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INTERNSHIP

DESIGN AND REALIZATION OF COMPOSITE MOLDS FOR A SOLAR CAR

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Preface

September 2012 was, for me, the start of an amazing mission. Together with 15 other students of University of Twente and Saxion Enschede, I was part of the brand new Solar Team Twente. At that moment, the process started which would lead us to the Australian Outback, where we would enter the battle for the championship in racing solar cars: The World Solar Challenge 2013 (WSC). In order to make a realistic change of winning from all the (top) universities from around the world, we started to design a car from scratch, which later would get the name The RED Engine (TRE).

My function within the team was Structural Designer; I was partly responsible for designing and building the body and the chassis of the solar car. This meant that I had to design an internal structure which could carry all the high loads of the driver and suspensions, as well as the carbon fiber body which had to have an outstanding aerodynamic performance, entirely out of composite materials.

In this report I would like to highlight the establishment of the molds for the carbon body parts. During the development, two companies played a very important role.

PolyWorx from Nijverdal develops simulation software which enabled us to minimize the risk during production. Also they provided practical support during the design, testing and production. I hereby want to thank PolyWorx for the tremendous contribution.

The realization of the molds took place at Fokker Aerostructures, situated in Hoogeveen. Not only did they provide all the necessary facilities and materials, but also the large amount of help, advice and enthusiasm from its employees really helped us forward. Beyond a doubt, this enabled us to join the small group of world leading solar teams. Special thanks to John Teunissen and Sake Bremer from the R&D department for the unconditional support and supervision during the entire project, even in the project's aftermath.

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Abstract

For the 2013 edition of the World Solar Challenge, Solar Team Twente designed a brand new solar car. In my role as a structural designer I was partly responsible for the internal structure of the car as well as the production of the body parts. The quality of the car's aerodynamic shape is mainly determined by the quality of the molds. During this report the design and production of the molds are outlined. In this way an overview is given of which design choices are made, how the process is simulated and how the theory worked out in practice during tests and production.

Several options for the production of the molds have been investigated. The choice for vacuum infusion was not only based on its technical capabilities. In a project like this, but also in most actual designs, the financial aspect plays a role. Also the availability of facilities and knowledge is important.

When setting up the criteria of the molds, the problem came across that it is very hard for an unexperienced team to specify certain requirements in measurable values. For example, the surface quality has to be very high. Of course a surface roughness can be specified, but then the problem arises of how rough is good enough and even more complex is how to chase after this required roughness during design. For this specific requirement we had to trust on the former team members and the professionals who helped us.

For the selection of materials, a lot of discussion took place. Which materials would result in the best mold? Every specialist seemed to have a different opinion. In the end a laminate was chosen that had specific layers for stiffness (glass fibers and core material) and specific layers for anti-print through. The latter layers had the job to make the surface of the mold as smooth as possible.

The company PolyWorx helped us with the simulation of the laminate in combination with our geometry. With these simulations the optimum injection strategy has been found. This strategy minimized the risk of air inclusions and other problems. Different aspects were collected from the simulations. Not only the optimal locations for injection and venting points were determined, but also the time and amount of resin needed.

Different tests have been carried out in order to test the performance of the laminate and a few variations, as well as to verify the simulations. Some improvements had to be made afterwards, but all problems encountered during the tests have been solved before the actual production started.

During production, which took place at Fokker Aerostructures, molds were made from total different scale in comparison with the tests. These larger scales brought some trouble. The exothermic reaction of the resin occurred faster than accounted for, which caused an air inclusion during the first injection. Also the first post-cure cycle revealed some weaknesses in the process. Although these problems cost a lot of time and energy, in the end also these troubles were solved. After about 2 months of testing and producing, all molds were approved for the next step in our project: the production of the actual car.

In the end some recommendations are listed in order to make even better molds in the next edition of Solar Team Twente. Also a personal reflection is given in which personal developement during the entire project is treated.

Contents

1 Introduction

This report will treat the development of composite molds for a solar car. These molds are used for the production of the body parts of the new solar car from Solar Team Twente. The entire design cycle will be treated, from design to production.

The importance of this process lies in the aerodynamic demands that the body has to meet. Therefore the molds had to have an outstanding surface quality. During the realization, many factors have influence on this property, and therefore I will try to explain in this report which route was taken in order to have the smoothest possible molds in the end. The question which I will try to answer in this report is:

How is the design of composite molds for The RED Engine established, and how was the realization?

The answer to this question will be given by looking at different aspects of the process:

- The technique used to produce the molds
- The choice of materials
- Simulation of the design
- Testing
- Realization

A clear overview will be given of how all these aspects contribute to the end result. Because all molds (11 in total) are pretty similar regarding to design and production, the focus during this report will be on the mold for the lower half of the body. This means that the step between the CAD-design and the actual body part is the main subject of this report, and that is exactly the step between figures 1.1 and 1.2 (both are upside down with respect to the configuration during use).

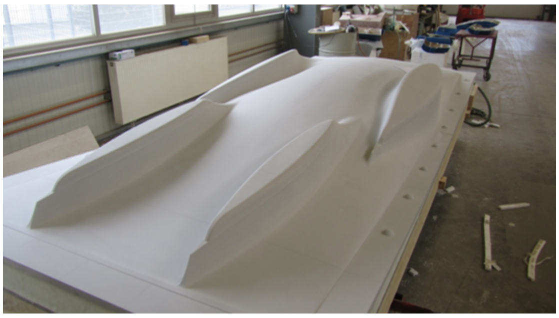


Figure 1.1: Milled CAD-design (plug)

Figure 1.2: Lower body part (product)

2 Requirements

The molds for The RED Engine can be seen as the base for a good aerodynamic shape of the car. When the molds are not perfect, the performance of the product will instantly suffer the consequences. For this reason some requirements are determined.

- In order to be able to withstand the cure temperature of the body parts of 120 degrees Celsius (see appendix A), the molds have to be temperature resistant up to 130°C. Furthermore, when a plug is used to make the molds (which is not necessary for all methods), the initial curing of the mold has to be done at a temperature lower than the maximum allowable plug temperature (approximately 70°C, see appendix A).
- The curing of the product asks for an overpressure of 2.7 bar (see appendix A), since this pressure is the maximum that can be applied on the core material of the product. This demands that the molds are free of air inclusions. Small air traps could implode when the outside pressure rises.
- Since the body parts determine the aerodynamic performance of the car, the smoothness of the molds is of high importance. However, it is very hard to determine a measurable requirement for this. Important is that there are no visible macro structures. This results in the demand that no print-through is visible and that volumetric shrinkage of the resin doesn't cause (local) deformations or a "orange peel skin" . Also the micro structure of the surfaces has to be smooth. In stead of setting a certain surface roughness for the molds, a few tests and the judgement of former team members will determine which surface layers perform best. Of course it was possible to determine a certain maximum surface roughness, but it is very complex to determine which surface roughness is good enough and also which combination of method and material will result in which roughness.
- The main shape of the car has to be maintained for the best aerodynamic performance. A perfect scaling with respect to the design, possibly caused by temperature effects, is not very critical for the aerodynamics as long as it is uniform. Non-uniform temperature effects have to be avoided. To prevent negative influence on the assembling of the mechanical parts like wheels, a tenth percent of the length and width of the car is kept as maximum (uniform) deviation of the outer measurements (this is 4.5mm in length and 1.7mm in width).
- As regards stiffness of the molds, it is also not easy to set certain demands. At the moment when the prepregs of the product are applied to the mold, a little deflection of the mold is not that problematic. It is only problematic during the cure proces of the body parts. When the product is cured in the autoclave, a uniform pressure is applied which doesn't cause deflection. The only reason of deflection during autoclave time, is due to its own weight plus the weight of the prepregs in the mold (which is very low for a solar car: approximately 15kg for the most heavy body part). The maximum deflection due to this will be set to a tenth of a millimeter, and this will be checked using Ansys Composite PrePost.

After the production of the molds, they will be evaluated according to these requirements.

3 Concepts

For the production of the molds, several options are available. In this chapter three different methods will be considered. These methods are the most common methods for making composite molds, and preceding teams which are an important source of knowledge, have some experience with them. First of all it has to be stated that a negative mold will be made since this causes the outside of the final products to be smooth (if the mold is smooth too).

Milling of epoxy-blocks

This technique is comparable with the conventional milling of metals. Using CNC milling enables a high dimensional accuracy, and a very low risk of deformation with respect to the car's design. Also the surface quality is very high since the epoxy blocks can easily be polished. Another advantage is that this method can be used to directly produce the negative mold, where the other methods need a positive plug first to produce the molds on. This is caused by the fact that the epoxy blocks already have a glass transition temperature high enough for the prepreg, where conventional plugs used for the other methods can only be used up to 70°.

A disadvantage is that this technique for molds of this size (approx. 2x5 meters per mold) becomes very expensive.

Wet lay-up

During wet lay-up a positive shaped plug is covered with dry fabrics and impregnated by hand with (epoxy) resin. Layer after layer this is repeated until the total lay-up is impregnated. Some advantages of this technique are its simplicity and the low costs. With some exercise everybody can learn to make a good product with wet lay-up, and all labor can be done by the team itself.

One of the disadvantages are the relatively high potential for air inclusions, which makes the mold unsuitable for autoclave usage. Also, the team from 2011 (who used this exact technique) suffered from epoxy allergies due to the long exposure to epoxy fumes.

Resin infusion

Using a vacuum pump and bag, resin can be transfered through the dry laminate. Making molds this way is relatively easy, but you have to be sure that the flow doesn't cause any air inclusions, so software has to be used to simulate the process since during the actual infusion no influence can be carried out on the flow front. The costs of this technique are low, and much less health risk is taken since there is barely exposure to epoxy fumes. Also the quality of this method is expected to be higher than wet lay-up, since the risk of airtraps is much smaller.

Selection of method

During the entire project, choices are not only depending on the technical possibilities an option offers. The limited budget, in this case, is the motivation to drop the option of milling. The costs turned out to be enormous, and no sponsorship was found for this favor.

A choice is also subjected to the amount of knowledge present or the amount of help you can receive. The company PolyWorx from Nijverdal was willing to help us with making the molds. They are specialized in software for resin transfer molding, and therefore the technique that will be used is resin infusion. The company can help us simulating the process in order to minimize the risk of failure, and they can also help us with practical tips. Fokker Aerostructures was willing to offer all facilities and practical assistance needed for the process.

The body parts will thus be made by 3 separate steps. First, the CAD-design will be milled from styrofoam with an epoxy top layer. This (positive) shape is used to make the negative molds. Then, in the negative molds the product can be made, such that the outer surface of the product has the smoothness of the molds. The aspect of smoothness will be the guidance to a lot of design choices.

4 Material selection

This chapter outlines the materials used for the molds. Both the dry laminate and the resin will be described, together with all their important properties. The selection is mainly based on the experience from PolyWorx and the database of material properties they gathered so far. The lay-up will be tested before use in order to optimize the surface quality.

Core material

At first, a core material is selected which enables perfect flow. It is called Soric® XF from Lantor, see figure 4.1. It is very commonly used in resin transfer molding since it consists of hexagons with in between low flow resistant channels. This ensures a good flow through the core of the laminate, as well as compressive strength and bending stiffness. In order to make the molds as stiff as possible, the thickest variant is chosen: XF6 (millimeters). This will consume more resin and it makes the molds more heavy, but these reasons are inferior to the stiffness since thickness is raised to the third power for stiffness.

Figure 4.1: Lantor Soric® XF6

Figure 4.2: Lantor Soric® TF2

Fibers

At both sides of the core, 4 layers of biaxial glass cloth is used in order to produce enough stiffness. The cloth (stitched unidirectional fibers) is preferred over a glass weave since the fibers are all straight, which reduces the risk of print-through and suffers less from strain since the fibers are not woven up and down. Because the molds can all be seen as some kind of open box, the stiffness in 0/90 direction comes mainly from the geometry. Therefore all fibers will be placed under 45/-45 degrees, to maximize torsional stiffness. Our limited budget is the reason for using glass in stead of carbon. The latter material costs roughly 3-5 times as much per square meter, and after discussion with some professionals in the industry the thermal expansion difference between the two is very small.

Anti-print through

Most important for the molds are its anti-print though properties. These are improved by using multiple special layers at the surface of the molds. When these materials are left out, there is some risk of print-through by the fibers or the honeycomb core, caused by the vacuum pressure as well as volumetric shrinkage.

At the surface, one layer of the wool-like, random woven Lantor Finishmat® D7760 is applied. This causes a very thin layer which is rich in resin. Then a layer of Lantor Soric® TF2 is applied, see figure 4.2. This is a non-woven polyester material which consists of randomly placed soft beads. It acts like a buffer for thickness/pressure disturbances in the fiber layers. The anti-print through layers are ended with a very fine and thin glass weave in order to slowly build op stiffness towards the much stiffer biaxial glass cloth.

As said before, these layers are of most importance for the surface quality and therefore they will be tested before the production really starts. These tests will be decisive for the actual lay-up. Table 4.1 shows an overview of the applied layers before testing.

Material	**Thickness**
[Plug]	-
Lantor Finishmat® D7760	<0.5mm
Lantor Soric® TF2	2mm
Plain weave glass fibers	<0.5mm
4x 600g/m^2 biaxial cloth	2mm
Lantor Soric® XF6	6mm
4x 600g/m^2 biaxial cloth	2mm

Table 4.1: Initial lay-up

Resin

The resin has to meet some important requirements. First of all it should be able to get a glass transition temperature of 130°C after post-curing. It also should be suitable for vacuum infusion, so the viscosity should be very low. This decides whether or not the infusion can be completed within the gel-time of the resin. Furthermore the resin should be able to cure initially at a temperature lower than the maximum temperature that the plug can withstand (76 °C).

A resin that meets all these requirements and is available within a short period and for a reasonable price is the resin Epikote® RIMR935 with hardener Epikure® RIMH 936 from Momentive. Table 4.2 shows some of the most important properties.

Property	**Value**
Gel-time (100 grams at 30°C)	120 min
Viscosity (at 30°C)	200mPas (suitable for infusion)
Maximum glass transition temperature	150°C
Minimum initial cure	25°C
Resin type	Bisfenol A+F
Hardener type	Cyclo-aliphatic amines

Table 4.2: Properties of RIMR935 and RIMH936

5 Simulation

In order to minimize testing time and risk, the company PolyWorx was approached for assistance. This company develops easy-to-use yet accurate software which is able to simulate RTM-processes. Besides, they offered help during the actual infusion of the molds. This chapter briefly describes what the software is based on. Also the input and output of the simulations will be discussed here.

Software

RTM-Worx can be used to decide which injection strategy is most preferred for a certain geometry. In short the software combines information from the geometry, the laminate and the resin, which results in a flow front and information about pressure, resin usage and filling time. With this, the product can be prevented form air traps and exceeding the gel time.

Mathematical background

The mathematics used [1] are a combination of hydrodynamics and finite element methods. Without extensive explanation of these subjects, a few basic principles will be explained here in order to get an overview of the work done by the software.

First of all, Darcy's Law (3D) describes the flow of fluids through porous media. This law originates from the description of water flowing through sand beds, but in it's general form it can be used for any (laminar) flow through porous media.

$$\overline{u} = -\frac{\overline{\overline{K}}}{\eta}(\overline{\nabla}p - \rho_r\overline{g}) \tag{5.1}$$

Where $\overline{u}$ is the flux in $[m/s]$, or $[m^3/s][m^{-2}]$, K the permeability tensor of the laminate in $[m^2]$, $\overline{\nabla}p$ the pressure gradient in $[Pa]$, η the viscosity of the resin in $[Pa \cdot s]$ and ρ_r the resin density.

Inserting this into the continuity equation yields:

$$\overline{\nabla}\left[-\frac{\overline{\overline{K}}}{\eta}(\overline{\nabla}p - \rho_r\overline{g})\right] = 0 \tag{5.2}$$

Using linear elements and Galerkin finite element calculations can solve this equation for the pressure gradient with satisfying accuracy.

The law of Kozeny-Carman is used to determine the permeability tensor of the laminate.

$$K = C \cdot \frac{(1 - V_f)^3}{V_f^2} \tag{5.3}$$

Where V_f is the volume fraction of fibers. The constant C describes the measure of shear within the laminate, and can be found by the infusion of a test laminate.

Injection strategy (basics)

For each product the designer is free to choose the injection and vacuum points but simulations and practical insight can make a certain strategy more preferable over the others. Most of the time, an entire injection consists of a mixture of different strategies. Basically three different strategies can be distinguished:

- Edge injection: inject the resin at one side of a (rectangular) strip/element and install the vacuum point to the other side.

- Peripheral injection: inject the resin at the entire outer edge of a product and put the vacuum point in the middle.
- Point injection: inject the resin in the middle of a product and put the vacuum at the entire outer edge.

All these strategies result in different injection times and flow fronts. These effects can cause and solve problems at the same time, and it is to the user of the software to place the vacuum and injection point exactly at the right place so that air traps and exceeding of the gel time is avoided.

Injection strategy

When the geometry is loaded into RTM-Worx, the user has to define the laminate. PolyWorx has an extensive database of often used materials and its properties. The input is verified with a simple edge injection of a flat plate to determine the permeability of an underformed laminate, see equation **??**.

Also the user has to find the right injection strategy for the model, this has been performed by PolyWorx. The first attempt is based on practical insight from the engineer. After some iterations a satisfying result has been obtained.

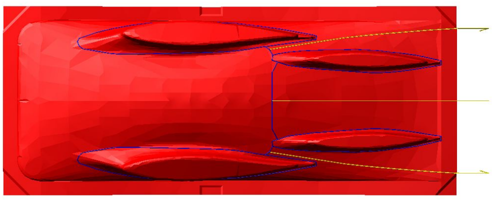


Figure 5.1: Injection lines (in blue)

Figure 5.2: Venting lines (in green)

As can be seen in figure 5.1, the main strategy is a combination of strategies. The parts where the wheels will be, the four bulges, are some kind of peripheral injected. In figure 5.2 it can be seen that this flow is vented at the top of the wheel locations. The same injection lines provide the resin for the rest of the body, but since this is vented at the outer edge of the product, this is more of a “point” injection, creating an outward flow. The middle injection line connecting both wheel encirclements (figure 5.1) provides a flow in the positive and negative driving direction of the car (to the left and right of the picture). This prevents the flows from the left and right wheel encirclements from meeting head-to-head, since in this way a nice V-shape flow will develop, see figure 5.3 to 5.7.

Model output

When the injection and venting points are located such that a satisfying result is obtained, the flow front predictions are given back to the user (figures 5.3 to 5.7). Also information is given about the filling time and resin usage.

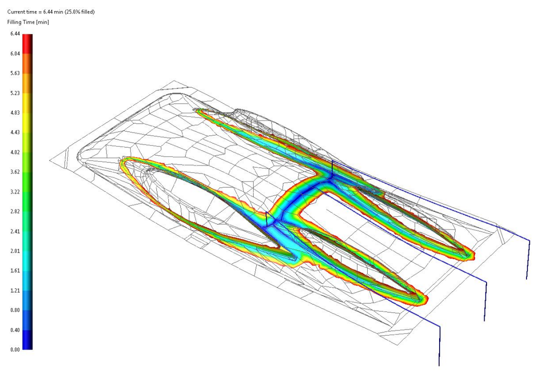


Figure 5.3: Time = 6:44 min

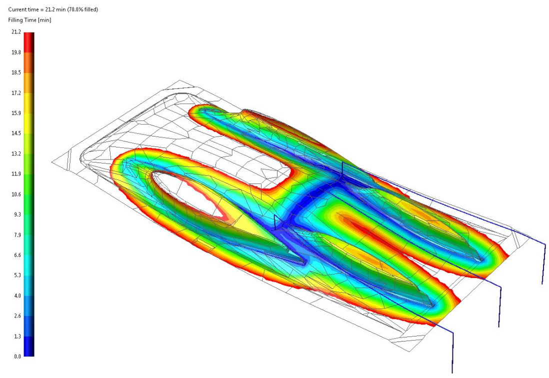


Figure 5.4: Time = 21:20 min

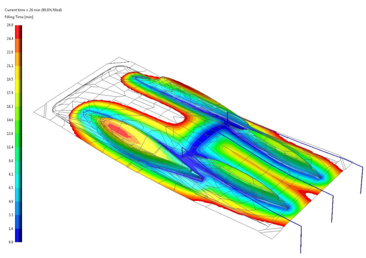


Figure 5.5: Time = 26:00 min

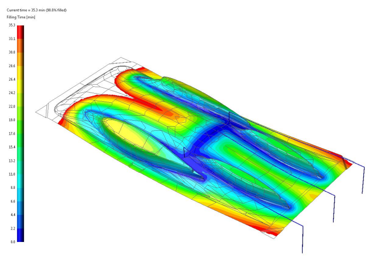


Figure 5.6: Time =35:30 min

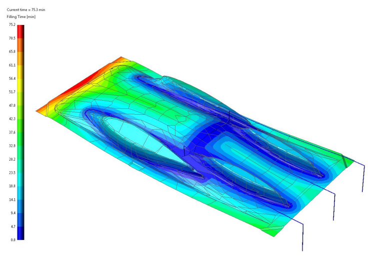


Figure 5.7: Time = 73:30 min

Some other interesting outputs are different process properties as function of (injection) time. First of all the degree of filling (figure 5.8) tells us how much time the injection takes, but it also gives insight in the deceleration of the flow front. Next, figure 5.9 shows the mass flow in kilograms per minute as function of injection time. This can be used to provide the right amount of freshly mixed resin at the right time in order to prevent the need of a giant storage tank where the resin is mixed at once. This could cause an unwanted premature exothermic chain reaction (since it is in a large, semi-isolated volume), which increases viscosity. Figure 5.10 shows the total amount of resin needed for the mold. This amount should be ready to use, in unmixed state, at the beginning of the process.

Summarizing, the infusion process will take approximately 75 minutes, and about 64 kg of resin will be used for this mold. From figure 5.9 follows at which moments during the injection the reservoir should be refilled with freshly mixed resin. As expected the flow front will slow down a lot when the degree of filling increases. This is caused by the fact that when the distance of the flow front with respect to the injection points increases, the amount of resistance increases.

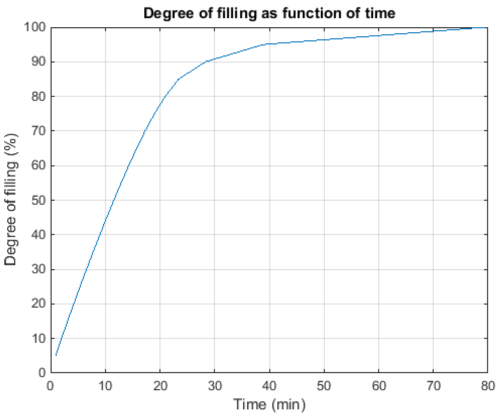


Figure 5.8: Degree of filling

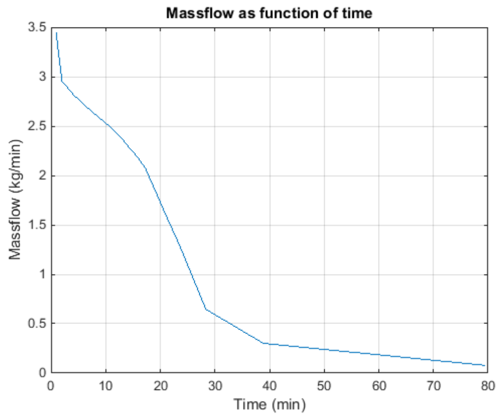


Figure 5.9: Mass flow

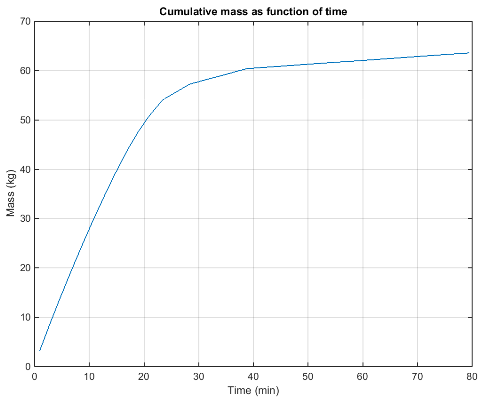


Figure 5.10: Cumulative mass

6 Curing process

This section describes the design of the cure and post-cure cycle. The (initial) cure cycle takes place right after the infusion process. This will be done with a slightly elevated temperature in order to make the resin less brittle. Post-curing is done in order to increase the glass transition temperature so that the mold becomes more temperature resistant. During post-curing the surrounding temperature is slowly increased. This enables more and more chemical reactions in the already cured resin. The higher energy level at high temperatures makes it possible for the epoxy to form more cross-links.

Initial cure

Initial curing of the mold starts at the moment when the resin and hardener are mixed. But for the used resin, the data sheet tells us the product will be very brittle when cured at room temperature. The manufacturer recommends a cure cycle of 2 hours at 50°C, see appendix A. And in order to prevent the exothermic reaction from being to aggressive, a ramp-up of 1°C/min will be used. This is shown in figure 6.1.

Post-cure

Since post-curing is a very sensitive process, it will take much longer than curing. The manufacturer recommends to post-cure in stages. First the temperature has to be raised to 80°C, where is should stay for 2 hours in order to give the resin the time needed to fulfill the entire chemical reaction before the next stage will be started. The next stage is 2 hours at 100°C, and the last stage has to be 130°C for 4 hours. Because more and more cross-links will be formed during the process, the polymers have less degrees of freedom left at the end, so it takes more time for the same amount of cross-links.

The ramp-up between stages is again 1°C/min. The most important reason for this is that the temperature of the mold shouldn't exceed the glass transition temperature, since it will get weak in that case. With a slow ramp-up the material gets the time needed for the reaction. The total process can be found in figure 6.2.

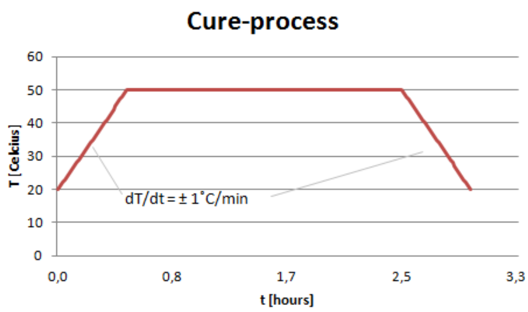


Figure 6.1: Cure process

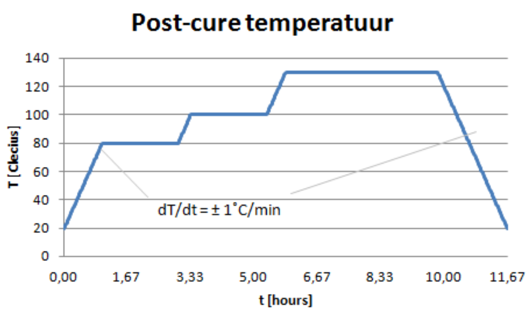


Figure 6.2: Post-cure process

7 Testing

Before the actual production starts, the current design has to be tested and optimized. The main goals for these tests are:

- How is the surface quality and how is this affected by different variations in the lay-up.
- Do the parameters used for the simulation agree with the actual situation.

Variation in lay-up

In the quest for the best possible surface quality, 3 different lay-ups are defined, tested and evaluated. Since the goal is to optimize the surface quality, the basic lay-up (4x glass - core - 4x glass) will not change. Table 7.1 shows the three different tests.

Variation 1	**Variation 2**	**Variation 3**
[basic laminate]	*[basic laminate]*	*[basic laminate]*
Glass weave 160g/m^2	Glass weave 160g/m^2	Glass weave 160g/m^2
Lantor Finishmat D7760	Lantor Soric TF2	Lantor Finishmat D7760
	Lantor Finishmat D7760	Lantor Finishmat D7760

Table 7.1: Anti-print through layer variations

The initial design corresponds with variation 2. However, there are some concerns about the flow through the layer of TF2. This layer has very good flow properties in thickness direction, but since it is placed close to the plug, the flow speed through the layer in thickness direction will be very low. Variation 1 is without the layer of TF2, so it has less risk due to this layer. On the other hand this variation is more sensitive for print through. Variation 3 has an extra finish mat in stead of TF2. It provides a thicker resinous layer at the surface, and thus in theory a better surface quality.

Furthermore, during the infusion of the 3 samples, their flow speed will be tracked. In this way PolyWorx can validate the model parameters.

Results

After the injection of the three samples, a curing and post-curing process has been executed. The tests directly proved to be useful, since a beginner's mistake was found. Especially the samples of variation 2 and 3 suffered form a noticeable amount of warping. The source of this was found after the samples were cut in half. The extra layers at the surface are relatively resinous with respect to the basic laminate, and it has a very low E-modulus. When a resin is cured, it always has some volumetric shrinkage. This causes a compressive stress at the surface of 1 side of the sample, and thus the sample warps towards that side. The solution for this problem is to make the laminate perfectly symmetrical.

Furthermore it could be concluded that the surface quality of variation 2 was better than that of variation 1 and 3, so the layer of TF2 did not bring the feared problems, and has a positive result of the quality. For this reason variation 2 (but symmetric) has been chosen to be the final lay-up. The flow speed and fill time of the samples were exactly as planned, so the model parameters can be considered correct. The new lay-up has been tested afterwards with satisfying results.

As mentioned in the requirements, it is hard to define how smooth the molds have to be. With the opinion of former teammates the surface has been assessed on basis of the requirements. Figure 7.1 shows the results of the test (variation 3 at the left and 1 at the right). Although this image doesn't show the detailed quality differences between the 3 variants, the glossiness tells something about the smoothness of the molds.

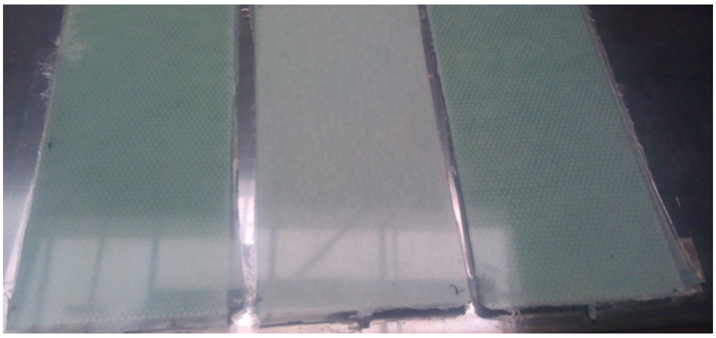


Figure 7.1: Surface quality of the 3 samples (in the order 3 - 2 - 1, from left to right)

8 Production

With the materials selected, the infusion strategy determined and all tests completed the production stage started. During this chapter, again the focus will be on the mold for the lower part of the outer shell. This chapter will discuss some of the aspects where unexpected or unwanted events came across, since they were very instructive and brought more insight in the complex understandings of composite materials.

Gel time

According to the manufacturer of the resin, the lowest viscosity can be reached when it is at approximately 30°C. In order to get maximum advantage of this property, it was chosen to execute the infusion process inside an oven at this temperature. The reason to do this was the believe that less viscosity brings less risk in fill quality.

As we found out the hard way, an elevated temperature works like a catalyst for epoxy resins. Since the entire process took place in the oven, all resin was already heated a little before it was actually injected. Just before the injection, the resin and hardener were mixed. At that moment, the exothermic reaction started and was accelerated by the elevated temperature. Also, the pretty thick laminate work like an isolator. All together the temperature of the resin raised pretty fast, which again increased the speed of the exothermic reaction. This caused a snowball effect.

Soon the awareness rose that the temperature in the laminate was nowhere near 30°C. This caused the viscosity to increase very rapidly, and parts of the flow front started to stagnate after the mold was filled for approximately 80%. The result was a huge air inclusion, which means a rejected mold. All time spend on placing the dry fibers and preparing the injection was gone and had to be done again.

The combination of the thickness of the laminate (approximately 12mm) and the elevated temperature at the start caused the resin being too hot. The effect of the temperature on the process was clearly underestimated. Thereby, the injection time of 75 minutes was too long for a resin at an estimated temperature of 50°C. The new molds were injected at room temperature (18°C). In this way the domino effect of the heat was slowed down a lot, which resulted in a more balanced process temperature-wise.

Post-curing

The rejected mold was used to test the post-cure cycle for a mold of this size and weight. It turned out to be a great decision to test it with this rejected mold. After measuring the shape of the post-cured mold at a lot of points we had to conclude that the mold was sagged. Especially at the points where the mold was supported by its supporting frame, it became clear that the glass transition temperature of the resin was exceeded because at these points slight humps were visible caused by the supportings. At more points one could measure that the main shape of the body was affected. For aerodynamic reasons this was unacceptable. So a solution had to be found.

After discussing the problem with engineers at Fokker, PolyWorx and the manufacturer of the resin, a new post-cure cycle was set up, one that would take much longer, with lower ramp-up speeds and more stages. Especially at temperatures above 100°C, the new cycle was very conservative in order to allow the resin to adapt to these temperature levels. The new ramp-up rate was set to 1°C every 3 minutes. Figure 8.1 shows the new cycle which at the end resulted in a mold with a perfect shape.

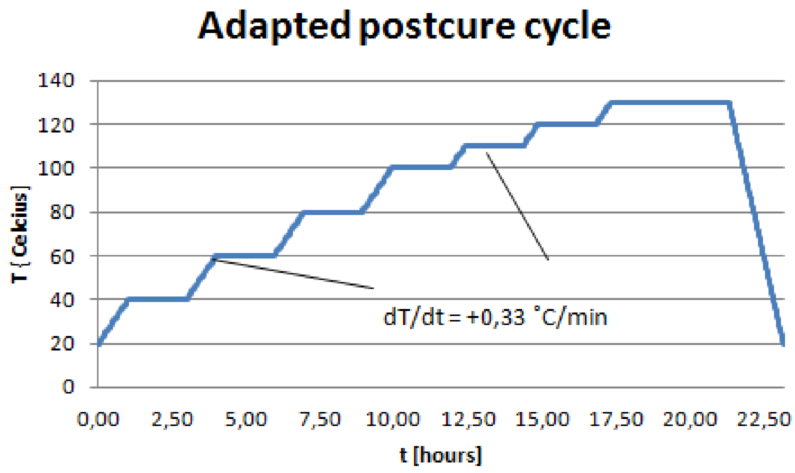


Figure 8.1: The new, very conservative post-cure cycle

Requirements

With all mentioned problems solved, a new mold was produced. The last stage was to check whether or not the mold meets his requirements. First of all it can be concluded that a temperature of 130°C can be withstand, since the proper post-cure cycle is used. Also no air bubbles were found so the mold should be good enough for autoclave usage. The smoothness of the molds was really nice, although a little sanding and polishing was needed in order to remove the residues of the release agent. No macro structure could be detected. And at last, after measuring multiple predefined points on the mold one could conclude that the main shape as well as the designed measurements were preserved.

9 Conclusions and recommendations

Solar Team Twente strives for continuity in its existence, so the knowledge gathered during an edition is documented for the next edition. In this documentation can be found which choices were made, what went very well and what went wrong. Also a recommendation is formulated for the next team which comprises suggestions about which path to follow. The conclusions and recommendations formulated here form a small part of transfer of knowledge to team 2015.

Conclusions

As discussed in the chapter about production, the final molds meet all requirements. Some of these were hard to formulate properly with measurable numbers, but in these cases the judgment of ourself, former teammates or professionals can be considered as accurate. Of course this is like trial-and-error, which brings some risk.

With the selected resin the method could be carried out. Also the requirements of the initial cure and post-cure processes were met. The aerodynamic shape deviated minimal from the CAD-geometry. The surface of the molds were glossy, this means that no macro structures were visible, and the micro structures were negligible.

The production, however, did not entirely go according to plan. The first infusion process yielded a rejected mold because the resin gained to much heat during the process, causing it to become more viscous and eventually stagnation occurred. Also the initial post-cure process was not suitable for molds of this size and weight with minimal support. These failures are mostly due to the inexperience of us regarding composite materials. The risks that come with it, especially temperature related effects, were underestimated for some cases.

Recommendations

First of all the method of resin infusion works pretty well. Especially with the knowledge of this edition, it is a good option for next year. Some minor changes have to be made, only the most important recommendations will be listed here. However, if a partner can be found that is able to mill the negative molds out of epoxy blocks for a reasonable price, then this option is preferable. This option brings much less risk, more accuracy and it costs less time for the team, which could be spend on other things.

Most trouble we encountered were the sagging of the mold during post-curing and the resin getting too hot and viscous during injection. Both problems had to do with the properties of the resin. Whatever resin will be taken, it is highly recommended to test it extensively. Preferably a resin is used with a longer gel-time than the one used this year, and comparable (or less) viscosity.

To prevent sagging of the molds, first of all a very conservative post-cure cycle has to be chosen. But this year's supporting frame also had its weaknesses. Due to its low amount of supporting points, a relatively large parts of the molds hung unsupported. During post-curing the stiffness of the molds decreased causing sagging. Therefore it is recommended to use a supporting frame that supports the molds on much more points. Probably an egg carton construction out of multiplex is the best option, as long as it doesn't clamp the mold when it expands due to heating.

But there were more problems that we met, that should be solved for the next edition. These didn't cause any trouble during the production of the molds but they did during the production of the products, the actual bodyparts. The thermal expansion of the molds did deviate noticeably from the thermal expansion of the product. During the assembly of the car's internal structure this caused some trouble since the molds were needed during this process. The car had become (just slightly) bigger than the molds and therefore it didn't fit properly into the mold afterwards. This problem of thermal expansion of composite products is pretty complex. But two factors that can reduce this problem are using carbon fibers in the mold, and reducing the volume fraction of resin in the molds. With this adaption the mold's thermal expansion should agree much more with the thermal expansion of the product.

10 Reflection

September 2012 until February 2014 was an amazing period for me and my team. We started with a clean sheet of paper and ended with a car that drove 3000 kilometers through the Australian dessert, finishing 3^{rd} among top-universities around the world. The only teams that beat us were the WSC veterans Delft (Netherlands) and Tokai (Japan). Among the lower classified teams are the universities of Michigan, Stanford (both US), Cambridge (UK), Leuven (BEL), Toronto (CAN), and lots more. Only competing in such a worldwide event is an incomparable experience.

High performance design

Throughout the project I've been involved in a complete design cycle. We started from scratch, worked on the design, tested and build products and eventually ended up with a fully functional racing car. For me it was very interesting so see that every choice we made in every stage of the project had a certain effect on the car's performance. This direct coupling between theory and practice cannot be learned or experienced so intense anywhere else. What it made even more learnful was the goal to make a car that would become world champion in a very mature event. This increased the challenge to get the best out of yourself, the team and the design. These high demands made it a high-performance team, as I often call it, which is an unique experience.

Multi-disciplinary team

The complete design cycle and its high demands made the project very educational in a technical way. I've learned a lot in terms of composite materials, not only on the theoretical part but also its production methods. But since the complete technical team, which were basically my direct colleagues, had much more disciplines I also learned some from the mechanics, aerodynamics, strategy, data-acquisition and even electronics. In fact, since some design choices are depending on partner companies or financial aspects, I learned a lot more than only technical knowledge. The obtained knowledge of working in such a multi-disciplinary team I consider very valuable. It is not something your can learn during courses at the university since the amount of disciplines (during group assignments) is limited and not from such a wide range.

Non-technical, personal development

During the project I developed a lot of discipline and ability to reflect. Working with all the motivated students and companies, and sincerely believing in your goals made me constantly able to go the extra mile. This discipline had its rewards not only at the moment we won the bronze medal, but still every time I see the car I feel satisfied and proud. Thereby, I'm able to very honestly point out the possible improvements of the design. In that way, becoming third might be more educational than winning, since it forces you to watch in the mirror and to formulate certain weaknesses of a design. Without an acknowledgment of your mistakes or incorrect insights, the next team starts with an incomplete representation of reality.

Technical development

From the technical knowledge I gained, I think experiencing the difference between theory and practice was the most valuable for me. Of course I have learned a lot about the theory of composites, but that is something you could also learn at the university. Actually using the materials in the workshop reminds you every time of the choices your made behind the desk. Seeing and feeling the materials and its behavior really tells you if you thought of everything. Especially if things go wrong, like during the production of the molds, you learn what aspect you forgot or underestimated. This gives more insight in the materials, and you will never make the same mistakes again.

References

[1] Koorevaar, A. (2002). *Simulation of liquid injection molding*, SAMPE 2002, Paris, France

11 Appendix A: Technical Data Sheets

The next pages show the technical data sheets from different materials which had an influence on design parameters.

It starts with the data sheet of the resin of the body parts. This determined the temperature and pressure properties required. Note that the resin of the product should be cured with a pressure of 6.2 bar, or the maximum allowed by core material. The core material used in the car could withstand a maximum pressure of 3.5 bar. With some safety margin the product was cured under 2.7 bar.

The next data sheet is the one for the epoxy layer of the plug. This determined the maximum initial cure temperature. The last data sheet is the one for the resin of the molds. This is used throughout the design.

MULTIPREG E722

120°C (248°F) Curing Modified Epoxy Resin Component Prepreg

E722 is a toughened epoxy resin system of medium viscosity for cures at 120°C (248°F), pre-impregnated into high performance fibers such as carbon, glass and aramid. Designed for structural applications in the motor racing and marine industries, E722 would also suit general aircraft fittings, sporting equipment, and a wide range of engineering applications.

*E722 is compatible for co-cure with Amber Composites 120°C (248°F) cure resin film EF72 and Amber Composites syntactic core Amlite SC72A.

CHARACTERISTICS:

- **Excellent drapeability – complex shapes easily formed**
- **60 day shelf life at ambient temperature**
- **Autoclave, vacuum bag or press cures**
- **Good surface finish**
- **Medium tack level, easily laminates to mold surface**
- **Tg (DMTA – peak tan δ) 138°C (280ºF) after 1 hr at 120°C (248°F)**
- **Low volatile content – no solvents used during processing**

RESIN PROPERTIES	
Density	1.21 g/cm³ (75.5lbs/ft³) at 23°C (73.4ºF)
Tg (DMTA) after 1hr at 120°C (248°F)	Onset: 120°C (248°F) Peak Tan δ: 138°C (280ºF)

PROCESSING

Following removal from refrigerated storage, allow prepreg to reach room temperature before opening the polythene bag, to avoid moisture condensation.

Cut patterns to size and lay up the laminate in line with design instructions taking care not to distort the prepreg. If necessary, the tack of the prepreg may be increased by gentle warming with hot air. The lay up should be vacuum debulked at regular intervals using a P3 (pin pricked) release film on the prepreg surface, vacuum of 980 mbar (29 ins Hg) is applied for 20 minutes.

For autoclave cures, use of a non-perforated release film on the prepreg surface trimmed to within 25-30mm of prepreg edge is recommended for the cure cycle, a vacuum bag should be installed using standard techniques.

CURING CYCLES

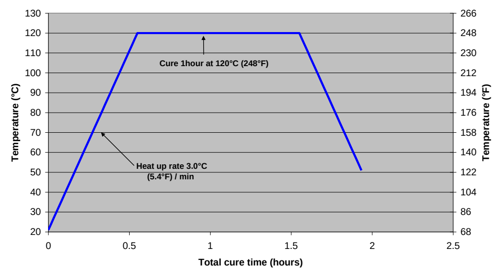
E722 can be successfully molded by vacuum bag, autoclave, or matched die molding techniques.

Increase autoclave pressure to 1.4 bar (20 psi) with vacuum applied.

Vent to atmosphere and raise pressure to 6.2 bar (90 psi) (or max allowed by the core material).

Increase air temperature at 3°C (5.4°F) / min and hold for 1 hour at 120°C (248°F). Allow to cool to 50°C (122°F) before removal of pressure.

120°C Cure Schedule - E722



EXOTHERM

In certain circumstances, such as the production of thick section laminates rapid heat up rates or highly insulating masters, E722 can undergo exothermic heating leading to rapid temperature rise and component degradation in extreme cases.

Where this is likely, a cure incorporating an intermediate dwell of 1 hr at 90ºC (194ºF) is recommended in order to minimize the risk.

TYPICAL LAMINATE PROPERTIES (at Room Temperature)

T300 (3K) 280g/m2 5HS carbon 0/90° configuration woven laminates, cured 1hr at 120°C(248°F), results normalised to 55% Vf.

Tensile Strength	641.2 MPa
Tensile Modulus	58.0 GPa
Tensile Poisson's Ratio	0.04
Tensile Strain to failure (%)	1.0
Compression Strength	605.8 MPa
Compression Modulus	75.1 GPa
Flexural Strength	901 MPa
Flexural Modulus	59 GPa
Apparent ILSS	68.1 MPa

T300 (3K) 280g/m2 4/4 twill carbon 0/90° configuration woven laminates, cured 1hr at 120°C(248°F), results normalised to 55% Vf.

Flexural Strength	900 MPa
Flexural Modulus	66 GPa
Apparent ILSS	59 MPa

STORAGE

Shelf life is 60 days at ambient temperature 20ºC (68ºF)

Refrigerated storage life is 12 months at –18ºC (0ºF)

To avoid moisture condensation: Following removal from cold storage, allow prepreg to reach room temperature before opening the polythene bag.

HANDLING SAFETY

Observe established precautions for handling epoxy resins and fibrous materials.

For further information refer to Material Safety Data Sheet.

FURTHER INFORMATION

Please contact Amber Composites for additional information.

SC 380

EPOXY TOOLING PASTE

DENSITY 0.82 – HARDNESS 65D Shore

DESCRIPTION

- *Large dimension tools / composite tooling and mocks-up production by extrusion process.*
- *Master Plugs.*

PROPERTIES

- *Very good surface aspect.*
- *Good behaviour on vertical support up to 30 mm*
- *Good thermal resistance.*

PHYSICAL PROPERTIES				
Composition		**RESIN**	**HARDENER**	**MIXING**
Mix ratio by weight		100	100	
Aspect		viscous paste	viscous paste	viscous paste
Colour		grey	white	grey
Viscosity at 25°C 0,9 s^{-1} (Pa.s)	RM 100 Lamy	600	700	600
Specific gravity at 25°C (g/cm^3) Specific gravity of cured product at 23°C	ISO 1675 : 1985 ISO 2781 : 1996	0.80 -	0.80 -	- 0.82

THERMAL AND MECHANICAL PROPERTIES (1)			
Hardness 7 days at 23°C 16 hours at 70°C	ISO 868 : 2003	Shore D1	65 67
Glass transition temperature (Tg) 7 days at 23°C 16 hours at 70°C	ISO 11359 : 1999	°C	50 83
Coefficient of thermal expansion (CTE) 16 hours at 70°C	ISO 11359 : 1999	$10^{-6}.K^{-1}$	60
Tensile modulus	ISO 527 : 1993	MPa	1,100
Tensile strength	ISO 527 : 1993	MPa	14
Elongation at break	ISO 527 : 1993	%	2.8
Flexural modulus	ISO 178 : 2001	MPa	1,100
Flexural strength	ISO 178 : 2001	MPa	24

(1) : Average values obtained on standard specimens / Hardening 24 hr at 23°C + 16 hr at 70°C

SC 380

EPOXY TOOLING PASTE

DENSITY 0.82 – HARDNESS 65D Shore

During processing the dispensing nozzle must be maintained perpendicular to the surface on which the product is applied. Ensure overlap of ribbon.

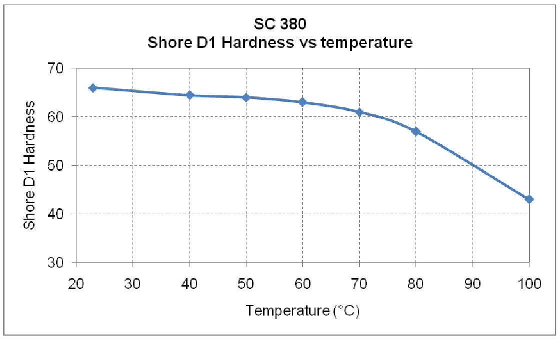
CAUTION : Exotherm mostly depends of the type of machine and of the working parameters such as :

- *Room temperature.*
- *Insulating property of support.*
- *The mixture temperature (depending of the type of mixer: static or dynamic) and the speed of mixing and output.*
- *Applied thickness.*

.

EXOTHERMIC PEAK AND HARDENING TIME *				
Thickness (mm)	Product temperature (°C)	Exothermic peak (hours)	Exothermic peak (°C)	Workability (hours)
25	27	2.5	60	24

** Room temperature : 20/22°C ; polystyrene support.*



PROCESSING CONDITIONS

On vertical support, it is sometimes recommended to apply a thin coat of product with a spatula; this will help to reinforce the bonding on the support.
For ceiling application,we recommend 30 mm of maximum thickness.
For dynamic mixing machine ,please contact us for parameters : composite@axson.fr

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SC 380

EPOXY TOOLING PASTE

DENSITY 0.82 – HARDNESS 65D Shore

HANDLING PRECAUTIONS

Normal health and safety precautions should be observed when handling these products :

- *ensure good ventilation,*
- *Wear gloves, safety glasses and protective clothes.*

For further information, please consult the product safety data sheet.

STORAGE CONDITIONS

Use within 9 months of the manufacturing date. Expiry date indicated on the packaging.

PACKAGING

RESIN	HARDENER	INTERNAL DIAMETER OF DRUMS
1 x 35.0 kg	1 x 35.0kg	360 mm
1 x 150.0 kg	1 x 150.0kg	570mm

GUARANTEE

The information of our technical data sheet is based on our present knowledge and the result of tests conducted under precise conditions. It is the responsibility of the user to determine the suitability of AXSON products, under their own conditions before commencing with the proposed application. AXSON refuse any guarantee about the compatibility of a product with any particular application. AXSON disclaim all responsibility for damage from any incident which results from the use of these products. The guarantee conditions are regulated by our general sale conditions.

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MOMENTIVE

Technical Data Sheet

Issued: August 2006

EPIKOTE™ Resin MGS® RIMR 935 and EPIKURE™ Curing Agent MGS® RIMH 936/937

CHARACTERISTICS

Approval	-
Application	Applications that require high heat resistances – boat and shipbuilding, automotive, tooling and moulding
Operational Temperature	-60 °C up to +130 °C (-76 °F up to +266 °F) after suitable heat treatment
Processing	At temperatures between 15 °C and 50 °C (59 °F-122 °F), preferably 25 °C - 35 °C (77 °F - 95 °F), infusion, hand lay-up and others
Features	Very high heat resistance, low mixed viscosity, good mechanical properties, pot life approx. 2-5 h, short curing times at elevated temperatures
Special Modifications	On request
Storage	Shelf life of 24 months in originally sealed containers

APPLICATION

Low viscous infusion resin system for processing of woven and non-crimp multiaxial fabrics of low to high areal weight. Due to its very good mechanical properties, this system is suitable for the production of components featuring high static and dynamic loadability and high heat resistance.

Infusion resin RIM 935 is based on bisphenol A/F resin. Hardener RIM H 936 and RIM H 937 are a modification of aliphatic and cycloaliphatic amines. As crystallisation of both A and B component is possible, special care should be given to this issue. It appears as a clouding or solidification of the contents of the container. Before processing, the crystallisation must be removed by warming up.

Pot life (100 g mixed at 30 °C/86 °F) is approximately 2 hours for RIMH 936 and 3,5 h for RIMH 937. Optimum viscosities for infusion are realized at temperatures in the range of 25 - 35 °C (77 ° - 95 °F). Pot life is then between approx. 1 h (RIMH 236 at 40 °C/104 °F) to 5 h (RIMH 937 at 25 °C/77 °F). Following initial curing at room temperature, the parts are still brittle and require heat treatment at a min. temperature of 50 °C/122 °F before processing or demoulding. Direct curing at elevated temperatures (60 °C-100 °C/140 °F-212 °F) is possible. The curing time can be reduced to a few minutes by this.

Non-tacky, high-gloss surfaces are obtained even with unfavourable curing conditions, such as low temperatures or high relative humidity.

The infusion resin system does not contain any unreactive components. All raw materials and additives feature a very low vapor pressure, therefore permitting processing of the material under vacuum even at elevated temperatures. Compatibility problems are not to be expected in combination with suitable gelcoats, various paints (e.g., PUR-based), etc., however comprehensive tests are indispensable.

These hardeners can be stored for at least 24 months in their carefully sealed original containers. Even though it is unlikely, these hardeners may crystallise at temperatures below +15 °C. The crystallisation is visible as a clouding or solidification of the contents of the container. If crystallisation of either component should be observed, it can removed by warming up. Slow warming up to approx. 50 °C-60 °C (122 °F-140 °F) in a water bath or oven and stirring or shaking will clarify the contents of the container without any loss of quality. Use only completely transparent products. Before warming up, open containers slightly to permit equalization of pressure. Caution during warm-up! Do not warm up over an open flame! While stirring up, use safety equipment (gloves, eyeglasses, respirator equipment).

The relevant industrial safety regulations for the handling of epoxy resins and hardeners and our instructions for safe processing are to be observed.

SPECIFICATIONS

		Infusion Resin RIMR 935
Density	[g/cm³]	1,14 - 1,20
Viscosity	[mPas]	300 - 600
Epoxy equivalent	[g/equivalent]	155 - 165
Epoxy value	[equivalent/100g]	0,61 - 0,64
Refractory index		1,5350 - 1,5450

		Hardener RIMH 936	Hardener RIMH 937
Density	[g/cm³]	0,92 - 0,97	0,95 - 0,96
Viscosity	[mPas]	10 - 50	30 - 100
Amine Value	[mg KOH/g]	550 - 650	450 - 500
Refractory index		1,4850 - 1,4920	1,485 - 1,505

Measuring conditions: measured at 25 °C / 77 °F

PROCESSING DETAILS

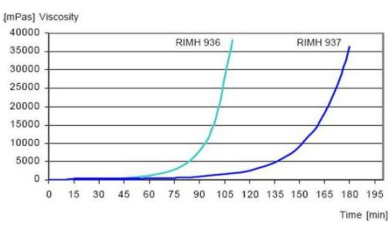
	Injection Resin RIMR 935	Hardener RIMH 936	Hardener RIMH 937
Average EP - Value	0,63	-	-
Average amine equivalent	-	45	59

MIXING RATIOS

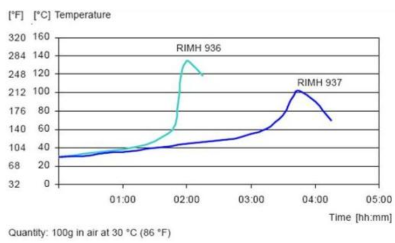
	RIMR 935 : RIMH 936	RIMR 935 : RIMH 937
Parts by weight	100 : 29 ± 2	100 : 38 ± 2
Parts by volume	100 : 35 ± 2	100 : 45 ± 2

The specified mixing ratios must be observed as exactly as possible. Adding more or less hardener will not result in a faster or slower reaction, but in incomplete curing, which cannot be corrected in any way. Resin and hardener must be mixed very thoroughly. Mix until no clouding is visible in the mixing container. Pay special attention to the walls and the bottom of the mixing container.

VISCOSITY DEVELOPMENT

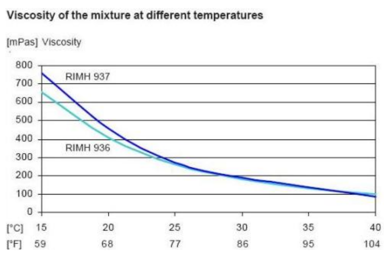


TEMPERATURE DEVELOPMENT



The optimal processing temperature is in the range between 20 and 25°C (68 - 77°F). Higher processing temperatures are possible, but will shorten pot life. A rise in temperature of 10 °C (18°F) will halve the pot life. Water (for example very high humidity or contained in fillers) causes an acceleration of the resin/hardener reaction. Different temperatures and humidities during processing have no significant effect on the strength of the cured product.

VISCOSITY OF MIXTURE

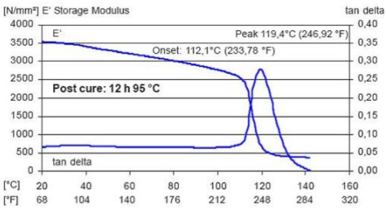


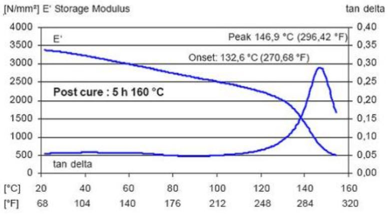
GLASS TRANSITION TEMPERATURE (TG) UNCONDITIONED

Max. TG at 80 °C (176 °F) post cure	90 - 100 °C (194 - 212 °F)
Max. TG at 100 °C (212 °F) post cure	105 - 120 °C (221- 248 °F)
Max. TG at 140 °C (284 °F) post cure	135 - 150 °C (275 - 302 °F)

DMA

DMA-Measuring after heat treatment
DMA-T_G(peak) tan delta: Infusion resin RIM 935 with hardener RIMH 937





Measuring conditions:

Frequency:	1Hz
Coupon thickness:	2mm
Heating rate:	2K/min

PDS-8221- (Rev.3/18/2014 6:57:09 AM)