Automated Fiber Placement Manufactured Composites for Science Applications

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ABSTRACT

Science instruments with large collecting areas that maintain dimensional stability, such as National Aeronautics and Space Administrations' (NASA) James Webb Space Telescope (JWST) and Wide Field Infra-red Space Telescope (WFIRST), and help achieve next generation science advancements. Composite materials often used for science applications include high modulus fibers in cyanate ester matrices to result in dimensionally stable structures with low contamination. Hand lay-up fabrication is the most common approach for science instrument structures. Automated Fiber Placement (AFP) using intermediate modulus fibers is commonplace in aircraft production reducing manufacturing time and increasing quality and consistency. AFP manufacturing for future large science instruments can similarly reduce costs and increase reliability. However, high modulus fibers are more prone to damage than intermediate modulus fibers. This study investigates the manufacturing viability of Tencate provided M55J/RS3C (Tencate) slit tape material using AFP processing. NASA Langley Research Center (LaRC) manufactured hand layup and AFP lay-up laminates under room temperature for initial trials,

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SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

Marshall Space Flight Center (MSFC) manufactured AFP laminates under room temperature and elevated temperature conditions to evaluate processing affects. Goddard Space Flight Center (GSFC) tested and evaluated tension and Coefficient of Thermal Expansion (CTE) properties by hand lay-up and AFP slit tape automated manufacturing for large science applications. These results show processing material warm reduces process induced fiber damage; leading to stiffness and CTE properties consistent with hand lay-up, while observing a slight degradation in tensile strength.

1. INTRODUCTION

1.1 Purpose

Space based observatories often have optical dimensional stability requirements in the micrometer range under challenging thermal and mechanical loading environments. Future space observatories plan larger primary mirrors for greater light gathering capabilities and higher resolution. NASA is studying the Large Ultra Violet Optical Infrared Surveyor (LUVOIR) with an aperture 1.2 to 2.2 times larger than JWST's aperture [1]. NASA's new heavy lift launch vehicle with an 8.4-meter (27.6 feet) diameter fairing further enables large observatory implementation. Past and current observatories such as Hubble Space Telescope, JWST and WFIRST rely on carbon fiber reinforced polymer composites material structures for high stiffness and near zero coefficient of expansion (CTE) designs. Almost exclusively these structures use polyacrylonitrile (PAN) fibers such as Toray's M55J, and low moisture absorbing cyanate ester polymers such as Tencate's RS3 or Hexcel's 954. These observatory composite structures are manufactured using hand layup approaches. Future observatories using automated composite manufacturing, employed in aircraft production (fig. 1), can reduce manufacturing costs, and improve part quality and reliability. Changing composite processing can change composite properties; accordingly, automated composite manufacturing for observatory materials designs are investigated. The purpose of this work is to establish if high stiffness fiber pre-impregnated composites (herein called 'pre-preg') processed with automated manufacturing can achieve stiffness, strength and the CTE needed for dimensionally stable observatories.



Figure 1: Composite Automated Processing, Electro impact AFP shown

1.2 The Manufacturing Challenge

Automation studies done on the effects of defects from gaps, overlaps, and twists, shows effect on lamina properties is around 5% [2]. These are on intermediate modulus aircraft based materials, and not on high stiffness fibers found in space observatories. The high stiffness fibers are brittle compared to intermediate modulus fibers and have more tendency to fracture, and fiber fracture can affect performance. Experienced people doing hand layup can mitigate fiber fracture by gently manipulating the material with heat and pressure where geometry dictates, thus those fiber's brittle nature is not a big issue in hand layup. Using the automated process, on the other hand, the fibers go through prepreg tape slit operations and go through robotic heads with winding paths, pneumatic brakes and cutters that can damage fibers. AFP using M55J/RS3C material are studied to assess if manufacturing dimensionally stable space structures with high stiffness fibers is viable. The metrics used to establish AFP viability compared to hand layup are fiber break counts, lamina strength and stiffness, and laminate coefficient of thermal expansion.

2. EXPERIMENTATION

2.1 The Materials

GSFC dimensionally stable structures almost exclusively use M55J with cyanate esters matrix material in unidirectional form. Tencate's RS3 and RS3C, the modified flow version of RS3, as well as Hexcel's 954-3 and 954-6 are the cyanate esters GSFC commonly uses. Tencate teamed with NASA on this work, providing material to test and assisting with potential fiber damage issues. The material selected is M55J 6K tow fibers impregnated with RS3C at 145 grams per square meter. This selection is relevant to existing materials being used and with past flight heritage. The material specified results in a nominal cure ply thickness of 0.137 mm at 60% fiber volume, the thickness used for data normalization. Tencate reports 1999 MPa (290 Ksi) tensile strength and 318.5 GPa (46.2 Msi) tensile modulus in the fiber direction. These baseline properties are the comparison basis for hand layup and slit tape-processed materials.

The experimentation used three material lots, one lot for hand layup, a first lot for LaRC slit tape processing, and a second lot for slit tape processing at MSFC. The slit tape material lots are, at the time of manufacture, in compliance with out-time and shelf life. The GSFC lot for hand layup are, at the time of manufacture, with-in out-time and out of date with respect to shelf life. Three glass transition temperature, ten short beam shear, and three fiber volume tests exceeded requirements to effectively extend the shelf life. Data in the testing further confirmed the adequacy of the hand laid materials as the results show.

2.2 The Manufacturing Methods

Hand layup and AFP methods were trialed. AFP manufactured composite laminate processing differ from hand layup processing in two fundamental areas, material manufacturing to achieve the slit tape product, and laminate manufacturing. Tencate performed material manufacturing followed by tape slitting at their Morgan Hill, CA facility. NASA sister AFP systems exist at LaRC and MSFC (fig. 2). The machining centers are nearly identical; both made by Electro-Impact and procured to the same technical specifications. The differences being layup platform types and

positioning. For the purposes of this work, the machines are effectively identical performing automated lay. Those robots use the 16 rolls of 6 mm slit tape material to apply a 102 mm wide pass. The feed-rate, heater, roller type, and pressure between the two systems were kept the same to start to perform laminate manufacturing, and varied temperature processing for cracking evaluations.



Figure 2: MSFC and LaRC Electoimpact AFP Machine Centers

2.2.1 Slit Tape Manufacturing

Slit tape materials come from traditional prepreg processing, and go through secondary processing to reduce the material to slit tape width of a specified size. Tencate performed the slitting process for this effort to reduce the 305mm wide unidirectional tape roll first into three 102mm wide rolls, and then reduced the 102mm rolls to 16 individual 6 mm slit tape rolls. Figure 3 shows the 102 mm prepreg material at the beginning of the slitter, a final a 6mm slit tape roll, and the circuitous route of the tape slitting process. That circuitous route that might damage fibers after pre-preg process is complete. To evaluate damage due to slitting two different slit processing temperatures were trialed, 22 ^{0}C and 26 ^{0}C. Inspections and tests from each lot identified the effect of tape slit processing on lamina performance.



Figure 3: Tape slit processing. A) The un-slit 102 mm wide tape material on 280mm diameter dowel. B) Circuitous fiber routing. C) The 6mm wide slit tape on a 76mm diameter dowel.

2.2.2 Laminate Manufacturing

Laminate manufacturing and processing were controlled to limit variability and attain relevant results. Cures completed all used the same vacuum, pressure and temperature profile as found in the RS3C datasheet. LaRC and MSFC team members used the same AFP machine parameters for machine feed, speed, applied heat and pressure. The AFP variables were different room processing temperature for tape slitting and lamination. Table 1 shows the variables evaluated. LaRC laminated the hand laid panels at 21 ^{0}C as the baseline. LaRC used the slit tape material that Tencate slit at 22 ^{0}C and laminated it at 21 ^{0}C. Tencate manufactured a second batch of material, that slitting process occurred at 27 ^{0}C, and sent it to MSFC. MSFC used this second batch of slit tape material and laminated panels at 22 ^{0}C and 26 ^{0}C.

Table 1: Material and laminate processing temperatures studied

Manufacturer and the relevant processing temperatures				
	LaRC		MSFC	
	Hand Layup	AFP	Hand Layup	AFP
Slit Tape Processing Temperature	N/A	22 ^{0}C	N/A	27 ^{0}C
Lamination Processing Temperature	21^{0}C	21 ^{0}C	N/A	22 ^{0}C and 26 ^{0}C

2.2.3 Experimental Tests

2.2.3.1 Tensile Testing

Fiber damage was a primary concern and motivation for this effort. A fiber dominated mechanical test property makes sense to evaluate fiber breakage. The 'Standard Test Methods for Tensile Properties of Polymer Matrix Composite Materials', ASTM D3039, is a fiber-dominated test well

used test in composites practice and used for these evaluations. The laminate made for these tests are 6 ply design, $[0]_6$. Five samples came from each laminate. No sample conditioning occurred, and tensile tests ensued at room temperature ambient conditions. LaRC tested the LaRC manufactured laminate coupons; GSFC tested the MSFC manufactured laminate coupons. Normalization occurred using a ratio of the average coupon thickness of 5 measurements to the theoretical cure ply thickness per Composite Material Handbook-17 [3].

2.2.3.2 Coefficient of Thermal Expansion Testing

Again, fiber damage was a primary concern and even anticipated. To ensure potential AFP manufactured structures will meet the critical dimensional stability requirements associated with science instruments, CTE tests were conducted. The laminate for these tests are an eight ply quasi-isotropic design, [0, 45, 90,-45]s , to result in a near zero CTE. No preconditioning occurred. The 'Standard Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry', ASTM E289-17, is a precision method for evaluating CTE and selected for the evaluations. Thermal strain measurements over a temperature range of 323 K to 98 K using a ramp rate of 1 K/minute in vacuum occurred. System error is less than 10 parts per million (ppm) over 300 K as confirmed with a single crystal silicon standard. Figure 4 shows the laser interferometer setup. Five coupons came from each LaRC laminate, and three coupons came from each MSFC laminate. Each coupon thermal expansions measurements saw at least 3 cycles from 303 K to 98 K, and those cycles measurements averaged. A best fit applied to the averaged thermal expansion data resulted in a polynomial equation, whose derivative provided the CTE reported in the results. All CTE measurements occurred at GSFC.

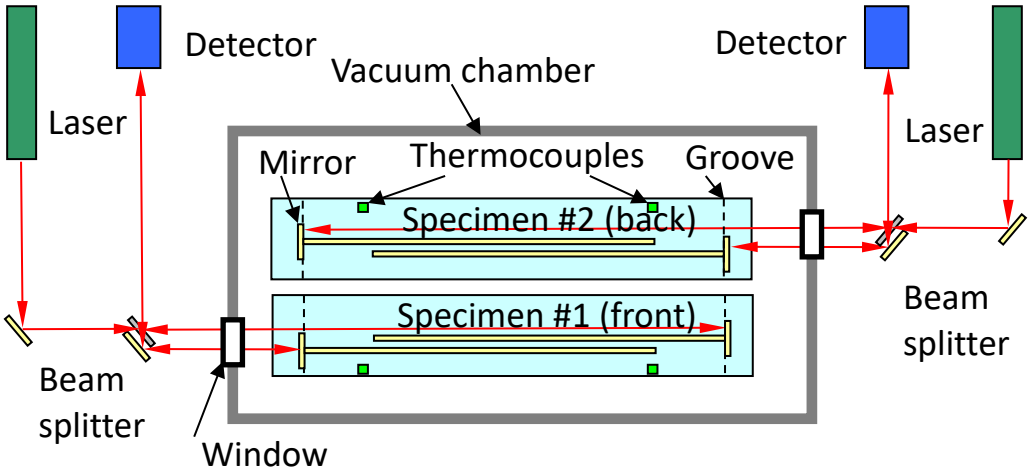


Figure 4: Laser Interferometer configuration

3. RESULTS

3.1 Material Processing

Material evaluations consisted of visual observations of the slit tape materials and the lamination processes. Incoming materials inspection showed indications of cracking. Figure 5 shows both traditionally processed prepreg and slit tape materials. The first batch of slit tape, used in LaRC

produced laminates, appears to have fractures. LaRC laminates showed fiber breakage during the processing. Of 4 LaRC panels AFP processed, there were 18 fractures. Most, 14 of 18, observed fractures are at the panel edges. This is where the machine either starts to put prepreg material down on the tooling or ends the material placement. Seeing both slit tape material cracks and lamination cracks led to second batch of slit tape that Tencate processed differently to establish if material cracking could be eliminated.

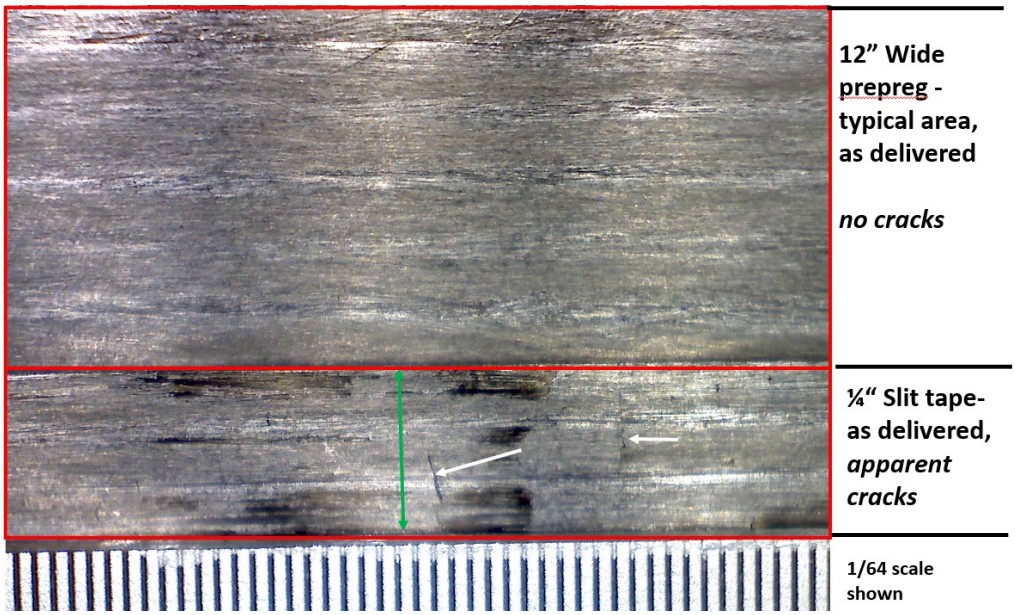


Figure 5: Images show typical prepreg (above) and slit tape with apparent cracks (below)

Tencate performed tape slitting at 27 ^{0}C (80 ^{0} F), used a more pliable backing material than the first lot, and lastly shipped rolls individually spaced to prevent roll to roll contact. Slit tape processed and shipped in this manner showed no apparent cracking at incoming material inspection. MSFC lamination used this second slit tape material batch.

For the 8 MSFC panels manufactured, to the same specification as LaRC panels, there were 29 observed fractures, 25 of those were in one panel, the CTE test panel number 1282231-3-1, laminated at room temperature. All those cracks were within the first 2 inches of panel edges, and outside the area of any test coupon cut from that panel.

3.2 Tension Test Results

The tension tests results compared to the Baseline data show strength reduction is a function of lamination process conditions. The Tencate RS3 datasheet baseline data shows an ultimate tensile strength in the fiber direction of 1999 MPa (290 ksi) and a modulus of 318.5 GPa (46.2 Msi). All tensile strength and moduli data presented in Figure 6 (the strength shown on the abscissa, the modulus is on the ordinate). Nineteen of the 20 coupons tested failed by longitudinal splitting, as is expected with a [0]6 laminate tensile test. The one outlier failed at the tab end due to the excessive grip pressure being applied, that single data point is dropped from the results.

The LaRC hand layup panel data shows agreement with the Tencate datasheet, the strength having a 3.5 % difference, the modulus being 2.0 % different. These are both well within one standard deviation of the hand layup test data. Furthermore, modulus values for all test data are within 6% across the dataset. Essentially, there is no effect of AFP on moduli. The large differences in the datasets are in the Tensile strength.

AFP processed panels have lower strength than the hand layup manufacturing process. The LaRC AFP panel processed at room temperature shows the highest number of observed manufacturing fractures as well as a 29.7 % strength reduction from baseline hand layup strength. The MSFC panels using Tencate second slit tape batch (recalling that process used higher processing temperature and less stiff backing) processed at room temperature improved on the LaRC AFP value with a strength 23.9 % lower than hand layup strength. Finally, the MSFC AFP panel processed warm shows additional strength recovery, showing only 17.3 % lower than the hand layup data. Summarizing, AFP processed slit tape material shows a tensile strength reduction, some reductions mitigated by increasing processing temperature. There is no associated change in tensile modulus.

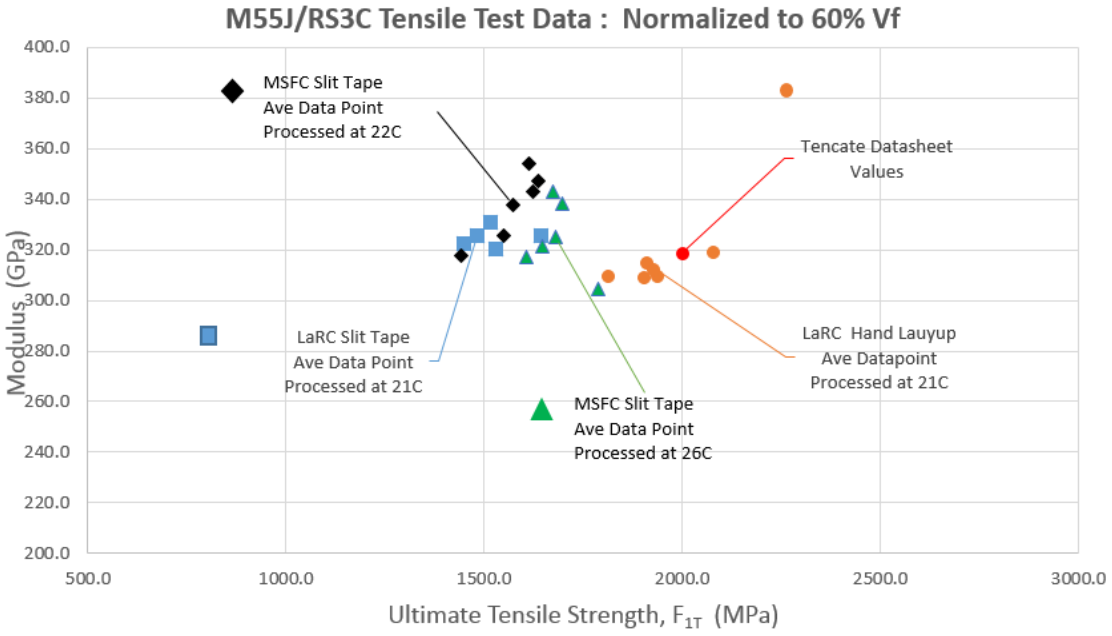


Figure 6: Fiber Tensile Strength and Modulus Data

3.3 Coefficient of Thermal Expansion Results

The CTE testing results (fig. 7), for hand layup and AFP layup, show the CTEs to be from 0.0 to -0.5 part per million per degree Kelvin (ppm/K), and is as expected for a Quasi-isotropic M55J/RS3C laminate. The measurement data shown are two types, the raw data showing change in length to original length, and the processed CTE, a derivative of the smoothed raw data, each provided to show overall CTE as well as some coupon apparent cracking of interest. The MSFC AFP shows a more pronounced decreasing trend from 320 K to about 240 K than the LaRC panels, and this is very small variation. To try to understand this better the thermal expansion data between the two centers were examined.

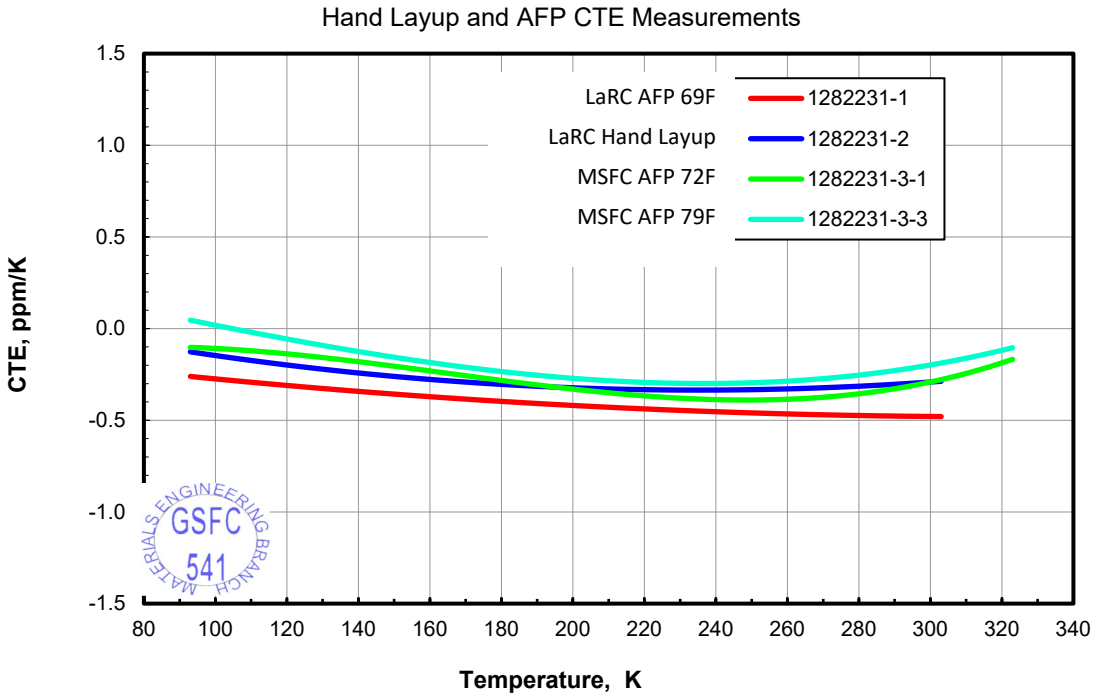


Figure 7: CTE Summary, all manufacturing approaches

3.3.1 LaRC CTE Results

Figure 8 shows LaRC hand layup and AFP layup CTE results. The hand layup CTE is -0.3 ppm/K, the AFP measured -0.4 ppm/K. As indicated before, these LaRC laminates were room temperature processed. The small difference shows that hand layup and AFP processed QI laminates can result in the same near zero CTE over the temperature range tested.

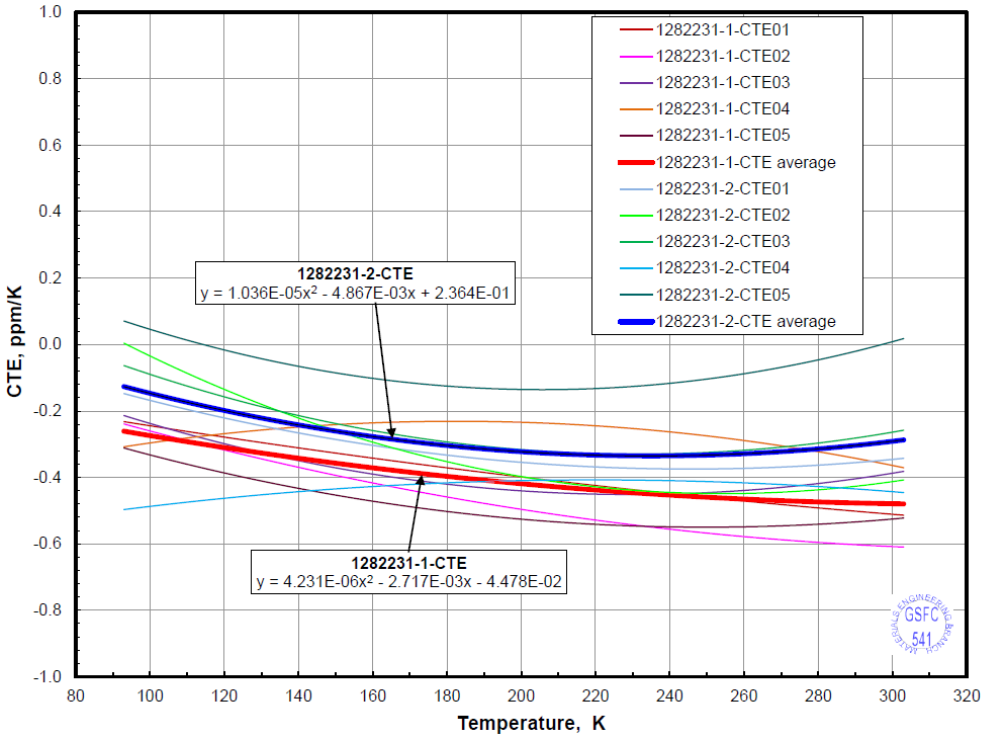


Figure 8: LaRC Average CTE over multiple coupons, Hand layup 1282231-2 panel and AFP layup 1282231-1 panel

3.3.2 MSFC CTE Results

Figure 9 shows MSFC AFP laminate CTE processed at 22 ^{0}C and 26 ^{0}C. The 22 ^{0}C processed laminate CTE average over the temperature range tested is -0.2 ppm/K, the 26 ^{0}C processed CTE

average is -0.3 ppm/K. The small CTE difference between the two processing temperatures indicate not apparent difference.

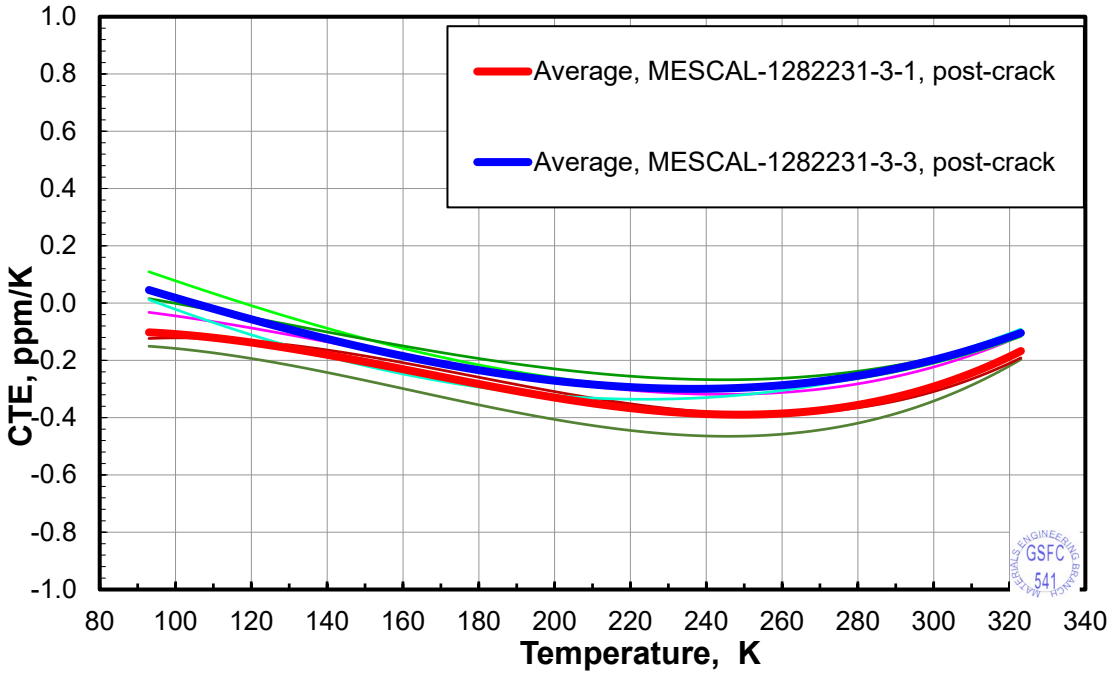


Figure 9: MSFC CTE Measurements, Post Cracking

The MSFC results differed in one aspect from the LaRC results, there did appear to be some cracking in the MSFC AFP panels during the first cool down in the CTE tests. Figure 10 shows thermal expansion data from the first cool down for all 6 MSFC AFP coupons. A sudden change in measured thermal expansion represents when a cracking event occurs. The temperature where the first crack event occurs is between 200 K and 170 K. As temperature continues to decrease more cracking occurs and the measurement is not valid anymore because the cracking causes the mirrors to move. Furthermore, laminate surface posttest visual inspections show apparent cracks along the fibers direction (fig. 11). The data from the first cycle is labeled ‘pre-cracking’, and the

data after the first cycle we label ‘post cracking’. The post cracking data represents the coupon CTE after the cracking is complete.

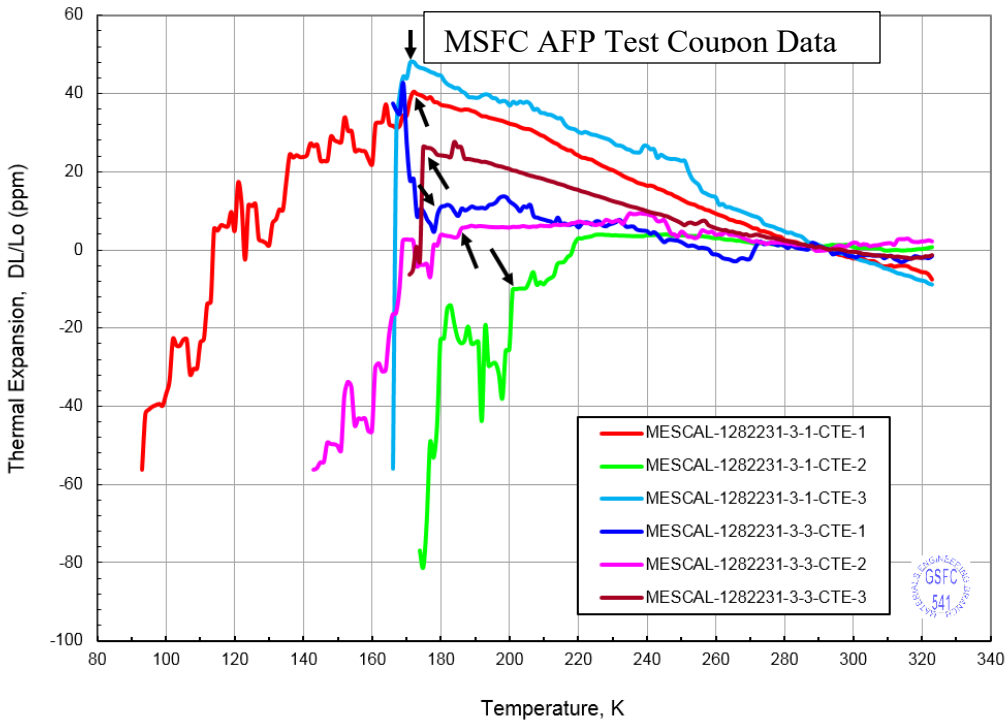


Figure 10: MSFC AFP thermal expansion during first cool down cycle. The arrows indicate where first cracking occurs.

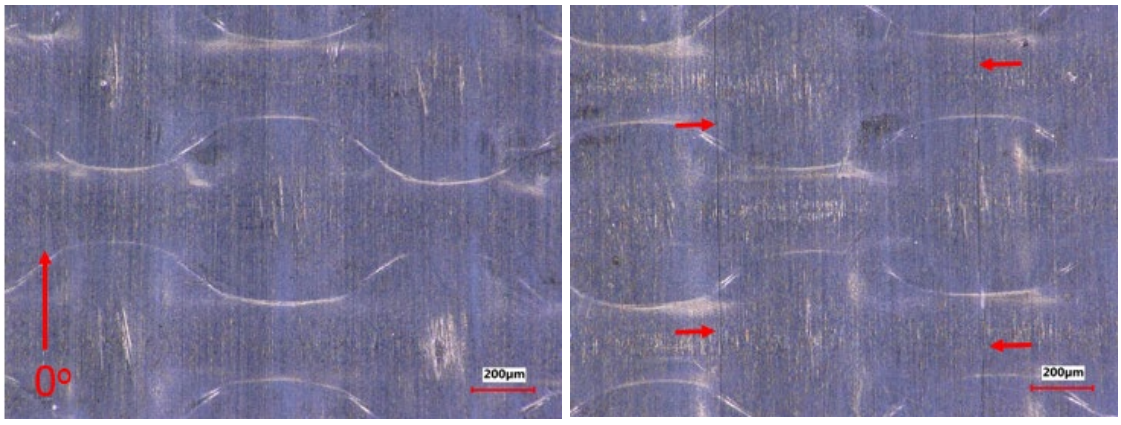


Figure 11: CTE coupon surface cracking observed

Figure 12 shows thermal expansion data both pre and post cracking data. For coupons 1282231-3-3-CTE-1 and CTE-2, from the same panel, the pre-cracking thermal expansion is lower than the post-cracking thermal expansion. However, there is little difference between the pre- and post- cracking thermal expansion for the other 4 coupons. The coupons 1282231-3-1 CTE-3 and 1282231-3-3 CTE-3, which are from two different panels, also show little difference in thermal expansion data between pre- and post-cracking, indicating that the cracking is not due to processing differences. Post cracking thermal expansion is consistent and results in low CTE.

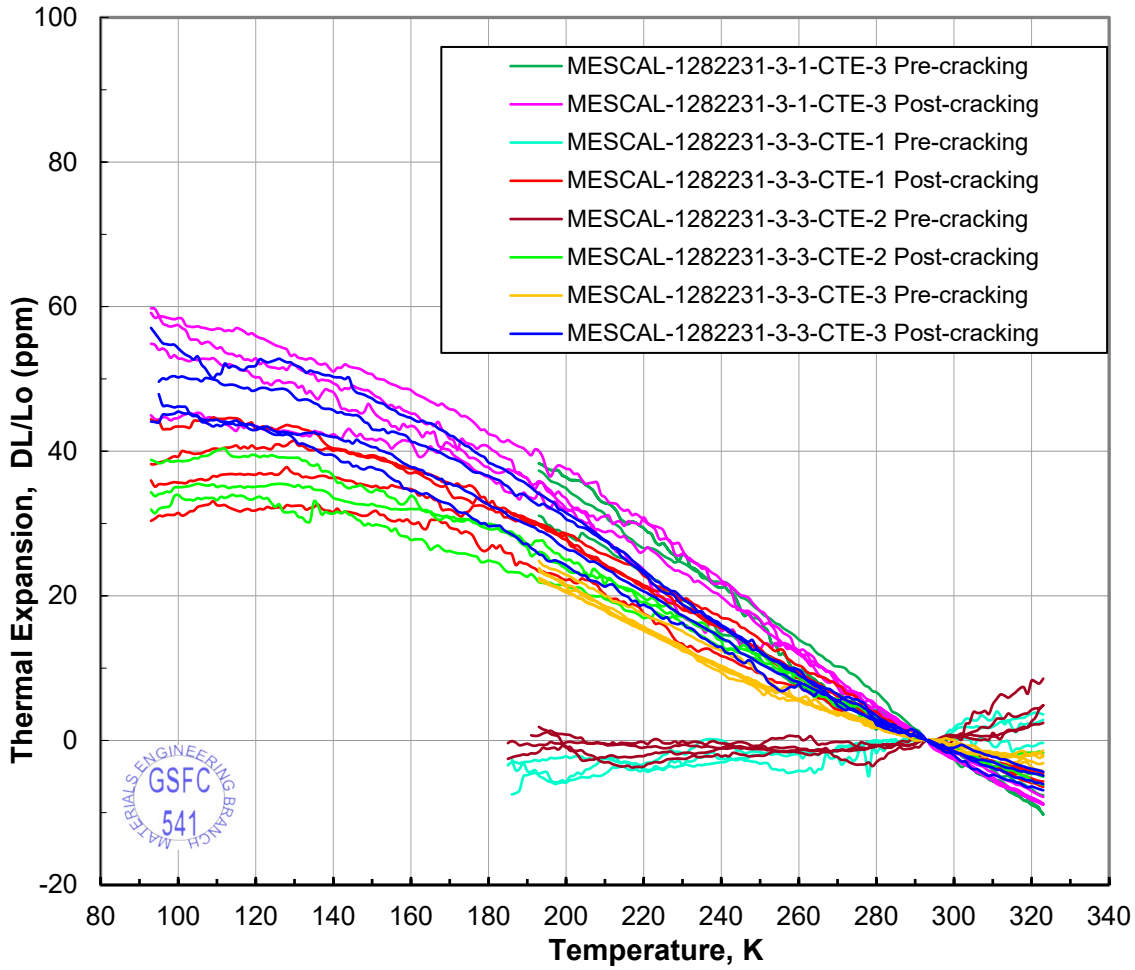


Figure 12: MSFC Panels, pre cracking and post cracking data

4. CONCLUSIONS

4.1 Material and Lamination Processing

Tensile testing results shows that AFP processed laminates will have the expected fiber direction tensile modulus and lower strength. It is concluded that the cure and test approach used in this experimentation are valid based on fiber direction tensile modulus and strength publish data agreement, with 2.0 % and 3.5% differences, respectively, to hand layup test data. From AFP testing, four conclusions are reached. First, the difference in manufacturing centers had little effect on tensile modulus and strength comparison based on LaRC and MSFC AFP laminates processed at room temperature. Secondly, AFP processing M55J/RS3C at room temperature lowers tensile strength from between 23.9 % to 29.7 % while not effecting the tensile modulus compared to the Tencate Datasheet. Third, slitting the prepreg tape warm reduces cracking and improves tensile strength by 5.8 %. Forth, AFP laminates processed at warm temperature provides another 12.4 % tensile strength improvement over laminate processed at room temperature. Given that only the lamination room was heated for these experiments, and that the robotic heads are possible to heat, we expect more strength recovery with additional processing control measures.

4.2 CTE Conclusion

CTE test results show that AFP processed M55J/RS3C laminates have the CTE as hand layup processed laminates. The MSFC individual test results show that some damage events occurred and those did not degrade CTE measurements.

4.3 What Is Proven and Next Steps

Stiff M55J fibers used in robotic manufacturing had no degradation on CTE, no degradation on tensile stiffness, and a moderate fiber tensile strength degradation compared to traditional hand layup M55J manufactured panels. The observed damage in the CTE testing indicates that in application structure temperature knowledge is important. Future testing should include thermal cycling before testing, as well as more evaluations to characterize damage as either fiber damage, matrix damage, or a combination of both. Additional testing should include tensile properties transverse to the fiber direction, compressive properties in both the fiber and transverse to the fiber directions, and in-plane shear properties to better understand overall effects of damage observed and enable structural analyses of a demonstration structure. Lastly, future processing work should focus how the robotic head heating and programming controls can further reduce tensile strength degradations observed in these studies.

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