and feed rates, which were TTS-shifted to a reference temperature, show that

- maximum prepreg-prepreg tack is significantly higher than maximum prepreg-steel tack; both occur at approximately the same shifted feed rate;
- the feed rate at maximum prepreg-prepreg tack decreases with increasing specimen out-time, while the maximum tack value decreases slightly.

Additional tack data show that, at a single temperature and feed rate,

- prepreg-prepreg tack increases continuously with increasing inter-ply angle;
- prepreg-prepreg tack increases with increasing compaction force and converges to a limit value; the rate of convergence is higher when a compliant peel roller is used than when a stiff roller is used.

The observations reported here on the effect of industrially relevant process parameters on tack should encourage adoption of the proposed test method in an industrial environment. The ability to produce consistent results using the upgraded test fixture should enable the exchange of tack data between prepreg suppliers and end users.

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