SOFT TOOLING FOR LOW PRODUCTION MANUFACTURING OF LARGE STRUCTURES

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ABSTRACT

A new technique for building large prototypes from layered substrate relies on a higher order construction algorithm to produce accurate prototypes from thick layers. The process is capable of producing a 4' by 8' by 20' object in less than two days. Using this technique to produce molds instead of parts allows construction of large castings and composite structures. Example parts include composite airfoils, a 19 foot canoe, and a custom fairing for a racing car.

INTRODUCTION

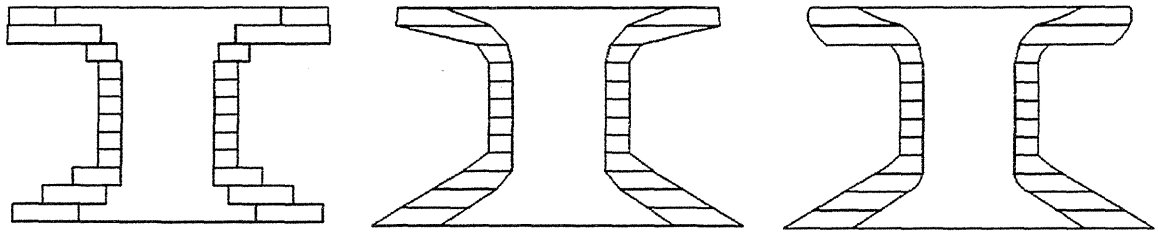
The common construction technique used by rapid prototyping (RP) devices commercially available in the current market such as Stereolithography (SLA) [9], Laminated Object Manufacturing (LOM) and Fused Deposition Modeling (FDM) [10], produce prototypes from 2D layers producing a stepped shape. Current devices move and work only vertically which is referred to here as the stepped cut algorithm (SCA). This stepped algorithm results in poor accuracy unless the layers are thin and thus is not efficient for building large prototypes.

There is a growing demand for prototypes of large objects, that can not be met by current techniques because of their size limitations. New prototyping techniques, using higher order construction algorithms (HOCA) developed at The Manufacturing Processes Laboratory at The University of Utah (MPL) address this problem. In this paper, two advanced algorithms are discussed as demonstrations of HOCA; ruled cut algorithm (RCA) and curved cut algorithm (CCA). The MPL has recently developed Shape Maker II (SM2) to implement RCA, and has been developing Shape Maker III (SM3) for CCA. These two new RP devices allow production of large prototypes up to 4' by 8' by unlimited length using HOCA. The devices cut 1/2" to 1.5" thick sheets of polystyrene foam using an electrically heated wire as a cutter.[1]

The polystyrene foam parts produced from these machines have little direct application other than as form models due to the poor mechanical properties of the foam. However, using techniques described below, the models can be converted to full strength engineering structures. The foam models can be used as expendable patterns for construction of large polymer composite structures. If the surface strength of the model is improved with a coat of fiberglass, the model can be used as a reusable pattern for low production quantities. Using a latex layer vacuum formed to the model surface, a rapidly changeable reusable mold can be produced. The text below introduces the HOCA algorithms and describes the various manufacturing applications.

CONSTRUCTION ALGORITHMS: Stepped Cut Algorithm (SCA)

SCA is the simplest algorithm used by most of existing RP devices. Since it uses a 2D profile instead of 3D for each layer, only vertical motions of a cut device are allowed. It assumes the geometry of a top cross section is same as bottom cross section of a layer. In other words, it ignores changes in shape along with building direction. Thus, SCA is inaccurate with thick layers, and acceptable in the case of very thin layers or layers not changing shape in the cut direction. These algorithms are explained pictorially in Fig. 1.



(a) (b) (c)

Figure 1: Cross section of a model with three construction algorithms: a) Stepped cut algorithm (b) Ruled cut algorithm (c) Curved cut algorithm

CONSTRUCTION ALGORITHMS: Ruled Cut Algorithm (RCA)

RCA produces layers of finite thickness that have general ruled surface edges. After getting geometry information of top and bottom cross sections of a layer, a control program must find the desired cutter path by matching the two cross section geometry's. With RCA, the cutter path is considered as a series of first order polynomial functions as follows;

$$\frac{x - x_1}{x_2 - x_1} = \frac{y - y_1}{y_2 - y_1} = \frac{z - z_1}{z_2 - z_1}$$

where $A(x_1,y_1,z_1)$ and $B(x_2,y_2,z_2)$ are points on the bottom and top cross sections of a layer.

Using RCA the cutter follows the exact geometry of the top and bottom cross section of each layer and approximates the geometry in between with a ruled surface. In comparison with SCA, RCA reduces error dramatically for parts with sloped or curved edges, and allows increased layer thickness with small errors. Increasing the layer thickness with small error means reducing manufacturing time and making large objects with an acceptable level of error. RCA has been successfully implemented as Shape Maker II (SM2), a RP device developed at the MPL.

CONSTRUCTION ALGORITHMS: Curved Cut Algorithm (CCA)

Though RCA is an advanced algorithm in comparison with SCA, performance can be further improved with CCA. CCA accommodates the all capabilities of RCA and adds more functionality for a more accurate approximation of actual object geometry. Among algorithms discussed here, CCA is the best for complex 3D shapes. To define a function representing a curved shape, the knowledge of coordinates of at least three points are required and an arc is completely specified by these three points. Two points, top and bottom points of a layer, are known since geometry information of cross sections can be obtained by slicing STL object, and it is reasonable to get a third point from an additional cross section spaced between the upper and lower surfaces of the intended slice. Three methods of manipulating these three points to get a function of a curve are discussed below.

Arc method : An arc can be defined by a center point, radius, and start and end points. Start and end points become top and bottom points of a layer to be matched. Center and radius can be found by calculating crossing point of two lines, which divide lines in half passing two of three points and are perpendicular to the lines.[1] If the three known points are $A(x_1,y_1,z_1)$, $B(x_2,y_2,z_2)$ and $C(x_3,y_3,z_3)$, the center and radius of an arc can be calculated as follows;

Step 1: shift and rotate : Shift points by $(-x_1,-y_1,-z_1)$ then rotate points about z axes in order to lie points on x-z plane. New points will be;

$$[A^1, B^1, C^1] = \begin{bmatrix} x_4 & x_5 & x_6 \\ y_4 & y_5 & y_6 \\ z_4 & z_5 & z_6 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 - x_1 & x_2 - x_1 & x_3 - x_1 \\ y_1 - y_1 & y_2 - y_1 & y_3 - y_1 \\ z_1 - z_1 & z_2 - z_1 & z_3 - z_1 \end{bmatrix}$$

where $\theta = atn \dfrac{y_2 - y_1}{x_2 - x_1}$ and $y_4 = y_5 = y_6 = 0$

Step 2: center and radius : Find center (x_c,y_c,z_c) and radius r of an arc with A^1, B^1 and C^1 on x-z plane. As described above, a center is a cross point of two lines;

$$z = -\frac{x_5 - x_4}{z_5 - z_4}\left(x - \frac{x_5 - x_4}{2}\right) + \frac{z_5 - z_4}{2}$$

$$z = -\frac{x_6 - x_5}{z_6 - z_5}\left(x - \frac{x_6 - x_5}{2}\right) + \frac{z_6 - z_5}{2}$$

Thus,

$$x_c = \left[\frac{(x_5 - x_4)^2}{2(z_5 - z_4)} - \frac{(x_6 - x_5)^2}{2(z_6 - z_5)} + \frac{z_5 - z_4}{2} - \frac{z_6 - z_5}{2}\right] \Big/ \left[\frac{x_5 - x_4}{z_5 - z_4} - \frac{x_6 - x_5}{z_6 - z_5}\right]$$

$$y_c = 0$$

$$z_c = \left[\frac{(z_6 - z_5)^2}{2(x_6 - x_5)} + \frac{(z_5 - z_4)^2}{2(x_5 - x_4)} + \frac{x_6 - x_5}{2} - \frac{x_5 - x_4}{2}\right] \Big/ \left[\frac{z_6 - z_5}{x_6 - x_5} - \frac{z_5 - z_4}{x_5 - x_4}\right]$$

$$r = \sqrt{(x_c - x_4)^2 + (z_c - z_4)^2}$$

and cutter path on x-z plane can be defined as;

$$(x^1 - x_c)^2 + (z^1 - z_c)^2 = r^2, \quad y^1 = 0$$

Step 3. Rotate about z axes (x_1,y_1,z_1) to original coordinates resulting (x,y,z) as follows;

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x^1 \\ y^1 \\ z^1 \end{bmatrix} + \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

Smooth surface method : For smooth surface of prototypes, the slopes at the top and bottom points of a layer should be equal to the slope of the same points of adjacent layers. The cutter path is defined by slopes at top and bottom points, and length of a path. Like the above method, all parameters are calculated in the x-z plane, then transform the coordinates to original system.

$$\left.\frac{dz}{dx}\right|_{layer\,i}^{top} = \left.\frac{dz}{dx}\right|_{layer\,i+1}^{bottom}, \quad \left.\frac{dz}{dx}\right|_{layer\,i}^{bottom} = \left.\frac{dz}{dx}\right|_{layer\,i-1}^{top}$$

$$length = \int L = \sum_{i=1}^{n} l_i$$

Second order method : Three points can define a second order polynomial. Three parameters in a second order function can be also found in x-z plane with known three points; top, bottom and middle points.

$$z = ax^2 + bx + c$$

NEW PROTOTYPING DEVICES: Shape Maker II (SM2)

SM2 is designed as 4 axis device as shown in Fig. 2 [1]. Two ends of a cutter, an electrically heated wire, are supported by carriers and each carrier moves in two independent directions (x,y). Thus, SM2 is able to cut ruled surface edges up to 45 degree (current machine design limit) implementing RCA. Each cutter carrier has a ball with a hole in the middle so that a cutter freely slides inside ball and adjusts its length when it tips. The current cutter design allows cutting thermoplastic foam less than 1.5 in thick. All axes are driven by stepper motors and a custom control software developed at MPL. Construction speed varies with geometry, and is roughly 6 in/hr for large objects when layer thickness is 1 in.

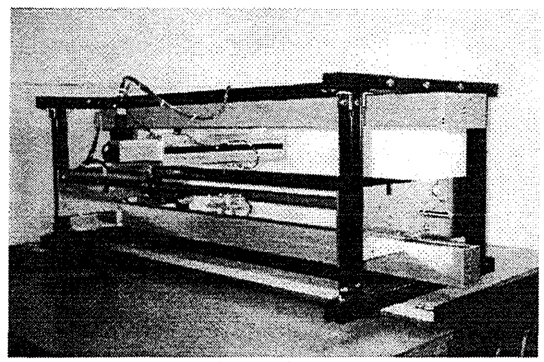


Figure 2: Shape Maker II [1]

NEW PROTOTYPING DEVICES: Shape Maker III (SM3)

SM3 is an 8 axis device which is an advanced version of SM2. It can produce curved surface parts using CCA. Four axes are used to position the top and bottom cutter carriers in x and y axes. In addition, there are tipping mechanisms to give angles to the cutter in three directions : one angle in common for the top and bottom of the cutter, and one independent angle at each end of the cutter. The last axes controls the length of the hot wire cutting surface. The control software will calculate 8 parameters $(x_1, y_1, x_2, y_2, \theta_1, \theta_2, \theta_3, \ell)$ and drive 8 motors. SM3 is currently under development.

APPLICATION TO COMPOSITE TOOLING

Mold tooling using fiber and resin is considered "soft" by comparison to steel mold tooling. Metal mold tolling is usually used for large production, while composite mold tooling is used for low production and critical applications where thermal expansion is a concern.[7] With traditional mold tooling methods, making a mold has required many steps of processing and handwork taking a couple of months in many cases. This traditional paradigm can be improved by applying RP technology to mold tooling. Furthermore, composite tooling can also take advantage of patterns/molds tooling made by a RP device. In this paper, the applications of foam patterns/molds made by Shape Maker to composite tooling of large structures are introduced.

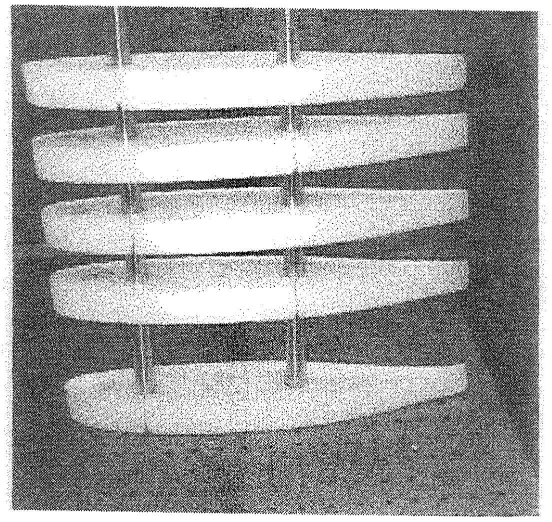
The proposed techniques have many advantages. First, foam patterns/molds for full scale large composite parts can be made economically, accurately within few days using Shape Maker (SM). Second, this technique eliminates several steps, and handwork normally needed in traditional mold tooling techniques which reduces manufacturing costs and time from months to few days.[7] Third, the computerized prototyping process is a semi-automated process, thus, increases accuracy. Finally, dealing with a 3D CAD drawing object is also a lot easier than working with the disposable 2D mylar drawings from traditional processes.

However, as thermoplastic foam is used, some limitations of foam mold tooling have been found. Since the maximum working temperature of polystyrene foam is around 140F, only low temperature cure epoxy resins are acceptable. Moreover, compressive yield strength is in the range of 23 to 44 psi. Thus, high pressure autoclave processing is not appropriate. Finally, the choice of resin is limited to phenolics or epoxies to avoid dissolving the foam.[5]

When applying foam patterns/molds made by SM to composite laminates, two methods are applicable. First, lay-up a final composite structure directly on the foam pattern or mold made by SM, and vacuum bag and cure at room temperature. Second, lay-up an intermediate composite mold tool on the foam pattern, so that the foam pattern becomes reusable, and lay-up final composite structure on the intermediate mold tool and cure at high temperature in an autoclave.[5] Examples of both cases are demonstrated and described below.

DEMONSTRATION: Foam Patterns

Tail Stabilizer Wing: This is the demonstration of a composite structure made by lay-up directly on a foam pattern. In this case, the foam pattern becomes a permanent part of the composite and, thus, can make only one final composite structure. A tail stabilizer wing for a military jet was created using a solid modeling CAD software. The chord length and chord height of the base cross section are 19.5 in. and 2.5 in. respectively, and those of top cross section are 10 in. and 1.25 in. The wing tapers along the length of 58 in. 58 layers of 1 in thick extruded polystyrene foam were cut using SM2, and assembled on a registration board as shown in Fig. 3. The accuracy of the foam pattern was improved by applying a thin plaster coat on the foam pattern and sanding. This process required 13 hours with a material cost of $45. The final composite part was made by applying three layers of plain weave 7 oz. E-glass fiber with a room temperature cure epoxy resin on the foam pattern. The finished composite wing was allowed to cure for 5 days. The initial foam pattern and final composite wing are shown in Fig. 4.[5]



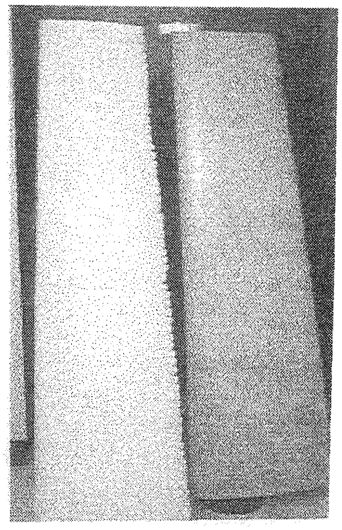


Figure 3 : Registration process of layers Figure 4 : Foam and composite pattern of tail stabilizer wing.[5]

Custom Fairing for a Racing Car: When desirable, the foam pattern can be used to create low production tooling instead of making only one part. For producing multiple composite parts, two step processes are involved. First, the foam pattern of a Formula I race car fairing was fabricated using SM2 requiring about 6 hours and $18 for materials. The foam model was transformed into a more rugged intermediate positive pattern by applying a resin and fiber glass weave on the foam pattern. Surface imperfections were minimized by a coating of epoxy putty and sanding. The final composite car fairing was produced by coating the intermediate pattern with a room temperature cure epoxy and fiber glass weave.[5] The intermediate pattern is reusable as many times as its surface lasts. An intermediate and finished composite car fairing are shown in Fig. 5.

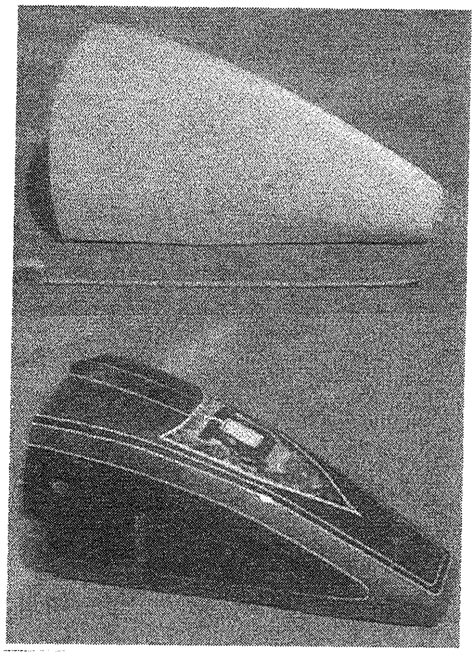


Figure 5: Intermediate Mold Tool and Finished Composite Fairing.[5]

DEMONSTRATION: Foam Molds

Fiber Reinforced Concrete Canoe: A foam prototype is used here as a large negative mold tooling. A disposable foam mold of a full scale 19 ft fiber reinforced concrete canoe was fabricated requiring $350 for materials, 25 hours labor, and consuming 54 sheets of 4' by 8' by 1" expanded polystyrene foam to cut 240 layers as shown in Fig. 6. The mold was coated with a thin layer of plaster, and the composite canoe was laid up by applying alternating layers of Type III Portland Cement and a mat of fiberglass Stucco Mesh until reaching the designed wall thickness of 0.375 in. The concrete was allowed to cure for about one week before removing from the foam mold. The final concrete canoe is shown in Fig. 6.[5]

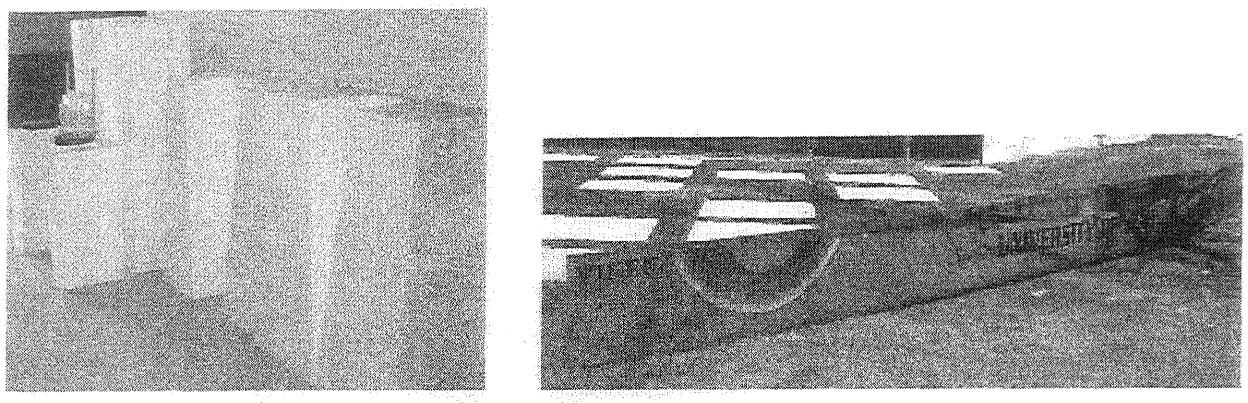
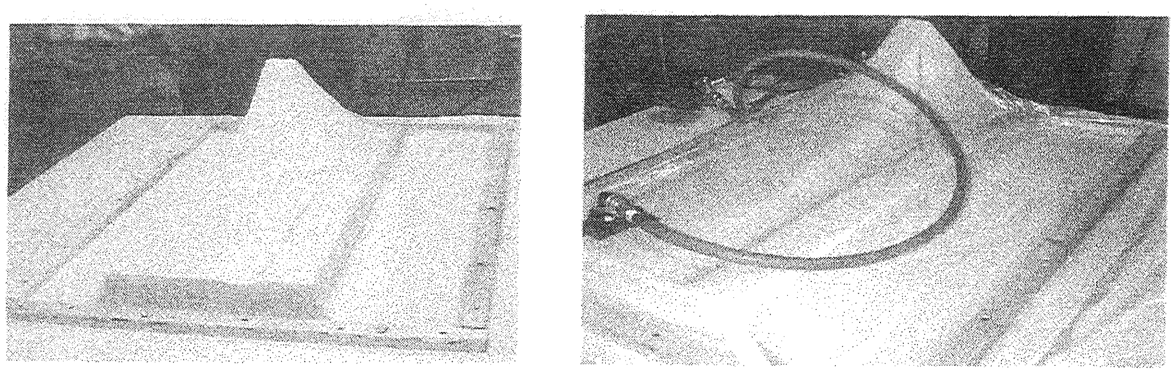


Figure 6: Canoe Foam Mold and finished canoe.

Wind Turbine Blade Airfoil: When curing fiber/resin systems, a certain amount of pressure is required. Without pressure, fiber/resin ratio varies throughout the structure and obvious flaws exist within the laminates. Since the compressive yield strength of polystyrene foam is in the range between 23 to 44 psi, vacuum bagging, which can provide pressure less than 22 psi, is the primary source for consolidating the lamina and drawing out excess resin to achieve the best fiber to resin volume ratio.

An example of this process is shown for multiple composite parts using a vacuum bagged negative foam mold of a 1/5 scale of NASA LS(1)-417MOD wind turbine blade. The blade was made by SM2 assembling 36, 1 in thick layers requiring 3 hours and $40 for materials. The foam mold was coated with plaster and sanded for a smooth surface. Then, a 0.01 in thick layer of latex rubber was vacuum formed onto the foam mold as shown in Fig. 7 (a) which provides a release ply and minimizes small surface defects on the foam mold. The application of 5 layers of



(a) (b)

Figure 7: Vacuum Bagging Process for Wind Turbine Airfoil: (a) Latex Rubber Vacuum Formed on the Foam Mold (b) Vacuum Bagged Wind Turbine Skin Panel.[5]

7 oz. plain weave E-glass fiber and room temperature epoxy resin was used to form the composite mold tooling. Next, the entire assembly was vacuum bagged as shown in figure 7 (b). The composite was allowed to cure to a self-supporting state for three hours, and cure 5 days at room temperature. The final composite structure is shown in Fig. 8.[5]

CONCLUSION

This paper presents various new techniques for full scale composite tooling of large structures using foam patterns/molds made by Shape Maker. Foam patterns/molds can be made rapidly, economically, and accurately by SM2, producing final composite parts through the proposed methods which reduce manufacturing time and cost. Though limitations on temperature, pressure and choice of resin are found, the experiments show that most composite mold tools can be fabricated in a short time at lower cost than traditional processes. In all, the application of foam parts made by SM to composite tooling techniques is successful in manufacturing large composite structures.

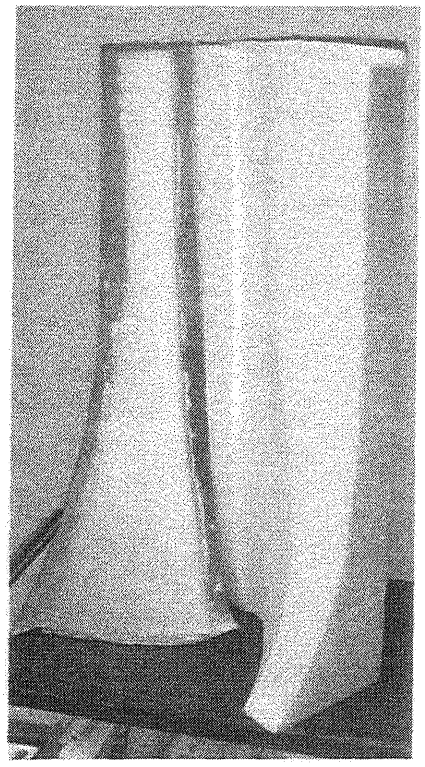


Figure 8: Finished mold tool for turbine skin panel.[5]

REFERENCES

[1] Lee, C. H., Gaffney, T. M., Thomas, C. L., *Proc. of the 6th ICRP*, SME, 131, (1995).

[2] Thomas, C. L., *An Introduction to Rapid Prototyping*, Schroff Development Corp., Mission, Kansas, (1995).

[3] Sollner, G., Molitor, M., *Composite Application: The Future is Now*, Ed. Thomas Drozda, SME, Dearborn, Michigan, pp. 194-201, (1989).

[4] Sauer, G. L., *Composite Application: The Future is Now*, Ed. Thomas Drozda, SME, Dearborn, Michigan, pp. 165-174, (1989).

[5] Gaffney, T.M., Rapid Prototyping Composite Mold Tooling and Patterns, Thesis, U. of Utah, under prep.

[6] Kruth, J. P., Annals of the CIRP, **40** (2),603, (1991).

[7] Thomas, C. L., Gaffney, T. M., Kaza, S., Lee, C. H., Proc. of the 1996 IEEE Aerospace Appl. Conf., IEEE, **4**, 219, (1996).

[8] Suh, K. W., *Handbook of Polymeric Foams and Foam Technology*, Ed. Daniel Klemper and Kurt Frisch, Oxford University Press, New York, 151, (1991).

[9] Jacobs, P. F., *Rapid Prototyping & Manufacturing: Fundamentals of StereoLithography*, 5th ed., SME, Dearborn, MI, (1992).

[10] Crump, S. S., *Proc. of the 2nd ICRP*, SME, 351, (1991).

[11] Kochan, D., *Solid Freeform Manufacturing*, Elsevier Science, New York, (1993).

[12] Wohlers, T. T., Manufacturing Engineering, **107**, 77, (1991).