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DEVELOPMENT OF A LOW-COST, MODIFIED RESIN TRANSFER MOLDING PROCESS USING ELASTOMERIC TOOLING AND AUTOMATED PREFORM FABRICATION

William J. Doane and Ronald G. Hall
General Dynamics Convair Division
San Diego, California 92186-5357

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SUMMARY

This paper describes the design and process development of low-cost structural parts made by a modified resin transfer molding process. Innovative application of elastomeric tooling to increase laminate fiber volume and automated forming of fiber preforms are discussed, as applied to fabrication of a representative section of a cruise missile fuselage.

INTRODUCTION

Advanced composite materials have found aerospace applications in which they help meet performance requirements of strength, weight, and radar signature reduction, although historically at very high production costs. Cost reduction is required if composite materials are to remain viable candidates for high-performance applications.

A low-cost structure development project was initiated as part of a study of ways to reduce the cost of cruise missiles. An integrated product development team was formed with representatives from design, manufacturing, materials, stress analysis, and cost estimating disciplines. A conceptual generic vehicle was created and is shown in F1. The team decided to evaluate composite structure for the midbody section of the vehicle and to develop a study configuration to aid in composite material process development. Guidelines for low cost were developed, such as fabricating large integral assemblies, integrating automation, providing low process cycle time, and eliminating bolted joints.

Trade studies were conducted on composite designs using filament winding, pultrusion, thermoforming, and resin transfer molding (RTM) processes. Cost, functional, and producibility evaluations led to the selection of the RTM process as the lowest-cost process with the greatest versatility. This versatility is illustrated by the many different features provided by the process, including the ability to make large integral assemblies and net shape moldings. Also, a wide variety of structural parts can be formed using the same design, process, and tooling technology. Our team chose to investigate the RTM process and to develop process modifications to increase its usefulness. The RTM process is generally applicable to all aerospace structural fabrication. For the purposes of this study, we chose to use a generic cruise missile structure.

This paper discusses the use of elastomeric tooling to provide a method of increasing fiber volume, resulting in a higher-quality laminate; a method of fabricating fiber preforms using automation; and design and fabrication of a demonstration section of an integral composite structure for a cruise missile midbody.

RUBBER-ASSISTED RTM

Elastomeric tooling was investigated as a method to increase fiber volume and laminate quality over conventional RTM methods. Rubber-assisted resin transfer molding (RARTM) relies on placing a rubber insert into the tool that expands a predetermined amount during cure, providing pressure to compact the fiber reinforcement. Comparison of the RTM and RARTM processes shows improvements in fiber volume and producibility. Our team has used the RARTM process to fabricate flat panels for material properties tests, stiffened panels for three-point bending tests, and skin stiffeners for the fuselage demonstration section.

Conventional RTM is a closed-mold, low-pressure process (R1). F2 is a diagram of the process. A dry fiber reinforcement called a preform is placed in a sealed tool cavity. The tool with preform and the resin to be injected is heated to a moderate temperature such as 130°F. After vacuum is applied to remove air from the tool cavity, the resin is transferred at low pressure. The temperature is then raised to the cure temperature with the resin remaining under pressure. The part is cured and then removed from the mold.

The RARTM process is shown in F3. The process is the same as conventional RTM except for the novel use of trapped rubber in the mold and a pressure relief valve to vent excess resin at the appropriate time in the process cycle. The rubber is sized (R2) to allow a low fiber compaction during the resin transfer stage of the process. This allows improved resin flow with better fiber wetting at a lower transfer pressure. After the resin is transferred into the preform in the tool cavity, the temperature is raised to the cure temperature. During this temperature rise, the rubber expands, due to its high coefficient of thermal expansion, and compacts the fiber reinforcement while squeezing out excess resin. A relief valve allows the excess resin to vent from the tool while maintaining adequate backpressure. Resin backpressure is required to produce a high-quality, low-void-content part.

An evaluation of the RTM and RARTM processes can be made by contrasting the processing parameters needed to produce comparable laminates. The processing parameters of interest are resin transfer pressure, resin transfer time, and total cycle time. "Comparable laminates" refers to fiber volumes of 65% for the finished laminates. The temperature and pressure cycles for the RTM process are shown in F4. For RTM, the fiber volume of the preform in the tool cavity at resin transfer is 65% because the tool cavity remains unchanged throughout the process. This results in a resin transfer pressure of 50 psi, a resin transfer time of 165 minutes, and a cycle time of 340 minutes. Temperature and pressure cycles for the RARTM process are shown in F5. The fiber volume of the preform in the tool cavity is 50% at resin transfer. This is less than for the RTM process and is possible because the rubber insert can be sized for easy resin transfer. After resin transfer and during the cure cycle, the rubber expands, forces out excess resin, and compacts the laminate. The resin transfer pressure of 20 psi, a resin transfer time of 25 minutes, and a total cycle time of 205 minutes are improvements over the conventional RTM process. T1 lists material properties for an RARTM panel at 66.9% fiber volume. This fiber volume is achievable with the conventional RTM process but with greater processing pressures and cycle time. The reduction in cycle time provides cost savings in the form of reduced labor and better tool utilization.

We have used the RARTM process to fabricate mechanical property test panels, tee-stiffened test coupons, and the skin stiffener in the fuselage demonstration section. These tools are shown with their rubber tool inserts in F6. In the case of tee and skin stiffeners, the rubber inserts have been shaped with a draft angle and made in two halves to facilitate loading the fiber preform into the tool cavity.

FIBER PREFORM FABRICATION

A low-cost method of forming fiber preforms was developed. Using a powdered epoxy resin product, called a tackifier, a consolidated flat sheet of reinforcing plies is fabricated at low temperature and pressure. The resin secures the plies together so they can be cut to shape on an automated cutter. Forming takes place over a tool form at the same low temperatures and pressures used in the consolidation step. Patterns and parts have been fabricated using this method with fiberglass and graphite reinforcements and RTM. F7 is a schematic representation of this sequence.

The tackifier is a fully reactive, granulated epoxy resin powder with no hardener and a melting point of 140F. The tackifier is applied to individual dry fiber plies in a quantity that does not exceed 5% of the resin weight of the final part. The desired thickness of plies is built up in this manner and consolidated in an oven at 140°F under vacuum. This process lightly secures the plies to each other and facilitates the cutting and forming operations. The operation of fabricating these consolidated preform modules can be automated.

A trial pattern (F8) was designed to test the feasibility of cutting the sheet preforms using an automated ply-cutting machine. The pattern consists of 10 plies of 181 style fiberglass at 0-deg orientation. The designer generated the pattern on a computer-aided design (CAD) workstation and electronically transferred it to the cutting system computer. This procedure eliminates the dimensional errors of making a template from a drawing and using the template for cutting the pattern. The test pattern was cut without problems. The plies maintained their adhesion to each other at the edges, fiber fraying at cut edges was minimal, and all corner radii down to the 0.25-inch inside corner radius were cut smoothly. Sharp corners, such as those at the corners of the squares, did result in a small cut into the sheet where the blade traveled beyond the corner. This type of corner would not be used, however, due to possible stress concentrations. There was no accumulation of tackifier material on the cutting blade.

The tackifier material also allows forming patterns cut from the sheet preforms. Vacuum pressure and heat, at 130° to 140°F, are applied to form the pattern over a tool form. The heat softens the tackifier to allow this forming but does not cure the resin material. The sheet preform can be reformed if necessary. Preforms made in this manner can be stored for long periods at room temperature. A pattern, tool form, formed pattern, and completed RTM frame are shown in F9.

A benefit of the preform fabrication process is consolidation of the plies, which provides easier tool closing and results in a part with a lower void content. The tackifier dissolves and reacts with the resin transferred through the reinforcement during the RTM process. Both fiberglass and graphite preforms have been fabricated with this method and used to fabricate parts with both conventional RTM and RARTM processes.

DEMONSTRATION ARTICLE

A stiffened/skin subassembly was designed to demonstrate the benefits of large parts, integral assemblies, and the advantages of the modified RTM process described above. The subassembly is a section of the midbody design used in our trade studies. Composite tools were designed and fabricated with a unique progressive resin transfer technique. Fabrication of the stiffened/skin subassembly was completed successfully.

A composite material midbody was designed for the generic cruise missile baseline vehicle using the RTM process; see F10. The design approach consists of upper and lower stiffener/skin subassemblies secondarily bonded to a separately fabricated RTM center structure. This two-part structural approach – skin subassemblies and center structure – was chosen to avoid complex enclosed cavities that would require segmented tooling or dissolvable mandrel tooling. The approach also provides for easier inspection of the parts.

The stiffened skin subassembly is shown in F11, along with the design of the mating structure: the wing cavity floor panel. The development section is 30 inches long and has a radius of 12 inches. The skin consists of four modules of graphite cloth. The stiffeners are S-2 fiberglass cloth. The secondary bond between the skin and the floor panel is a stepped lap joint. A 350°F curing epoxy resin is used.

The subassembly tooling is laminated graphite and fiberglass epoxy, as shown in F12. An outer shell stiffened with support frames forms the smooth outside surface of the skin. The inner shell is made with cavities for rubber inserts at the skin stiffener locations. The two shells are bolted together and sealed with an O-ring seal. Combination resin injection and vent ports are provided at three levels in the tool.

Fabrication of the subassembly begins with fabrication of glass preforms for the skin stiffeners. The skin stiffeners are formed by placing several fiberglass angles back to back. The fiberglass plies are formed into preform sheets three plies thick, cut, and then formed into an angle over a tool form at 140°F with vacuum pressure. The angles are assembled into the rubber inserts and placed into the tool. Next, preparation of tackifier graphite cloth preforms for the skin is completed. These are made in modules of four plies. The modules are placed on the inner shell over the tee preforms and inserts. Four modules are stacked to provide the 0.25-inch skin thickness required. A problem developed with wrinkles as the modules were formed over the 12.0-inch radius of the inner tool. Due to time constraints, a solution was not worked out at the time and the plies were laid down on the tool individually. Techniques to eliminate the wrinkling problem are in progress and involve using a line or grid application of the tackifier rather than a broad area application and fewer plies in a module. A layer of cured radar-absorbing material (RAM) material is placed on the outside surface of the skin. The tool is then closed, bolted together, and leak-checked.

The resin transfer takes place at a temperature of 120°F and a pressure of 20 psi. Vacuum is drawn on the part before resin transfer. With the tool standing on one end, the resin is transferred by a batch pressure pot pumping system at the low end of the tool through three ports. To avoid problems with loss of resin pressure through the length of the preform, dual resin inlet and vacuum ports are placed at the middle of the tool and near the top end. As resin appears at these dual ports, the vacuum line is closed off and resin is transferred into the tool at that point. This method of progressive resin transfer aids in fabrication of large parts. Total injection time for the 23.9-lb subassembly was 180 minutes, including a 40-minute purge time.

Lessons learned from design and fabrication of the demonstration article (F13) include:

- A two-part structural approach simplifies tooling and inspection.
- Progressive resin transfer aids resin transfer molding of large integral assemblies.
- Composite tools contribute to shorter part cycle times through faster heating and cooling rates.
- Vacuum and positive pressure leak checks should be performed.
- RARTM can reduce tool closing forces and resin injection pressures.

CONCLUDING REMARKS

The RARTM process allows a low-cost process to compete with more expensive processes in fiber volume and laminate quality comparisons and provides improvements in processibility over the conventional RTM process. These improvements are lower resin transfer pressures, shorter process cycle time, easier tool closing forces, and simplified part removal from the tool.

The method of preform fabrication described offers benefits that reduce the cost of the RTM process. Individual cutting and placing of plies is eliminated by a method that allows full or partial automation at the sheet stage, pattern cutting, and forming operations. Hand labor and the problems of securing dry plies in a shaped mold are also eliminated. Additionally, the use of the tackifier resin provides preforms that are preconsolidated, aiding closing of the tool.

Producibility advantages have been shown through fabrication of the demonstration section. Large integral assemblies incorporating different structural features, graphite and fiberglass reinforcements, and a radar-absorbing coating can be fabricated using RARTM and consolidated preforms. RARTM, the progressive resin transfer method, and composite tooling provide lower part cycle times through lower resin transfer pressures, maintaining transfer pressure, and faster tool heating and cooling.

Composite fabrication costs can be reduced through the use of low-cost processes that produce parts with a high fiber volume, use automation in making preforms, and allow fabrication of large net shape moldings integrating many parts. The resin transfer molding process was chosen as the lowest cost process to produce composite structure for cruise missiles. Our trade studies have developed advanced composite structures that meet the requirements of the next-generation cruise missile and can be produced at a cost of $60 per pound. The conventional RTM process can be improved upon by using elastomeric tooling in the RARTM method and by the automated fabrication of fiber preforms.

REFERENCES

1. *Engineered Materials Handbook*, Volume 1 Composites. ASM International Handbook Committee, November 1987.
2. *A Guide To Trapped Rubber Molding*, D Aircraft Products Inc. Anaheim, Calif.

Table 1 Material properties for RARTM

Property	Average Value
Fiber volume	66.9%
Resin content weight	26.8%
Tensile strength	553.9 MPa (80.3 ksi)
Tensile modulus	55.8 GPa (8.09 msi)
Tensile strain at failure	9,767 $\mu\epsilon$
Compressive strength	371.7 MPa (53.9 ksi)
Compressive modulus	53.0 GPa (7.68 msi)
Compressive strain at failure	7,467 $\mu\epsilon$
Interlaminar shear strength	52.0 MPa (7.55 ksi)
Flexural strength	621.4 MPa (90.1 ksi)
Flexural modulus	37.0 GPa (5.37 msi)

Graphite · AS4 6K 5HS, 0.15 ply [0, +45, -45,0,90]s
All properties in longitudinal direction

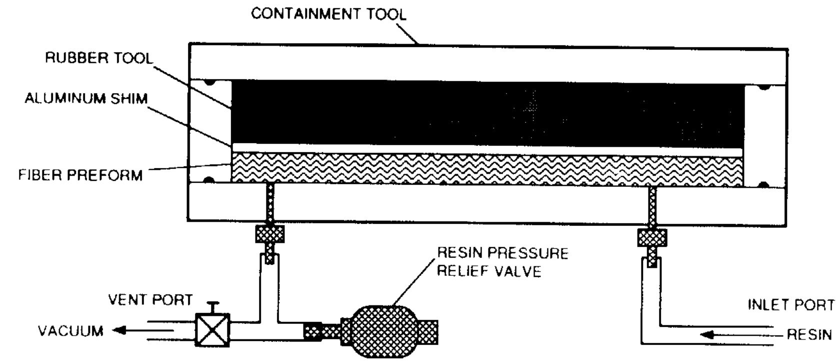

Figure 3. Rubber-assisted RTM diagram

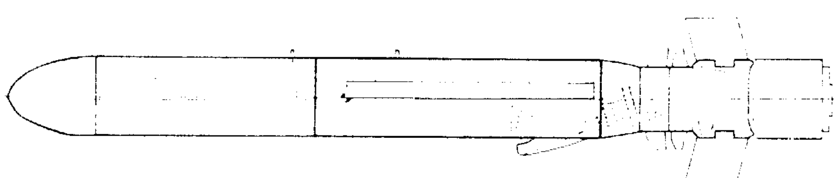

Figure 1. Generic cruise missile configuration

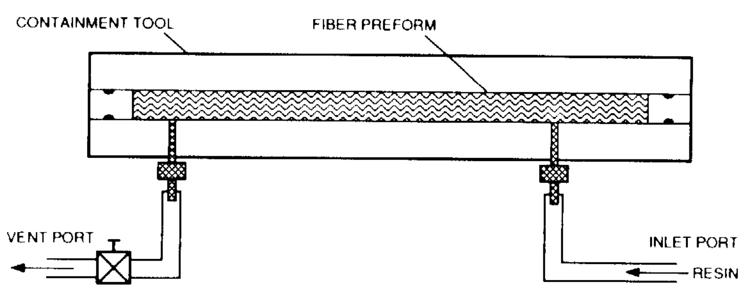

Figure 2. Conventional RTM process diagram

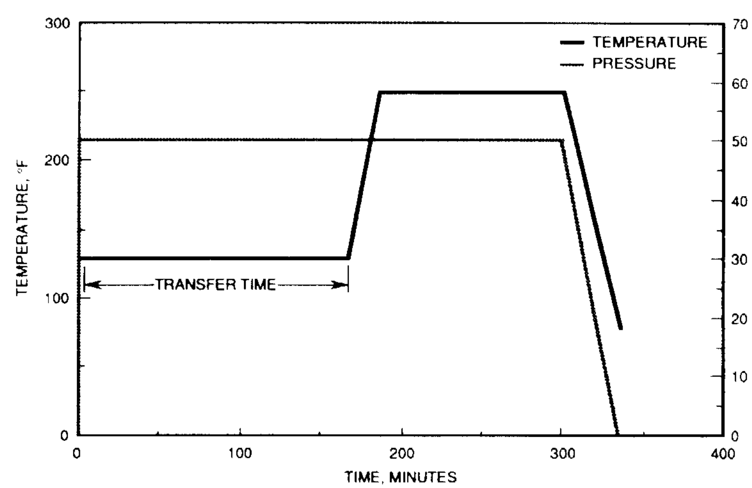

Figure 4. RTM pressure, temperature, and time cycles

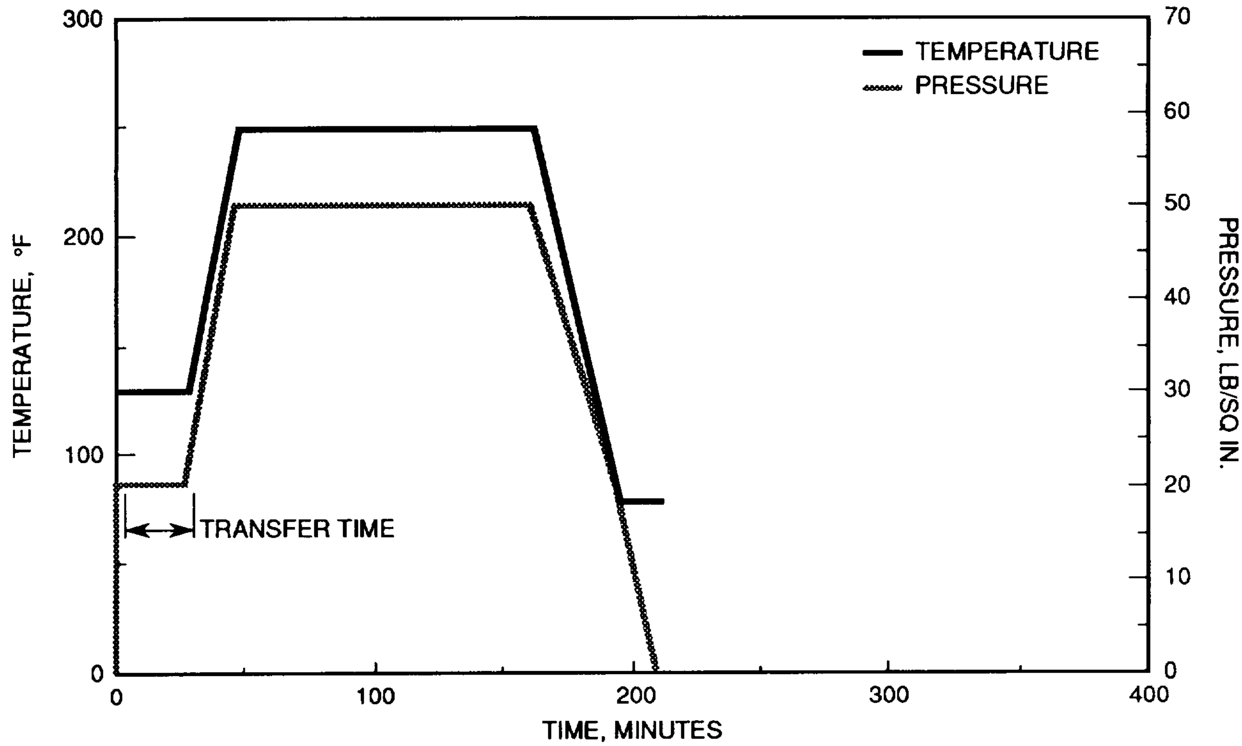

Figure 5. RARTM pressure, temperature, and time cycles.

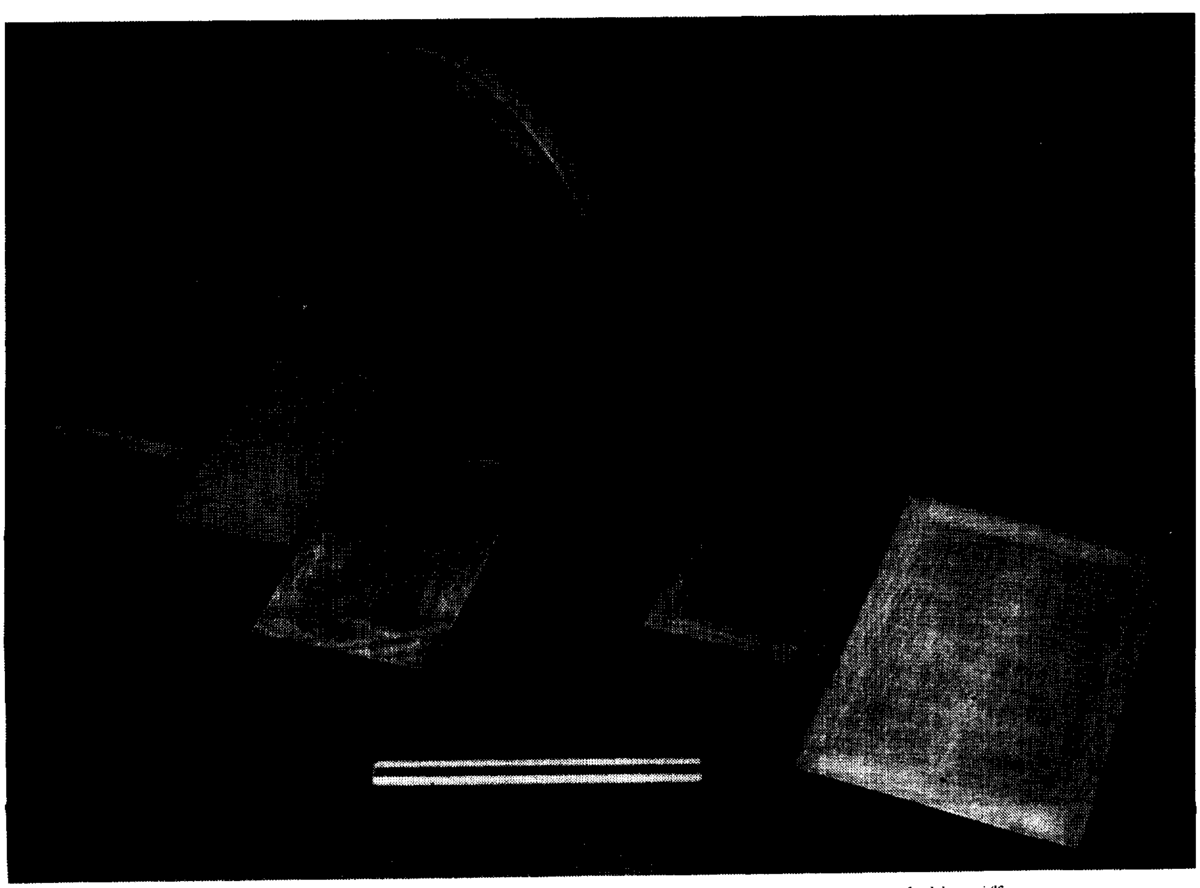

Figure 6. RARTM tools, mechanical property panels, tee stiffeners, and skin stiffeners.

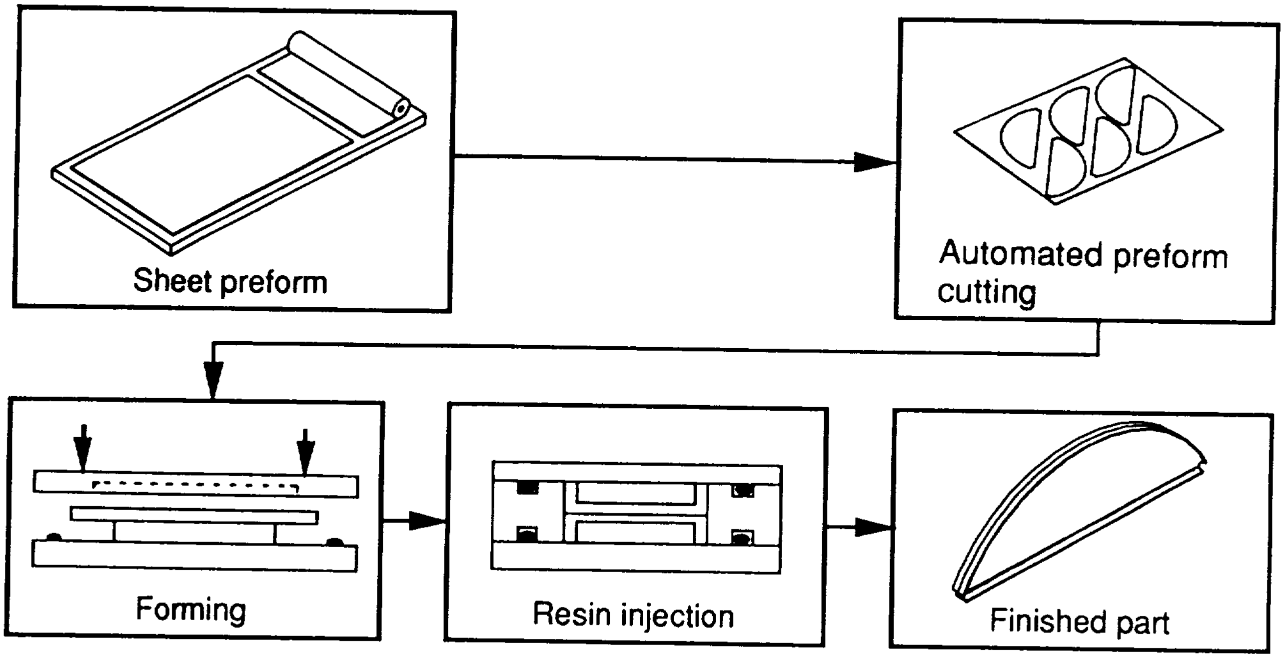

Figure 7. Automated preform fabrication sequence.

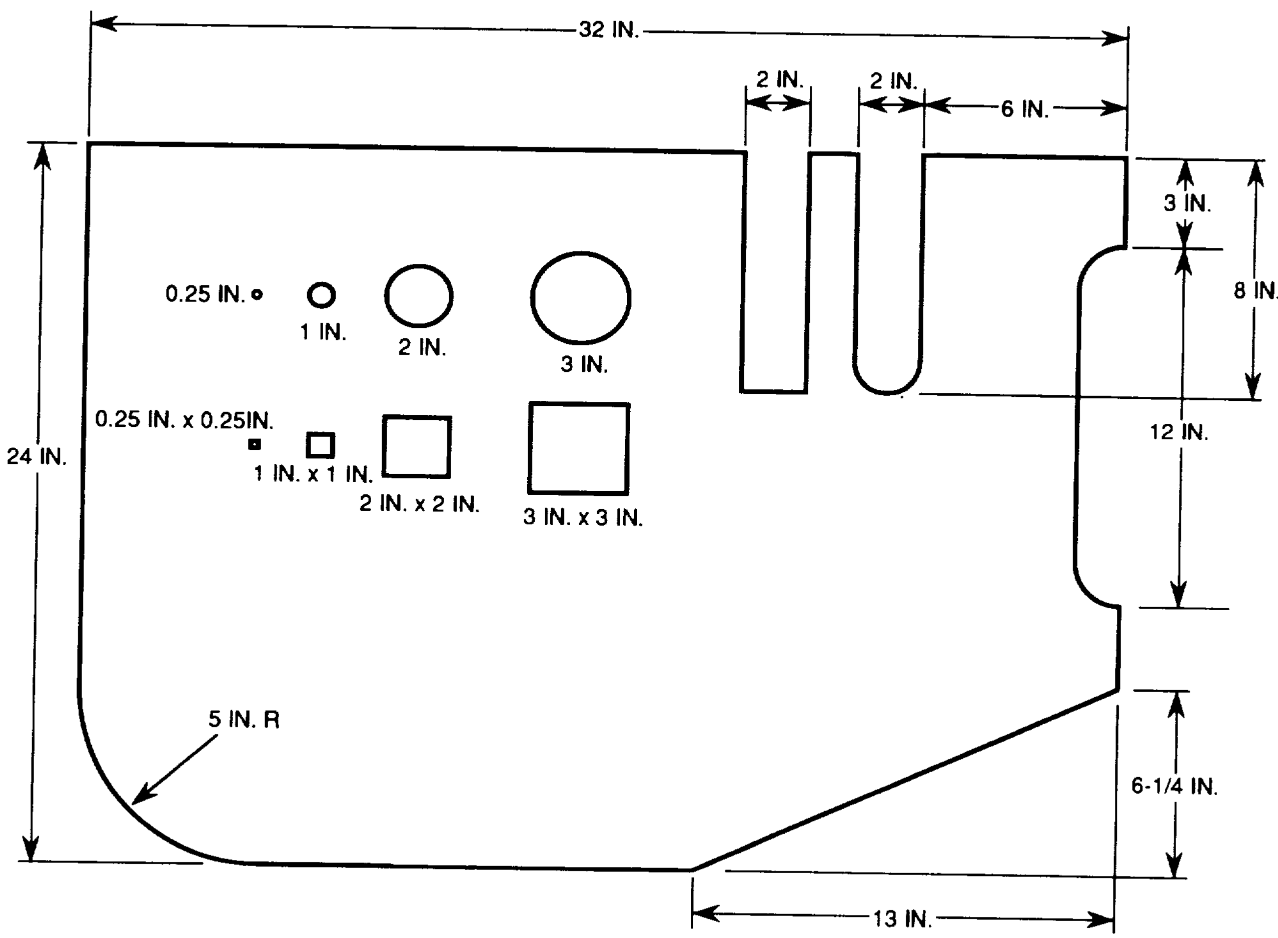

Figure 8. Test pattern for automated preform cutting.

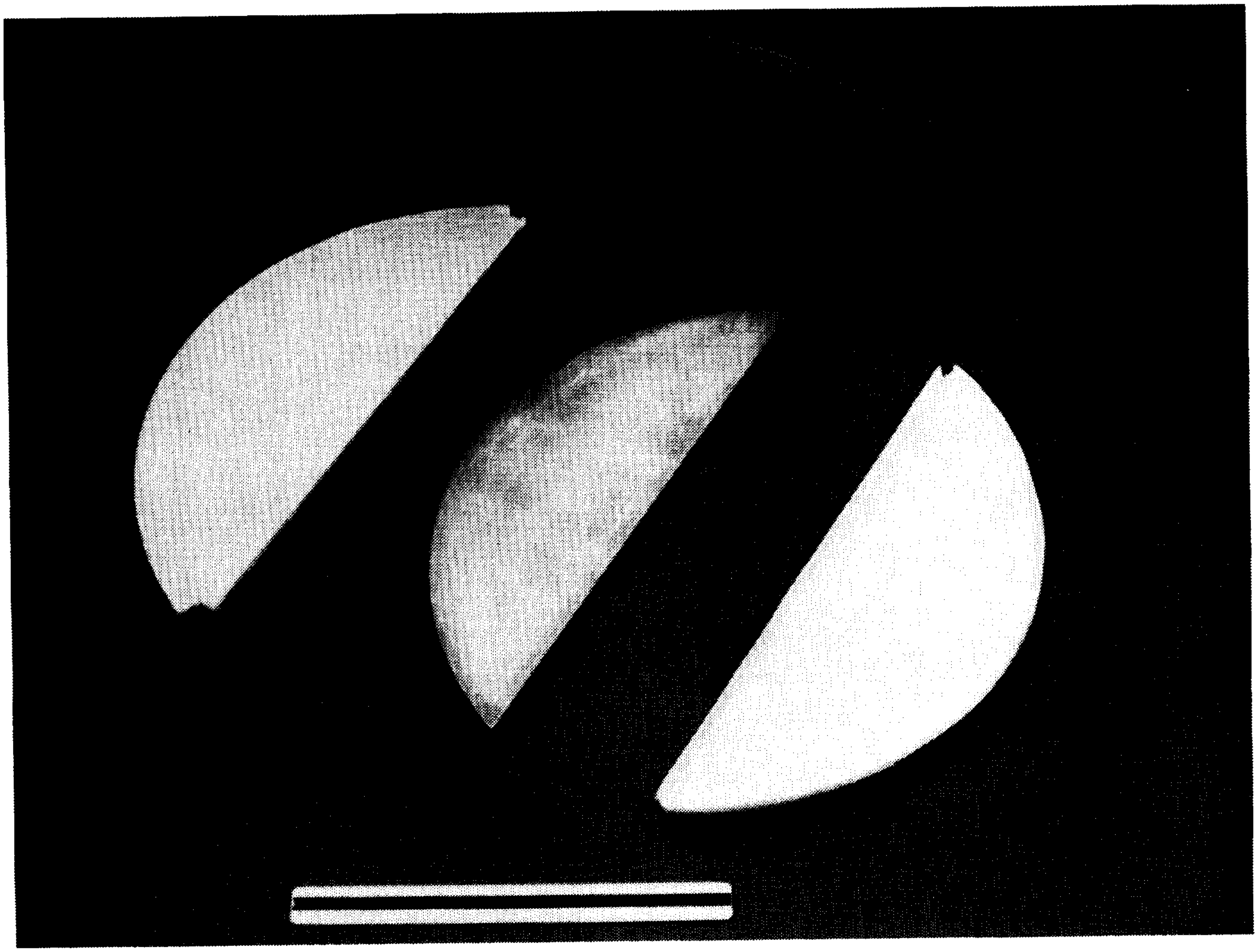

Figure 9. Forming operation for fiber preforms.

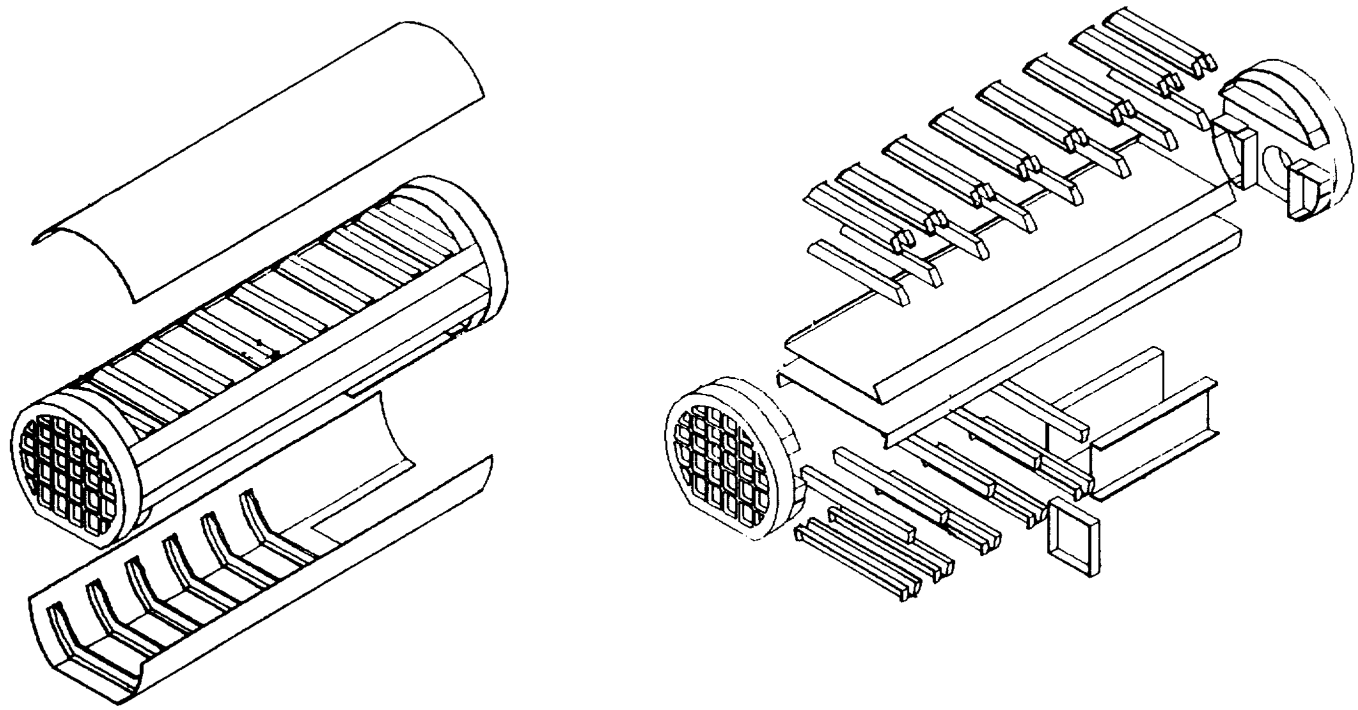

Figure 10. RTM midbody design configuration.

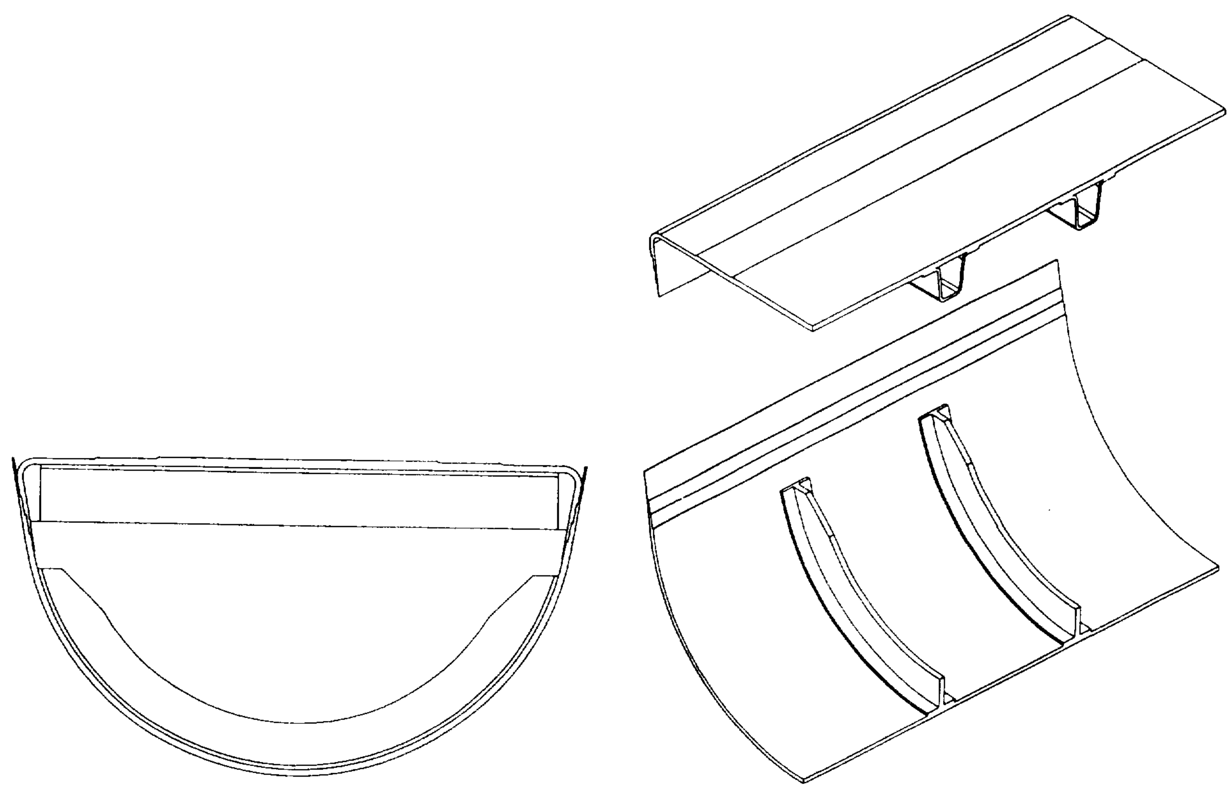

Figure 11. RTM midbody demonstration article design.

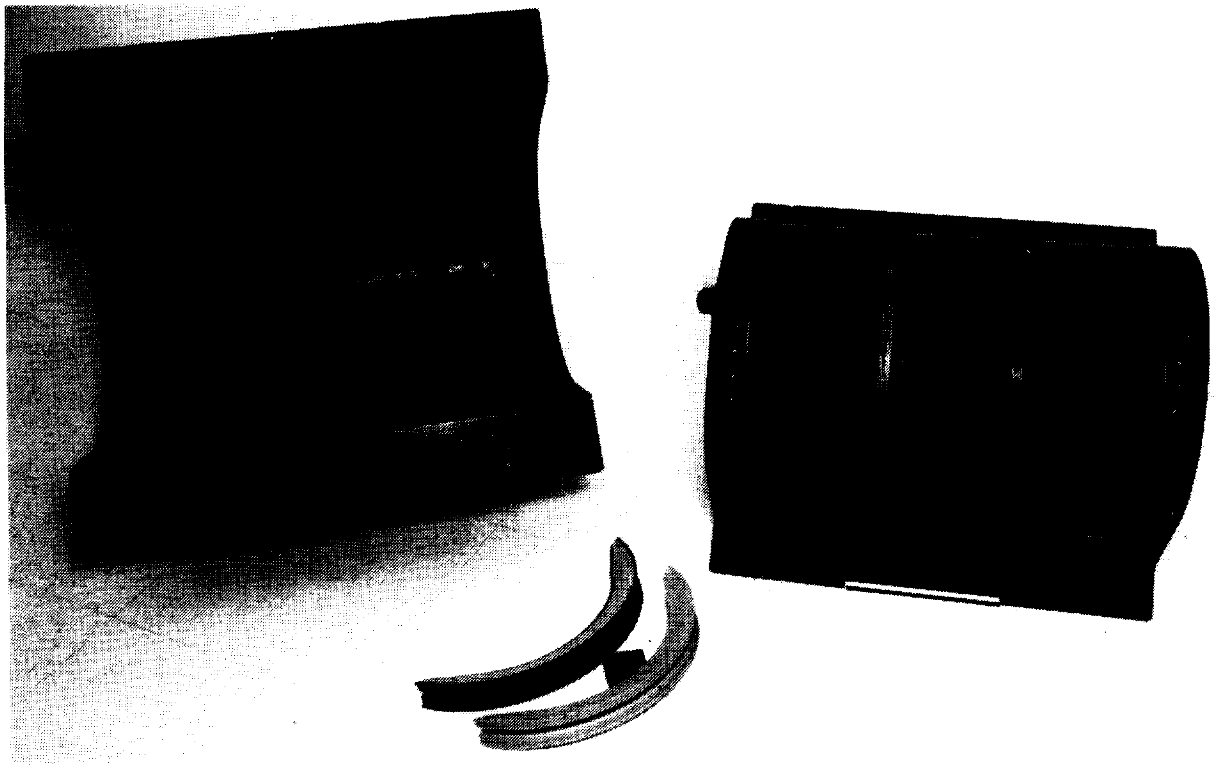

Figure 12. RTM midbody demonstration article tooling.

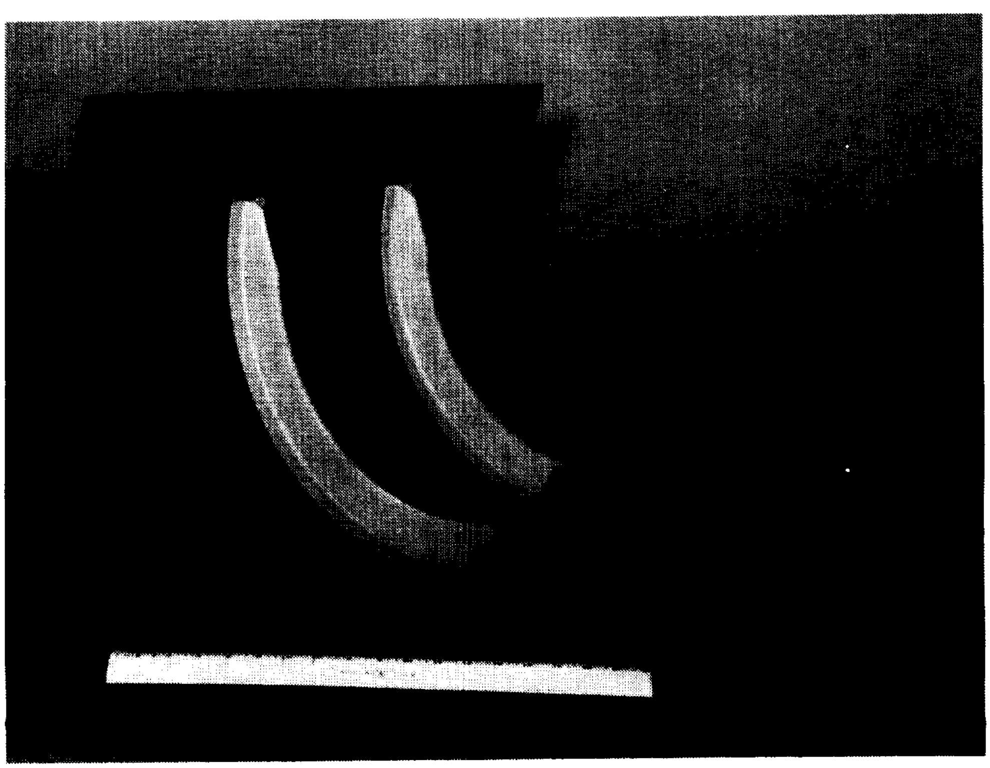

Figure 13. RTM midbody demonstration article.

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