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MASTER'S THESIS

Rapid Automated Induction Lamination (RAIL) of Carbon Fiber Weave and Thermoplastic Film

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1. INTRODUCTION

This work is a continuation of the RAIL - Rapid Automated Induction Lamination - process developed by S. Yarlagadda et al. [1] & [2] at the Center for Composite Materials, CCM, at the University of Delaware. The RAIL process was developed and optimized for lamination of AS4/PEI unidirectional pre-impregnated carbon fibers (called prepregs) using induction as the heat generating system.
For this report the work has been focused on a different setup where the multilayer composite consists of a stack of plain carbon fiber weave and a thermoplastic film, in this case Nylon™. An alternative molding process has also been investigated with the aim to obtain a non-flat laminate. The goal was to obtain composite profiles and the process would be an alternative to pultrusion.

1.1 BACKGROUND

The RAIL process was developed at the CCM in collaboration with US ARL, Alliant Techsystems and Accudyne Systems. The project was founded by DARPA/ARDEC. The RAIL process was developed and optimized for laminating prepregs, i.e. pre-impregnated carbon fibers that are oriented parallel to each other and then formed as a sheet 12” x 36”. These sheets are stacked so that there is always an angle between the fibers of two sheets that are in contact with each other. If the angle is zero degrees there will be no heat generated in the induction heating zone due to the fact that conductive loops are required for heating to occur.
It was also found that the stack needs to be symmetric in order to avoid warping during and after lamination.


Figures 1-2 - The factory laminator successfully completed trials and is now fully operational at Alliant TechSystem’s production line. The photos were taken in the CCM lab during the development work.

1.2 PROJECT GOALS

This project’s primary goal was to test an alternative combination of carbon fiber and thermoplastic polymer and run it in the already existing RAIL machine. Carbon fiber weave would be stacked with thermoplastic film and after processing the stack in the RAIL machine the result would be a flexible and strong composite. Both raw materials could be delivered to the machine separately, on rolls, and the need for pre-impregnation would be eliminated. This would reduce the raw material cost compared to prepregs.

A requirement was that the quality of the final composite had to be at least as good as the same composite manufactured in a hot press.

The secondary goal was a continuation of the primary; it consisted of modifications of the RAIL process stages, allowing manufacture of non-flat laminates. For this purpose, aluminum molding dies were designed and manufactured and the process would then be a combination of lamination and a variant of pultrusion.
During this processing it is important that the composite is deformable. As both the fiber weave and the polymer film that were used are highly flexible, this requirement was fulfilled.
As no trials were performed with these dies they will not be further discussed. Drawings and photos of the dies are attached in Appendix A.

2. SUMMARY

The experiments that were carried out showed that it would be possible to replace prepregs with stacks of carbon fiber weave and thermoplastic film in the RAIL process. All experiments were done with Nylon™ as resin. Optical microscopy revealed that the process can heat the fiber weave enough to melt the resin and then evacuate the air in the stack at the consolidation stage. The cooling seemed sufficient as no voids were created.
The preheat zone in the RAIL process was developed because impregnated carbon fibers were used at the time and it was necessary to melt the resin so that contact between the fibers could be achieved. Tests with carbon fiber weave and Nylon™ film indicated that the preheat station was not needed in order to reach the processing temperature because the majority of the heating occurs by induction heating inside each layer of the carbon fiber weave.
However, preheating was still used for the evaluated laminates because the temperature distribution across the laminate turned out to be much easier to control with the preheating station active.

The resulting laminate is very flexible and can easily be cut if desired. It is possible that the amount of resin should have been larger than what was used in these trials.
Molding dies were designed and manufactured. The purpose was to give the laminate a profile-type shape directly after the lamination stage. The cooling rollers would then have been replaced by the stationary molding dies. Unfortunately, there was not enough time to try them in the RAIL machine. Drawings and photos are available in Appendix A.

3. Machine description

Figure 3 shows the machine set-up where the laminate travels from right to left:

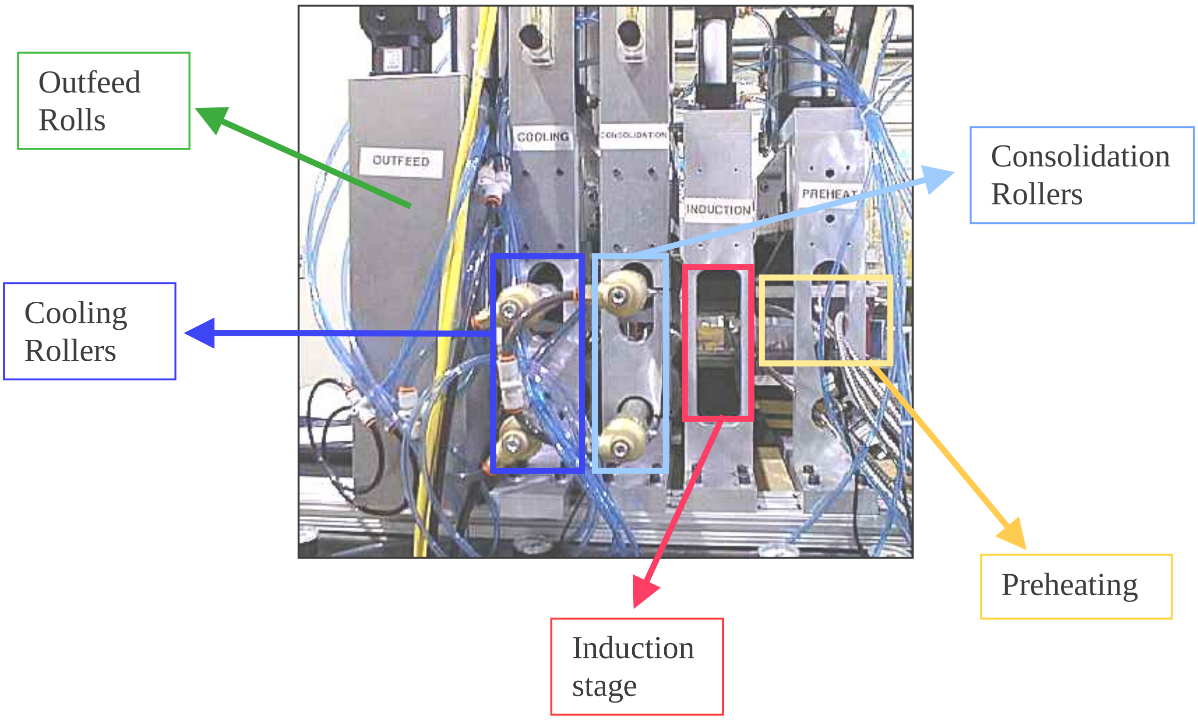


Figure 3 – Core components in the RAIL process

3.1 Preheating

The preheat stage is essential when running prepregs (pre-impregnated carbon fibers) in the machine because the prepreg layers consist of parallel carbon fibers in a polymer matrix. The layers are arranged so that there is an angle between each layer. This creates the basic requirement for the possibility to heat carbon fibers using induction heating; the heat is generated by mechanisms that occur when there are conductive loops present in the alternating magnetic field and these loops are formed by fibers from two or more different layers.

When a woven carbon fiber structure is introduced in the magnetic field there are already conductive loops in the weave and the preheating is thus not essential in this case. However, it was observed that use of the preheating stage gives a better temperature distribution in the induction stage. When thin polymer films are placed between the weaves, the preheat stage allows the films to melt, resulting in better contact between the fiber weaves and therefore heating between them, not only within the weaves. In this case the thickness of the films tested was 1 mil (25μm) thick.

3.2 Induction heating

The induction heating stage in the process is designed to bring the laminate's temperature up to the process temperature of the polymer in the laminate. Induction heating is very energy-efficient compared to other heating mechanisms (see chart below for comparisons where the Y axis is logarithmic). In practice, this means that an induction based heating system takes up less space as the heating zone can be considerably smaller compared to other heating systems, yet provide the same amount of energy needed. A smaller heating zone also means smaller area/volume to control. Unique for induction heating is that volumetric heating is achieved, i.e. heating occurs inside the material, not only from the surface as for all other heating systems. The utilization of the system's energy is therefore very high as little of the energy is "wasted". Thanks to the volumetric heating, the temperature is pretty much uniform throughout the thickness of the material, whereas a temperature gradient is inevitable for other systems. Another advantage is that it is a non-contact form of heating. It allows high-speed operations, which is particularly important when expensive materials, such as carbon fiber, are used. A short cycle time can often compensate for high raw material costs to produce high-performance composites at reasonable costs.

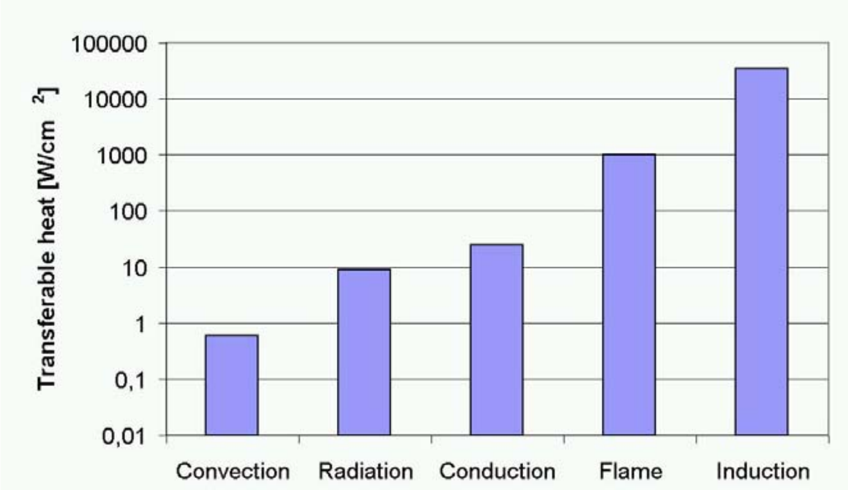


Figure 4 - Transferable heat for different heating mechanisms [4]

Induction heating as a heating mechanism for carbon fibers has been studied by a number of authors, for instance Rudolf et al. [3], Benkowsky et al. [4], Ashbee [6], Fink et al. [7], Border et al. [9] and Miller et al. [10]. Rudolf states that when it comes to carbon fiber reinforced thermoplastics, not all authors have always agreed on which mechanisms contribute the most to the heating of carbon fibers when they are introduced in an alternating magnetic field. For instance, Miller et al. conclude that the heat is generated by Joule loss while Fink found that the heat is a result of dielectric losses in the polymer between the fibers. However, it can easily be proven that the carbon fibers need to form conductive loops in order to generate heat. In this report only carbon fiber weave has been used and thus there is already contact between the fibers. It is assumed that most of the heating is generated within each layer of fiber weave and not between the weaves. The reasoning above suggests that the heat is generated only between the outer layer of the fiber tows in the weave. Perhaps it would be a good idea to use a weave with an even smaller tow size so that a higher number of conductive loops per area unit would be formed. This would possibly result in a more stable heating.
A schematic description of the heating mechanism is shown below.

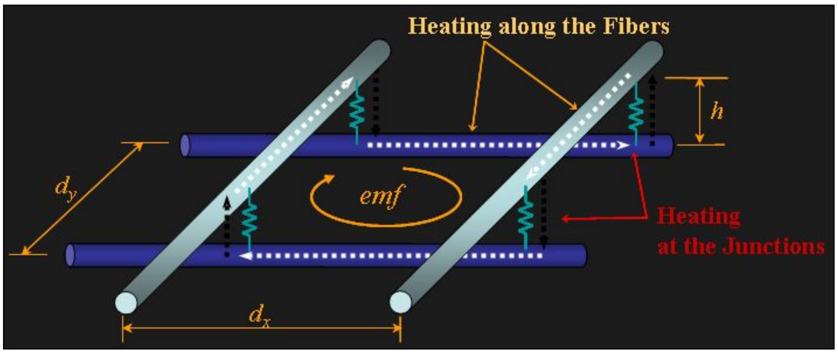


Figure 5 – Heating mechanism for carbon fiber conductive loop in alternating magnetic field [12]

The preheated stack is fed through the induction heating zone where the material is brought up to desired processing temperature through volumetric heating. The induction coil had previously been optimized for the process (see figures below). It is made from a copper pipe and is internally cooled with deionized water.

Figure 6 - Copper induction coil optimized for the RAIL process

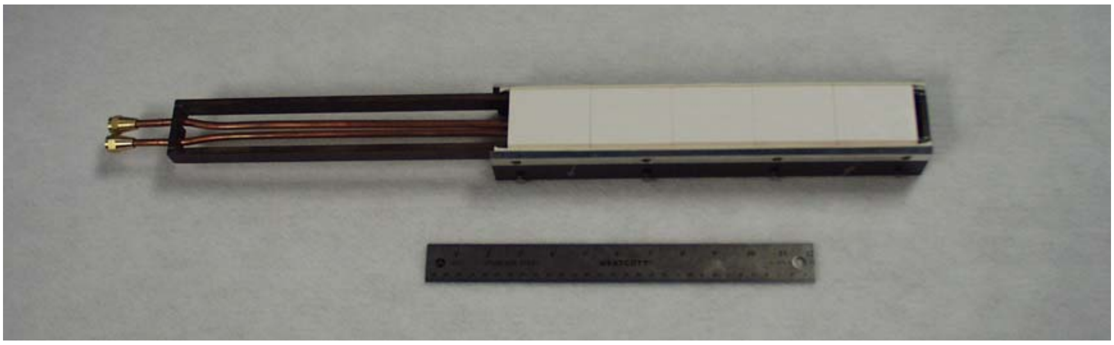


Figure 7 - Induction coil in its "case" made from quartz plates

3.3 CONSOLIDATION

After heating, the laminate is consolidated between two water-cooled rollers. The rollers exert pressure to ensure that the void content within the laminate is minimal. They also act as heat exchangers, evacuating the majority of the heat in the laminate. The pressure on the rollers is adjustable with air pressure valves.

3.4 COOLING

The temperature in every point of the laminate has to be reduced below the glass transition temperature of the resin so that the physical shape of the laminate can be controlled and so that no new voids are created. Water-cooled rollers are used for this purpose as the consolidation rollers cannot evacuate all the heat themselves.

3.5 OUTFEED

Two rollers are pulling the stack through the machine. The pressure has to be high enough to ensure sufficient friction between the roller's surface and the outer surfaces of the laminate so that the laminate will travel through the machine at constant velocity.

3.6 TIMING SEQUENCE FOR AUTOMATION [2]

This paragraph is an extract from reference [1] S. Yarlagadda et al., DUAP Semi-Annual Report, Task 1.1, Optimization and Prove-out of 8-ply Experimental Laminator, 2000, p. 26-30. It explains how the different stages in the machine work together.

"There are five stages to the DUAP laminator: preheat, induction, consolidation, cooling and outfeed. Each of the five stages can be actuated independently except for induction which is slaved to the preheat stage. The stages are actuated with respect to the relative position of the eight-ply CF/PEI sheet. The displacement of the sheet from its initial position is calculated from the surface speed v of the outfeed roller and the elapsed time t:

$$d = \upsilon \cdot t$$

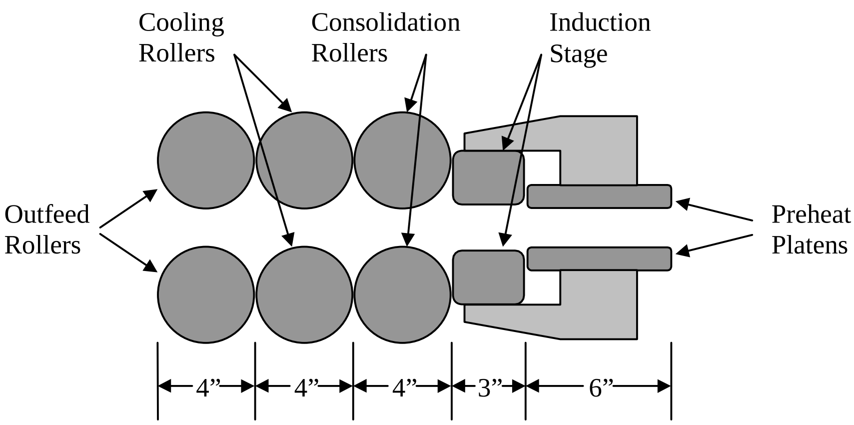


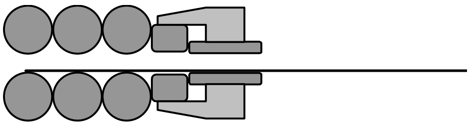
Figure 8 - DUAP laminator configuration and dimensions

Therefore, the actuation sequence is reduced to an exercise in timing so long as the speed remains constant. In the case of the DUAP laminator the speed does remain constant and is calibrated in feet per minute. According to the dimensions shown in figure 1 and the equation for the displacement, the timing equations are as follows:

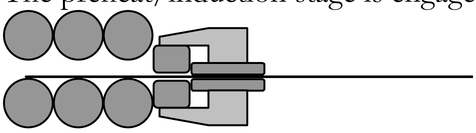
t_1=c*1+k
t_2=c*5+k
t_3=c*9+k
t_4=c*(L-14)+k
t_5=c*(L-13)+k
t_6=c*(L-12)+k
t_7=c*(L-8)+k-x

t_8=c*(L-4)+k-x
t_9=c*L+k-x

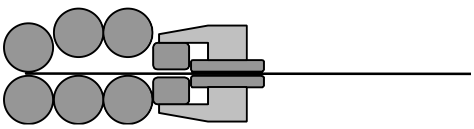
The value L represents the length of the CF/PEI sheet in inches. For the DUAP laminator L=36 in. The value c contains the speed and conversion factors such that when a number with units of inches is multiplied by it a number with units of seconds is obtained, c=5/v . The delay factor k is added to the equations to compensate for the time it takes for the outfeed rollers to engage the sheet, k=1. The advance factor x is subtracted from some equations to avoid having the rollers hit against one another as the sheet passes out of them, x=1. A feature of the equations is that the sheet length and speed are variables, which enables the DUAP laminator to accommodate a range of sheet lengths and many throughput speeds.
The sequence of events corresponding to the times calculated is as follows.
The unconsolidated stack of four staked two-ply CF/PEI sheets is inserted into the laminator so that the leading end is at the top of the lower outfeed roller.



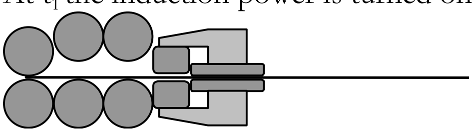
The preheat/induction stage is engaged.



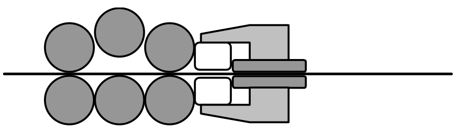
The sheet dwells for t_d, which equaled 3 seconds for the DUAP laminator.
The outfeed rollers are engaged. This action is the zero of time relative to which all times are measured.



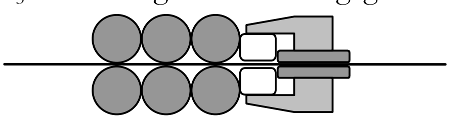
At t_1 the induction power is turned on at the high power level.



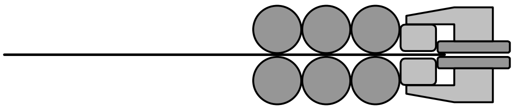
At t_2 the consolidation rollers are engaged.



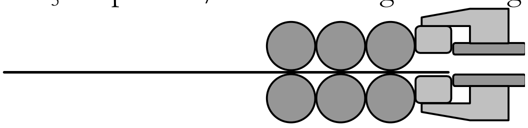
At t_3 the cooling rollers are engaged.



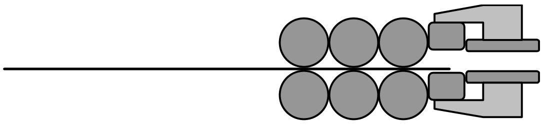
At t_4 the induction power is lessened to the low power level.



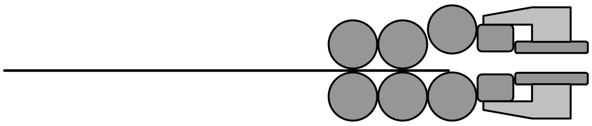
At t_5 the preheat/induction stage is disengaged.



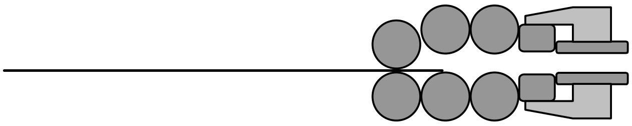
At t_6 the induction power is turned off.



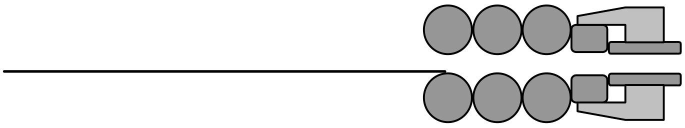
At t_7 the consolidation rollers are disengaged.



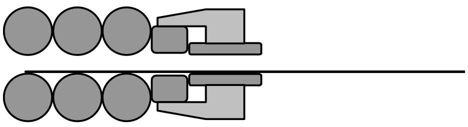
At t_8 the cooling rollers are disengaged.



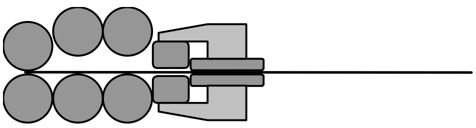
At t_9 the outfeed rollers are disengaged.



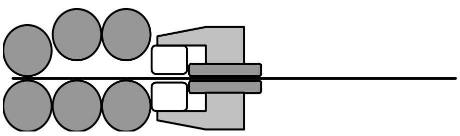
At this point, half of the sheet is consolidated. The sheet is then reinserted so that the consolidated end of the sheet is at the outfeed rollers.



The outfeed rollers and preheat/induction stage are engaged together. This action is the new zero of time relative to which the next bunch of times is measured.



At t_1, the induction power is turned on at the high power level.



The actions at t_2 through t_9 then proceed as in the first pass.
This completes the sequence of actions needed to achieve a fully laminated sheet.
The actuation sequence was executed in the form of a computer program. Commands were communicated to the Parker 6K2 programmable logic controller through a serial connection."

4. Materials

4.1 *Carbon Fiber Weave*

The construction principle of the fiber weave that was used in this work is shown in Figure 9 below. Figure 10 shows what the actual weave looks like.

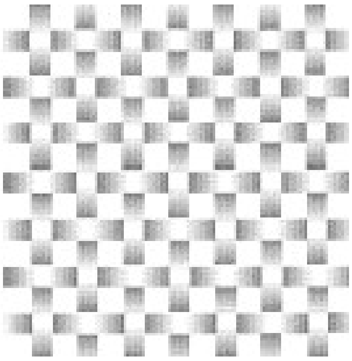


Figure 9 – Sketch of the carbon fiber weave design

The weave is approximately 0.01" (~0.25mm) thick and the tow size is 2400 fibers/tow. The tow width is about 0.08" (~2mm).

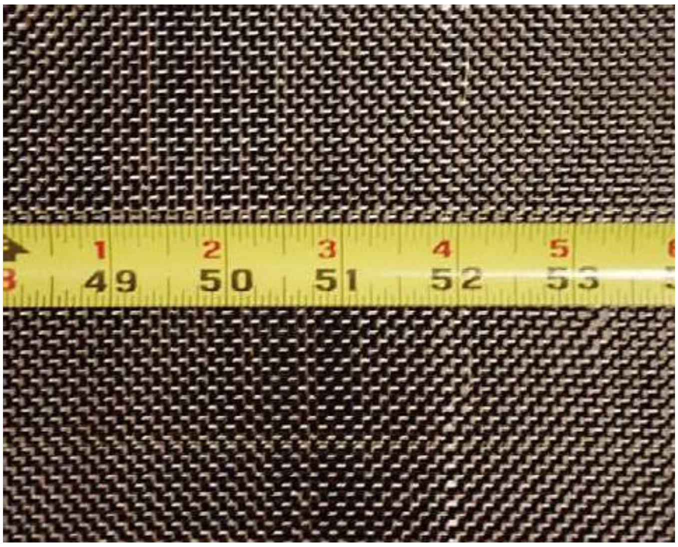


Figure 10 – The carbon fiber weave that was used in the experiments. Scale in inches.

4.2 *Crystal 22 Nylon™ Film*

Crystal 22 is a heat stabilized Nylon™-6 polyamide film from GEM Polymer Corporation. Its process temperature lays within the operational temperature range for the RAIL process. Nylon™ is a relatively cheap material and the accessibility is high since it is commonly used.
Note that this particular film was chosen because it was readily available and it met the very basic criteria for the experiments (thermoplastic film with a higher melt temperature and "better" physical properties than most variants of polymers like LDPE, HDPE and PP). No technical data sheet was available.

4.3 KAPTON™ FILM

In order to prevent build-up of resin and fibers on the machinery parts of the laminator, the stack of fibers and polymer had to be sandwiched between two protective sheets (Figure 11). For this purpose, Kapton™ film, manufactured by DuPont, was used. Kapton™ is a tough, aromatic polyimide film with very high dimensional stability over a wide temperature range and is therefore suitable for this application. In addition, the surfaces are pretreated with a chemically inert release agent that prevents sticking between the Kapton and the nylon films.

5. EXPERIMENTAL AND RESULTS

5.1 EQUIPMENT FOR MEASUREMENTS AND EVALUATIONS

Infrared camera: CoolSNAP-Pro, Media CyberneticsR
Software for processing infrared images: Image Pro Plus
Preparation of samples for optical microscopy: Buehler three-station polishing table
Microscope: Leitz METALLUX 3

5.2 LAMINATE SETUP

A sandwich structure consisting of carbon fiber weave and Nylon™ film was set up. Figure 11 shows an example of the structures that have been evaluated. In this case there are three layers of fiber weave. Each of these layers has one own Nylon™ film on each side. The idea is that the film will melt and when external pressure is applied, the polymer will wet all fibers so that a solid, flexible composite is achieved. To ensure that the laminate will not stick to the different parts of the machine that are in direct contact with the laminate, the entire structure is placed between two layers of heat resistant film that is treated with a release agent.

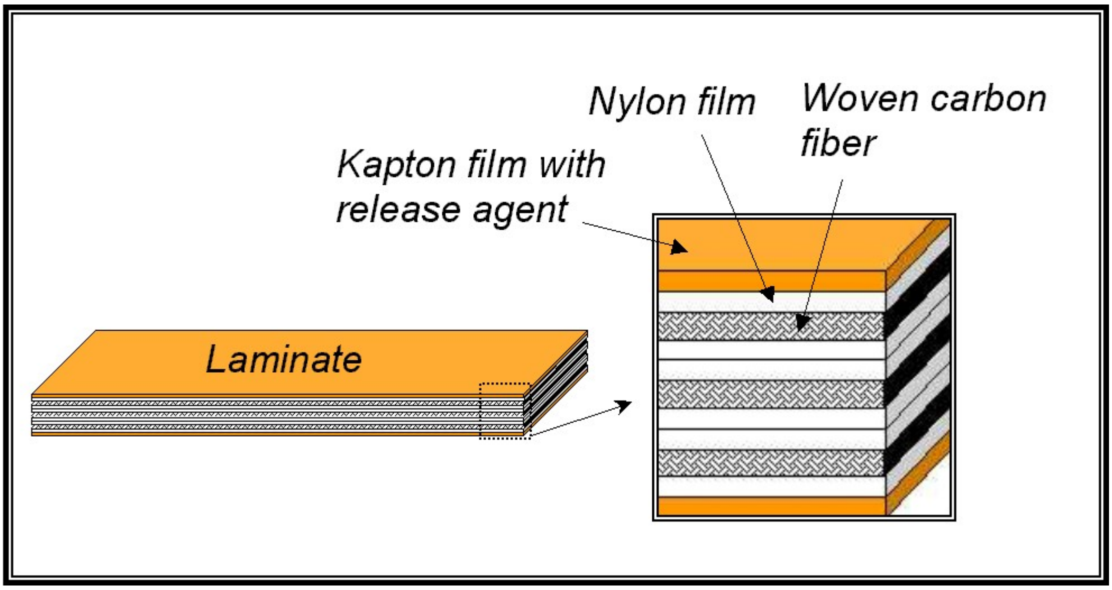


Figure 11 - Layer structure

5.3 VARIABLE PARAMETERS

The following parameters were varied during the trials:
Feed speed
Preheat temperature
Induction power
Number of carbon fiber layers
Number of Nylon™ film layers

5.4 PROCEDURE RAIL

The fiber weave, Nylon™ film and Kapton™ film were cut by hand into sheets of manageable size (12 x 36" = 30,5 x 91,5 cm) that corresponded to the operational width of the machine (12"). The layer configuration was established and the stack was placed in the machine so that one end was clamped between the outfeed rollers. The software that controls all machine movements was started and followed the sequence described in chapter 3.6 - Timing sequence for automation 63H[2]. After this cycle, only half of the stack had been consolidated, so the stack was placed into the machine again, but now turned 180°, in order to process the other half of the stack.
For high-volume production all materials would be supplied to the machine on rolls so that the process would be continuous. But for this work, all tests were done with sheets.

At this time, the one parameter that was of interest to measure in-line on the laminate was the temperature after the induction heating and before the consolidation stage. Several failed attempts to measure the internal temperature with different types of thermocouples were made. The thermocouples are also subject to the alternating magnetic field in the induction heating zone and the output signals are therefore heavily distorted. One idea was to record the read value just after the IH zone but at this point the thermocouples were always severely damaged because of the heat and/or tension and/or pressure that they were subject to from the preheat station. Some attempts to protect them were made but with no success.
It was then concluded that an IR camera would be used to monitor the surface temperature of the laminate instead. One disadvantage with the IR camera is that only the surface temperature can be observed but it was judged to be "good enough" for this work. One advantage is that the entire surface on one side of the laminate can be monitored so that cold or hot spots can be identified. It was noticed that the design of the induction coil was quite well balanced and worked well also together with the woven fiber. Only close to the edges was the temperature a bit unstable.

Some components in the machine had been changed, and some were even damaged or missing, since the optimization work for CF/PEI sheets was done and the control software had to be modified to fit these changes. The initial trials were therefore executed on a trial-and-error basis. These (many) trials were not documented because they were not relevant to the purpose of this work.
The following was tested and adjusted on the machine so that it would be possible to use with the intended materials: Consolidation-, cooling- and outfeed roller pressure, preheat plate pressure, preheat plate temperature, distance between all stages, distance between induction coil and laminate, and induction power. A new induction coil was also manufactured since the original one was damaged.

It was now time to investigate how the fiber weave would behave in the process. Some basic criteria were established:

- Preheat plate temperature was set to 392°F (200°C), in some cases no preheating was used
- Induction power: 50-80%. Lower power did not give sufficient temperature and higher power resulted in uneven/unstable temperature across the width of the laminate. Higher power also resulted in fire at the edges of the laminate and was excluded for safety reasons.
- Number of fiber weave layers: 1-5
- Number of Nylon™ film layers on each side of the fiber weave: 1-2

First of all, static heating rate (i.e. the laminate is not moving) of different numbers of layers of carbon fiber weave was measured for different levels of induction power (Chart 1 -Chart 3). At a feed speed of 1 fpm each point of the laminate would be subject to induction heating for approximately 10 seconds.

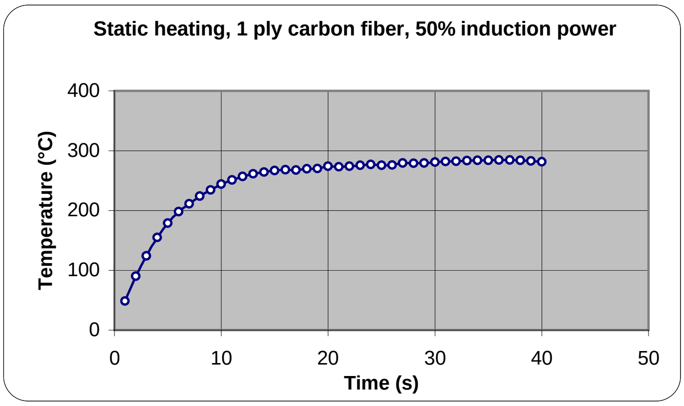


Chart 1

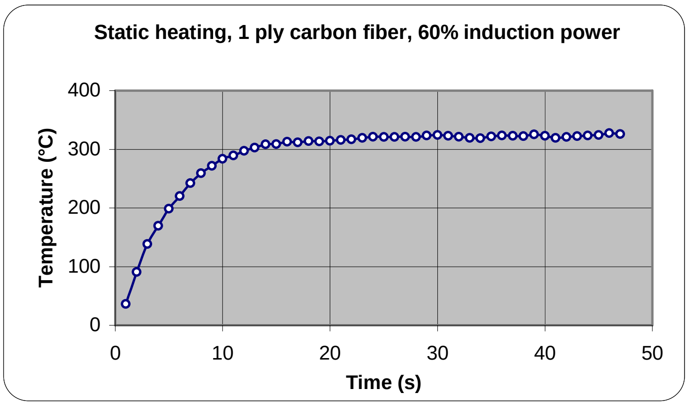


Chart 2

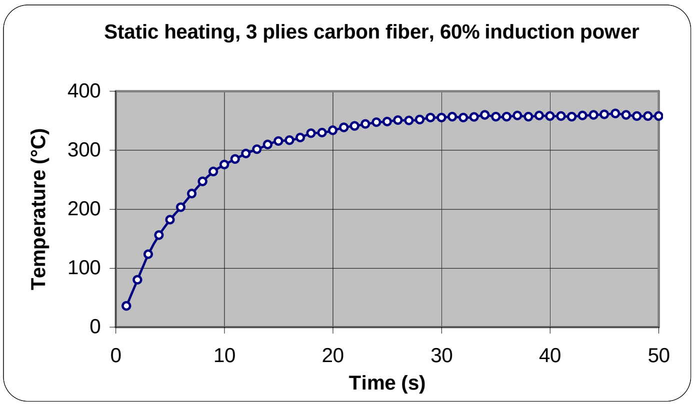


Chart 3

The second step was to let carbon fiber weaves alone run through the laminator. No preheat was used, only induction heating was applied.

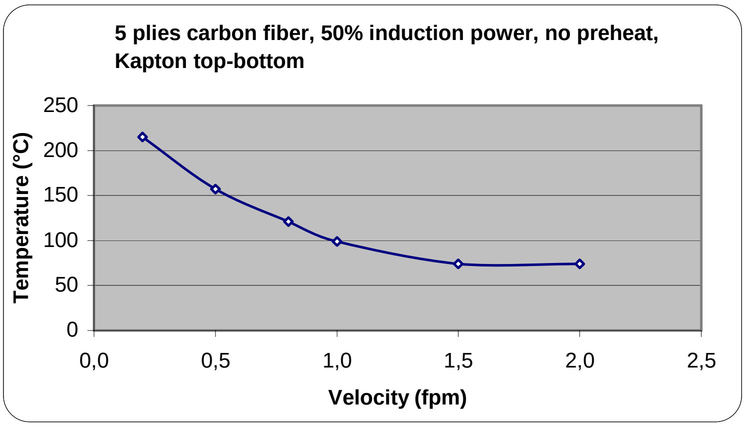


Chart 4

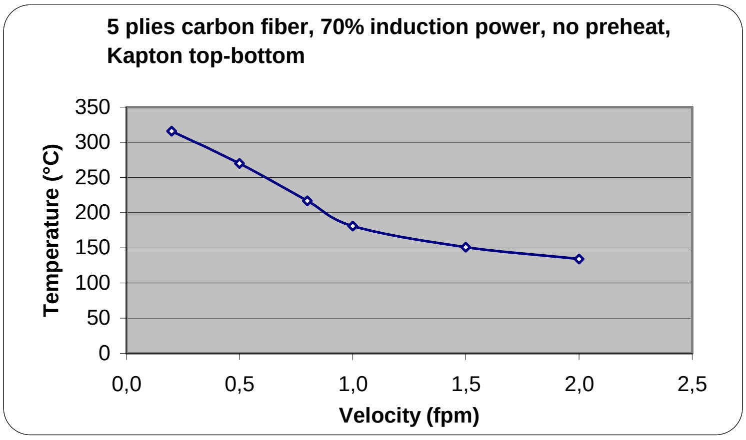


Chart 5

This was then repeated for different numbers of layers of carbon fiber weaves, enclosed by two layers of Kapton™ film, and the feed velocity was limited to 2 feet per minute because it was assumed, based on above charts, that the induction source would not be able to provide enough energy to heat the laminates efficiently enough for higher velocities, especially as the heat distribution turned out to be quite difficult to control at higher power levels.

When performing these experiments it was noticed that the Kapton™ film would wrinkle uncontrollably between the preheat and the consolidation stages. This problem was solved by enclosing the whole laminate between two layers of a composite prepreg consisting of unidirectional carbon fibers and a PEEK resin. As the fibers in the prepreg are parallel to each other and as there is no contact between the prepreg and the woven carbon fibers, this composite would not absorb any (or possibly very little) of the energy emitted by the induction coil and it would thus work as an inert, mechanical support for the fiber weave.

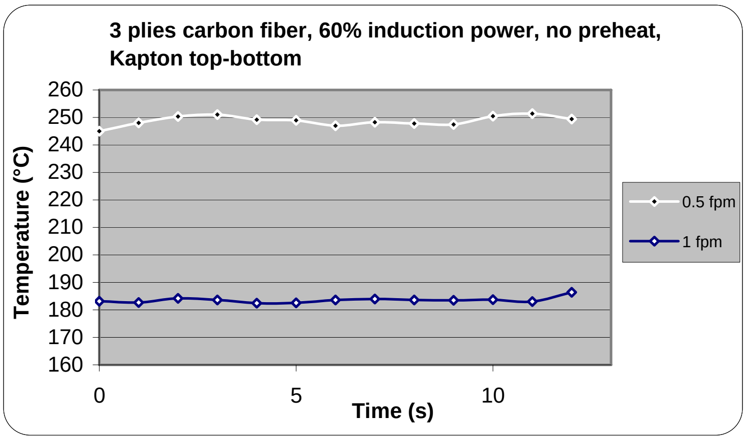


Chart 6

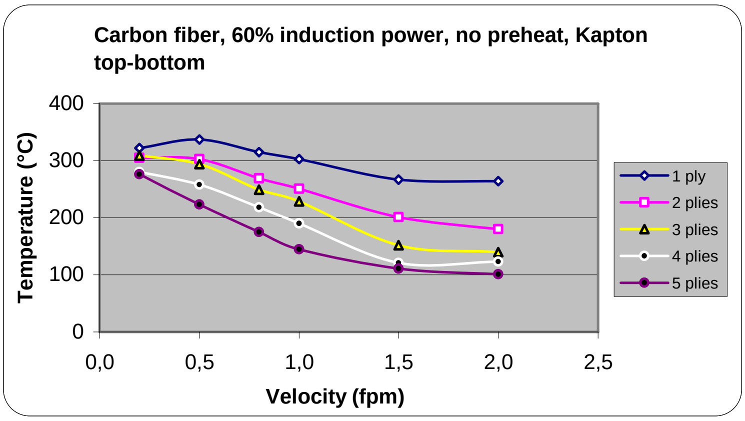


Chart 7

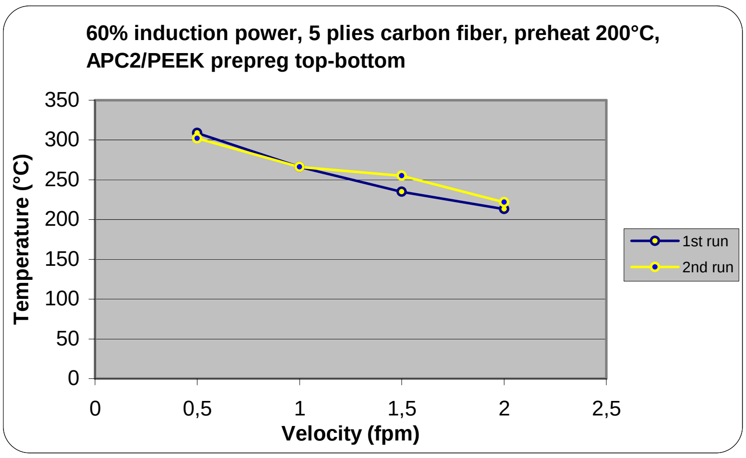


Chart 8

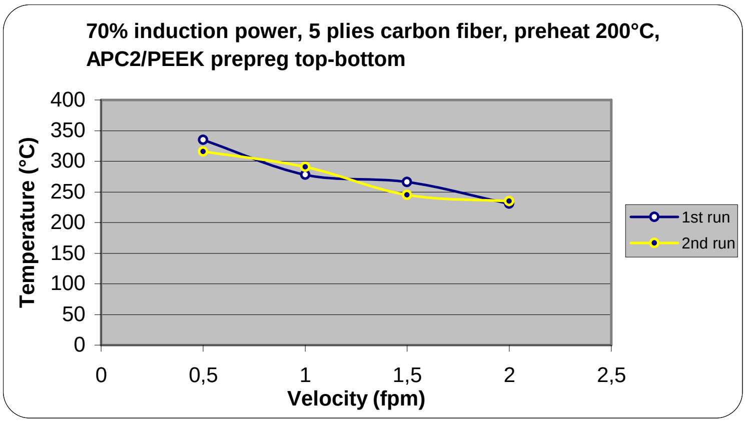


Chart 9

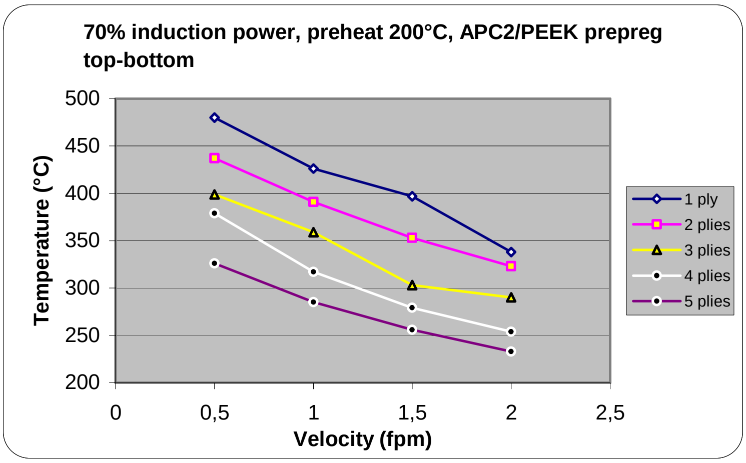


Chart 10

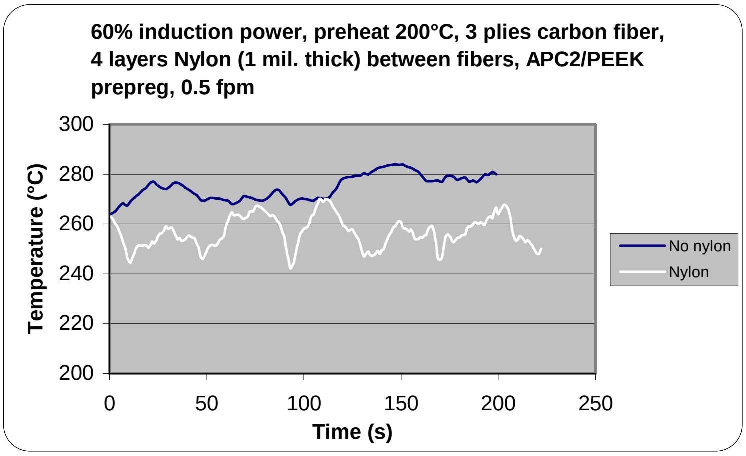


Chart 11

One problem when using the prepreg layers as support is that the surface temperature is probably lower than the temperature inside the laminate. But, as the prepregs are subject to heating due to physical contact with the heating shoes and then affected by heat transfer in the form of convection from the carbon fiber weaves through the Kapton™ films, it gives an idea of how the system will respond when running laminates of various thicknesses through the laminator at different velocities.
The volumetric temperature should also be measured so that the polymer films would be processed at their correct process temperatures. This measurement could be performed with the aid of thermocouples but here, as explained before, the thermocouples themselves would be affected by the magnetic field and the thermocouples were also physically damaged due to high temperature, tension and pressure.

5.5 Procedure Hot Press

The Hot Press process is based on two heated steel plates that are pressed together. The layer structure is shown in the figure below. The size of the laminates was 12x12" (30,5 x 30,5 cm). The force on the hot plates was 3 tons (≈3000x2.2=6600 lbs). This gives a pressure of

$$\frac{3000x2,2}{12^2} = 46\frac{lbs}{in^2} \text{ or } \frac{3000}{30.5^2} = 3.2\frac{kg}{cm^2}$$

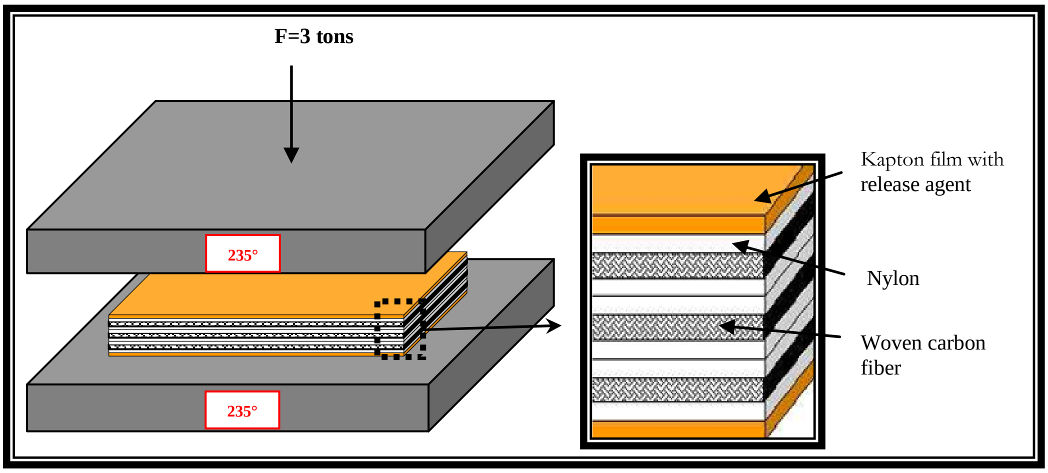


Figure 12 - Layer setup for hot press trials

Two samples were manufactured, in the first case the pressure was applied for two minutes and the in the second case the pressure was applied for 20 minutes. A temperature T, slightly higher than the crystalline melting point (104°F=220°C) of the nylon, was chosen: T = 113°F=235°C. The most suitable process temperature for the nylon was unknown but 235°C was chosen because it was considered likely to be in the range of the process temperature window.

5.6 *THERMAL IMAGING*

Figures Figure 13 and Figure 14 below show the temperature distribution for static induction heating and for the continuous RAIL process, respectively. The numbers indicate the average temperature along the drawn lines.
The static heating reveals the true heating pattern. One can see that the induction coil actually renders two heating zones in the machine direction. This means that the laminate is subject to heating at three occations: preheat and twice in the IH zone.
Note that the temperature distribution is not uniform close to the edges of the laminate. In the top end the temperature was considerably lower and in the bottom end it was significantly higher that in the middle of the laminate. Therefore, all evaluated samples were taken no closer than 1" from the edge.

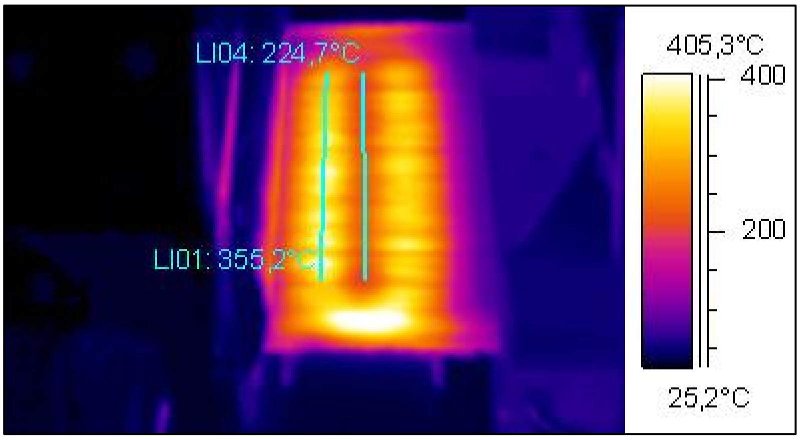


Figure 13 – Average temperatures along lines for static heating

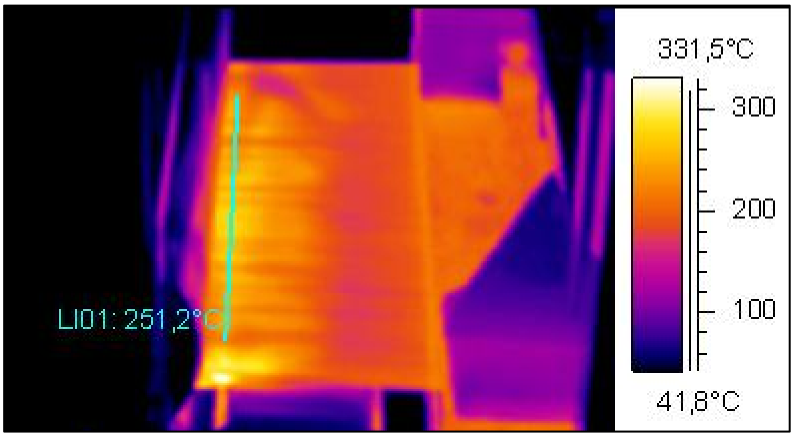


Figure 14 - Average temperatures across the machine direction for continuous RAIL process

5.7 OPTICAL MICROSCOPY

Four laminates were studied in an optical microscope. Two laminates, named L1 and L2, were made using the Rapid Automated Induction-based Laminator and a Hot Press was used to make two other laminates, L3 and L4. The latter two were used as the benchmark laminates for the comparative evaluation of the RAIL composite.

For the RAIL process, three layers of woven carbon fiber were placed between Kapton™ films. In L1, two layers of Nylon™ were placed between the weaves and one layer of Nylon™ was placed between the Kapton™ film and the carbon fiber. Previous tests showed that the surface temperature of this setup, but without Nylon™, was about 270°C when the outfeed velocity was 1 foot per minute and the induction power was 60% of the maximum power. The laminates were also preheated to 200°C. It was then assumed that the peak temperature would be about 230-250°C if the Nylon™ films were introduced. The same line of reasoning was used for L2 where the number of layers of Nylon™ film was doubled, i.e. four layers of Nylon™ film were placed between the fibers and 2 layers between the Kapton™ film and the fiber weave. The induction power was 70% and the outfeed velocity was 0.5 feet per minute.

For the hot press the surface temperature was fixed at 235°C and both laminates L3 and L4 were identically with L1. The difference between L3 and L4 is that they were exposed to pressure (46 lbs/in^2 or 3 kg/cm^2) for different amounts of time, 20 and 2 minutes, respectively.

Four specimens of each laminate were cut out and mounted in a plastic cup. The cup was filled with epoxy so that the specimens could be polished in the Buehler three-station polishing table (see figures below). Representative photos were taken and are presented on the following pages.


Figures 15 and 16 – Composite specimens prepared for microscopy

L1 3 plies carbon fiber 2 layers Nylon™ Crystal 22 film (1 mil.) between fibers and 1 layer bottom-top Preheat 200°C 70% Induction power Velocity 1 fpm	**L2** 3 plies carbon fiber 4 layers Nylon™ Crystal 22 film (1 mil.) between fibers and 2 layers bottom-top Preheat 200°C 60% Induction power Velocity 0.5 fpm
L3 3 plies carbon fiber 2 layers Nylon™ Crystal 22 film (1 mil.) between fibers and 1 layer bottom-top Hot press 235°C 20 min 3 tons	**L4** 3 plies carbon fiber 2 layers Nylon™ Crystal 22 film (1 mil.) between fibers and 1 layer bottom-top Hot press 235°C 2 min 3 tons

Table 1 – Optical microscope specimen details

Comments to the photos on the following pages:

L1, Figure 18 and Figure 18:
The Nylon™ films have melted together properly and they are also well bonded to the carbon fibers, surrounding the "edges" of the tows. A great void content indicates that the amount of Nylon™ used was too low.

L2, Figure 20 and Figure 20:
The amount of Nylon™ is doubled and it is nicely bonded to the carbon fibers. The void content is much smaller than for L1 even though the amount of resin could be even higher.

L3, Figure 22 and Figure 22:
Here, the thickness of the Nylon™ layers is quite uniform and it has not filled the spaces around the "edges" of the fiber tows. It is likely that the temperature and/or the pressure were too low.

L4, Figure 24 and Figure 24:
Obviously, the temperature has not fully reached the melting point of the Nylon™ as the films are separated at several places. The short pressing time could be the reason, possibly in combination with too low temperature and/or pressure.

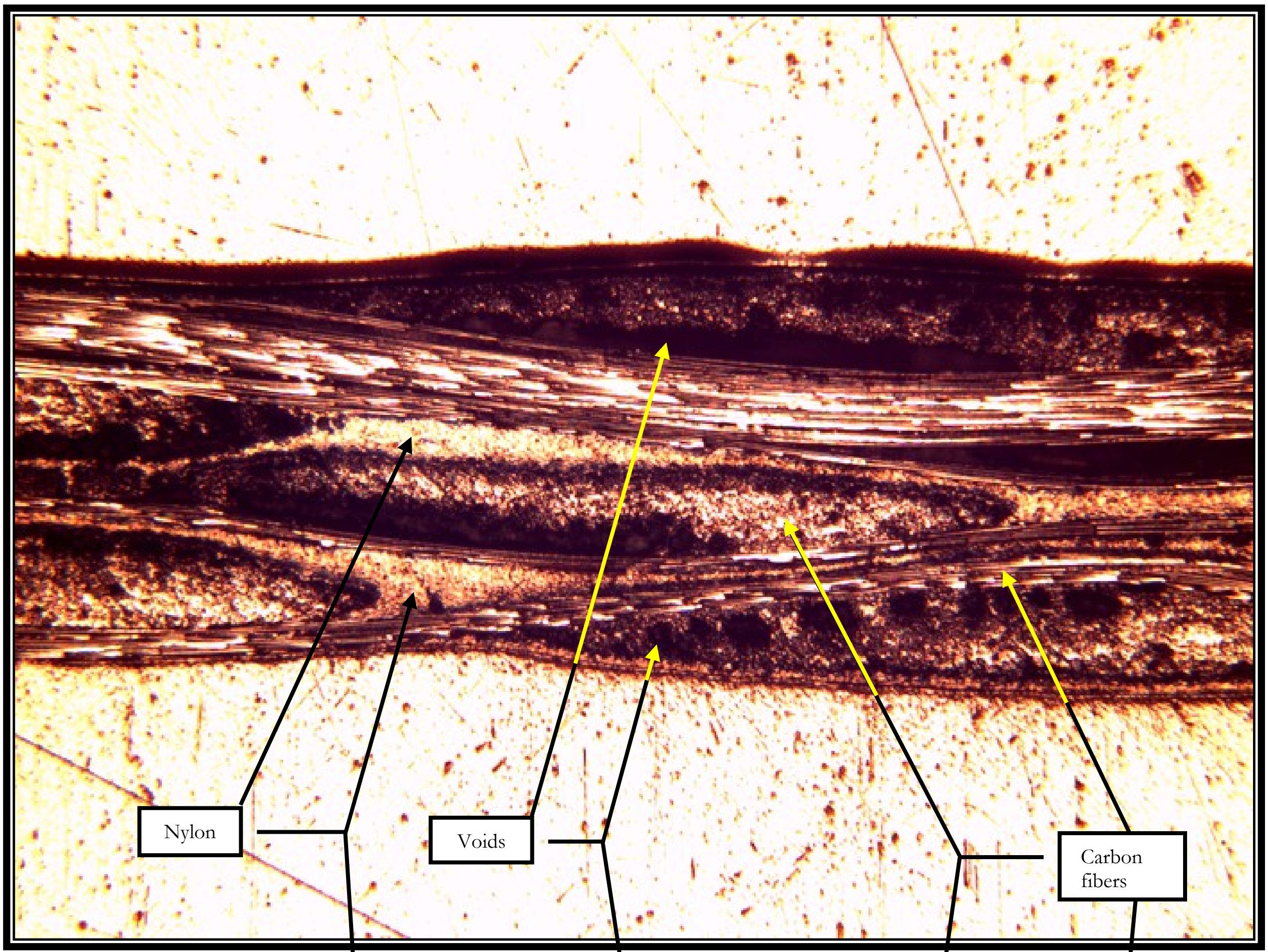


Figure 18: L1 - 25x magnification

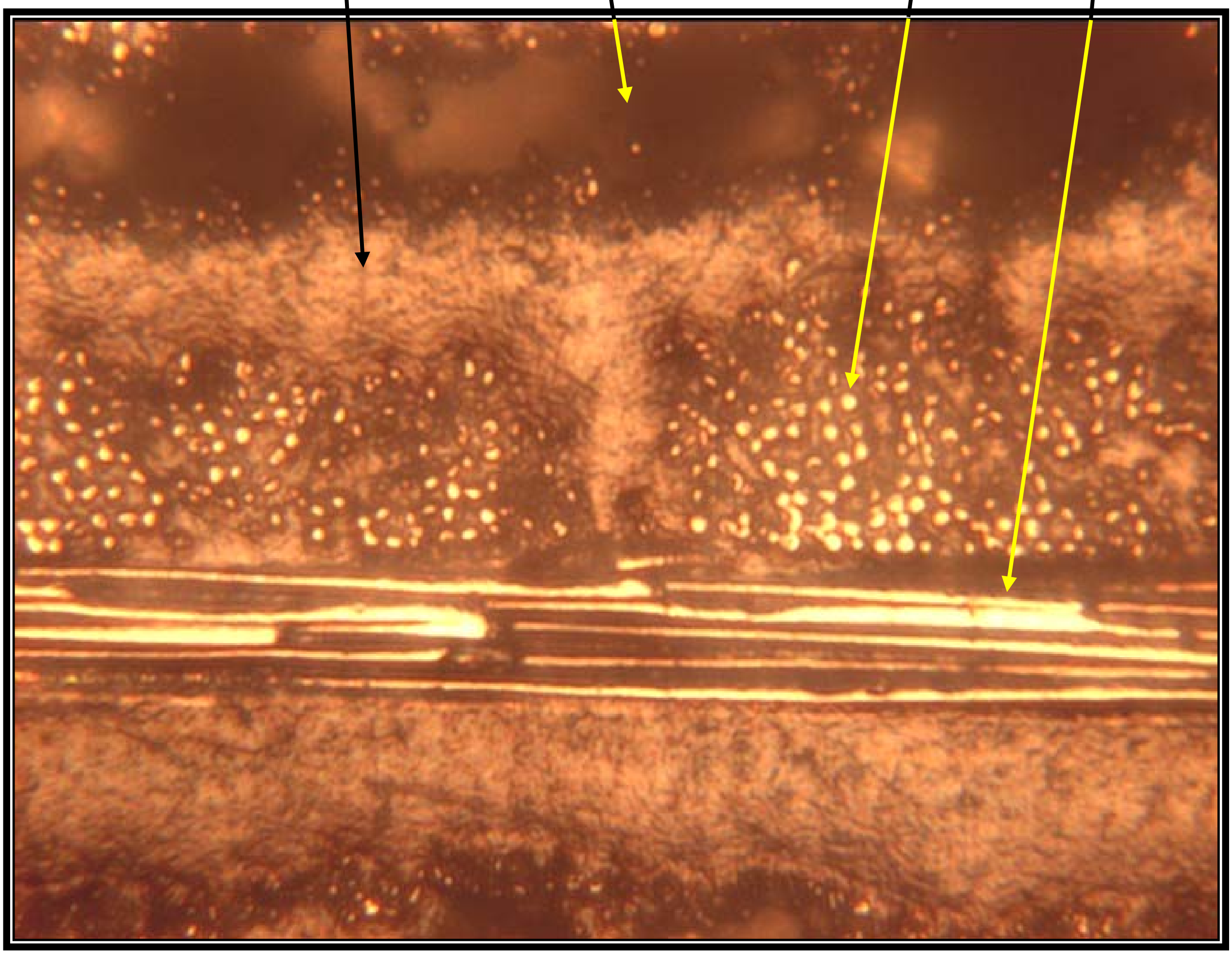


Figure 18: L1 - 320x magnification

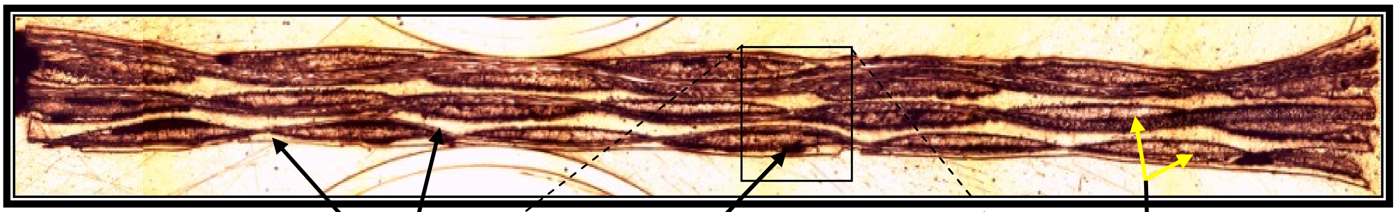


Figure 20: L2 - 10x magnification

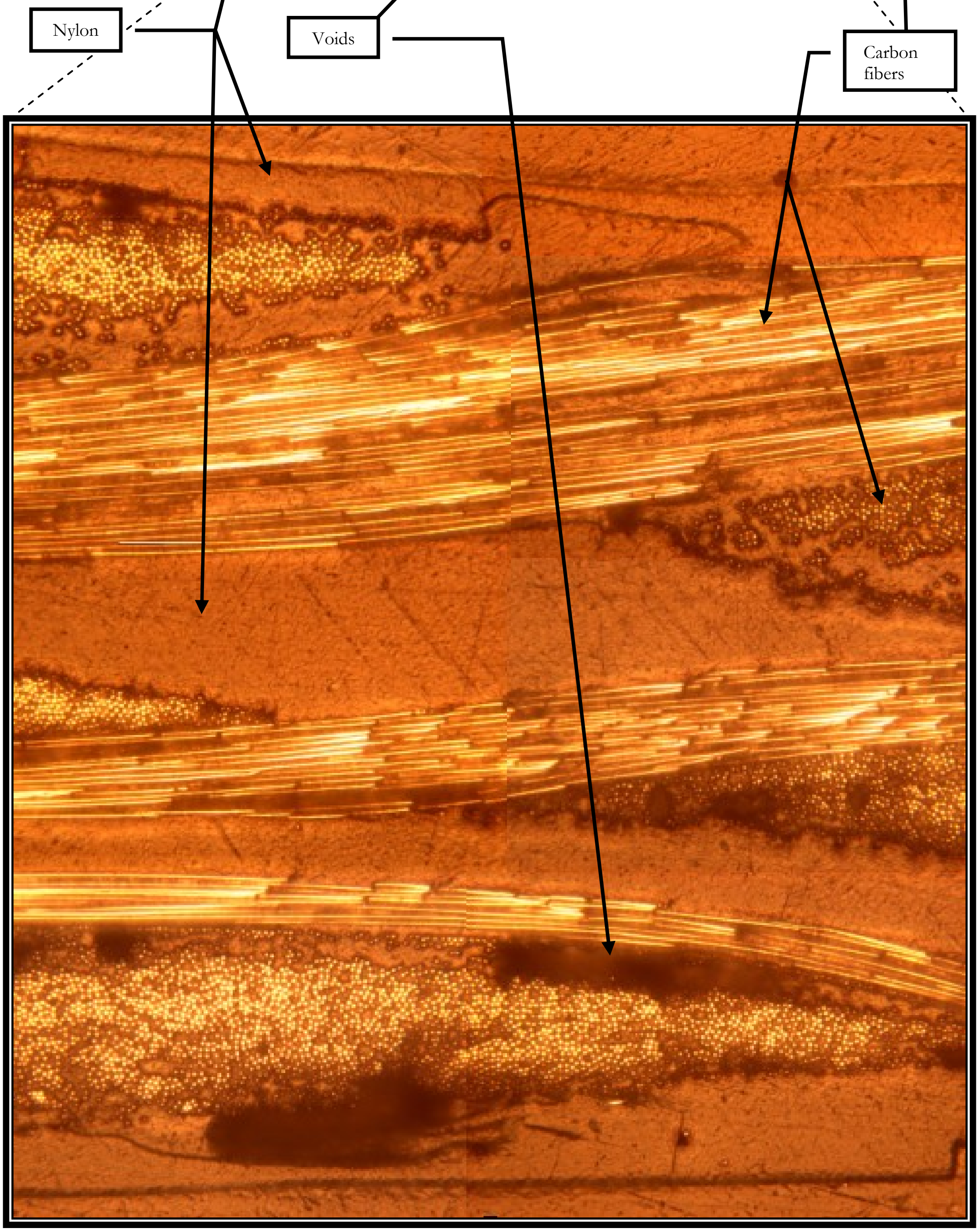


Figure 20: L2 - 200x magnification

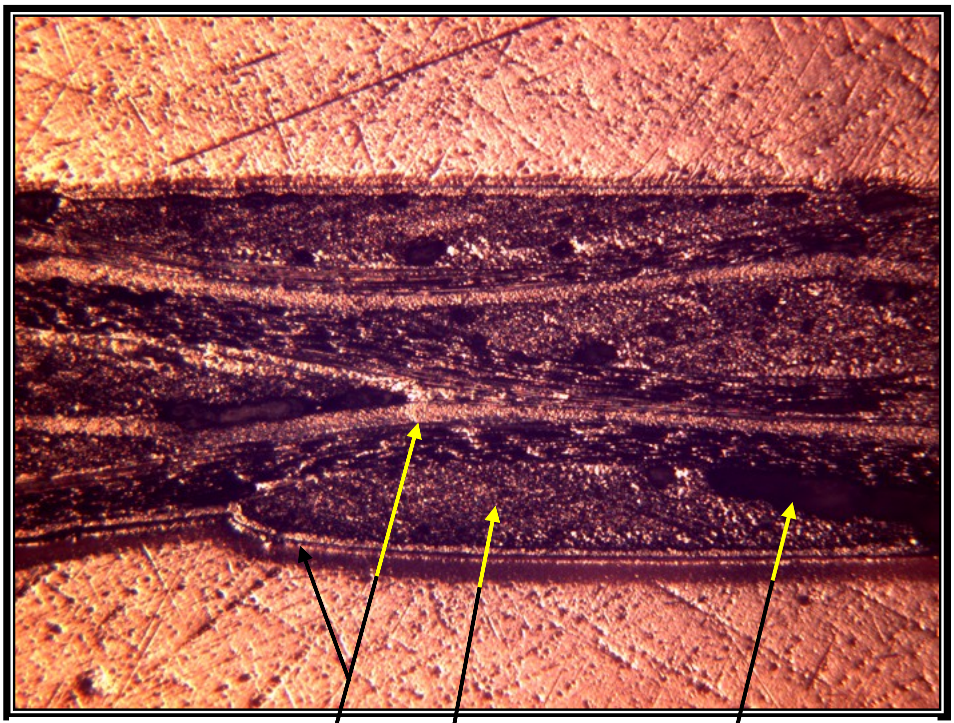


Figure 22: L3 - 25x magnification

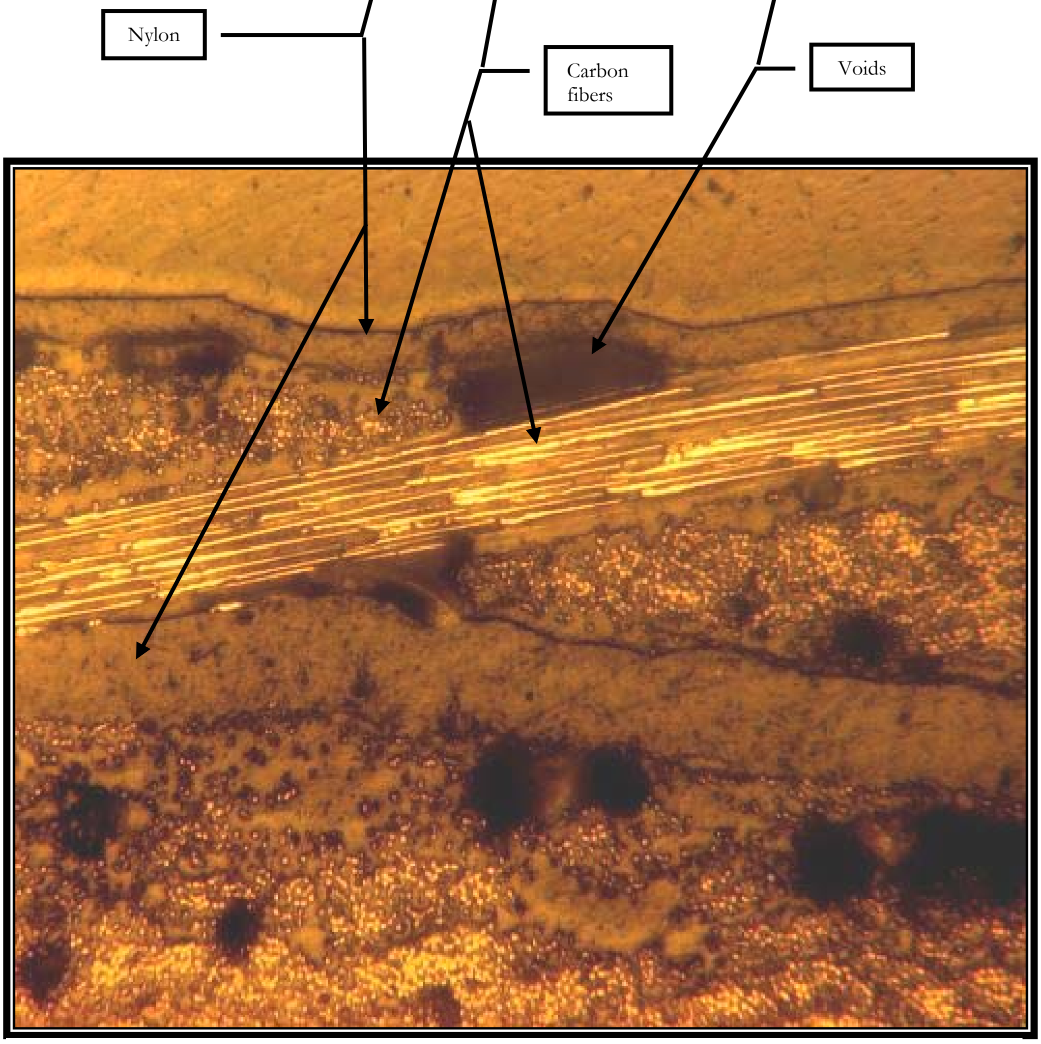


Figure 22: L3 – 200x magnification

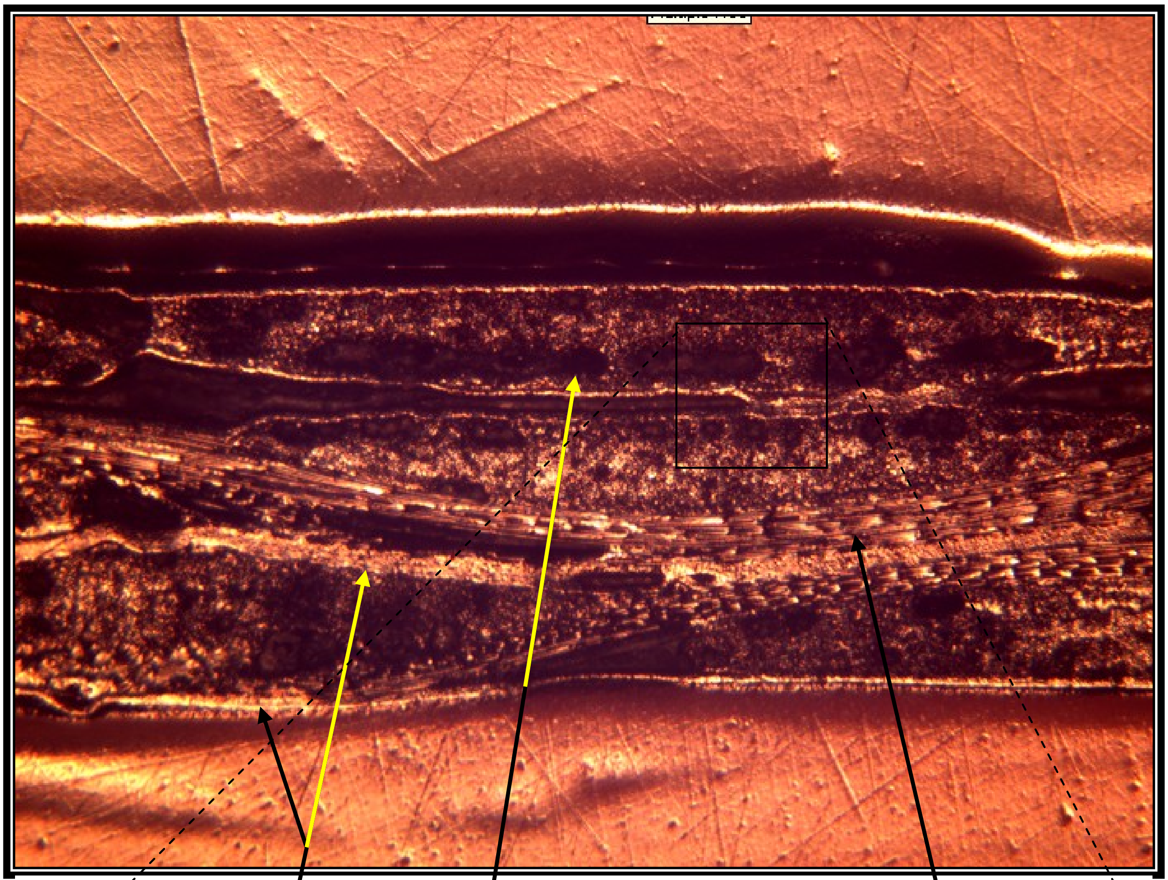


Figure 24: L4 - 25x magnification

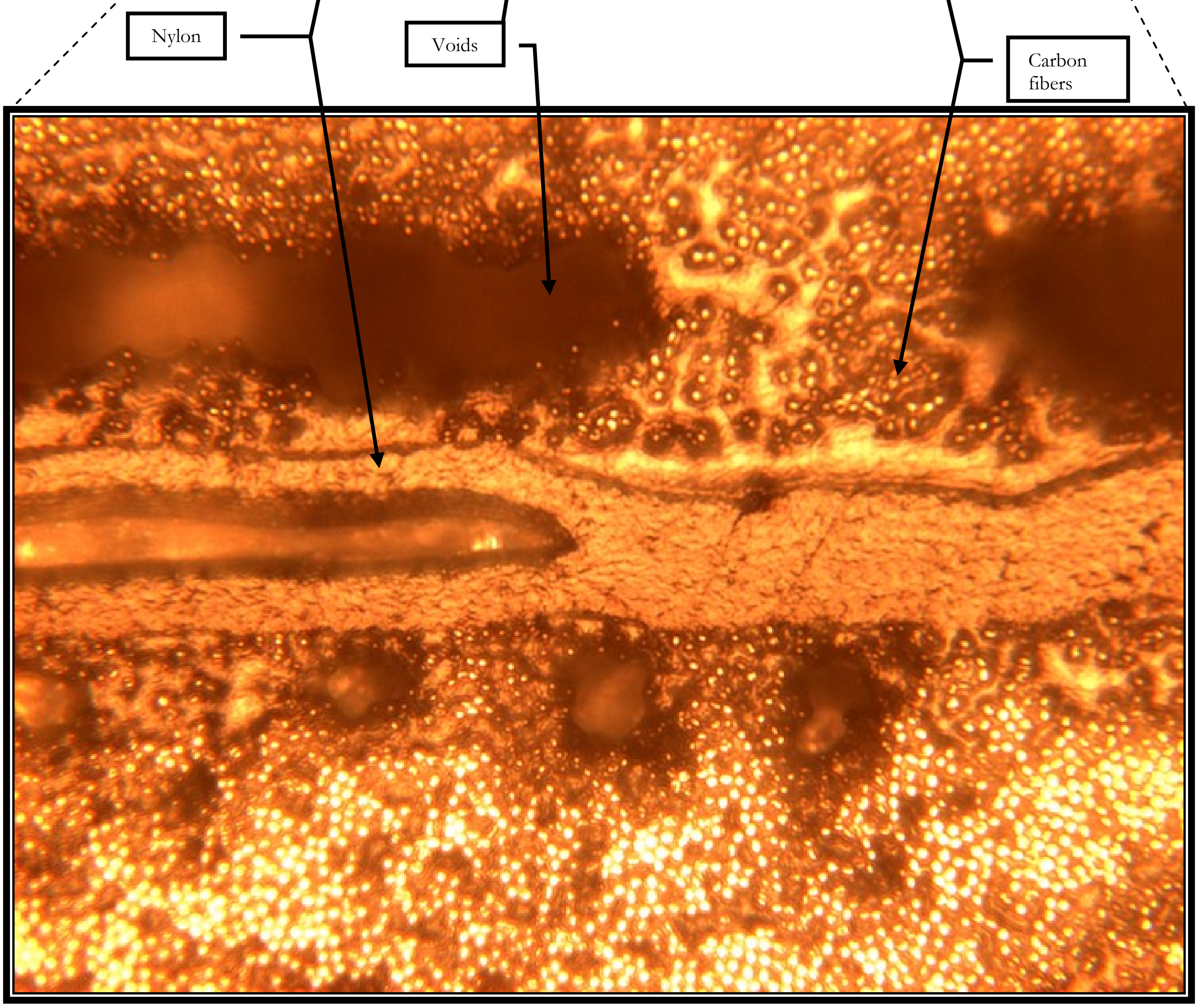


Figure 24: L4 - 200x magnification

6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The RAIL process was developed and optimized for laminating prepregs. The work resulting in this report was carried out in order to determine if the process would also be suitable for laminating a thermoplastic film with a carbon fiber weave and it should be regarded as a pre-study.
The heat generated by the woven carbon fiber in the alternating magnetic field is sufficient to bring Nylon™ to its process temperature. For the coil that was used, the preheat station is necessary to obtain a uniform temperature profile across the laminate structure. When using prepregs, the preheating is necessary because the unidirectional carbon fibers need to be in good contact with those in the neighboring prepregs to create closed loops. This is not a requirement when using fiber weave as the conducting loops are created inside the weave.

When the manufactured laminates are examined one can conclude that the material distribution is at least as good as that of the benchmark (hot press). The material structure has not been optimized in terms of amount of material in each layer. Process parameters such as roller pressure, roller size, feeding speed, preheat temperature, induction power and frequency should be optimized once a material structure has been chosen.

The greatest advantage for the RAIL process over the benchmark is the shorter cycle time, which is reduced by up to 90-95% depending on the setup of both processes. Another great advantage is that the RAIL process is continuous; all layers could be delivered to the machine in the form of rolls instead of sheets and a cutting station could be installed downstream so that there would be no limitations on the length of the laminated article.

From a material point of view a wide range of thermoplastic materials seem to be possible to process. One trial, not included in the report, visually evaluated a blown Polypropylene film that showed no indications of process related problems but the induction power had to be lowered slightly due to the lower melting point compared to Nylon™.

Based on the results and observations, one suggestion would be to decrease the tow size of the fiber weave, giving the possibility to have a higher number of conductive loops. This could result in a more even heat distribution and thus better control of the induction heating. Future work should also include testing a range of thermoplastic films.

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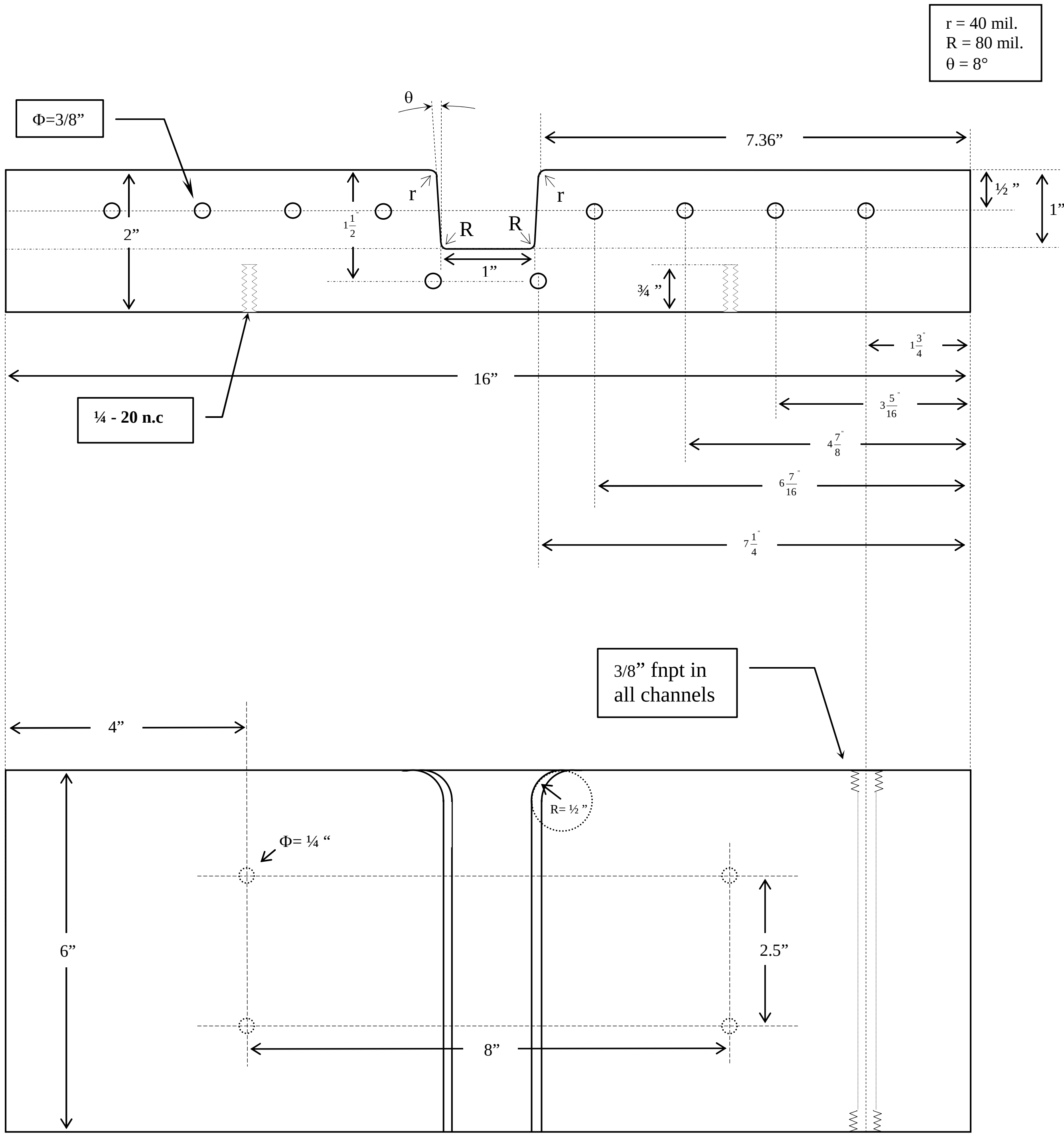
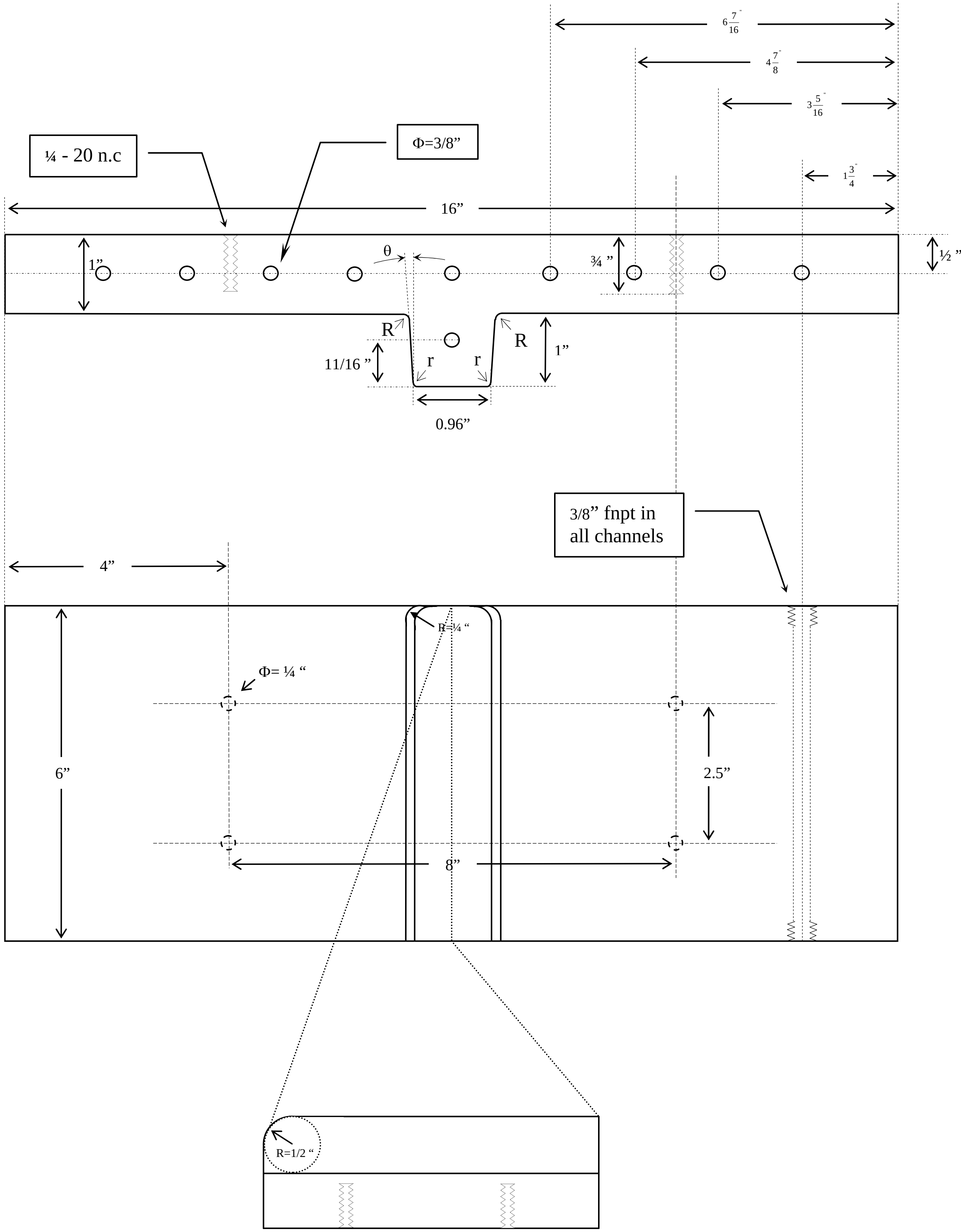
Appendix A – Molding dies for continuous forming of laminated composite sheet




6 7/16"
4 7/8"
3 5/16"
1 3/4"
¼ - 20 n.c
Φ=3/8”
16”
1”
θ
¾ ”
½ ”
R
R
r
r
11/16 ”
1”
0.96”
3/8” fnpt in
all channels
4”
R=¼ “
Φ= ¼ “
6”
2.5”
8”
R=1/2 “