PROCESSING OF POST-INDUSTRIAL UNIDIRECTIONAL PREPREG TAPES USING SMC EQUIPMENT

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PROCESSING OF POST-INDUSTRIAL UNIDIRECTIONAL PREPREG TAPES USING SMC EQUIPMENT

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LIST OF SYMBOLS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
ATL	Automated Tape Laying
CF	Carbon Fiber
DSC	Differential Scanning Calorimetry
GF	Glass Fiber
KST	Knife Sharpness Tester
Lbs.	Pounds
PSI	Pounds per Square Inch
RPM	Revolutions per Minute
SMC	Sheet Molding Compound

SUMMARY

The aerospace industry has an issue of what to do with waste, unused carbon fiber unidirectional prepreg tapes. One idea is to repurpose unused prepreg tapes for the manufacture of sheet-molding compound (SMC). The resulting material, per Sultana [1], should be stronger due to their carbon fiber and high strength epoxy resin, as compared to traditional SMC, which has lower strength glass fibers and epoxy resin. The cure state of the epoxy resin in the prepreg tapes, which is affected by the amount of time the material has spent at elevated temperatures or room temperature, significantly changes the ability of the material to be chopped into short fiber SMC. In addition, several equipment-related factors impact the material's ability to be chopped into SMC. This thesis characterized each of the factors impacting the process and used statistical methods to design experiments to investigate the impact each of these material-related and equipment-related factors on the success of the cutting portion of the process. The cure state, as measured by endothermic peak, glass-transition temperature (T_g), or heat of reaction/degree of cure, has the greatest impact on the cutting process. For material with a moderate level of cure, the sharpness of the blades in the cutting roller also has a major impact on the success of the process. The cutting pressure, roller speed, and tape tension also have an impact on the success of the process, but impact of these factors lessens for feedstock prepreg with a sufficient high level of cure. An optimal setup was determined, and general rules of thumb for selecting material and equipment settings were established.

CHAPTER 1. INTRODUCTION

Sheet-molding compound (SMC) and other chopped-fiber composite materials have been used for decades to manufacture quasi-isotropic, thin-wall parts with highly-variable geometries. These parts demonstrate the lightweight, high-strength properties for which fiber-reinforced composites are known, but they achieve these properties at a much more affordable price as compared with traditional prepreg or wet layup carbon fiber composites. In certain automotive applications, SMC parts are cost-competitive with stamped steel for low to moderate production volumes, per Mazumdar [2].

The aerospace industry is a heavy user of composite materials. Per Justin Hale [3], Boeing's most recent aircraft, the 787, uses more composite materials than any other in the company's fleet. The composite materials used in the aerospace industry are typically high-quality prepreg sheets or tapes that are placed onto a mold, then cured in an autoclave. When prepreg tapes are used, these tapes are often used as feedstock to a process like Automated Tape Laying (ATL). In ATL, the unidirectional tapes are placed on a mold, with the fibers oriented in a direction that maximizes stiffness and/or strength. Using ATL allows for the stiffness and strength of a part to be tailored to the structural application with minimal weight added. As with most prepreg-related processes, using prepreg tapes creates waste when a certain length of the prepreg tape left on the roll is too short for the ATL process to use. Currently, may aerospace companies dispose of this waste in a landfill.

Previous research was conducted through the Georgia Tech-Boeing Strategic University Partnership by Sanzida Sultana and members of the author's thesis committee that investigated repurposing unused prepreg tapes for the manufacture of chopped-fiber sheet-molding compound (SMC). Per Sultana [1], the SMC manufacturing technique was employed for processing repurposed prepreg tape, a method for evaluating properties of the incoming prepreg material was developed, and mechanical properties of the SMC parts made from prepreg tape were evaluated.

Sultana [1] determined that the SMC technique could be used to process the prepreg tape with some equipment modifications. She also determined that the prepreg, whose thermal history is assumed to be unknown prior to being received, could be characterized using Differential Scanning Calorimetry (DSC). Finally, she determined that the tensile and impact strengths of the carbon fiber prepreg SMC remained comparable regardless of cure state prior to processing; thus, prepreg tapes both “fresh” and “aged” can create prepreg SMC with good mechanical properties.

With these conclusions drawn, this thesis research effort focused on improving the modified SMC manufacturing process by determining the optimal prepreg cure state for manufacturing and determining the equipment setup resulting in a process with high percent yield. The following dissertation presents this work. In Chapter 2, background is provided on the materials, manufacturing processes, and statistical methods used in this project. In Chapter 3, the method of characterizing the cure state properties of the prepreg material used is presented. In Chapter 4, the methods of characterizing the equipment processing parameters, including off-line tests for those factors that could not be easily modified, are shown. In Chapter 5, the setup of the experiment that evaluates both the material-based and equipment-based factors affecting the success of the process is discussed. Finally, in Chapter 6, the results from that experiment are discussed and recommendations are provided for future manufacturers of prepreg-based SMC.

CHAPTER 2. BACKGROUND

To aid the reader in better understanding the scope of the project, a review of the research literature is presented. In this, background is provided on sheet molding compound, including its typical composition, manufacturing processes, and applications. Next, information is provided on carbon fiber prepreg tape, including its composition, manufacturing process, typical storage procedure, and applications. Then, the process that was used in this research effort to manufacture carbon fiber prepreg SMC using modified SMC equipment is introduced. Finally, an introduction to Design of Experiments methodology and its implementation through JMP software is presented.

2.1 Sheet Molding Compound

2.1.1 Typical Sheet Molding Compound Composition

Sheet molding compound is a composite material composed primarily of chopped fibers, uncured resin, and fillers, with small portions of thickeners, mold release, and other minor components. The chopped fibers are typically glass and are randomly oriented to provide quasi-isotropic mechanical properties. The resin system is typically a thermoset such as polyester or vinyl-ester, which cures under the heat and pressure of a compression molding machine. According to Mazumdar [2], the fillers “reduce the overall cost, increase dimensional stability, and reduce shrinkage during molding.” The composition of a typical SMC, as developed by Mazumdar, is shown in Table 1.

Table 1 - Composition of a Typical SMC [2]

Ingredient	**Purpose**	**Weight %**
Chopped glass fibers	Reinforcement	30.00
Unsaturated polyester resin	Base resin	10.50
Calcium carbonate	Filler	40.70
Styrene monomer	Co-monomer	13.40
Polyvinyl acetate	Low shrink additive	3.45
Magnesium oxide	Thickener	0.70
Zinc stearate	Mold release (lubricant)	1.00
t-Butyl perbenzoate	Catalyst (initiator)	0.25
Hydroquinone	Inhibitor	Trace

2.1.2 Manufacturing Process for Sheet Molding Compound

Sheet molding compound is manufactured in the manner shown in Figure 1. Dry, continuous glass fibers are drawn from a roll into the gap between the cutting roller and the anvil. The cutting roller has evenly-spaced steel blades inserted around its outer surface to ensure each chopped fiber is the same length. The anvil is a steel cylinder covered with a removable sleeve, typically polyurethane. This sleeve provides a surface against which the cutting roller can chop the glass fibers without damaging the blades. The cutting force that chops the glass fibers is controlled by two pneumatic cylinders on the ends of the cutting rollers; the pneumatic pressure is easily adjustable on the machine operated for the purpose of this project. The cutting speed is controlled by a motor fastened to the anvil. When pressure is applied between the two rollers, the anvil drives the cutting roller.

The chopped fibers fall freely onto a lower carrier film coated with a thin layer of resin mix, which includes resin, fillers, and other additives. Next, the upper carrier film, also coated with a thin layer of resin mix, is placed on top of the chopped fibers. This sandwich (from top to bottom: upper carrier film, resin mix, fibers, resin mix, lower carrier film) is compressed together by rollers in the compaction zone. Finally, the SMC composite is rolled up for easy handling by the SMC collection roll.

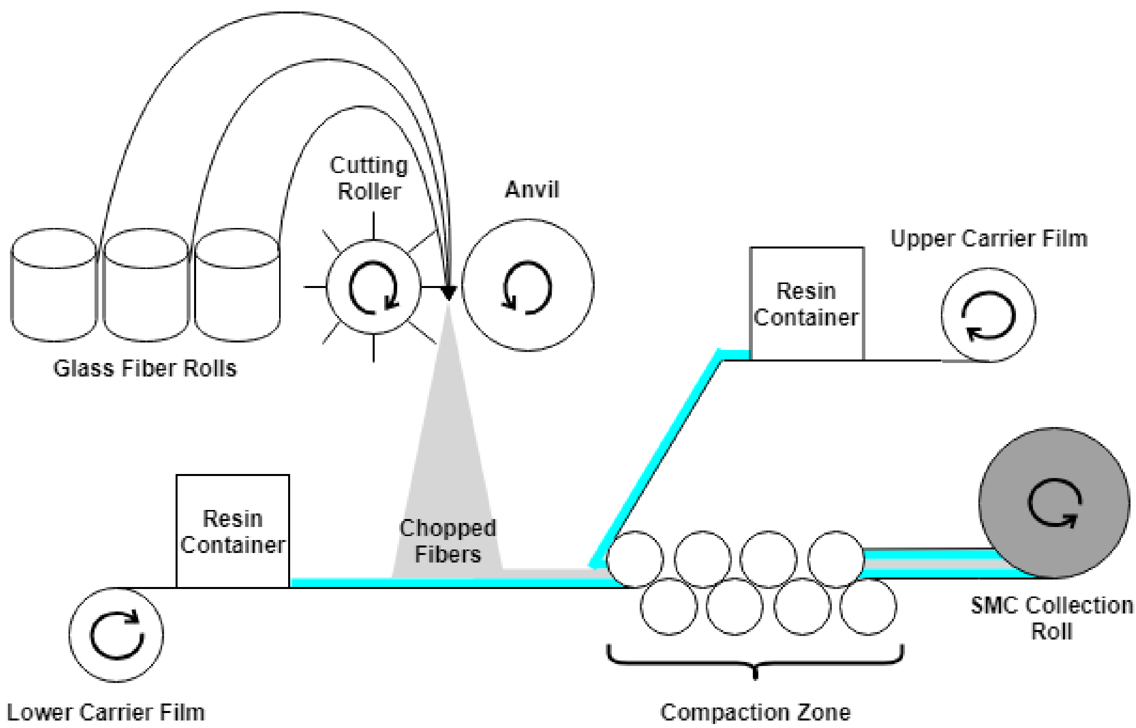


Figure 1 - SMC Manufacturing Process

The actual equipment that performs this process is shown in Figure 2.

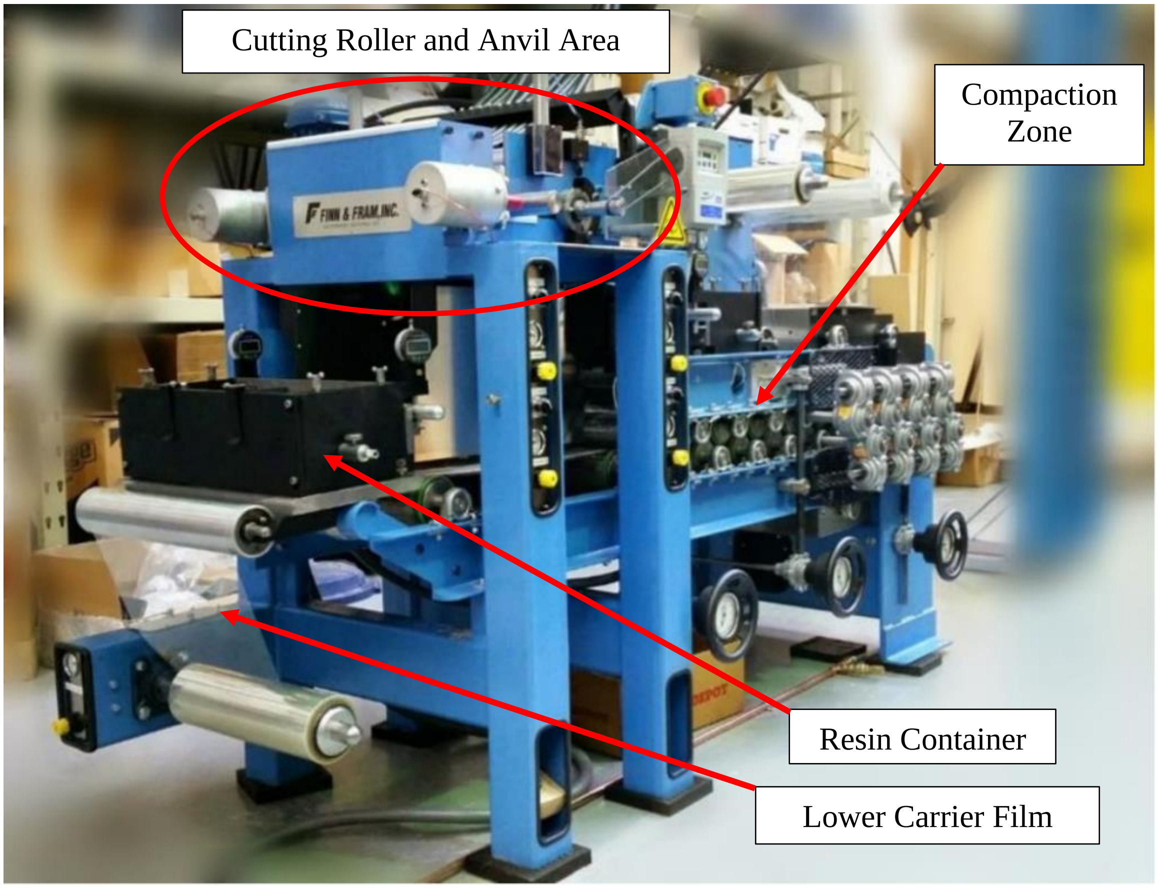


Figure 2 - SMC Equipment

From this point, the SMC composite can be cut into an appropriate size and loaded into a hot press to be compression molded into an SMC part.

2.1.3 Applications for Sheet Molding Compound

Per Mazumdar [2], compression-molded SMC composites are used extensively in the automotive industry to make one-piece or two-piece panels. SMC is often used as a lightweight, less expensive (for low to moderate production volumes) alternative to stamped steel or aluminum. In components such as roof panels, fenders, and spoilers, one-piece panels are used because the component is supported across most of its surface. In other components such as doors and hoods, two-piece panels (see Figure 3) are used where the component must be sufficiently stiff without as many supports. In these cases, an adhesive bond secures the two SMC pieces together.

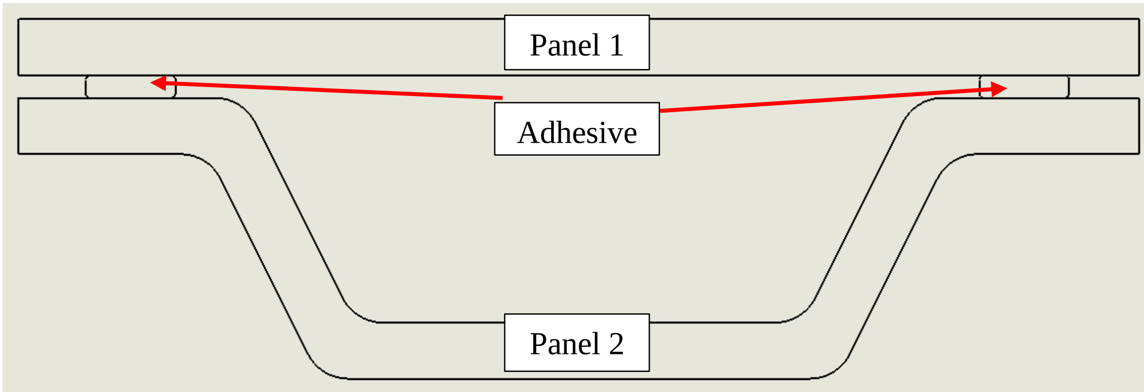


Figure 3 - Two-Piece SMC Component

2.2 Prepreg Composites

A prepreg is a resin-impregnated, fiber-reinforced polymer that is geometrically flat and typically rolled onto a cylinder. Prepreg refers to the method whereby the fibers come pre-impregnated with prepolymer ready for layup onto a mold. By contrast, a wet layup is one in which dry, unimpregnated fibers must be infiltrated with resin before being laid up onto a mold. The term "tape" is usually used to describe prepregs of a relatively small width, but prepregs can be made as wide as needed. Per Mazumdar [2], parts made from prepreg typically provide better mechanical properties than parts made via wet layup because the fibers are fully wet-out, the fiber and resin content is more precisely controlled, and there are fewer voids.

2.2.1 Typical Carbon Fiber Prepreg Tape Composition

Prepreg tapes are primarily composed of a fiber (usually carbon fiber) and a matrix material (usually epoxy resin). The fibers, which are used in the feedstock for the prepreg SMC produced in this project, are unidirectional, but fibers can also come in woven patterns for sufficiently wide prepregs. Unidirectional fibers provide high strength and stiffness for loads applied in the direction of the fibers, but they have significantly lower strength and stiffness in the directions perpendicular to the fiber orientation. Woven prepregs have fibers that are woven together, which allow for high strength and stiffness along the two fiber directions that are at an angle, typically perpendicular, to one another. Woven prepregs also allow for easier draping around a tightly-contoured surface as compared with unidirectional prepregs.

The matrix material in a prepreg can be either a thermoset or a thermoplastic polymer. The more common matrix is a thermoset resin, and this is also the matrix material in the prepreg used in this project. Thermosetting resins chemically cure under heat and pressure, and cannot be returned to their original state once cured. Thermoplastic resins melt under heat to become pliable and fill the shape of their mold, then return to their solid state when cooled after they have formed the desired shape. Because thermoplastics do not chemically react when used to form a part, they can be recycled fairly easily. Thermosets and prepregs that use thermosetting resins, however, are difficult to recycle because they cannot return to their original, uncured state. Thus, repurposing post-industrial prepregs made with thermosetting resins, which are not fully cured, to manufacture SMC provides the motivation for this project.

2.2.2 Manufacturing Process for Prepregs

The fibers of a prepreg are impregnated by either a hot melt process or a solvent dip process. For unidirectional prepregs, only the hot melt process is used, so only that process will be discussed.

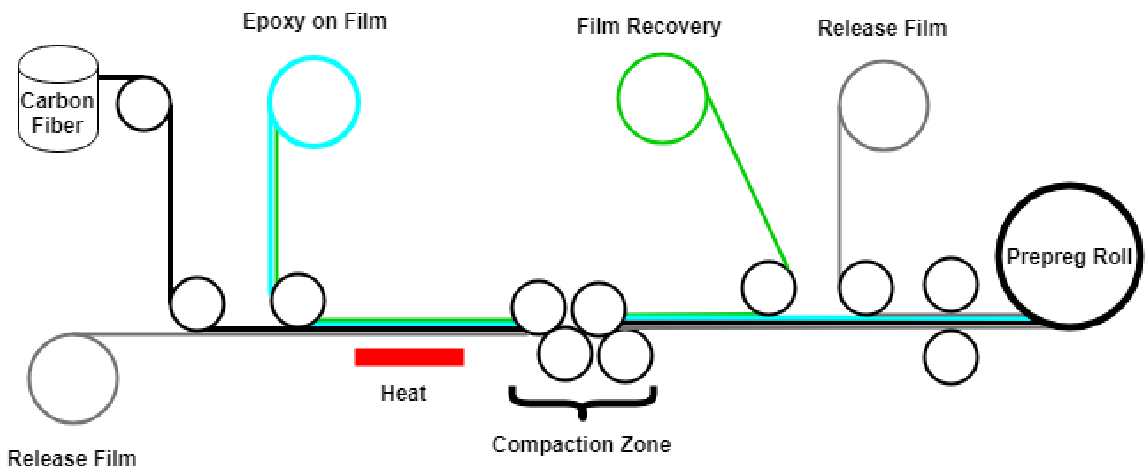


Figure 4 - Hot Melt Prepreg Manufacturing Process

In the hot melt prepreg manufacturing process shown in Figure 4, the fibers are drawn from a roll onto moving release film. Next, wet epoxy on a backing film is drawn from a roll onto the fiber and release film. Then, heat is applied to melt the epoxy and wet the resin. The sandwich (from top to bottom: epoxy film, epoxy, fiber, and release film) is compressed together to ensure the fibers are adequately impregnated by the resin. After compaction, the residual epoxy film is removed and replaced by release film. This new sandwich is compressed together one more time before being collected on a roll of prepreg.

2.2.3 Storage Procedure for Prepreg Composites

The thermosetting resin in prepregs begins to cure and lose its tack at room temperature, so prepreg is typically stored in freezers set at or below -15°C. Prepreg manufacturers often specify the maximum freezer storage time and maximum room temperature storage time to ensure the final product made from the prepreg is of the desired quality.

2.2.4 Applications for Prepreg Composites

Prepregs, which provide high quality properties at a high cost and typically high scrap rate, are used frequently in the aerospace industry to make lightweight, strong, and stiff components. Per Fibre Glast Developments Corporation [4], they are essentially used for any layup or ATL process in which the material property advantages over typical hand layup outweigh the additional cost, limited shelf life, and necessary heat cure associated with using prepregs.

2.3 Modified SMC Manufacturing Process for Carbon Fiber Prepreg

To make SMC from post-industrial carbon fiber prepreg tapes, typical SMC equipment was modified to allow the prepreg to serve as feedstock. The method used for this project was drawn from the method described by Sultana [2], with some adjustments that are detailed below. In this process, a roll of prepreg is loaded on a creel, then the prepreg tape is fed from the creel, over the locating shaft, and in between the cutting roller and anvil, as shown in Figure 5.

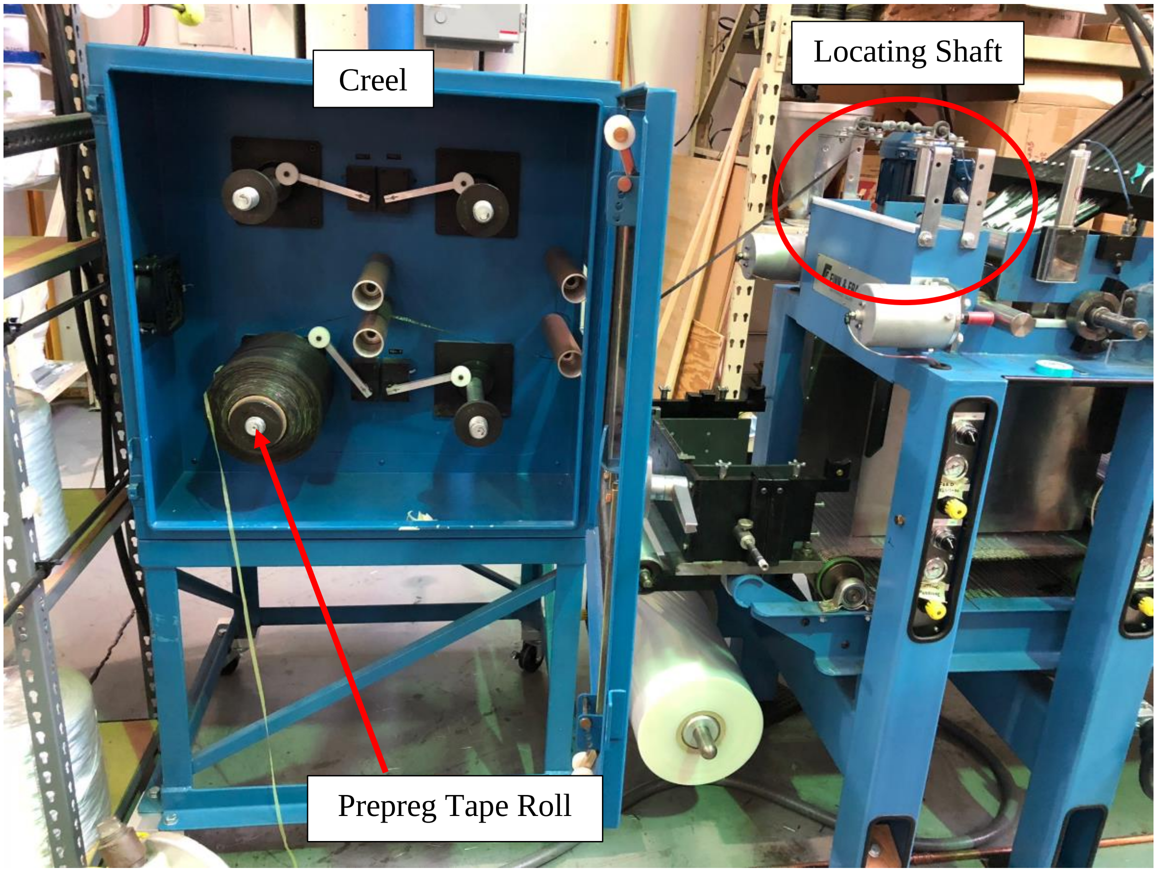


Figure 5 - Routing Prepreg Tape

Once the prepreg tape is cut into chips, the chips descend freely onto the moving lower carrier film. The upper carrier film comes down on top of the prepreg chips, and the compaction zone rollers sandwich the upper carrier film, prepreg chips, and lower carrier film together. The compacted prepreg SMC is then collected in the SMC collection roller for easy handling. This process is documented in Figure 6.

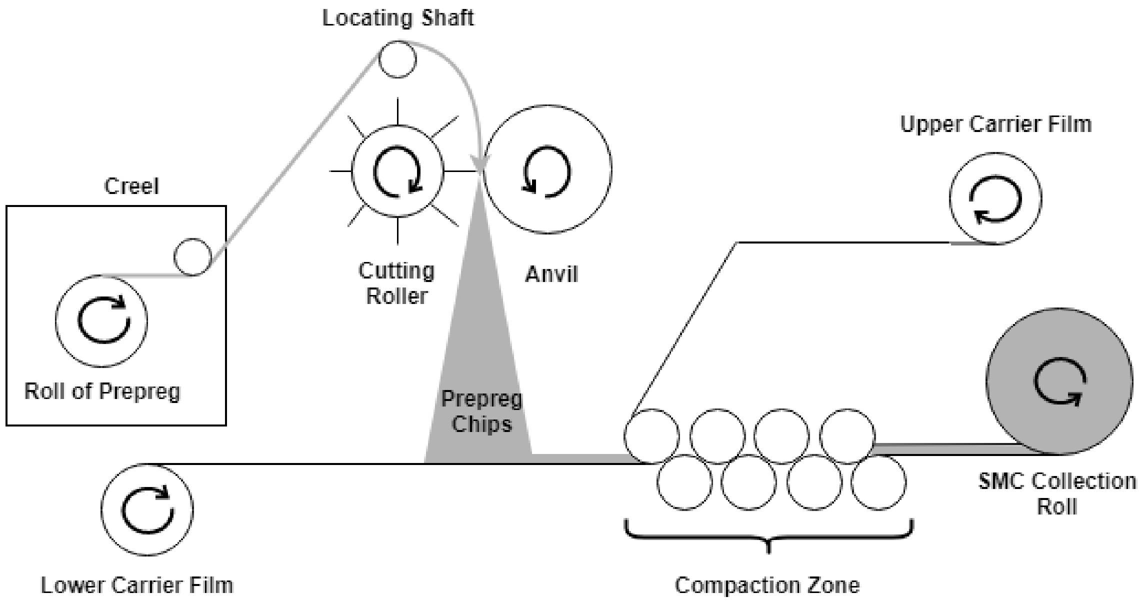


Figure 6 - Modified SMC Manufacturing Process for Carbon Fiber Prepreg

2.3.1 Differences between Traditional Process and Modified Process

A few notable adjustments needed to be made in order to process carbon fiber prepreg SMC on this equipment rather than traditional glass fiber SMC. Some of these were documented in Sultana's dissertation [1], but there are differences between the setup described in her thesis and that used for this project, so these modifications are listed again.

The method of feeding material into the cutting head differs between the traditional process and the modified process. In the traditional process, fibers are drawn as rovings through black tubes (see Figure 7) to the cutting head (see Figure 8).

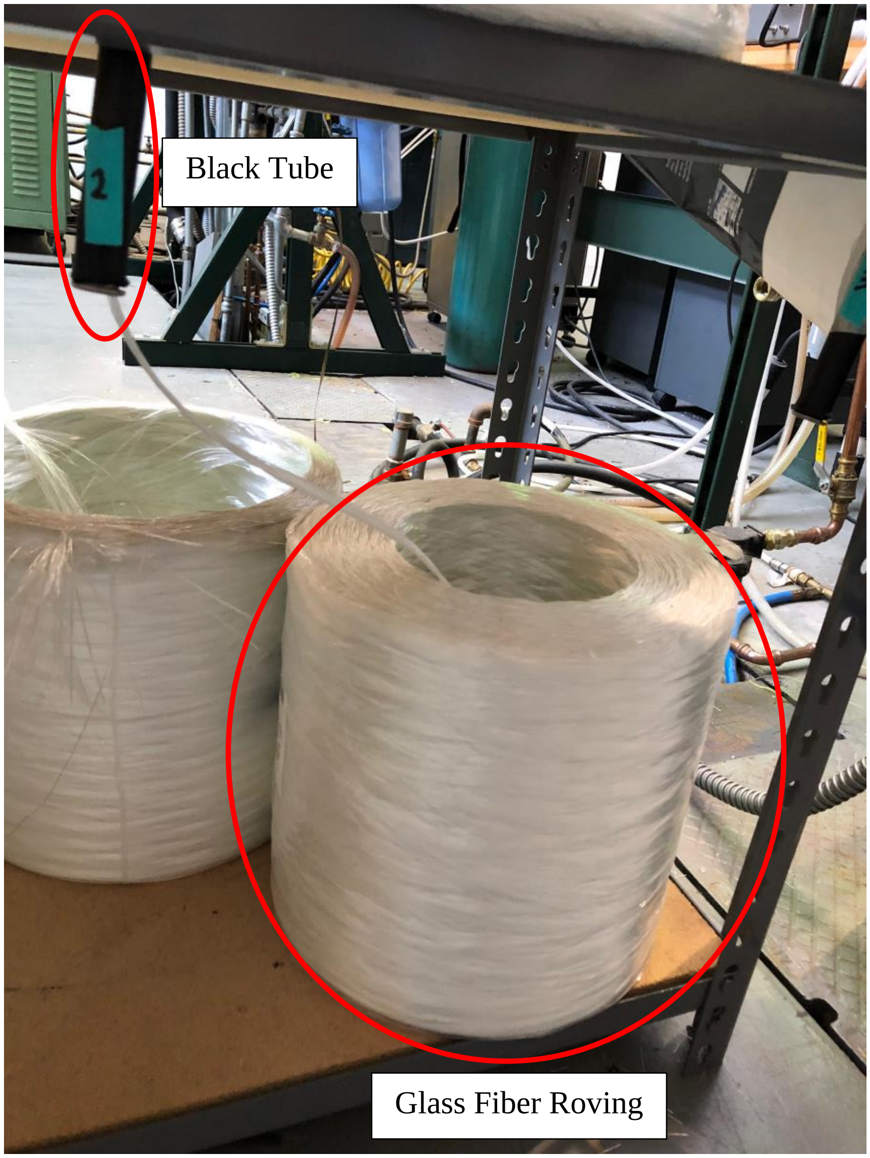


Figure 7 - GF Roving

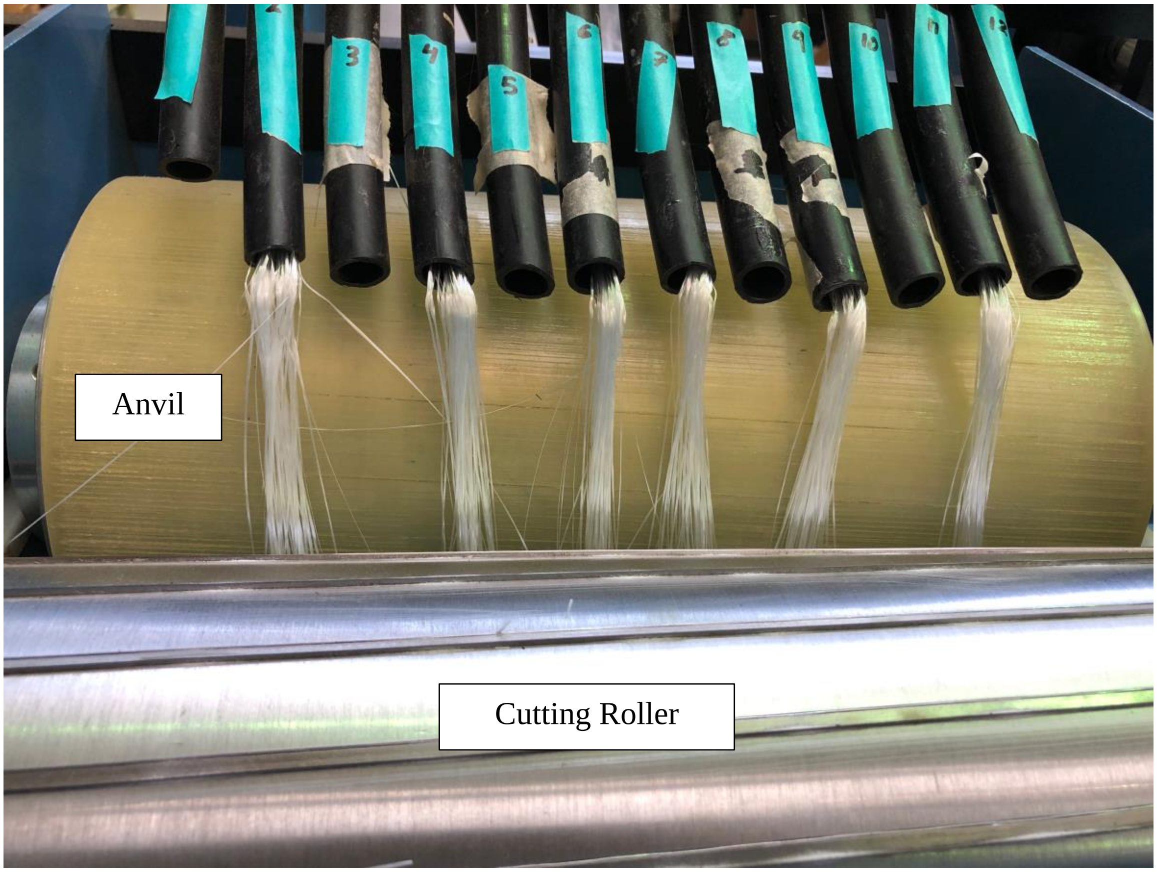


Figure 8 - GF Feeding into Cutting Head

In the modified process, prepreg tapes are drawn from a roll on a creel (see Figure 9) over the locating shaft (see Figure 10), which was designed specifically for this use by Yunpei Yang. For most of the experiments conducted by the research team for this project, only one roll of tape prepreg was used at one time.

Figure 9 - Creel Feeding Prepreg into SMC Equipment

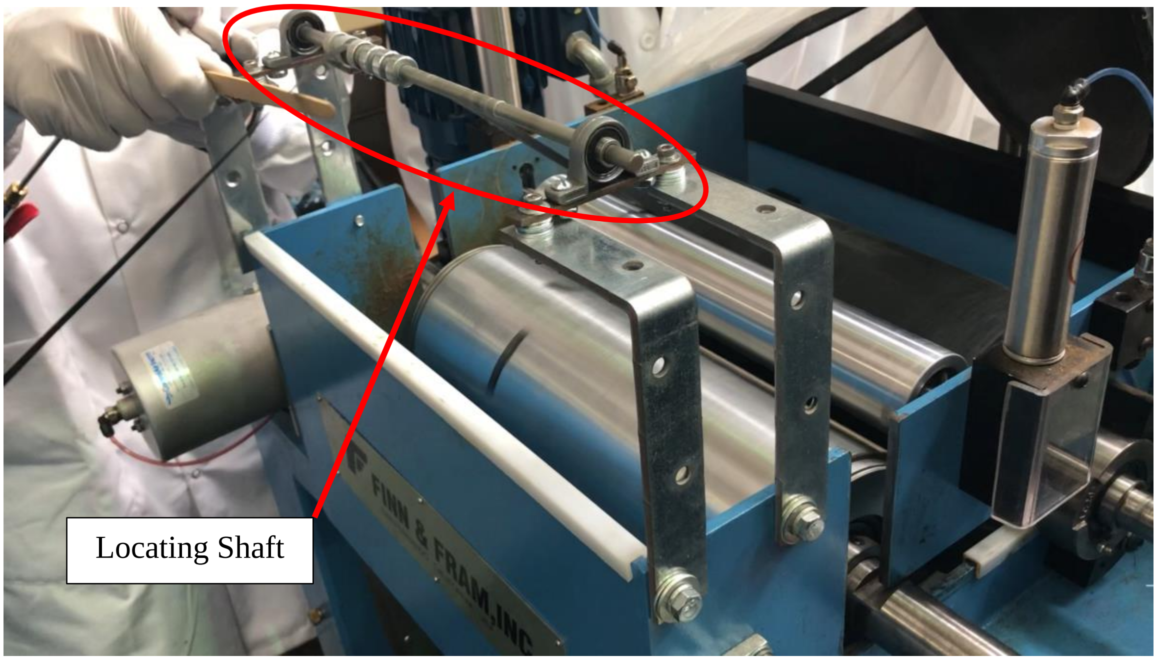


Figure 10 - Locating Shaft

The addition of resin after chopping provides another difference between the traditional process and the modified process. Since the material being chopped in the traditional process is only dry glass fibers, resin (and other additives) must be added to form the SMC. In the modified process, the fibers come pre-impregnated with resin, so no more is added.

Finally, the modified process requires the use of a Venturi blower (see Figure 11) to peel away the backing polymer from the prepreg tape. This blower takes compressed air and provides a constant air flow which pulls the backing polymer away from the roll of prepreg. The traditional process does not require this blower.

Figure 11 - Venturi Blower

2.3.2 Challenges in Using Modified Process

The primary challenges associated with the modified process are related to the cutting portion. The presence of resin in the prepreg tapes causes issues because it makes the tapes much tackier and compliant than dry glass fibers. This tackiness and compliance cause the tapes to adhere to the blade and the steel on the roller between the blades. Because the tacky tapes stick to the cutting roller and do not drop onto the lower carrier film, the next tape stacks onto the original tape when attempting to be cut. This process continues until there is a stack of tapes on the cutting roller, none of which can be completely cut.

Experimental evidence indicates that this effect is lessened when the resin in the prepreg has a higher degree of cure. Increasing the degree of cure of the resin makes the tape less tacky and stiffer, so the tape is less likely to adhere to the cutting roller or form to the blade shape, respectively.

Another challenge with using the modified SMC process is in the compaction zone. SMC produced using the traditional process compacts easily because the resin is wet and tacky. The fibers are easily impregnated with resin, and the SMC adheres together. In the modified process, prepregs may be used that have a higher degree of cure and thus do not adhere well to one another or the carrier film encasing them. This causes the SMC made with the modified process to slip relative to the carrier film while being drawn up to the SMC collection roll. This issue can be partially alleviated by placing the SMC collection roll at the same height as the compaction zone, rather than above the compaction zone. This issue was not directly addressed in this thesis.

2.3.3 Controllable Parameters of Modified Process

In the area of the process in which the material is fed into the cutting head, the controllable parameters are as follows:

1. The prepreg being used, including the type, tape width, degree of cure, and degree of crystallinity.
2. The back tension on the prepreg tape provided by the creel.
3. The way that the prepreg tape is fed through the creel.

For this project, the type of prepreg being used was Toray P2362W-19 and its width was 6.35 mm for the entirety of the testing. In addition, the prepreg tape was fed through the creel in the method shown in Figure 9 for the entirety of testing. The prepreg cure properties, development of crystallinity, and back tension were studied in this project.

In the cutting head, the controllable parameters are as follows:

1. The properties (material and geometry) of the sleeve on the anvil roller.
2. The cutting pressure between the cutting roller and the anvil.
3. The type of cutting roller used. The two options are a coarse-spaced roller (with fixed one-inch spacing between blades) and a fine-spaced roller (with adjustable – minimum 0.125” – spacing between blades).
4. The sharpness of the blades. This factor is not easily controlled, as the blade sharpness is a function of the axial location on the blade and the level of wear the blade has endured.
5. The speed of the roller rotation, and therefore the linear speed of the tape.

For this project, only the fine-spaced roller was used because the tapes generally adhered less to the roller with less steel surface area. Otherwise, each of these factors was studied in this project.

2.4 Design of Experiments and JMP

Engineering experiments are performed regularly in today’s manufacturing environments. These experiments may investigate the impact that certain factors have on the yield, throughput, or quality of an output product which is produced by a certain process. Alternatively, these experiments may seek to determine the root cause of excessive variability in a production process. The effect of input factors on an output can be investigated using Design of Experiments (DOE) methodology.

The use of DOE is preferred over a less efficient method of determining the effect of various inputs, such as the One-Variable-At-a-Time (OVAT) method. In the OVAT method, one factor is varied while the others remain constant. This method requires massive amounts of experimental data in order to allow the engineer to identify trends. In the DOE method, multiple input factors may be varied simultaneously. In both of these methods, it is desired to use experimental data to predict the output of a process given the selected inputs.

In many production processes, the output may be affected not only by the individual input factors, but also by their interactions with one another. Thus, DOE seeks to identify the impact of the individual input factors and their interactions with one another to predict the output. For example, if factors A, B and C were identified as possibly having an impact on a production process, then the output prediction would need to include the effect of factor A, the effect of factor B, the effect of factor C, the interaction effect of factors A and B, the interaction effects of factors B and C, the interaction effect of factors A and C, and the interaction effect of factors A, B, and C.

In a full-factorial experiment design, all factor effects and interaction effects are tested. For an experiment with several factors or whose factors have more than two levels, full-factorial experiment designs become quite complicated. For these, fractional-factorial experiment designs may be used. With fractional-factorial experiments, experimenters assume that higher-order interactions (third order and higher) have a negligible effect on the output and are thus neglected. This allows for a fraction of the full-factorial experiment to be run, which saves time and resources while losing little value.

2.4.1 Using JMP to Design Experiments

Statistics software JMP, which was developed by the SAS Institute, can be used to design experiments and visualize data quickly and easily. JMP's DOE Custom Design tool allows the user to define the factors, interactions, and responses of the process, then enter the experimental data, and finally visualize the experimentally-derived predictions using interactive slider-based graphs or response surfaces.

2.4.2 Application of DOE and JMP to Evaluate Prepreg SMC Mfg. Process

As the performance of the modified SMC manufacturing process that uses carbon fiber prepreg tapes as its feedstock is affected by several factors, a fractional-factorial experiment using DOE methodology is an efficient form of gaining information about the process. To obtain elegant, useful surface response plots, each factor should be defined numerically. That is, pressure should not be defined as “high” and “low” or blade sharpness defined as “sharp” or “dull”, but rather these levels should have numbers associated with them and be continuously varying. The application of DOE and JMP to the prepreg SMC manufacturing process is further explained in Chapter 5.

2.5 Chapter Summary

In this chapter, sheet molding compound was introduced as a composite material. Its typical composition, manufacturing process, and applications in industry were detailed. Next, prepreg composites were introduced, including their typical composition, the hot melt manufacturing process that makes them, the freezer storage techniques required to store prepregs, and their applications in industry. The modified SMC manufacturing process that uses carbon fiber prepreg tapes as feedstock was then introduced. The parts of the process that differentiate the modified SMC manufacturing process from the traditional process were detailed, and the challenges regarding cutting and compacting resin-impregnated carbon fiber tapes were presented. The controllable parameters of the modified process were listed and will be investigated for their impact on the success of the process in future chapters. Finally, an introduction to DOE, fractional-factorial experiment designs, and the use of JMP software to implement experiments using these methodologies were provided.

In the next chapter, the methodology characterizing the cure state of the carbon fiber prepreg used as feedstock for the modified SMC process is presented.

CHAPTER 3. CARBON FIBER PREPREG MATERIAL EVALUATION METHODOLOGY

To properly assess the processability of the prepreg tape material serving as feedstock to the modified SMC manufacturing process, its properties needed to be determined. The prepreg's fiber properties remain constant, but its matrix properties change as the thermosetting resin cures. This cure occurs as a function of room-temperature out-time as well as oven-aging at elevated temperatures. The following chapter details the methods used to evaluate the cure properties of the prepreg used in this project, as well as the results of those methods.

3.1 Introduction to Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) is a method of measuring the energy required to change the temperature of a material. Per TA Instruments [5], the calorimetry equipment evaluates thermal transitions in a material by recording the energy absorbed or produced as a function of the precisely-controlled temperature of the material. This used a TA Instruments Q2000, Serial Number 1988. It was calibrated by a representative from TA Instruments on June 1, 2018, and this calibration expired in June 2019.

Major components of the DSC equipment include the chamber into which the sample is placed, the Refrigerated Cooling System (RCS), and the nitrogen tank (not pictured), as shown in Figure 12. During operation, the nitrogen was used as an inert purge gas in the chamber to provide more efficient heat transfer to the sample pan than is possible through air. The nitrogen also helped remove moisture and oxygen which degrade the cell. The heating mechanism is part of the equipment below the chamber. The cooling equipment (RCS) is separate from the chamber and delivered cool air through a thermally-insulated tube.

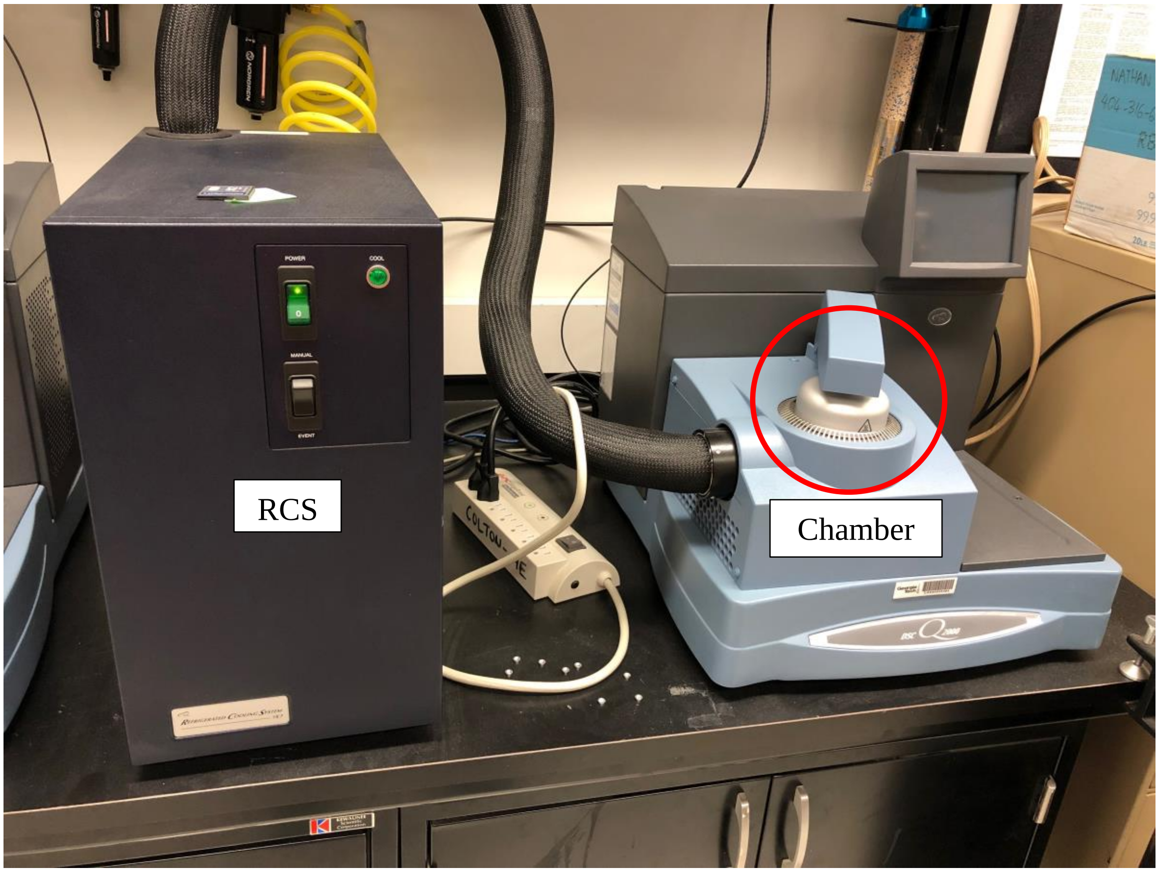


Figure 12 - DSC Equipment

Inside the chamber, the sample pan and the reference pan were placed on two platforms (see Figure 13). The reference pan was nearly identical to the sample pan, except the sample pan contained the sample material and the reference pan was empty. The energy flow recorded in a DSC measurement was the difference between the energy of the sample pan and the reference pan. Using the difference between the two ensures that the energy flow being measured came only from the sample material and not the pan material.

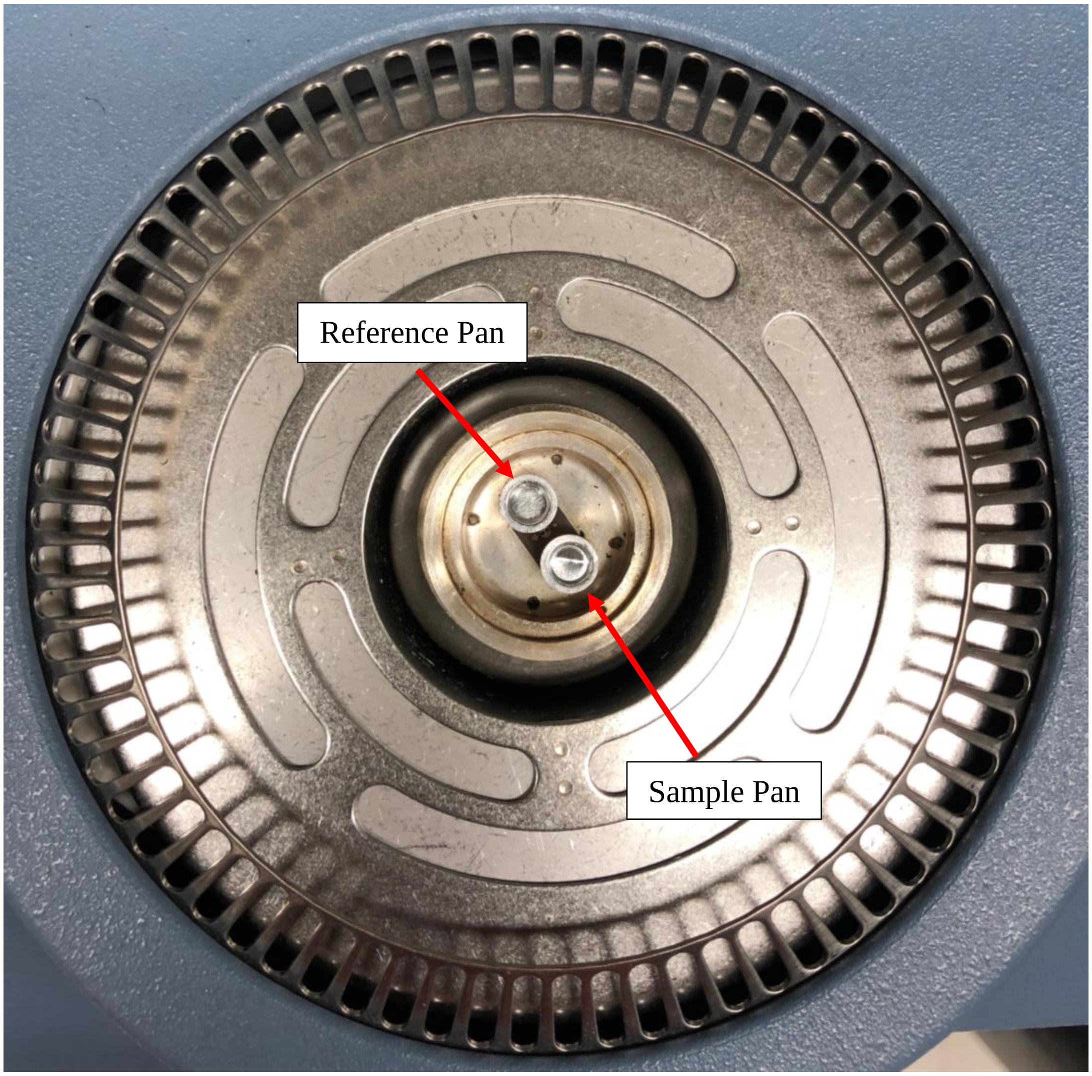


Figure 13 - DSC Chamber

3.2 Method of Using DSC for Carbon Fiber Prepreg

The method used by the research team to evaluate cure properties of the carbon fiber prepreg tape is described in this section.

3.2.1 Cell Conditioning

To ensure that any material from previous measurements would not affect the result of the planned measurement, the chamber needed to be purged of any outside material before a test could be run. This was done by running a cell conditioning cycle. In the cell conditioning cycle, the chamber was ramped to 75°C, at which temperature it remained for 60 minutes. After the 60 minutes had passed, the heater was deactivated and the RCS was activated until the chamber was sufficiently cool. After this point, the chamber was ready to accept a sample. The results from this cell conditioning cycle needed not to be logged.

3.2.2 Indium Calibration

The TA Q2000 should undergo Indium Calibration weekly, per the TA Instruments representative who conducted the overall equipment calibration. During the Indium Calibration, a sample pan containing a known mass of Indium was placed in the chamber alongside the reference pan. A prescribed temperature profile was followed that heated the Indium through its melting point, and the Cell Constant and temperature calibrations were calculated. The Cell Constant calibration corrected for the thermal resistance between the sample and the thermocouple, and the temperature calibration corrected for the onset of the melting point.

3.2.3 Preparing the Sample

The materials used to prepare a sample for the DSC were T_{zero} Pans, T_{zero} Hermetic Lids, the prepreg tape of interest, scissors, a scale (Kern ACS 220-4), T_{zero} DSC Sample Encapsulation Press, tongs, Kimberly-Clark Kimwipes, and isopropyl alcohol (IPA). The following steps were taken to prepare a sample:

1. Clean the scissors, scale, press, and tongs using a Kimwipe soaked with IPA.
2. Weigh a pan and a lid, record the weight, and zero the scale.

3. Cut a piece from the prepreg of interest, then slice it into small pieces that can fit inside the pan.
4. Remove the pan from the scale and place the small pieces of prepreg into it.
5. Weigh the prepreg sample. The sample mass should equal 10.0 mg ± 1.0 mg. Add or remove material as needed. Record the prepreg mass.
6. Press the lid onto the pan containing the sample using the T_{zero} DSC Sample Encapsulation Press.
7. Load the sample pan and reference pan into the DSC chamber.

3.2.4 Heat Cycle

For relatively uncured prepreg tape samples, a simple heating cycle was used because these materials had not developed crystallinity. Therefore, these samples did not demonstrate an endothermic peak. Instead, they could demonstrate only a glass transition temperature (T_g) and heat of reaction (Q). These values are shown in Figure 14. In this cycle, the material is ramped from -10°C to 300°C at a ramp rate of 10°C per minute.

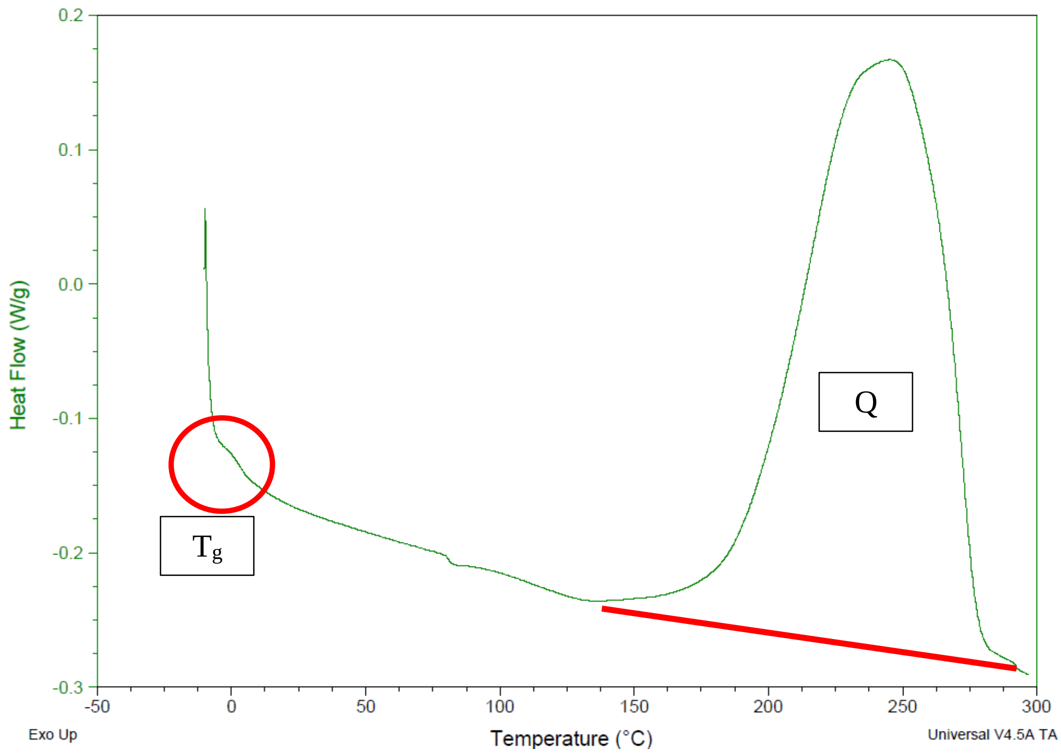


Figure 14 - DSC Heat Cycle

3.2.5 Heat-Cool-Heat Cycle

The heat-cool-heat cycle was used for prepreg samples that had a moderate to high level of oven-aging or room-temperature aging. These samples had typically developed an endothermic peak, which demonstrated the sample's degree of crystallinity. In order to properly capture the material's T_g and endothermic peak, the sample was heated from -10°C to 100°C, cooled from 100°C back to -10°C, then heated again from -10°C to 300°C. The first heat cycle pushed the sample through its endothermic peak, and the second heat cycle demonstrated the sample's T_g and heat of reaction.

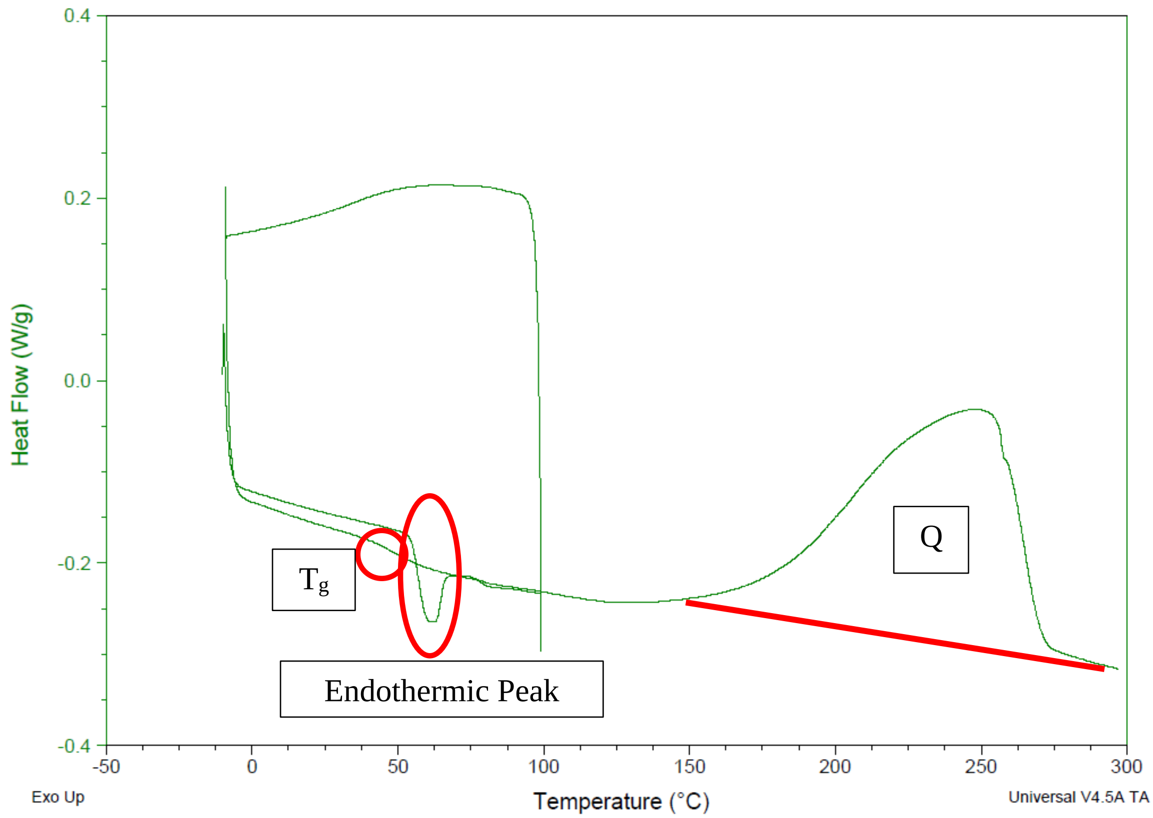


Figure 15 - DSC Heat-Cool-Heat Cycle

3.3 Evaluating Cure Properties from DSC Results

The following important cure properties were derived from DSC results.

3.3.1 Glass Transition Temperature (T_g)

T_g is a useful indicator of the prepreg's cure state. This metric was found by identifying the S-shaped curve on the heat-temperature plot provided by the TA Universal Analysis tool, then using the T_g tool to identify the actual temperature where the step transition occurred. In the example shown in Figure 16, the T_g was 24.76°C, and the S curve is shown within the red oval.

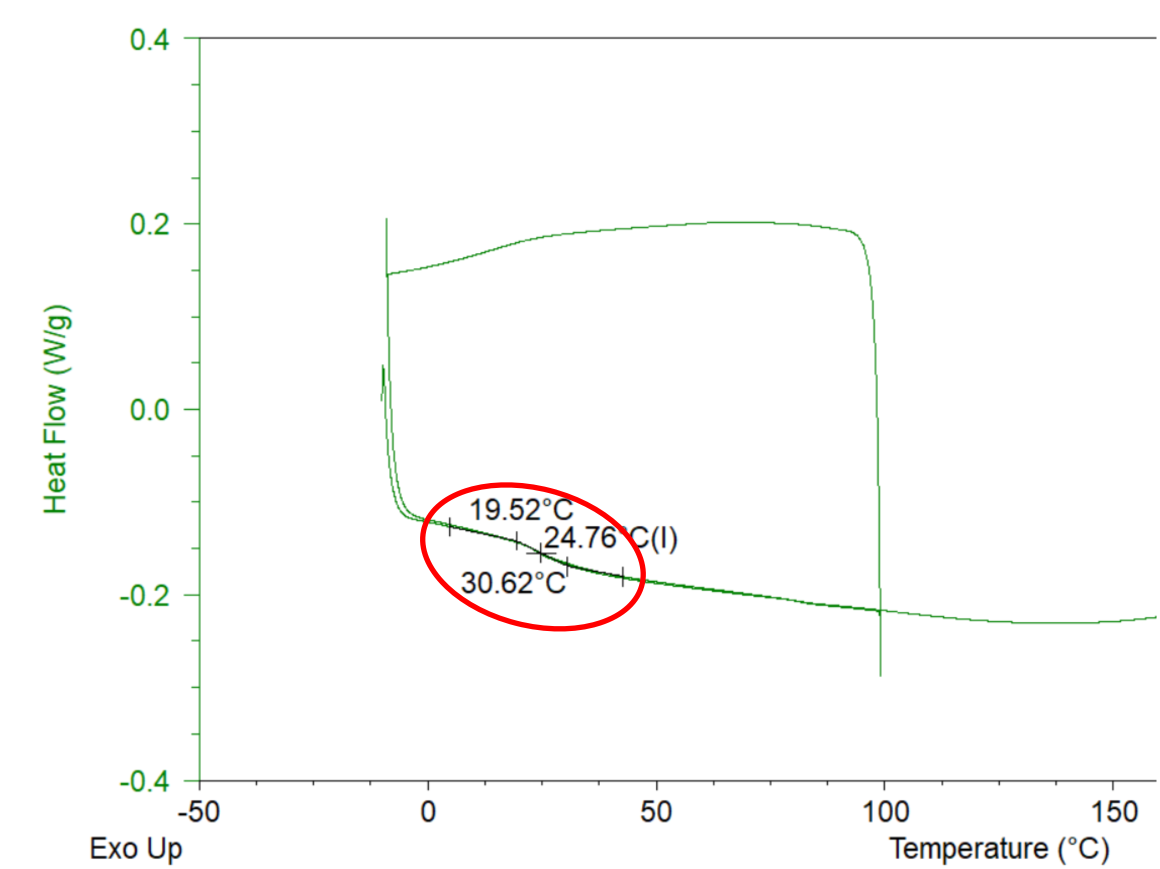


Figure 16 - DSC Glass Transition Temperature

For the carbon fiber prepreg used in this project (Toray P2362W-19), the T_g was tracked using DSC measurements as a function of oven-aging at 70°C and of room-temperature aging starting from when the material was received. The oven-aging time was on the order of dozens of hours, whereas the room-temperature aging was on the order of weeks. The results from this testing are shown in Figure 17. Note the oven-aging, room-temperature aging (up to week 22), and related DSC measurements were performed by Yunpei Yang. The room-temperature aging (after week 22) and related DSC measurements were performed by the author.

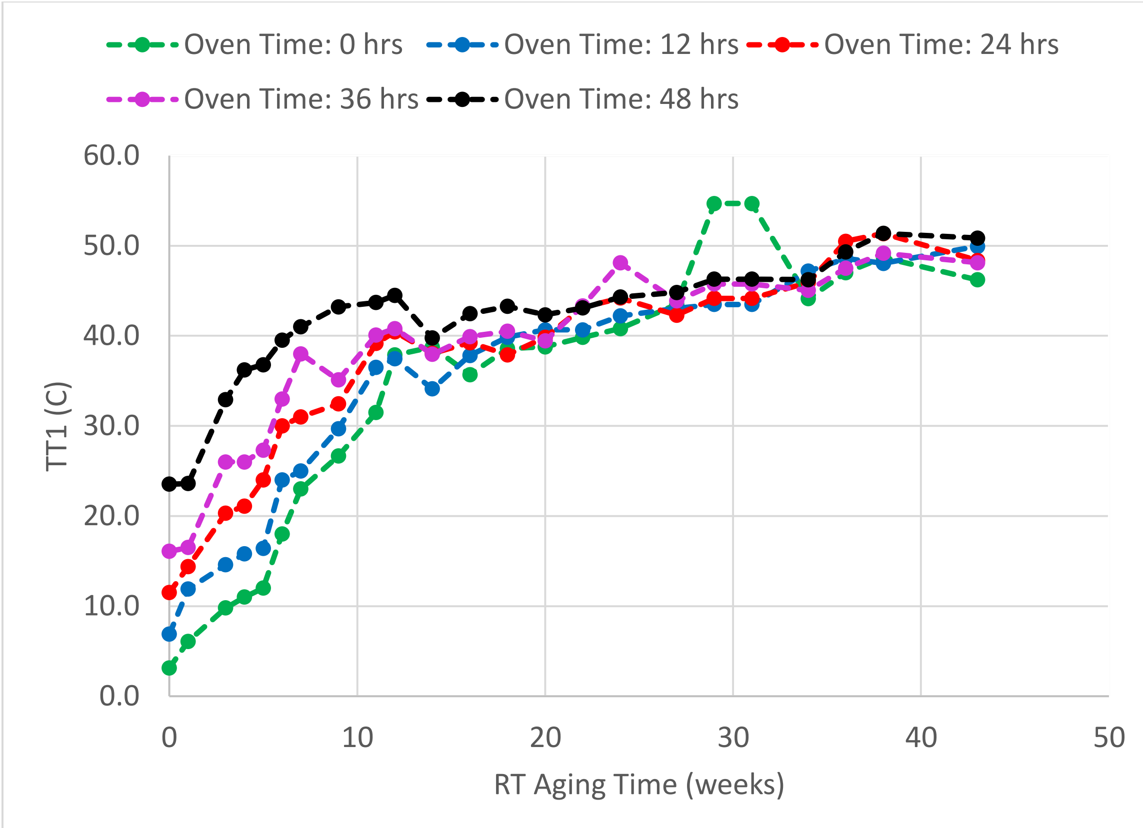


Figure 17 - Glass Transition Temperature vs. Aging

In the Figure 17, the T_g values were differentiated initially by the oven-aging time each sample underwent. Predictably, more oven-aging resulted in a higher T_g. As the samples progressed through several weeks of room-temperature aging, the differences between those with more oven-aging and less oven-aging decreased until all samples began to approach an asymptotic T_g near 50°C.

3.3.2 Heat of Reaction (H_R) and Degree of Cure (DoC)

The heat of reaction is the area under the heat-temperature curve, as calculated by Equation 1. Here, the heat of reaction is the amount of energy released by the thermosetting resin in the prepreg tape while the sample's temperature is increased to 300°C. The heat of reaction is taken as a per-unit-mass value (Joules per gram), so the mass of the sample is divided out of the equation. Ideally, the resin content in the sample would have been known so the calculation could have be performed on a per-unit-mass-of-resin basis, but this testing was not performed. It was assumed that the resin content per unit mass in each sample was nearly the same, which was a source of error in the result for heat of reaction and heat of endothermic peak. The degree of cure is a number greater than zero and less than one which represents the portion of the cure cycle the material has undergone, as calculated by Equation 2. Note H_0 is the heat of reaction for a completely uncured prepreg sample. Therefore, H_0 should be greater than or equal to Q.

$$H_R = \int_{120°C}^{295°C} \frac{dH}{dT} dT \quad (1)$$

$$Degree\ of\ Cure = 1 - \frac{H_R}{H_0} \quad (2)$$

In the TA Universal Analysis tool, the heat of reaction was measured from a DSC result using the “Integrate Peak Linear” tool, with integration limits manually set as 120°C to 295°C. In the result shown in Figure 18, the sample had a heat of reaction of 126.1 Joules per gram.

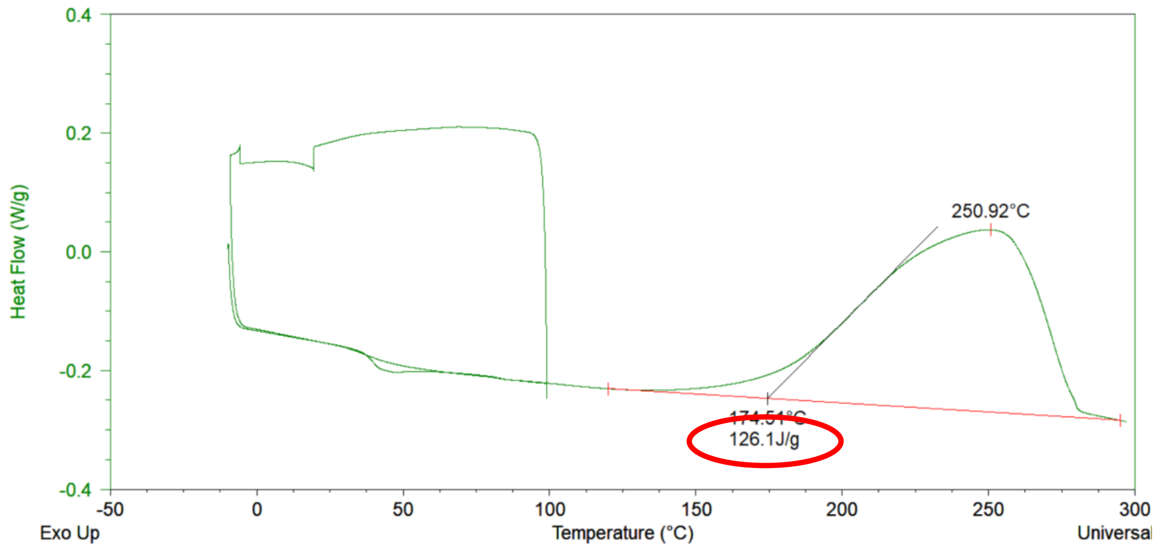


Figure 18 - DSC Heat of Reaction

Similar to T_g, the heat of reaction data were measured for samples with varying levels of oven-aging time and room-temperature aging time. The heat of reaction was converted to degrees of cure using Equation 2. For the data shown in Figure 19, H_0 was 165.1 Joules per gram, as measured by putting a "fresh" prepreg sample through a DSC cycle.

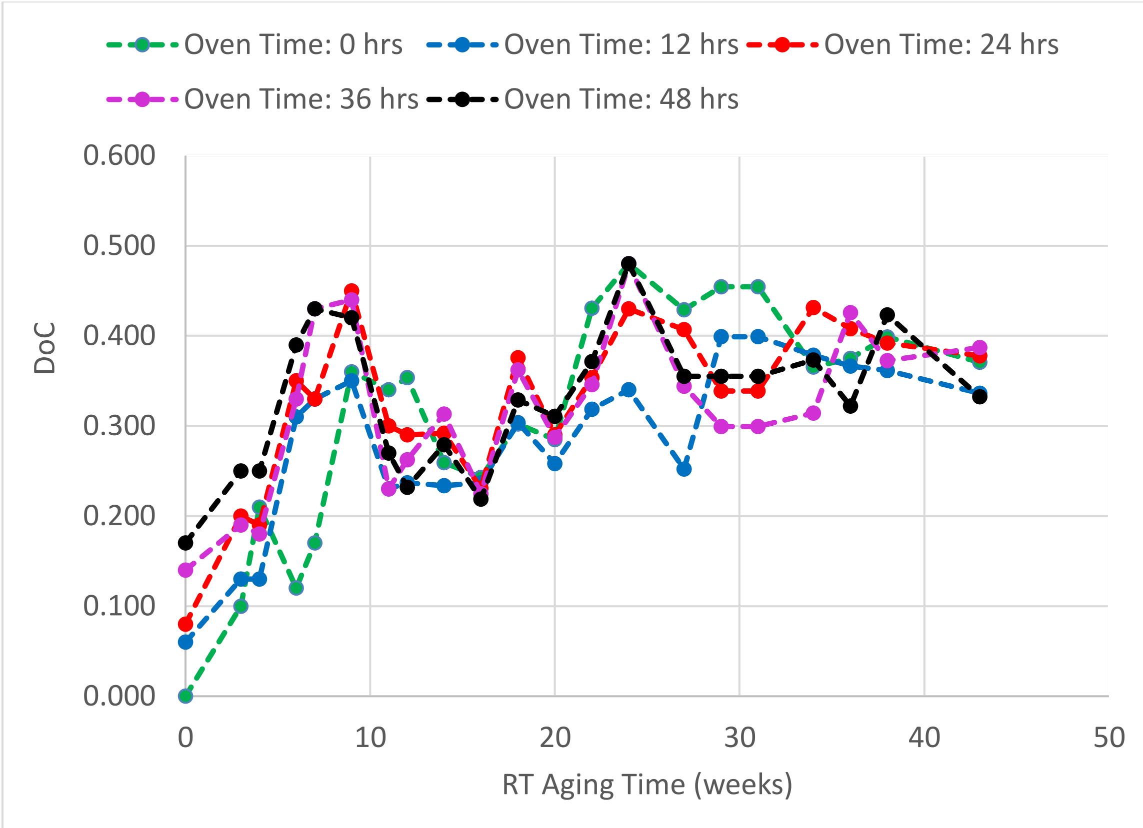


Figure 19 - Degree of Cure vs. Aging

Similar to the T_g data, the prepreg degrees of cure results were initially differentiated by the amount of oven-aging each sample had received. Predictably, more hours of oven-aging result in a higher degree of cure. Also, similar to the T_g data, the differences between the degrees of cure of samples with different levels of oven-aging tended to decrease with increases in room temperature aging.

The degree of cure data were not as clean as the T_g data – the numbers varied quite widely while approaching an asymptotic degree of cure of around 40-50%. This is likely due to variations in the resin content relative to the fiber content in the samples. Resin content can vary along the width of the tape, so effort was made to capture the entire width in the DSC samples. Samples with higher resin content for the same overall sample weight would likely demonstrate a higher heat of reaction, and therefore a lower degree of cure. The resin content did not affect the T_g data because the T_g is simply a property of the resin given a certain cure state and ambient conditions, and it does not depend on the weight of the sample.

3.3.3 Endothermic Peak and Crystallinity

As the resin in the prepreg tape cures due to a combination or oven-aging and room-temperature aging, thermoplastic additives in the resin develop crystallinity. This means the additives change from an amorphous solid to a crystalline solid. An amorphous solid undergoes a glass transition under changes in temperature, whereas a crystalline solid undergoes an endothermic melting reaction.

For prepregs of sufficient aging (either through oven-aging or room-temperature aging), this crystallinity revealed itself in the DSC results by the form of an endothermic peak. The onset of this endothermic peak occurred near the glass transition temperature, as shown in Figure 20.

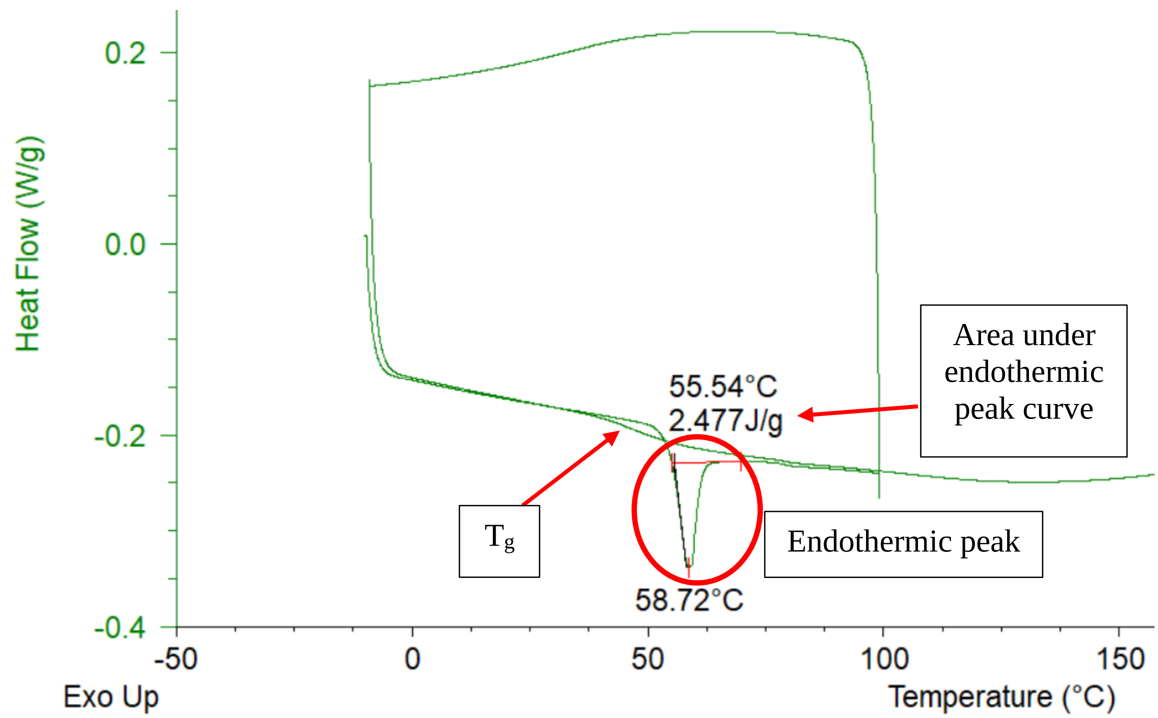


Figure 20 - DSC Endothermic Peak

The area under the endothermic peak represents the heat given off by the thermoplastic additives in the resin in the prepreg sample during the endothermic melting reaction. Similar to T_g and heat of reaction/degree of cure, this value is another indicator of the cure state of the sample, albeit a less direct indicator. When the endothermic peak first developed in the prepreg samples being measured after approximately 9 weeks of room-temperature aging, the area under the endothermic peak began to be tracked as a function of oven-aging time and room-temperature aging time. These measurements are shown in Figure 21.

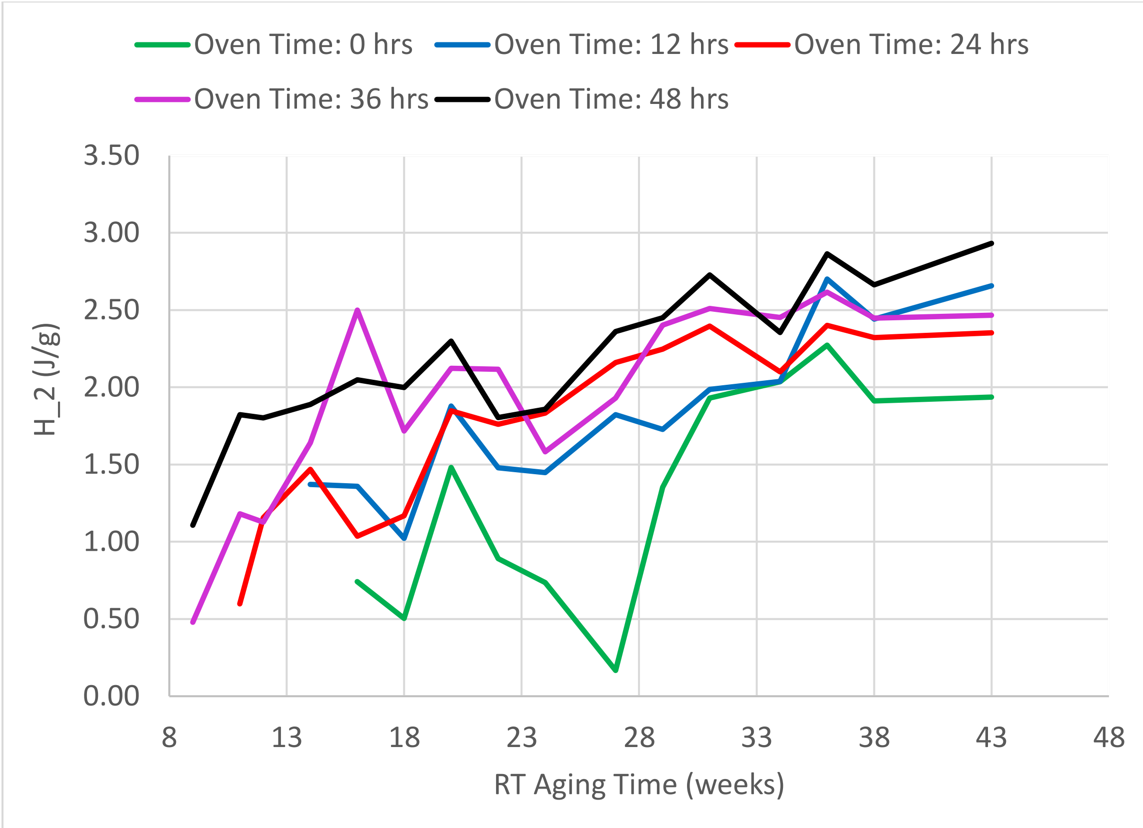


Figure 21 - Endothermic Peak vs. Aging

The endothermic peak first developed for the 36-hour and 48-hour oven-aged prepregs. With more room-temperature aging, the other prepregs progressively developed endothermic peaks. These data, like the degree of cure data, varied quite a bit from week-to-week because the heat absorbed during the endothermic melting reaction was a function of the resin content in the sample.

3.4 Chapter Summary

In this chapter, the method used for evaluating the carbon fiber prepreg tape serving as feedstock to the modified SMC manufacturing process was introduced. Differential Scanning Calorimetry (DSC) was introduced, and the useful results from taking DSC measurements of the resin content in the prepreg tapes were presented. The three DSC measurements that could evaluate the cure state of the resin in the prepreg were the glass transition temperature (T_g), the degree of cure (calculated from the heat of reaction, H_R), and, for prepreg samples with more advanced cure state, the area under the endothermic peak curve. Plots demonstrating how these three metrics changed with oven-aging time and room temperature aging time were presented.

Differential scanning calorimetry can be used to characterize the material being processed using the modified SMC manufacturing process described in this dissertation. With several quantifiable metrics able to be captured using DSC measurements, there may be a way to correlate the DSC results with the material's ability to be chopped and processed in the SMC machine. These results are investigated in the following chapters.

In the next chapter, the equipment-related factors that impact the success of the modified SMC process are presented and characterized according to methods developed by the research team.

CHAPTER 4. SMC EQUIPMENT EVALUATION METHODOLOGY

The many components of the SMC equipment also greatly impact the ability of this modified SMC manufacturing process to make SMC. In the following chapter, each critical component of the modified SMC manufacturing process and the method by which it is measured are presented. Before studying each factor of the tape-cutting portion of the process, the method by which the cutting process was first characterized is demonstrated.

4.1 Characterizing the Cutting Process

Since the prepreg tapes were cut by hard steel blades against a compliant, low-hardness polyurethane surface, it was suspected that the cutting mechanism for which the system is designed relies on is bending the tape until it reached a critical radius. This failure mode is demonstrated in Figure 22. Thus, an initial characterization of the cutting process sought to identify the critical radius as a function of the prepreg fiber thickness (diameter) and the strain-at-failure.

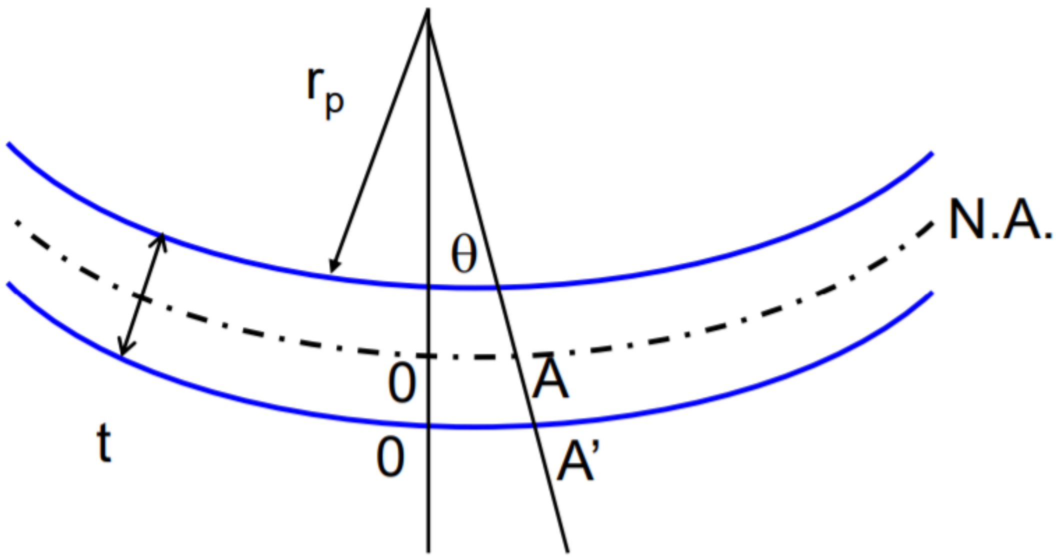


Figure 22 - Sheet Metal Bending

Using the equation that calculates the strain at the point furthest from the center of the sheet thickness (see Equation 3), one is able to solve for the critical bend radius, as shown in Equation 4. In these equations, *e* is the strain at the point furthest from the center of sheet thickness, r_p is the bend radius, and *t* is the sheet thickness.

$$e = \frac{\Delta l}{l} = \frac{\overline{OA'} - \overline{OA}}{\overline{OA}} = \frac{1}{\frac{2r_p}{t} + 1} \tag{3}$$

$$r_p = \frac{t}{2}\left(\frac{1}{e} - 1\right) \tag{4}$$

When applying this model to cutting prepreg, it is conservatively assumed that the fibers spread out when cut. Thus, the equivalent sheet thickness is the diameter of a single fiber rather than the thickness of the entire tape. This model also assumes that the resin negligibly affects the cutting process. Using the T-300 carbon fiber data from Mallick [7], a fiber diameter (sheet thickness) of 0.007 mm and a strain-to-failure of 1.4% would result in a critical bend radius of 0.247 mm. Using the same material with the full thickness of the prepreg tape, which was measured to be 0.25 mm, the critical bend radius would be 8.8 mm. This value is much larger than any usable blade radius, which provides evidence that the single fiber diameter should be used in the equation.

To ensure the blades on the SMC cutting roller can slice through prepreg, the blade radius should be less than the critical bend radius, with some safety factor incorporated. To measure the blade radius, images needed to be taken of the blade cross section. To do so, the blade needed to be cut at an interval of interest to the research team. Because cutting the blade to measure its sharpness would have distorted the blade cross section, and because the sharpness varied so much along the length of the blade, this method of evaluation and model of cutting was ultimately not used.

4.2 Anvil Sleeve Properties

The equipment-related factors investigated for their impact on the cutting portion of the process were those associated with the anvil sleeve. The nature of the tests that were developed allowed for some evaluation of the cure state's impact on the cutting process, as well. Three hypotheses related to the anvil sleeve and the prepreg cure state were investigated, as follows:

1. It was hypothesized that increasing the hardness of the anvil sleeve would improve the yield of the cutting operation because the sleeve would deflect less under the pressure of the cutting blade, and there would be less force required to chop the tape. Finn & Fram, the SMC equipment manufacturer, sells polyurethane anvil

sleeves of three different hardness levels (ranked from lowest hardness to highest hardness): 80-85 Shore A hardness, 90-95 Shore A hardness, and 70 Shore D hardness.

Shore A and Shore D hardness levels are measured on different scales, but there is some overlap between the two scales. According to data provided by Mechanical Rubber [8] (see Table 2), 80-85 Shore A corresponds to 29-33 Shore D and 90-95 Shore A corresponds to 39-46 Shore D. Therefore, the polyurethane sleeves supplied by Finn & Frame were of ~30 Shore D, ~40 Shore D, and 70 Shore D hardness. The research team at Georgia Tech, at the beginning of testing, owned only the 30 Shore D hardness sleeve, that is, the one with the lowest hardness.

Table 2 - Shore A vs. Shore D Hardness (Source: Adapted from [8])

Shore A	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Shore D	6	7	8	10	12	14	16	19	22	25	29	33	39	46	58

2. It was also hypothesized that the force and displacement required to cut the prepreg tapes should increase as the tapes cure because the resin in the prepreg tapes cause them to stiffen and embrittle as they cure. However, it should be noted that if the cutting model identified in 4.1 was followed, the force and displacement required to cut the prepreg may decrease because the curing and stiffening of the resin may cause the elongation at break to decrease. This would mean the cutting force would decrease because the radius at which the tape breaks is smaller.
3. The final hypothesis was that decreasing the thickness of the anvil sleeve, which is significantly softer than the steel cylinder that it covers, could result in a greater

effective hardness of the system because the effect of the hardness of the steel cylinder becomes more pronounced when the sleeve is thinner. Therefore, reducing the sleeve thickness may result in a decreased force and displacement required to cut the prepreg tape. Per Sridhar et al [9], the effective stiffness of a layered structure is a function of each material's Young's modulus and Poisson's ratio. Because these material properties and the indented surface geometry were not readily available, the effect of this layering was to be investigated experimentally.

Because the sleeves are relatively expensive and difficult to install, and because it would have been difficult to develop a test using the actual SMC equipment that isolates the hardness and thickness of the anvil sleeve, an off-line simulation of the cutting operation was developed, which could evaluate the effectiveness of using harder anvil sleeves, thinner anvil sleeves, and prepreg tapes with higher degrees of cure.

4.2.1 Test Setup

To test these hypotheses, the cutting operation was simulated using an Instron test rig (Figure 23). The equipment used for these tests was an Instron 33R 4466 Load Frame with a 10 kN Instron 2525-804 Load Cell. The blade-holding component was designed for the test by Yunpei Yang; a drawing of this part is found in Appendix A.1.

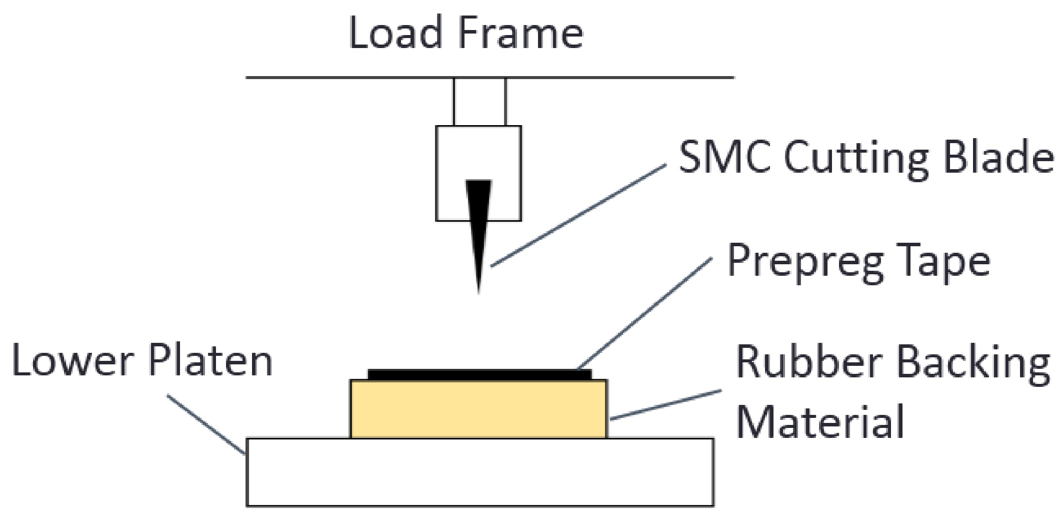


Figure 23 - Tape Cutting Test Instron Setup

In this test, a blade was attached to the Instron, and this blade descended upon a prepreg tape whose fiber axis was oriented perpendicular to the blade axis. The prepreg was set on a polyurethane block, which represented the anvil sleeve. The intended outcome of this test was to determine whether the force required to slice completely through a prepreg tape and the distance that the blade must travel through the prepreg tape to slice it changed as a function of the polymer backing material hardness, the polymer backing material thickness, and the prepreg tape aging history. The blade remained constant for all tests, but the hardness of the polyurethane block, the thickness of the polyurethane block, and the cure state and thermal history of the prepreg tape varied.

4.2.2 Test Method and Limitations

In this test, the blade from the SMC cutting roller was secured to a blade holder by three set screws. The blade holder was then fastened to the load frame by screwing bolts into two threaded holes on the holder. The polyurethane sleeve was placed on a steel platen, and the prepreg tape was placed in the middle of the polyurethane sleeve, oriented with its fiber axis perpendicular to the blade axis.

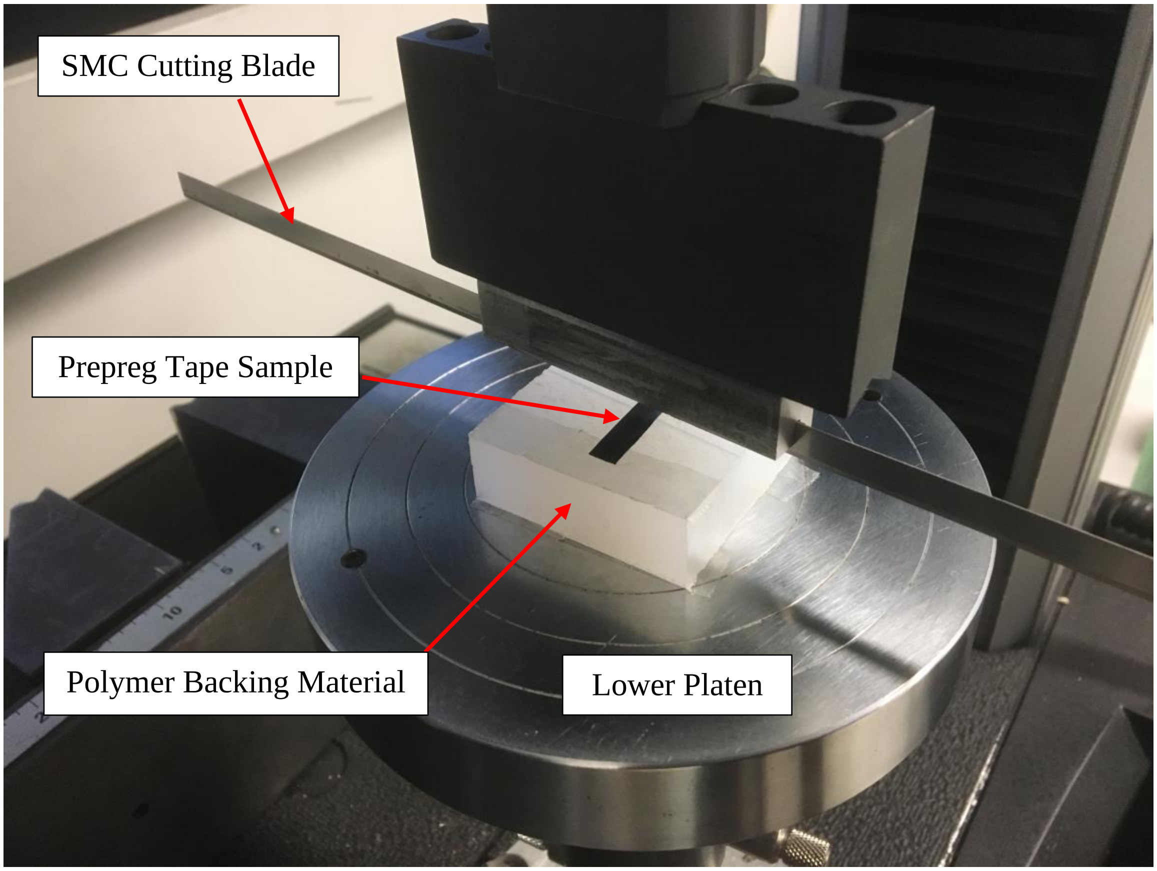


Figure 24 - Tape Cutting Test Picture

The Instron device was programmed as a compression test with displacement stopping conditions and force stopping conditions. After some initial tests, the test was programmed to stop after a certain displacement or force, whichever was achieved earlier, that allowed the blade to slice through the prepreg completely.

For the first tests, which evaluated cutting performance as a function of backing material hardness and prepreg degree of cure, three blocks of 15.2 mm thickness were made from polymethylmetacrylate (PMMA), polypropylene (PP), and polyurethane (PU). These materials were chosen because their hardness values are within the same range as the anvil sleeves supplied by Finn & Fram. Their hardness values are listed in Table 3. Prepreg tapes of 6.35 mm width were prepared by oven-aging them for 0, 12, 24, 36, and 48 hours.

Table 3 - Test Polymer Hardnesses

Material	PMMA	Polypropylene	Polyurethane
Shore D Hardness	90	75	32

For the second tests, which evaluated cutting performance as a function of backing material thickness and prepreg degree of cure, three blocks of PP and three blocks of PU with 12.7 mm, 15.2 mm, and 17.7 mm thickness were made. The prepreg tape samples used for these tests were rectangular 6.35 mm by 25.4 mm samples cut from “fresh” Toray P2362W-19 tapes of width 38.1 mm. This material had been stored in the freezer since being received at Georgia Tech, and had ~0% degree of cure and glass transition temperature <10°C.

It is worth noting that this test method is not entirely representative of the actual cutting process. This test operates as a guillotine-style cutter in which the blade comes vertically down against the prepreg tape and polyurethane block, whereas the cutting head on the SMC equipment is a rotary cutting motion in which the tape is cut when a blade on the cutting roller is approximately parallel to the ground and normal to the surface of the anvil sleeve. Then, the brief period when there is contact between the blade and the prepreg tape against the anvil sleeve is when the tape is cut.

In addition to the actual cutting motion differing from the simulated cutting motion, the speed at which the tape is cut differs greatly between the two cutting methods. In the actual cutting motion on the SMC equipment, the anvil (to which the motor is attached) rotates at 10 to 30 revolutions per minute, which translates to a linear velocity at the blade of 96.4 to 289 millimeters per second, respectively, per Equation 5 and Equation 6.

$$\omega = \frac{10\ rev}{min}\left|\frac{1\ min}{60\ sec}\right|\left|\frac{2\pi\ rad}{1\ rev}\right| = 1.047\ radians\ per\ second \tag{5}$$

$$v = \omega \times R = 1.047\ \frac{rad}{sec} \times 3.625\ in\left|\frac{25.4\ mm}{1\ in}\right| = 96.4\ millimeters\ per\ second \tag{6}$$

These magnitudes of linear velocities are not achievable with the Instron test machine, which is limited to a maximum speed of 8.5 millimeters per second.

The shear thinning behavior of the epoxy resin [10] makes the cutting behavior at a slower test speed less representative of the cutting behavior at the higher speed seen on the SMC machine. Decreasing the shear rate of the resin by slowing down the cutting mechanism results in a higher viscosity than that seen at SMC machine speeds. Therefore, the cutting force required to cut the prepreg at test speeds may be higher than the cutting force required at higher SMC machine speeds.

Despite these limitations, it was decided that the test method was suitable to observe trends in the forces and displacements required to cut prepreg tapes.

4.2.3 Test Results

A typical result from this Instron test is shown in Figure 25. Provided the load cell was zeroed prior to its use, the load measured by the load cell was typically negligible until the blade contacted the prepreg tape. Then, the load increased approximately linearly with increasing displacement until the prepreg tape was sliced completely, at which point the load suddenly dropped. After a slice through the tape resulted in a drop in the load measured, the load again increased linearly as the blade pressed into the polymer block. Shortly after the blade began to press against only the polymer block, the test reached one of its stopping conditions.

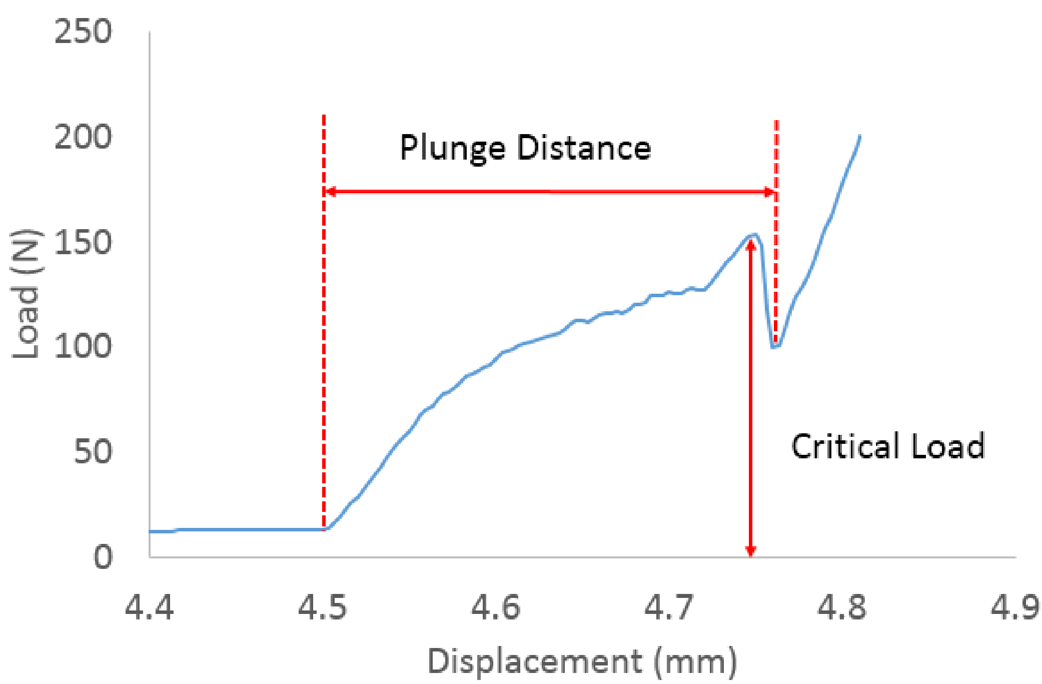


Figure 25 - Instron Cutting Test Result Example

Using the critical load and plunge distance as metrics, tests were performed that evaluated the cutting performance as a function of backing material hardness and prepreg tape aging, which is directly correlated with resin degree of cure. In Figure 26, the critical load values for the harder polypropylene (70D) and PMMA (90D) materials are significantly lower than the critical load values for the polyurethane (32D), regardless of the oven-aging undergone by the prepreg tape sample being cut. The critical load values for the harder propylene and PMMA increase slightly with increases in oven-aging of the prepreg sample, but the critical load values for the lower-hardness polyurethane increase at a much higher rate with increases in oven-aging of the prepreg sample.

In Figure 27, the plunge distance values for the harder polypropylene and PMMA materials are, again, significantly lower than those for the polyurethane, regardless of the level of oven-aging the prepreg has undergone. The plunge distance measured when using polypropylene and PMMA backing materials appears to not change with the level of oven-aging, whereas the plunge distance measured when using the less-hard polyurethane backing material increases approximately linearly with increases in oven-aging within the bounds tested.

Figure 26 and Figure 27, respectively, therefore demonstrate that less force and less plunge distance is required when cutting prepreg tapes against harder material. This is in agreement with hypothesis 1, which stated that cutting against harder materials can increase yield because it requires less force and penetration. These figures also provide support for hypothesis 2, which stated that greater force and plunge distance are required to cut prepreg of higher degree of cure. It must be noted, however, that the two harder materials (PMMA and PP) demonstrate nearly identical behavior. This likely indicates that there is a "critical" backing material hardness of at most 75D above which the cutting force and displacement do not continue to change with increases in backing material hardness.

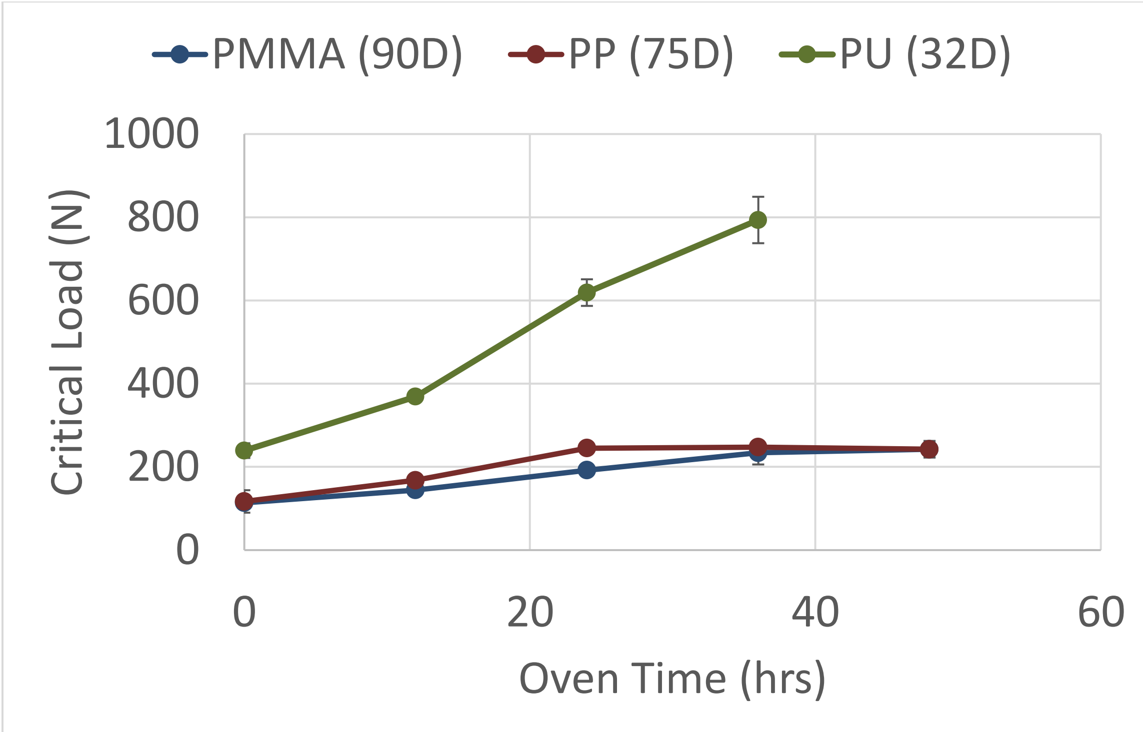


Figure 26 - Critical Load vs. Hardness and Oven Time

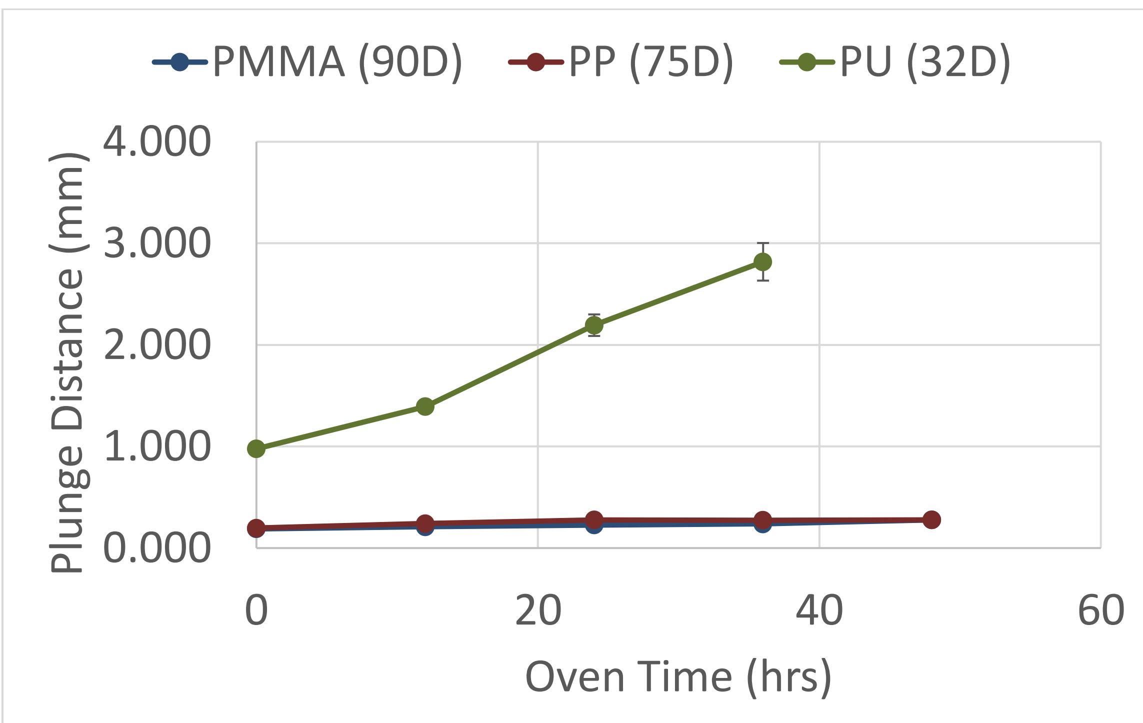


Figure 27 - Plunge Distance vs. Hardness and Oven Time

With these conclusions reached, the next tests that were run tested hypothesis 3, which stated that decreasing the thickness of the backing material would cause a greater effective hardness, thereby decreasing the critical load and plunge distance required to cut the tapes.

As shown in Figure 28, the critical load values measured when using the harder polypropylene backing material were consistently lower than those measured using the less-hard polyurethane material. There, however, did not appear to be any trend between the backing material thickness and the critical load when using either backing material.

As shown in Figure 29, the story was quite similar for the plunge distance values. The plunge distance values were consistently lower for the hard polypropylene backing material than for the polyurethane. Again, there appeared to be no trend between backing material thickness and plunge distance.

The results shown in Figure 28 and Figure 29, like those shown in Figure 26 and Figure 27, demonstrated that increasing the hardness of the backing material results in lower critical loads and plunge distances, which provides more support for hypothesis 1. However, these figures also demonstrate that the critical load and plunge distance are not affected by changes in the thickness of the material. This finding contradicts hypothesis 3, which stated that decreasing the thickness would result in a greater effective hardness, thereby resulting in lower forces and displacements required to cut the tape. Note that each circular data point shown in both Figure 28 and Figure 29 represents the average of measurements made identically. The standard deviation of these measurements is represented by diamond-shaped data points.

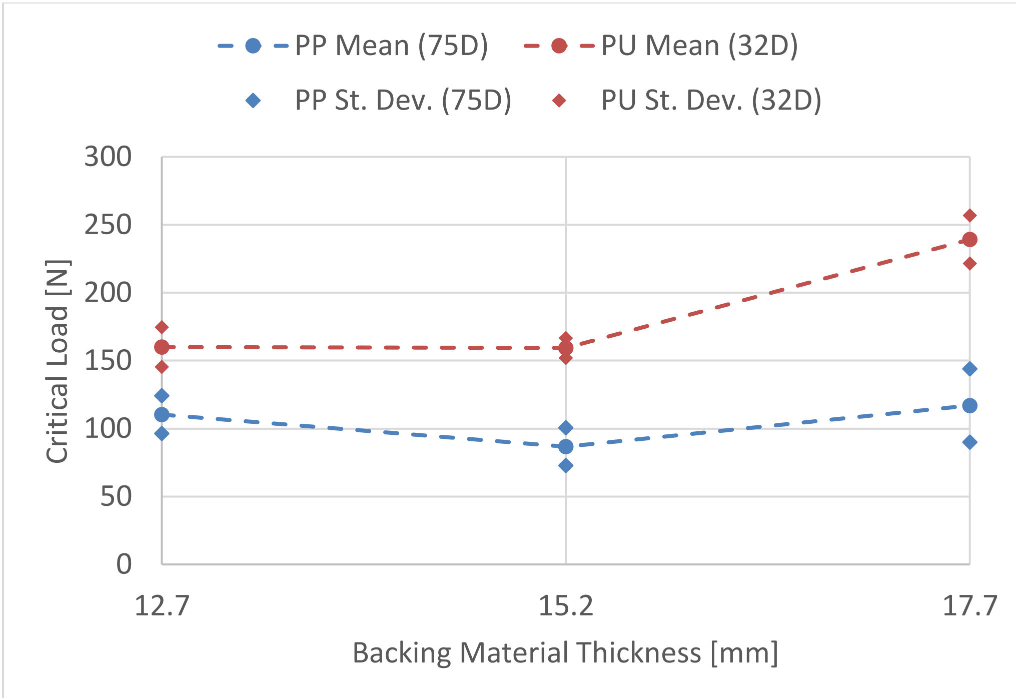


Figure 28 - Critical Load vs. Backing Material Thickness

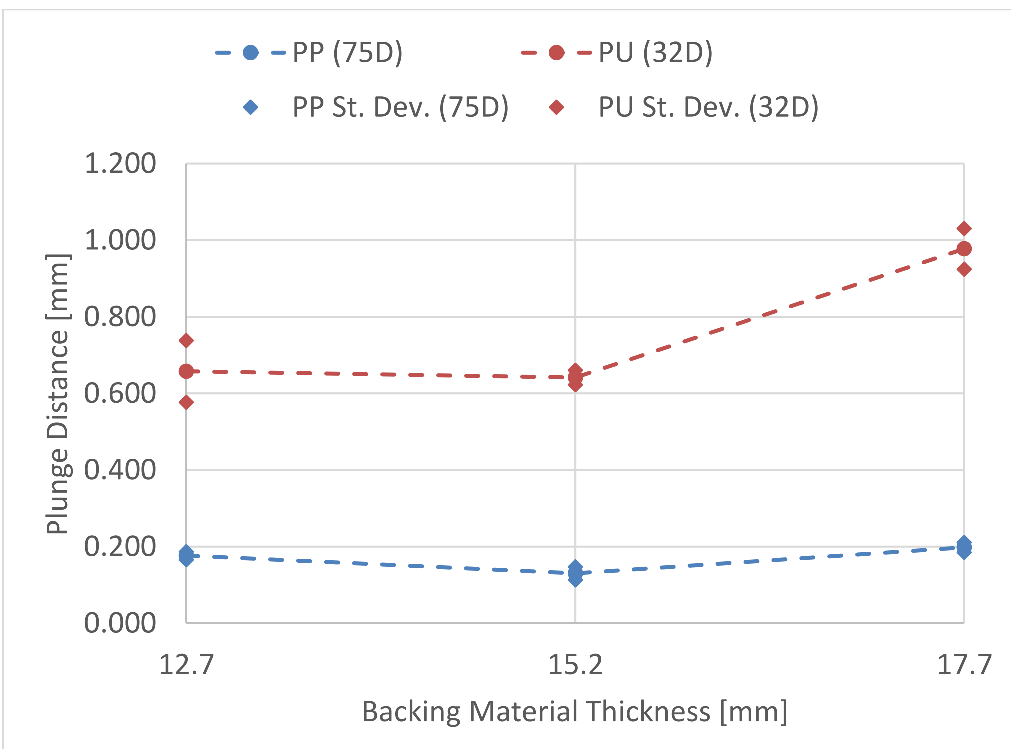


Figure 29 - Plunge Depth vs. Backing Material Thickness

4.2.4 Discussion and Conclusions

From this simulation of the cutting operation, it was concluded that increasing the hardness of the backing material results in a lower force and displacement required to fully cut a prepreg tape. In addition, increases in prepreg aging and cure state result in lower forces and displacements required to fully cut a prepreg tape. Finally, the thickness of the backing material does not appear to have any correlation with the force and displacement required to cut the tape (within the range tested).

Due to the first result, the research team at Georgia Tech decided to purchase Finn & Fram's hardest anvil sleeve, whose hardness was advertised as 70 Shore D. This sleeve was extremely difficult to install onto the steel cylinder and required the use of an Arbor press. When the sleeve was used on the machine, its ability to chop prepreg tapes was not able to be accurately determined because the cutting roller's steel blades fractured. This level and type of wear far exceeded that which had ever been seen while using the original sleeve of ~30 Shore D hardness.

To illustrate this wear, high-resolution microscopic images were taken of unused blades and worn blades which had been used with the hard anvil sleeve. The microscope used was a Leica DMRM manufactured in Germany, and the camera used was a Leica DFC420 manufactured in Germany in September 2009. The images were taken at a magnification of 5x. Shown below are an undamaged blade (Figure 30), a blade with minor abrasion (Figure 31), a blade with significant abrasion (Figure 32), and a chipped blade (Figure 33). Minor and sometimes major abrasions are found during the regular use of a steel blade cutting against the original anvil roller. However, the use of the harder anvil sleeve caused widespread major abrasion and, worse, chipping. This issue was not seen during the guillotine-style cutting tests because the rotary nature of the actual cutting process was not accurately replicated. With the new, harder anvil sleeve, the blade would lodge in the hard roller, then bend until breaking as the anvil and cutting roller rotated. Because of abrasion and chipping issues, it was decided to discontinue the harder sleeve and rather to concede that percent yield gains in the cutting portion of the prepreg SMC manufacturing process would have to come from other equipment or prepreg material changes.

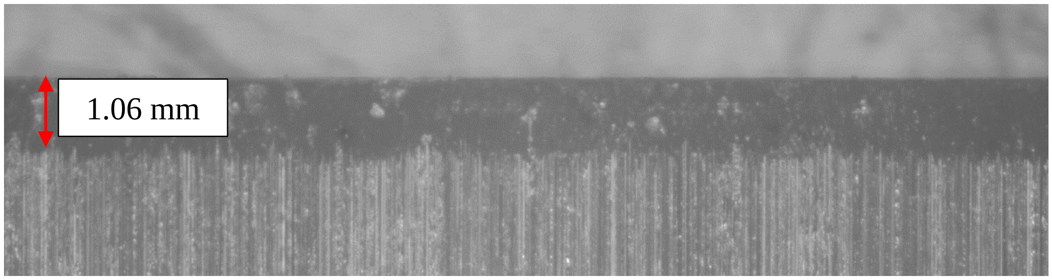


Figure 30 - Undamaged Blade

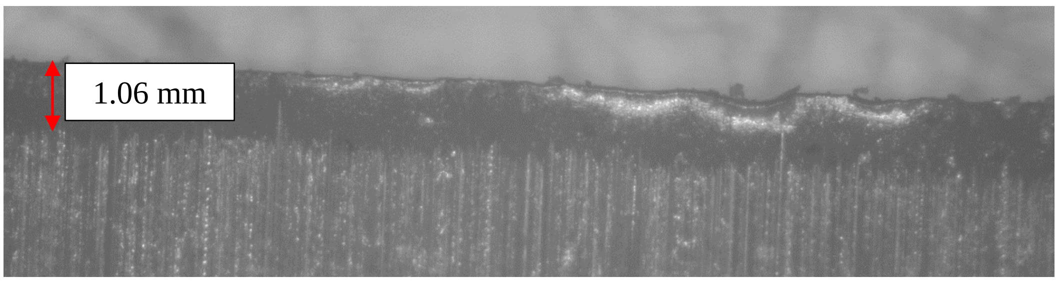


Figure 31 - Blade with Minor Abrasion

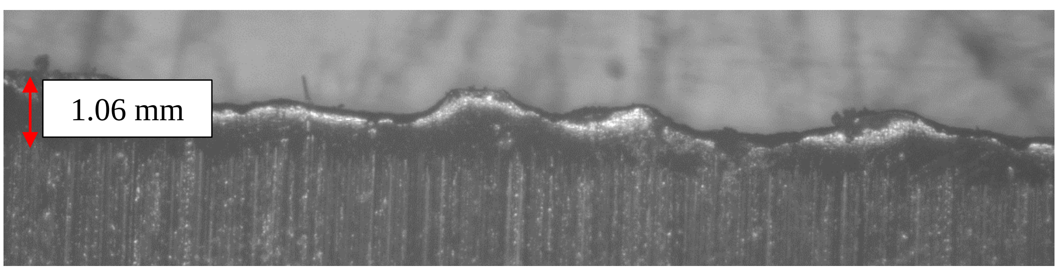


Figure 32 - Blade with Major Abrasion

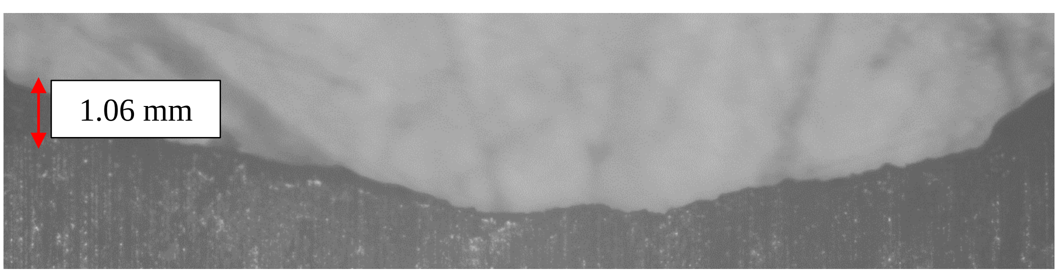


Figure 33 - Chipped Blade

The second result could not be directly translated to improved cutting. In practice, prepregs of lower degrees of cure were tacky and compliant, which caused them to adhere to the steel cutting roller in between the blades and stack on top of one another, resulting in incomplete cutting. Thus, even though the force and displacement required to cut through "fresh" prepreg tapes may have been less than those required for "aged" prepreg tapes, implementation on real SMC equipment was challenging. From these findings, it was desired to determine the minimum amount of resin cure which allowed the tapes to be cut without adhering to the blades and cutting roller.

The third result made things easier because, rather than having to devise a sleeve of new geometry that would have involved machining non-machinable polyurethane, anvil sleeves can be simply purchased from the supplier, Finn & Fram.

It is assumed that these trends remain regardless of the cutting speed. That is, it is assumed that the same trends would be seen if the cutting speeds seen on the SMC cutting head were achievable on the Instron test.

4.3 Blade Sharpness / Blade Wear

Next, the impact of the sharpness of the blades on the process was studied. The blades in the cutting roller are used to chop the prepreg tapes against the anvil. Intuition suggests that increasing the blade sharpness (that is, decreasing the blade's wear) will result in enhanced cutting performance. However, blade wear occurs as a function of the blade cutting material, so the blade's ability to cut prepreg tapes diminishes over time. Blade sharpness is therefore not a directly-controllable factor.

In addition to the difficulty in controlling blade sharpness, it is challenging to simply define and measure blade sharpness. A summary of the available methods for measuring blade sharpness follows.

4.3.1 Options for Determining Blade Sharpness

Presented below is a review of literature and industry practices regarding blade sharpness evaluation, which describes three primary methods for evaluating blade sharpness: cut a standard test medium and record the force required, take high-precision images or measurements of the blade cross-section, or take a 3D measurement of the surface shape and roughness using an optical profiler.

4.3.1.1 Cutting a Standard Test Medium

The cutting of a standard test medium and recording the force required appeared to be a logical choice because of access to an Instron testing machine, the relatively low cost associated with designing and making the tooling required to set up this Instron-based sharpness tester, and the speed with which measurements could be taken. In addition, there were industry-grade pieces of equipment which could accomplish this task at a high level of precision.

The industry-grade equipment that was most heavily considered was the Anago Knife Sharpness Tester (KST). Per Anago [11], in this test, a blade is loaded into the device and moves along guides at a 45-degree decline, as shown in Figure 34. This angled decline allows for the entire blade, from tip to root, to penetrate the test media. As the test media (see Figure 35) is a mesh, several discrete measurements, which result in a continuous graph, are taken along the length of the blade. The device measures the tension on the test media caused by the blade pressing against it and converts that into a sharpness measurement. The sharper the blade is, the less tension it will put on the test media before cutting through the test media.

Figure 34 - Anago Knife Sharpness Tester (Source: Adapted from [11])

Figure 35 - Anago KST Test Media (Source: Adapted from [11])

With the Anago KST, the sharpness profile (taken at discrete points) along the entire length of the blade is measured, and the test data are converted to a convenient format by the Anago software (see Figure 36). Purchasing this system costs $20,000-30,000, and renting it costs $6,000 per month. Simply sending worn blades for testing by Anago themselves costs under $1,000 and requires one-to-two months of lead-time. Because the intention of measuring blade sharpness is to evaluate how the blade loses its ability to cut as it wears continuously, it did not make sense to have Anago test this research's blades for they could not do so at the frequency or cost desired.

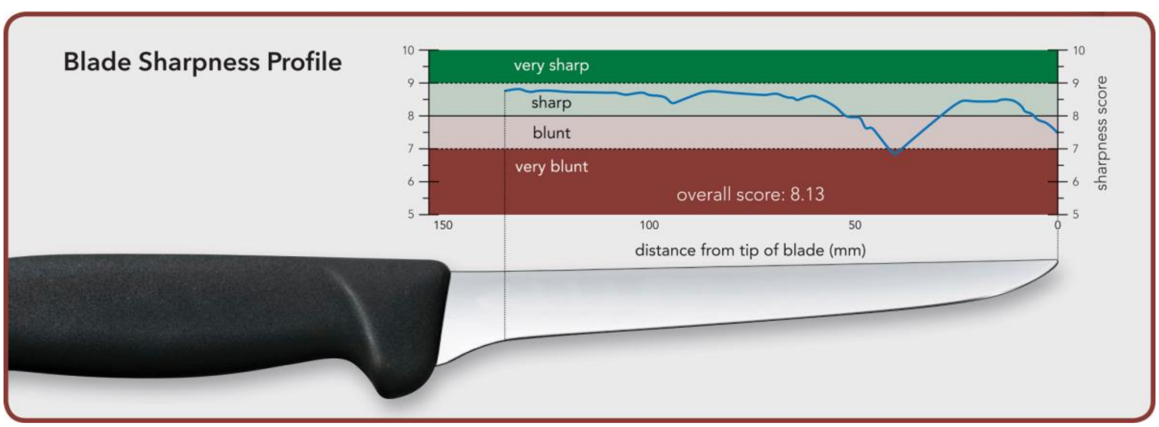


Figure 36 - Anago KST Blade Sharpness Profile (Source: Adapted from [12])

Another option for measuring blade sharpness by cutting a standard test medium is one that can be developed in-house. In this test, a particular standard fiber could be loaded at standard tension, and then the blade could be pressed against the fiber. This test could be implemented on the Instron test machine. A downside of this test versus the Anago KST is that developing a sharpness profile along the length of the blade would take much longer, so only small portions of the blade could feasibly be tested at once.

4.3.1.2 High-Precision Images of Blade Cross-Section

Using a microscope fitted with a camera described above, high-precision images of the blade cross-section could be taken. These images would ideally show the blade sharpness diminishing as a function of use on the SMC equipment. From these images, the radius of the blade could be measured and compared, so that a critical beyond which the blade can no longer cut tapes successfully could be determined. An obstacle to using this camera is that the blade samples would need to be cut much shorter than their original length to fit in the microscope. Cutting these blades with a bandsaw or a similar abrasive method may ruin the blade cross-section of interest.

4.3.1.3 Optical Profiler

Per Zecchino et al [13], an optical profiler could be used to take a 3D scan of the blade. This scan would show the geometry and surface roughness of the blade, both of which contribute to a blade's ability to cut. This information is captured without any contact with the blade, thus avoiding wear during the evaluation process. Optical profilers like this start at $2,000-5,000.

4.3.2 Sharpness Evaluation Method Selection and Test Setup

Developing an Instron-based sharpness test method was chosen as the best method for measuring blade sharpness. This method was considered relatively cheap and effective enough for this research's purposes. While this method can only take sharpness measurements at discrete locations, this was deemed acceptable because the prepreg tape has only a limited width where it dulls the blade. In addition, this method seemed quick enough to use while operating the SMC equipment with only limited downtime.

Note that the premise behind this test method is that the force required to cut a standard test medium is lower if the blade is sharper, and the force is higher if the blade is duller. Thus, the force required to cut a test medium was to be measured on the research team's existing Instron test machine.

4.3.2.1 Tooling Needed

To complete this test, the following tooling is needed: test media with consistent ability to be cut, a mechanism for holding the test media, a tensioning device for the test media, and a mount that attaches the blade to the load frame. The test medium selected was monofilament fishing line. This material is widely accessible, affordable, and has consistent properties. Braided fishing line, for comparison, is composed of several fibers wound together; this was not chosen because the blade would cut each fiber one-by-one rather than at once.

A rig for holding the test medium was designed and machined to mount onto the existing Instron tooling. The test medium was looped through the left hole and tied in a knot on one side, strung through the middle of the test medium holding part, and then loaded in tension by a suspended weight. To mount the blade to the load frame, the mount from the backing material cutting tests was reused. The entire test setup is show in Figure 37.

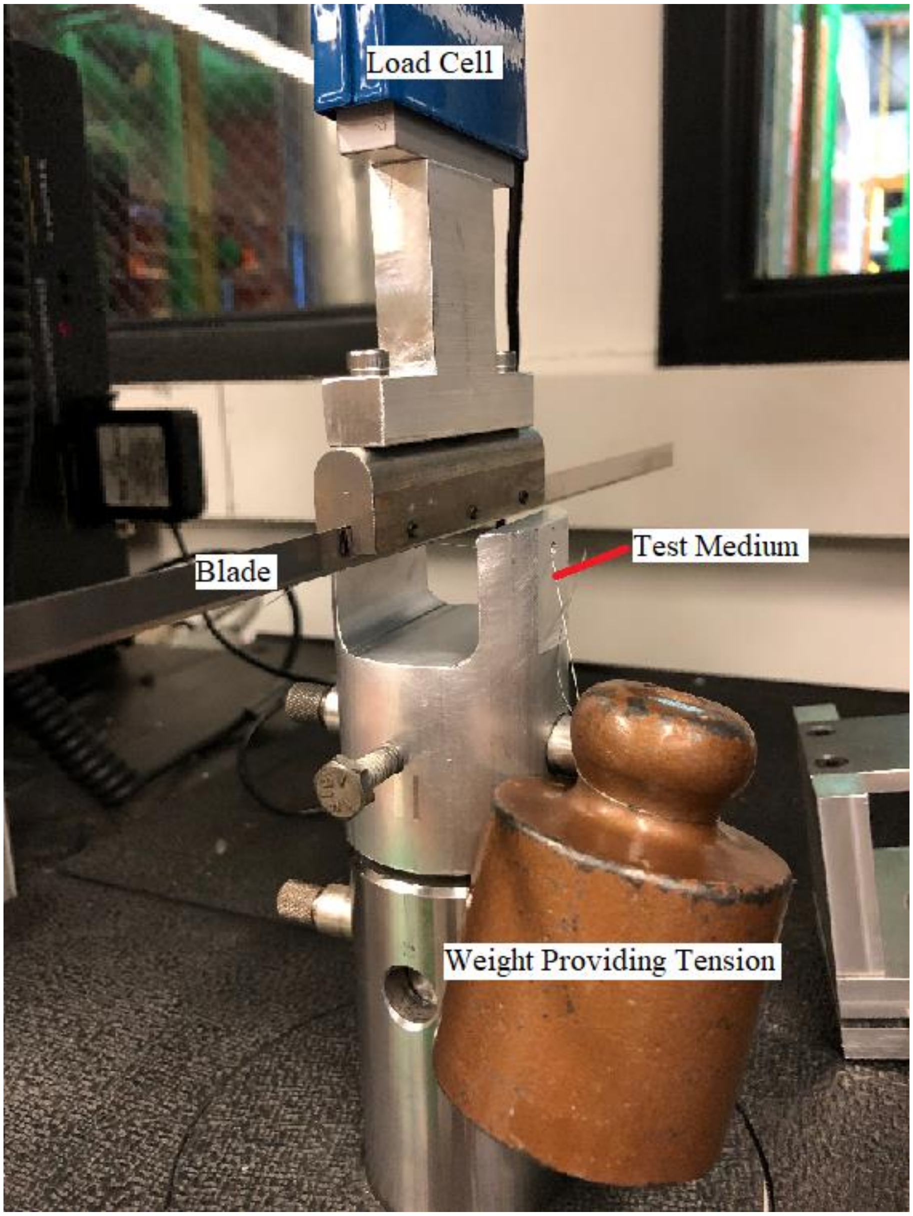


Figure 37 - Sharpness Test Setup

4.3.2.2 Instron Programming

Similar to the Instron cut tests for the backing material experiments, the Instron was programmed for this test to reach a stopping condition when a certain displacement was reached. These displacement stopping conditions were derived empirically, as described in the following section. The equipment used for these tests was an Instron 33R 4466 Load Frame with an Interface, Inc. (Scottsdale, AZ) SMT1-25N load cell rated at 25 N.

4.3.2.3 Test Calibration

With the test method and tooling in place, the test medium and tension needed to be selected from empirical testing. The test setup with the lowest variance was desired. The strength or "weight" of fishing line is defined in terms of "pounds test," which means the tensile force the line can withstand before breaking. Four "weights" of fishing line were evaluated as possible test media: 6 lb, 8 lb, 10 lb, and 12 lb. In addition, two levels of tension were evaluated: 0.3 kg and 1.0 kg. Again, these levels of tension were achieved by tying weights of 0.3 kg and 1.0 kg to the end of the test media.

A typical load-displacement curve is shown in Figure 38. There is negligible load measured by the load cell until the blade extends far enough to make contact with the test medium. Once contact is made, the load increases linearly with the blade extension until the test medium is instantaneously cut. Then, the load returns to zero until the displacement stopping condition is reached. The critical load is defined as the force required to sever the test medium.

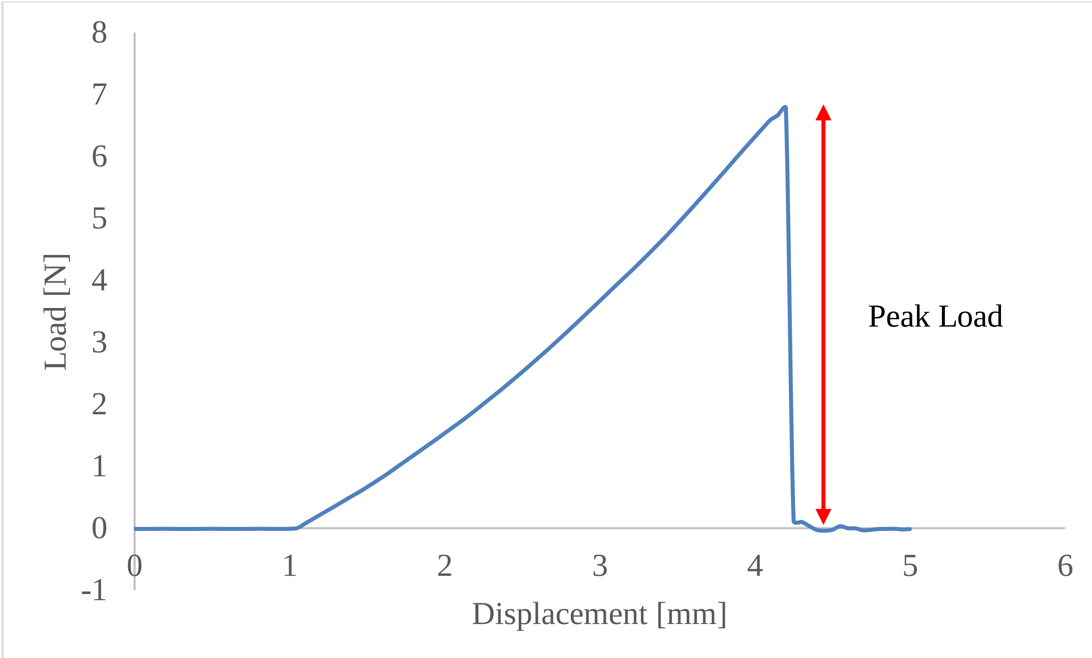


Figure 38 - Typical Load-Displacement Curve for Sharpness Test

If the test was a precise measurement of the blade sharpness, the critical load would be consistent each time the test is performed for a given blade, axial location on that blade, and level of wear. Therefore, the criterion against which the test medium and tensions were evaluated was the coefficient of variation of the critical load values (see Equation 7).

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Mean} \qquad (7)$$

The coefficient of variation was chosen over the standard deviation because the variation is normalized by the mean. The results show that the heavier fishing line may have a slightly higher standard deviation than the lighter fishing line, but the mean critical load values for the heavier fishing line may be several times higher than those of the lighter fishing line. Using a test with the lowest coefficient of variation is akin to using the greatest signal-to-noise ratio.

The data shown in Figure 39 display the peak load values measured using this test as a function of the four fishing line (test media) weights and the tension applied. The peak load values generally increased as a function of the fishing line (test media) weight, which was expected. Although only two levels of tension were tested, the peak load values appeared to cluster around the same number for the tension provided by both the 0.3 kg weight and the 1 kg weight, which suggests that the peak load is a function of the test medium and not a function of the tension applied. There was, however, much more variance in the data points created using the 1 kg weight to apply tension than those created using the 0.3 kg weight. This would appear to indicate that using the 0.3 kg weight to apply tension to the test media resulted in more consistent test results.

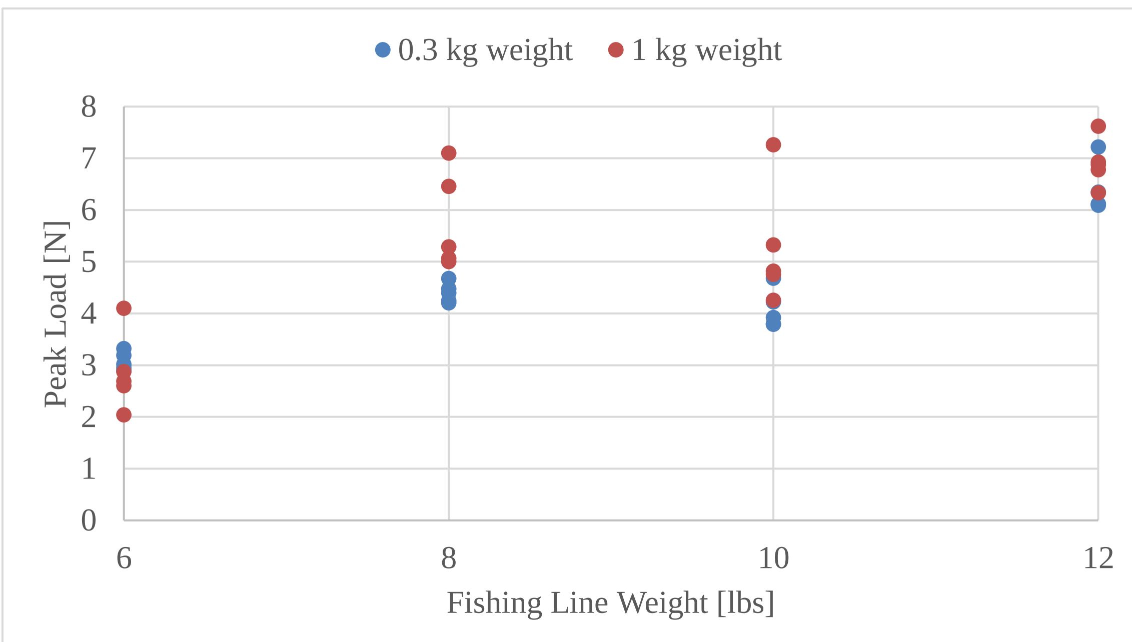


Figure 39 - Peak Load vs. Fishing Line Weight and Tensioning Weight (Raw Data)

To more properly study the peak load variance as a function of the fishing line (test media) weight and the tension, the coefficient of variation was plotted for each combination. As Figure 40 demonstrates, using the 0.3 kg weight to tension the test medium generally resulted in a lower coefficient of variation, and the coefficients of variation were similar for each weight of fishing line when using the 0.3 kg weight. Combining the data for the tension from 0.3 kg weight and the tension from the 1 kg weight, the 12 lb fishing line typically provided the lowest coefficient of variation. Therefore, the 12 lb fishing line and the 0.3 kg tensioning weight were chosen as standard for the sharpness tests.

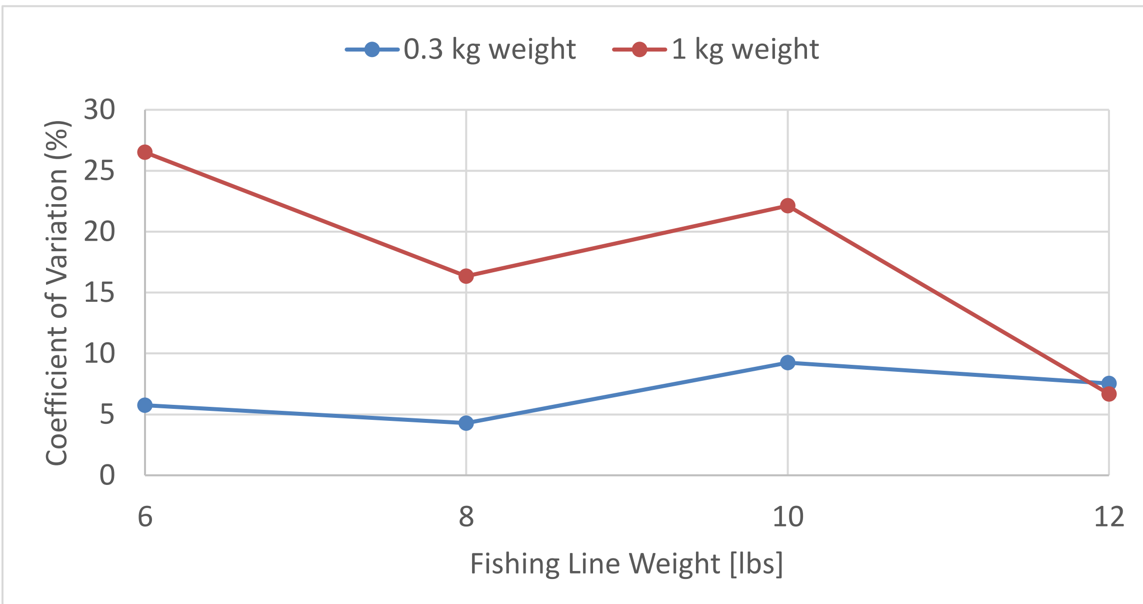


Figure 40 - Coefficient of Variation vs. Fishing Line Weight and Tensioning Weight

4.3.3 Wear of the Blades

To evaluate how blade sharpness decays as a function of the number of cuts made with that blade, multiple fresh blades were purposefully worn by using them to cut prepreg tape on the SMC equipment. The process of applying and measuring the effect of blade wear on the peak load values measured using the sharpness test setup is demonstrated in this section.

4.3.3.1 Prepreg Feedstock Material

The prepreg used as feedstock for the modified SMC process was Toray P2362W-19 of width 6.35 mm. This material was oven-aged at 70°C for 48 hours and underwent approximately 48 hours of room-temperature aging. Its T_g was measured at 20°C and its degree of cure was 33.4%.

4.3.3.2 SMC Equipment Settings

The fine-spaced cutting roller was used with relatively worn blades at a 1-inch spacing. One of the eighteen blades was removed and replaced with the test blade, which was fresh (unused) from Finn & Fram. The cutting pressure was set at 20 psi. The anvil motor speed was set at 11.7 RPM to allow for the smaller-diameter cutting roller to rotate at 15.0 RPM, which allowed for easier calculations downstream. The tape tension was set at 2 lbs.

4.3.3.3 Sharpness Test Settings

The 12 lb fishing line was used as the test media. The 0.3 kg weight was used to provide tension on the test media. The stopping condition used for the Instron was a displacement of 15 mm.

4.3.3.4 Procedure

The following procedure was used to purposefully wear the blades:

1. Take sharpness test measurements on the left, middle, and right parts of the blade of interest. Take three measurements at each location.
2. Load the fresh blade into the fine-spaced cutting roller alongside the relatively worn blades.
3. Load the cutting roller into the SMC machine.
4. Set up the locating shaft such that the prepreg tape is directed to the area marked “middle” on the blade of interest (see Figure 41).

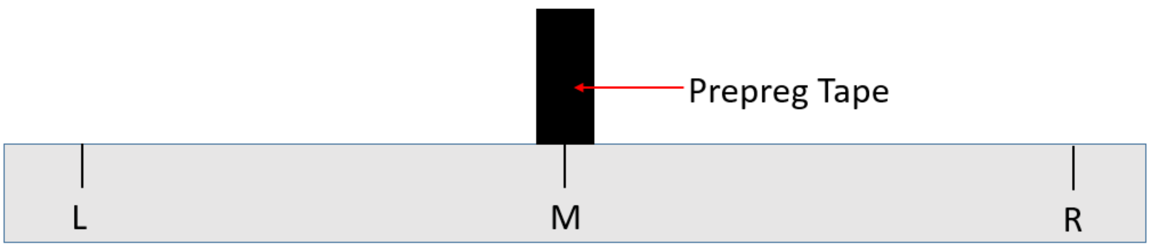


Figure 41 - Blade Undergoing Purposeful Wear

5. Operate the SMC equipment at the aforementioned settings for the proper length of time to achieve the number of cuts desired – typically five minutes of cutting time, resulting in 75 cuts per blade.
6. Remove the cutting roller from the SMC machine.
7. Carefully remove the blade of interest from the cutting roller.
8. Take sharpness test measurements on the left, middle, and right parts of the blade of interest. Take three measurements at each location.
9. Repeat steps 2 through 8 until a enough wear has occurred or the blade has broken.

4.3.3.5 Results

The peak load values were taken for blades at locations left, middle, and right for varying levels of wear (see Figure 42). Recall that the only portion of the blade in contact with the prepreg tape was the middle – not the left or right. This figure demonstrates that, although there may be some increase in peak load at the left and right locations due to the blade rubbing against the anvil sleeve, the primary driver for the increase in peak load is the prepreg being cut by the blade. The data points for “0 cuts” also demonstrate that there does not seem to be any increase or decrease in peak load as a function of the axial location on the blade.

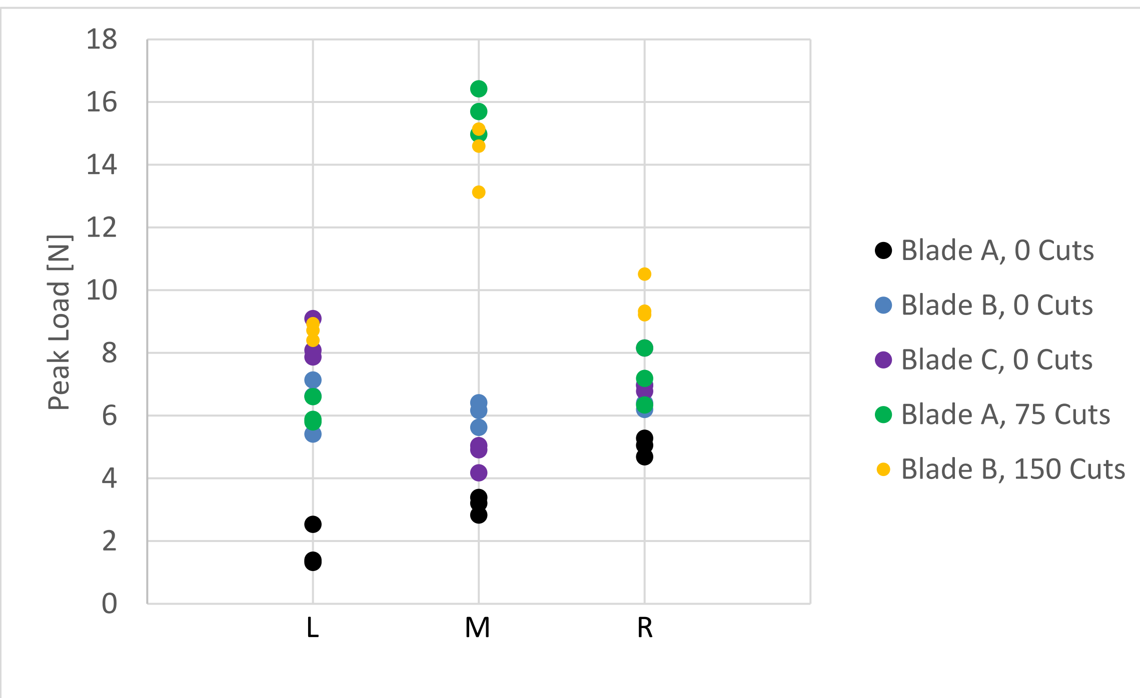


Figure 42 - Peak Load vs. Axial Location and Number of Cuts

For clarity, Figure 43 shows the same data points as the previous figure, but with the unworn blade data points colored blue and the worn blade data points colored red.

Again, there is some increase in peak load at the left and right sides due to rubbing against the anvil sleeve, but the middle data points demonstrate that the primary source of blade wear was cutting prepreg tape against the anvil sleeve.

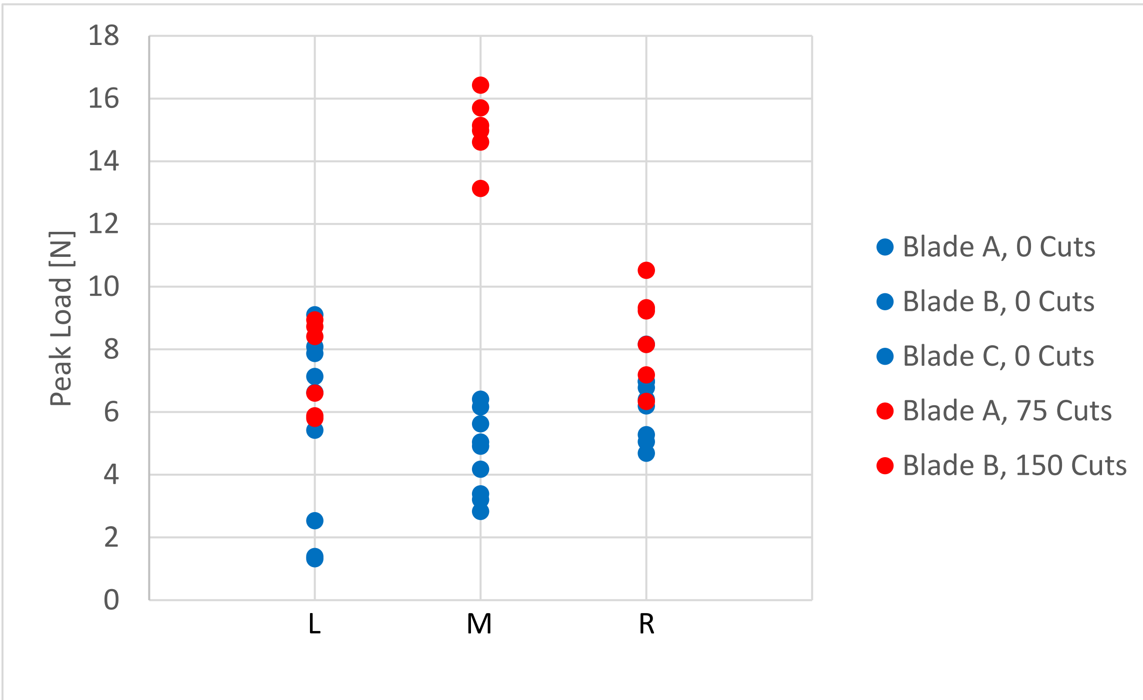


Figure 43 - Peak vs. Axial Location and Number of Cuts (Different Color Scheme)

Rather than strictly using peak load values to characterize the blade sharpness (or, more accurately, blade dullness), it was desired to develop a metric to characterize blade sharpness that used the peak load values from the sharpness test. After considering several options, blade sharpness was characterized according to Equation 8.

$$Blade\ Sharpness = \frac{Worn\ Peak\ Load - Sample\ Peak\ Load}{Worn\ Peak\ Load - \ Fresh\ Peak\ Load} \quad (8)$$

In this equation, the worn peak load and the fresh peak load values are constants. The worn peak load value is a high number (~30 N) representing the sharpness test result when testing a blade with significant wear that can barely chop prepreg tapes properly. The fresh, peak load value is a low number (~5 N) representing the sharpness test result when testing a completely fresh, unused blade. The sample peak load is the sharpness test result from the current blade being evaluated; its sharpness test result is typically greater than that of a fresh blade but lower than that of a worn blade. If the sample blade being tested is completely fresh, its blade sharpness result converges to 1. If the sample blade being tested has undergone significant wear, its blade sharpness result converges to 0.

To determine the worn peak load, dull blades which had been heavily used in the SMC equipment and had undergone mild to moderate abrasion were tested in the sharpness tester. The peak loads from these tests can be found in Table 4. The value used for the worn peak load to calculate blade sharpness was 29.3 Ns.

Table 4 - Random Dull Blades

	Peak Load (N)
Worn Blade 1	28.3
Worn Blade 2	32.1
Worn Blade 3	27.5
Mean (N)	**29.3**
Standard Deviation (N)	**2.46**

To determine the fresh peak load, the data points for blades A, B, and C at zero cuts from Figure 42 and Figure 43 were used. The average of these points was 5.47 N. This value was used as the fresh peak load value in the blade sharpness calculation.

With the blade sharpness calculation determined, the sharpness testing results were plotted for the middle location – that is, the axial location on the blade that underwent wear from cutting the prepreg tape. These values were plotted as a function of number of cuts (see Figure 44). Note each data point represents one sharpness test.

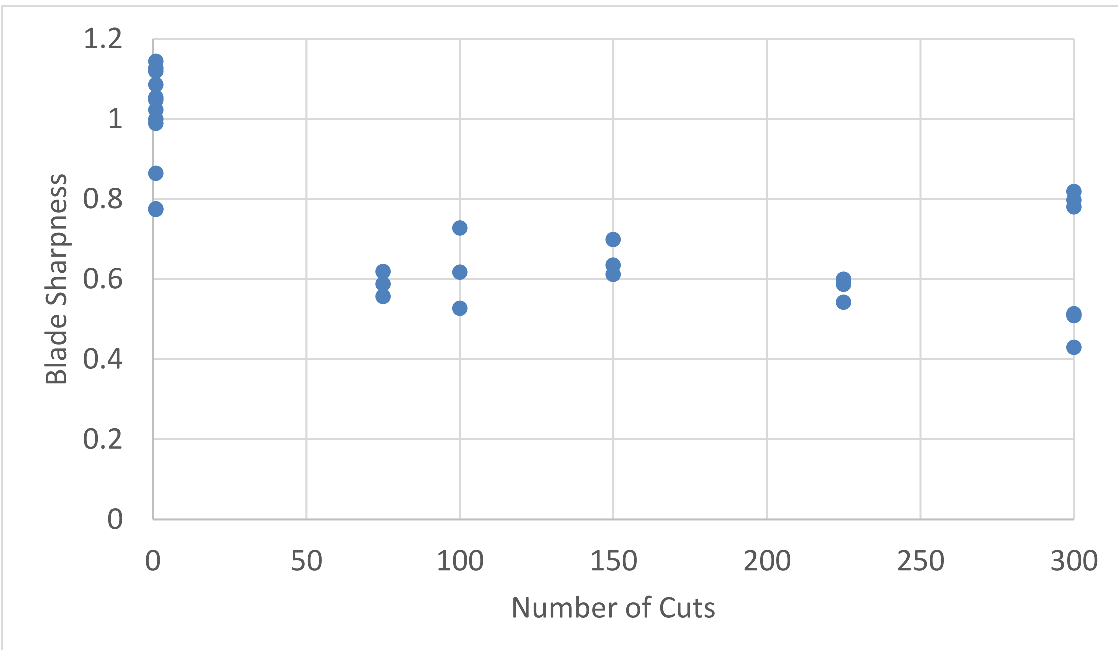


Figure 44 - Blade Sharpness vs. Number of Cuts

These blade sharpness values certainly appeared to trend downward as the number of cuts increased, which indicates that the sharpness test may be a useful metric for determining the blade's ability to slice through prepreg tape. However, there was some amount of variation in blade sharpness between blades of the same level of wear. This could have been due to the tester not testing the blade sharpness at the exact same point on every blade, minor variations between blades, or variations within the test method.

When a linear trend line was plotted with the data (see Figure 45), there appeared to be a weak, negative correlation between the number of cuts and the blade sharpness. Plotting a logarithmic trend line (see Figure 46) with the data resulted in an improved R^2 value, which indicates that the blade sharpness values may decrease relatively quickly at low numbers of cuts, then decrease at a slower rate at higher numbers of cuts. Plotting the data with the X-axis in a logarithmic scale (see Figure 47) demonstrates this trend a little more intuitively.

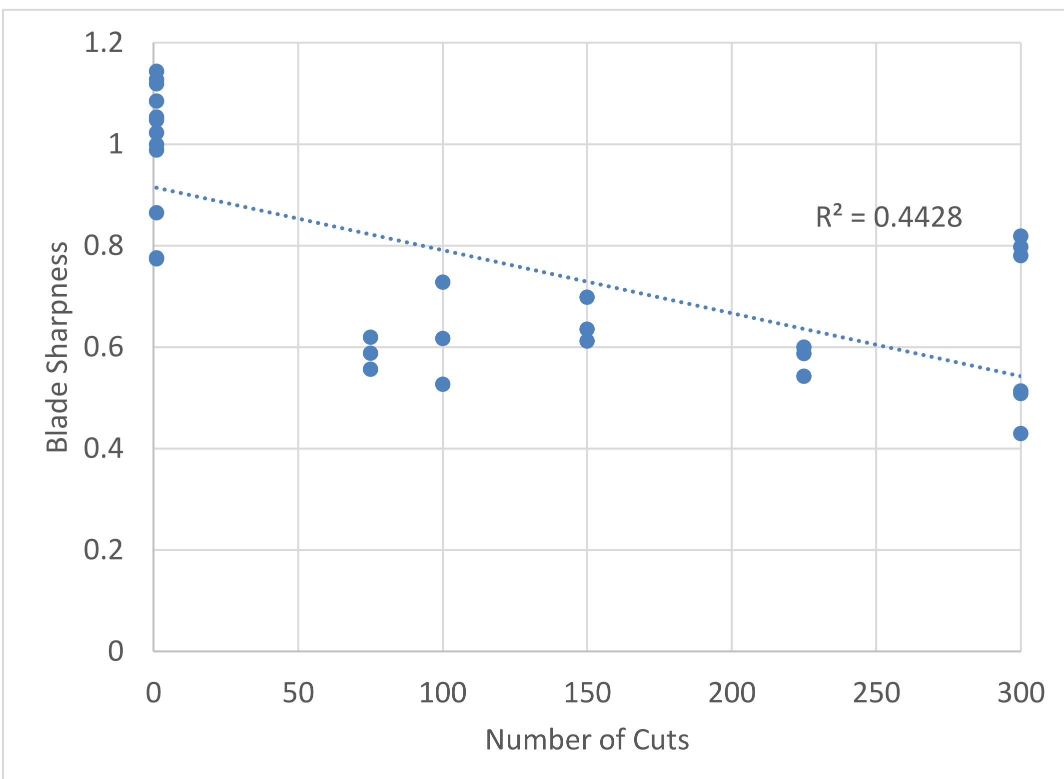


Figure 45 - Blade Sharpness vs. Number of Cuts with Linear Trend Line

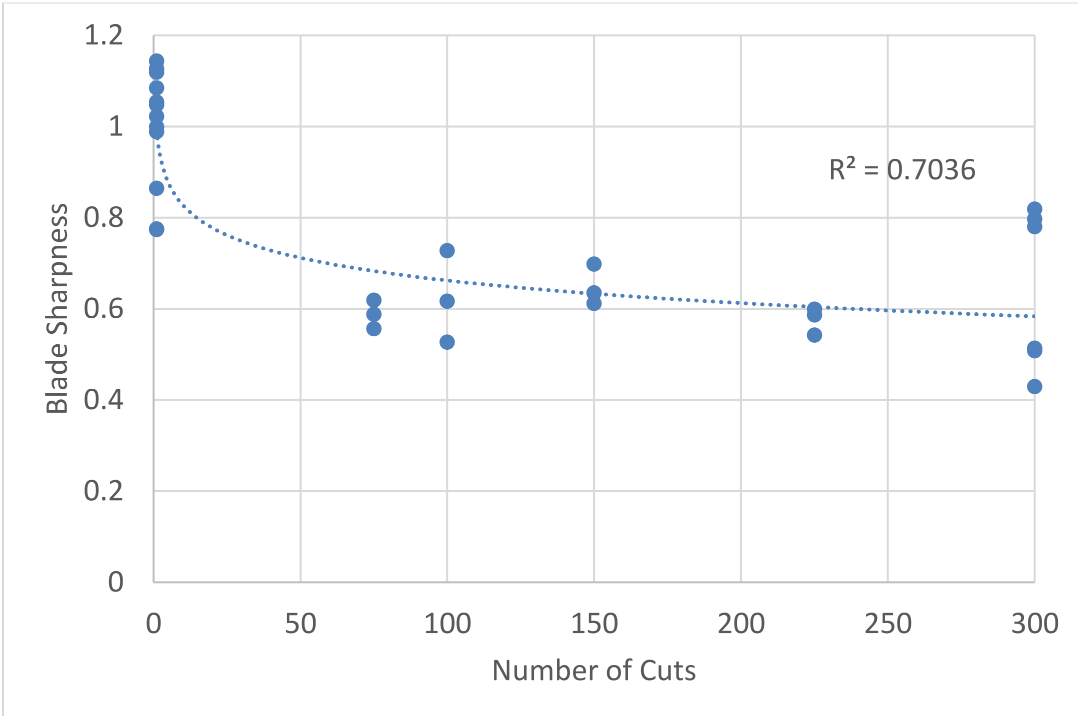


Figure 46 - Blade Sharpness vs. Number of Cuts with Logarithmic Trend Line

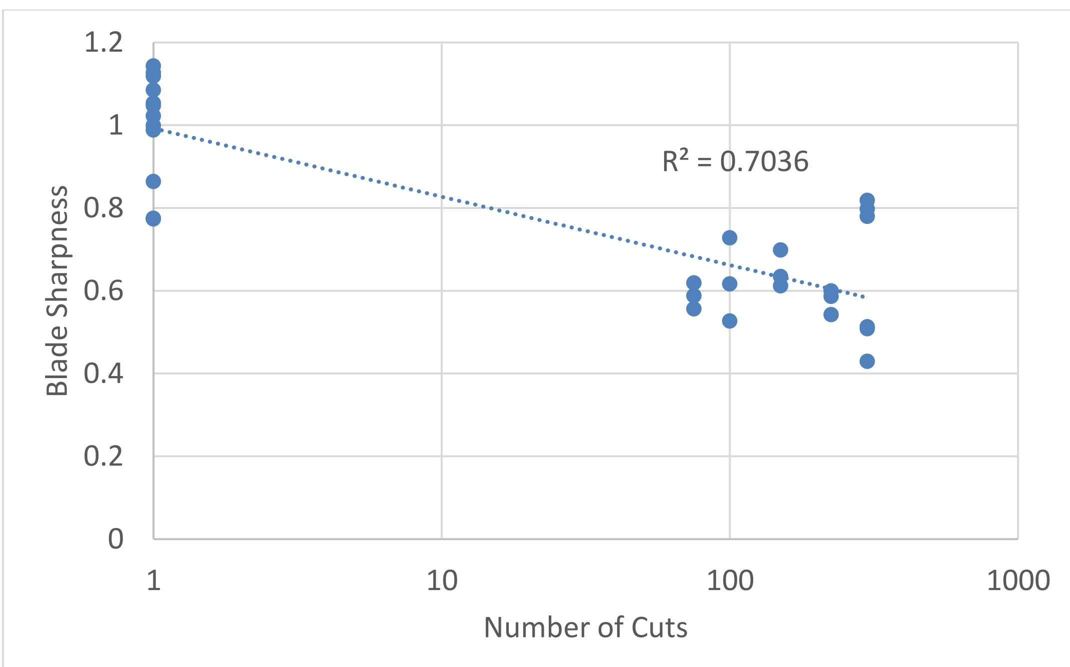


Figure 47 - Blade Sharpness vs. Number of Cuts with Logarithmic Trend Line and X-Axis

This method for evaluating blade sharpness was imperfect, but it provided some insight into the level of wear the blade had experienced and its ability to cut prepreg. This method was used for quantifying the blade sharpness when conducting trials on the full SMC equipment, as discussed in Chapters 5 and 6.

4.4 **Other Equipment Processing Parameters**

While the effects of adjusting the backing material hardness, backing material thickness, and prepreg cure state could be studied with a reasonable degree of accuracy using an off-line test, the effects of other SMC equipment processing parameters could only be evaluated with reasonable accuracy on the SMC equipment itself. In addition, these parameters could be easily adjusted on the equipment. These factors are discussed below.

4.4.1 Cutting Pressure

Cutting pressure, measured in pounds per square inch (psi), refers to the pressure imposed on the cutting roller by pneumatic pistons located at the cutting roller's supports. This pressure is then translated to the anvil roller at the interface between the cutting roller and the anvil sleeve surface. This pressure can be adjusted by turning the knob shown in Figure 48.

Figure 48 - Cutting Pressure Adjust Knob

4.4.2 Roller Speed

Roller speed, measured in revolutions per minute (rpm), refers to the rotational speed of the motor attached to the anvil roller. This can be translated to the prepreg tape's linear speed using Equation 5 and Equation 6. This roller speed can be adjusted using the buttons shown in Figure 49.

Figure 49 - Roller Speed Adjust Interface

4.4.3 Tape Tension

Tape tension, measured in pounds (lbs), refers to the back-tension applied to the tape by resistance torque on the creel's roll mount. This tension can be adjusted using the dials shown in Figure 49.

Figure 50 - Tape Tension Adjustment Interface

4.5 Chapter Summary

In this chapter, the equipment-related factors impacting the ability of the modified SMC process to create chop the prepreg tapes were presented. The cutting mechanism was characterized, the method for and results from characterizing the effect of the anvil sleeve hardness were discussed, the method for and results from characterizing the sharpness of the blades were presented, and the method of adjusting the other equipment processing parameters. Useful data for the blade sharpness as a function of number of cuts attempted were also presented, which would likely be of use to a future manufacturer of SMC derived from prepreg tapes.

Key takeaways from this chapter include: there is a negative correlation between backing material hardness and the force/displacement required to slice through prepreg, but sleeves too hard would break the blades; blade sharpness can be evaluated numerically using an Instron-based test, and it decreases as a function of blade wear; and the other equipment processing parameters identified (cutting pressure, roller speed, and tape tension) can be easily adjusted on the machine.

In the next chapter, the impact of these equipment-related factors, in conjunction with the material-related data, on the process's ability to chop prepreg tapes is investigated. The setup of the experiment that investigates these factors is presented.

CHAPTER 5. EXPERIMENT DESIGN

After gaining an understanding of prepreg material characteristics and the equipment processing parameters, the impact each of these factors had on the success of the production process were investigated. This investigation was performed using a fractional-factorial experiment design implemented with JMP. The current chapter illustrates how this was performed.

5.1 Success Criterion: Percent Yield

To evaluate the performance of the modified SMC manufacturing process, in particular the cutting portion, a success criterion needed to be determined. The problem with the cutting portion of the process as initially designed was that the prepreg tapes would adhere to the cutting roller and stack on top of one another, causing incomplete cuts and often jamming the process. Therefore, the success criterion needed to incorporate the ability of the blades to chop completely through the prepreg tape. The success criterion chosen was percent yield, as demonstrated in Equation 9. This was the success criterion against which the impact of all modifications to the process were evaluated.

$$Percent\ Yield = \frac{Number\ of\ Properly\ Cut\ Tapes}{Number\ of\ Properly\ Cut\ Tapes + Number\ of\ Improperly\ Cut\ Tapes} \times 100\% \tag{9}$$

5.2 Prepreg Tape Selection and Preparation

It was desired to evaluate all three metrics which evaluate the cure state of the resin in the prepreg: heat of reaction/degree of cure, T_g, and endothermic peak. To ensure all three of these were tested, material with no endothermic peak, material with a small endothermic peak, and material with a more substantial endothermic peak were used. These could be considered low cure state (low degree of cure, no endothermic peak, low T_g), medium cure state (medium degree of cure, low endothermic peak, medium T_g), and high cure state (high degree of cure, high endothermic peak, high T_g) materials.

The prepreg tape used for this test was Toray P2362W-19 of 6.35 mm width. For rolls 1 and 2, this prepreg was kept uncured in the freezer until 8 weeks prior to testing. At that point, rolls 1 and 2 were removed from the freezer; one roll underwent 48 hours of oven-aging at 70°C and the other underwent no oven-aging. Rolls 1 and 2 were then allowed to cure at room temperature until the one which had undergone oven-aging developed an endothermic peak. This occurred after 8 weeks of oven-aging. Roll 3 underwent 48 hours of oven-aging at 70°C, then was allowed to cure at room temperature for 33 weeks. The DSC curves for Roll 1, Roll 2, and Roll 3 can be found in Appendix B.1, Appendix B.2, and Appendix B.3, respectively. Their material properties are summarized in Table 5. Note the H_0 used to calculate the degree of cure was 165.1 J/g.

Table 5 - Prepreg Characteristics

Roll	Oven-Aging @ 70°C (hrs)	RT Aging (weeks)	Degree of Cure (%)	T_g (°C)	Heat of Endothermic Peak (J/g)
Roll 1	0	8	11.8	12.00	0
Roll 2	48	8	23.6	35.61	1.007
Roll 3	48	33	51.7	61.27	1.812

5.3 Equipment Settings

To evaluate the importance of the equipment-related factors and to determine the optimal setup, the following factors were set at the noted settings shown in Table 6.

Table 6 - Equipment Settings

Factor	Low Value	High Value	Justification
Tape Tension	0 lbs	5 lbs	High end set by max motor torque.
Cutting Pressure	25 psi	40 psi	Low end set by drop-off in yield for less cured prepreg. High end set by max motor torque.
Roller Speed	15 rpm	25 rpm	Low end set by minimum speed before motor stall. High end set by max allowable equipment vibrations.

The process window for the tape tension and cutting pressure was also limited. A combination of low tape tension and low cutting pressure resulted in incomplete cuts, regardless of the other settings and prepreg type used. A combination of high tape tension and high cutting pressure provided too much resistance for the motor to overcome. Therefore, the corners of this operating window were limited in the manner shown in Equation 10 and in Figure 51.

$$30 < Tape\ Tension\ (lbs) + Cutting\ Pressure\ (psi) < 40 \tag{10}$$

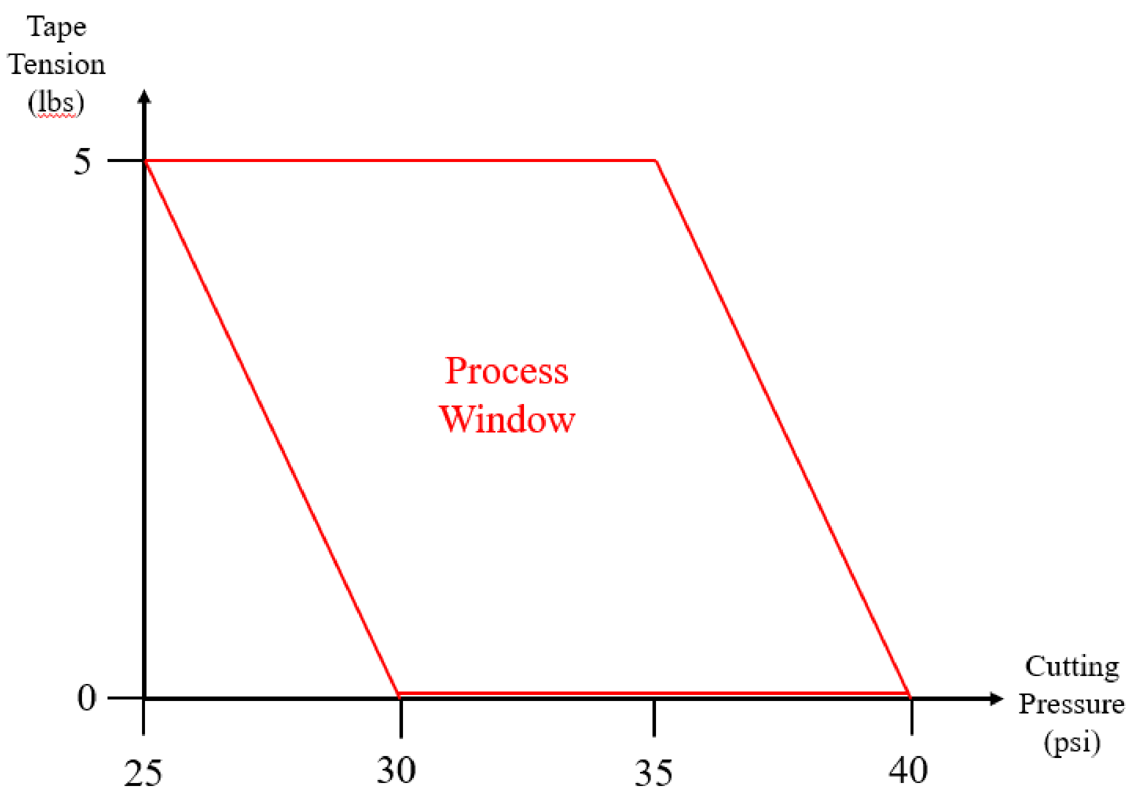


Figure 51 - TT + CP Process Window

Blade sharpness was also evaluated, but it was not set directly. Rather, blade sharpness was measured using the sharpness test described in Section 4.3 after every four runs. Blade sharpness was evaluated for three of the 18 blades, spaced equally 60° apart from one another. Because previous blade sharpness tests indicated that there was little variation between tests taken using the same blade at the same location, only one sharpness test measurement was performed for each blade at each location.

The equipment settings that remained constant because they were either too difficult to adjust or did not significantly affect the percent yield include the following:

- Anvil Sleeve: Polyurethane, 80-85 Shore A (~30 Shore D), 7.25" diameter.
- Cutting Roller: Fine-spaced roller, 1" spacing, same blades for every run, blades were fresh for first run, sharpness measured for three of the 18 blades after every four runs.

5.4 Implementation in JMP

With the prepreg properties and equipment setting process windows known, investigation of the importance of each factor was implemented in JMP. First, the responses were defined. As the research sought to maximize the ratio of the number of complete cuts (Properly Cut Tapes) to the total number of cuts attempted (Total Tapes), "Properly Cut Tapes" was defined as the response whose goal was to be "Maximized." To make the quantity a proportion of the total, "Total Tapes" was defined as the response with no goal.

Next, the input factors were defined. These could be categorized as "Categorical" or "Continuous" factors. Categorical implies discrete options for the factor, and continuous implies that the options are continuous within the specified bounds. "Prepreg Endothermic Peak" was listed as a continuous factor with a range of 0 to 1.812 J/g. Note the upper and lower bounds refer directly to roll 1 and roll 3, respectively. The T_g or degree of cure could also have been used as the prepreg cure state-related factor.

Cutting pressure was listed as a continuous factor with a range of 25-40 psi. Roller speed was listed as a continuous factor with a range of 15-25 rpm. Tape tension was listed as a continuous factor with a range of 0 to 5 lbs. These input factors are summarized in Table 7.

Table 7 - DOE Factors for JMP

Factor	Categorical or Continuous?	Low Value	High Value
Prepreg Endothermic Peak (J/g)	Continuous	0	1.812
Cutting Pressure (psi)	Continuous	25	40
Roller Speed (rpm)	Continuous	15	25
Tape Tension (lbs)	Continuous	0	5

Next, factor constraints were defined. Factor constraints limit the process window to accommodate for limitations of the process when certain factors are combined with one another. As mentioned previously, the process window for Tape Tension and Cutting Pressure was limited according to Equation 10 and Figure 51.

Next, interaction terms and power terms were added to the model. Interaction terms incorporate the possibility that the effect of any factor on the percent yield may depend on the value of another factor. Choosing to check for interaction terms adds complexity to the experiment, but it often reveals useful information about the process. For this experiment, second-degree interactions for each of the factors were investigated, and higher-order (greater than second-order) interactions were neglected. Second-degree power terms were added to the model for each of the continuous factors. Doing so allows for the experiment to test using not only the low and high values within the range, but also the values in between the low and high values.

Next, the number of runs was determined. Based on the use of four continuous factors, second-degree interaction terms, and second-degree power terms for the continuous factors, the minimum number of runs possible was 21. The recommended number of runs was 32. As detailed information about the process was desired and because doing extra runs did not occupy too much time, 32 runs were selected. See Appendix C.1 for the experiment setup screen in JMP.

Finally, design was generated by JMP and the data was gathered using the run procedure documented below.

5.5 Run Procedure

The procedure used for doing runs in this experiment is documented as follows:

1. Run sharpness test for three blades whose sharpness is being tracked. Sharpness only needs to be evaluated at the point along the blade axis where it cuts the prepreg.
2. Load blades, including those whose sharpness was measured, into fine-spaced cutting roller, then load cutting roller into SMC equipment. The blades whose

sharpness is being tracked should have the exact same amount of runtime as the other blades on the cutting roller.

3. Load prepreg roll into creel and route tape into cutting head per Figure 9. Route backing film to the Venturi blower.
4. Adjust locating shaft such that the tape is cut by the portion of blades tested in the sharpness test.
5. Ensure the cutting pressure, roller speed, and tape tension settings are correct according to JMP-generated experiment design. Ensure a bin is in the chamber below the cutting head to collect the chopped prepreg tapes.
6. Run SMC machine for an amount of time that allows for the same amount of material to be cut every time (see Table 8).

Table 8 - Roller Speed and Run Time

Roller Speed (rpm)	Run Time (sec)
15	60
20	45
25	36

7. Collect all chopped prepreg tapes and separate the properly-cut 1-inch tapes from the tapes that were not properly cut (generally >1”).
8. Because counting the number of chips is too time-intensive, weigh the properly cut and the not properly cut tapes on the scale (Kern ACS 220-4) and record their weights. This generates a percent yield figure for the run.

9. Use compressed air to blow off the SMC equipment to ensure the cutting head and the chamber beneath the cutting head are completely clear of prepreg tapes.
10. If a sharpness test is required, repeat steps 1, 2, and 5 through 9. If a prepreg roll change is required, repeat steps 3 and 5 through 9. If neither is required, repeat steps 5 through 9.

5.6 Chapter Summary

In this chapter, the four controllable factors – prepreg endothermic peak, cutting pressure, roller speed, and tape tension – were discussed and their operating ranges presented. The method for setting up the experiment using JMP's DOE Custom Design tool was documented. The run procedure for the experiment which evaluate these factors and blade sharpness was shown.

In the next chapter, the results from this chapter's experiment setup are presented and discussed.

CHAPTER 6. RESULTS AND DISCUSSION

The previous chapter discussed the method by which experiments were run. These experiments evaluated the percent yield of the chopping process as a function of the prepreg endothermic peak, blade sharpness, cutting pressure, roller speed, and tape tension. In this chapter, the results will be presented, shown graphically, and discussed. The actual results from all 32 trials can be found in Appendix D.1.

6.1 Effect Summary

As shown in Figure 52, the factors and factor interactions that demonstrated an impact on the percent yield were those with a p-value below 0.05. Those factors and factor interactions were, in order of significance and therefore reverse order of p-value, (1) roller speed-tape tension interaction, (2) cutting pressure-roller speed interaction, (3) endothermic peak (quadratic), (4) roller speed (quadratic), and (5) tape tension (quadratic).

Source	LogWorth	PValue
Roller Speed (rpm)*Tape Tension (lbs)	18.843	0.00000
Cutting Pressure (psi)*Roller Speed (rpm)	5.490	0.00000
Endothermic Peak (J/g)*Endothermic Peak (J/g)	5.294	0.00001
Roller Speed (rpm)*Roller Speed (rpm)	1.480	0.03311
Tape Tension (lbs)*Tape Tension (lbs)	1.363	0.04338
Endothermic Peak (J/g)*Roller Speed (rpm)	1.225	0.05954
Blade Sharpness*Tape Tension (lbs)	0.395	0.40285
Blade Sharpness*Cutting Pressure (psi)	0.368	0.42826
Endothermic Peak (J/g)*Cutting Pressure (psi)	0.360	0.43662
Cutting Pressure (psi)(25,40)	0.342	0.45550 ^
Endothermic Peak (J/g)*Tape Tension (lbs)	0.323	0.47530
Blade Sharpness(0,1)	0.205	0.62335 ^
Endothermic Peak (J/g)(0,1.812)	0.198	0.63380 ^
Endothermic Peak (J/g)*Blade Sharpness	0.193	0.64104
Blade Sharpness*Blade Sharpness	0.179	0.66179
Roller Speed (rpm)(15,25)	0.163	0.68698 ^
Blade Sharpness*Roller Speed (rpm)	0.127	0.74730
Cutting Pressure (psi)*Tape Tension (lbs)	0.117	0.76336
Tape Tension (lbs)(0,5)	0.106	0.78379 ^
Cutting Pressure (psi)*Cutting Pressure (psi)	0.003	0.99213

Figure 52 - Experiment Effect Summary

Recall that when a factor multiplied by itself appears as in the effect summary, as is the case with endothermic peak, roller speed, and tape tension, this demonstrates that the factor has some quadratic effect on percent yield. This means the factor may result in low percent yield at the low end of the factor's operating range, then may result in a high percent yield at the middle of the factor's operating range, and finally may result in a low percent yield at the high end of the factor's operating range. If the factor appeared in the effect summary without being multiplied by itself, this indicates that the factor has a linear relationship with percent yield.

Recall also that when a factor multiplied by a different factor appears in the effect summary, this indicates a factor interaction. For example, the factor interaction between roller speed and tape tension indicates that, depending on a certain roller speed, tape tension may have a greater or lesser impact on the percent yield. Likewise, depending on the tape tension, the roller speed may have a greater or lesser impact on the percent yield.

For simplicity and because of the drastically higher levels of significance associated with them, only the top three factors/interactions were investigated.

6.2 Prediction Profiler

Shown below in Figure 53 is a prediction profiler from the JMP software. This allows the user to see the predicted percent yield as a function of the five continuous factors that can be set by the user. The prediction profiler presented in Figure 52 has the highest endothermic peak, which indicates the highest-aged prepreg (roll 3), and the moderate blade sharpness selected. Clearly, the expected percent yield is 100% regardless of the cutting pressure, roller speed, and tape tension. This demonstrates that prepreg tape with a high level of cure can easily be chopped regardless of the equipment settings, within the limits of these experiments. Note that there is a steep drop-off in predicted yield for blade sharpness below ~0.35. This drop-off is likely due to the limitations of testing, which did not evaluate blades with a sharpness level that low; there are therefore no data points for those combinations.

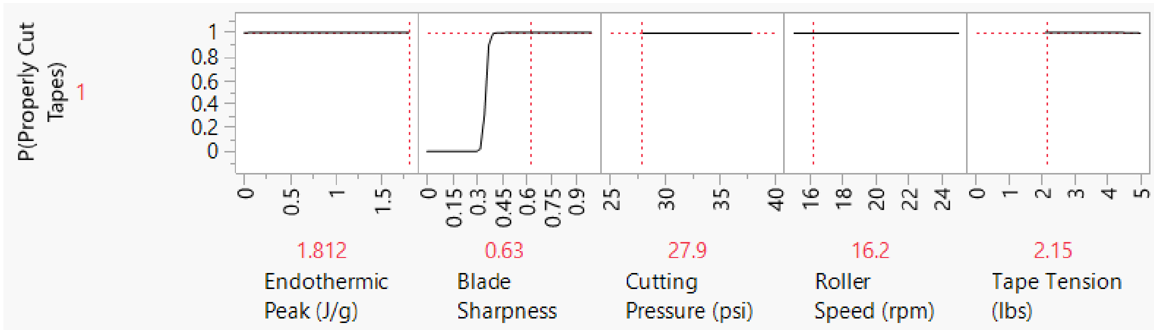


Figure 53 - Prediction Profiler with Roll 3's Endothermic Peak Selected

Shown in Figure 54 is the prediction profiler with a moderate endothermic peak, which indicates the middle-aged prepreg (roll 2). Blade sharpness remains at a middling 0.63. The completely flat curves for cutting pressure, roller speed, and tape tension demonstrate the process's dependence on the prepreg's cure state; for this moderately-cure prepreg, the yield is predicted to be 100% given any combination of the equipment parameters.

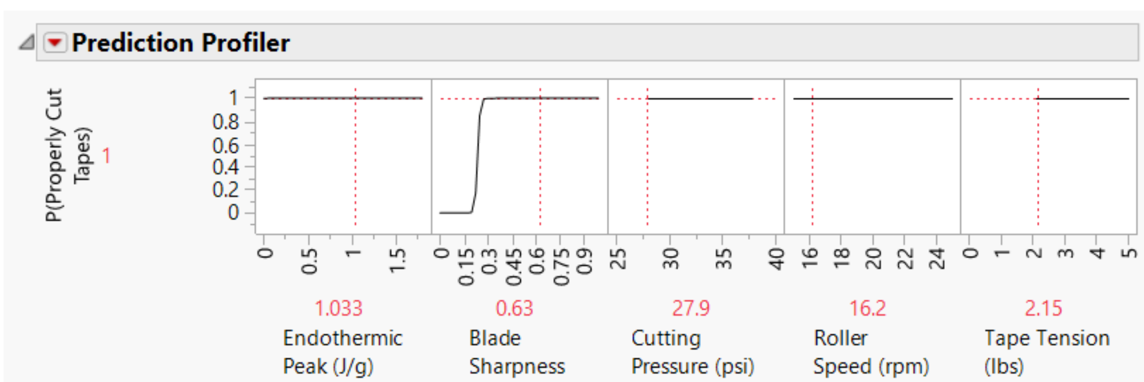


Figure 54 - Prediction Profiler with Roll 2's Endothermic Peak Selected

Finally, shown in Figure 55 is the prediction profiler with the lowest endothermic peak selected, which refers to the prepreg with the lowest level of cure (roll 1). The plots in this prediction profiler differ greatly from those of the previous two. These show that there is a major drop-off in predicted yield with roller speeds between 19 and 23 rpm and with tape tensions near 0 and near 5 lbs.

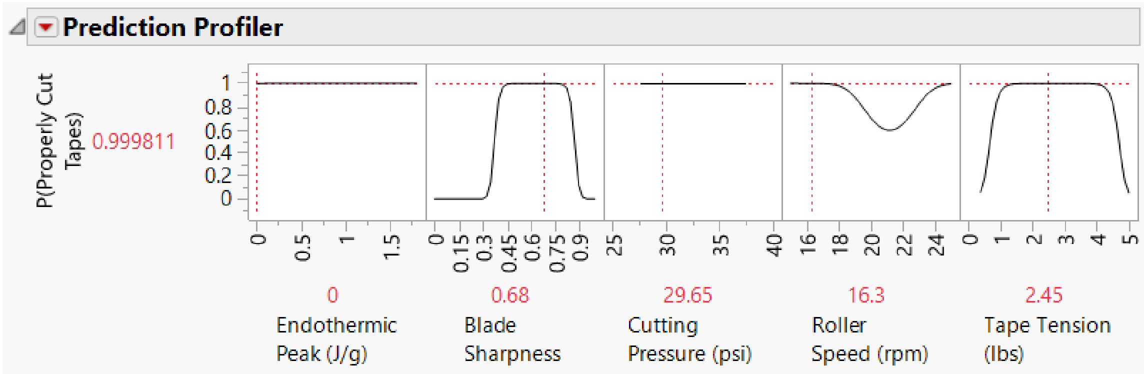


Figure 55 - Prediction Profiler with Roll 1's Endothermic Peak Selected

Figure 56 demonstrates an important phenomenon. In this prediction profiler, the tape tension selected is near-zero (0.35). The resulting predicted percent yield is near-zero for every value of blade sharpness, cutting pressure, and roller speed. This demonstrates the reliance that the percent yield has on tape tension given the "fresh" prepreg.

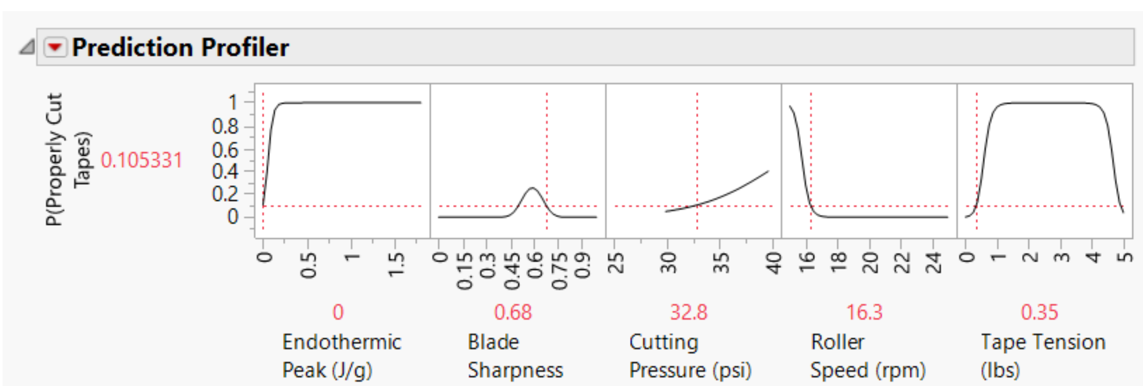


Figure 56 - Prediction Profiler with Roll 1's Endothermic Peak Selected and 0.35 lbs Tape Tension Selected

Per JMP's "Maximize Desirability" function, the combination of factor settings that provides an optimal result is (1) an endothermic peak of 1.27 J/g, (2) a blade sharpness of

0.72, (3) a cutting pressure of 26.6 psi, (4) a roller speed of 24.3 rpm, and (5) a tape tension of 4.1 lbs, as shown in Figure 57. These exact numbers, of course, should be taken with a grain of salt. In general, it is best for the prepreg to have a high endothermic peak in order to cut well, but there is some endothermic peak below the "optimal" 1.27 J/g that will still cut well. In addition, the optimal blade sharpness should be 1.0, but the blades that were available for the test were not that fresh, so data were not collected for that level of blade sharpness. It is useful that the optimal cutting pressure is near the lower end of the spectrum; this lower cutting pressure would may result in less resistance torque for the motor to overcome and less blade wear. In addition, the optimal roller speed being at the top of the spectrum is useful because that provides maximum product throughput. As predicted, the optimal tape tension is near the top of the operating range, but anecdotal evidence suggests that any moderate amount of tape tension (above 2 lbs, perhaps) is sufficient for good cutting.

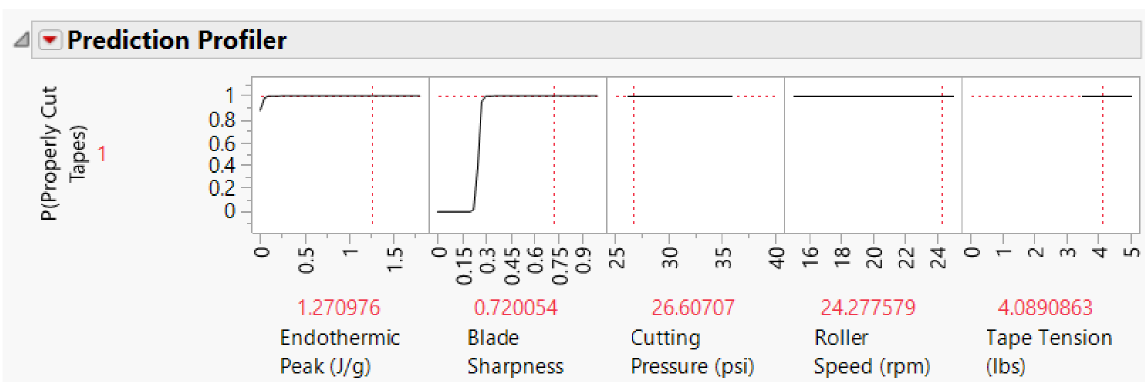


Figure 57 - Prediction Profiler with Desirability Maximized

6.3 Suggestions for Future Manufacturers

In addition to the factors and interactions that the JMP software predicted to have a high impact on the predicted percent yield from the process, there are some important takeaways that did not totally reveal themselves in the statistical data for this experiment. In an earlier experiment, which was conducted prior to the development of the blade sharpness test, the blade sharpness was taken as a two-level categorical factor with "sharp" and "dull" as the two possible selections. "Sharp" was defined as the blades that were able to easily chop the prepreg with low cutting pressure, and "dull" was defined as the blade which were not able to chop the prepreg with low cutting pressure. In this experiment, the prepreg remained constant as a material with no endothermic peak but with a higher T_g and cure state than Roll 1. Cutting pressure, roller speed, and tape tension were continuous factors. In this experiment, the JMP results indicated that blade sharpness was the most important factor by far.

In general, the blade sharpness and prepreg cure state should be taken as the most important metrics for predicting the percent yield of the chopping process. For a sufficiently high-cure state prepreg with blades of sufficiently high sharpness, the cutting pressure, roller speed, and tape tension have large acceptable operating ranges.

6.4 Chapter Summary

In this chapter, the results from experiment setup documented in Chapter 5 were presented and discussed. The factors and factor interactions whose p-values were lowest and which therefore had the greatest impact on the percent yield of the chopping process were presented. Then, these factors and factor interactions were investigated using the prediction profilers generated by JMP. Finally, some statistics-based and anecdotal-based recommendations were provided for manufacturers of carbon fiber prepreg SMC.

CHAPTER 7. CONCLUSION

7.1 Conclusions

In this dissertation, the work of Sultana [2] was expanded upon. The process for repurposing carbon fiber prepreg tapes into chopped-fiber sheet-molding compound using a modified version of the traditional SMC process was further developed and investigated. The primary issue with using the modified SMC manufacturing process was the adherence of the tacky, resin-impregnated prepreg tapes to the cutting roller, which jammed the entire cutting operation. This issue was investigated, and the factors (both material-related and equipment-related) were characterized.

The method for evaluating the cure state of the prepreg using DSC was presented, and the important characteristics of the DSC curve were shown. Data were recorded that tracked the cure state characteristics for prepreg tape as a function of oven-aging at 70°C and room-temperature aging. These data were used to characterize and select rolls of prepreg tape for the experiment discussed in Chapter 5 and Chapter 6.

Next, the equipment-related factors impacting the process were studied. The impact of the anvil sleeve hardness and thickness on the force and displacement required to slice through prepregs of different levels of aging was determined through an off-line Instron-based test developed by the research team. From this test, it was determined that increasing the hardness of the anvil sleeve would result in lower forces and displacement required to cut the material. Unfortunately, implementation of a harder anvil sleeve on the actual SMC line resulted in an unacceptable level of blade wear. It was also determined that using prepreg with lower levels of cure resulted in lower forces and displacements required to cut the prepreg. Unfortunately, implementation on the SMC equipment showed that this material adhered more easily to the cutting roller than material with a more advanced level of cure.

As it was hypothesized that higher blade sharpness would result in better cutting results, effort was expended to define and test blade sharpness. An Instron-based test method was created to evaluate the force required to cut a standard test medium at a standard tension. These force values were used to develop an equation for blade sharpness, and blade sharpness was recorded as a function of the number of cuts attempted. Predictably, the blade sharpness tended to decrease as a function of the number of cuts attempted.

The other equipment-related factors impacting the cutting portion of the modified SMC process were introduced. The methods for adjusting these were shown.

Next, an experiment was designed using JMP's DOE Custom Design tool. The process output was defined as percent yield, and this was the metric whose impact the input factors was determined through the experiment. The factors and their interactions were inputted to the JMP software, and an experiment was designed. This experiment required 32 runs to collect the data. The method by which the runs were conducted was presented.

Finally, the results from this experiment were presented and discussed. For feedstock prepreg with a sufficient high endothermic peak (and, therefore, level of cure), the yield was found to easily approach 100% with wide acceptable ranges for blade sharpness, cutting pressure, roller speed, and tape tension. When using the prepreg with a low endothermic peak (and, therefore, a low level of cure), the percent yield was much more sensitive to the other input factors. For example, for a tape tension near 0 lbs, the yield dropped to nearly 0%. An optimal setup for each of the factors was determined using JMP's "Maximize Desirability" function. It was noted that previous experiments indicated that blade sharpness had a high impact on the percent yield if the prepreg remained constant with a level of cure between that of Roll 1 and that of Roll 3.

7.2 Future Work

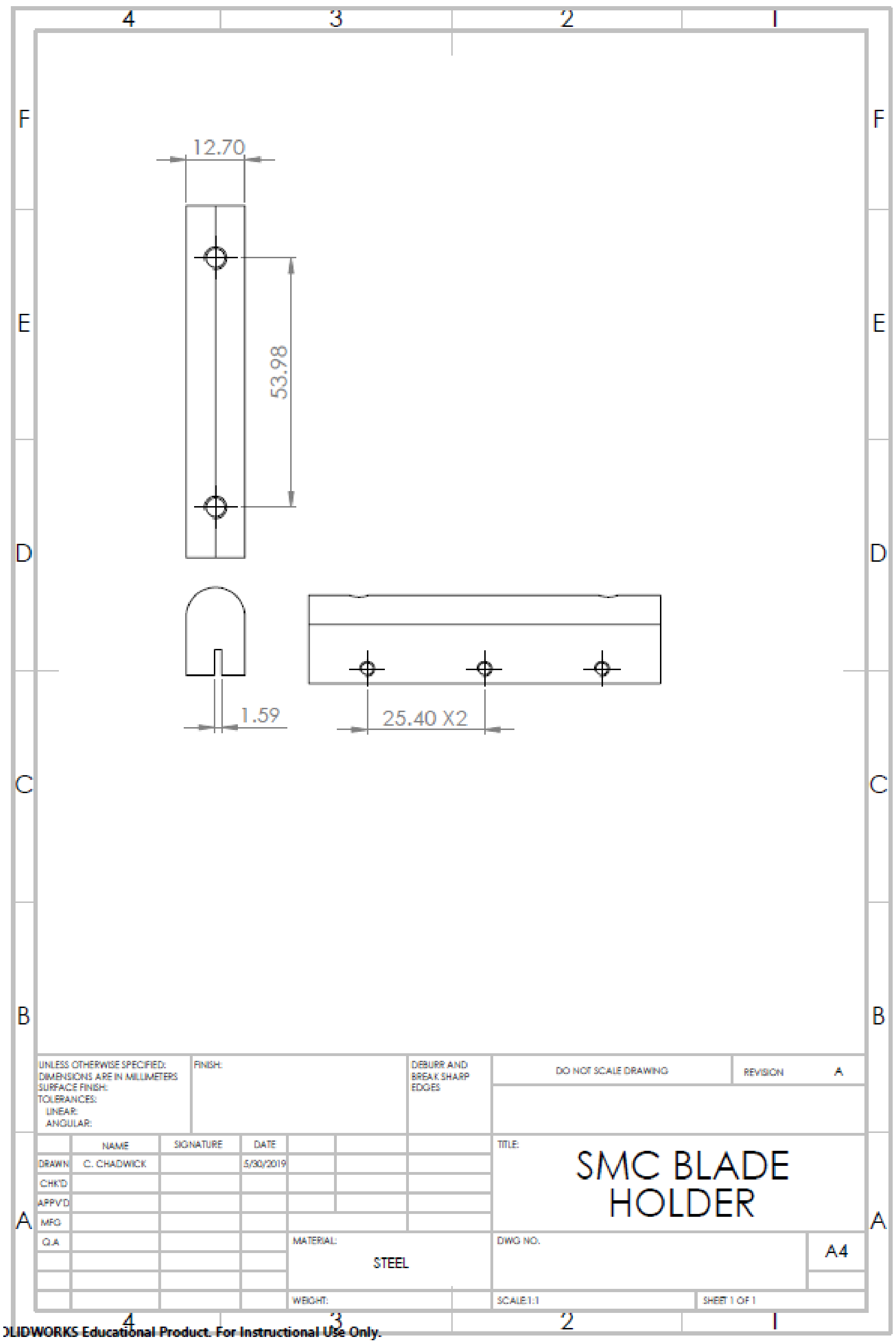
To make this process production-ready, there are a number of further tests and studies to be completed. Regarding blade sharpness, more data should be collected until there are data points mapping blade sharpness all the way from 1 to 0 as a function of number of cuts attempted. In addition, a sharpness test that produces more consistent results and is less time-consuming to produce would be ideal. Removing the blades to test them in the Instron-based tester caused the blades to break, rendering them unfit for more wear. Ideally, the sharpness tester would not require the blades to be removed from the cutting roller.

In addition, more work can be completed to identify the critical level of cure after which the prepreg can be easily chopped. This would provide the lower bound on the acceptable process window for the prepreg cure state.

Finally, to create a process which can produced material at an acceptable rate, SMC equipment should be developed that can handle chopping multiple tapes of prepreg at one time. In the Finn & Fram setup used in this dissertation, the motor was not suited for pulling several tapes at once. Many lessons learned from the testing and experimentation documented in this dissertation, however, can be used when chopping multiple tapes at once.

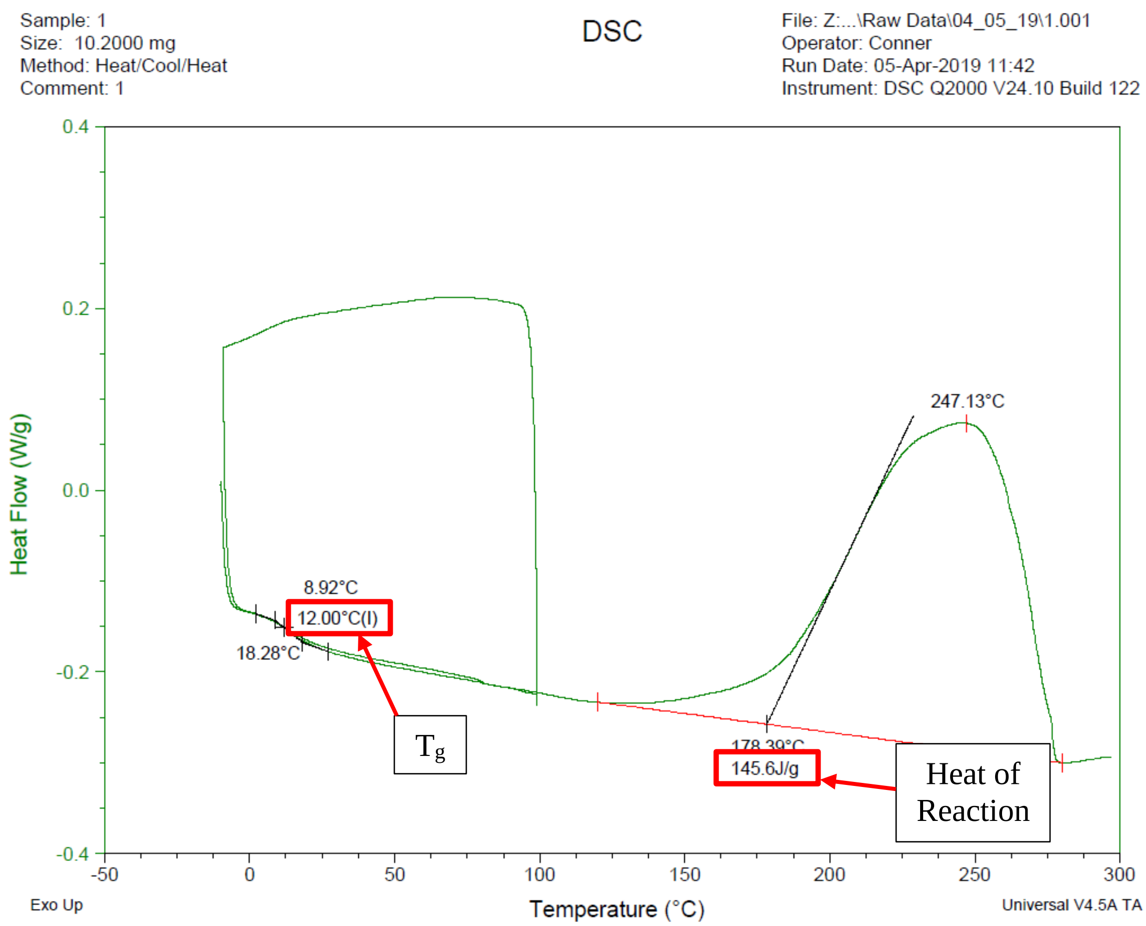
APPENDIX A. PART DRAWINGS

A.1 SMC Blade Holder Drawing

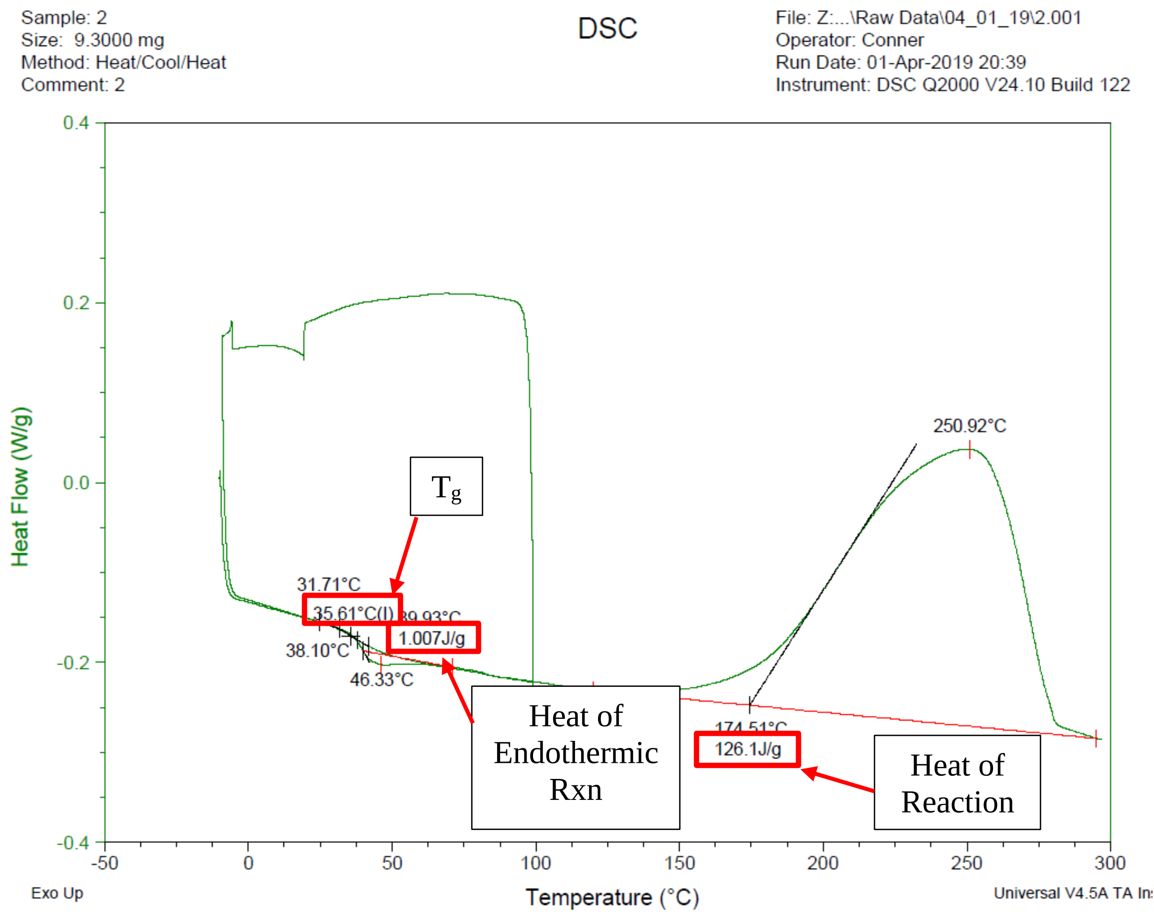


APPENDIX B. DSC CURVES

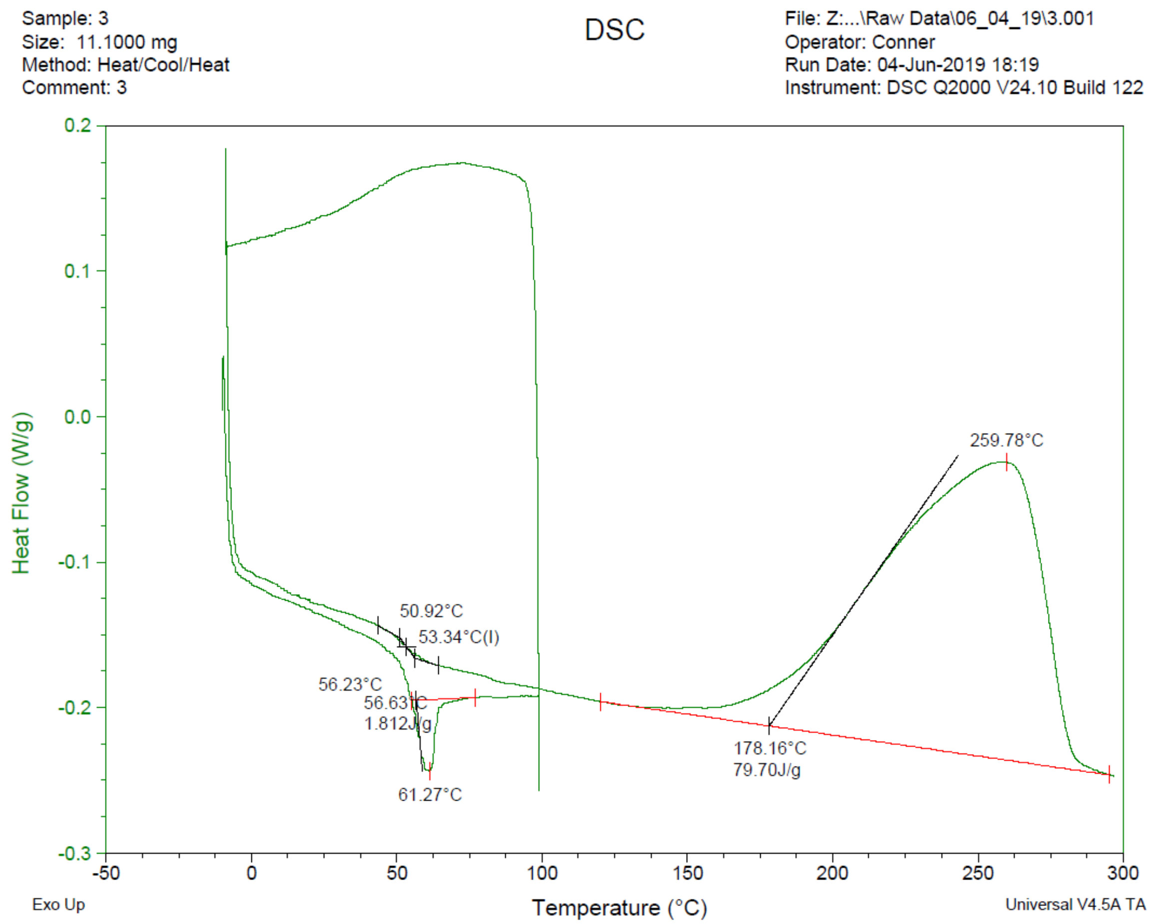
B.1 Roll 1 DSC Curve



B.2 Roll 2 DSC Curve

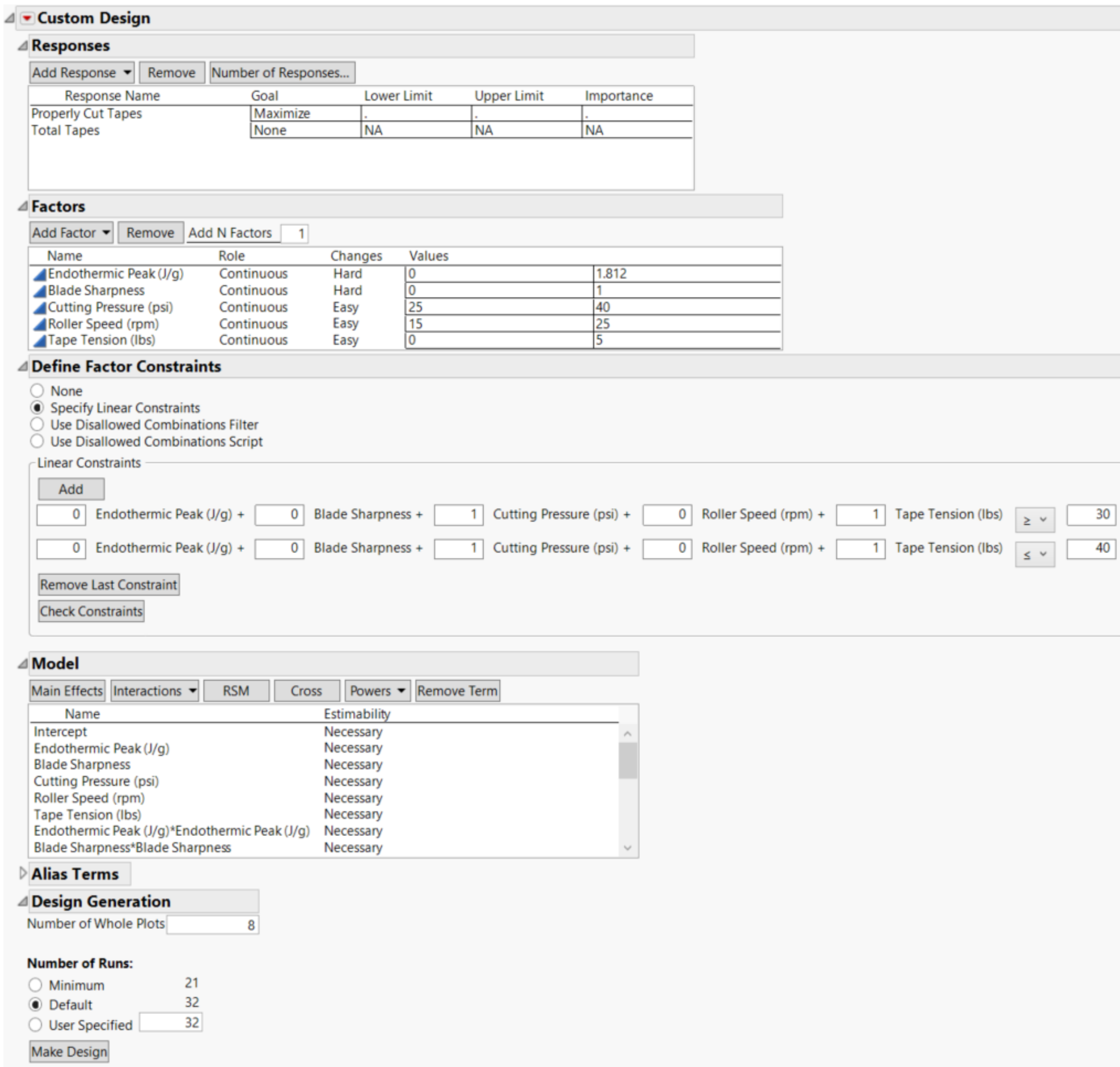


B.3 Roll 3 DSC Curve

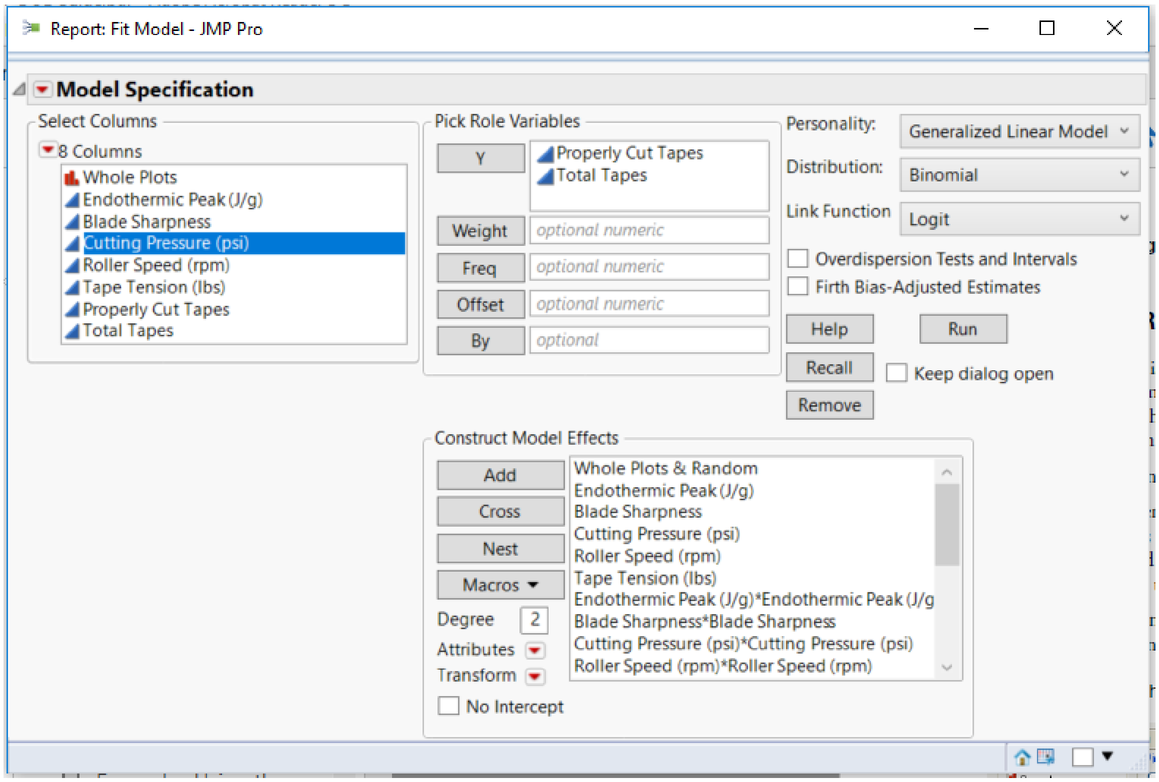


APPENDIX C. JMP SCREENSHOTS

C.1 JMP DOE Setup Screen



C.2 JMP DOE Model Setup Screen



APPENDIX D. EXPERIMENTAL RESULTS

Run	Endothermic Peak (J/g)	Blade Sharpness	Cutting Pressure (psi)	Roller Speed (rpm)	Tape Tension (lbs)	Percent Yield
1	0.906	0.61	35	15	5	1.00
2	0.906	0.61	30	15	0	1.00
3	0.906	0.61	32.5	25	2.5	1.00
4	0.906	0.61	25	20	5	1.00
5	1.812	0.90	40	15	0	1.00
6	1.812	0.90	28.3587956	20	1.6412044	1.00
7	1.812	0.90	25	15	5	1.00
8	1.812	0.90	35	25	5	1.00
9	0	0.69	40	15	0	0.85
10	0	0.69	35	25	5	0.83
11	0	0.69	25	15	5	0.82
12	0	0.69	30	25	0	0.00
13	1.812	0.82	40	15	0	1.00
14	1.812	0.82	30	25	0	1.00
15	1.812	0.82	30	20	5	1.00
16	1.812	0.82	37	25	3	1.00
17	0.906	0.70	35	25	0	1.00
18	0.906	0.70	25	15	5	1.00
19	0.906	0.70	30	15	0	1.00
20	0.906	0.70	37.5	20	2.5	1.00
21	0	0.69	25	25	5	0.49
22	0	0.69	40	25	0	0.00
23	0	0.69	35	15	5	0.63
24	0	0.69	30	15	0	0.26
25	0	0.62	28.9050664	25	1.09493365	0.13
26	0	0.62	35	25	5	0.44
27	0	0.62	40	20	0	0.00
28	0	0.62	30	15	5	0.45
29	1.812	0.67	35	15	5	0.99
30	1.812	0.67	25	25	5	1.00
31	1.812	0.67	40	25	0	1.00
32	1.812	0.67	28	15	2	1.00

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