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Fully-Cored Hulls Using Infusion

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In 2000 Giuseppe graduated from the University of Naples - Frederico II by presenting his thesis entitled 'Design & Characterization of Absorbing Composite Scaffolds for Tendons and Ligaments'. He then joined the research team of the University that was studying composite materials design and technologies. His particular interest was lamination theory as it relates to semi-automatic technologies such as infusion, pultrusion and filament winding. As a result of his composites materials work he was awarded a Ph. D. In September 2003, Giuseppe joined Fiart Mare SpA (one of Italy's leading producers of pleasure boats up to 50 ft. [15 meters]) as Manager of the Composite Department. He has been instrumental in moving the company to fully-cored hulls using core infusion technology.

Introduction

Infusion technology has been increasingly adopted by the many boat builders due to its environmental advantages, laminate performance, quality benefits and its ability to allow the industrialization of a process that in the past has been predominately a manual operation.

This paper will explain how Fiart Mare has re-engineered its production process in order to take full advantage of infusion molding.

It will cover material choices (resins, fibers, core materials), structural design decisions, process options and the implementation and start-up of the new process. The latter will include the structured re-training of existing personnel to facilitate the smooth introduction of the new process.

The paper will conclude by presenting a series of comparisons between infusion molding and hand lay-up.

Background

For the last 40 years or so hand and spray lay-up have been the predominant manufacturing processes for the manufacture of glass reinforced plastic boats. They are relatively easy to use, allow the use of female molds and, until recently, the regulations regarding emissions were fairly relaxed. In fact, until the advent of stricter emissions regulations, there was very little motivation for the vast majority of boat builders to change their working practices.

Hand/Spray-Up Limitations

The most commonly used matrix for GRP boats is undoubtedly polyester resin. Polyester resins are produced through a process of poly-condensation between poly-basic acids and polyvalent alcohol. If the acid is unsaturated, these polyesters can co-polymerize with styrene, the unsaturated monomer obtained out of de-hydrogenation of the ethyl benzene at atmospheric pressure and at about 600°C. The product that is created is a polymer with a three-dimensional structure that is infusible and insoluble. Evaporation of the styrene during hand or spray laminating process is a harmful chemical-physical process that is almost completely eliminated by the use of infusion molding techniques.

However, in addition to the environmental issues, there are many negative aspects to the hand/spray-up process particular in terms of quality as the finished laminate is heavily dependent on the relative skill of the individual. Moreover, even when the skill level is high, it is difficult to achieve fiber fractions of more than 40% and to eliminate the problems associated with air entrapment.

Regarding mechanical properties, it is clear that laminates manufactured using the infusion process are considerably superior to those produced by hand lay-up. Four point bending tests to ASTM 790 Norm show that infusion laminates have 20% higher flexural strength than an equivalent hand lay-up laminate.

Equally important, is that it is difficult to efficiently plan a serial, multi-stage production operation where a significant element (the hand/spray lay-up component) is subject to time variations due to the varying skills/speed of the operators. This last point convinced us that if a company wants to be really competitive in serial, multi-stage production it has to concentrate absolutely on the increase of the qualitative production performances instead of improving the time and production methods. In fact, its only in this way that we believe that it will be possible to offer a competitive product on the market with a high quality/good price relationship.

Approach to the Infusion Process

After some consideration, it was decided at Fiart Mare SpA to focus our resources on the study and application of infusion technology.

Following the careful evaluation of proposed solutions from different companies, the technical management of Fiart Mare chose DIAB SpA (a leading company in the production of core materials and associated technical services for boat yards) to provide advice and process support. This decision was taken by the technicians at Fiart Mare because of the simplicity and efficacy of DIAB Core Infusion Method. This method, like every infusion system, consists of the dry application (following a manual skin coat) of a certain number of fiber layers, the core materials, the resin feed lines, the vacuum lines, a flexible vacuum bag, the resin trap connections and a vacuum pump.

Once the lay-up of the materials is complete and all connections are made, the actual infusion process takes place with the vacuum both drawing the resin through the laminate and providing laminate consolidation. With the DIAB approach, the transfer of the resin through the laminate is carried out by the core material which features a series of grooves at 0/90° and perforations.

Once the decision was taken to use the DIAB infusion method, a plan was implemented to re-engineer the product, re-train production personnel and re-organize the production line.

Basic Materials

The first thing a boat yard has to do when it decides to apply a new composite manufacturing technology, is to re-evaluate its current materials. In the pleasure boat sector, this choice is reduced to three fundamental elements: the fiber, the resin and possible core materials.

In manual molding (in Europe at least) chopped strand mat (CSM) and woven rovings tend to be the dominant materials. Following a carefully analysis of both materials, it was decided for two reasons that neither of these was suitable for the resin infusion process:

1. The random nature of CSM does not allow a smooth resin flow.

2. Both materials cannot be readily conformed to the shape of the mold when in their dry state.

Therefore we needed to choose new reinforcements that would offer equal or superior mechanical characteristics than the existing products one while at the same time being compatible with the infusion process. We decided to opt for multi-axial reinforcements.

In the multi-axial technology, the fibers in each layer are not woven but run parallel to each other. This type of more 'open' reinforcement not only allows the resin to more readily flow and adhere to every fiber but also better resin penetration between each layer. The end result is complete impregnation in less time than more traditional 'boat building reinforcements'. Moreover, the better conformability of multi-axials makes it easier for the operator to lay them up in their dry state.

With infusion - compared to manual lamination – the resin polymerizes in mass. In other words, while with hand lay up, laminating layer by layer, the polymerization is carried out with relatively small amounts of resin. With infusion this is the contrary. As a result, with infusion there is a greater chance of experiencing shrinkage problems that could directly impact on the surface finish of the vessel.

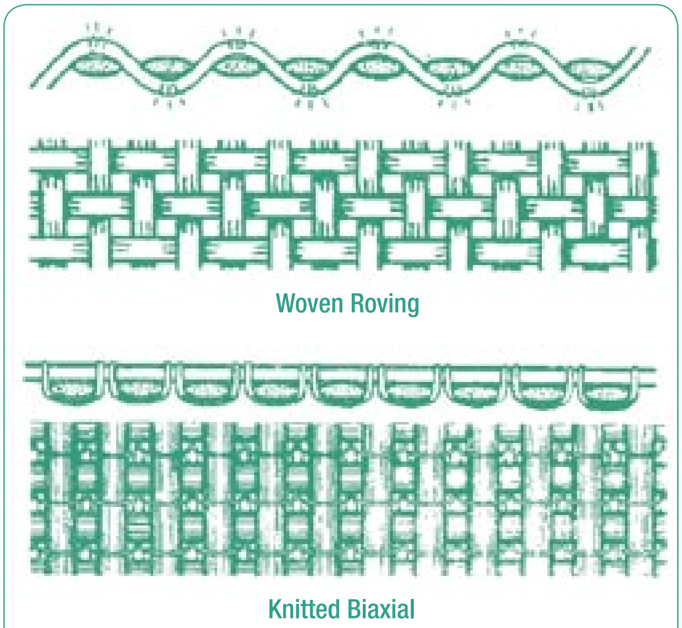

Fig. 1 - Comparison between woven rovings and stitched biaxial.

With the construction of the multi-axials, on the other hand, there are much fewer areas where resin could accumulate leading to shrinkage problems.

Once the fibers have been chosen, the next task for the boat yard is to select a resin that is suitable for the particular infusion process that is going to be used.

There are two basic parameters that the technical team have to take into consideration during the evaluation process. The first is the resin flow characteristics. Conventional hand lay-up resins cannot be used due to their relatively high viscosity. Secondly a good infusion resin must ideally have zero shrinkage to ensure an A1 surface finish. In the pleasure boat market, the quality of the surface finish of the hull can be as important to the customer as the absence of structural defects.

Therefore at Fiart Mare, although we are currently evaluating 'anti-print through' gelcoats, we still use a skin coat or as it sometimes too referred to - a tie coat. After a lengthy series of experiments, we decided to opt for an epoxy-vinylester for the skin coat and an isophthalic polyester infusion resin. The principle characteristics of the isophthalic polyester infusion resin are shown in Tables 1 and 2.

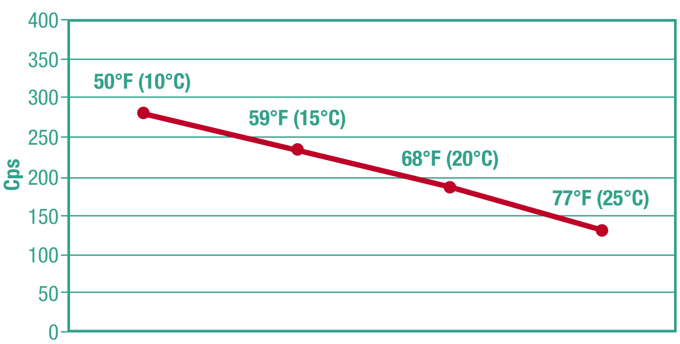

Table 1 - Resin viscosity related to temperature,

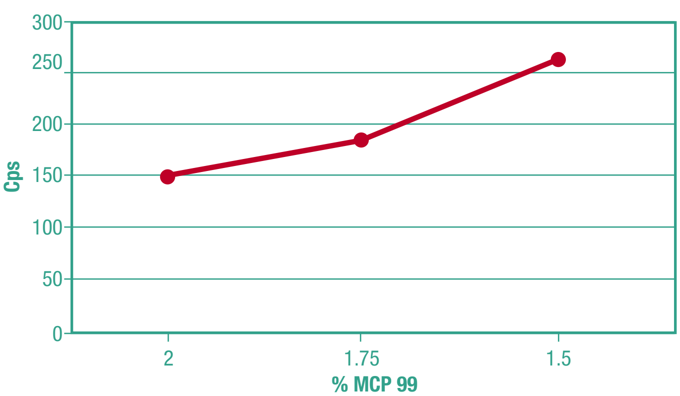

Table 2 - Resin gel time at 64.4°F (18°C).

Another fundamental choice that has to be made when going the infusion route is what medium should be used to rapidly and efficiently transfer the resin through the laminate stack. In our view the core infusion approach is particularly strong in this area. Whereas the DIAB grooved and perforated core is an integral part of laminate - increasing flexural strength and stiffness - flow media such as nets and mats add cost to the process, are purely 'sacrificial' and have to be removed and disposed following infusion.

The final thing that the boat yard has to evaluate is the use of pre-cut foam kits. At Fiart Mare we believe that using pre-cut, shaped and numbered kits can reduce build times and save labor costs by eliminating the on-site shaping and cutting of flat sheets.

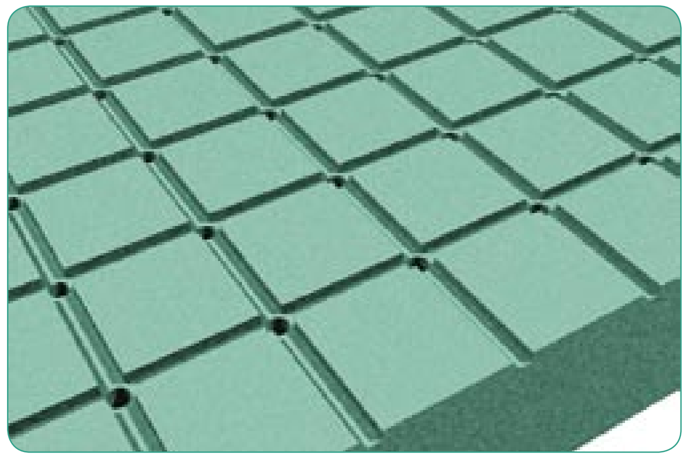

Fig. 2 – Grooved and perforated infusion foam.

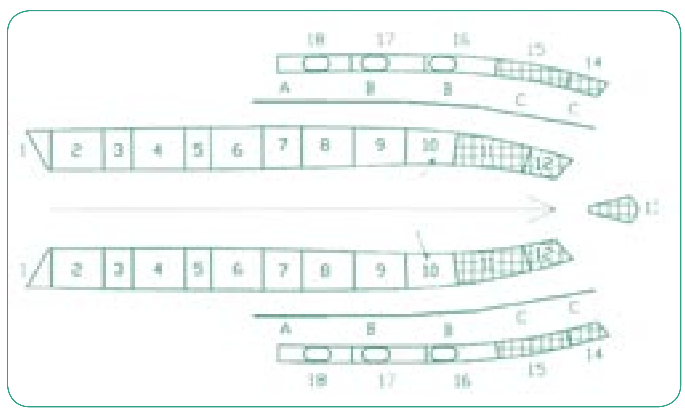

Fig. 3 - A schematic diagram of a core infusion kit.

Structural Design Considerations

The structural design of a boat is, in most cases, carried out in accordance with 'design rules' laid down by an appropriate certification authority such as RINa, DNV, ABS and Lloyds Register of Shipping.

Until very recently, when building a GRP boat, the 'design allowables' only took into consideration whether hand or spray lay-up was used. No consideration was given for structures produced using infusion molding. In this context, I examined the structural dimensioning according to R.I.Na (Italian Naval Register) and with particular reference to section B of the third chapter.

a) The gc parameter represents the glass content of the layer. It is presumed to be equal to 0.34 for CSM and 0.5 for woven fibers.

b) The Gc parameter represents the glass content of the laminate. This is assumed to be between 0.25 and 0.50.

c) The thickness (t) of the single layer is calculated as a function of the mass of the fibers of a single layer expressed in grams per square meter and the relative gc.

d) The mechanical characteristics (strength and elastic modulus) of the laminate are calculated as a function of the Gc

If we examine the situation we can recognize that all these presumptions are not valid for the infusion technology. In fact, with vacuum infusion molding, the fiber fractions are completely different from the ones suggested by the certification register.

Some experiments, carried out in the Fiart Mare Research and Development laboratory and in conjunction with technical information from fiberglass manufacturers show the following results:

Process	Gc CSM Mat	GC Continuous Filament Mat	Gc Woven Roving	Gc Knitted Biaxial
Hand lay-up	0.29	-	0.50	0.55
Infusion	0.55	0.31	0.60	0.66

Table 3 - Coefficients of experimental impregnation.

It is clear that, while the coefficients for manual impregnation shown in Table 3 are similar to those suggested by the certification body, the values for infusion are at least 20% higher. Therefore if the designer does not want to over engineer the laminate the new figures for infusion impregnation need to be taken into account.

In reality, in every polymer composite material, the optimization of this resin/fiber relationship is very important. Too little resin could result in fiber bonding problems. Too much could would be economical wasteful.

Moreover, the micro-mechanical properties of the lamina are influenced directly by this relationship.

To better explain this, we will briefly refer to the Theory of the Lamina Micromechanics, from which can be deduced a functional relationship between the mechanical properties of the composite material and the relative percentages of its constituents.

We will examine the case in which we would like to determinate the Elastic Modulus E of a composite lamina.

Let us presume that we have a lamina that is composed of unidirectional fibers that are aligned in a specific direction. This we will identify as di. Then let us presume to subject the laminate to a uniform load over the crosssection in the direction 'di' which we will call Fcomp.

This force, in turn, can be subdivided into two: the first - which we will call Ff – represents the total force in the fibers, the second – on the other hand we will call Fm – represents the total force in the matrix. Following this consideration we can consequently write:

$$Fcomp = Ff + Fm \qquad (1)$$

At this point, by definition of force:

$$Fcomp = \sigma_c S_c \qquad (2)$$
$$Ff = \sigma f\, S \qquad (3)$$
$$Fm = \sigma_m S_m \qquad (4)$$

The σi represents the stresses (which appear in the composite material, in the single fiber phase, and in the single matrix phase) while the Si represent the areas. At this point, substituting (2), (3), (4) in (1) we obtain:

$$\sigma c\, Sc = \sigma f\, Sf + \sigma m\, Sm \qquad (5)$$

Now, applying the Hooke's Law, on the base of which σ =

E ε, we will obtain:

$$Ec\ \varepsilon c\ Sc = Ef\ \varepsilon f\ Sf + Em\ \varepsilon m\ Sm \quad (6)$$

Starting from the hypothesis of a perfect adherence between the fibers and the matrixes, the deformation $(\Delta L/L0)f$ undergone by the generic fibre will be equal in terms of the one $(\Delta L/L0)m$ undergone by the matrix

It will be possible to simplify the expression (6) eliminating the εi

$$Ec\ Sc = Ef\ Sf + Em\ Sm \quad (7)$$

If we finally divide the obtained expression by Sc we will obtain the next comparison which arranges the calculation of the longitudinal Modulus of a composite lamina in function of the volumetric fractions of the fibers and of the matrixes.

$$Ec = Ef\ Vf + EmVm \quad (8)$$

This one is called 'Mix law' for composite materials

Accordingly, while adapting to the used theoretical model for the calculation of the longitudinal form, there can be deduced the law of the calculation of the tensile strength of the lamina which can adopt the following form:

$$\sigma 1 = \sigma f\ Vf + \sigma m\ Vm \quad (9)$$

That is why (8) and (9) demonstrate to us that the mechanical properties of an composite lamina are tightly connected to the volumetric fractions of the fiber and the matrixes, in other words, the fiber/resin ratio that we indicated at the beginning of this chapter.

We would like to propound the statement that we just made with a very simple calculation example.

Let us examine the specific case of a single lamina of a typical laminate used in the production GRP pleasure boat.

To simplify the calculation we use a lamina composed of a unidirectional fiberglass impregnated with polyester resin. The mechanical properties of the fiber and resin in the following table:

	Young Modulus (MPa)	**UTS (MPa)**
Glassfiber	70,000	1,700
Polyester resin	3,500	70

Table 4 - Mechanical properties of composite lamina constituents.

Knowing that based on experimental data that is widely documented for a manual laminating carried out like it should with the maximum contents in weight Gc of the required glass reinforcement amounts 0.5 (which translates itself in a Vf equal to 0.3) while with using a vacuum molding process there can be easily obtained a Gc of 0.65 (which translates itself in a Vf of 0.5), we can calculate the (8) and (9) the following values:

	Fiber Contribution (MPa)	Resin Contribution (MPa)	Total Value (MPa)
Young Modulus - Hand lay-up	21,000	2,450	23,450
Young Modulus - Infusion	35,000	1,750	36,750
UTS Hand lay-up	510	49	559
UTS Infusion	850	35	885

Table 5 - Theoretical mechanical properties of a lamina.

Looking at the figures in Table 5, it is clear that infusion offers much higher mechanical properties than hand laminating.

Production Parameters

During the last year, Fiart Mare successfully completed infusion projects for three different boat models ranging from 32 to 42 ft. (10 to 13 meters) L.O.A. In reality, the development program has been relatively gradual due to the time taken for experimentation and process improvements.

We started with '2D' infusion of the 32 feet hull and then following a series of experiments we optimized and developed the process into a '3D' infusion system that included the longitudinal stiffeners. The same path was taken and extended further for the 38 ft. hull resulting in the series production of hulls that included the longitudinal beams, support structures, ribs and transom.

These excellent results led us to start up a similar process for the Fiart 42 Genius model. At the time of writing we were in the process of carrying out the first '2-D' infusion of the hull. The goal of the company is to successfully develop the infusion process for all the hulls (we also have a 50 ft.). We are also currently studying infusion programs for the decks of the entire range.

I will now cover in some detail the development program that was carried out for the Fiart 38 Genius. In addition to being one the most important models in the range, the 38, together with 32, has been the subject of the greatest amount of trials and testing.

As result of our experimentation and analysis, we broke down the infusion process into eight simple steps as shown in Table 6.

Phase	Name	Description
1	Gelcoat	The gelcoat is applied to a clean and waxed mold.
2	Skin coat	The skin coat is laminated by hand onto the fully cured gelcoat. The skincoat is highly recommended in order to minmize print-through problems.
3	Spray rails	This is where the spray rails are levelled in order to minimise areas where resin could accumulate and to ensure a smooth resin flow.
4	Flange	Here strips are positioned to hold the fibers to the edge of the mold and to secure the vacuum line. Tacky tape is used to provide the seal for the flexible vacuum bag.
5	Fibers & Core	The dry reinforcements, core materials etc. are laid up onto the fully-cured skin coat.
6	Lines & Bag	The 'internal' resin feed lines, vacuum line, associated valves and catchpots are installed followed by the vacuum bag and the external resin feed lines.
7	Infusion	Following a series of 'drop tests' to check bag integrity, the vacuum pump activated. The resin is drawn into and through the laminate using a vacuum pressure of 0.9 of an atmosphere.
8	Consumables removal	After the laminate is fully cured, the various consumable materials (vacuum bag, tacky tape etc.) are removed.

Table 6 - The principal steps of the DIAB Core Infusion Process.

Fig. 4 – The fully-cured skin coat.

Fig. 5 - Levelling the spray rails.

Fig. 6 - The strips that hold the fibers in place on the flange and the tacky-tape for the vacuum bag.

Fig. 7 – Laying up of the dry fibers.

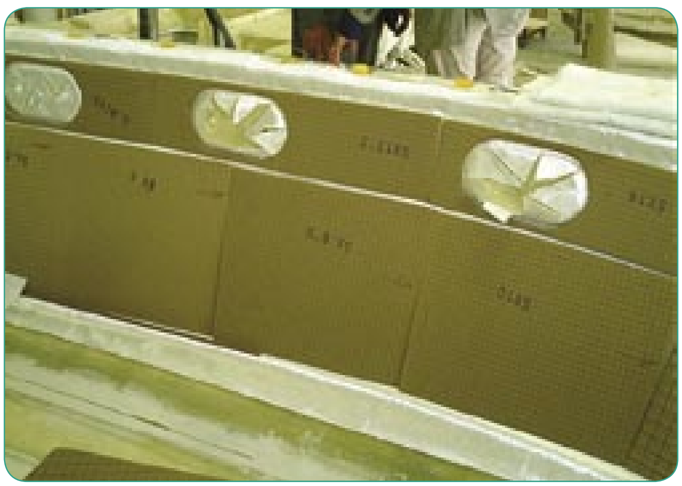

Fig. 8 – Installation of the core kit.

Fig. 9 – Checking the vacuum bag.

Fig. 10 – Infusion underway.

Fig. 11 – The hull following demolding.

Analyzing the process phases for the manual lamination of the same model of boat shows a smaller number of steps as shown in Table 7.

Phase	Name	Description
1	Gelcoat	The gelcoat is applied to a clean and waxed mould.
2	Skin coat	The skin coat is laminated by hand onto the fully cured gelcoat. The skin-coat is highly recommended in order to minmize print-through problems.
3	Laminating of plies 1,2 & 3	This is the phase where the layers are manually stratified after the skin coat
4	Laminating of plies 4, 5, & 6.	This is the phase where the layers are manually stratified before the core materials
5	Core material.	The core glued to the outer skin with a core bonding adhesive (putty).
6	Laminating of plies 7, 8 & 9.	This is the phase where the last layer are stratified manually upon the core materials.

Table 7 - The principal steps of hand lay-up.

Once this first distinction is made, it is very important to carry out an evaluation of the difference in labor costs when the boat is produced using the two processes. It should be stressed the time of the process does not include the preparation of the hull strengthening elements (beam, ribs and support structures) being a 3-D infusion. In order to provide an objective comparison more data is required. Tables 8 and 9 provide a breakdown of the number of operators and the hours spent on each phase for, respectively, infusion and hand laminating.

Phase	Operators	Hours/ Operator	Total Hrs.
1. Gelcoat	2	2	4
2. Skin coat	4	6	24
3. Spray rails	2	2	4
4. Fiber positioning	3	8	24
5. Flange preparation	2	2	4
6. Lines/bag positioning	2	8	16
7. Infusion	4	4	16
8. Removal of consumables	2	3	6
		Total	**100**

Table 8 - Production timetable for infusion molding.

Phase	Operators	Hours/ Operator	Total Hrs.
Gel coat	2	2	4
Skin coat	4	6	24
Lamination 1,2 & 3 plies	4	8	32
Lamination 4, 5 & 6 plies	4	8	32
Foam core	4	8	32
Lamination 7, 8 & 9 plies	4	8	32
		Total	**158**

Table 9 - Production timetable for hand laminating.

It is interesting to note that after having only infused just over 15 units for the Fiart 38 Genius we had reduced labor costs by about 35% by using infusion. In addition, we also looked at mold utilization time - an import consideration for a production company because the speed of mold turn round can have a direct effect on overall production rates. Tables 10 and 11 show the mold usage time for, respectively, infusion molding and hand laminating.

Phase	Period
Gelcoat	-
Skin coat	Day One
Spray rails	Day One
Laying up reinforcements/cores	Day Two
Flange preparation	Day Two
Installing vacuum line and bag	Day Three
Fitting resin lines	Day Three
Infusion	Day Four
Removal of consumables	-
Elapsed Mold Usage Time	**4 Days**

Table 10 - Mold usage time for infusion molding.

Phase	Period
Gelcoat	-
Skin Coat	Day One
Laminating plies 1, 2 & 3	Day Two
Laminating plies 4, 5 & 6	Day Three
Core installation	Day Four
Laminating plies 7, 8 & 9	Day Five
Elapsed Mold Usage Time	**5 Days**

Table 11 - Mold usage time for hand laminating.

As a result of these comparisons we are able to see that by using infusion molding there is a time saving of about 20% compared to hand laminating.

It is therefore clear that the principle benefits of moving to infusion for a production boat builder are a reduction in production time, better mold utilization and the saving in labor costs. This is shown in Table 12.

	Working Hours	Mold Usage
Infusion	100 hours	4 days
Hand lay up	158 hours	5 days
Infusion Savings	37%	20%

Table 12 - Production time comparison between infusion molding and hand laminating.

Laminate Quality Control

The laminate quality that we have achieved has been confirmed by an analysis of the samples (both by Fiart Mare and an independent specialist analysis company). These were obtained when holes were drilled in the hull to fit the sea cocks.

In addition, several of the hull have been tested using an ultrasound analysis system by QI Composites Srl., a specialist composite materials quality control company. Figure 12 shows the coordinates for the control points of which there were over 300 at intervals of 20 in. (50 cm). The results of this analysis are illustrated Table 13.

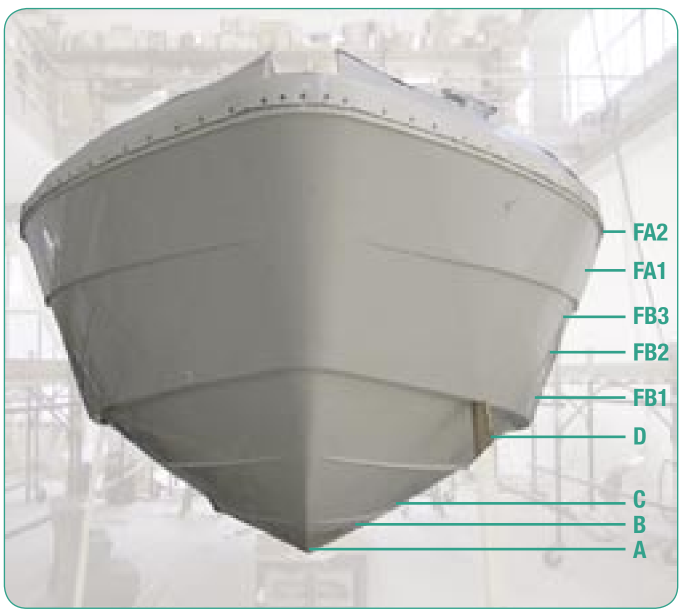

Fig. 12 - Reference coordinates for the control points.

An analysis of the data demonstrates the high quality level of the infusion method. There have been no registered defects that could damage the structural integrity of the boat nor defects connected with the applied technique. There have been some aesthetic problems that were linked to the kinetics of the reaction of the catalyst. The large energy release during curing can result in deformations of the skin. The is more evident in zones of monolithic lamina. Moreover, we have not been found any porous areas in the laminate.

Coordinates	Laminate	Theoretical Thickness	Left Actual Thick.	Right Actual Thick.	Average Actual Thick.	Thick. Variation
BOW						
A	solid	9.2	12.3	11.7	12	2.8
B	solid	9.2	9.4	9.8	9.6	0.4
C	solid	9.2	9.4	9.8	9.6	0.4
D	solid	9.2	9.4	8.8	9.1	-0.1
FB1	sandwich	2.9	5.1	4.7	4.9	2
FB2	sandwich	2.9	5.1	4.5	4.8	1.9
FB3	sandwich	2.9	5.1	4.5	4.8	1.9
FA1	sandwich	2.9	4.7	4.5	4.6	1.7
FA2	sandwich	2.9	4.7	4.5	4.6	1.7
CENTRE						
A	solid	9.2	13.7	10.9	12.3	3.1
B	solid	9.2	8.8	8.8	8.8	-0.4
C	solid	9.2	8	7.4	7.7	-1.5
D	solid	9.2	8.2	8.4	8.3	-0.9
FB1	sandwich	2.9	4.5	4.7	4.6	1.7
FB2	sandwich	2.9	4.3	4.7	4.5	1.6
FB3	sandwich	2.9	4.5	4.5	4.5	1.6
FA1	solid	5.3	6	6.2	6.1	0.8
FA2	solid	5.3	6	6.2	6.1	0.8
STERN						
A	solid	9.2	11.5	11.7	11.6	2.4
B	solid	9.2	7	7.4	7.2	-2
C	solid	9.2	8.6	7.4	8	-1.2
D	solid	9.2	8.4	8	8.2	-1
FB1	sandwich	2.9	4.7	4.5	4.6	1.7
FB2	sandwich	2.9	4.9	4.7	4.8	1.9
FB3	sandwich	2.9	4.7	4.7	4.7	1.8
FA1	solid	5.3	8.4	8.2	8.3	3
FA2	solid	5.3	6	5.7	5.85	0.55

Table 13 - Quality control thickness table.

Regarding the consolidation of the reinforcements, we believe that we have achieved high fiber fractions throughout the hull without any voids. We have also found that we are able to achieve consistent laminate thickness throughout the hull that closely match the original design thicknesses.

This means that providing we use the same amount of fiber and resin each time the resulting hulls will be identical to one another.

Conclusions

All our experiences to date confirm that moving to vacuum infusion molding has enabled Fiart Mare to substantially reduce VOC emissions, increase overall laminate quality and considerable improve productivity. However, it should be stressed that this has been achieved as a result of a competent and dedicated development team. It is doubtful that these improvements could be achieved by just the process itself.

The vacuum infusion of resin is a technical process that requires the person running the project to have a general knowledge of composites and materials as well as an understanding of the chemistry and physics that rule the process. Moreover, of no less importance, is the effective re-training of the existing workforce whose previous experience is likely to be confined to more traditional laminating methods. In fact, re-training is likely to be fundamental to the success of the whole process.

At Fiart Mare we can confirm that to achieve success it is necessary to invest in research, development and manpower in order to achieve satisfactory results in a reasonable short space of time.

Figures 13, 14 and 15 show the results of the successful infusions that FIart Mare have carried out in the last year.

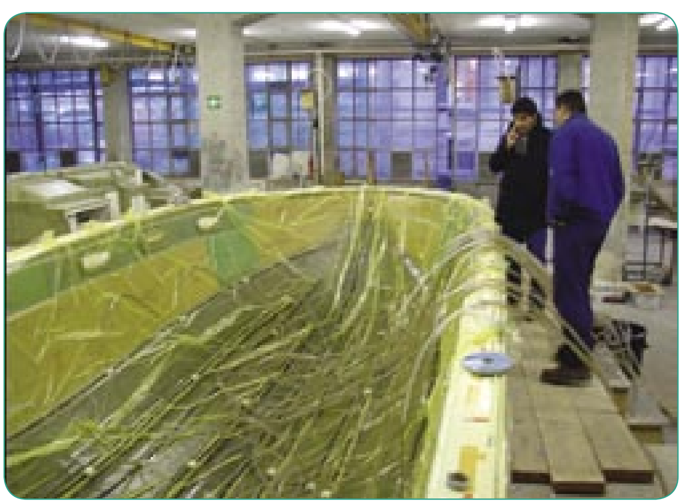

Fig. 13 - 3-D infusion of a 32 feet hull.

Fig. 14 - 2-D infusion of a 42 ft. hull.

Fig. 15 - 3-D infusion of a 38 feet hull.

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