LOW COST MANUFACTURING OF COMPOSITE INTEGRAL ARMOR USING RESIN TRANSFER AND RESIN INFUSION MOLDING PROCESSES

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ABSTRACT

The current generation of composite armored vehicle (CAV) uses an integral armor concept to provide a multi-functional multi-layered integrated structure in its upper hull and side skirts. The design of the armor serves multiple functions including, ballistic protection, multi-hit capability, fire protection, signature management, low radar visibility, easy repairability, survivability and deployment. The cross-section of the armor comprises a phenolic liner for fire protection, a EMI mesh for radar invisibility, a thick composite structural load bearing laminate for energy absorption, a rubber layer for multi-hit damage capability, ceramic plate for ballistic shock resistance, and a durability cover for wear and tear. Cost considerations are key in large scale manufacturing of thick composites and integral armor parts. In the current study, two low cost manufacturing approaches have been considered that hold promise to produce large size parts – Resin Transfer Molding (RTM) and Vacuum Assisted Resin Infusion Molding (VARIM). Paper also presents tension-compression fatigue performance of thick composite structural load bearing laminate manufactured by using RTM and VARIM techniques.

INTRODUCTION

Armor Considerations

The integral armor is a primary structure in the upper hull of the Composite Armored Vehicle Advanced Technology Demonstrator (CAV-ATD) program of interest to the U.S.Army. Recent developments in the CAV-ATD program have been well illustrated in [1]. The composite integral armor is designed to provide multi-interface, multi-functional capability, easy reparability, quick deployment, enhanced ballistic damage protection, and lightweight advantages. Reduction of manufacturing costs is a prime consideration in the design of the integral armor [1]. In the current study, two low cost composite processing techniques including VARIM and RTM have been implemented in manufacturing of the structural load bearing S2-glass composite laminate and durability cover for the armor, along with innovative damage tolerant concepts at other interfaces. S2-glass armor systems provide higher areal densities, equivalent ballistic protection in comparison to aramid

systems, lower finished part cost, excellent fire and smoke performance and easier fabrication. Furthermore, S-2 glass armor complements other materials such as ceramics in composite system applications providing a synergy of performance characteristics while lowering material and finished part costs. They are inherently non-conductive and offer low radar and thermal profiles, thereby providing the military the opportunity to see without being seen.

VARIM AND RTM PROCESSING

VARIM is a single sided tooling process where the dry preform is placed into the tool and vacuum bagged in conjunction with resin injection and resin ejection lines. A low viscosity resin is drawn into the preform through the aid of vacuum. As is illustrated in the current work, preforms upto 2.54 cm thick are easily processed through this method with rapid fill times. The part is held under vacuum until full cure occurs. The technique holds promise to minimize processing costs and is adaptable for very large, complex shaped parts as well [2]. In the RTM process, a closed mold placed in a press which holds the preform, while a low viscosity resin is injected from a mixing, metering and dispensing under pressure into the mold [3]. Typically, the resin is injected at the center of the top mold and flows radially outward till it reaches the vent lines. In both VARIM and RTM, the flow of resin occurs in plane as well as in the transverse directions to the preform. The permeability of the preform, fiber architecture and fabric crimps have an influence on the wetting of the fabric [4]. In this paper two processing approaches are presented for the fabrication of a composite integral armor which is of interest to the CAV-ATD program.

INTEGRAL ARMOR COMPONENTS AND MATERIALS

The typical design of the integral armor as shown in Fig. 1 is seen to utilize the following components:

a) *Durability Cover and Signature Layer* for outer shell and ground plane comprising four layers of S2-glass, each ply 0.58 mm thick, 2x2 twill weave with 933 sizing (Supplier: Owens Corning [4]), two layers of plain weave graphite fabric, 0.31 mm, Style 8863 - Fiberite Inc. and four layers of the S2-glass; b) *Ceramic Tile* for Ballistic Protection of 17.78 mm thickness AD-90 alumina tile (Supplier : Coors Ceramic, [5]), c) *EPDM Rubber* for multi-hit damage tolerance, which is a 5.08 mm thick with grooved texture and channels on one side and plain finish on the backside, d) *Thick Composite Backing* which is the primary structural load bearing component, 20.3 - 25.4 mm thick comprising 45 layers S2-glass, 22 mil, 2x2 twill weave with 933 sizing, e) *EMI Mesh* for electromagnetic shielding, comprising plain weave aluminum mesh 23x24 count bonded to composite backing with a 0.28 mm E-glass scrim cloth, and f) a *Phenolic Liner* for flammability protection with a glass/phenolic backing sheet, 3.175 mm thick bonded to the EMI mesh with an additional E-glass scrim cloth.

Current versions of the armor include automated fiber placement and partial use of VARTM to make the thick S2-glass/epoxy composite load bearing laminate [1]. The current paper describes two routes of processing the structural load bearing member using

liquid molding approaches namely; *vacuum assisted resin infusion molding (VARIM)* and *resin transfer molding (RTM)* and the steps adopted in fabricating the integral armor.

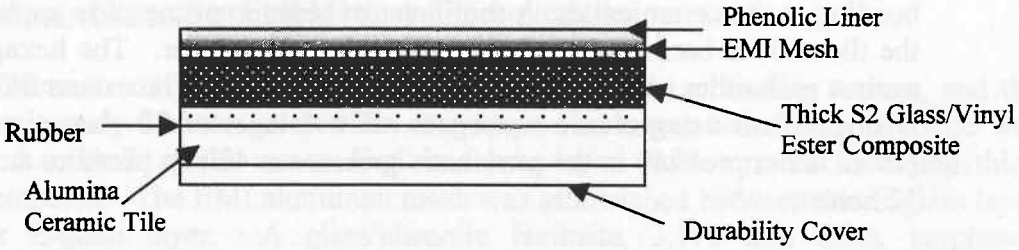

Fig. 1 Cross-Section of a Composite Armor

MANUFACTURING OF INTEGRAL ARMOR USING RTM AND RESIN INFUSION ROUTE OF PROCESSING

Steps in the Fabrication of the Integral Armor using RTM Route

The main feature is that the structural load bearing member is fabricated in a closed mold RTM process. The following section describes a step-by-step procedure for fabricating the armor panel.

Step 1 : Preparation of the Rubber Layer

The EPDM rubber sheet is abraded with 600 grit sand paper on both its sides. The sheet is cleaned with acetone on both sides. Holes of 1.58 mm diameter are drilled in a 5.08 cm x 5.08 cm square grid through-the-thickness for the entire dimensions of the panel. The sheet is cleaned with acetone once again. A thin layer of polyepoxy paste filler is applied to the grooved channel side of the rubber sheet. A layer of microballoon mixed resin is applied to the microtexture grooved surface of the rubber. Unidirectional S2-glass fabric strips are laid out in the grooves to build up the groove thickness. Vinyl ester resin is applied to wet the fabric strips to weakly keep them in place in the grooves.

Step 2 : Stitching of 5 layers of S2-Glass Fabric of the Structural Panel Side to the Rubber

Five layers of S2-glass are hand stitched to the rubber sheet (the S2-glass is placed over the grooved channel side with the fabric strips) using a 6K E-glass roving using a needle. The stitching is done by locating the holes in the rubber sheet. This procedure was adopted to provide a damage tolerant interface between the rubber sheet and the structural composite backing.

Step 3 : Preparation of Ceramic Tiles

Hexagonal AD-90 ceramic tiles are cleaned with acetone on all sides and wetted with a highly compliant SC-11 resin. A thin layer of rubber primer (Chemlok, Supplier: Lord Chemicals) is applied to the plain side of the rubber sheet in preparation of the side for bonding to the ceramic tiles. A thin layer of ceramic primer was applied to all the edges of the tile and its back surface that will bond to the rubber. The hexagonal tiles are butted against each other and pressed together from all sides. The excess SC-11 that squeezes out is stripped off using plastic squeegees. The 5 layer of S2 glass + rubber + tile lay-up is placed under pressure in the pneumatic pressure at 420 Pa pressure at room temperature for 12 hours.

Step 4: Resin Infusion of the Durability Cover and Signature Layer

The stitched S2-glass layers + the rubber sheet is placed S2-glass side down (facing the mold) on the aluminum mold. A sheet of vacuum bag film is placed on the mold side first to prevent resin from wetting the S2-glass, since this was to be used to make the structural load bearing thick composite. One layer of S2-glass is placed on the ceramic tiles and lightly pressed to loosely hold against the ceramic layer. Subsequently the dry lay-up for the ground (S2-glass layers) and signature plane (graphite fabric) is laid up over this layer in a resin infusion setup. A vacuum bag is applied over the entire part and debulked for about 2 hours. Resin is then infused into the preform. The 45.72 cm x 50.8 cm panel was infused in about 20 minutes of fill-time. The part was then stripped. Now the evolving armor part had the rubber + ceramic tiles + durability cover + signature plane and 5 dry layers of the S2-glass (from step 2).

Step 5 : Preparation of Stitched Preforms of the Thick Section Structural Load Bearing Member

To enhance the damage tolerance, stitching was adopted in the thick composite backing as well. Five blocks of ten layer each were stitched through-the-thickness using the E-glass 6K roving at 50.8 mm grid spacing over its entire area. In this manner we had five blocks of stitched preforms.

Step 6 : Resin Transfer Molding of Structural Load Bearing Thick Composite

The part described in Step 4 was laid durability cover side "down" into the bottom portion of a RTM mold. The five blocks (total 50 layers) were placed over the 5 layers of S2-glass 2x2 twill weave that were already bonded to the rubber in Step 2. Five additional layers (not stitched) were placed over the preform to yield a total of 60 layers. The bottom mold containing the preform + existing part was then wheeled into the press and the two halves of the mold were aligned. A 413 Pa pressure was applied. Vacuum lines were already attached to the top platen of the mold. The part was debulked for 4 hours. RTM was then performed using vacuum assist. The pressure on the press was maintained at 550 Pa. Vinyl ester resin VE-350 was used with 2,4 P, MEKP and CoNap as the catalyst, retarder and promoter respectively. The resin and the catalyst were placed in Tank A of the Compact Variable Ratio (CVR) Liquid Control Corp. metering, mixing and dispensing system. The resin and promoter were placed in Tank B of the CVR instrument. The mixture was mixed

in a 1:1 stream at the dispensing head. Resin was injected until the excess resin was observed in the vent lines. Resin was continued to be pumped until the vent lines showed clear resin emerging from the molds. The part was allowed to cure under room temperature.

Step 7 : Bonding of Lay-up to EMI Mesh and Phenolic Liner

The thick structural composite was lightly abraded to provide a bonding surface, and the residue was cleaned with compressed air. Aeropoxy, an epoxy based bonding paste was used to bond a 23x24 plain weave E-glass fabric layer (0.23 mm thick) to the thick structural composite. The EMI aluminum mesh was sandwiched between this E-glass layer and another E-glass layer. A glass/phenolic laminate, 3.175 mm thick, purchased commercially was sanded on one side with a 600 grit sandpaper to provide a bonding surface and then cleaned with acetone. Superepoxy bonding based paste was applied to the bonding surface and epoxy paste resin was applied to the phenolic layer. Then the phenolic sheet was bonded to the E-glass sheet facing the aluminum mesh. All this operations were done in sequence as an integral step. The lay-up was wheeled back into the press and compressed for 12 hours to achieve full bonding of the EMI and phenolic layer to the armor plate. The part was then trimmed on a Felker tile saw with a diamond blade. The operation took about 10 hours of machining time.

Steps in the Manufacturing of the Integral Armor using Resin Infusion Route

The main feature is that the structural load bearing member is fabricated in a single sided tooling using a resin infusion process. The remaining steps are similar to that used in the RTM route and have not been repeated here. The attractive feature of this process is that the entire operation is achieved using low-cost tooling, processing and labor costs [1]. The following section describes a step-by-step procedure for fabricating the armor panel.

Steps 1 through 4 were identical to those adopted in the Resin Transfer Molding Route.

Step 5 : Resin Infusion Molding of Structural Thick Section Composite

Thirty-eight layers of S2-glass, 2x2, twill weave fabric were laid in a vacuum bag. A co-injection scheme was adopted to ensure wetting of all the layers in the thick preform. The preform was debulked for about 3 hours. Vinyl ester VE-350 resin was then infused into the preform. The resin was fed simultaneously to the top and the bottom locations through the co-injection scheme. Full wetting was achieved within 20 minutes of fill time. The part was cured at room temperature for 14 hours. A laminate of approximately 2.54 cm thickness was obtained.

Step 6 : Bonding of the Thick Structural Composite Laminate to the Armor

The thick composite panel processed through resin infusion was bonded to the rubber+ ceramic+ durability/signature layer. The panel was sanded with 600 grit sandpaper on two sides. Compressed air was used to clean the surface thoroughly. A superepoxy filler paste was applied to the rubber surface and a layer of 23x24, 0.23 mm thick E-glass layer was lightly bonded to the surface. The thick structural laminate surface was prepared by the

filler. The E-glass fabric was wetted with a microballoon thickened epoxy resin mixture and the structural laminate was placed over the E-glass. The whole lay-up was compression molded for 10 hours and 90 degree C and 100 psi pressure to bond the structural laminate to the armor.

Step 7 was identical to that adopted in the RTM route of processing.

Table 1. Physical Property Measurements

Panel	Weight (kgs)	Areal Density lb/ft^2	Dimensions (cm)	Volume Fraction*	Weight Fraction*
RTM	25	136 kg/m^2	45.22 x 40.64 x 6.35	48%	65%
VARIM	11	109 kg/m^2	38.80 x 26.03 x1 4.82	50%	62%

* *Volume and Weight Fractions of the Thick Composite Laminate of the Armor*

As discussed earlier, in the typical design of the integral armor as shown in Fig. 1 one of the important component is *Thick Composite Backing* which is the primary structural load bearing component, 20.3 - 25.4 mm thick comprising 45 layers S2-glass, 22 mil, 2x2 twill weave with 933 sizing, This component along with the other components are expected to be under fatigue loading. To assess the feasibility of this material manufactured through Resin Infusion (VARIM) and Resin Transfer Molding (RTM), it is very important to understand the fatigue behavior of these composite materials.

Number of fatigue tests were were performed on MTS testing machine with Instron Controller 8500 and with Instron Hydraulic Grips (300 KN). Static tests were performed using the fabricated coupons to evaluate the basic properties such as tensile modulus, ultimate tensile strength, and Poisson's ratio. In the fatigue tests, the applied σ_{max} was varied from 45% to 20% of the ultimate tensile strength. The R ratio (σ_{min} /σ_{max}) was kept -1 so that it was a complete stress reversal with $\sigma_{min} = -\sigma_{max}$. Fatigue tests were conducted for all various σ_{max} and corresponding fatigue life cycles (N_f) were obtained. Strain was measured by clip gage extensometer. Peak values of loads and strains were recorded over the entire fatigue life. Stiffness degradations in all the specimens were monitored from those values during the testing. All the fatigue tests were performed at 1 Hz frequency.

RESULTS AND DISCUSSION

Static tests were performed for two test samples followed by fatigue tests. For these test samples, the applied σ_{max} was varied from 45% to 20% of the ultimate tensile strength. In the present test program, there were two RTM panels with different resin content (see Table 2).. Their properties were quite different which are presented below and discussed later. Comparison of static test results in Table 3 shows that moduli and ultimate tensile strength of RTM2 and RI panels are comparable. This is because of the same amounts of fibers and

resin volume fractions (see Table 2). But moduli and ultimate tensile strength of RTM1 is less than those of RTM2 and RI. This is because the same amount of fibers in all the panels but volume of resin is different which accounts for the variation. Fatigue tests results are presented in Table 4. The endurance limit for RTM material system is 25% of the ultimate tensile strength and that for RI material system is 20% of the ultimate tensile strength.

SUMMARY

Composite integral armor panels were manufactured through liquid molding processing techniques. Infiltration of the thick structural laminate (2.03 cm - 3.81 mm) in both RTM and VARIM processes was extremely rapid and cost-effective. Integral armor panels of average areal density of 123 kg/m^2 were obtained. The fatigue studies of VARIM and RTM panels resulted into following conclusions:

- Moduli and ultimate tensile strength of RTM and VARIM panels were comparable, if the fact that volume of fibers was same but resin content was different in all panels, is taken into account.
- The endurance limit for RTM material system is 25% of the ultimate tensile strength and that for RI material system is 20% of the ultimate tensile strength. (Table 4)
- The ratio of logarithms of fatigue life cycles of two differently processed panels, i.e. RTM and RI, is almost constant.
- Fatigue performance depends on the resin content.
- With the same amount fibers and with more resin, RTM process improved the fatigue performance over RI process.
- With the same amount fibers and resin, the fatigue performance of RTM and VARIM processed panels are comparable.
- In general, RTM and VARIM have poor fatigue performance under tension-compression (R= -1) as compared to tension-tension (R= .1). [6]

Table 2. RTM and RI Panels Parameters

Panel	Average Thickness	V_f
RI	0.83" (21.1 mm)	0.50
RTM 1	0.96" (24.4 mm)	0.43
RTM 2	0.92" (23.4 mm)	0.48

Table 3. Comparison of Static Test Results for RTM and VARIM Panels

Properties	RI	RTM1	RTM2
E (GPa)	28.7	25.6	27.05
σ_{ult} (MPa)	429.2	380.80	451.0

Table 4. Comparison of Fatigue Test Results for RTM and VRIM Panels

% σ_{ult}	N_f RTM1	N_f RTM2	N_f RI	Logarithmic Ratio RTM1/RI	Logarithmic Ratio RTM2/RI
100	1	1	1		
41.6	920	664	327	1.18	1.12
36.4	5,736	1,106	1,610	1.17	0.95
31.2	74,894	15,894	8,272	1.24	1.07
28.5	291,384	26,863	35,740	1.20	0.97
26	500,000	N/A	124,491	1.12	N/A

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