

Pultrusion Revolutionizes Composite Ship Structures Cost Paradigm

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ABSTRACT

The Navy is currently developing advanced surface combatants like DDG 1000, CVX, LPD-17, and LCS to meet challenges of the 21st century. The desire to reduce maintenance cost and weight makes the use of composite structures very attractive, but cost of manufacturing and joining large composite ship structures remains a significant barrier to widespread composite implementation. This paper provides an overview of several shipbuilding-related pultrusion processing innovations underway at KaZaK Composites that offer significant opportunities to reduce cost of composite ship structures. Most importantly, design and implementation of very wide composite panels with integrated self-aligning edge joints has the potential to both reduce the cost of panel fabrication and also significantly reduce the cost of composite structural assembly. Additional cost savings are anticipated by reducing or eliminating use of balsa or other pre-manufactured core material, substituting a novel fire-resistant paste material directly injected into the die. In combination, these technologies are expected to reduce cost of composite topside structure to less than half the cost of similar Vacuum Assisted Resin Transfer Molding (VARTM) structure. With the expected lower composite implementation cost described in this paper, an opportunity to revolutionize the shipbuilding industry exists as the cost of composite primary ship structure approaches that of conventional steel fabrication.

One very important benefit of the pultrusion process compared to baseline VARTM is pultrusion's ability to readily accommodate the use of epoxy resins in place of the infusible vinyl ester currently being used for carbon reinforced parts of DDG 1000. Because of its elevated temperature cure and more compatible sizing, carbon/epoxy pultruded properties can be as much as 30% better than carbon/vinyl ester VARTM. Therefore, in addition to reducing touch labor for panel production and assembly, pultruded panels with integrated joints can actually be lighter and use less of the expensive carbon fabric than competing VARTM panels.

KEY WORDS: Pultrusion, Applications – Marine, Joining/Joints/Bonding

1. INTRODUCTION

1.1 Aerospace Composite Background

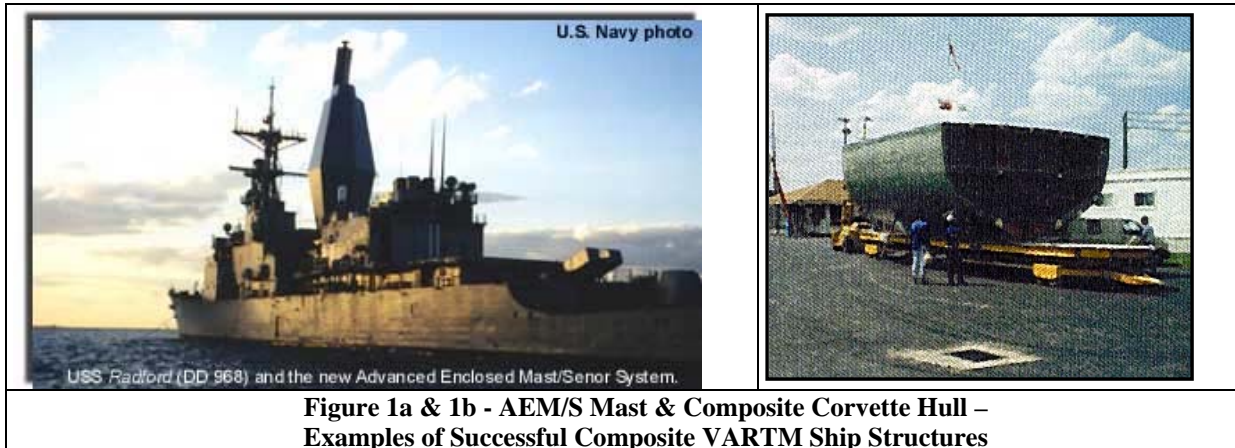
Usage of composite materials in aerospace applications has gradually increased as manufacturing technology matures and confidence in the material's long term behavior improves. For example, more than 25% of the structure of the F-22 Raptor is compositeⁱ, while next-generation commercial aircraft such as Boeing's 787 are being designed with more than 50% of the aircraft's structural weight, and all of its exposed surfaces, fabricated from composite materialsⁱⁱ. Today, the aerospace industry views carbon and glass fiber reinforced composites as mature, viable competitors for metal alternatives.

The initial and a still-important motivation for aerospace industry application of composite material in place of metal is performance enhancement via weight savings, often in combination with other advantageous material-related behaviors such as low thermal expansion and/or reduced radar cross section. Interestingly, while it can often be shown that there is significant life cycle cost advantage associated with selection of a composite structure in place of an equivalent metal design, this factor is often of relatively low importance in material selection decisions since the acquisition and operational budgets usually come from different and unrelated pools of money. In other words, if a composite structure has an initially higher cost to purchase, it has traditionally proven to be a very hard sell to have it inserted into a design over a less expensive metal structure even if there are many other compelling technical and life cycle cost advantages to the composite alternative.

In recent years, acquisition cost has grown in importance as a measure of relative merit in metal versus composite material selection trades, often being the dominant parameter driving metal versus composite material choices for most new aerospace partsⁱⁱⁱ. It is generally difficult to introduce a composite part into a new aircraft design based strictly on weight, life cycle cost, or other arguments that traditionally favor composites over metals. It has become increasingly common that a higher-performing composite part needs to most importantly have the same or lower acquisition cost compared to metal for the composite to be selected for implementation. The growing usage of composites by both the military and commercial aerospace industry indicates that, at least for these traditionally weight-sensitive applications, composite material and process engineering has done a good job of keeping production cost of high performance composite structures competitively low.

1.2 Composite Background in US Navy Ships

The US Navy is being driven to apply composite materials to major sections of ship structures by many of the same weight, corrosion resistance, life cycle cost and radar cross section arguments that initially motivated the aerospace industry. In particular, the use of large, lightweight composite topside structure provides an attractive solution to persistent performance issues associated with undesirably-high centers of gravity on many military vessels. The Navy has had several successful demonstrations of large composite structures made by the generically-described Vacuum Assisted Resin Transfer Molding (VARTM) process, with important early hardware demonstrations fabricated using the patented SCRIMPTM process, a VARTM derivative. Two early and successful examples of large VARTM military ship structures are:



1. **Advanced Enclosed Mast/Sensor (AEM/S).** This next generation glass/vinyl ester mast is 87 feet tall, 35 feet in diameter and weighs 40 tons. It protects ship sensors and antenna from the weather because they are fully housed inside this RF-transparent composite enclosure. The AEM/S enclosure saw many years of at-sea service while installed on the USS Radford, and survived a variety of harsh environments such as a hurricane and a collision with another ship (Figure 1a). This successful program later led to the design and installation of two smaller electronics masts on the LPD-17 ship class currently under construction by Northrop Grumman Ship Systems.
2. **Corvette-class ship VARTM demonstration.** This 280' long representative hull section is typical of a military vessel's midsection. The VARTM demonstration unit weighed 23,000 pounds, and included numerous design details of an actual hull design, exhibited a high glass-to-resin ratio and required 3,154 man-hours to fabricate^{iv} (See Figure 1b).

The Navy is undergoing a similar evolution in its cost / performance thinking.

2. VERY LARGE VARTM STRUCTURES HAVE BECOME PROBLEMATIC FOR COST-DRIVEN SHIP APPLICATIONS

Technical success of early implementations of composite ship structures helped convince the Navy to develop new ship classes with large portions of critical structure baselined to be made with composite materials. The most notable example is the Navy's new DDG 1000 Zumwalt class of destroyer - formerly known as DD(X). DDG 1000 will have its entire deckhouse (essentially all the above-main-deck structure, similar in size to a six-story building laid on its side) fabricated with composite materials^v. Other large composite implementations are being studied for the next-generation aircraft carrier, CVN(X), the new class of cruisers, as well as submarines and a variety of smaller ships.

Like the early implementations of composite materials in the aerospace industry, DDG 1000 composite usage was initially motivated by compelling performance advantages projected for the composite deckhouse structure compared to steel and other more traditional metal deckhouse alternatives. A greater acquisition cost for the VARTMed composite structure was judged to be justified by major performance advantages associated with composites in this application.

Unfortunately, well publicized rising costs for the new destroyer have resulted in major cost reduction efforts for the composite deckhouse structure. Current projections are \$3.4 billion to complete construction of two new DDG-1000 destroyers, based on White House and Pentagon FY 2008 budget requests^{vi}.

Like previous the aerospace industry experience, the motivation for composite usage has evolved in recent years. Initial Navy implementations of composite structure were performance-driven technology insertions, with acquisition cost viewed as an important but secondary factor. In other words, it was acceptable to pay moderately more up front for a composite ship structure made by the well characterized VARTM process since the higher acquisition cost would be offset by valuable performance enhancements, and perhaps life cycle cost benefits as well. This insightful view, balancing higher initial cost with lower operational cost, has been modified by current economic reality. Now, the Navy program offices are providing an unambiguously clear direction with respect to composite structures (as well as all new technologies). Acquisition cost is the number-one factor in material and process trades associated with new ship design. For a composite structure to be selected over an alternative metal structure for future implementations, the composite structure must be less expensive than the more traditional metal structures it seeks to replace. This point was repeatedly and pointedly made, for example, by several high level Navy decision makers at a recent conference devoted to military ship technology^{vii,viii}. Thus Navy composite shipbuilding priorities have followed a path similar to composites in aerospace applications. In each market, composites will generally only be used when they can be shown to be competitive with metal alternatives on an acquisition cost basis.

An overriding emphasis on acquisition cost could potentially present a significant barrier for near-term insertion of large composite structures into new Navy ships. The Navy is heavily invested in the development and verification of the composite panels made by the VARTM process. Current Navy shipbuilding technology first VARTMs large flat balsa-cored sandwich panels. These panels are then scarffed together at panel to panel edges, adding considerable additional labor and material cost on top of the VARTM cost to create large areas of composite structure. While technically very successful, the VARTM structures are unfortunately more expensive by a considerable margin than similar broad expanses of flat ship structure made by conventional steel fabrication technology. While costs tend to be closely guarded information, few in the shipbuilding industry object to use of \$5/lb of finished steel ship structure. Cost of a similar expanse of VARTMed composite sandwich panel is easily \$10/lb or more. Somewhat surprisingly, the major portion of the cost difference between metal and composite ship structure is associated with the higher labor cost of the VARTM process compared to traditional steel ship fabrication practice.

Clearly, to meet the new directive from Navy ship owners that composites should not be used in new structure if they result in an increase in application cost, something other than VARTM processing will be required to fabricate large areas of ship structure. KaZaK Composites has been working for several years (with funding from both Navy and private industry as well as our own internal R&D) to develop several pultrusion-based manufacturing methods that will allow the cost of large composite ship structures to be competitive with baseline steel construction. Two of these technology advancements, very wide sandwich panel pultrusion with integrated

edge joint detail, and a synthetic replacement for the expensive balsa core material, will be discussed in the following sections.

3. VERY WIDE PULTRUDED PANELS WITH INTEGRATED JOINT DETAILS REDUCE COST OF COMPOSITE SHIP STRUCTURE

VARTM is an excellent process for making large composite structures of arbitrary shape. It can easily accommodate complex geometries such as the curvatures near the bow of a ship and can even be used to produce parts as complicated as a ship's propeller. The VARTM process has had a long and successful association with shipbuilding, and represents a logical processing choice for early innovators in the military composite shipbuilding field such as the Navy and Northrop Grumman Ship Systems. When attempting to minimize cost of finished composite structure, however, VARTM has a major shortcoming - it is very labor intensive. The geometric flexibility that led initial material and process innovators to use VARTM is also its downfall for building cost-effective ships with large expanses of flat panel structure, since the shape flexibility inherent in the VARTM process comes at the cost of relatively high labor content. When flat panels can be used, other manufacturing technologies become more appropriate.

Since many modern ships are built with broad expanses of constant section flat panel, the geometric flexibility of VARTM becomes an unnecessary cost detriment, and pultrusion, an automated process for making a continuous stream of constant cross section panels, becomes far more economically attractive. For example, the DDG 1000 deckhouse (Figure 2) is flat-sided for radar cross section considerations. The Navy high speed demonstration vessel, War Fighter, is similarly slab sided, and derives no benefit from VARTM's ability to make composite structures with multiple curvatures.



Figure 2 –Flat-Sided Ship Designs such as DDG 1000 (left) and War Fighter (right) are Ideal Candidates for Fabrication using Pultruded Flat Panels with Integral Joints

Pultrusion Reduces Composite Ship Acquisition Cost

Revolutionary improvements to both cost and performance of military and commercial cargo ships can be achieved by designing future vessels to be made using large flat pultruded panels. It is expected that by employing “Design for Manufacturability” concepts from the outset, properly designed pultrusion-based composite ship structure can become cost-competitive with metals.

KaZaK Composites has been actively involved in a number of Navy-funded studies related to the application of the pultrusion process to the fabrication of various ship components. KaZaK operates the world's largest pultrusion equipment, capable of continuous production of constant cross section composite structural elements and sandwich panels greater than 10-feet wide, 1-foot thick and with a length limited only by shipping and handling considerations. These large panels (with integrated joints) are the key to developing cost-effective ship structure.

Why Pultrusion?

Pultrusion technology represents the only method currently capable of producing structural composite parts on a continuous basis and of unlimited length. The process is illustrated schematically in Figure 3, in this case using an injection system to impregnate a fiber preform with resin. In the pultrusion process, reinforcing materials in the form of dry unidirectional fibers, cloth, multi-axial stitch bonded materials, braided pre-forms and specially-produced 2-D and 3-D reinforced materials are continuously pulled from spools or woven using in-line winders and braiders prior to being passed through an optional preheating furnace. Preheating serves to dry the materials and improves resin wet-out. This collation of dry reinforcing material then passes through forming cards, where foam cores can be inserted when making sandwich panels, before entering an approximately one meter long heated steel die. The die compacts the material into the final geometry. Resin is applied to the preform, either by pulling it through a wet-bath or by directly injecting liquid matrix into the die. Resin injection offers a number of advantages for high performance product production, although it requires more complex tooling and longer development efforts in some cases. The wet fiber/resin assembly is then cured as it moves through the heated portion of the die. The resin inside the die is exposed to the appropriate temperature and pressure conditions required to achieve a nearly complete cure before the material exits the downstream end of the tool. A pair of hydraulically-activated gripping plates is used to alternately grab and pull the material through the system at a constant speed. Tractor-puller systems are also used for simpler part geometries.

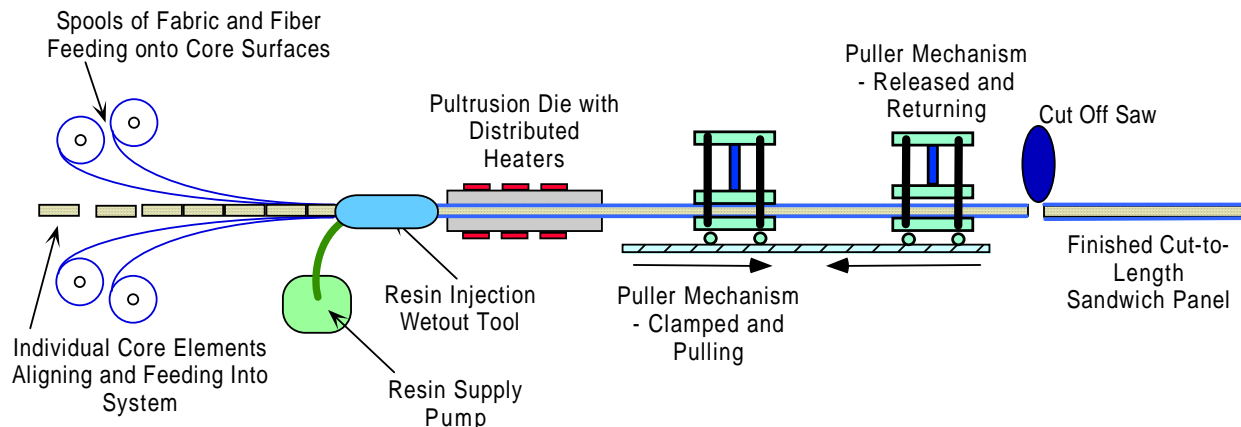


Figure 3 - Pultrusion Process Schematic

The pultrusion process is by far the most cost-effective technique for fabricating high performance structural composite hardware. Pultruded products can be produced at a cost that approaches raw material cost (~20% greater) in large-scale production because labor and other

overhead costs fall into the noise level of calculations on a per-pound basis. For example, a single operator managing a small pultrusion machine can continually produce finished composite hardware at rates as high as hundreds of pounds per hour. In comparison, rates of a few pounds per hour are the norm for composite construction based on hand lay-up, or ten to a hundred pounds of finished structure per hour for most other structural composite production methods. A 10-foot wide pultrusion machine (the largest in the world) can produce up to *25,000 pounds of finished composite structure per hour*. The material throughput of the pultrusion process, with minimal labor content, translates into a pronounced reduction of direct labor cost per pound in the finished part. Pultrusion is most likely the only process capable of making composite panels at a cost that is affordable for large, general purpose shipboard structures.

Pultrusion Cost Study

As part of a Navy-funded study, KaZaK Composites worked with a major US shipbuilder to compare the cost of fabricating a ship set of DD(X)-like panels (various quantities of seven different balsa-cored sandwich panel configurations). The baseline for comparison was the estimated cost of making the panels using the VARTM process. For the pultruded composite case, the deckhouse structure was optimized for fabrication using 10-foot wide pultruded glass and carbon fiber reinforced balsa cored sandwich panels made with integrated joint edge details built into the panel edges during the pultrusion process. A typical pultruded panel cross section used for this cost comparison is shown in Figure 4a-b. The portion of 10-foot wide panel being held in Figure XXXa would weigh more than 400 pounds if fabricated with equivalent bending stiffness in steel. Figure XXXb shows the section through an assembled panel to panel bonded joint. These joints are designed to carry the full panel bending load, and also serve as self fixturing assembly aids that provide additional cost reduction. Figures 5a-b show the male and female edge details being pultruded into the 10-foot wide balsa cored sandwich panels used to develop pultrusion versus VARTM cost comparisons. The pultrusion process as illustrated runs at approximately 1 foot per minute, so about 600 square feet of panel are made each hour with at most \$150 in loaded labor cost. Thus the labor content of the pultruded panel is approximately 25 cents per square foot in this example.



Figure 4a – Single Width of 10-Foot Wide Pultruded Panel Used as Basis for Ship Construction Cost Comparisons



Figure 4b – Detail of Bonded Joint Connecting Parallel Sections of 10-Foot Wide Pultruded Ship Panel



Figure 5a – Male Joint Edge Integrally Pultruded in 10-Foot Wide Sandwich Panel

Figure 5b – Female Joint Edge Integrally Pultruded in 10-Foot Wide Sandwich Panel

Figure 6 provides a cost comparison of a set of seven different pultruded panels of the type that would be used on DD(X). Three production scenarios were evaluated, with 1, 2 or 3 ship sets of each panel type pultruded in a single production setup. The bars on the lower portion of the plot breakdown the major cost components of the pultruded production run. Notice that the cost of producing the panels is almost entirely driven by raw material cost, with other cost factors like labor barely appearing in the plots. The tops of each of the three bars represent the total cost of pultruding various quantities of panel in a single setup, with the decrease associated with amortization of the labor and

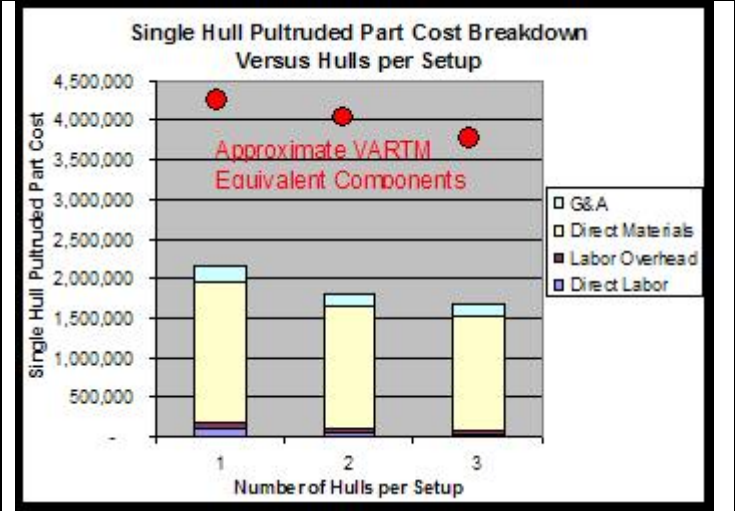


Figure 6 – Cost Comparison of 1, 2 and 3 Ship Sets of Pultruded Versus VARTM Panels for a DD(X)-like Ship Structure. Pultrusion Reduces Cost by 50%.

decreased scrap when multiple ship sets are made at the same time. Price of the illustrated panel set ranges from slightly more than \$2 million per ship set when only a single set of panels is made at a time. This price falls to slightly more than \$1.6 million when three ship sets are simultaneously produced. The most important data points in this chart are the three large dots located above each of the bars. These dots represent the cost of making the same set of panels using the VARTM process. The VARTM panel cost in this example is approximately twice the cost of the same set of pultruded panels. Calculated average panel price in this example, which includes a mix of glass and carbon sandwich panels, is about \$5 per pound. VARTM panels average more than \$10/pound.

This cost study did not include the additional significant cost savings derived for the incorporation of self-aligning joints in the edges of the pultruded panels (for example, like those shown in Figure 7). These details greatly reduce the cost of panel joining, which is a significant cost for the VARTM baseline structure. Shipyard studies have projected that the use of this type of integrally jointed pultruded panels can result in a finished composite ship structure that can be approximately equal in cost to traditionally fabricated steel ships. If, as expected, these cost projections are supported by planned fabrication of large pultruded demonstration structures, the pultrusion process offers the possibility of breaking the cost paradigm currently restricting the application of composites in large ship structures, with potentially revolutionary impact on the entire military and commercial shipbuilding industry.

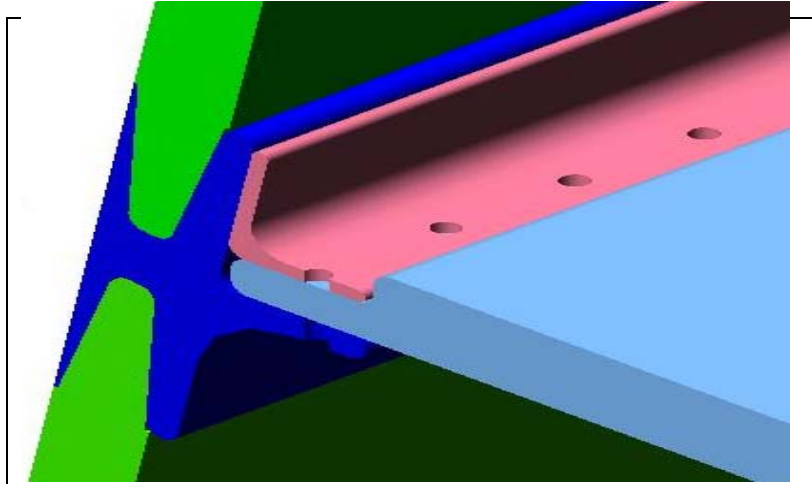


Figure 7 – Typical Example of Pultrusion-Optimized Ship Assembly Based on Large Pultruded Panels with Integrally-Created Joint Details.

4. IN-LINE CREATION OF SYNTACTIC PHENOLIC CORE FOR BALSA REPLACEMENT

Figure 6 illustrates the fact that the acquisition cost of a pultruded ship structure will be dominated by the cost of raw materials. For the DDG 1000 and other planned Navy composite ship structures, the baseline panel configuration is a balsa-cored sandwich panel. Balsa has very good specific mechanical properties, particularly its through-thickness compressive strength. However, there are several issues with balsa that diminish its appeal in large ship structures. Because it is a natural product, there is a great deal of mechanical property variation from point to point in a balsa sheet. In addition, the material is porous and must be coated to prevent resin absorption during VARTM processing. Balsa can absorb moisture, rot and be attacked by insects. In the current acquisition-cost driven environment, however, the greatest concern with continued use of balsa is cost. The raw material in large sheets is relatively expensive, representing a significant percentage of the total raw material cost, and therefore also the finished part cost, of a pultruded panel. For creation of panels with integral joints, the cost of machining the tapered joint details into the balsa cores is also a major contributor to overall cost.

KaZaK is working with Navy funding to develop a unique pultrusion-optimized alternative to balsa core that is created in line with the pultruded panel, rather than being fed into the pultrusion process as sheets, as is currently practiced. In KaZaK's system a syntactic foam is created by mixing a base resin (which can be any resin including vinyl ester, phenolic or epoxy) with

ceramic microballoons and other additives to create a very thick paste with the consistency of putty. Special feeder tooling is designed to form and insert metered core material between the skins of a sandwich panel as it is being pultruded. The proto-core paste enters the heated pultrusion die with enough resilience to provide the required pressure between the reinforcing fibers and the surface of the tool for a successful pultrusion. More importantly, the paste is sufficiently compliant to fill details of the pultrusion, including rather complex tapers at the male and female ends of the jointed panel. The process is schematically illustrated in Figure 8a-b.

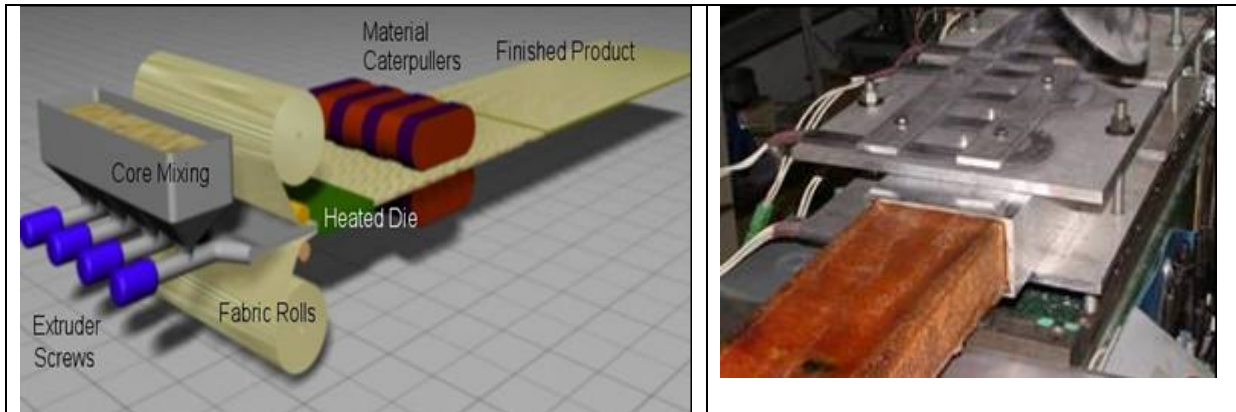


Figure 8a and 8b –Schematic of KaZaKore Process for Continuous Mixing and Injection of Core for Creation of Pultruded Sandwich Panels (left). Phenolic-Based Sandwich Panel Production (right).

KaZaKore material reduces acquisition cost in several ways compared to balsa. First, the cost of the constituent raw materials is less than the raw material cost of the balsa. Second the cost associated with machining the tapers into the edges of balsa core stock material is eliminated. Finally, resulting panels will be more consistent from point to point since the variability associated with balsa is eliminated. With the exception of through-thickness compression strength (not usually an important design parameter in sandwich panel cores), KaZaKore has properties competitive with balsa. In particular, when formulated with phenolic resin, KaZaKore meets the Navy fire performance specifications described by UL 1709. Figure 9 illustrates the fire resistant properties of the KaZaKore material.

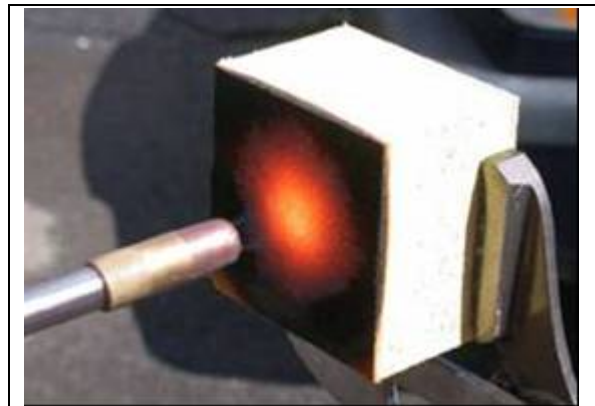


Figure 9 – KaZaKore is a Cost-Effective Alternative to Balsa, and Meets UL 1709 Fire Requirements

5. CONCLUSIONS

Significantly improved performance can be gained by replacing traditional steel ship structure with composite materials. However, current cost realities which require acquisition cost competitiveness with steel baseline structure pose a major barrier to the widespread introduction of composites to major ship components. The use of the VARTM process, the current Navy baseline approach for large composite ship fabrication, has been found to approximately double acquisition cost compared to steel.

Considerable work has been done to demonstrate the viability of large scale pultrusion processing. Results to date suggest that new ship designs optimized for fabrication using pultruded sandwich panels made with built-in male / female edge joints has the potential to create acquisition cost equivalent to that of metal structures. Additional cost benefits can be achieved by replacing balsa core materials with phenolic syntactics created in line with the pultruded skins.

Successful demonstrations of pultruded composite ship structure planned to occur in the next few years have the potential to break the current cost paradigm inhibiting use of composites in place of steel military ship structure. Once implemented in military vessels, a much greater potential market exists for the use of composites in the much larger US and international commercial fleet.

6. ACKNOWLEDGEMENTS

The work described in this document has been supported by IR&D funding at KaZaK Composites, as well as significant outside funding provided by major military shipbuilders, and in particular, by the following DOD SBIR Phase I and Phase II contracts: DAAN02-98-C-4042, N47408-00-C-7136, N00014-02-M-0086, N00014-04-C-0404.

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