LOW PRESSURE RESIN TRANSFER MOLDING FOR COST EFFECTIVE AIRCRAFT QUALITY STRUCTURES

Daniel E. Davenport, Richard Petrovich, & Gerald Sutton,
North Coast Composites, Cleveland OH

ABSTRACT:

Typically aerospace components produced using the Resin Transfer Molding (RTM) process are required by specification to use very high final injection pressure. This is believed to be necessary to produce a laminate that is void free and that produces structural equivalence to historical autoclave moldings. However, a low pressure RTM process has been developed, tested, and validated that produces structurally equivalent properties to components molded using these specified high final hydrostatic pressures. The significance of using low pressure is that it allows Aircraft Quality Composite Structures to be fabricated with lower cost, less massive tooling, improved cycle times and higher production throughput. Comparative test data will be presented showing physical test results along with case studies developing theoretical Aircraft components and typical cost savings expectations.

KEYWORDS: Resin Transfer Molding (RTM), Tools/Tooling Materials/Tooling Technology, Applications – Aerospace

1. INTRODUCTION

Low Pressure Resin Transfer Molding (RTM) is a modification of conventional RTM processing normally used for Aerospace components. It involves utilizing lower resin injection and final hydrostatic pressures during RTM cure cycles.

Conventional wisdom suggests that high (300 psig or higher) final hydrostatic resin pressures are necessary in RTM processing to minimize porosity in cured laminates by forcing any entrapped air bubbles into solution prior to and during cure initiation. This appears to be a “Belts and Suspenders” approach to parts fabrication and may force the manufacturer to utilize drastically over designed tooling and endure unnecessarily extended processing cycles. This becomes a physical and economical barrier to entry as part size increases such as for large commercial or military aircraft components.

This paper will present an alternative Low Pressure RTM process, along with physical test data and Tooling criteria, that disputes this conventional wisdom and offers the potential for cost effective large aircraft quality part manufacturing, while maintaining all the benefits of matched die RTM processing.

2. WHY RTM

Designers and manufacturers began looking for an alternative to autoclave molding and turned to RTM as a means of fabricating aircraft quality structure with tighter control of tolerances. As the process grew in acceptance and more development was applied it became apparent that there are several advantages to the RTM process. Designers "developed designs that integrate parts, simplify the structure, eliminate the autoclave and, thus, reduce costs. Out-of-autoclave methods are not only faster and less expensive, but fabricators also have optimized them for greater *manufacturability* and eliminated most secondary processes, yet molded parts of greater complexity." (1)

2.1 Control of tolerances

It goes without saying that one great advantage of RTM is the control of tolerances on the molded component as compared with one sided molding processes. The mold completely surrounds the part and defines all surfaces, thus making it possible to mold composite structures with tight tolerances.

Parts made by one-sided methods employ control of the tooling surface only and the internal surfaces are left to float. This is great for parts that have no secondary bonding or added internal structural assemblies, but adds cost down the line for those that do. RTM offers the advantage of controlling all surfaces, and in some cases those internal assemblies can actually be molded integral to the part.

2.2 High performance structure

RTM started out being a process considered for secondary structures and fairings for aircraft. Early thinking in the process was that while it did offer a cost reduction possibility, it came with the cost of "knockdown" on the structure as compared to well established data from autoclave molding.

Over time and with considerable testing however this was proven to be a false assumption. Properly controlled RTM molding can and does produce structure that compares favorably with the data. This has been proven and can be seen in applications like the F22 where critical structure is molded using RTM.

2.3 Volume processing

One advantage of RTM is the ability of the process to produce higher volumes while offering those aspects considered desirable by the process. This can be achieved through a number of methods.

One method is by multi-cavity tooling. This method is generally employed where a large number of parts is required in a cost competitive production requirement. Jet engine by-pass vanes is one example of this application. One advantage of RTM is the ability for the preform to be produced separately from the mold and subsequently loaded into the RTM tool for molding. This allows for faster turns in the RTM tool as well. Using this method makes the multiple cavity approach very cost effective.

Tools designed for rapid heat-up and cooling also allows for faster cycle times. This involves integrally heated tooling that employs oil or electrical heating with a method of cooling. This allows for faster turn over in the molds and therefore higher volumes of parts in a given time frame.
Another method of achieving volume process from RTM is the use of modular tooling, where more than one part can be produced from a single tool set using interchangeable inserts. In some cases this has been found effective “because of the tight schedule constraints, choosing modular tooling enabled faster production." (3)

3. HOW WE GOT HERE

3.1 Basics of RTM

Resin Transfer Molding is an old process that employs the use of a reinforcement placed into a closed mold and subsequently injected with a thermosetting resin. The process was actually developed in the 1940’s, but never really came to prominence for aircraft component manufacturing until the late 1970’s and early 1980’s.

3.2 Typical Loaded Structure Processing

As the process evolved, the application to higher loaded structure followed. Highly loaded structure requires higher levels of fiber volumes to carry the loads. This required development of resin systems that afforded the ability to flow through these higher levels of reinforcement while still able to produce composites that met the requirements.

Eventually, because of the need for the application of unidirectional fiber materials, a hybrid of both Prepreg and dry fiber was developed. “The challenge in RTM'ing a prepreg lay-up is establishing hydrostatic pressure within the mold sufficient to consolidate the lay-up and suppress voids that occur as gases evolve during cure. In the autoclave, this state is created as pressurized nitrogen applies external force to the vacuum bag. In a closed RTM tool pressure is applied externally, but directly to liquid resin, to force it into and throughout the mold cavity.” (1)

3.3 Forcing porosity into solution

One thought process in RTM is to design molds such that the “air” is pushed out by the resin flow front into the vents. This assumes that air is trapped by the reinforcement during the processing procedure. In order to overcome this, one “approach is to rely on very robust tools and relatively high injection pressures.” (1)

The use of higher pressure to reduce void content by suppressing the air into the resin can be seen by some specifications that require very high final hydrostatic pressures in the processing parameters, and is especially prevalent in combining prepregs into the structure as stated above.

3.4 High cost to overcome pressures

As the RTM process developed into applications requiring higher loading, the process also evolved into a high pressure process. In many applications and specifications the final hydrostatic pressure of the resin can be as high as 300 psi. This requires tooling that has special considerations. "All varieties of resin transfer molding (RTM), where positive pressure is used to push resin into the reinforcement are methods that employ only positive pressure and require a more expensive matched mold, with hard B-side tooling, to resist what can be very high injection pressures." (2)

With traditional RTM feeding the mold cavity with resin under moderately high flow rate and pressure is limited by the structural ability of the molding tool and perimeter clamping or press system to sustain mold closure. Working within these concerns, building RTM tooling and clamping systems with structure great enough to sustain the flexing caused by the highest expected injection pressure during the molding cycle" becomes necessary. (4)

With the higher pressures comes a cost penalty that is seen in these larger more robust tools. Increased concerns in handling the larger, heavier tool pieces also takes place. In addition, cycle times are increased due to tool mass. All of these are a direct result of the need to overcome these higher molding pressures.

4. LOW PRESSURE RTM

4.1 Going Full Circle – Low Pressure Processing Re-Visited

As discussed earlier, the Composite parts manufacturing arena has undergone dramatic change over the years with regard to processing pressures. Even within the RTM processing world, dramatic and steady increase in final hydrostatic pressures has been the rule over the past two decades. Today many aerospace RTM specifications require upwards of 300+ psig final holding pressure prior to and throughout cure initiation.

This ever increasing pressure requirement brought with it the need for stiffer and more massive tooling to withstand and react against the high molding pressures in order to maintain mold cavity and part dimensional integrity. RTM tooling has progressed from composite to machined Aluminum, and now to machined Steel and Invar in order to meet the demanding dimensional accuracy of Aerospace components.

This increased RTM molding pressure is really only significant when we are talking about Out-Of-Press, self clamping tooling, which is what we are referring to throughout this discussion. Obviously if a press is used to clamp the mold shut, adding additional in-mold pressure just required an increase in the press clamping force to accommodate the increase.

Not surprisingly the increasingly demanding processing parameters had the very predictable effect of driving up the cost associated with RTM processing. As tooling became more massive and tooling materials more difficult to fabricate, the cost of these tools naturally went up. In addition, heavier and more massive tools take longer to heat up and cool down which drives up cycle times, reduces part throughput, and increases overall costs to produce RTM parts. Heavier tools require more sophisticated handling provisions for opening and closing, cleaning, storing, and moving through the processing line, all of which also contribute to driving the part costs higher.

All of these factors have in part led to the decline in RTM being considered for new programs and development projects. In today's environment where a component or manufacturing process must buy it's way onto a vehicle or platform with an ever shrinking Return-On-Investment (ROI) time frame, the high Non Recurring Cost associated with RTM is often perceived as cost prohibitive.

Not ready to give up on the benefits offered by the RTM process, innovators within the industry began to explore alternatives or modifications to the process that offered the potential to reduce the high Non Recurring Tooling costs. Enter the VARTM process or Vacuum Assisted Resin Transfer Molding. VARTM and a large number of variants to this process have been developed which offer the benefit of reduced tooling cost while reportedly maintaining a very high percentage of the structural integrity of conventional RTM and Autoclave manufactured components. Most if not all of these processes utilize a single sided permanent mold surface along with a flexible or semi-flexible mating surface such as a vacuum bag or thin composite laminate. Resin infusion is conducted under vacuum alone or using relatively low positive pressures which eliminates the need for massive tooling to react the pressures. Resin cure is typically accomplished through the use of an oven, autoclave, heated platens, or through integral heating provisions in the tooling.

These lower pressure Resin Infusion processes are being widely explored and becoming more readily accepted for commercial and military aerospace applications. It appears the industry has come full circle with regards to processing pressures in an effort to control ever rising manufacturing costs.

4.2 Going Low – Reducing RTM Pressures to Lower Cost

Logic would suggest that if, over time, processing pressures were steadily increased to improve the Fiber to Resin ratios and optimize the strength to weight ratios in composite laminates, reducing the processing pressures to vacuum only would have an inverse effect on these ratios as well. In fact, many composite industry experts were skeptical of the initial success stories and reports associated with these lower pressure processes. However, as more and more data was published indicating little or no knockdown in structural integrity or Fiber Volume Fraction, the interest in these innovative resin infusion processes has blossomed.

Based on the increasing acceptance of these lower pressure processes, North Coast began to explore the idea of Low Pressure RTM using conventional matched metal tooling. If these low pressure infusion processes were acceptable using a vacuum bag as the mating tool surface then it would surely work using conventional tooling where the dimensional precision of matched die tooling would be maintained. While this approach, if successful, would not in itself reduce the non recurring tooling costs, it would open the possibility of reducing the mass of both tooling surfaces which has the potential to dramatically reduce non recurring costs.

4.2.1 Investigating the Concept

To prove out the concept, North Coast began molding test components while experimenting with modified RTM processing parameters including progressively lower processing pressures. These experiments proved very successful with regards to producing parts that showed no visible defects even at very low hydrostatic pressures. Based on these preliminary results, a plan was formulated to expand the testing and to gather physical test data to evaluate and compare with components processed at conventional high hydrostatic pressures. A panel testing program in conjunction with NASA Glenn Research Center (GRC) in Cleveland, OH was developed in which North Coast molded a series of panels using various pressures and NASA personnel performed the physical testing as part of a larger, comprehensive testing methods study. The NASA study is also being presented at this conference in another paper.

4.2.2 NASA Panel Testing

The test plan called for a series of 24” X 24” X .125” flat panels to be molded at varying final hydrostatic pressures. Coupons from the panels would then be subjected to a series of physical tests to evaluate any difference in properties based on molding pressure. All other parameters within each resin system series were kept constant, including molding and cure temperatures and times. We were not concerned with actual numeric test results, only the difference in results that could be attributed to the change in molding pressure.

The panels were fabricated using Toray T700 carbon fiber braided fabric oriented in a quasi-isotropic lay-up and molded with commercially available epoxy resins. Two different resin systems were utilized, one with very low viscosity and one with substantially higher viscosity in order to explore a range of possible available resin systems and to evaluate the validity of Low Pressure RTM for low and higher viscosity resin systems. Hexion’s EPON 862 epoxy with “W” curing agent and Cytec’s CYCOM 5208 epoxy resins, along with braided fabric from A&P Technology, were used for the panel fabrication. The EPON 862 is a very low viscosity, easy to process resin system that has been widely used in RTM processing. The 5208 system is an un-toughened epoxy that has been widely used in the aerospace industry in pre-preg form, but is not a widely used RTM system. The melt viscosity of 5208 is on the high end for RTM and the processing window is relatively small. As mentioned above, NASA is conducting other studies and 5208 was of key interest for their program so it was chosen for this panel project as well.

Experiments were conducted to determine the lowest pressure at which complete mold fill could be obtained within a reasonable injection time frame not to exceed 30 minutes. Pressure gauges were positioned at the resin inlet port as well as at the vent locations and the final equalized pressures were measured. Once determined, this pressure was established as the low end of the hydrostatic processing range and additional panels were fabricated at this pressure to validate this threshold. For the 862 this low pressure was determined to be 15 psi, and for 5208 it was 41 psi. A high end pressure of 300 psi for 862 and 350 psi for 5208 was selected to replicate the range that is being used on many aerospace structures today. Panels at two additional intermediate pressures between the high and low were molded with each resin system to investigate the possibility of a sliding scale loss of physical properties as injection pressures were decreased. The following table shows the panel molding matrix.

Table 1 - North Coast / NASA Test Panel Fabrication

Series #	Panel ID	Description	Resin	Fiber	Final Pressure
1	1A	.125 THK x 25" x 25"	EPON 862	T700	100 PSI
	1B				
	1C				
	1D				
	1E				
	1F				
	1G				
	1H				
2	2A	.125 THK x 25" x 25"	EPON 862	T700	300 PSI
	2B				
	2C				50 PSI
	2D				
	2E				15 PSI
	2F				
3	3A	.125 THK x 25" x 25"	CYTEC 5208	T700	200 PSI
	3B				
	3C				
	3D				
	3E				
	3F				
	3G				
	3H				
4	4A	.125 THK x 25" x 25"	CYTEC 5208	T700	41 PSI
	4B				
	4C				100 PSI
	4D				
	4E				350 PSI
	4F				

4.2.3 Coupon Test Results

All panels were tested for Void Content to determine if the molding pressure had an effect on void content and to insure that void content did not adversely affect the physical testing results. These results are further discussed below.

In addition, Non Destructive Evaluation (NDE) was performed by NASA for all panels. While the full NDE results are not presented here, NASA personnel report that all panels passed NDE evaluation according to typical aerospace acceptance criteria.

4.2.3.1 Void Content Results

Table 2 – 862 Panel Void Content Results

Sample #	Molding Pressure (psi)	Resin	Fiber	% void
1	100	E862	T700s	< 1.0
2	100	E862	T700s	< 1.0
3	100	E862	T700s	< 1.0
4	100	E862	T700s	< 1.0
5	100	E862	T700s	< 1.0
6	100	E862	T700s	< 1.0
7	100	E862	T700s	< 1.0
8	100	E862	T700s	< 1.0
9	50	E862	T700s	< 1.0
10	50	E862	T700s	< 1.0
11	50	E862	T700s	< 1.0
12	50	E862	T700s	< 1.0
13	50	E862	T700s	< 1.0
14	50	E862	T700s	< 1.0
15	50	E862	T700s	< 1.0
16	50	E862	T700s	< 1.0
17	15	E862	T700s	< 1.0
18	15	E862	T700s	< 1.0
19	15	E862	T700s	< 1.0
20	15	E862	T700s	< 1.0
21	15	E862	T700s	< 1.0
22	15	E862	T700s	< 1.0
23	15	E862	T700s	< 1.0
24	300	E862	T700s	< 1.0
25	300	E862	T700s	< 1.0
26	300	E862	T700s	< 1.0
27	300	E862	T700s	< 1.0

28	300	E862	T700s	< 1.0
29	300	E862	T700s	< 1.0
30	300	E862	T700s	< 1.0
31	300	E862	T700s	< 1.0

Table 3 – 5208 Panel Void Content Results

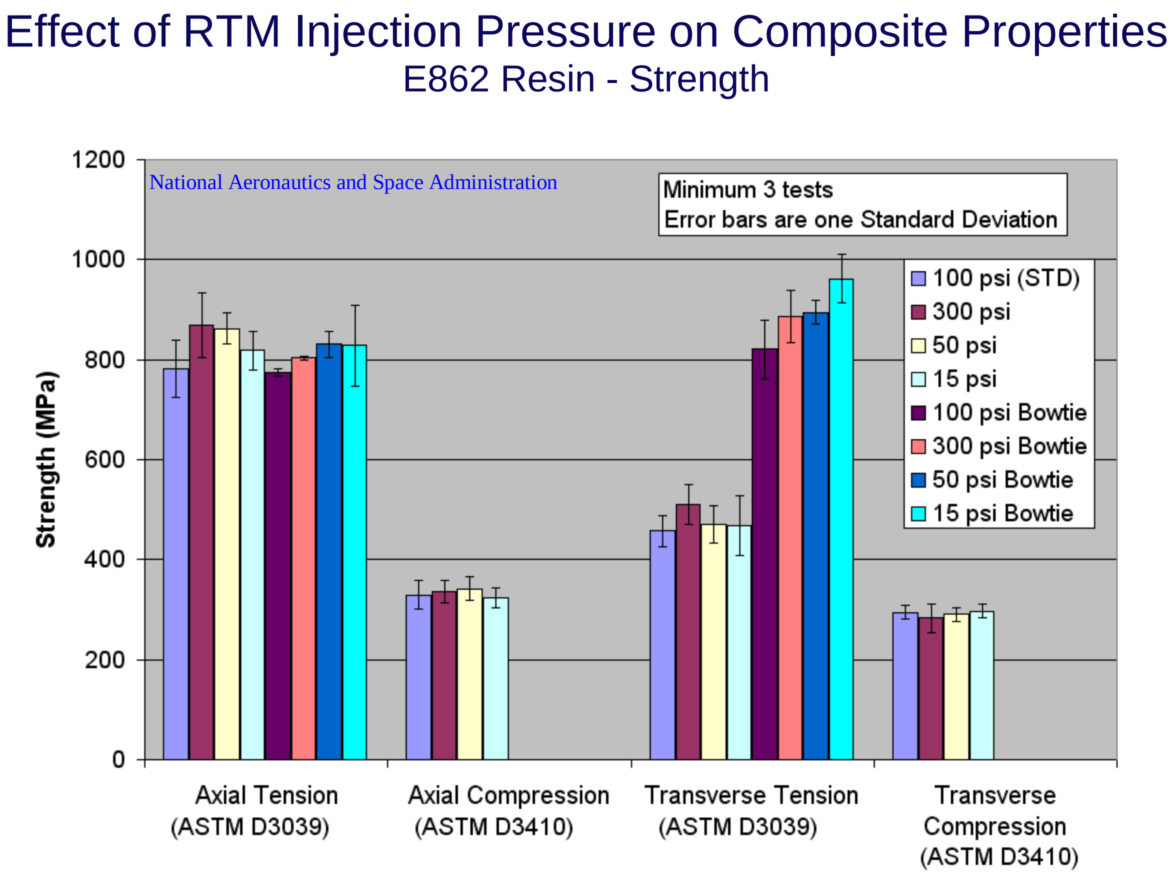
Sample #	Molding Pressure (psi)	Resin	Fiber	% void
1	200	5208	T700s	< 1.0
2	200	5208	T700s	1.10
3	200	5208	T700s	< 1.0
4	200	5208	T700s	< 1.0
5	200	5208	T700s	< 1.0
6	200	5208	T700s	< 1.0
7	200	5208	T700s	< 1.0
8	41	5208	T700s	< 1.0
9	41	5208	T700s	< 1.0
10	41	5208	T700s	1.03
11	100	5208	T700s	< 1.0
12	100	5208	T700s	< 1.0
13	100	5208	T700s	< 1.0
14	100	5208	T700s	< 1.0
15	100	5208	T700s	< 1.0
17	100	5208	T700s	< 1.0
18	100	5208	T700s	< 1.0
	100	5208	T700s	< 1.0
19	350	5208	T700s	< 1.0
20	350	5208	T700s	< 1.0
21	350	5208	T700s	< 1.0

Despite opinions to the contrary, the above void content results conclusively show that void content is not a function of molding pressure. When processing parameters such as vacuum integrity, mold sealing, and resin handling techniques are tightly controlled, low pressure RTM can be successfully used to mold very low void content components.

4.2.3.2 Physical Testing Results

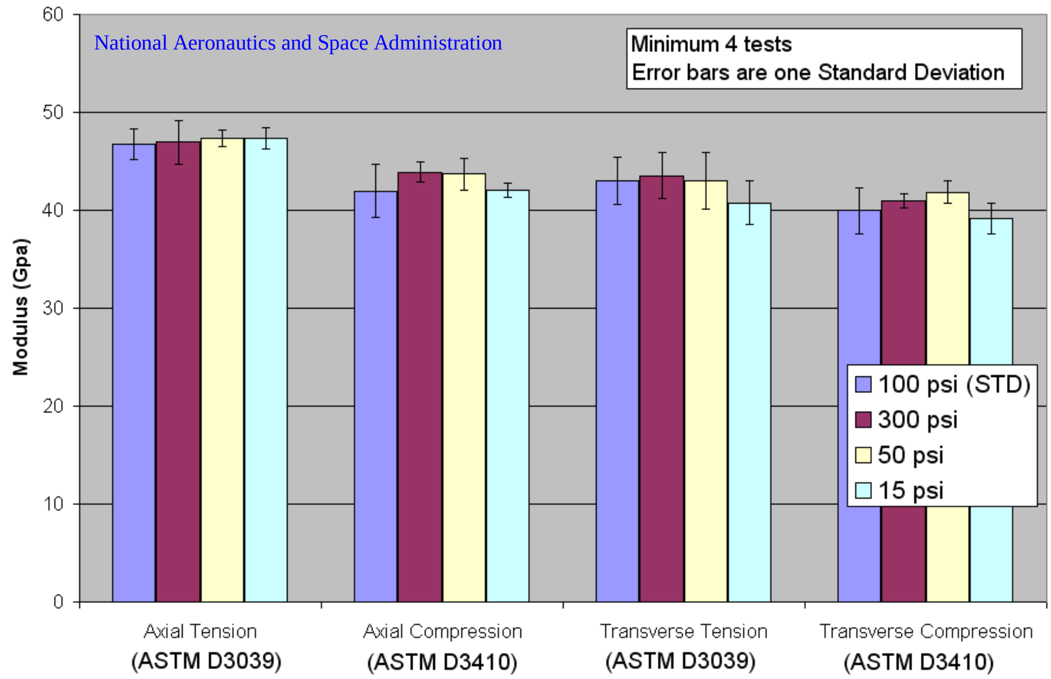
Once the void content question was answered, it was then time to determine if lower molding pressures would have any adverse affect on physical properties. NASA conducted a series of basic physical tests to evaluate what effect the molding pressures had as described above.

The following summary tables show the results of the testing performed at NASA GRC.



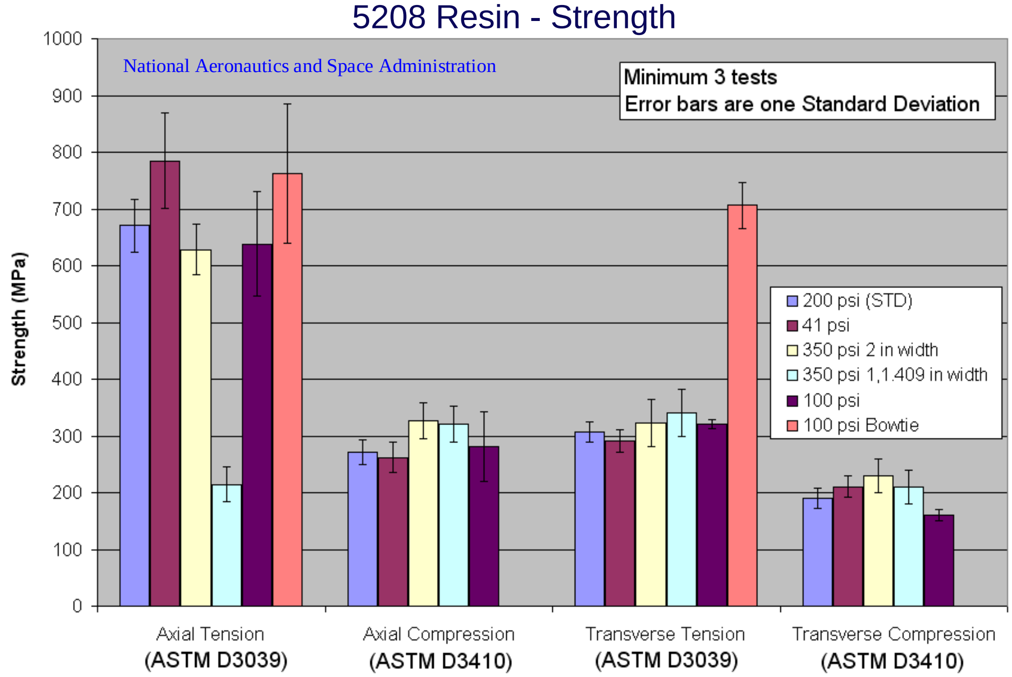
Effect of RTM Injection Pressure on Composite Properties

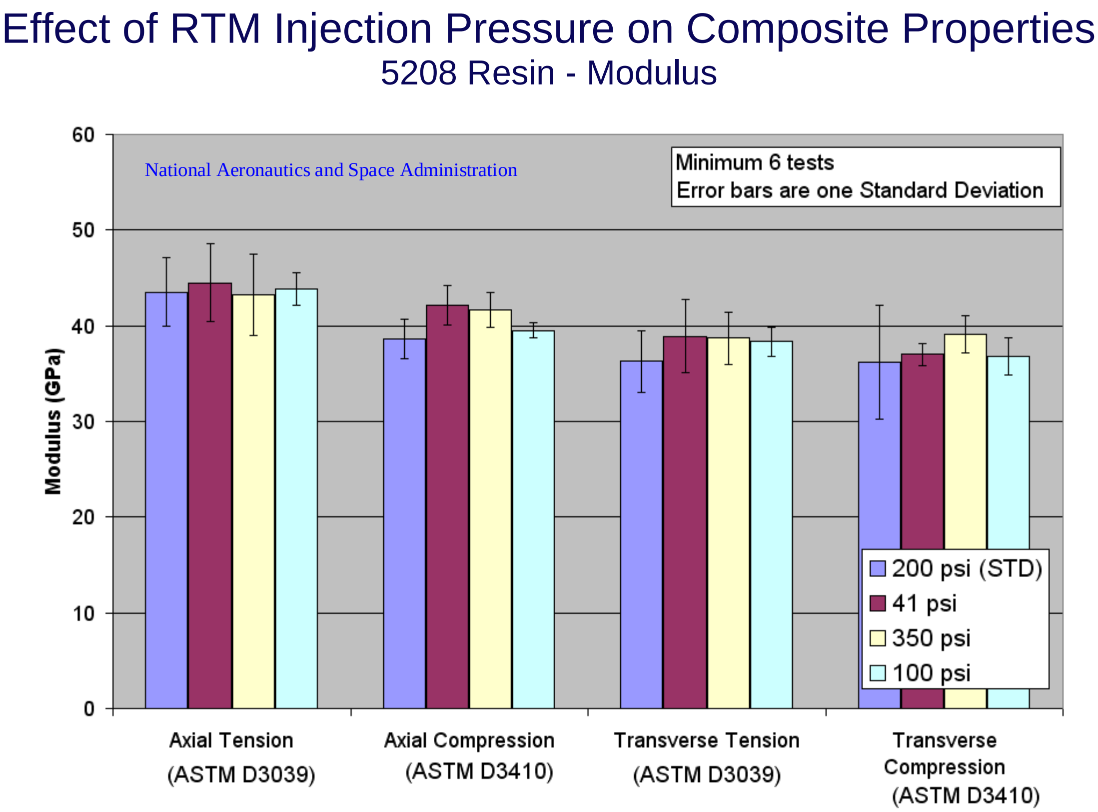
E862 Resin - Modulus



Effect of RTM Injection Pressure on Composite Properties

5208 Resin - Strength





5. WHAT DOES THIS MEAN FOR TOOLING

5.1 Less Mass

The first and most obvious impact of using the Low Pressure RTM process is the potential to use less massive tooling. The lower in-mold hydrostatic pressures require less stiffness in the mold cavity to react the lower internal pressures while maintaining the same level of mold deflection. A real life example will best demonstrate this potential.

Using standard material strength and stiffness tables, North Coast has developed a spreadsheet to help calculate the required plate stock thicknesses for RTM mold fabrication at various molding pressures. For a simple 24” X 24” flat panel mold, the following table demonstrates the potential mold weight savings of converting from a steel tool designed for 300 psi processing to an aluminum mold designed for 75 psi processing.

Injection Pressure (psi)	Total Load (lbs-force)	STEEL Required Plate Thickness (in)	ALUMINUM Required Plate Thickness (in)	STEEL Mold Weight (lbs)	ALUMINUM Mold Weight (lbs)
15	6,615	1.55	2.24	503	258
30	13,230	1.96	2.82	634	325
75	33,075	2.66	3.83	860	441
100	44,100	2.92	4.22	947	486
150	66,150	3.35	4.83	1084	556
200	88,200	3.68	5.31	1193	612
250	110,250	3.97	5.72	1285	659
300	132,300	4.22	6.08	1365	701
350	154,350	4.44	6.40	1437	738

As can be seen, the weight of the mold goes from 1365 lbs for the steel mold, to 441 lbs for an aluminum mold. This represents a weight reduction of over 67% on a straight, flat part. For highly contoured or curved parts the weight savings can be even more dramatic.

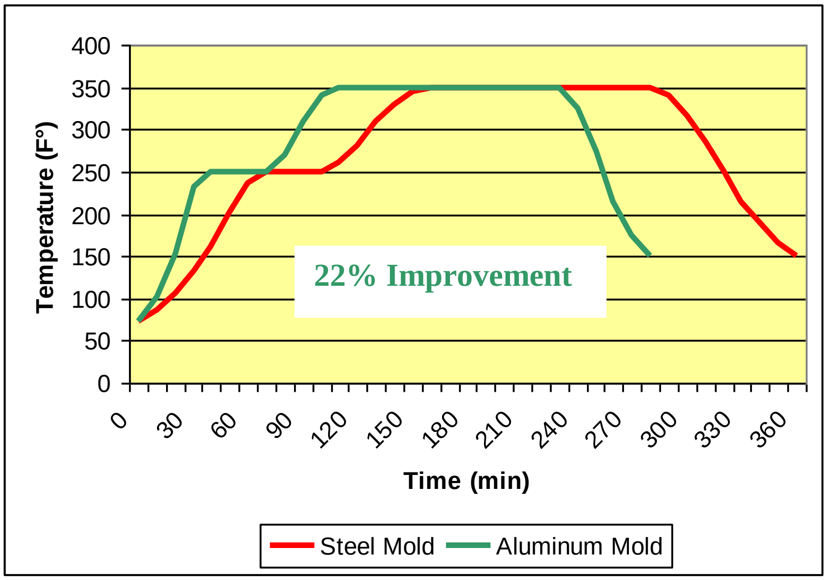
5.2 Improved Cycle Time

Reducing the mass of RTM tooling has the very real effect of dramatically reducing molding cycle times simply due to basic physics. Less mass means more rapid mold heat up and cool down rates which improves cycle times and increases daily throughput for production operations. While the exact amount of improvement is directly related to mold size and shape, our experience shows that normal cycle time improvements range from 15% - 40% for aerospace RTM components when Aluminum molds and Low Pressure RTM are combined.

Reducing the tooling mass has several other benefits which also contribute to improved cycle times as well as reducing the risk of injury to employees and damage to tooling. Less massive tools means they are easier to move through the shop and require less labor or mechanization to open and close. In addition, lighter tool details are easier to handle when using overhead hoists or cranes which means tools are less likely to be damaged and workers are less likely to be injured.

The following chart shows a real life cure cycle comparison of similar molds constructed of steel and aluminum. This cycle was for a typical aerospace epoxy system and consisted of an initial ramp up to the resin injection temperature of 250° F. Following injection the molds were heated to the 350° F cure temperature and held for 2 hrs. At completion of the cure, the molds were ramped back down to 150° F prior to opening and part removal. In this particular case, the aluminum mold demonstrated a cycle time reduction of 80 minutes or approximately 22% improvement over the steel mold. As stated above, these results will vary depending on mold size, shape, resin system and cure schedule required.

Typical RTM Cure Cycle



5.3 Potential to use Cast Tooling

Once we were convinced that the use of aluminum tooling was a viable alternative for production RTM processing, we began experimenting with using Cast Aluminum materials to replace plate stock for RTM mold fabrication. Our calculations showed that additional mass could be reduced by casting tools with nominal wall stock thickness along with a grid stiffener pattern on the back of the mold surfaces to maintain the same or improved stiffness as the wrought plate materials.

For curved or contoured parts, we found that castings could be made that followed the part contour which further reduced the tool mass by eliminating the extra material normally associated with using rectangular plate stock as a starting point. Through fabrication of the first 4 molds using this casting technique, our estimates are that an additional 15% to 30% in weight savings was achieved over conventional plate materials. While the extent of additional weight savings is somewhat dependent on part shape, we believe that tools for all parts will show significant weight savings with this approach.

5.4 Better Temperature Control

In addition to further reducing mass of the tools, using cast aluminum tools led to the additional improvement in the Low Pressure RTM process of providing better temperature control during mold heat up and cool down. The casting process offers the ability to easier control the location and spacing of all heating and cooling lines within the mold which can have a dramatic impact on mold temperature control.

During mold design we are able to calculate the most efficient and optimized layout for oil heating and cooling line locations. Once optimized, the oil line pattern is seamlessly fabricated using stainless steel tubing that is bent and contoured to precisely follow the mold cavity as necessary. This tubing assembly is then delivered to the casting house which then locates the tubing in the casting pattern and casts the aluminum directly over the steel tubing. This results in a mold cavity with precisely located integral heating and cooling lines when it arrives back at the tool fabrication shop for final machining.

The conventional process for oil passage installation in plate stock materials is to layout and gun drill a series of holes with cross drilled holes at each end to create a serpentine pattern within the mold. Since gun drilling is a straight line process, depending on contour or elevation changes along the part surface, this can sometimes result in heating lines that are not uniformly offset from the mold surface which can lead to inconsistent heat up and cool down rates across the part surface. Using the cast in place oil lines, we have been able to achieve mold temperature control across the cavity surfaces within ± 3 F° throughout RTM cure cycles.

5.5 Reduced Cost

The cost benefit of improved cycle time due to less massive tools has already been discussed, but there are other, more tangible cost benefits associated with cast aluminum tooling. The first cost reduction comes from the basic change from Steel or Invar to aluminum for mold construction. Invar is the most expensive of the three materials, often costing 5X to 10X the cost per pound for steel or aluminum. It is also very time consuming to machine requiring multiple stress relieving cycles throughout the machining process to insure dimensional stability.

While the raw material costs per pound for aluminum and steel is relatively close, because aluminum is approximately 1/3 lighter than steel for the same volume, the resulting raw material cost for aluminum is roughly 1/3 less than steel, assuming you can use the same stock dimensions. Furthermore, aluminum is much easier to machine than steel and typically requires approximately 20% less machining time compared to the same cuts in steel. The lower raw material cost and less machining time alone will generate a typical tool cost reduction of 25% - 50% compared to steel and 40% - 80% compared to Invar.

As already discussed, the cast in place oil heating lines completely eliminates all gun drilling operations, which can be expensive and a somewhat limiting operation as part lengths increase. In addition, the ability to cast to contour can eliminate a tremendous amount of rough machining time and can dramatically reduce mold fabrication costs, depending on part configuration. Combining the cost benefits of using the casting process along with the above mentioned savings of using aluminum over steel or Invar has the potential to dramatically reduce mold fabrication costs for the Low Pressure RTM process.

5.5 Limitations of Aluminum Tooling

Common questions asked by customers during mold design discussions are: 1) How long will the mold last in production before it will need to be refurbished?, 2) Don't we need to use steel in production for better durability? and 3) What about CTE? How can we get dimensionally accurate Carbon/Epoxy parts when the difference in CTE between aluminum and Carbon/Epoxy is so large?

Steel is obviously more durable than aluminum for production tooling and is less likely to be damaged during the mold life cycle. However, for most aerospace production runs, mold surfaces do not wear out due to molding cycles. Most mold refurbishment is necessitated due to improper handling by operators.

Because aluminum is softer than steel, extra care must be taken to train operators how to handle mold surfaces and particularly loose piece tooling details which are easily dropped or dinged. In addition, special attention must be made to prevent loose fibers from getting between matched metal surfaces along parting lines. Loose fibers when squeezed between matched aluminum details will leave permanent indentations much more readily than on steel tooling. While there are special surface treatments that can be applied to aluminum to improve surface durability and even release properties, in general greater operator care must be exhibited with aluminum RTM tooling.

Another common issue when evaluating tooling material for composite parts is the CTE of the tooling material. Because of the relatively large difference between the CTE of aluminum and carbon composites, aluminum is often not considered for production applications. The CTE of aluminum, however, is very well understood and predictable. By calculating the CTE at the anticipated cure parameters for the resin system, and adjusting the mold machining programming accordingly, molded parts can be molded accurately and consistently within dimensional accuracy specifications. In situations where the mold cavity will shrink down on the part during cool down and might generate the risk of cracking the part, extra steps need to be taken to loosen clamping devices or bolts during cool down to prevent damage to the part. Some parts may even need to be de-molded at elevated temperatures but with proper safety gloves and equipment, this is a manageable issue.

The bottom line is, with proper attention, there is no reason that aluminum tooling can not be used for production runs into the thousands of parts.

6. CONCLUSIONS

- Low Pressure RTM processing is capable of producing very low void content components that are comparable in some physical properties with those molded using more conventional, high pressure techniques.
- Additional physical testing using other resin systems may be required to fully define the extents and limitations of Low Pressure RTM processing.

- Low Pressure RTM opens the possibility of using less massive aluminum tooling due to the lower stiffness requirements necessary to withstand mold deflection during processing.
- Less massive tooling can reduce Low Pressure RTM cycle times and improve part throughput by reducing heat-up and cool-down rates during process cycles.
- Cast aluminum tooling with grid stiffening and integral oil passages can be used for Low Pressure RTM to further reduce mold fabrication costs.
- Low Pressure RTM can maintain all the benefits of conventional higher pressure RTM at substantially lower costs.

7. ACKNOWLEGMENTS

The authors would like to thank NASA-Glenn Research Center for their continued support of this effort. In particular we would like to thank Mr. Gary Roberts and Mr. Charles Ruggeri (NASA GRC) for their assistance and performance of all physical testing and data compilation. Special thanks to Mr. Jay Evonovich and Mr. Dale Smith (North Coast) for their engineering contributions and assistance in the fabrication of all test panels and RTM parts to support this effort.

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