Tackiness characterization of thermoset prepreg materials

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Abstract

Tackiness characterization of thermoset prepreg materials

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Defects formation during Automated Fiber Placement (AFP) process is inevitable. So far, various studies have been conducted which look for ways to improve produced sample properties and to limit defects formation. However, there is a lack of comprehensive investigation in this field to provide helpful insight to manufacture a part with the lowest possible defects. The aim of this study is to find a deep understanding of the mechanism during lay-up and how changing individual parameter will affect properties of the layup. In addition, optimum condition for lay-up towpreg, resulting in the lowest possible defects, will be studied. Several parameters are comprehensively investigated in this work namely compaction force, feed-rate, heat-gun temperature, dwell-time and roller materials. Peel-rate is the other parameter that affects the outcome and will be studied. Two in-house set-ups are designed and manufactured. The first one is able to lay-up the towpreg on the substrate surface with different processing conditions (AFP simulator) and the second one is used to measure the peel force which is an indication of the tackiness of the laid-up towpreg. The Taguchi method is used for the design of experiment (DOE), and its prediction is correlated by real tests samples. Results show that for each roller material. The optimum condition is changed. Feed-rate, compaction force and heat gun temperature must be optimized to achieve the tackiest laid-up towpreg.

Key words: AFP, towpreg, tackiness, peel test, Taguchi method.

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INTRODUCTION

1.1. Fundamental of Composite

A composite can be defined as a material consisting of two or more parts. Polymer composites normally contain resin and reinforcements. Composites materials have synergic properties which means they have some properties of one part and some properties of the others, so they have some properties of reinforcements and some properties of resin which makes them very high rank in properties and very complicated to study. They have lightweight, high strength/stiffness to weight ratio, good corrosion resistance, and long fatigue life. Moreover, due to their anisotropy properties – different properties in different directions – they are increasingly used when loads in each direction are not the same, particularly in aerospace applications. In similar dimension, composites are mostly stronger and have lighter weight than metals. In the early 1980s, Boeing Company utilized composites in 747 series and now we can call those years booming development of composites in aerospace that made composites widespread. Nowadays, aircrafts such as Airbus A350X and the Boeing 787 consist of advanced composite components by more than 50% in weight. Additional fields where there is an increasing interest for advanced composites are renewable energy and automotive industry due to corrosion-resistant and lightweight properties of composites. In hybrid and luxurious cars, composites are largely used. Advanced composites are costly in material and manufacturing processes in comparison to their counterparts like metals and this puts a limit for using them in all industries [1-6].

1.2. Fibers and resins

Fibers are in the form of chopped, woven, or unidirectional infused with resin (matrix) to form composites. The primary purpose of using fibers in a composite is to provide strength and stiffness. Fiber has anisotropic properties, although they provide strength in their longitudinal direction, they show weakness in the normal direction. Mostly there are three different types of fibers: glass fiber, organic fiber, and carbon fiber. Generally, glass fiber is the best when lightweight, normal quality and low price are important like boat hulls. Another application of glass fiber is for sound isolation. Kevlar fiber is used when impact absorption is the main required factor like in bulletproof jacket. For critical applications, when high-quality material is required, carbon fiber represents the best quality. Carbon fibers have the best properties, low density, slightly negative coefficient of thermal expansion, and electrical conductivity. The most critical factor which limits their wide usage is price; carbon fiber is the most expensive one. Individual fibers are grouped to make tow form and the larger the tow size the faster the manufacturing process will be. However, larger tow makes the wetting process more difficult. The optimum tow size depends on the application. In some applications, tows are weaved together to make a braid. Mainly braids are used when isotropy properties required [7-12].

To use fibers efficiently, matrix is used to keep them in the same direction, transfer the load between them, and protect fibers from moisture heat and corrosion. In addition to these, resin provides transverse shear strength for whole composite materials. The matrix can be metallic, ceramic, and polymeric materials. Polymeric matrices can be either thermoplastic or thermoset [8,13].

1.3. Thermoplastic

Generally, thermoplastic matrix has a large molecule that leads to relatively high molecular weight. Due to the high molecular weight of thermoplastic, their viscosity is relatively high and at room temperature they are solid. Thermoplastics matrices reactions are completed before the manufacturing process. Thermoplastic manufacturing is known as a one-step process completion and there is no need for post-processing [14]. During processing, they do not perform any chemical reaction; they only need to be melted and poured all over the fibers, after the wetting process is completed the last step is cooling down the material to have a composite. As a consequence, thermoplastics can be reproducible by reheating. They just need to be heated up and melted, then cooled down again to make another part. Moreover, this property is useful even to repair probable flaws in the final parts. However, for thermoplastic resins, there is a limit for reproducing or repairing process. After numbers of reproducing circles, the resin gradually degrades (because the melting temperature is close to composites degrading temperatures) and is not usable anymore [15-17].

1.4. Thermoset

Thermoset matrix has smaller molecules than thermoplastics which results in low molecular weight and low viscosity, consequently, they are liquid at room temperature. To have a solid structure, the resin must be cured. Curing is an irreversible chemical reaction. Bonding two molecules together is an exothermic process and releases energy as heat (by the reaction process heat is generated). During the curing process, thermoset matrices make 3-D cross-linked structures. Therefore, the curing is an exothermic reaction. To start this reaction, it is required to provide a certain amount of activation energy. Activation energy can be provided mechanically or chemically or simply by heating the matrix. Normally small amount (less than 1%) of the activator is added to the resin to start the curing process. After a specific span, which is mentioned on the resin datasheets, curing takes place completely and as a result, the solid structure will be made. As a consequence, there is a limited time to use the mixed resin [8,18,19].

1.5. Manufacturing

Requirements of manufacturing high-quality composites are: uniformly distributed fibers in the proper orientation, limited amounts of voids and a good amount of fiber volume fraction (V_f), entire bonding between resin and fibers, and proper solidification and curing process which leads to final parts with a defined dimension. (V_f is the volume of fiber divided by the volume of composite). To put it simple, manufacturing process is to wet completely fibers with resin and to make the space between fibers as little as possible, in other words, make V_f as high as possible. To address this challenge, resin must be available in the fiber surface and also be compatible with fibers.

There is a fundamental equation called Darcy's law which explains the resin movement inside porous media such as bundle of fibers:

$$\mathrm{Q} = \frac{S.\partial P}{\mu.\partial X}.$$

Q = flow velocity

S = permeability

∂p = pressure difference

∂x= distance be covered by the flow

μ= fluid viscosity

As the equation states the flow rate is inversely related to the distance ∂x and resin viscosity μ. The applied pressure to resin and permeability have a direct effect on the flow rate. (Permeability K depends on fiber orientation and braid types). The higher the flow rate, the more available the resin is. Although it seems very simple to address this equation, the manufacturing of parts and structures using composite materials has many difficulties, complexities, and challenges. Just to mention that fiber diameter is about 10 microns (size of human hair is about 100 microns), to make a small size sample it is required to wet about 10^{12}fibers. Moreover, thermodynamically speaking, solid fibers must have higher surface energy than liquid resin so that resin can wet the fibers (compatibility properties) [6-8].

1.6. Prepreg

As explained above, manufacturing a composite part is an art, one must wet the entire fibers with the minimum amount of resin to have high-quality products, which is immensely complicated, especially in thermosets because there is a time limit as well. After finishing the process, if there is an extra resin in a location, it makes a resin rich area which is prone to growing microcracks. In addition, if there is a dry fiber area (the fiber that is not completely wet by resin), the location can also be prone to failure. Considering all these difficulties, in some special applications, it is required to have a resin system hard enough to be handled and soft enough to be formidable as well. It means the wetting took place completely, but curing or solidification partially did which allows making favorable final structure afterwards. To have such a resin system, one must stop the reaction or solidification at the middle stage (when it is partially done). The best way is to reduce the temperature until there is not enough energy for the reaction. This middle stage product is called prepreg (pre-impregnated). This material will restart the reaction again if the required amount of heat is provided [7,10,11].

1.7. Glass transition temperature

In manufacturing the most important characteristic considered to select a resin system is glass transition temperature T_g. This T_g is the temperature at which the crosslinked polymer chain is not twisted completely together, and in thermoplastic the temperature at which materials become semi-solid semi-liquid. If the service life of the composite – the time that composite is under applied load and service – is very short, the resin can be used near its T_g. Otherwise, the glass transition temperature should be at least 50-degree centigrade higher than service temperature (the temperature that composites reach on the services). Generally, the glass transition temperature for thermosets is higher than thermoplastics [20,21].

1.8. Toughening

Thermosets matrices possess several advantages over thermoplastics, however, their rigidity and highly glassy properties, as a result of a cross-linked reaction during curing, are major limitations. It could be considered an advantage in the high-temperature application to keep fiber stable during services load, but this property leads them to be susceptible to the impact in general and low-velocity impact in particular. Both types of impacts will result in delamination. There is more concern about low-velocity impact because the low-velocity impact will cause internal damages that cannot be detected by visual inspection, while high-velocity impacts result in visually detected damages [22-24]. There are two solutions to these limitations: First, using damaged tolerated thermoplastics – which is not the materials used in this study – and toughened thermoset composites.

There are several approaches to toughen thermoset composites namely: alternating the network, second-phase toughening via rubber elastomer, thermoplastic elastomer toughening, and interlayer toughening. In toughened thermosets, the low-velocity impact resistance is increased, and the resin capability of load-carrying is improved. These improvements are at the cost of a loss of resin modules, strength and heat resistance as well. The impact resistance growing mechanism is the consequence of increasing the impact area. Since the impact area is larger, when the sample is subjected to failure load, the toughened system will not fail, thanks to its larger impact area [7,25-27]. In this study, Cycom 977-2 resin is used, which is “toughened epoxy using thermoplastic toughening mechanisms”.

1.9. Automated material placement

There is a daily increase in utilizing high-quality composites for various applications. Therefore, several aspects of the composite manufacturing process need to be improved to meet such huge requirements in the large structure industries. Total cost is one of the most important restrictions for the widespread use of composites. It can be reduced by reducing waste material. The labor cost is the other financial parameter that affects the final product price. Another aspect that needs to be improved is lay-up quality. Technician skill and experience to a certain context affect the lay-up properties and therefore affect final part quality. For example, airplane parts used to be made commonly by hand lay-up. To make a part prepreg sheet must be cut that causes a large amount of waste of materials. Moreover, since hand lay-up is done by technicians, the

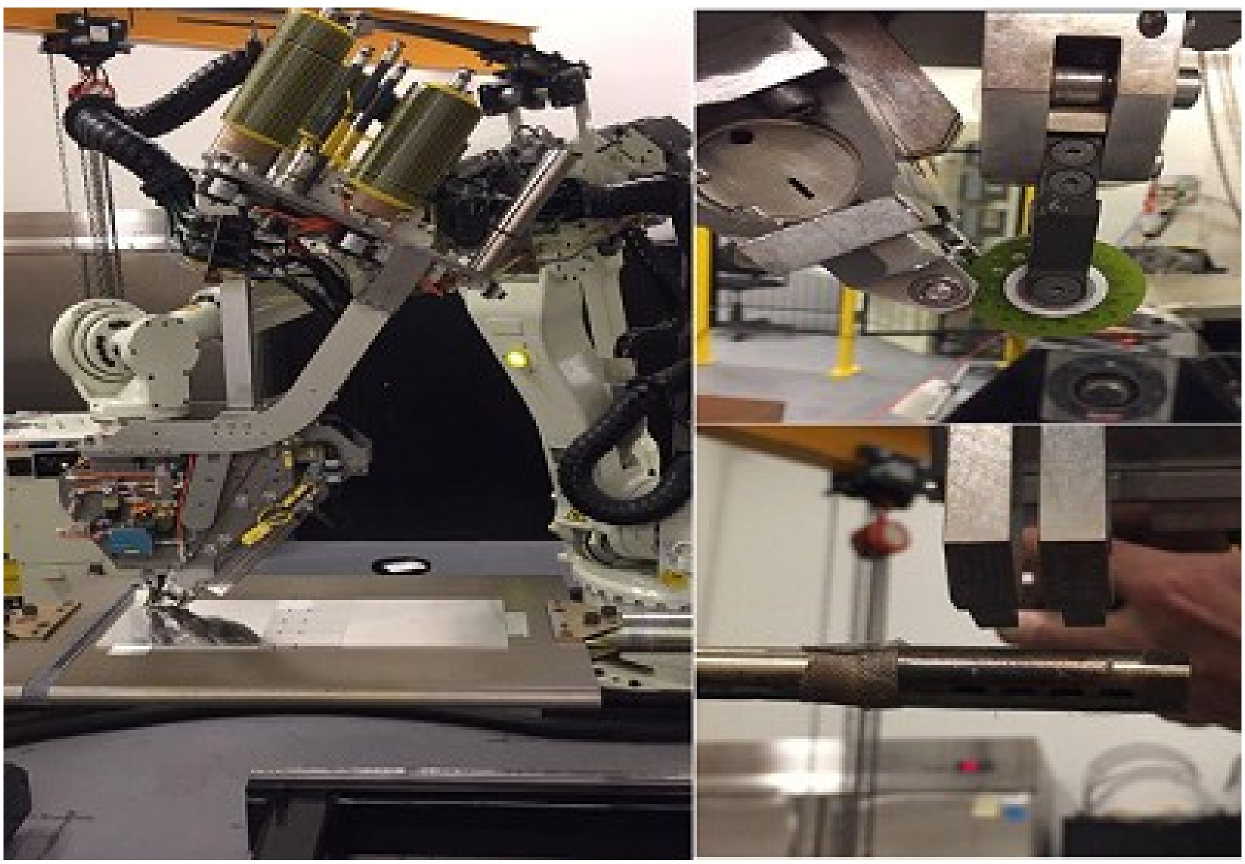


Figure 1 A. AFP Robot B. compaction roller system C. Heat gas torch

expert technicians and labor hours generally cost a large amount of money for a company. On top of that, lay-up properties are affected by their concentration and the worker skills. Sometimes human errors cause waste part of the entire final product and unfortunately, human errors can be inevitable part of the lay-up process. The automation process could be a solution that leads to having a cost-effective process of advanced composites structures manufacturing and having thoroughly consistent quality. More importantly, Automated Fiber Placement AFP and Automated Tape Lay-up ATL can increase material usage and reduce layup errors, which results in lower material wastage. For example, the reported results show an increase in material usage from 40 percent up to 90 percent by using an automated lay-up process. A similar report shows about 40 percent decrease in price. Automated lay-up also decreases process time by 30 percent. Therefore, through automation new markets and applications may open their doors for composite products such as renewable energy, automotive, and aerospace [19,28-32].

AFP (Automated Fiber Placement) and ATL (Automated Tape Lay-up) are two methods in automated lay-up of composites prepreg. ATL and AFP can be explained as an inverse machining or additive manufacturing. During machining products built up by removing materials, whilst in tape/fiber lay-up part is made by adding materials [19,28].

Automated fiber placement (AFP) is used extensively in modern composite manufacturing. It has been a few decades that industries use ATL as the most efficient tool to produce high-quality parts. This process not only reduces the costs of manufacturing in long run, but it helps to manufacture parts in less time than before as well. Initially, studies focused on ATL (Automated Tape Lay-up) process, after several studies, it was found that to improve the properties of the final part, it is required to limit the tape width which pushes the process toward AFP (Automated Fiber Placement). Although in the last three decades plenty of studies were conducted regarding AFP, several aspects of this process remain mysterious and studies in some aspects must be continued to find the best possible solution to make the process efficient in time, cost and final parts properties. The lay-up property is one of the imperative factors that have a major effect on final parts properties. Although ATL and AFP solve problems related to human error, it was new and the lack of information about the process and effective parameters constrains its extensive usage. New types of defects happen during the AFP process, some visible and others related to interlaminar defects that need particular evaluation to detect. Final part properties rely on the number of defects. The fewer defects during lay-up, the higher the quality of final part will be. Tackiness is the most important aspect of the lay-up process. Every single factor that improves tackiness results in an improvement in the final part.

Material temperature, mold surface temperature, feed rate (layup speed), moisture, compaction force, and material tension are the factors that can be controlled during lay-up. The prepreg properties can be modified for both AFP and ATL by changing the above-mentioned factors. The degree of impregnation, backing paper material, mold surface roughness, and roller types are other important factors in the AFP process [33,34].

In this work, we have tried to investigate the effect of different parameters on prepreg tackiness to optimize AFP process conditions such as temperature, compaction force, and feed-rate, besides the roller type to find the best possible condition to do the AFP process.

2. Literature review

2.1. History of AFP/ATP

Although study and discussion about ATP and AFP have drawn attention in research recently, the first automated patent refers to Chitwood and Howeth in 1971. This method described laminating composite tape on the surface of a rotatable mold using CNC (Computer Numeric Control). At that time most ATL systems were Flat Tape Laminating Machines (FTLM). It was not able to make a curvy surface. After a decade of study, Stone presented a commercial ATL system in 1984 from Cincinnati Milacron (now Mag-Cincinnati) which solved the curvy surface problem. To be able to tape laminating with up to 15̊ curvature, this system used an ultrasonic tracking system, which makes it the first system of Contour Tape Laminating Machine (CTLM) which can go along with the curvature of the surface. Nevertheless, uniform quality and reliability, lay-up feed-rate speed and precisely following elaborated mold surface, remained unsolved problems. To top it all off unspecified debulking cycles and compaction force were two issues that CLTM was inefficient to address these problems while laminating. Ply backing breakages cause relatively low reliability. Modifying the lay-up head increased productivity, but there was no improvement in lay-up speed which was slow [2,35]. By the end of the 1980s, automated system ability had improved to laminate complex geometry, using a soft roller. Although it was able to lay-up curvature, it causes uneven tape tension and various lay-up compaction forces. The new issue was ply alignments; sometimes ply moved transversely while compaction force was applying to it, because of tape tension issue and applied compaction force on the soft roller. To solve ply movements issue and have a ply with correct alignment, lay-up pressure was controlled accurately and incorporated with controlled tension applied to the tape. There is not clearly defined the time when heating was used the first time, the oldest report of using heat during process refers to 1991 using heat for thermoplastic by irradiation. Benda and Stupt added a heating system as hot-gas to ATL to have a better attachment between complex contour and tape [2,36].

2.2. AFP

The general lay-up operation process of AFP is similar to ATL. Many aspects of the AFP process were already studied and were available such as roller design, materials impregnation, heating system, system-controlled lay-up speed, compaction pressure, tool, and prepreg temperature. So the studies done for understanding ATL were directly used for AFP as well. One of the ATL problems is when relatively sharp curvatures and complex shapes are required to be made, however, the prepreg tapes used in ATL are typically 75, 150, or 300 mm wide, so blistering and wrinkling happen during the lay-up process. Narrower prepreg would solve the blistering problem or at least minimize these problems. This is the time that manufacturer started looking forward to Automated Fiber Placement. The widths of prepregs used for AFP normally are 3.2 mm, 6.4mm, and 12.7 mm. Here is a controversial issue, the wider the prepreg, the faster manufacturing process and the narrower prepreg, the more complex curvature shape that can be made. AFP makes high quality process with fewer defects, but this benefit needs more time, which means the more expensive process. To solve this controversy, the main manufacturers of AFP, change the machines and the robots so that they can deliver a few tows in a single stage. The new AFP machines can simultaneously lay-up 32 tows [2,28,37].

Normally in the AFP system, each tow is individually driven and can be cut and start lay-up again during the manufacturing process. This results in lower wastage of material. Moreover, controlling each individual tows makes it possible to lay-up over complex and curved geometries and enabling tow steering. For example, in structures such as windows cut-outs in the plane fuselage, it is beneficial and, results a decrease in material wastage and may improve productivity as well [38].

Different types of defects happen using automated systems, such as gaps and overlaps, wrinkling, out-of-plane wrinkles, blisters, circular delamination, and tow pull-ups, which may affect the mechanical properties of the final part. Recently, more studies have been done regarding this issue, for example, Belhuj et al. studied “Wrinkle formation during steering in automated fiber placement”[39] and Bakhshi et al. studied “the defects appeared during tow steering in automated fiber placement” [40,41].

2.3. Tackiness and tackiness effect of prepreg properties

Tack, which means the capability of adhesive materials to form bonds immediately, is one of the most important characteristics of the prepregs. Adhesive tack is the property that controls the immediate formation of a bond once a surface and an adhesive contact with each other.[42] A key performance requirement in many pressure-sensitive adhesive products is the ability to quickly and practically bond two surfaces together. Tackiness or tack is a key property for the effective bonding of the adhesive. In the pressure-sensitive adhesives – PSA – the capability of an adhesive to form processes of bonding and debonding to a substrate under light pressure after brief contact is defined as tack force for any kind of application or industry sector [43]. For measuring adhesion there are common affecting factors, and similarly, the process that is used for measuring the force – bonds must be made and broken to evaluate the strength of the bond [44]. By touching the material one can distinguish tacky materials, in other words, the tack of a material is the sensation that one feels while trying to detach one's finger from sticky material. However, measuring this feeling and transforming it into the force that is reported scientifically and statistically remains a problem. Furthermore, it is not feasible to compare debonding force and strength of bonds. So, to characterize the materials or to improve the quality of products, it is essential to have a more measurable method. Moreover, these two quantities (strength and debonding force) do not necessarily develop in the same way when test conditions are changed [45].

Although measurement of tackiness are often thought as simple property, it depends on different factors and the interaction between them which is very complex and, as a consequence, the tackiness is characterized by several values [44]. Tack is one of the major properties that govern the ability of prepreg to be laid up. Therefore, the tack of prepreg has to be characterized to improve the manufacturing of such complex composite materials.

Even the tack definition is a little bit different in the community of composite. Tack is the property required to appropriately bond between adjacent prepreg layers, but not too much so that a misdirected prepreg ply can be repositioned. This definition is similar to the pressure-sensitive adhesives(PSA) requirements [33,46].

Same as PSA, at first there was no precise method for measuring tackiness of prepreg. Manufacturers are used to specify its levels as simply low, medium, or high, by use of the probe or roller methods in combination with touch testing. Besides, due to the existence of reinforcing fibers, prepreg tack is more complex than a PSA. However, difficulties come across in the characterization of prepreg tack and precise measurement of tack so far remains a problem.[33]

In the Automated Fiber Placement (AFP) process, one of the various critical factors that affect final product quality is prepreg tack. Improving prepreg tack results prevention of defects formation during manufacturing like blisters, puckers, and wrinkles. Therefore understanding the effects of environment and manufacturing parameters is critical to be able to predict defects formation during the process [47].

By controlling process parameters, tack can be empirically controlled as a material property [40]. Various tack test methods are generally simple and straightforward to perform, however, obtaining a reliable report can be a problem. Although different practical rules have been developed to understand the tack's phenomenon, an accurate mechanism of tackiness is still not comprehensively understood [42].

2.4. Tackiness measurements methods

There are various methods to measure the tackiness. For example, put the sticky material on a vertical wall and measure the time that it takes to completely remove spontaneously from the plate surface. However, this method is neither scientific nor reliable. Among all tests utilized in Pressure Sensitive Adhesive (PSA), four methods use in measuring prepreg tackiness, namely: the rolling ball test, loop tack measurements, probe test, and peeling test [48]. Each method is briefly explained in the next sections.

2.4.1. Rolling bar test

In this method, a steel ball is placed in the hole of the release mechanism. Then by pressing the release lever, the ball rolls over the inclined surface freely and after rolling a distance on the surface of the sample it stops rolling. Measuring the distance of the sample traveled by the ball is the means to determine the tackiness. The shorter the distance, the higher the tackiness is. Although this test is easy to run, fast, and requires a low amount of investments, it is not useful for measuring prepreg tack. Because the tackiness measured in this way, was not only related to the thickness of the adhesive layer, stopping distance related to rolling friction in addition to tackiness, and it is not easy to relate properties to stopping distance. This method results are different from other methods results.

The equipment used in this method is not expensive, it is an easy to run test, and normally gives good repeatability, however, it is not a good test to make a comparison between various

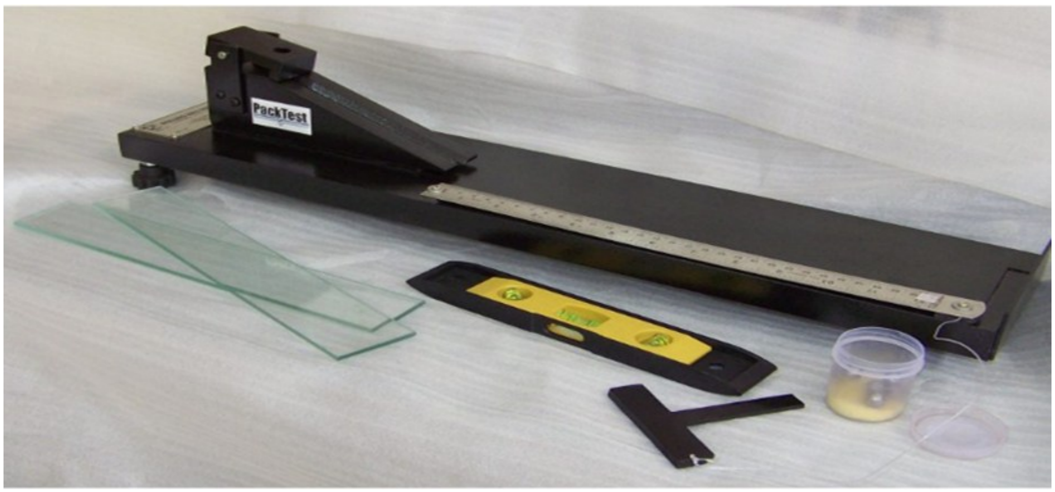


Figure 2 Rolling ball tackiness measurement method

adhesives, during tests ball is covered with a layer of adhesive, and the reported result is not just for surface tackiness [42,49-50].

2.4.2. Loop tack test

One may use the loop test to measure tackiness. The substrate material can be a steel plate. The upper grip goes down until the coated side of the adhesive contacts the substrate. Then, the loop is pressed onto the surface, compressing the adhesive. After that, the loop is pulled up and eventually debonds from the substrate. Measuring the pulling force is the means to determine the tackiness of the sample. This test is done using tensile Machine so there is no need for special equipment. However, contact area and dwell-time (time between making bond and testing) cannot be measured exactly and this will affect the result and cause different results by repeating the same experiments.

Figure 3 Loop tack test

Loop tack test can measure and report the tackiness force precisely, using a normal tensile machine for the tests makes it standard and the results for various materials are simply comparable. Besides, the separation rate can change and report accurately. However, contact pressure and time are not easy to define, and the contact area is not the same for different tests. Loop tack test improves the quality of measurements than rolling ball test, but still, there are some undefined parameters to use this test for measurements of tackiness [42,44,51].

2.4.3. Probe test

Rolling ball test and Loop tack method have unprecedented errors and uncertainty that lead scientists toward the new method which is called probe test. This test is done using a tensile machine with a special fixture. In this method, the part of the adhesive sample that cut before is stuck to the weight ring. The weight ring is hanged on the sample stage. Then speed and dwell-time (the time that the intimate contact between the substrate and the prepreg surface is recognized) are adjusted in the tensile machine, and the test is run. Force transition is recorded by software and report as tackiness. Stainless steel with radio 5mm is used as a standard prob [45,52].

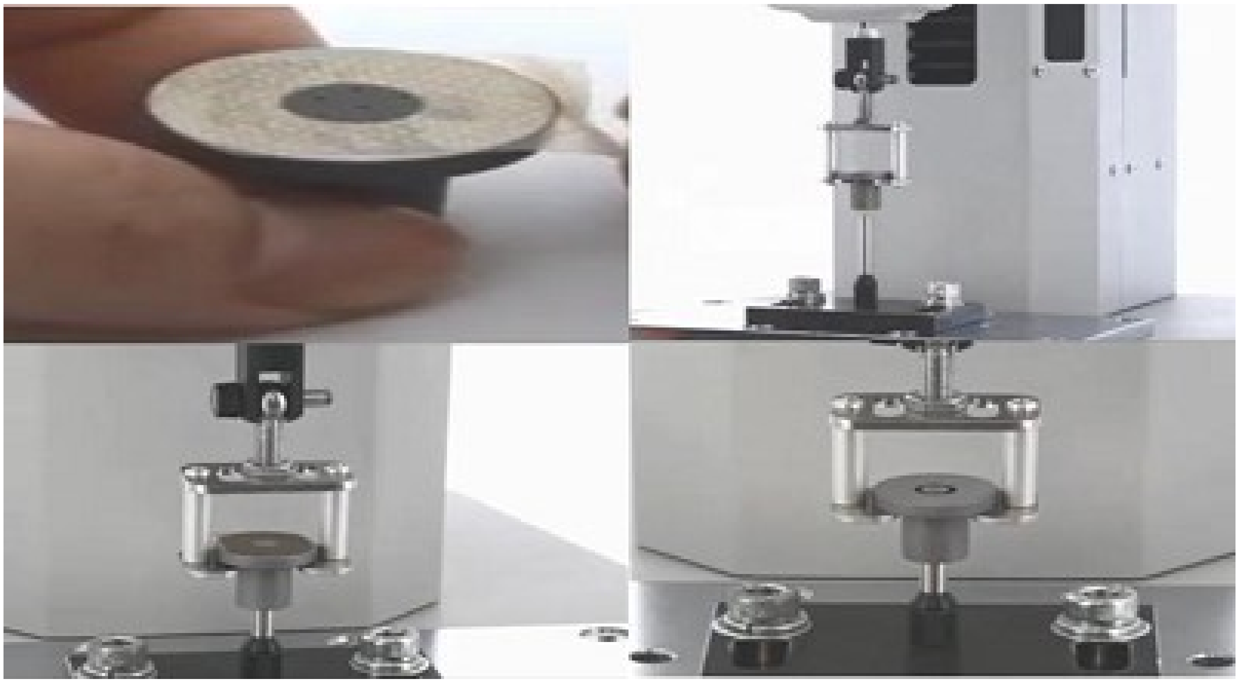


Figure 4 probe test method

In this method, contact pressure, dwell time, and separation speed simply can be measured. The surface of prepreg with the probe always remains the same. Still, this method measures the small part of the sample, and a few tests must be done to find reliable results. Besides, the equipment is expensive and is not versatile. In probe tests, the speeds of the compression and retraction are reported as a factor that has negligible effects on results (normally, these two speeds are the same speed). It is worth to mention that, probe test method for finding the tackiness seems very straightforward; however, it is not easy to match some actual process parameters with the observations made during this test [4,33,42,45].

2.4.4. Peel test

This method is a combination of two separate processes. In the first process, a sample is laid-down on the surface of a plate or substrate materials. Then the next process is to detach the adhesive material by peeling force. In this test, a sample can be made either using AFP or hand lay-up. The peel test can be done at 180 degrees or 90 degrees peeling angle. Peeling angle must be maintained during peeling test. After laying-up, the samples, the open end of the sample is connected to the tensile machine keeping 180 or 90 degrees. The peel angel has an effect of measuring tackiness and should be defined carefully. One difficulty is about how to adjust the peeling angel. The separation rate (peeling rate), the constant force required for peeling, can be adjusted between 12($^{mm}/_{sec}$) to 250($^{mm}/_{sec}$). By starting the tensile machine, the force is recorded by the software, and tackiness is reported as a force per width. The dwell time highly depends on how long it takes to lay up the adhesive layer. This test is done over at least 76 (mm) part of the sample (first 25 (mm) part of the sample must be disregarded), so it does not have the issue of a small part of the sample, which is tested like a probe testing. Moreover, the peeling force and speed are adjustable using tensile machine software, dwell time, and compaction force are easily measurable [42,53].

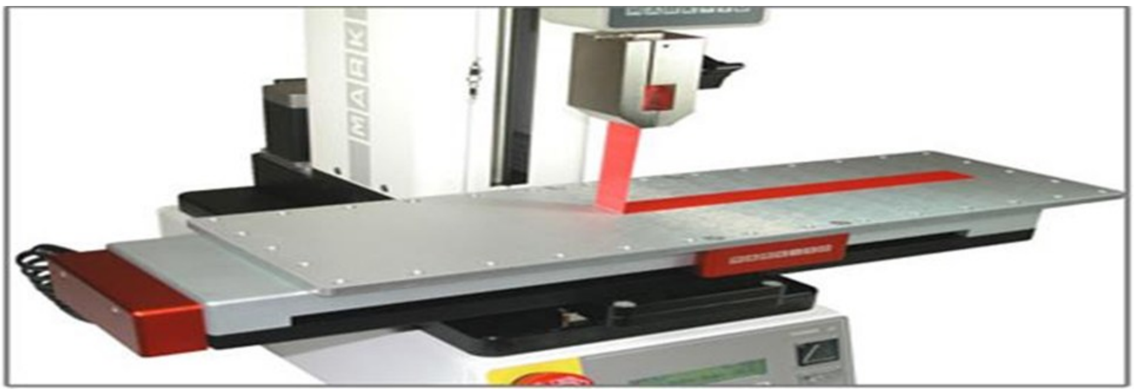


Figure 5 Peeling test method

Peel tests widely used in the pressure-sensitive adhesive industry for different types of adhesive tapes or shoe industries. It also can be used for the understanding of the tacky behavior of prepregs. There are several reasons why Peel tests are considered a more accurate method than probe methods. Peel test is done on a reasonable amount of prepreg length and the reported results are more reliable compared with the other methods. Peel-rate can be adjusted by prescribing the speed of the tensile machine. Peel tests are done normally in constant displacement condition, and application time is long, which can be named as a limit of the process for reproductivity of automated fiber placement and tape lay-up. Normally this method does not express or contain the stage of laying-up the adhesive to the substrate [54]. Unavoidably, reported force by tensile machine for this method includes tension of the tape and bending of the tape as well. Since the amount of peel force for a prepreg is very low (less than 5N), there is no concern for issues mentioned above and reported force is completely due to the peeling of prepreg from substrates.

There are at least three types of numbers reported in previous studies; first pick in force, average force, and maximum force. In this study, average forces are reported. To conclude, in this study using unidirectional prepreg materials, 90-degree peel tests, and cohesive failure zone are considered. The key factors are: compaction force, feed-rate, temperature, tool surface materials, duration of lay-up, and peel rate.

The peeling method is found as a comprehensive method because it measures the whole samples, and the results are recorded precise; however, there are some issues about the peel rate that must be considered; otherwise, the result would be neither accurately reported nor valuable. Although Peel rate does not have any effect on prepreg tackiness (laying up prepregs already is completed) to interpret the data correctly, it is required for the peel rate to be defined accurately since it will affect the reported force data and might lead to an invalid conclusion. In other words, two samples made in the same conditions (temperature, compaction force, etc.) might have completely different results, testing with low-speed and high-speed peel rates. Also, the angel of peeling is another factor that should be reported; different peeling angel results in different peeling force.

Generally, to do 90 degrees peeling, a tensile test machine with a special fixture is used to make sure that the peeling angle is kept at 90 degrees. All tests are done in a constant displacement mode on tensile machine which is defined by peel rate speed.

Peel test using AFP is somehow impossible to do continuous lay-up and peel off, but by measuring time effect on tackiness, one can predict properties in general and tackiness immediately after AFP. In addition, the adhesion strength measured for the unidirectional prepreg at 45 degrees gave more than 0 and 90 degrees, which can be explained by an increase in the area between the substrate at 45 degrees and the prepreg layer at 0 degree above [46,54-57].

Different method of tackiness measurement

Table 1 Tackiness measurement methods

Method	Rolling ball	Loop tack test	Probe	Peel test
Apparatus	Ball, the inclined surface	Tensile machine	Tensile machine, fixture	Tensile machine, carriage
Price	The cheapest	Average	Expensive	Average
reliability	Good reliability	the contact area is not the same	Measure a small part of the sample	Reliable, repeatability
Advantage	Repeatability, easy to run, fast	Report force as a number, precisely	Separation speed, contact time and pressure can be measured	Parameters are the same as AFP, Larger samples
Disadvantage	Not good to make a comparison	Contact time and pressure cannot be measured	Force and Temperature applied in a way different than AFP	Results include tension of the tape, two separate steps

2.5. Lay-up process

The most crucial factors that must be considered in the lay-up process are the temperature of prepreg and substrate, compaction force applied by a roller, the contact time that is inversely proportional to feed rate, surface roughness, and substrate material. In the peeling procedure, peel rate, and peeling angle are important factors.

AFP process is relatively new, and several aspects of this method remain mysterious and unknown so far. Also changing the whole production line from hand lay-up process to a new unknown AFP robot requires a lot of labor education and changing the entire standard process. To top it up, sometimes the expensive AFP final product quality is worse than hand lay-up products. There is a lack of information about what is happening before and during the lay-up process. A robot works more reliable than a human; however, to run a robot efficiently, it is required to have profound knowledge and enough information about the entire process. Measuring the amount of the final product defects and analyzing different types of defects – like gap and overlap, wrinkle, blister, buckling, splitting of tow, and local delamination – are the best way to qualify the AFP robot made product quality, and reliability of the process. So it all leads the composite scientist to try to improve the quality of the final product by examining different factors [19,38,41].

Bakhshi et al. studied the effect of compaction roller type on final product quality. In their study, they use 5 different roller types. The rollers that they used are various in material and structure as well. AFP real robot is used and also to have a good understanding of compaction force distribution and roller deformation simulation of stationary roller deformation is done. They found that different load distribution causes some point with a weak tackiness that leads to defects formation. Also, they found that changing the roller changes the dwell time and local pressure as well. They found that hard roller, in compliant with a complex surface, provides better quality rather than a perforated roller. Since perforated roller products force fluctuation up to 50 percent. Which is challenging to use the perforated roller in the industry [58].

Sreehari et al. studied time and temperature effect on out-of-plane wrinkle formation, and they used DIC to quantify the effect of temperature, the radius of curvature, and investigate the wrinkle formation. They examined different local pressure and heating to produce a sample with minimum defects. Their study focuses on finding a critical towpath. They found that the passage of time after lay-up affects wrinkle amplitude, and heating the laid-up tow results accumulating wrinkle together and stiffness loss [55].

Belhaj et al. studied the effect of steering radius on wrinkle formation using the Rayleigh-Ritz approach to predict wrinkle formation. They reported that the wrinkle formation is noticeably affected by the lay-up speed and AFP process temperature [39].

C. Schmidt et al. studied the effect of temperature distribution on final product properties. They used process thermal monitoring to reduce defects. They found that lay-up speed, tool temperature, and compaction force affect reliability in the AFP process [59].

Ebrahim et al. did a review on the AFP defects. They found that feed-rate, lay-up speed, temperature, and force have a strong influence on final product quality. They reported that changing the fiber orientation angle causes gaps and overlap consistency.

All the above-mentioned studies focus on varying a single or a couple of parameters to improve final product quality, while they all mentioned that the viscoelastic behavior of prepreg plays an essential role in defect formation. To be able to comprehensively study all factors' effects on the viscoelastic behavior of prepreg, scientists came up with the investigation of prepreg tackiness effect on defect formation. In other words, investigation of the effect of roller type, compaction force, lay-up speed, and temperature on the final product, respectively, is not accurate to report; they all are dependent together and must be studied at the same experimental process. For example, varying lay-up speed changes the time that heat is applied on prepreg surface, consequently changes prepreg temperature as well. Tackiness is responsible for final product quality, and every single factor that changes tackiness will affect the lay-up property and the final product quality as well. The following studies concentrate on the investigation of prepreg tackiness.

D. Budelmann et al. investigated the effect of various parameters on prepreg tack. They did all tests in the room temperature, and laid-up material using hand lay-up. In the study rheometer is used for probe testing as an apparatus; they transform all factors in the AFP process to rheometer parameters. However, they could not imitate all the factors in the AFP due to restrictions of the apparatus. To analyze the data response surface methodology is used to be able to study two different parameter effect on tackiness simultaneously. They found that increasing compaction force steadily increase tackiness, and tackiness is very sensitive to temperature. It is mentioned that the study needs to be proved by the AFP made samples [57,60].

Studies show that the prepreg tackiness is mostly depended on the viscoelastic behavior of prepregs. So, every variable that can affect the viscoelastic behavior influences tackiness as well [48,56,60-62]. Viscoelastic behavior relates to resin completely, and one can study this behavior on the resin [45,57].

O. Dubois et al. studied property of resin and prepreg and made a comparison between them. They use the prob testing method and draw the force-displacement curve. The results show that the graphs' (for the resin and the prepreg) are mostly the same, but the slop was a bite different between resin and prepreg. They found that increasing probe temperature decreases resin viscosity, which results in more resin movement, resin loses its properties, and consequently, the debonding force decreases. They also conclude that increasing the debonding rate will result in the higher required debonding force, and, in the lower debonding rate, the fibrillation phenomena were explained by them. It was reported that in order to find out the influence of relative humidity, x-number of tests is not sufficient [45].

C. Wohl et al. used DOE (design of experiment) to study the effect of different parameters, respectively and without the superposition effects. They used the probe test method to record tackiness and used pressure-sensitive film to report the compaction force precisely. They reported that an increase in relative humidity, a decrease in temperature, and a compaction force result increase in tackiness. More dwell time is another factor that improved tackiness. They suggested having a better understanding of tackiness behavior, more tests be done using the peel test method [47].

The temperature effect on the tackiness of prepreg measured by probe test method might have some inconsistencies in certain conditions to what practically happens using the AFP; heating the prepreg (which decreases the resin viscosity) might cause flow of the resin away from the probe surface in the probe test. Additionally, after the prepreg is laid down during the Automated fiber placement process, typically heat is dissipated shortly, but in the probe test, this is not the case. Accordingly, for very high temperatures, tackiness may be underestimated in this method (due to applying too much heat on prepreg surface).

These studies applied probe test method to measure tackiness force, and probe test samples are small in size, and also the way that load and heat are applied to the prepreg is not in the same way as in the AFP process, so all the results must be verified by AFP made samples.

R.Crossely et al studied the ATL(automated tape lay-up) process for two different parts of composites: glass fiber composites and carbon fiber composites. ATL machine is used to make samples and peel tests to record the tackiness. They reported two different types of failure happening in the peeling process; dry failure and wet failure. Increasing temperature causes a decrease in tackiness in Glass fiber prepreg, while in carbon fiber, tackiness increases by increasing temperature. They reported that depends on failure mode, feed-rate speed has a different influence on prepreg tackiness. In the wet failure, the faster feed-rate the more tack force is reported, but in dry failure, lower feed-rate speed results in a stronger bond between prepreg and substrate surface. It was reported that in order to understand the tackiness behavior, it is required to determine the failure mode at the first step [33,54,56].

Endruweit et al. simulated AFP process by the new apparatus. Their study tested the feed-rate, temperature, surface combination, compaction pressure, and different types of delamination (adhesion and cohesion) comprehensively. They used the peel test method to report the tackiness force. In their set-up, lay-up speed is the same as peeling speed, so changing lay-up speed changes peel-rate as well. They reported that neat resin shows a similar tack to prepreg with a shift in graphs. The tack force is higher between prepreg-prepreg than prepreg-steel, increase in tack by increasing relative humidity and increasing compaction force. Besides, they reported that the Gaussian curve can approximate the feed-rate effect [46].

Berend Denkena et al. studied the effect of temperature variable between tool and prepreg on defects formation. They analyzed defects such as gaps and overlaps and tried to improve the quality of the final parts by monitoring lay-up temperature. They reported that temperature at prepreg NIP point is lower than the tool, and at the gaps, the temperature remains the same as tool temperature. However, in the overlaps area, the temperature is lower than the NIP point temperature. They have found that by controlling process temperature, steady quality assurance is achieved and defects formation is detectable [63].

All studies mentioned above are about parameters and characteristics that happen during the AFP process. Some other factors and parameters affect lay-up properties and, at some point, affect the way that data is reported, such as peeling, and the substrate surface roughness.

To make a comprehensive comparison of the peel test as the most reliable method for measurement is chosen (As discussed before). Although the method is known and looks very straightforward, tack measurements depend on several steps, from surface preparation to peel test condition, which makes measuring tack properties and comparing different conditions difficult.

In the peel test method, the first step is bonding formation. Besides the abovementioned parameters, there are a few factors that can change the result, such as substrate porosity, wetting ability, and surface energy, and it is discussed overall in the surface roughness section. In the AFP process normally, aluminum is the tool material; so, there is not a diverse option for the tool materials. However, tool properties such as coating, moisture, cleanness, and release agent are important factors in surface preparation. Surface preparation affects bonding. Some surface properties are uniform in the entire tool surface, but coating and surface roughness effects must be examined. The other factor that might affect bonding properties is the characterization of adhesive [64,65].

In this study, the prepreg properties are kept the same rate, so surface energy, degree of cure, and viscoelastic behavior of resin are the same in whole tests. The most operative part in this study is related to the factors which will change the bonding process, namely, prepreg and tool surface temperature, contact time – measuring as feed rate –, contact pressure.

As discussed before, the best method for measuring the tackiness is peel test; however, separation angel, a different type of clamping, adherent and adhesive properties, rate of debonding are the factors that must be considered. Although lay-up is completely done and the peel test does not have any effects on that – since the sample is made before tackiness peel testing – peel test parameter affects the way that data is recorded and if not being investigated comprehensively might lead to an erroneous conclusion about effects of lay-up parameters.

Creep, stress relaxation, and other properties of adherent could be effective, but in prepreg cases, these factors are negligible [66][53][67].

Several studies are done regarding PSA (pressure sensitive adhesive) quality by peel tests. I.K. Mohammed et al. (Ref.) studied peel test at constant peel rate with different angles and use a cohesive zone model to simulate the process by finite element. He used a polyethylene as a substrate and acrylic pressure-sensitive adhesive. They studied peel angles of 45°, 90°, and 135° degree and reported a decrease in peel force by increasing peel angles [66].

Liang Zhang et al. used a cohesive zone model to investigate the effect of the peeling angle, and peel-rate on peel force. They reported an increase in peel-force by increasing peel-rate. Also, increasing the peeling angle from 90° to 150° reduces the peel force. There is a negligible difference between 150° and 180° degree reported peel force [68].

In this study, the author tries to simulate the AFP process by an indoor set-up to be able to do lay-up at different conditions. To measure the tackiness of the laid-up prepreg peel test method is used following the D6862 − 11 standard. This study contains three different parts; in the first part, the effects of temperature, feed-rate, and compaction force are comprehensively studied using a soft rubber roller. Then in a separate series of experiments, the effect of roller types and dwell time are reported. In both series, DOE (design of experiment) using MINITAB software is done, and the Taguchi method is applied. At the last step, the series of experiments are done to measure how surface roughness affects lay-up properties in general and tackiness of prepreg in particular.

All the studies so far were aimed at measuring the tackiness for the AFP process, but the issue of considering all possible conditions and predicting tack levels remained unresolved. In this study, the author tried to find a way to predict tackiness regarding different conditions and properties. The measurement method was testing, and the prepreg side with backing paper is used.

Summary of previous work

Table 2 studies regarding a single parameter

Single parameter effect on the final product				
BAkhshi and Hojjati	Sreehari and Micheal	Belhaj and Hojjati	C. Schmidt and Denkena	Ebraim and Gangadhara
Effect of compaction roller defect formation	Effect of heating and local pressure on wrinkle formation	Effect of steering radios to wrinkle formation	Effect of temperature to reduce defects	Effect of pressure temperature and feed rate
AFP, FE	AFP + DIC	AFP + Rayleigh-Ritz approach	AFP+ infrared camera	AFP, Final product quality

Table 3 studies regarding tackiness effect

Tackiness Measurements				
D. Budelmann and Detampel	O. Dubois and Le Cam	C. Wohl and Alireza	R. crossely and schubel	Andres Endruweit and Choong
Hand lay-up, prob testing + Response surface area	Probe testing + Resin and prepreg	Probe test, DOE	ATL + peel test Glass and carbon prepreg	New apparatus, Continuously lay-up and peel test
Temperature, compaction force simultaneously	Probe test, temperature, debonding rate	Effect of temperature and humidity, compaction force dwell time	Failure types: Dry and wet	same speed for lay-up and peeling

3. Material and Methodology

3.1. Methodology

Previous studies show that the peel test method is more reliable than a probe test. So, it is chosen to measure prepreg tackiness. In this study, the effects of temperature, compaction force, feed-rate, and roller are comprehensively studied. As mentioned in the literature review, the peel test method includes two steps: lay-up and peeling. These two must be done respectively and with the lowest possible time difference between the process. The lay-up parameters change in the experiments, but peel test parameters remain the same to be able to make a comparison between two samples.

3.2. Material

The material used for this study is Cycom 977-2/35-12K HTS-145 unidirectional prepreg with thw width of 6.35 mm (1/4 in). It is a toughened epoxy resin curing at 177 ^{o}C (350 ^{o}F) which is formulated for press molding or autoclave. The glass transition temperature is 170 ^{o}C (338 ^{o}F). Cycom 977-2 at 22 ^{o}C (77 ^{o}F) maintain tackiness for minimum 10 days, and for large structure fabrication is suitable. It also has 12 months of shelf life at -18 ^{o}C (0 ^{o}F), it can be used and stored for a month if every single time of usage is recorded carefully [69].

3.3. Peel test

Before starting lay-up, the peeling set-up must be ready to avoid time effect on laid-up samples. Also, peel set-up must be designed precisely to control the peel test parameters. In this study, peel test is done using a tensile machine. Simply by connecting one end of laid-up prepreg to the top grip of the tensile machine, fix the plate to the bottom grip of the tensile machine, and start the machine peeling process could be done, but peeling angle changes continuously that affect the reported data.

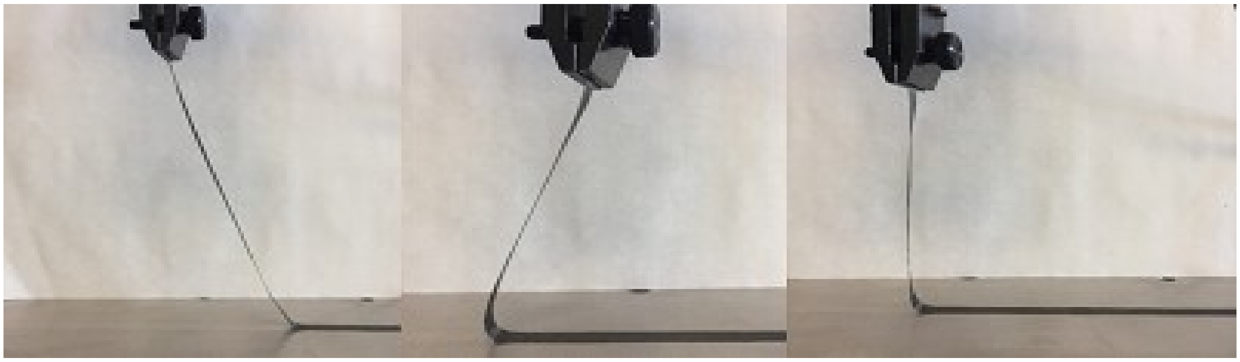


Figure 6 Peeling angle during test for fixed plate

It is required to move the plate with the same speed as the tensile machine to keep the peeling angle the same while the peeling process is completing. The best solution is using a carriage to connect the plate with a pulley to the top grip of the tensile machine. The carriage is fixed to the bottom grip of the tensile machine, and the plate is placed on top of the carriage using two butterfly screws. Fortunately, the top grip of the tensile machine has a bar, which makes it simple to connect a wire; the difficulty is with the moving plate. A screw is placed on the side at one end of the carriage, and pulley is put on the screw. Another screw is placed on the same side at the other end of the carriage. The cable is connected between the far end of the carriage and the top grip of the tensile machine through a pulley. A low friction cable and pulley are prepared to provide such a movement with the lowest amount of friction. Even if there is friction in movement, it must be recorded and calculated before start peeling tests. The pulley changes the vertical movement of the tensile machine to the horizontal movement of the plate placed on top of the carriage (Figure 6).

After a peeling test set-up is made, before starting the peel test, it is important to make sure that carriage moves without resistance, or if there is any probable friction, it must be reported accurately. As it is shown in the graph, the amount of friction for the peeling set-up is lower than 0.0001 N, so the set-up can be considered without any friction (Figure 8)

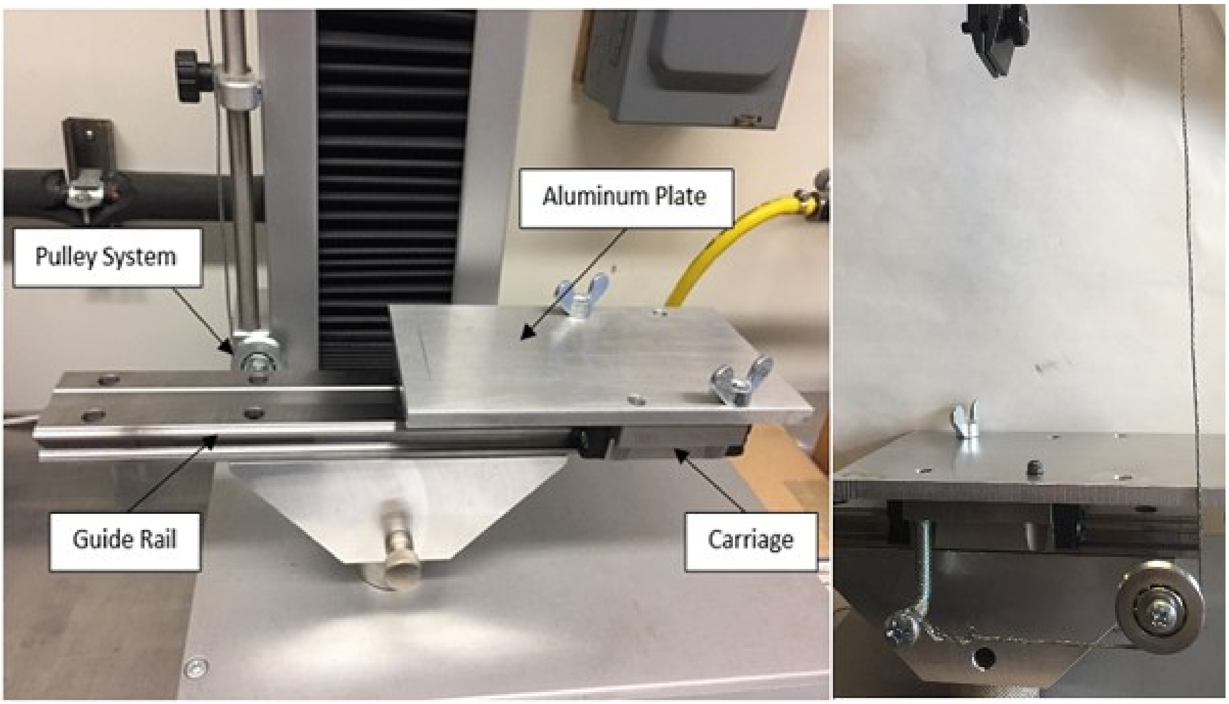


Figure 7 carriage and pulley system

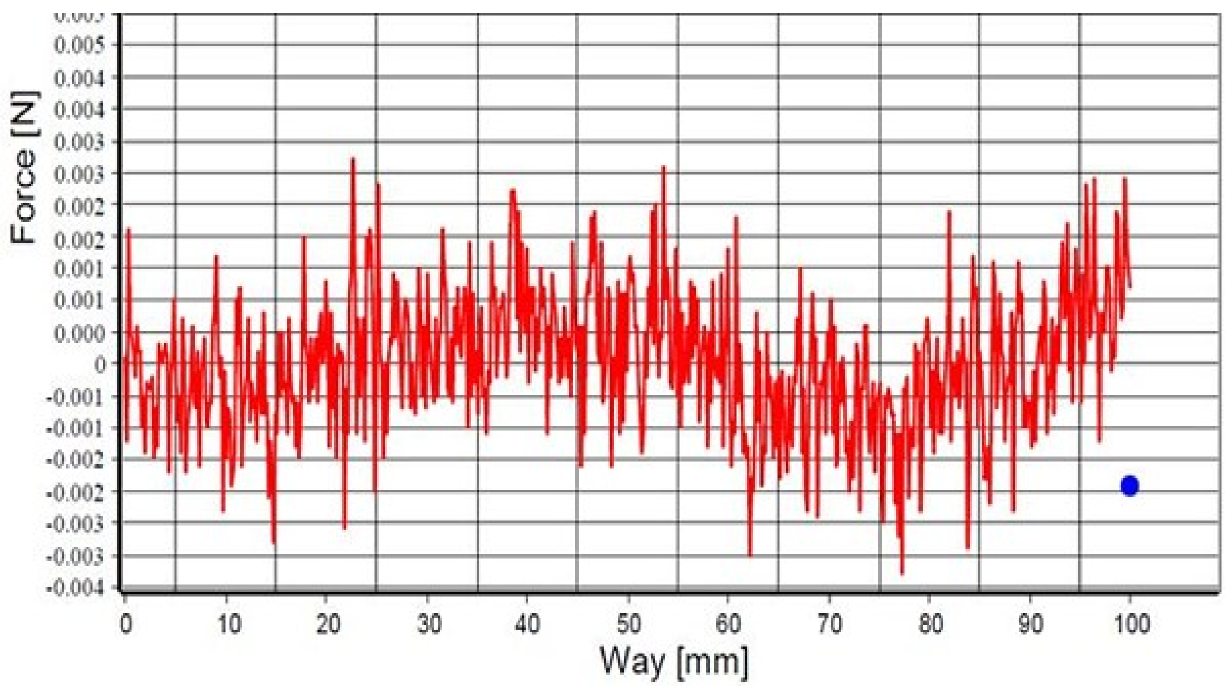


Figure 8 Friction of pulley system and peeling error

As the graph shows, the design of carriage and wire are so accurate, and the amount of error is less than 0.001 newton, which is negligible in comparison to peel force, which is reported as a number from half a newton up to two newtons. Now the mechanical part of the set-up is ready and the peeling parameter must be defined by software in the computer to make sure all the tests are done in the same distance and peel-rate.

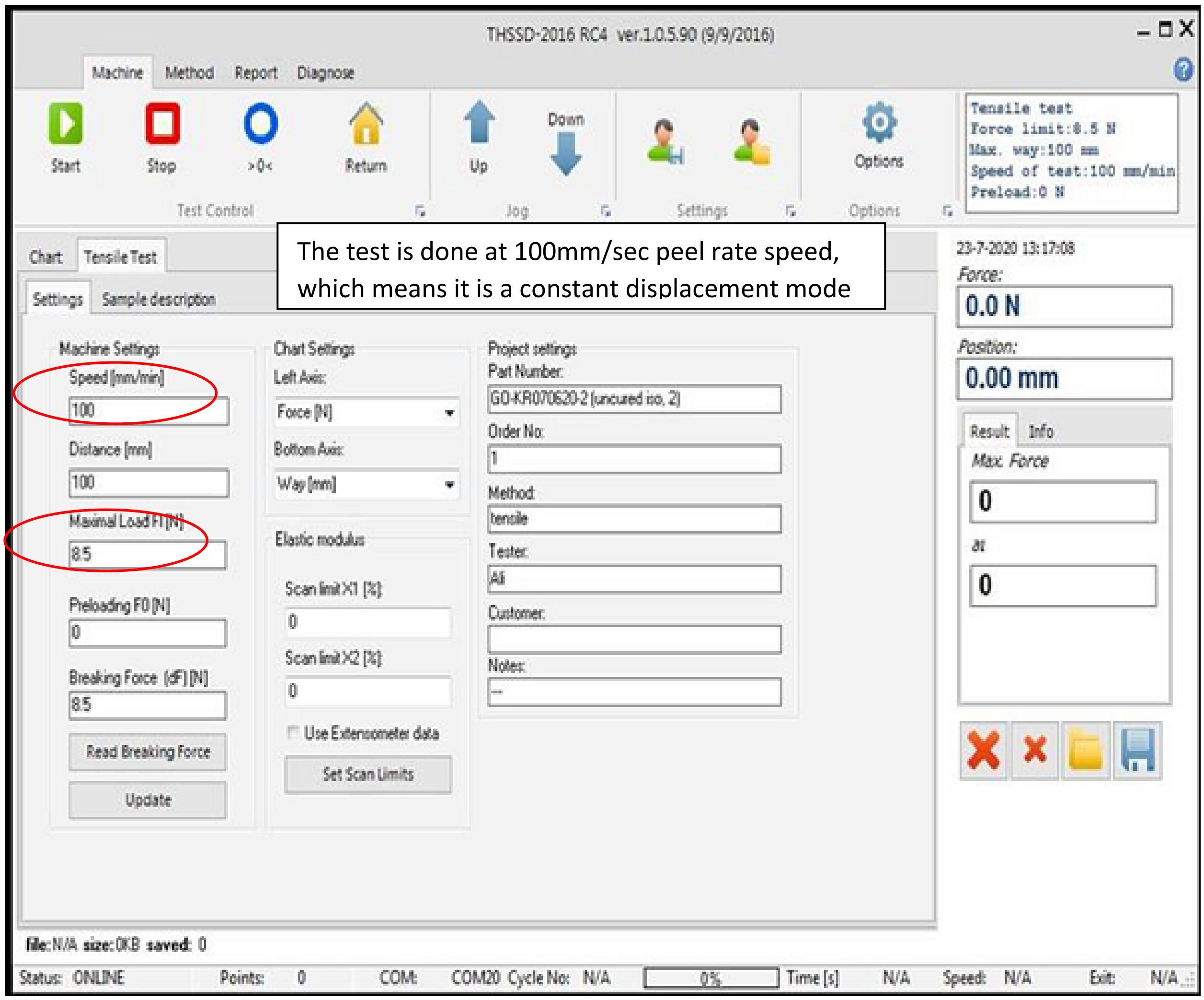


Figure 9 peel-test software. Peel rate speed must be recorded. Maximum load set at 85% of load cell capacity

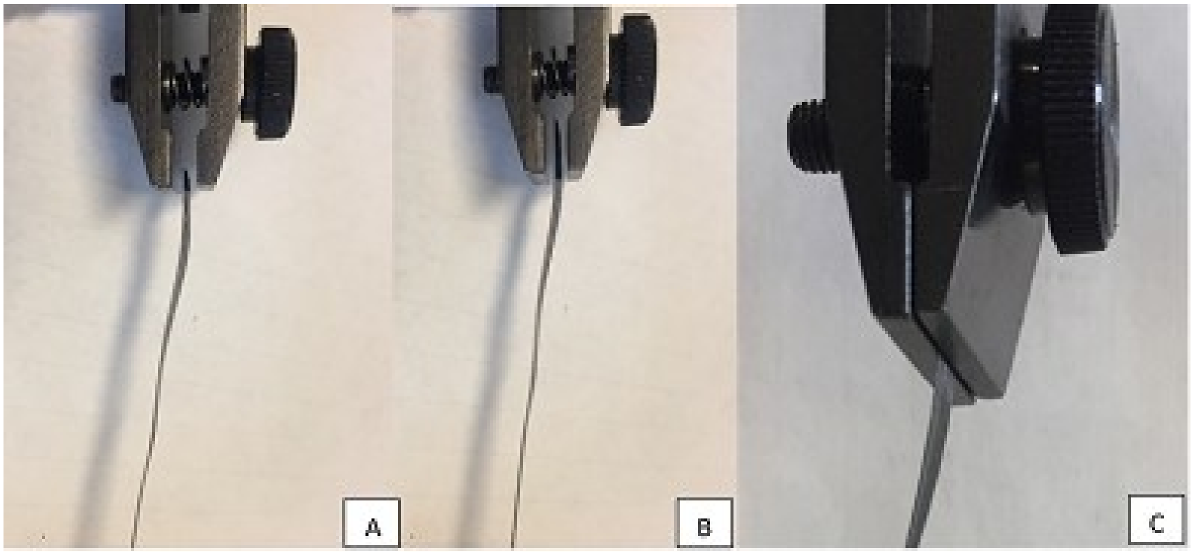


Figure 10 A.there is not enough engaged. B. enough length engaged. C. prepreg placed at the center of the grip

According to the D6862 – 11 Standard for peel test, the test must be done at a 90-degrees angle of peeling. The tensile machine must be able to provide a peel-rate speed between 12 mm/min up to 250mm/min. The breakage load that entered to the software must be a number between 15 % to 85% of loadcell capacity to avoid damaging the loadcell. Since the peel force reported in previous studies are up to 2 N, the loadcell with the capacity of 10 N is selected, and the breakage load defined as 8.5 N. The outer end of prepreg must be engaged with the grip as least one inch and it must be exactly at the centerline of the grip.

Now the peel-set up is assembled and ready to start peel testing. In the reported peel force graph there are a few numbers, first pick, average, minimum, and maximum peel force. According to D6862 – 11 Standard the average force must be reported over at least 3 inches (76 mm) of samples, disregarding the first one inch (25 mm). The average force must be reported as newton per unit width. The minimum and maximum load can be reported as well. It is necessary to report the failure type, cohesive, or adhesive. It is claimed that the following reported data for peel-force is accurate and the peel test and reported data do not affect the results. In this study, the author repeats each set of peel tests three times to make sure the results are reliable.

The reported peel force for these three samples made in the same conditions is the average of three reported average, which is (0.61+0.58+0.56)/3, which is equal to 0.5834 (N). The reported averages in the graph are calculated using data for displacement from 25 mm to 100 mm. The first 25 mm must be disregarded according to standard.

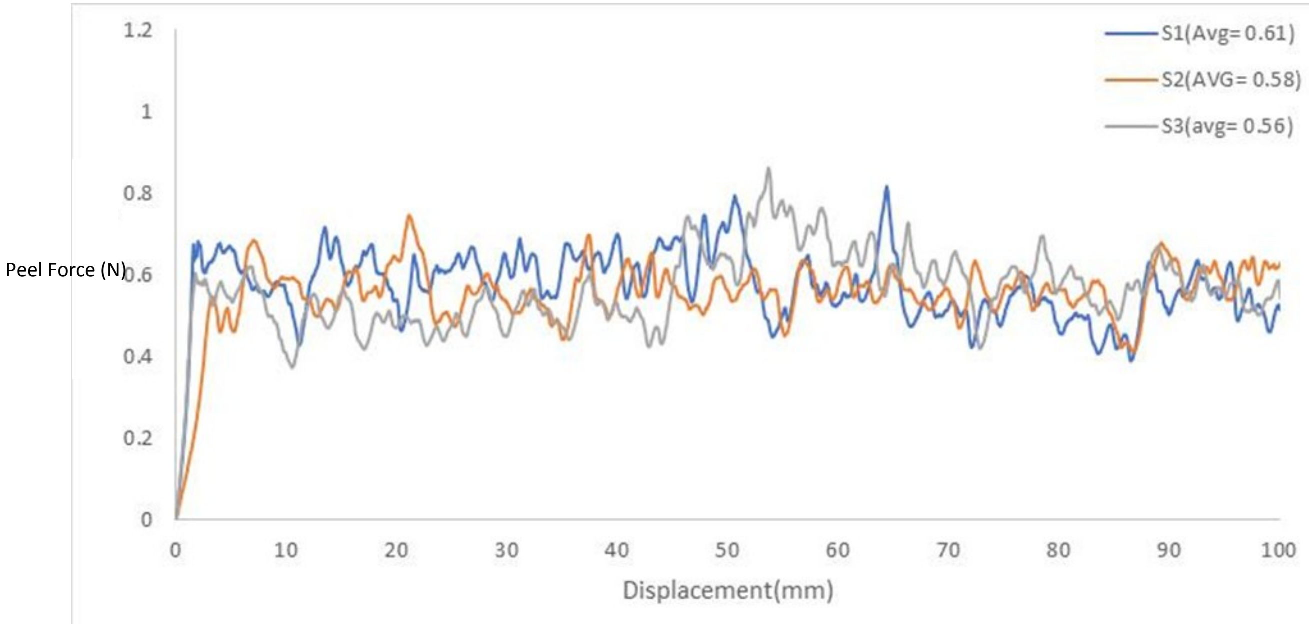


Figure 11 Test results of three samples made in the same conditions

3.4. Lay-up

Since the study is focused on different parameters that affect the AFP process, the sample should be made by AFP robot at the CONCOM center. The first run test is done, and samples achieved. However, the peel test result was unexpected; investigation of the issue shows that the AFP huge mandrel temperature is a limit to do perfect lay-up. Since the lay-up process to make a peel sample is less than 10 seconds, there is not enough time for the mandrel to get warm. Mandrel and aluminum plate temperature is the same as room temperature, which makes it impossible to do lay-up. Preparing AFP robots to do lay-up takes at least 30minutes, and preheating is required to achieved decent results [70]. All in all, running the AFP machine to make a small size sample at least more than twenty times per day is neither logical nor reasonable. So, the set-up must be designed by which all AFP parameter is simulated and provided precisely.

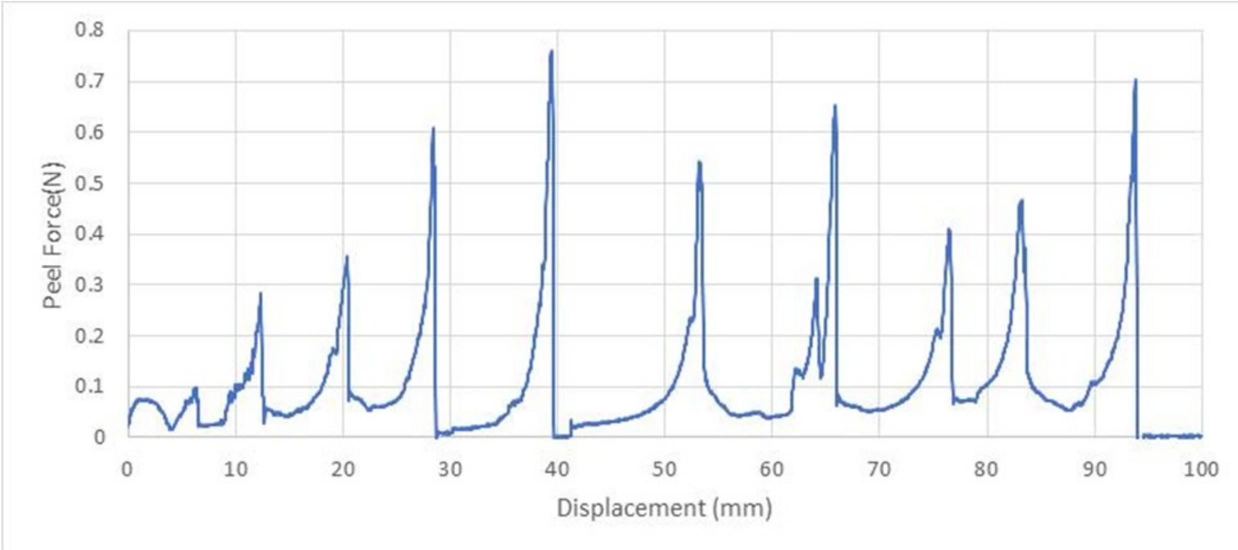


Figure 12 peel test report for samples made by AFP robot

3.5. Design Assembly

An overall overview, the apparatus consists of a pneumatic pressure to apply the force and a load-cell to report the compaction force, a very sensitive linear guide to controlling lay-up speed and fixed heating gun to provide constant heat.

3.6. Feed-rate

A linear guide has been required to provide roller movement. However, this movement must be recorded precisely and reported as a feed-rate speed that affects the tackiness of prepreg. So, the linear-guide needs an electrical motor by which the movement speed is provided. To be able to adjust and control the movement speed of the linear guide, a gearbox is required.

The linear-guide must be able to move under a compaction force of 449 (N) (450N). So, gearbox and electric motor must be chosen carefully to be compatible together and support the compaction force. Since the movement is under pressure, two couplings are provided to avoid force fluctuation damages gearbox or an electrical motor. The moving table is fully designed and ready to be made.

Figure 13 linear guide, gear box, electrical motor, coupling

Considering the components price, compatibility of different pieces, and the required time for assembly, it is evident that if there is a similar linear guide is shops, it will save time and money. The ball screw linear guide is more accurate than the linear belt actuator. So, a ball screw linear guide is selected to be able to control precisely. Also, it is requested to accompany a linear guide with a stepping motor powering supply and stepping motor controller to provide and adjust moving speed. Stepping motor controller can simply change feed-rate by a volume controller. Looking through different providers, the "Ruixin ball screw motion guide RXS 100" linear guide capable of supporting 100 KG force is ordered from "Chengdu Ruixin Precision Mould company."

3.7. Compaction Force

To be able to apply constant pressure on the roller, there are different choices—for example, constant spring or pneumatic system. Since spring constant might change pressure slightly after a long time, so the pneumatic system is preferred, however, how to use pneumatic air pressure to both sides of the roller is a bit challenging. The best way is to follow the design of the AFP robot. Instead of using two different cylindrical air pressure, one pneumatic air pressure is provided. To supply the same load to both sides of the compaction roller, a u-shaped bracket is required to distribute the load equally. It should be considered that bracket must be rigid so much

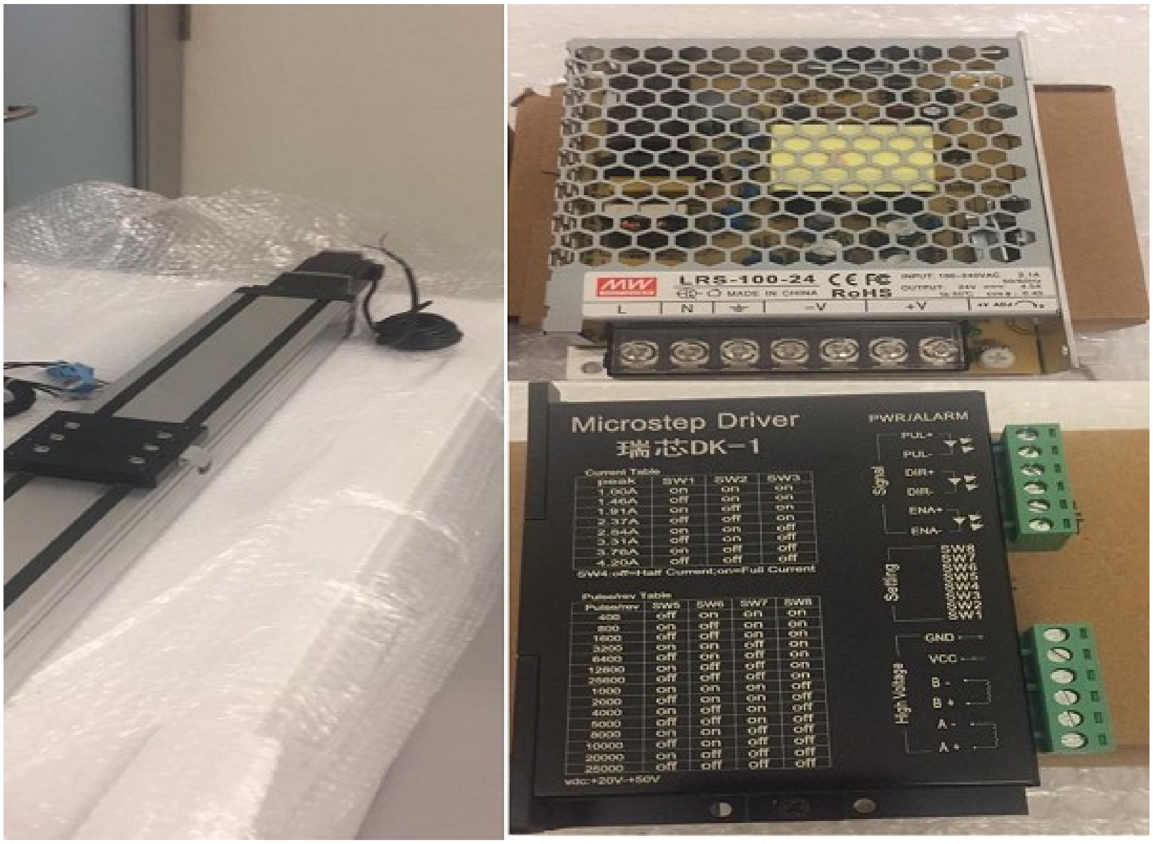


Figure 14 ball screw linear guide, stepping motor

so that it can transfer the load without deformation and changing the direction of the compaction force.

At first aluminum bracket was tried, but while applying compaction pressure more than 40 LB, it deforms and as a result the compaction force was not pure. Considering this, Stainless Steel material is selected. The pneumatic system needs a regulator to control the air pressure and airflow to adjust the applied pressure.

Using a regulator gauge (located on pneumatic air pressure system) one can change the air pressure and subsequently report the force. However, precisely measuring compaction force needs more consideration, since force is not delivered purely on the roller, and there is some waste of force on the other parts of the structure. To solve this ambiguity, a load cell is applied under pneumatic gage and on top of the roller bracket to measure the force with the minimum possible error. The reported force quantity by loadcell is relatively precise, reliable in scientific and research areas. The compaction roller needs to turn while moving during the lay-up process.

Two bearings are placed on each side of the roller, and a shaft is ordered to connect the bracket to the roller. The shaft must be fixed to hold roller and also turn inside bearing to help the rotating

movement of the roller.

Two grips are placed on the two ends of the shaft. Bracket size must be wider than roller

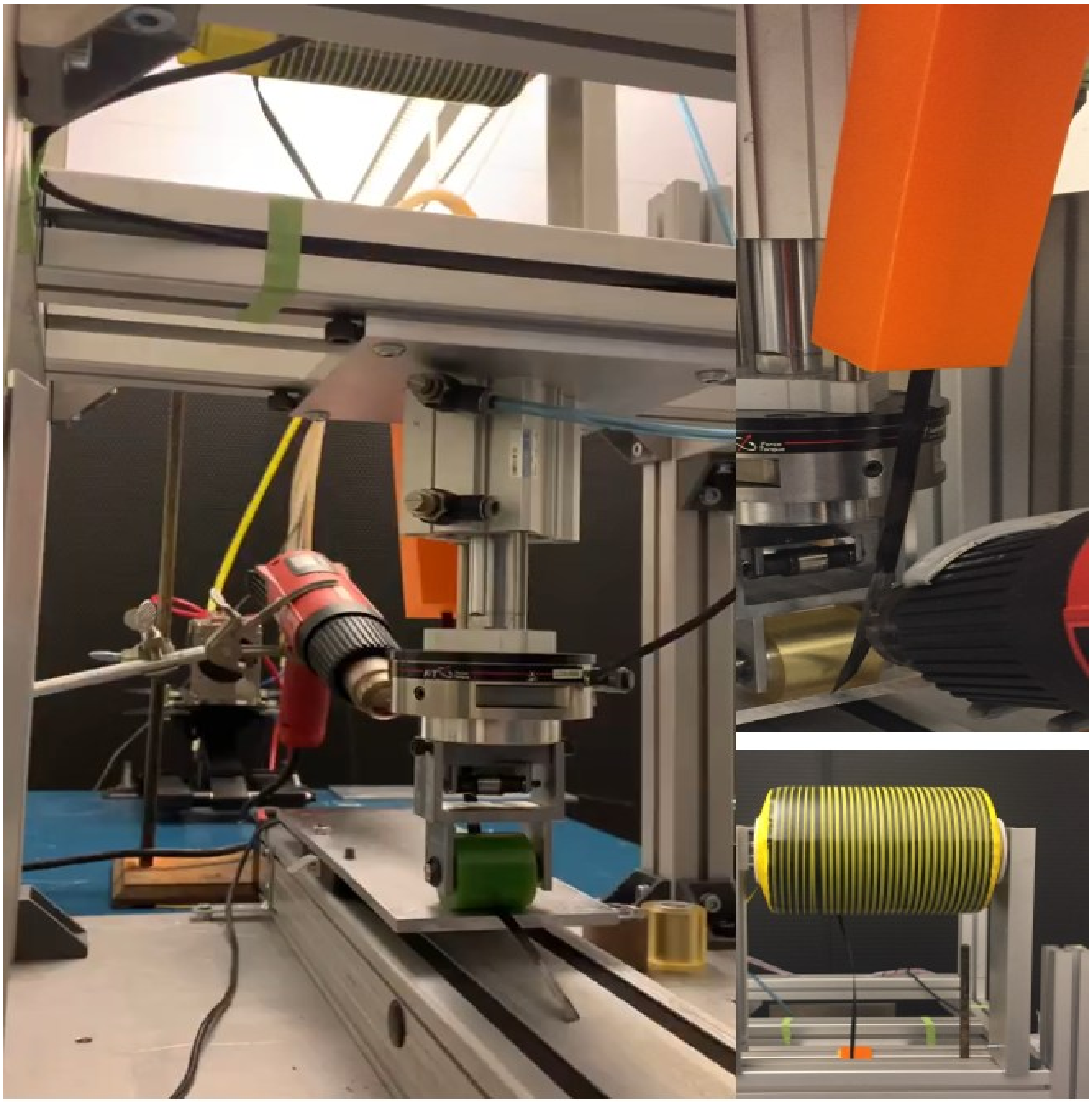


Figure 15 compaction force assembly

so that roller does no touch bracket while rotating; it should not be bigger than the width of bearing to make sure that bearings are inside roller while moving.

3.8. Temperature

Heat-Gun

AFP robot is used to make a part in industry and scientific labs. However, for adjusting lay-up temperature and to have a high-quality lay-up, sometimes they have to change the parameters for the beginning part of each layer. First layer lay-up parameters are not usually the same as the other layers lay-up parameters. Because the heat torch temperature is not able to heat the prepreg and mandrel (usually mandrel temperature is the same as the room temperature). In some cases, they preheat the tool before laying-up the first layer. For thermoset prepreg, there are two choices to provide the heat: Heat-gun and IR Lamp. Heat-gun found more accurate than the IR lamp. Generally, the IR lamp temperature is adjusted using a dimmer to adjust the voltage.

In this study heat gun is used to provide a specific air temperature for the lay-up time. It is

Figure 16 Heat-gun and LCD readout

worth to mention that the heat-gun angle – focus on NIP point – and distance must be precisely recorded. The slight changes in angle would change the NIP point temperature. A stand holder with two grips is used to fix the heat-gun location during experiments. It is suggested to adjust the temperature and measure heat effect while using the same heat flow to lower the variables. Milwaukee Heat-gun has an LCD readout digital display to monitor heat-gun temperature during the process. It can provide heat in the range of 100 to 1100 Fahrenheit (38 to 593 centigrade). Four different airflow rates are available from 10.6 to 17.6 cu.ft.min, to limit the effect of heat airflow, the amount of 17.6 cu.ft.min (29.9 m3/hr) is chosen for airflow. The heat increment is ten centigrade, and the LCD shows the internal temperature of the heat gun, which is different from air-flown temperature. Previous studies show that an effective curing process takes place at a range of 70 – 100 C.[71]

Berend Denkena et al. used a thermal infrared camera to report prepreg, roller, and tool temperature during the process. Their study focused on the effect of temperature variable between tool and prepreg on defects formation. They reported prepreg temperature for the AFP process between 32 and 36 degrees centigrade. While tool temperature reaches 38 degrees during the process [63].

A. Hajili et al. studied the effect of temperature on the AFP process. They have tried to regulate temperature during the process and simulate the heating system. However, they did not mention how they measured NIP point temperature [14].

To check the nip point temperature accurately and the precisely infrared thermal camera is used. An infrared camera should be adjusted at the point in which the nip point and tool and prepreg temperature can be recorded easily. It is also preferred not to a single touch the gun while making samples, using a single-pole switch to turn off/on heat gun is a solution to make sure that heat gun position is completely fixed.

Figure 17 IR camera

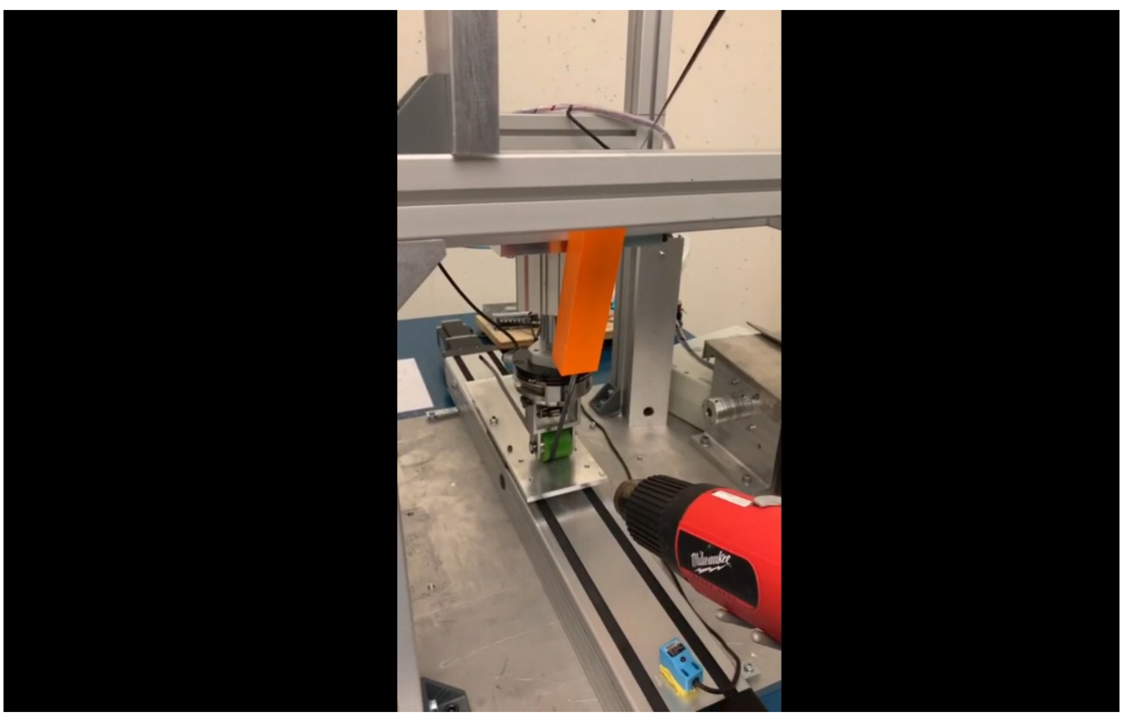


Figure 18 lay-up set up

The heat-gun to provide the required temperature for the lay-up process, linear-guide to supply feed-rate, and pneumatic air jack to provide compaction force are entirely designed. There are two possibilities for the set-up movement: connecting all the parts to the linear guide and moving through the length of the fixed aluminum plate to do lay-up, or fixing all the pieces on the table and attach the aluminum plate to the linear guide. In first, the roller moves on the surface of the fixed plate, in second, roller and heat gun are stationery and just the plate moves. It is found easier to connect the aluminum plate to the linear guide and to have a stationary roller and heat-gun.

Now the design is completed, and the lay-up process can be launched. After running the

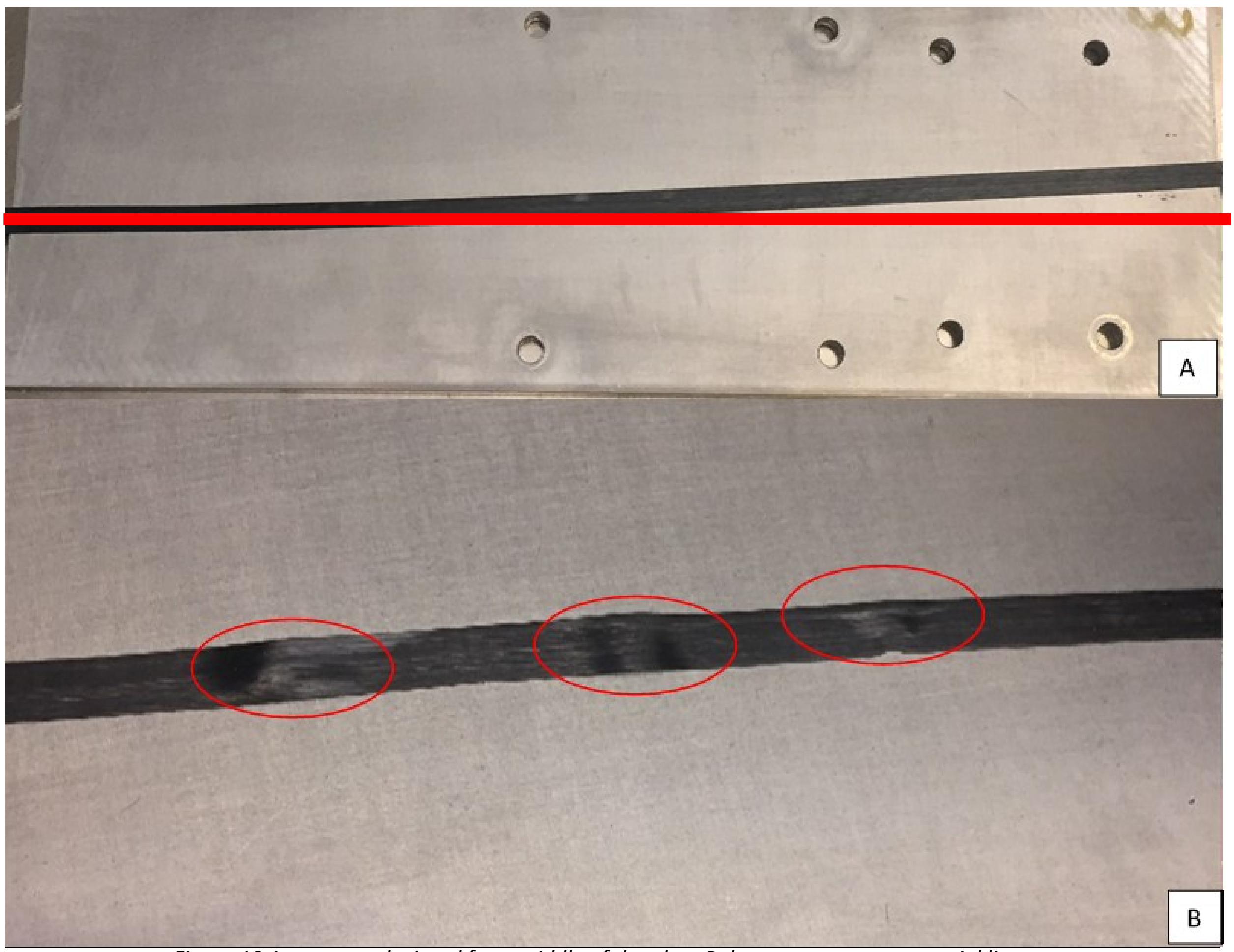


Figure 19 A. towpreg deviated from middle of the plate B. loose prepreg causes wrinkling

first samples, it is seen that the prepreg is loose, and it shows wrinkles all over the samples. To avoid this problem, an air clutch is placed on top of the set-up to apply tension on the prepreg. The amount of tension can be controlled by adjusting the regulator. The test ran, and the new issue is about laying up prepreg in a straight line in the middle of the aluminum plate. Since the spool is rotating and the prepreg is displaced during lay-up, it is required to hold the prepreg in the middle of the aluminum plate. To solve this problem, a plastic guide is designed and made by the 3-D printer to keep prepreg in the middle of the aluminum plate. After all the difficulties and obstacles, appropriate samples are made. The samples are brought to the carriage, and the peel test is done using the tensile machine.

3.9. Taguchi Method

Since the set-up is a simulator of the AFP robot, the parameters' ranges are all selected using AFP robot parameters. Compaction force between 89 (N)to 267 (N), the feed rate between 0.5 inches to 5 inches per second. But for the heat-gun, the temperature must be higher than the gas torch temperature that is between 70-200 degrees centigrade of the AFP machine (since in AFP robot, the gas torch is closer to the prepreg 1 inch, but here the distance is about 8 inches). So, the heat-gun temperature is selected between 200-500 degrees centigrade. This study contains three different parts; at first, the effect of heat-gun, compaction force, and feed-rate speed is studied. Afterward, the impact of the various roller is investigated, and surface roughness is the last factor considered. Study the effect of all parameter at the same time required many samples to be made. Four different rollers, four different surface roughness, four heat-gun temperatures, four compaction forces, and four feed-rate which means 4*4*4*4*4 = 1024 samples. Even using DOE software leads to at least 200 samples. It is worth to mention that each sample result must be repeated three times to have a reliable report. To limit the sample number, the surface roughness and roller effect are investigated in a separate experiment. Still, it must be done after understanding the process and impact of compaction force, feed-rate, and heat-gun temperature. So, the first step is to study the effect of heat-gun temperature, compaction force, and feed-rate.

3.10. Investigation the effect of different parameters on prepreg tackiness

As mentioned above, the range of each parameter is defined using a previous study of AFP robots [39][40]. The range of heat-gun temperature is between 200 to 500 degrees centigrade, the compaction force must be between 20-267 (N), and the feed-rate speed is between 2.5 mm/sec to 12.5 mm/sec. For each parameter, four different amounts are selected.

According to the common factorial method, 4*4*4 = 64 tests must be done. Each test should be repeated 3-5 times to be able to prove repeatability of results; simple calculating shows that 64*3 = 192 tests must be done to be able to report reliable results. In a day, a limited number of samples can be made, so making 192 samples needs at least an entire day of a month. To do lay-up and study tackiness, the prepreg material must be taken off the fridge at least two hours before running the tests. After finishing daily tests, preoreg must be put back inside the fridge again. passage of time causes Prepreg degree of cure to be changed. Different degree of cure drastically affects the results. I to avoid all this to happen, it is suggested to reduce the numbers of samples using DOE.

3.11. Taguchi DOE

Taguchi method designs a series of the experiment by which the process can predict the results for all the tests, whether they are done or not. So, there is no longer a need to do all 64 numbers of the tests; In other words, one can simply use the result produced by Taguchi prediction. At first, it is necessary to define different heat gun temperatures, compaction force, and feed rate speed to design a series of experiments. The selected heat gun temperatures are 200,300,400,500 degrees centigrade. Since the heat gun is placed 100mm away from NIP point with 15 degrees angel, the prepreg temperature will not exceed 60 degrees centigrade. Chosen compaction forces are 20, 30, 40, 267 (N). Fore feed-rate 25,50, 75, 125 mm/sec are selected. Entering this range of data to the MINITAB software shows that in the first round of this study, the Taguchi process needs 16 tests to be able to predict the 48 remaining results. The required tests are reported in table 4.

For each sample, at least three repeats are done to have a reliable report. Peel tests are done according to D6862 – 11 Standard. It is done over 100 millimeters of the laid-up sample, and the average force is reported. The peel-rate speed for the entire process is set at 100 (mm/sec) to make sure that the peel-rate does not affect the recorded force. Recorded peel force is for the width of a tow; It must be divided be tow width to report force per unit width to report the peel force accurately.

Table 4 DOE defined by Taguchi method

Sample	Compaction Force (N)	Heat gun Temperature (̊C)	Feed rate speed (mm/sec)
1	89	200	2.5
2	89	300	5
3	89	400	7.5
4	89	500	12.5
5	133	200	5
6	133	300	2.5
7	133	400	12.5
8	133	500	7.5
9	178	200	7.5
10	178	300	12.5
11	178	400	2.5
12	178	500	5
13	267	200	12.5
14	267	300	7.5
15	267	400	5
16	267	500	2.5

After all, the 16 runs are done, and the respective peel forces per unit width are recorded. By entering the peel force into MINITAB software, and using Taguchi prediction function of software, peel force associated with 48 remaining tests are acquired. Among the predicted results, one random case is selected to be proved by real test and find out the probable percentage of error in Taguchi prediction. In this case sample for the heat-gun temperature 400 (̊C), compaction force 40 (LB), and feed-rate 50(mm/sec) is selected.

3.12. Roller effect

The effect of temperature, compaction force, and feed-rate is investigated, and running 16 tests helped to have a good understanding of the process. Roller type is the other factor that affects the tackiness. Three different rollers are studied; stainless steel with a coat on its surface, hard rubber with 85 durometer stiffness, and perforated roller with the same material as hard roller different texture.

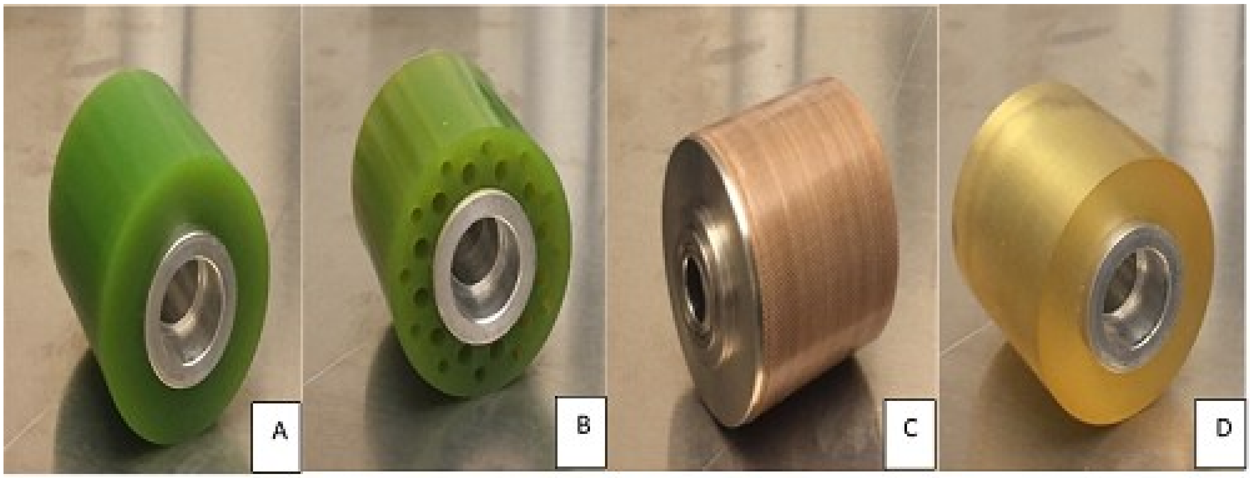


Figure 20 Roller types. A. hard rubber roller B. perforated roller C. Stainless steel roller. D. soft rubber roller

The ranges of other factors are limited (since they are already studied) to minimize the number of tests, and they are chosen in the range of optimum points found in the previous section. The range of heat-gun temperature are 350, 400, 450-degree centigrade and for the feed-rate 25, 50, 75 mm/sec is selected. The compaction force causes roller deformation. Hence it is the most crucial factor that affects the roller effect, so it must be chosen carefully. To select an appropriate range for compaction force, simple experiments are done to measure roller deformation under the load. After doing compaction force on the stationary roller, 20,30,1178 (N)is selected as compaction forces for investigation of the roller types effects.

Considering three types of roller, at three different temperatures, compaction forces, and feed-rates leads us to do tests at 81 different runs. Therefore, MINITAB software is used, and DOE using the Taguchi method helped to limit the number of test runs. In this case, the Taguchi method suggested two options: L9 and L 27 orthogonal array. (L9 means nine runs to do, and L27 means 27 runs). Since the effect of other parameters in the previous section is comprehensively studied, L9 is selected, and the above table for different nine runs is acquired.

Table 5 DOE using Taguchi method for different types of roller

	Compaction Force (N)	Roller type	Feed-rate (mm/sec)	Heat-gun temperature (̊C)
1	89	Metal	25	350
2	89	Perforated	50	400
3	89	Hard	75	450
4	133	Hard	50	350
5	133	Metal	75	400
6	133	Perforated	25	450
7	178	Perforated	75	350
8	178	Hard	25	400
9	178	Metal	50	450

The peel forces for nine runs are acquired and entered into the MINITAB software to predict remaining runs. It is worth to mention that reported data must be peel force per unit width, for metal and hard roller prepreg width before and after experiments are different. So during lay-up and peel tests, careful observation is necessary. To verify the Taguchi predicted data since various rollers demonstrate different deformation, for each roller, three random samples are chosen, respectively. For perforated roller 133 (N), 350̊ C,50 mm/sec, for metal roller 89 (N), 400̊ C, 50 mm/sec and for hard roller 133 (N), 350̊ C, 75 mm/sec are selected.

3.13. Effect of surface roughness

According to the literature, surface roughness effect must be studied in two different conditions: at low temperature when dry failure happens, and at very high temperature when failure mode changes to wet failure. Three different roughness are selected and at 300, and 600 degrees centigrade lay-up is done. The very high temperature is studied to have a better understanding of surface effects in general. At the same time, wet failure and 600 degrees centigrade are not the cases to be studied in the tackiness of prepregs [40,64-65].

4. RESULT and DISCUSSION

4.1. Effect of heat, compaction force, and feed-rate

The first series of experiments are done using soft rubber roller (35 durometers), and the following peel forces are recorded. The reported peel forces in Table 8 are the average of three samples.

Table 6 peel test results for the first run

Sample	Compaction Force (N)	Heat gun Temperature ̊(C)	Feed rate speed (mm/sec)	Average peel force (N/mm)
1	89	200	2.5	0.79
2	89	300	5	0.83
3	89	400	7.5	0.87
4	89	500	12.5	0.84
5	133	200	5	0.78
6	133	300	2.5	0.90
7	133	400	12.5	0.83
8	133	500	7.5	0.91
9	178	200	7.5	0.86
10	178	300	12.5	0.84
11	178	400	2.5	1.02
12	178	500	5	0.97
13	267	200	12.5	0.72
14	267	300	7.5	0.85
15	267	400	5	1.00
16	267	500	2.5	0.82

4.1.1. Prove of Taguchi prediction

Using the Minitab software, Taguchi predicts that the tackiest prepreg is got at 400 (̊C), 40 (LB), 50 (mm/sec), the peel force per unit width is predicted 0.170 (N/mm). It is required a real test to prove Taguchi's prediction. Figure 18 shows that the forecast is in a good correlation with the actual test. The result is predicted by 2.4 percent error. According to the peel test standard, the first 25 mm must be disregarded. The pink area is the prediction area adding ±2.4 % of error.

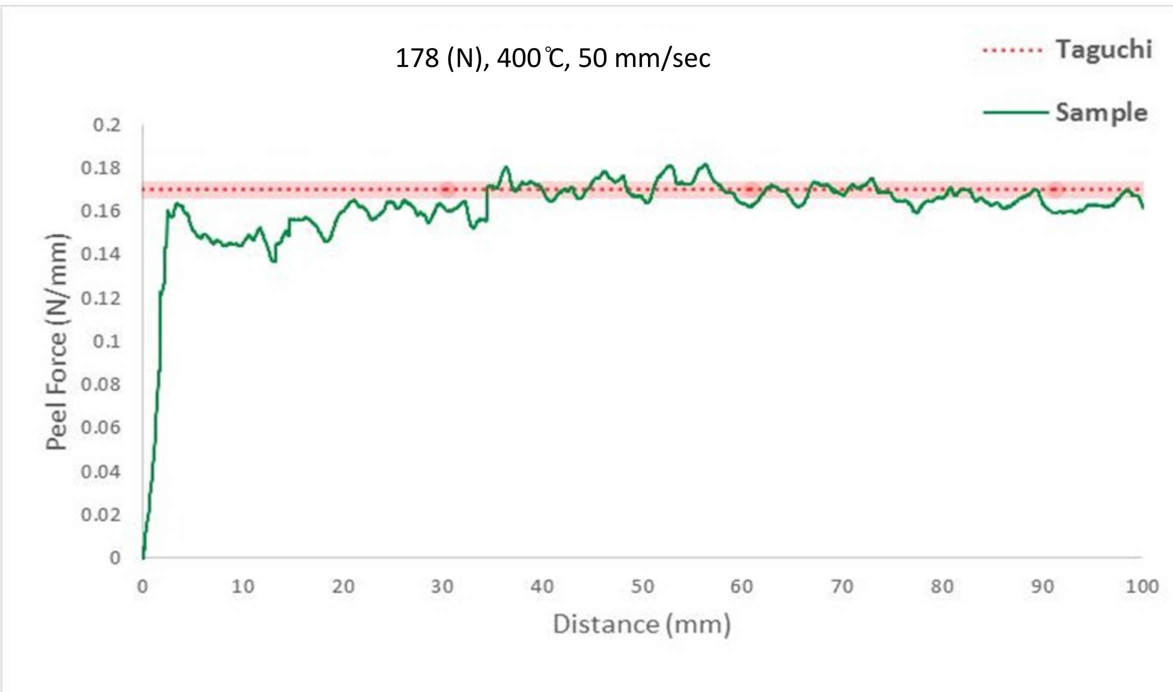


Figure 21 Taguchi prediction vs real test

Percentage error is an expression of the difference between a predicted value and real test value. The following is the calculation of percentage of error:

$$\varepsilon = \frac{|P_F^T - P_F^R|}{P_F^R}$$

$$P_F^T = Peel\ Force\ predicted\ by\ Taguchi$$

$$P_F^R = Mean\ of\ Peel\ Force\ in\ Real\ Test$$

$$\varepsilon = \frac{|0.170 - 0.166|}{0.166} = 2.4\ \%$$

4.1.2. Taguchi Prediction

After verifying Taguchi's prediction by the real test, the remaining data are predicted by MINITAB software as well. The following chart shows part of Taguchi's prediction. The results for entire data are available in appendix 2. The best condition is at the point that 178 (N) compaction Force, 400̊ C heat gun temperature, and 50mm/sec feed-rate speed. The amount of peel force for the feed-rate speed 12.5 mm/sec, 89 (N), and 200̊ C are lower than others. As shown in the graph, red conditions are not recommended, blues are fair, and the green is the optimum condition.

Using the MINITAB software also shows which parameter is the most effective one, and how a single parameter affects tackiness.

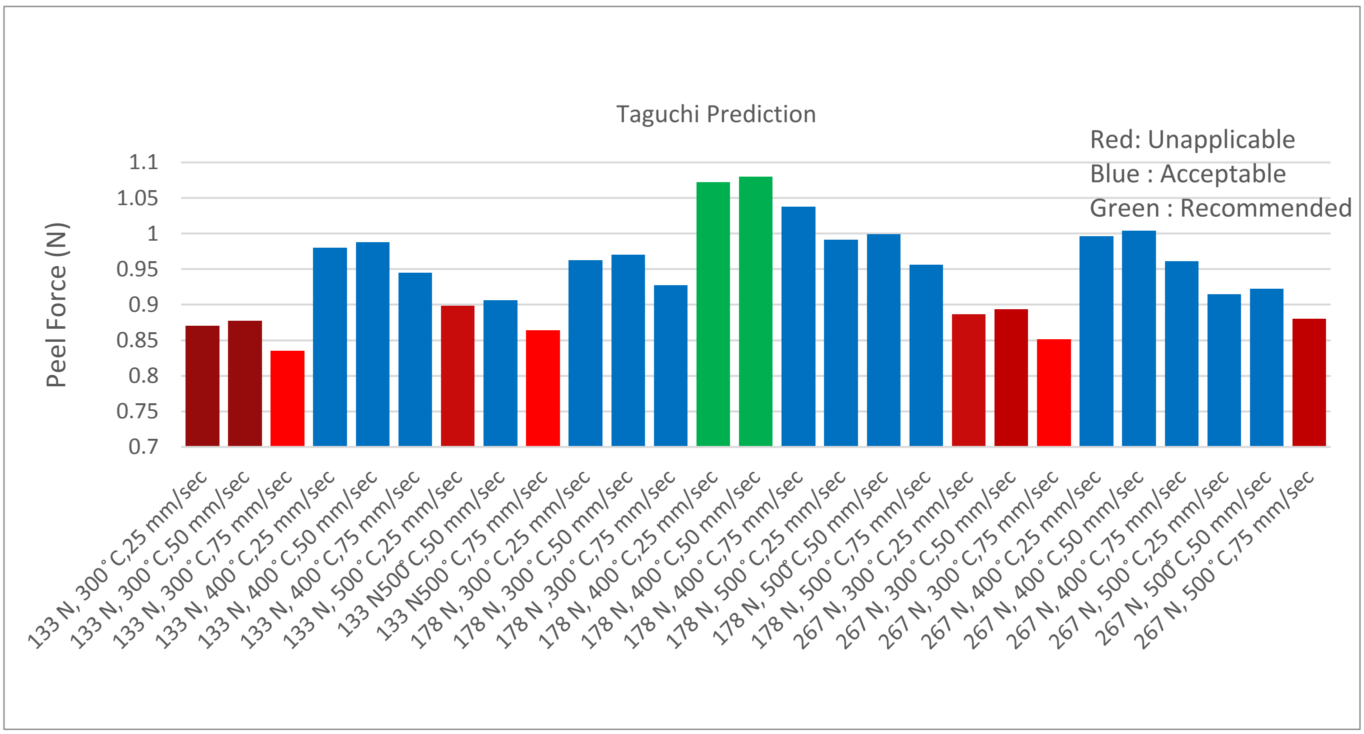


Figure 22 Taguchi predicted peel force

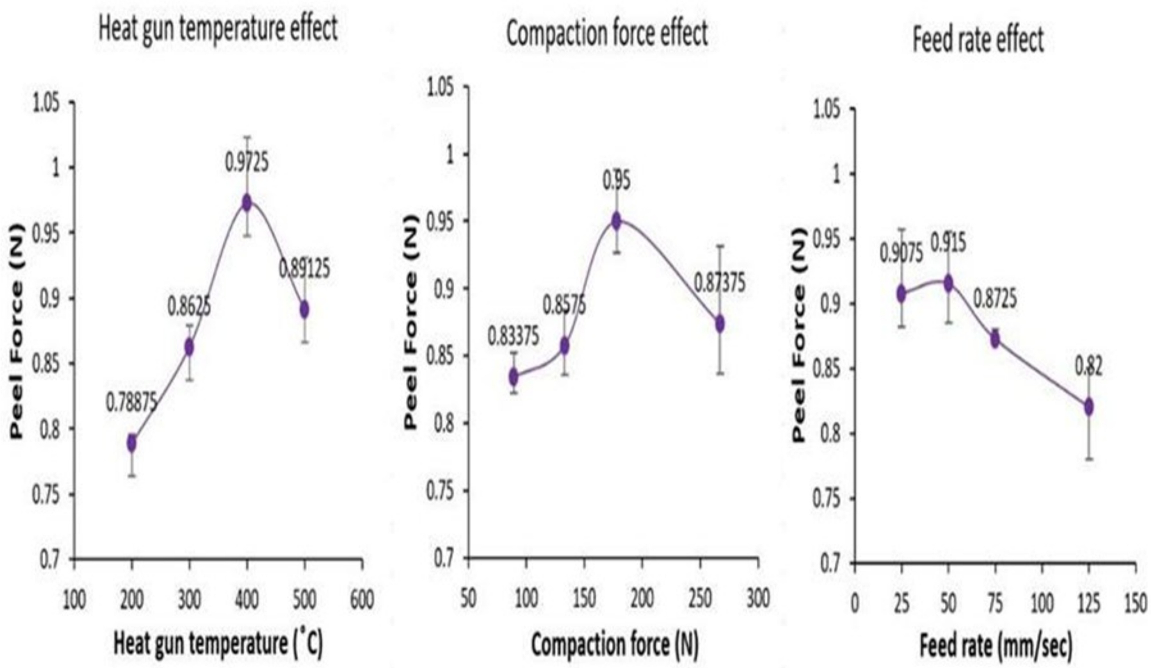


Figure 23 parameters effectiveness A. temperature B. compaction force C. Feed-rate

4.1.3. Temperature

Previous studies reported that in automatic fiber placement, the tackiness is highly dependent on heat torch temperature so that they claimed temperature is the most effective parameter that affects the final product and lay-up quality. Higher temperature lowers the viscosity of resin that causes more resin movements. More resin movements result in better intimate contact. Prepreg with higher tackiness force is achieved by more intimate contact. However, there is a pick in tackiness force as a function of temperature graph for prepreg and pressure-sensitive adhesive as well. The reason is increasing temperature reduces resin viscosity (improve tackiness force), and at the same time, resin loses its strength (lowers tackiness). To a certain point, improvement is more than weakening. Accordingly, the tackiness is increasing after an optimum point loss of resin strength is, so that results in lowering overall tackiness.

According to the Crossley report, at a very high temperature, failure mode changes from adhesive failure (failure at the interface between substrate and prepreg) to cohesive failure (failure within resin). So it is predicted that the highest tackiness force is achieved at the point that temperature is high enough to make good intimate contact, but not too much to change the failure mode [33,40,72].

Dubois group, however, presents a contradictory report about the effect of temperature, they studied the impact of probe temperature on tackiness. The report was utterly opposed to previous studies; increasing probe temperature continuously decreases tackiness force. Likewise, previous studies mentioned that increasing temperature lowers resin viscosity, which causes resin movements. As a consequence, there is a lower amount of resin on the surface of the probe, which causes weaker debonding force [45].

To be able to study the effect of temperature, Crossley group comprehensively examined two different types of prepregs: glass fiber and carbon fiber. They found that temperature profoundly affects prepreg similarly to Dubois, but, they did not use probe tests in the same way as Dubois; they used the peel test method to report the tackiness force. At first step, they did experiments on glass fiber prepreg; the results were in accordance with Dobius results, they reported a decrease in prepreg tack with increasing temperatures. These results are totally against the design of AFP. In the AFP process, heat torch is fitted to provide heat and which could result in increasing tack levels. If the heat has a detrimental effect, there is no more need for heat torch on the AFP robot. So, the decrease in recorded tack is opposite to aerospace experiences and unexpected. This leads Crossley to do the peel test on carbon fiber prepreg because glass fiber is not the common material to use with AFP robots. They tried carbon fiber prepregs, until a certain point of temperature, the observation was utterly different from glass fiber prepreg. Increasing temperature results in higher tackiness force. They explain that the reason for this controversy is the difference between carbon fiber prepreg and glass fiber prepreg failure mode. The failure mode for carbon prepreg before the critical point was correlated to dry interfacial failure. This failure mechanism is not the same as wet cohesive failure in glass fiber prepreg. After passing this critical point, increasing the temperature results in the same behavior in both carbon and glass fiber prepreg. The failure mode in peeling of glass fiber prepreg was found to be wet cohesive failure. In the peeling of carbon fiber, at the lower temperature, failure mode was attributed to dry adhesive failure. However, by increasing the thermal budget, failure mode switched to wet cohesive that is the same experiments as glass fiber prepreg. Crossley et al.

repeated the tackiness measurements with neat resin and probe test as well. Their findings showed increasing the neat resin temperature increases the tackiness [33,45,54,56].

The above findings show that the effect of temperature in all types of composites lay-up depends on the type of failure. In wet cohesive failure, higher temperature results in more contact area and more resin flow. However, it has a degradation effect on resin properties and internal strength. In dry adhesive failure, increasing the temperature results in more resin movement and a better intimate contact, resulting in tackiness improvement. In other words, in wet failure, increasing temperature decreases the tackiness. On the other hand, in dry failure increasing temperature result in larger tackiness. In carbon fiber prepreg which is focus of this study, tackiness force peak is expected to be observed at the point that wet and dry failure have an overlap.

The investigation of results demonstrates that temperature is the most important factor that affects peel force. In other words, prepreg tackiness is highly dependent on prepreg temperature during the lay-up process. In fact, the viscoelastic behavior of resin is responsible for tackiness.

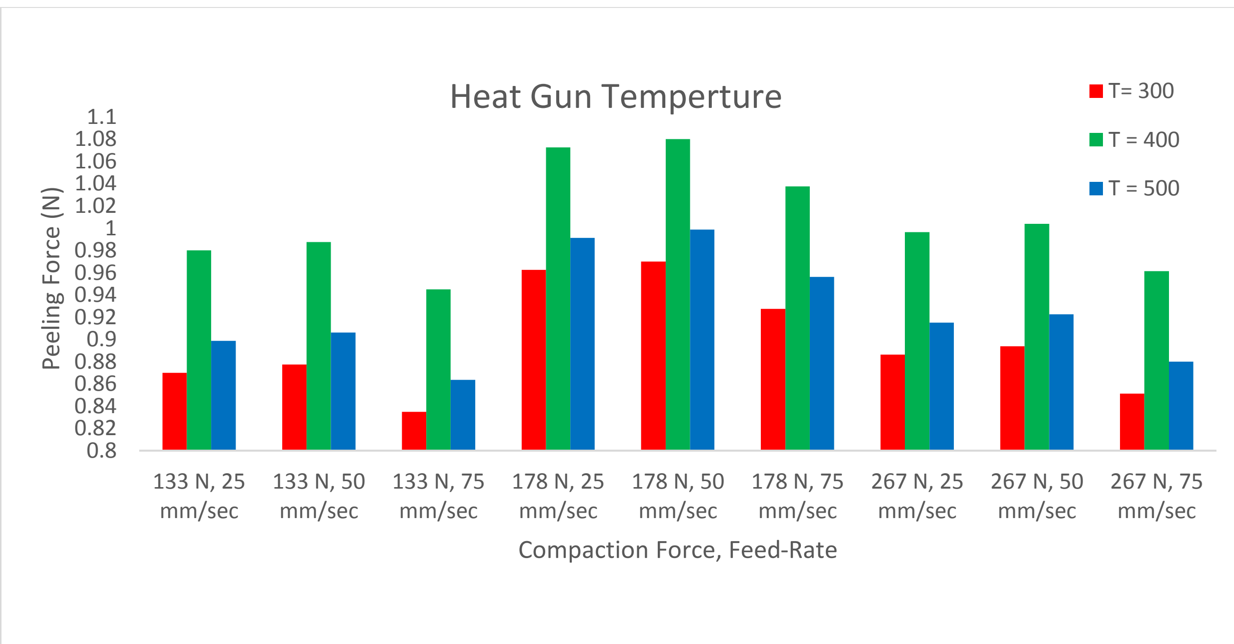


Figure 24 Taguchi prediction for temperature

Parameters that affect viscosity also affect tackiness. Heating up the prepreg decreases resin viscosity, resulting in a better intimate contact. Taguchi prediction shows a peak in the tackiness force. Generally, heating up the prepreg results in tackiest ones. However, in this study, it is predicted that the tackiness drops after a heating threshold point. This observation can be correlated to the reduction of resin viscosity (with increasing temperatures) which is accompanied by weakening the strength of the resin. It can be explained by the different types of failure hypothesis. There are two types failures mechanisms in the debonding process: (a) dry interfacial failure and (b) wet cohesive failure. As can be seen in Figure (26), below the peak temperature, the failure mechanism is dry and refers to adhesive failure. While above the peak temperature, resin loses its strength and there is a slight print of resin on the tool surface, which is due to resin cohesive failure. Figure. The most peel force is achieved at the point that cohesive failure and adhesive failure are happening at the same time. Simply resin is soft enough to move and to bound to the substrate. It is also strong enough to resist before peeling from the substrate. In summary, Failure temperature depends on the failure mechanism.

figure 25 shows in certain compaction force and feed-rate, the peeling force at 400̊ C is more than 300̊ C, 500̊ C heat gun temperature.

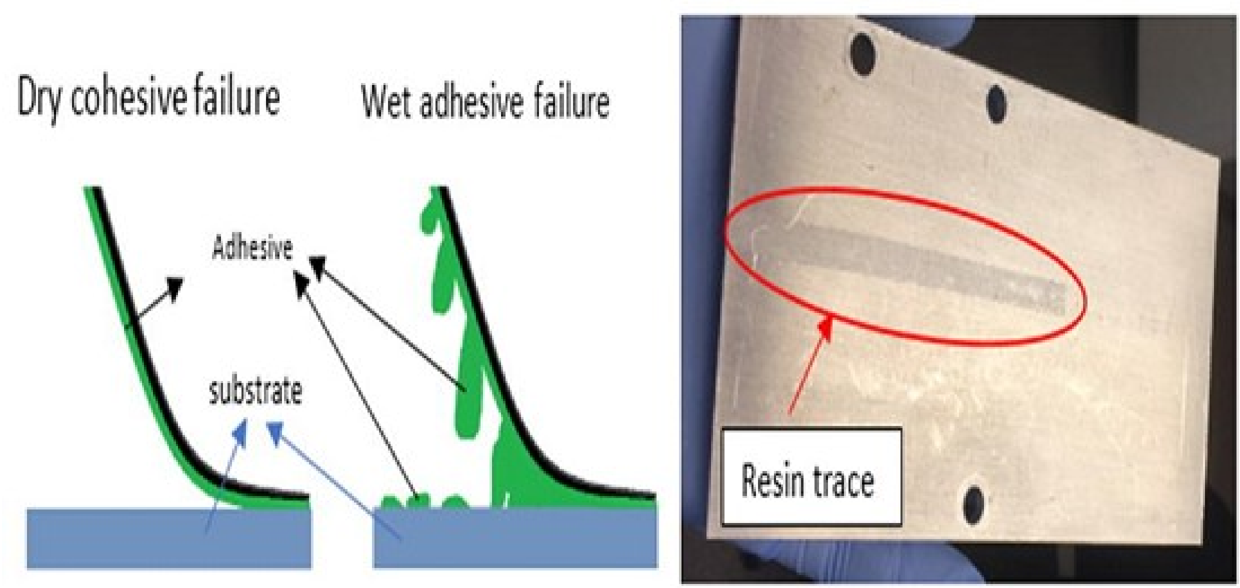


Figure 25 A. Failure types at adhesive peel test. B. Trace of Prepreg on plate at 600̊ C (wet failure)

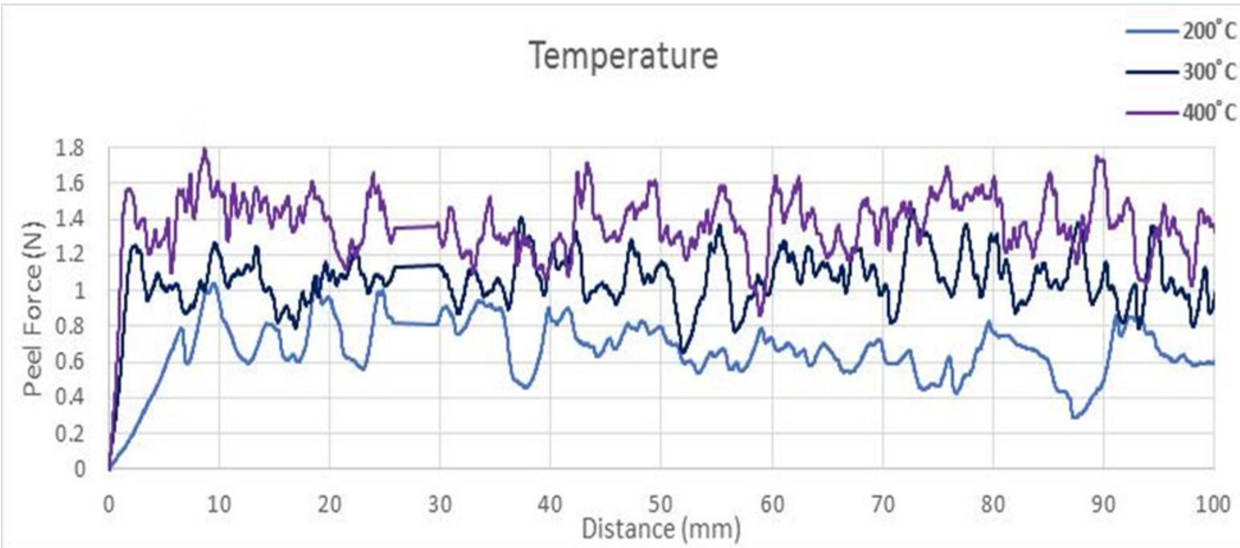


Figure 27 heat-gun temperature effect

To demonstrate temperature effect, four samples were made at 50mm/sec feed-rate speed, and178 (N)compaction force, and hard rubber roller (60 durometer). The temperatures are 200,300,400, and 500˚C. The NIP point temperature during lay-up is 26^{o}C, 28^{o}C, 31^{o}C, and 35 ^{o}C for heat gun temperature 200^{o}C, 300^{o}C, 400^{o}C, and 500^{o}C respectively. The plates are preheated up to 25 ^{o}C before starting each run of the test (the heat gun temperature limit is 500 ^{o}C). Two

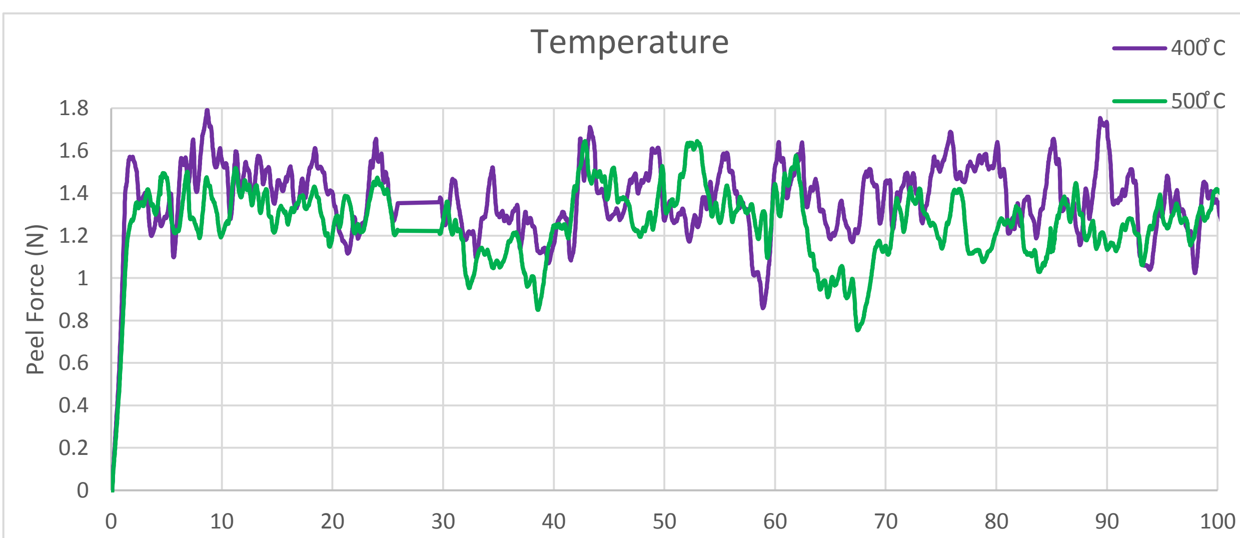


Figure 26 effect of over heating

graphs 26 shows that increasing temperature up to 400̊ C improves tackiness. However, increasing the temperature from 400̊ C to 500̊ C slightly decrease tack force.

4.1.4. Compaction force

Several groups have reported larger compact force applied to prepreg, in the lay-up process, eases the molecular mobility and the bounding formation between prepreg and substrate, both of which improves tackiness.

Endruweit et al. studied the effects of the force through two different compaction rollers. They showed after applying compaction force, compaction roller is deformed and compaction area increases, resulting in a decreased applied load on prepreg. They reported softer roller results in more contact area between prepreg and roller, resulting in a lower compaction pressure. Larger compaction area results in an increased dwell time that facilitates bonding. The more bounds made, the more tackiness force prepreg has. Hence, higher compaction pressure results in larger resin movements and longer dwell time, both of which increases tack. In their study, they found after a certain point increasing force does not show any thickness improvements and it only lowers the resin properties. Their findings showed, at a very high compaction force, increasing the force results in loss in resin properties and consequently lowers tackiness. It is worth noting that lay-up and peel off has been done at the same rate in this study [30,46,73].

Bakhshi et al. also studied the tack as a function of compaction force and compaction roller. Their study showed an increase in the contact area with the soft roller results in a longer dwell time and an improved tackiness. In this report defects investigation was done in steering prepreg, and they showed, after an optimum load point, larger force results in spreading of the resin. They have also reported a contraction after releasing the load. These two effects facilitate debonding of substrate and prepreg, resulting in a weak tackiness [40,41,58].

D. Budelmann and H. Detampel studied the effect of compaction force on tackiness. They reported stronger compaction force results in an increased tackiness. However, their findings showed, after an optimum pressure, increasing the compaction force slightly affect tackiness. They found that at a lower temperature optimum pressure is larger. They correlated this observation to the resin property at different temperature. At higher temperature resin viscosity is lower and the required force for moving the resin is lower, while in lower temperature the resin has lower flowability and harder to move, so more compaction force is needed [57].

Ivanov and Li et al. studied the effect of compaction load on prepreg movement. In this research, the minimum amount of load at which the beginning of prepreg movement happens is called *compaction limit*. They found compaction limit depends on transverse flowability of the resin, the thickness of the prepreg sample, and temperature. They reported resin viscosity has a negligible effect on compaction limit, and samples can reach compaction limit even at low temperature with high viscosity [61,74,75].

Figure 28 A: Roller deformation vs Static pressure. B: roller deformation under 89 (N). C: Roller deformation under 267 (N).

It is well known that a change in compaction force, by affecting the molecular mobility, varies bounding between prepreg and substrate. When compaction force is larger, bonding will be easier. After a certain point (optimum compaction pressure), stronger force results in widening the prepreg and a lower thickness.   In all the sample analysis, roller is made up of Polyurethane (35 durometers), and deformation can be seen in Figure 26.

When the force is applied to the compaction roller, it is deformed, thus, the softer the roller, the more contact area between prepreg and roller is achieved [ref. Bakhshi].

It is reported that in the middle part of the roller the load is constant and there is no compaction pressure difference in towering width (6.35 mm). So, there should not be any concerns regarding the uniformity of load distribution in these samples.

The best bonding was found to be for the rubber roller with 35 durometers (178 (N) compaction force). Findings shows at a certain feed-rate and heat gun temperature, 178 (N) compaction force leads to the most peeling-force.

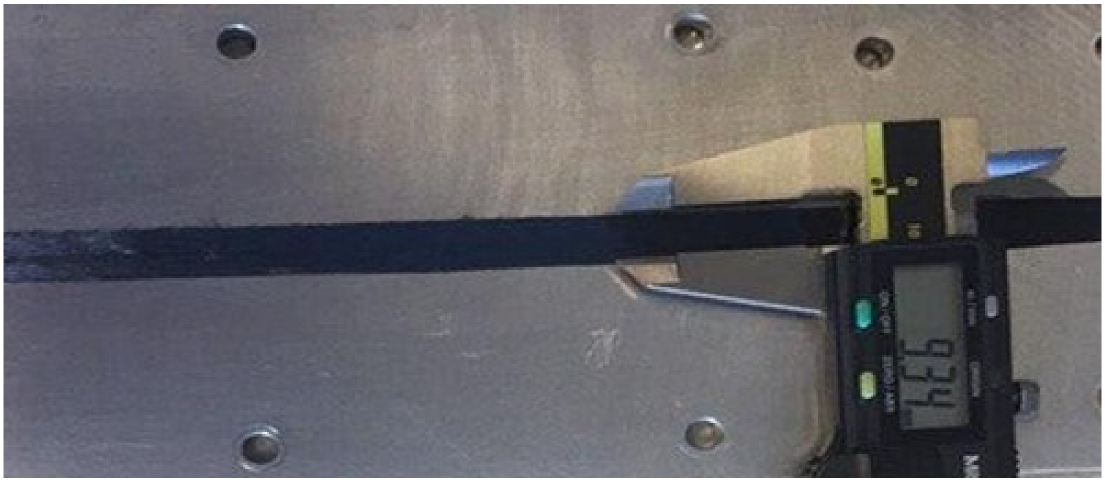


Figure 29 Towpreg expansion over a high compaction Force

To be able to have a reliable report, applied force needs to be normalized per unit width, and every single expansion must be precisely reported during lay-up.

Figure 27 shows towpreg expands when 449 (N) pressure is applied. The pressure is exaggerated to be able to be clearly shown the effect of overloading. Before lay-up, prepreg width is 6.35 mm (a quarter an inch). However, after lay-up under 449 (N) compaction force, it expands 3 mm. It needs to be mentioned that all the tests were done using soft rubber roller (35 durometers) and peel-test over 100mm of samples. In the first run of experiments, it was found that increasing the heat gun temperature results in a lower viscosity. This changes failure mechanisms from dry cohesive to wet adhesive. Findings showed at 400℃ heat gun temperature the optimum tackiness is achieved. At this temperature (400C), dry and wet failure happens at the same time which can be the dominant factor for the optimum tackiness. Roller deformation affects dwell time. The more time that towpreg is subjected to compaction force, the more intimate contact is has with roller. Compaction force more than178 (N)have a detrimental effect on prepreg properties. Compaction force is important to help resin movement and to ease bonding. Larger compaction force results in the formation of more bonds. Results show that the compaction pressure of more than 178 (N) results resin loses its internal properties, causing lower tackiness. For the rubber roller, with 35 durometers hardness, the optimum condition was found to be at178 (N)compaction force, 400℃ heat gun temperature, and 50mm/sec feed-rate speed.

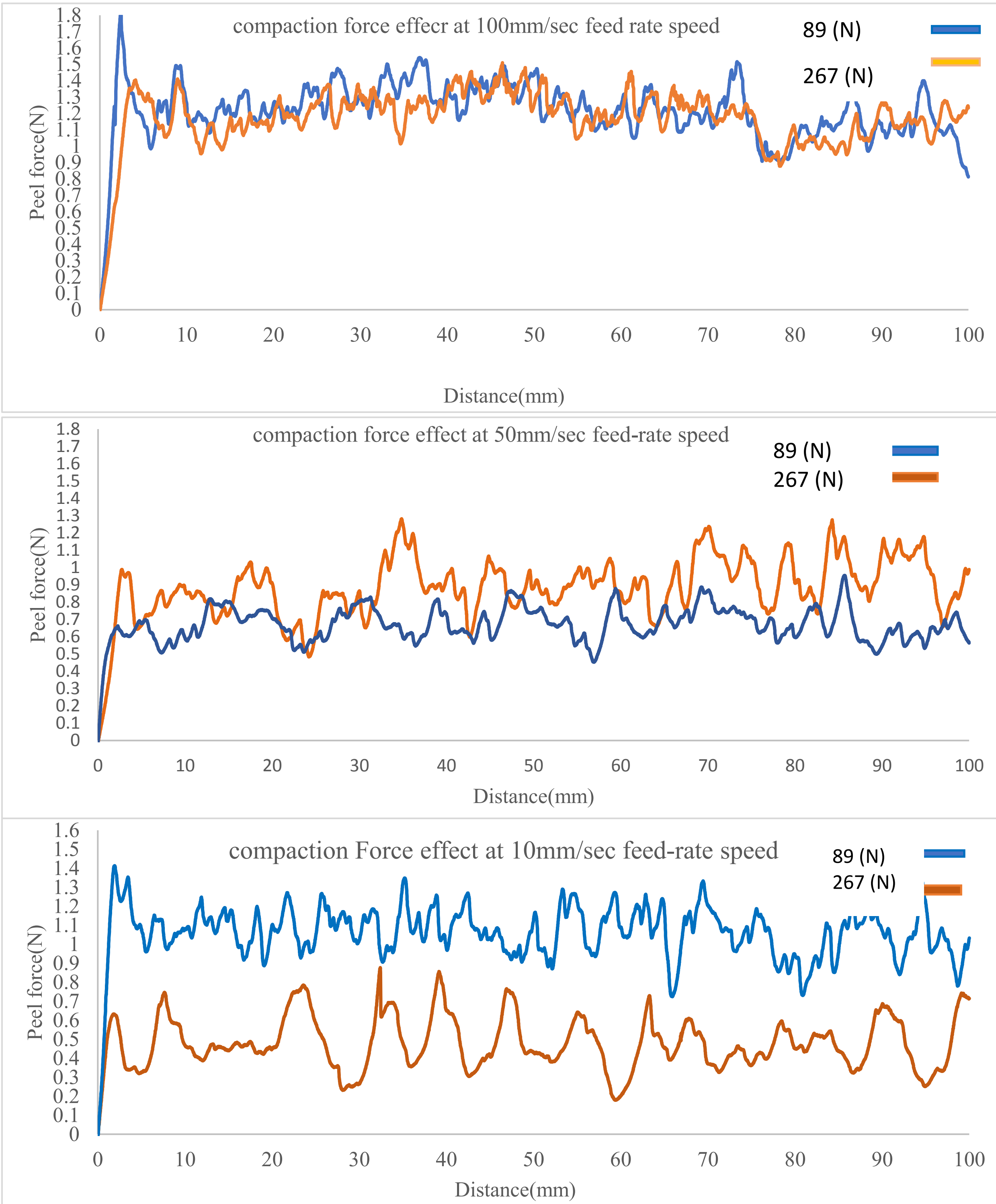


Figure 30 Compaction force effect at fast feed-rate speed

Fig. 30 shows the effect of different compaction forces at different feed-rate speeds. As can be seen in Fig. 30, the effect of compaction force becomes lower at faster feed-rate speed, since there is not enough time for the load to cause resin movements. To demonstrate the compaction force, the feed-rate speed set to the 50 mm/sec, Fig. 30. As can be seen in Fig. 31., decreasing the feed-rate at a high compaction force degrades resin and lowers tackiness force. In this research, to show the degradation effect clearly, the feed-rate speed was set at a very low rate (10 mm/sec).

Figure 31 shows that by decreasing the feed-rate, high compaction force can damage resin and results in lowering the tackiness force. To show the detrimental effect, the feed-rate speed is set at very low (10 mm/sec).

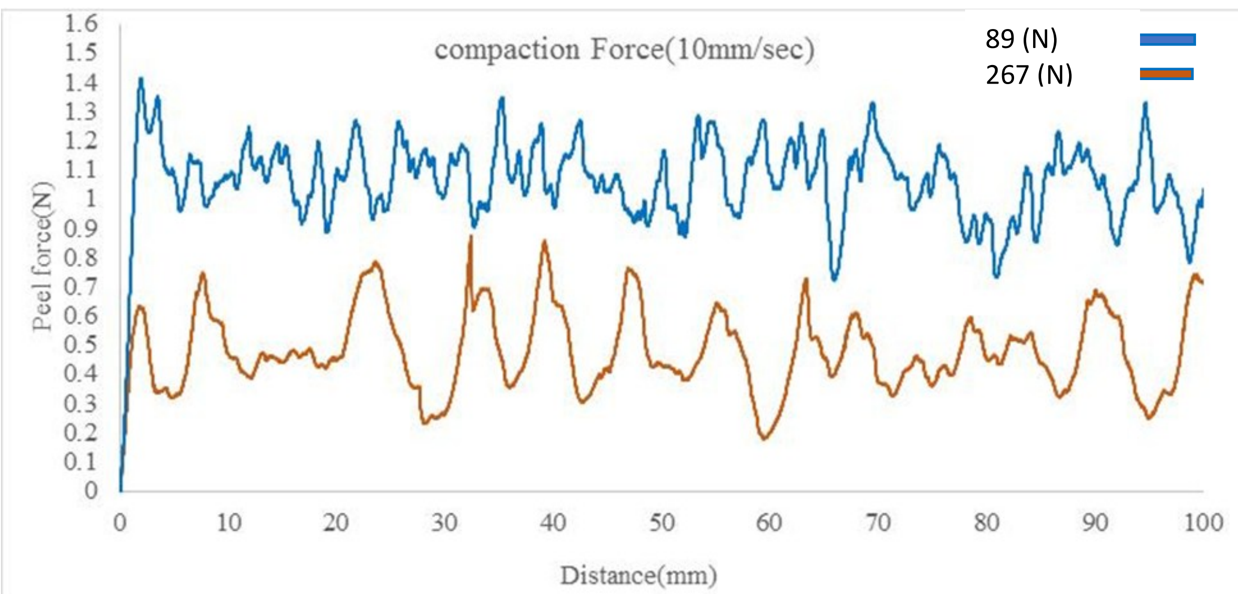


Figure 31 Very slow feed rate and inverse effect of compaction roller

4.1.5. Feed Rate Effects

To explain the effect of feed-rate, it is required to understand dwell time. Dwell time is the time that prepreg is under compaction pressure. Slower feed-rate causes longer dwell time and increasing feed-rate speed results in shorter dwell time.

R.J Crossley, who did several tests to measure the effect of feed rate isolated feed rate effect on tack, He found that changing feed rate can affect tackiness more than 90%. He found that tackiness is dependent on contact time and process time, which can be controlled by feed rate. He claimed that at low feed rates they observed a great resin deposition with wet failure mode (like high temperature) while increasing feed rate results like low temperature and lead to dry failure. Interfacial dry failure is a result of reducing contact time at a high feed rate. There is a peak in the feed rate tackiness graph; the wet failure is related to prior to peak and dry is after the peak. The highest point (the most tackiness) is related to the point where two failures happen at the same time. Two different types of failures are completely discussed in the following section.

According to his study, cutting and steering processes require a lower feed rate. Also, at the start of each ply, AFP robot must move slowly. He believed that by decreasing the feed-rate, tackiness increases. This effect is more noticeable at a lower temperature (25℃) than in a higher temperature of prepreg (45 ℃). He reported that the relationship between feed rate and the temperature is inverse logarithmic. His collecting data shows that at high-temperature, maximum tack is in high feed rate when lowering the temperature shift process toward low feed rate, since more time is required for bonding between substrate and prepreg. Lowering the feed rate assists with more molecular movement in resin which will result in stronger bonds. As mentioned earlier , the highest tackiness is at the transition point between adhesive and cohesive failure.[The report shows that William-Landel- Ferry equation is able to predict feed rate effect on tackiness.[33][56][54]

Endruweit and Choong [Reference] believe that feed rate has inversion relation with the duration of compaction. They found that a maximum tack force happens at low feed-rate when the temperature is low, and increasing temperature shifts the feed-rate speed toward higher amounts. Their study shows decreasing feed-rate since it increases the time for the bond to form between prepreg and substrate, which improves adhesive failure, and decreases cohesive failure[46].

There is an optimum speed feed-rate if the other conditions such as temperature, compaction force, surface roughness remain constant. Feed-rate has an effect on the viscoelastic behavior of composite and changes tackiness as a consequence. To maximize tackiness at a certain temperature and compaction force, the feed rate must be controlled.

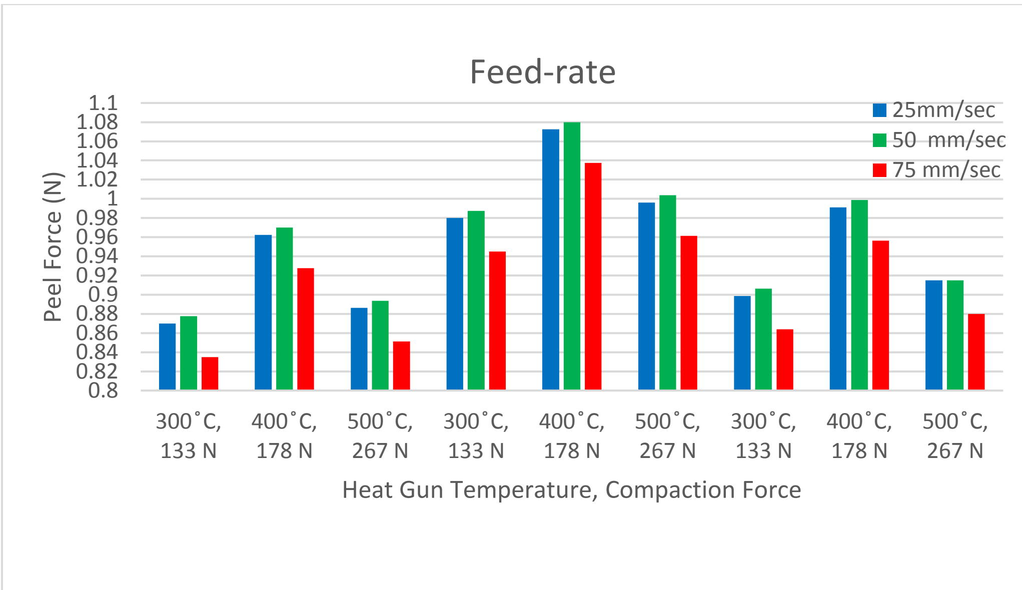


Figure 32 Peel force per unit width at Different Feed-rate Speed

Several tests have been performed to measure the effect of feed rate. Isolating feed rate effect on tack, it has been found that changing feed rate from 25 mm/sec to 125 mm/sec can affect tackiness up to 20%. It is observed that at low feed rates (like high temperature) there is a resin movement, while increasing feed rate results in (like low temperature) lowering resin movement, which leads to less bonding with the substrate, and lower peeling force. The faster the roller moves, the shorter the dwell time results in less tackiness. It is proposed that tackiness will increase by decreasing feed rate. However, after a certain speed, moving slower causes too much pressure and heat on resin, which consequently lowers resin viscosity too much and it loses its properties, resulting in lowered tackiness. It is found that tackiness is dependent on contact time and process time, which can be controlled by feed rate. The tackiest prepreg (the maximum peel force) is made by the feed rate where the speed is low enough for resin deposition and fast enough to avoid too much heat and pressure on resin so that its properties could be maintained.

That feed rate is optimum in certain process conditions such as roller type, temperature, compaction force, surface roughness, etc. Changing process parameters will push the optimum point to a different feed rate speed.

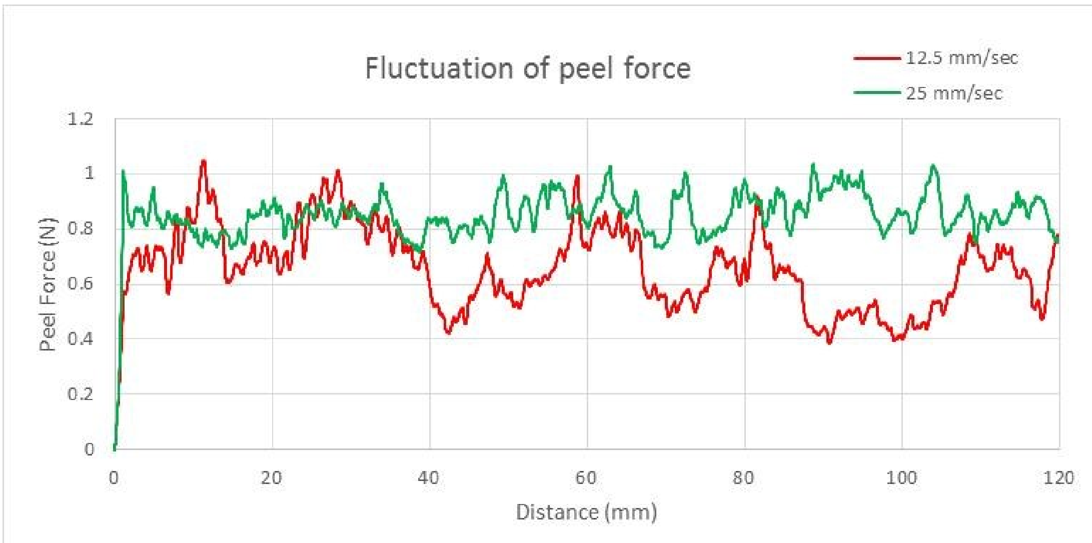


Figure 33 Feed-rate effect

Previous studies showed that at the high temperature maximum tack is at a higher feed rate while lowering the temperature shifts the process toward a low feed rate since more time is required for bonding between substrate and prepreg. In low compaction force, the optimum feed rate moves toward lower lay-up speed, while in high compaction force, the optimum point moves toward higher speed. As mentioned above, the highest tackiness is at the point with the most resin movement, while resin keeps its own properties. There is a fluctuation in the peel force; figure 33 states that decreasing feed rate will result in smaller range of force. Lowering the feed-rate helps with more molecular movement in resin which will result in stronger bonds. As the graph demonstrates, increasing feed-rate from 25 mm/sec to 125mm/sec increases the range of peel force in a sample. It is not safe to have a wide range of peeling force. It causes local buckling in areas with low tackiness, which induces premature failure.

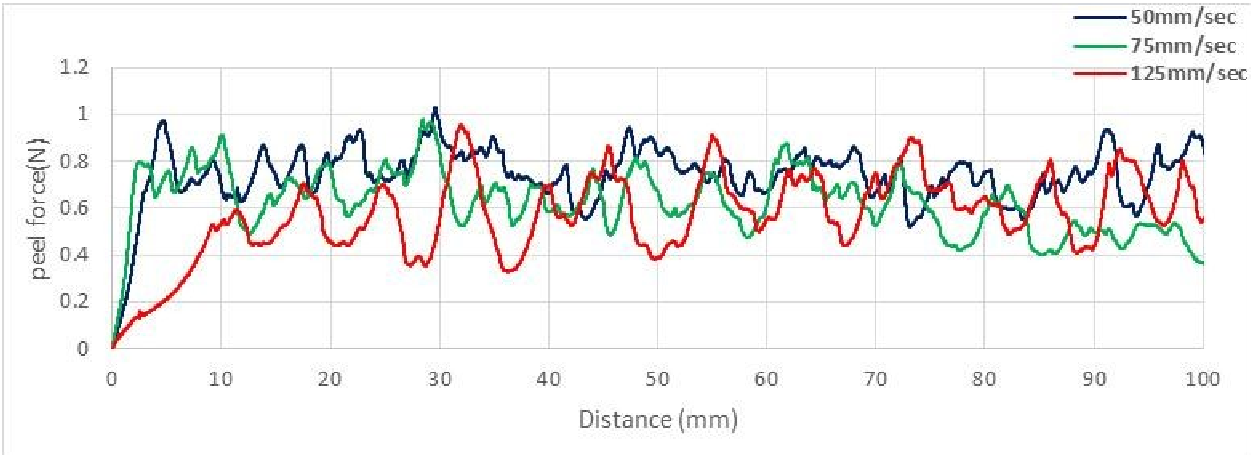


Figure 34 Feed-rate effect

Unless the amount of temperature and compaction force are enough to make a good bonding, the study could not be performed. Figure 34 demonstrates that at 89 (N) compaction force, the amount of maximum peel force for all three samples are the same. However, the faster feed-rate the more fluctuation peel-force graph shows. Feed-rate effect is less than temperature and compaction force.

4.2. Compaction roller effect

4.2.1. Roller type

To understand the effect of the roller, A. Endruweit used two different types of soft and rigid rollers. They observed that at the same compaction force, using a soft roller will result in lower tackiness, and also the optimum compaction pressure for soft roller is more than the force for rigid roller. Despite the fact that the compaction pressure is smaller with the soft roller, the dwell time is longer, which would result in higher tackiness. (There is more time for bounds to be made). [46]

Bakhshi et al. studied the effect of five different rollers on defect formation and quality of the final part. They studied hard, perforated, soft robber roller and steel roller. They found that hard rubber roller produces higher quality sample than the perforated roller because the load is evenly distributed in hard rubber roller while in perforated, roller architecture causes changes in load distribution and local tackiness. Moreover, due to their uniform deformation, which leads to longer dwell time and equal load distribution, hard rubber roller represents samples with higher quality than samples made by stainless steel rollers[65]. Few studies regarding the effect of the roller are done and required to be investigated thoroughly.

In order to be able to investigate the effect of compaction roller, before running the tests it is necessary to have an understanding of roller behavior under compaction load. Perforated, hard rubber, and metal roller are installed on the AFP simulator set-up and 20,40,50,60, and 80 LB compaction force are applied respectively, and the deformation of rollers are measured.

Force	Perforated Roller	Hard Roller	Metal Roller
89 (N)	9mm	8mm	Line contact
178 (N)	13mm	11.5mm	Line contact
222 (N)	15mm	13mm	Line contact
267 (N)	16mm	15mm	Line contact
356 (N)	16mm	15mm	Line contact

Table 7 roller deformation

Testing three rollers at different forces and measuring deformations show that increasing the force on polymeric rollers causes deformation up to a certain amount of force, after 267 (N) compaction force, the deformation becomes steady since there is no extra room for roller to deform (because of the metallic core inside). Instead of compaction load, the new term is defined as compaction pressure that is compaction force divided by the contact area. For the metal roller, no deformation is observed by changing the compaction force, so the compaction pressure remains the same at different compaction forces.

To investigate the effect of roller types, a range of heat gun temperature, compaction force, and feed-rate must be selected so that the roller types effect become observable and easy to measure. For example, at low compaction force, 89 (N), or high compaction force, 267 (N), the deformations of perforated and hard rubber roller are similar amounts and it is not clear to distinguish between these two types of rollers.

	Compaction Force (N)	Roller	Feed-rate (mm/sec)	Heat-gun temperature (̊C)	Average peel Force (N/mm)
1	89	Metal	25	350	0.143
2	89	Perforated	50	400	0.101
3	89	Hard	75	450	0.113
4	133	Hard	50	350	0.093
5	133	Metal	75	400	0.123
6	133	Perforated	25	450	0.140
7	178	Perforated	75	350	0.095
8	178	Hard	25	400	0.169
9	178	Metal	50	450	0.113

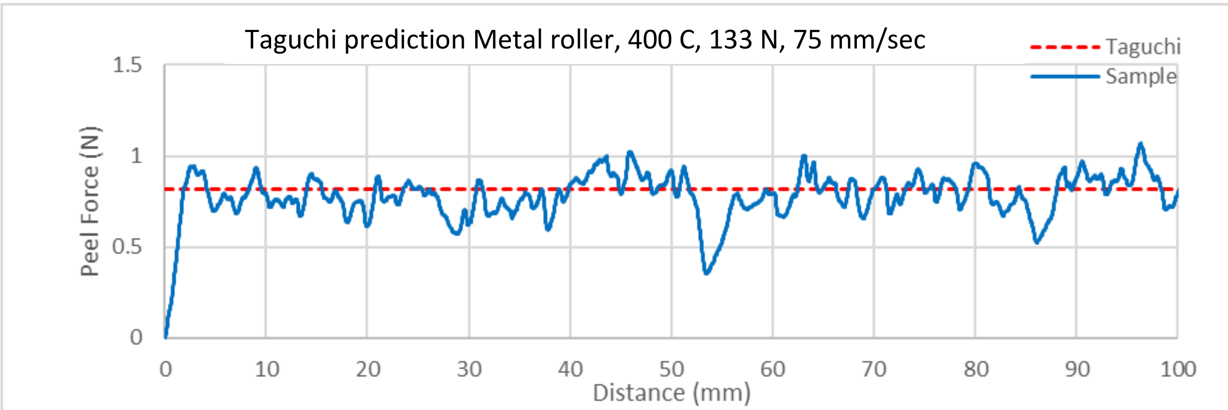
Table 8 DOE for investigation of roller effect

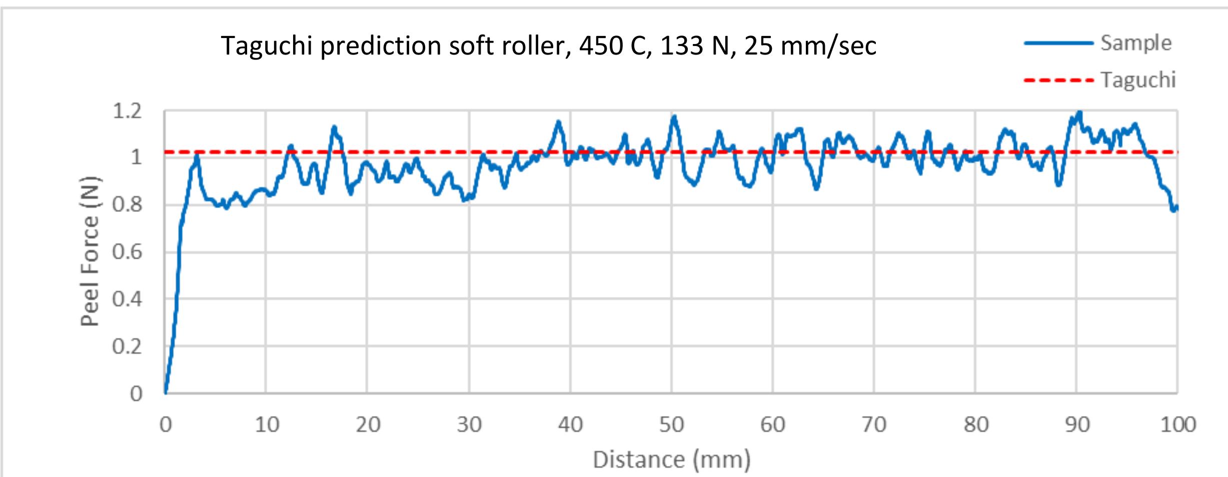
Three rollers, three feed-rate speed, three compaction force, and three heat gun temperature. Using a common factorial method requires 81 different tests, to be able to get reliable data. At least each test must be repeated three times simple calculation with suggested 243 different tests. Using Minitab software and Taguchi Design of Experiment method suggests two orthogonal arrays for this series of experiments, L9 (Taguchi series require 9 tests to be done) and L 27 (Taguchi series require 27 tests to be done). Since the effect of heat gun temperature, compaction force and feed-rate are studied earlier, there is no need to do L27, so L9 is selected. After running the series, the data is input to MINITAB software, the remaining will be predicted. Here is the experiment table designed by DOE. (Each test must be done three times and the average of three tests is reported.)

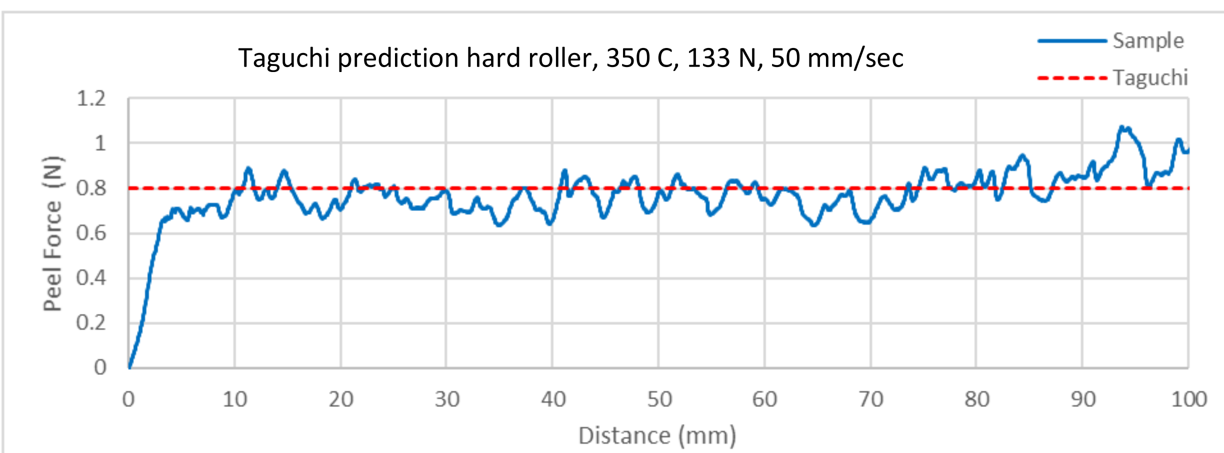
and Taguchi prediction is compared to the real test measurement.

Compaction force is a factor that causes roller deformation, consequently, dwell time and compaction pressure. Simply roller type has an intermediary effect, changing roller changes dwell time and compaction pressure at the same time.

A significant factor that can remarkably affect the tackiness of the prepreg is the dwell time (the time that the intimate contact between the substrate and the prepreg surface is recognized). Bakhshi et al. claimed that increasing dwell time facilitates bond formation. Also, they report that dwell time is influenced by roller type; keeping the same feed-rate speed, softer roller represents more dwell time. More importantly, they reported that the longer dwell time provides steady and uniform compaction force all over the prepreg. [40,41,58]. To be able to verify the roller effects, for each type of roller, a random sample is selected.







O. Ben-Zion and A. Nussinovitch studied the effects of dwell time, surface roughness, and load on the formation of the bond using different types of pressure-sensitive adhesive. They designed a new apparatus to be able to measure dwell time as well as controlled pressure. Increasing dwell time is equivalent to decreasing lay-up speed, so it helps the resin to wet the substrate surface in a sufficient amount of time. They found that the dwell time effect is the same as feed rate and peel rate. In addition, decreasing dwell time shortens the time for molecular attaching and will result in gradual loss of tackiness. The longer time the resin has, the stronger bond it will make. In other words, longer times allow more intimate contact and more surface area to be wetted [42,67].

Measuring dwell time for the AFP process is more sophisticated than the prob tests. Because the silicon rubber roller using in AFP is softer than the aluminum tool used in prob testing. So, when compaction force is applied, the compaction roller is deformed and not only the compaction pressure is changed but also the dwell time got longer. Since at different compaction pressure, architectures of rollers are changed, this series of experiments are explained in three different compaction forces.

Analyzing the results shows that at 89 (N), 25 mm/sec feed-rate, the metal roller leads the experiments to the best tackiness (slightly better tackiness than a hard roller). The reason is Metal roller shows no deformation and conducts the force directly to the linear area of prepreg. The applied load to the prepreg cross-section is the same as the compaction force. However, in hard and perforated roller under 89 (N) compaction force there is a roller deformation and the load are applied on the wider area, which increases the dwell time but it costs lower compaction force in linear cross section. Although the dwell time is long for hard and perforated roller, the force is not big enough to be able to make strong bonds. At 50 mm/sec and 75 mm/sec feed-rate speed there is a substantial drop in reported tackiness. The reported force is a very low number

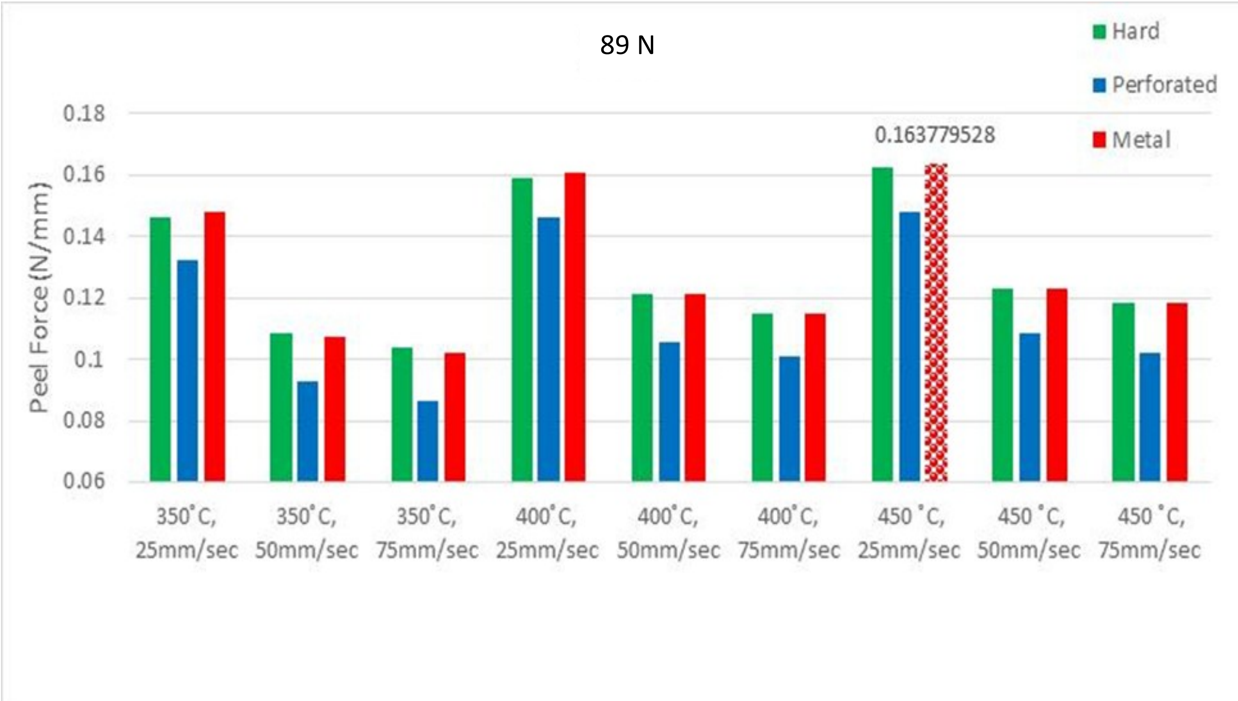


Figure 36 Peel force per unit width at 89 (N)compaction Force. The most peel force is highlighted

(hard roller has the most peel force at these speeds). Because while using metal roller conduct more compaction force, the time is very short at feed-rates faster than 25 mm/sec, even the force is strong enough, there is not sufficient time for bonds to be made.

At 133 (N), there is an overall increase in reported data for tackiness rather than 89 (N). The hard roller gives the better results than metal and perforated roller. The force is enough for bonding and there is sufficient dwell time, which causes the hard roller declares the best tackiness. For the perforated roller, the force is not strong enough to be able to make stronger bonds than metal roller (compaction pressure effect); metal roller has lower dwell time than hard roller (dwell time effect).

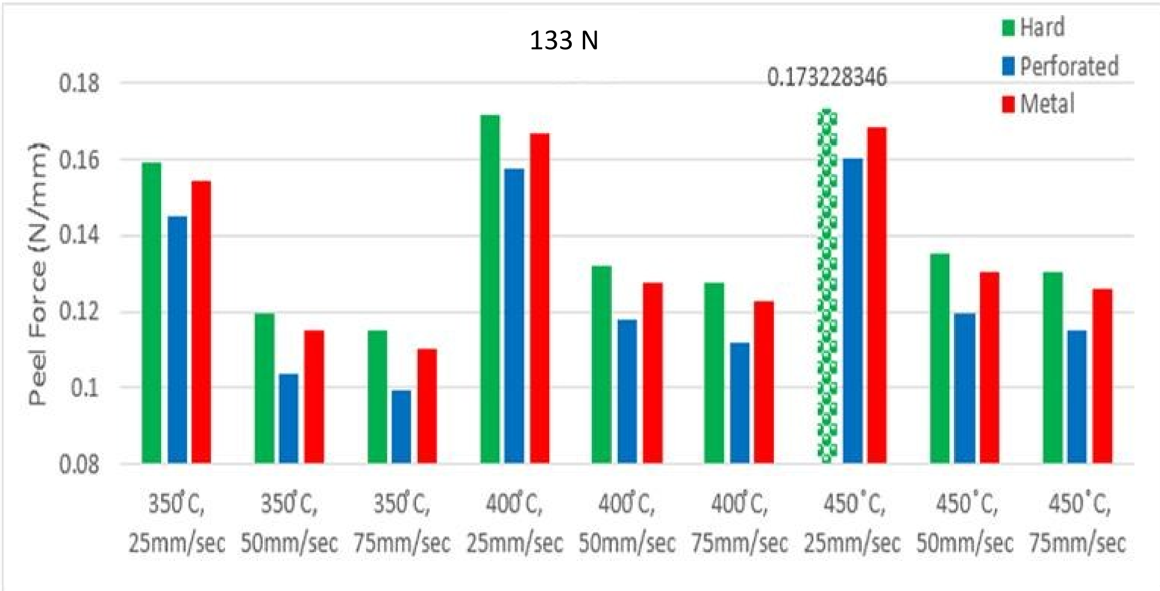


Figure 37 Peel force per unit width at 133 (N)compaction Force. The most peel force is highlighted.

At 40 LB, Metal roller shows the lowest amount of tackiness in comparison with other rollers. The reason is, the amount of applied force on prepreg cross section is too much which causes resin moves on the plate and after lay-up, the width of prepreg measured 8.5 mm. For metal roller increasing force more than 133 (N) results resin loses its properties. At 450̊C heat gun temperature and 25 mm/sec feed-rate speed perforated roller reports more peel force than hard roller. For hard roller, the compaction pressure is strong, the dwell time is long, and the temperature is high, consequently resin loses its properties, that results lower tackiness than perforated. In contrary, for the perforated roller, although dwell time is more than hard roller, the compaction pressure (force applied on linear cross section) is lower than hard roller that does not have detrimental effect on prepreg. So, at 25 mm/sec perforated results better tackiness than hard roller. However, increasing feed-rate speed causes hard roller shows better tackiness than perforated one. Since time is not too long for hard roller to damage prepreg, so hard roller reports more peel force than perforated roller.

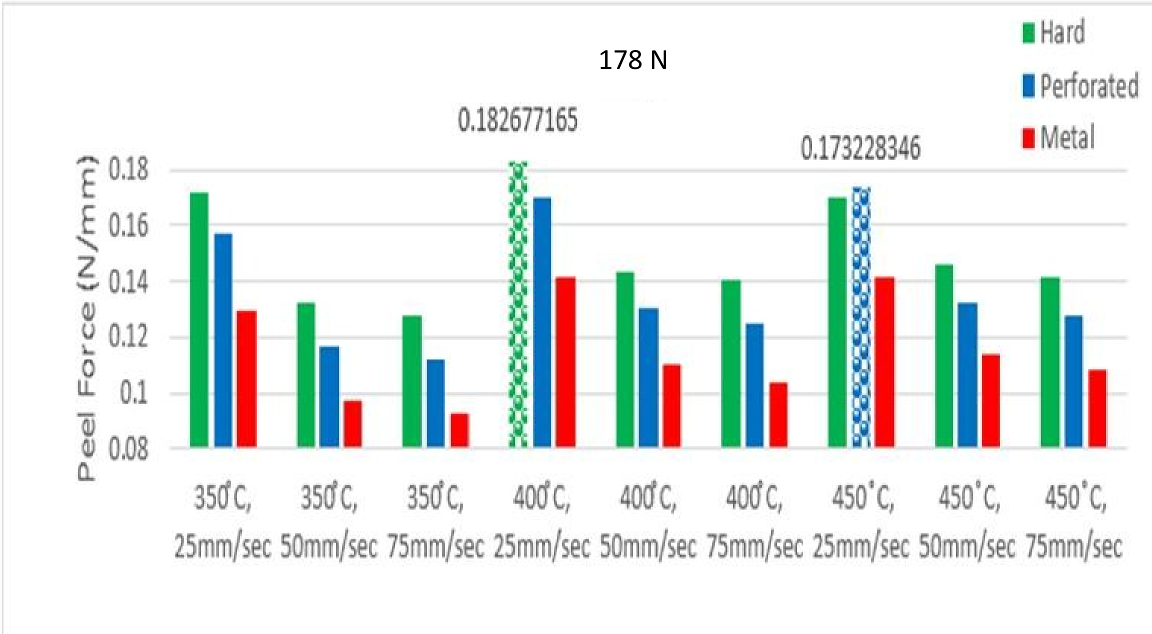


Figure 38 Peel force per unit width at178 (N)compaction Force. The most peel force is highlighted.

4.3. Surface roughness

Yana Peykova et al used optical video imaging and prob tests to study the effect of surface roughness on the tackiness of the PSA (pressure sensitive adhesive). To understand the detachment mechanism, during takeoff, a microscopic analysis of video images of the sequence is used. Despite the fact that the release processes are linked to the deformation and rupture of the fibrils which are controlled by the viscoelastic properties of the polymer, the roughness of the surface - either of the tool or the adhesive, has a significant effect on adhesion. The surface roughness influences the number of cavities and their size. The increase in roughness leads to an increase in the number of cavities, which results in a decrease in the adhesion force and a weaker adhesion. Adhesion to the surface depends on the total contact between the adhesive and the surface. Adhesion is a low-speed process and depends on the flow rate and the wetting capacity of the adhesive under pressure. At low temperatures, when the adhesive is viscose, such as prepreg materials, the surface roughness has a detrimental effect on the contact, which leads to a weaker adhesive force. However, at high temperatures, the viscosity of the adhesive decreases, and the resin can fill the surface cavities. Thus, at high temperature, the increase in roughness will lead to better adhesion. At high temperature the larger the surface of the cavities, the greater the adhesion force. They discuss three different stages for detachment:

1. At maximum force, cavity formation begins.
2. Growth of the cavities in the lateral and normal directions respectively.
3. Failure occurs in the mood for adhesion or cohesion.

Adhesive failure occurs when the temperature is not too high - less than 160 degrees Fahrenheit - (within the range of prepreg in an automatic fiber placement process). Their comprehensive study shows that the value of the release force decreases sharply with the increase in the roughness of the tool. Increasing the temperature can increase the wetting capacity of the resin, improves the contact between the tool and the handle, and therefore changes the failure mode to cohesive mode, which is the failure of the resin. It should be mentioned that at a temperature above 160 degrees Fahrenheit, increasing the roughness of the surface will increase the contact between the tool and the adhesive and give increased adhesion strength. However, curing will occur when the placement of the fibers is not completely finished and the part is partially cured at room temperature, which has a detrimental effect on the final part. At temperatures above the range, the resin loses its properties and becomes less sticky. In conclusion, the peel force of the adhesive is increased by the surface roughness or the roughness of the adhesive, if the breaking mode is in the adhesive range and not in the cohesion range, otherwise the adhesion strength will decrease in increasing the roughness of the surface.[64][65]

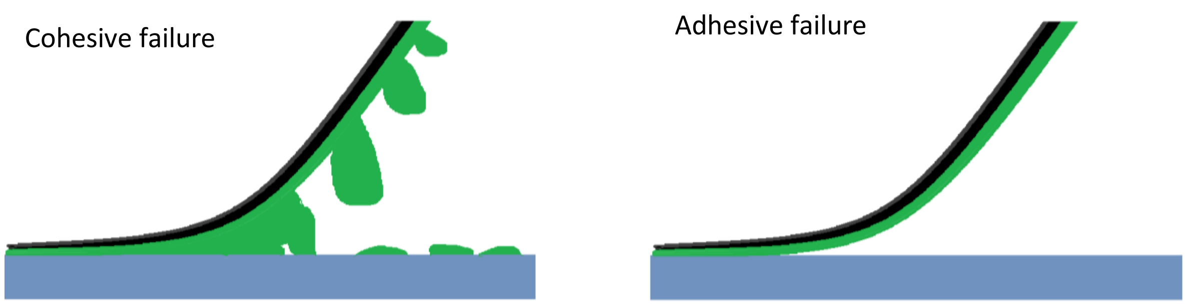


Figure 39 types of failure

O. Ben-Zion and A. Nussinovitch studied the effect of surface roughness on PSA tack using a probe test method. They tested five different tacky materials, and reported in most cases increasing compaction force can compensate for the effect of surface roughness. Decreasing dwell time augments the effect of surface roughness and lowers tackiness.[67]

W. Kim and I. Yun used the fracture energy mechanism to investigate the effect of surface roughness. They claimed that surface roughness indirectly changes the failure mode from adhesive to cohesive failure. According to them, surface roughness does not improve the debonding force unless an increase in surface roughness causes failure mode to change from adhesive to cohesive.[65]

"This part is done using hand lay-up".

In this study, four different surface roughness, R= 0.27, 0.33, 0.42, 0.57 µm are studied. Using the soft roller, 400 C heat-gun temperature, and hand-lay-up.

The average forces for four roughness are 1.05, 0.86, 0.78, 0.63 (N).

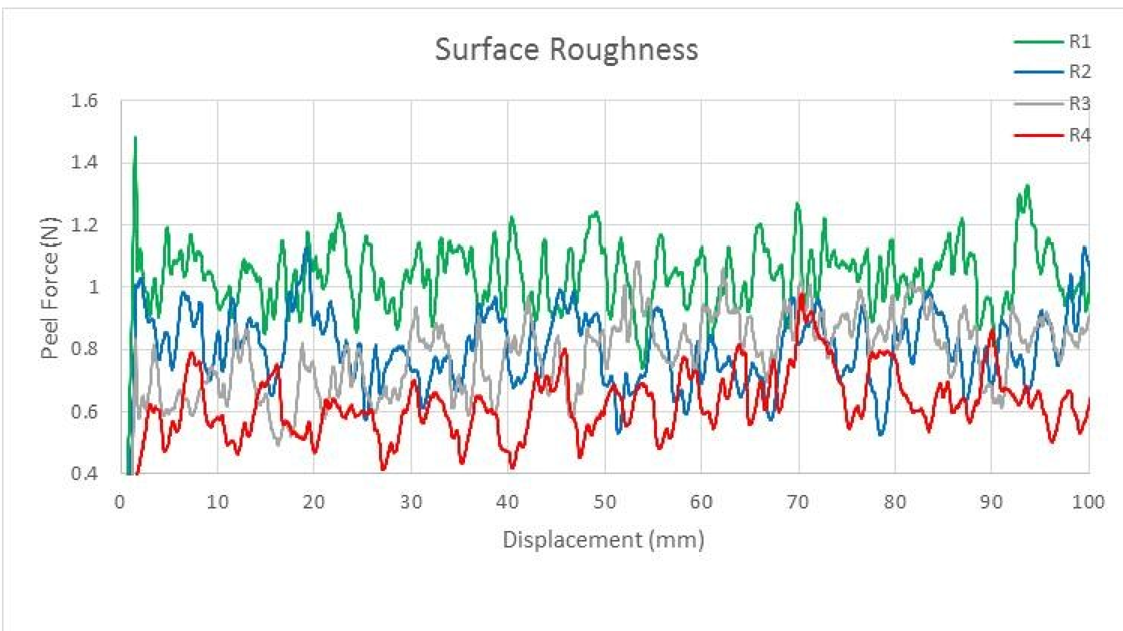


Figure 40 Surface roughness effect. R1= 0.27 µm, R2= 0.33 µm, r3= 0.42 µm, R4= 0.57 µm

Figure 40 shows the effect of surface roughness on tackiness in four different roughness. It proves that at hand-lay-up condition, increasing surface roughness lowers the tackiness force.

The peel force fluctuation is in accordance with surface roughness. Increasing surface roughness results weaker bond between prepreg and aluminum surface, and also peel force fluctuation increases in a sample.

4.4. Different substrate materials

Before discussing substrate materials, it is worth to consider that the towing strips are covered on one side with backing paper and on the other side that has no paper. In all reports, to be reliable, it must be certain which side of the tow strip is used to measure tack. The side with backing paper has a material on its surface which facilitates the removal of the backing paper, which causes changes in the properties of the resin and the distribution on the surface of the prepreg, therefore, the results are different in due to different contacts and a different wetting capacity due to the different properties of the resin. For example, Andreas Endruweit et al tested with different sides of the prepreg and found that the surface of the prepreg with backing paper shows more tackiness than the other surfaces. They made a special fixture to do peel testing. They studied tackiness between prepreg and cleaned steel surface on the tool. They defined two different surfaces for prepreg, one in contact with backing paper and the other side. So, they study all the possible probabilities, paper side of prepreg on the side without back paper, and prepreg with or without back paper on the steel surface. [46]

The AFP process is between tool surface (normally aluminum) and prepreg surface without backing paper. To measure prepreg tackiness, they have done their tests on two different surfaces of prepreg. to do prepreg surface on prepreg surface tackiness test, they used double-sided adhesive tape to assure that the rebounding force might not be affected during the tests. They also showed the differences between volume and distribution of resin on two sides of the prepreg surface and found that the results are different on each side.

It is been reported that in their tests prepreg-prepreg tackiness was generally more than two times than prepreg-steel tackiness. In addition, the tackiness between two sides of prepreg - both on backing paper - is more than one side of backing paper and the other side. The results are affected by resin volume, the surface with more resin will result in more tackiness. They describe this behavior with physical properties on the steel surface and polymer chain behavior in resin.

For substrate materials, steel, aluminum plate or 0, 45, 90 degrees prepreg can be used and search for results. Again, even for the lay-up, the side of the prepreg used should be mentioned and the result should be discussed. Fortunately, it is evident when using prepreg as a substrate, the adhesive strength is much higher than the metal plate. This can be explained by the fact that, while measuring the adhesiveness in two bonded prepregs, due to the properties of the resin on the two surfaces, the prepreg is better connected than with a metal plate. But the problem is during the peel test, the substrate layer must connect completely to the tool, otherwise peeling could occur between the prepreg layers and the tool surface. In addition, the adhesion strength measured for the unidirectional prepreg at 45 degrees gave more than 0 and 90 degrees, which can be explained by an increase in the area between the substrate at 45 degrees and the prepreg layer at 0. degree above. Overall, to fully measure the process, the diverse substrate of the metal plate and prepreg should be examined, and then the result should be interpreted [46,54-57].

"This part is done using hand lay-up".

To be able to study different substrate materials, hand lay-up is selected and lay-up is done on aluminum plate. To be able to do lay up on prepreg surface, first two towpregs are placed at the surface of aluminum plate using hand lay-up. both ends of the towpreg is completely attached to the plate using a tape. Then, second layer of prepreg is placed on top of laid-up prepreg. Peeling test must be done very carefully so that pregreg layer placed underneath not to be peeled off from aluminum plate. Figure 41 shows that the peel force for prepreg laid-up on prepreg is more than peel force for prepreg on aluminum surface.

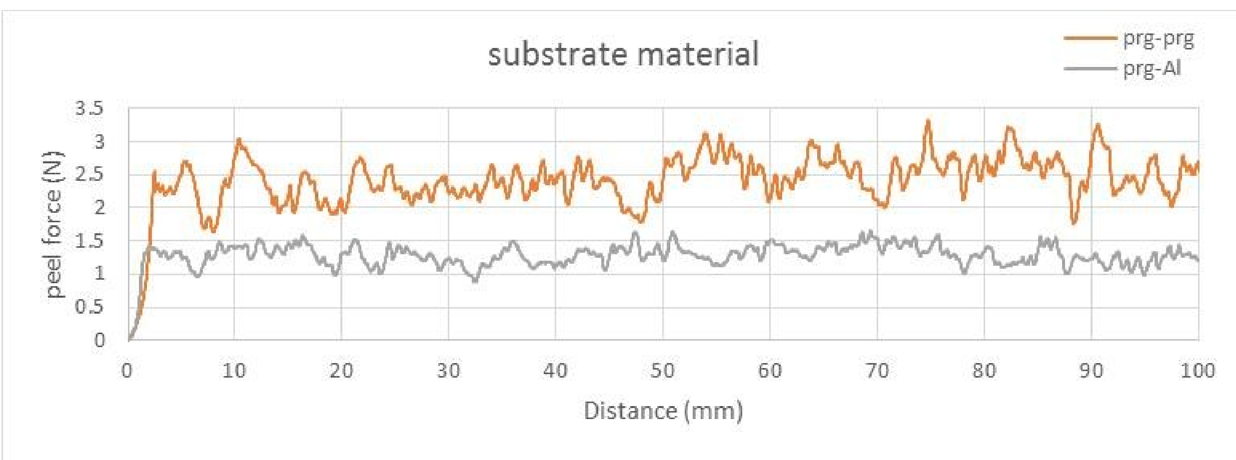


Figure 41 different substrate materials

4.5. Peel Rate Speed

After the lay-up process has been completed by AFP or other devices, to make a comparison between two samples, a peel test must be carried out. Although the peeling rate does not affect the properties of the lay-up process (since the manufacturing is already finished), it considerably affects the reported peeling strength.

L. Zhang and J. Wang studied the PSA peel test. They reported an increase in the reported debonding force by increasing the speed of the peel-rate.[68] Mohammed and Charalambides studied peel force while keeping the peel rate speed constant to be able to model the peeling process for PSA.[66] There are few studies on the effect of the peel rate, and in some cases, this misleads the study reports. For example, A. Endruwiet studied the effect of different parameters on the adhesiveness of the prepreg; however, in their configuration, the peel rate must be identical to the feed-rate which changes the whole results.[46] Regarding this problem, for example, at low temperatures, when the feed rate is low, the tackiness is high, but the peeling test is carried out at low peeling speed, the results show the opposite. Thus, by increasing the feed speed, at low temperatures, the tackiness decreases, while the peel speed increases, which shows better results than expected. It should be mentioned that increasing the peel rate leads to an increase in peel strength, which means high tackiness. So, peel-rate and feed-rate, inversely effect at low temperature, and the effect is emphasized in high temperature. To wrap it up, it is required to have the same peel-rate to make a comparison between two samples precisely.

"This part is done using hand lay-up".

Three different peel rate speed, 50, 100, 200 mm/min are investigated. The results show that increasing peel-rate speed cause an increase in reported peel force.

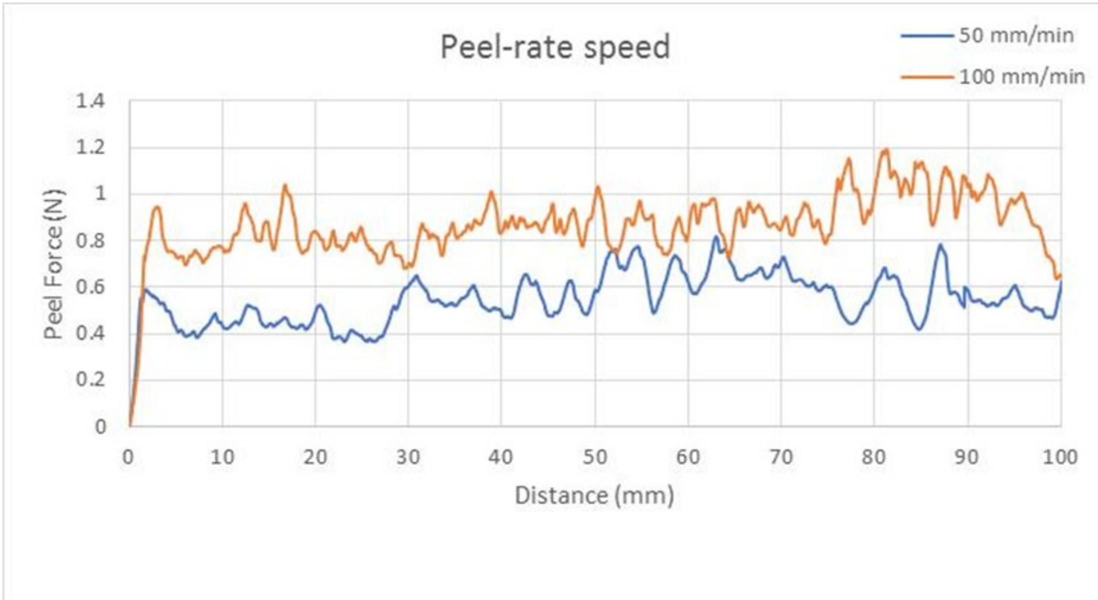


Figure 42 peel rate speed effect in hand lay-up

5. Conclusion

The final lay-up produced by AFP creates a different type of defects. Tackiness properties of laid-up towpreg play an imperative role in defects formation. Several factors affect tackiness; In this study, compaction force, heat gun temperature, feed-rate speed, dwell time, and roller materials were comprehensively investigated. Two indoor set up was used to lay-up prepreg and measure tackiness force. Tests result shows that increasing heat gun temperature results in lowering viscosity, which causes failure mode changes from dry cohesive failure to wet adhesive failure. It is found that for soft rubber roller at 400 ℃ heat gun temperature, the optimum tackiness is achieved because, at this temperature, dry and wet failure happens at the same time. Feed-rate affects dwell time, so the slower the feed rate, the more time towpreg is under compaction force. The optimum feed rate speed for soft rubber roller is found at 50mm/sec. Feed-rates lower than 50mm/sec had a detrimental effect on prepreg properties since the load is applied on prepreg for a long time. Compaction force is essential to help resin movement and to ease bonding. The more compaction force, the more bond to be made. Results show that for soft rubber roller the compaction pressure more than 178 (N) results resin loses its internal properties, which cause unexpected lower tackiness. For the soft rubber roller with hardness 35 durometers, the optimum condition is found at178 (N)compaction force, 400 ℃ heat gun temperature, and 50mm/sec feed-rate speed.

Changing roller types changes dwell time and compaction pressure. At low compaction force, it is the metal roller which leads to the tackiest prepreg, in higher compaction force hard roller showed the tackiest prepreg laid-up. At high temperature, low feed rate speed, and strong compaction force, it is a perforated roller, which shows the highest peeling force. For metal roller the optimum condition is found at 133 (N)compaction force, 450℃ heat gun temperature and 25mm/sec feed-rate speed. For hard rubber roller with 60 durometer toughness,178 (N)compaction force, 400℃ heat gun temperature and 25mm/sec feed-rate speed is the optimum condition. For perforated roller the optimum condition is at178 (N)compaction force, 450℃ heat gun temperature and 25mm/sec feed-rate speed. The optimum condition differs regarding roller, changing roller from metal to perforated, changes optimum condition towards higher compaction force.

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