OUTLINE OF A METHOD FOR THE AUTOMATED MANUFACTURE OF LAMINAR WINGS

Day Chahroudi
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Summary

A method is outlined to reduce the manufacturing costs of wings to a fraction of present costs. With the rapid rise in energy costs over the past decade, there has been a renewal of interest in maintaining laminar flow over the surfaces of aircraft. Since profiling laminar flow wings consumes most of the labor in their production, a method has been designed to produce laminar flow wings which may be accurate enough not to require profiling. This method uses very little human labour and would have a cycle time of less than an hour with jigging that would be relatively inexpensive, provided production runs are large enough. This method is suitable to a variety of materials which have been designed specifically for this process; it is suitable for any wing loading or planform, but requires that all curvature be simple and not compound. The structural topologies used are conventional, with either single skin or sandwich elements and either ribbed or ribless construction, but the materials and assembly methods are not conventional. The materials include: pre-cured FRP sheets and ribbons, foam plastic or honeycomb, curing adhesives that are hot-melt or pressure-sensitive, and easy to clean plastic film finishes. The assembly equipment includes hot-melt adhesive dispensers, a specially designed light oven, and vacuum molds for the top and bottom wing halves which hinge together in the usual way.

Introduction

When the sailplane building industry changed from aluminium to fibre reinforced polymer (FRP) materials, there was widespread hope that the theoretical performance of laminar flow wings could be achieved in practice for the first time. This hope has been realized. There was also another expectation at that time, in the 1960's, an expectation that the use of FRP materials would result in rapid, low labour and extremely low cost mass production. This expectation was based on the plastic industry's reputation for low materials costs and rapid cycle time on automated machinery. But to date, this second hope has been disappointed for several reasons. First, there is no precedent for mass production in the aircraft industry. No matter how many of a particular model are built and no matter how many jigs are used, almost all assembly operations are by hand. Second, there is no familiarity in the aircraft industry with the extremely diverse vocabulary of processes accessible through FRP and polymeric materials. Third, certification procedures for aircraft made of novel materials are too expensive for the small ventures which have an economic incentive to innovate.

The result of these blocks to the application of FRP technology to the automated manufacture of aircraft has been that FRP is now used in aircraft in ways which usually result in cost increases rather than reductions. For example, the modern glider has more than its sleek lines in common with a thoroughbred racehorse. Where parts of aircraft or even whole helicopter fuselages are made from FRP in the aerospace industry, prodction methods either use a great deal of hand labour or else use very expensive machines which perform hand-labour processes. The reason why this suboptimal use of FRP technology is so expensive is that the machines are using materials and processes designed and developed for hand labor.

Thus, designing and inexpensive automated production process and then designing materials to fit should result in much cheaper aeroplanes. The production processes for wings outlined in this paper are a direct result of this approach. The author is currently designing processes and materials for the automated production of fuselages, where some structural efficiency is sacrificed for the ability to make compound curves.

The example presented in this paper is sailplane wings, but the important applications for this technology are to commercial aircraft, where production costs and fuel consumption are the primary concerns. This example can be translated to commercial aircraft simply by changing dimensions and, for wet wings, specifying exising fuel-proof materials throughout. With the rapid rise in energy costs over the past decade, there has been a renewal of interest in maintaining laminar flow over the surfaces of aircraft. In this context, sailplanes can serve as a model, or at least a starting point, for the design of fuel-efficient aircraft, in both structural efficiency and laminar flow. Unfortunately, both of these properties are coupled to the use of fibre reinforced polymers, which are extremely labour intensive. Thus the question is formulated: How is it possible to maintain the accuracy of surface contours necessary for laminar flow and the structural efficiency while eliminating the labour intensive hand layup method currently used to make sailplanes?

From the outset, three properties of any solution to this problem are evident: first, that the materials should be designed to conform to the manufacturing process, and not the reverse, as is usually the case. Second, due to the extreme accuracy requirements placed by laminar flow, any process which involves volume changes such as curing or heating large parts can be eliminated. Third, since automation always involves machinery and jigging which is more expensive, the cycle time of the process should be short and production runs long.

The solution presented here is not a general solution. It can produce only those shapes with simple or one-dimensional curvature. Thus this paper deals only with the manufacture of wings, although application of this method of tail surfaces and some portions of fuselages are obvious. Although only glider wings are discussed here, this method is equally applicable to wings of an loading, size or planform. The wing components illustrated in this discussion are of ribbed sandwich construction because that is the most complex. Substituting single skin components or ribless construction does not change the manufacturing process except by eliminating some of the steps. Although sheets of pre-cured fib reinforced polymer (CFRP) and plastic foam are the skin and core materials discussed here, others, such as aluminium sheet and honeycombs, are just as suitable to this method. The manufacture of flat CFRP sheets and plastic film finishes and coating them with a curing pressure-sensitive adhesive (CPSA) and release paper are existing industrial processes that use similar materials for the building and electronics industries. Thus it is assumed that the CFRP/CPSA sheets and plastic film finishes will be supplied to the aeroplane factory made to specification and ready for use.

Manufacturers interested in exploring this method are invited to contact the author.

Materials

Since the curing of skins produces volume changes, pre-cured skins are used. They can be either sheets of CFRP or aluminium. CFRP sheets are produced in a heated press from a prepreg. Any fibre in any weave with almost any thermosetting polymer matrix can be used. The most suitable materials for aircraft are glass, aramid, or carbon fibers in an epoxy matrix. A matrix with a higher glase transition temperature than epoxy would be desirable, so that structures would be less prone to creep after years in the sun, but an imide matrix may be too expensive, and a phenolic too slow to cure. The unidirectional prepreg is placed in the curing press in several layers with orientations to suit the final use of the CFRP sheet. For wing skins, fibres running in three equally spaced and weighted directions are probably best, while for sparcaps a single direction is best. Due to the pressure, temperature and process control, this method produces CFRP with significantly better properties when compared to hand layup methods.

The sheets of CFRP are next coated on one side with a CPSA which is then covered with release paper until ready for use. This adhesive has the property of curing soon after it is activated with a curing agent. Just before use, after the release paper is removed, the CPSA is wiped with a solvent bearing the curing agent. Then, in a period of minutes to days, determined by the type of curing agent, the adhesive turns from a tacky rubber which creeps and adheres well to a tack-free rubbery plastic which does not creep.

The core material used for sandwich wing skins, ribs, and webs can be plastic foam or a honeycomb, depending on the end use of the wing. However, the adhesive method used to fasten the core to its skins which is presented here is suitable for foam cores only, and another method of applying adhesive would be necessary for honeycomb cores. Since creep is a much more critical problem with foam cores than with their fiber reinforced skins, a foam polymer with a high glass transition temperature, or possibly a fibre-reinforced foam, is essential. To avoid a heavy adhesive layer between the foam and its skins, the foam must be small celled. The same adhesive and release paper which was applied to one side of the CFRP sheets is applied to both sides of the foam core material.

The leading edge is the region where the profile must be maintained with the greatest accuracy. It must also be strong and hard enough to resist impact. An injection-moulded high-density foam leading edge in, say 3 foot sections, would satisfy these requirements, but the cost of the moulds is objectionable. Hand profiling the leading edge from high-density foam is an intermediate cost option for small production runs. Pressure moulding of foam bar stock is intermediate in setup costs between hand profiling and injection moulding.

The wing frame consists of the leading edge, the ribs, the spar web and the trailing-edge web, as shown in figure 1. These

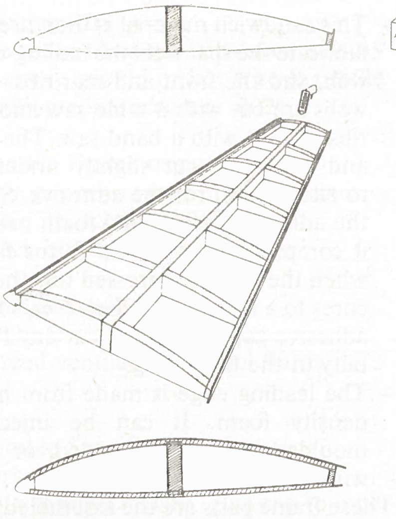

Fig. 1. Frame and completed wing.

are assembled using a hand-held hot-melt adhesive gun which extrudes a ribbon of melted adhesive of about the same width as the thickness of the material being adhered. The adhesive cures after application owing to the heat of the extrusion process. The jig used to assemble the frame is merely a table with registration pins for each part. To reduce weight, the hot-melt adhesive is a high-density foam. The same adhesive and dispenser may be used for applying the adhesive which joins the frame to the wing skins, or this adhesive may be applied as a tape.

The wing is finished by covering it with a thin white plastic film which is coated on one side with CPSA and release paper. Teflon would be a good film material because it is extremely weather resistent and easy to clean. However, it is not wetted by water, so laminar flow would be destroyed by rain. For this reason, a matt-finish acrylic film may be better.

Special Equipment

There are two pieces of special equipment that this manufacturing process is designed around. The first is a vacuum mould, shown in figures 2 and 3. It is used first to assemble the sandwich skins, when they are used, and then to join the frame to the wing skins. The second piece of special equipment is a light oven, shown in figure 4, which is used to melt the adhesive which joins the frame to the wing skins.

The vacuum mould is the heart of this process, and would be the major capital investment in setting this process up. It requires an accuracy of ± 0.002 inches (0.005 mm) over its entire surface, and has a grid of small holes through which a vacuum is applied to maintain the contour of the wing skins during assembly. To ease construction and repair of the mould, it is made of small modules which are fabricated and replaced independently. These modules each have their own registration pins to keep the upper and lower halves of the mould in alignment.

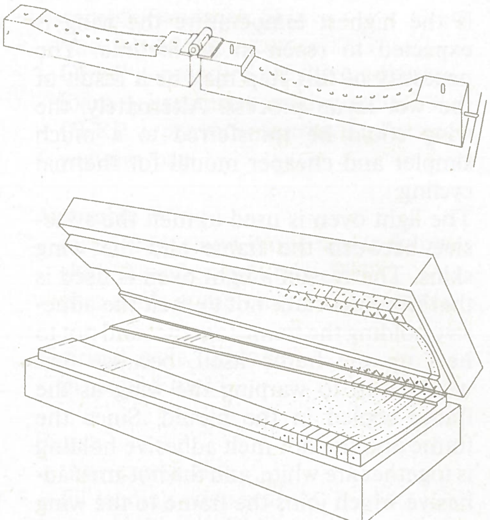

Fig. 2. Vacuum mold.

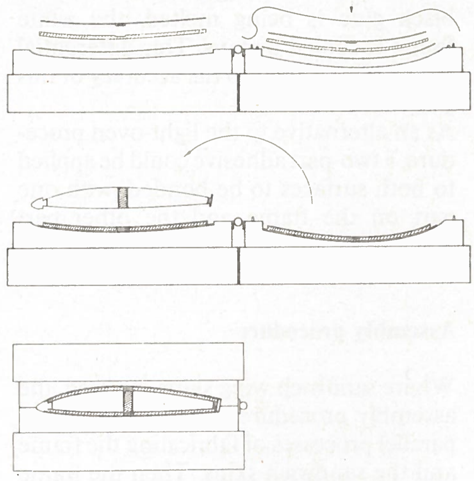

Fig. 3. Assembly procedure.

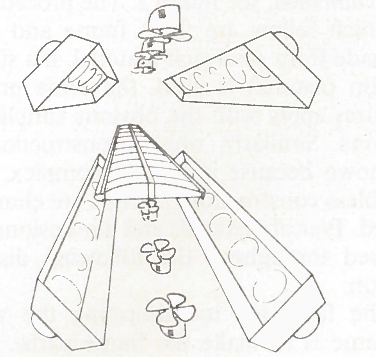

Fig. 4. Light oven.

The modules are fastened to rigid sandwich panels which give the mould its rigidity. They could be fastened with epoxy putty, which is used in optics for precise alignment. The mould halves for the upper and lower wing skins are hinged to assemble the complete wing, following the usual procedure for assembling sailplane wings.

It may be necessary to thermal-cycle the wing in the mould after it is assembled. This step would greatly increase the cycle time in the mould and thus make the process more expensive, so it is hoped it can be avoided. In conventional sailplane wing fabrication, the mould, with the completed wing in it, is placed for 12 hours in an oven whose temperature is the highest temperature the wing is expected to reach in its lifetime. The necessity of this step may be a result of the wet layup process. Alternately, the wing could be transferred to a much simpler and cheaper mould for thermal cycling.

The light oven is used to melt the adhesive between the frame and the wing skins. The reason a light oven is used is that it is important not to melt the adhesive holding the frame together and not to heat up the frame itself, because that would lead to warping the wing as the frame cooled in the mould. Since the frame and the hot-melt adhesive holding is together are white, and the hot-melt adhesive which joins the frame to the wing skin halves it black, only the black adhesive is heated in the light oven. While the black glue is being melted, the white frame is cooled by fans. This differential heating is essential to the accuracy of this process.

As an alternative to the light-oven procedure, a two-part adhesive could be applied to both surfaces to be bonded, with one part on the frame and the other part on the skins.

Assembly procedure

Where sandwich wing skins are used, the assembly procedure consists first of the parallel processes of fabricating the frame and the sandwich skins. Then the frame and skins are joined when the two halves of the mould are hinged together like a clamshell, see figure 3. The procedures which follow are for a frame and skin made from sandwich material. If a single skin material is used, the same procedures apply with the obvious simplifications. Similarly, ribbed construction is shown because it is more complex. For ribless construction, the ribs are eliminated. Typical materials and dimensions are used throughout the following discussion.

The first step in fabricating the wing frame is to make the frame parts. This consists of:

- assembling the sandwiches for frames and webs by: laying a sheet of CFRP/CPSA with the adhesive side up on a flat table. The release paper is removed and the adhesive is wiped with a solution of curing agent. Then an equal size sheet of foam with the release paper removed from one side is painted with a solution of curing agent and then placed on the CFRP/CPSA. The second sheet of release paper is removed from the foam, release paper is removed from a second sheet of CFRP/CPSA, a curing agent applied to both adhesive surfaces, and the second sheet of CFRP/CPSA is placed on top of the foam. The assembly is then vacuum bagged for 10 minutes and possibly left to cure for 24 hours.
- This sandwich material is then used to fabricate the spar web, the trailing-edge web, and the front and rear ribs. The webs are cut with a table saw and the ribs are cut with a band saw. The ribs and webs are cut slightly undersize to allow room for the adhesive. Since the adhesive is a melted foam rubber, it compresses, flows and forms fillets when the parts are pressed together. It cures to a rigid plastic, however, so the adhesive gap does not incur any flexibilty in the final wing.
- The leading edge is made from high-density foam. It can be injection moulded, pressure moulded, or hot-wired and profiled.

These frame parts are the assembled, see figure 1.

- A table jig with registration pins is used. A hand-held dispenser extrudes a ribbon of melted foam adhesive which is white, so that it is not melted in the light oven. Since the adhesive is rigid as soon as it cools, the frame can be removed from the jig soon after it is assembled.
- Black hot-melt adhesive is applied where the frame joins the upper and lower wing skins. This adhesive is either applied using the same glue gun as for the white adhesive or is applied as an adhesive tape.

The completed frame is next placed in a light oven, see figure 4, for a few minutes to melt the black hot-melt adhesive. It is then ready for insertion into the wing skins in the vacuum mould.

We now take up the second track, which runs parallel to frame fabrication. This is fabricating the upper and lower sandwich skins in the vacuum mould halves. This is done as follows:

- Two sheets of foam are cut to size and a groove cut in one side to accommodate the spar cap.
- The four CFRP/CPSA sheets which form the sandwich skins to the upper and lower wing skins are cut to size. The skins which face the inside of the wing are laid on a flat table with the adhesive side up. A strip of release paper is removed where the spar cap will be.
- The spar cap is formed by adhering ribbons of unidirectional CFRP/CPSA from the wing root, toward the tip, with each ribbon shorter than the last, to build up a spar cap with tapered thickness.
- The two CFRP/CPSA sheets which form the wing's outer surfaces are then put in the vacuum mould, aligned, the vacuum applied, release paper removed, and curing agent applied.
- The release paper is removed from the side of the foam cores which does not have a groove for the spar cap, the curing agent for the CPSA is applied, and the foam is aligned and pressed into the vacuum mould.
- The remaining release paper is removed from the foam cores in the mould halves and the release paper is removed from the CFRP/CPSA sheets with the spar caps. The curing agent for the CPSA is applied to both surfaces, and then these sheets are placed in the moulds and adhered to the foam cores.
- The above sandwiches are then covered with a plastic film vacuum bag and a vaccum applied for 10 minutes to consolidate the sandwich.

The skins in the vacuum mould are now ready to receive the frame from the light over with its melted adhesive.

- The frame is quickly removed from the light oven and placed on one of the wing skin halves in the vacuum mould. It is aligned with pins.
- Then the other half of the mould is hinged closed over the frame and the mould is clamped shut for about 15 minutes while the black hot-melt adhesive cools.

If necessary, the wing can then be transfered to a cheaper thermal-cycling mould which holds it in place during a day or so of elevated temperatures. Such a step would also insure that all adhesives were well cured before they could creep.

The wing is now ready for finishing, which involves:

- Trimming away any glue that squeezed out of the leading edge seams and filling in any cracks in those seams.
- Covering the wing with a finish film supplied with a CPSA and release paper.

The above processes are summarized, with typical materials, dimensions and tolerances for a sailplane, in the following chart:

Summary of the automated manufacture of laminar wings

Typical materials

Skins, Ribs & Webs
sandwich for sailplane: cured FRP sheet – glass, aramid or carbon/epoxy, multi-directional, .03″ to .01″ thick + small cell foam – Rohacell, specific gravity .03, .3″ thick

Sandwich Skin Adhesive
curing pressure sensitive adhesive-neoprene, .003″ thick

Spar Cap
adhesive tape – carbon/epoxy, unidirectional, .75″ x .015″ thick + curing pressure sensitive adhesive, neoprene, .001″ thick

Leading Edge
foam-Rohacell, specific gravity .3

Frame Adhesives
curing hot melt foam tape – neoprene/epoxy, specific gravity .3, .5″ x .1″ thick. White for frame assembly & black for frame to skin.

Cover Film
matt acrylic – white, .002″ thick + curing pressure sensitive adhesive-neoprene, .001″ thick

Special equipment
- Vacuum Mold, for assembly of sandwich skins and whole wing
- Light Oven, to melt black hot-melt adhesive
- Hot Melt foam adhesive gun

Assembly procedure
Make Frame Parts
- flat table & vacuum bag: assemble sandwiches for ribs & webs
- table saw: spar & trailing edge webs accuracy .05″
- die cut or band saw: ribs, accuracy, .05″
- pressure mould or hot wire & profile: leading edge, accuracy .002″

Assemble Frame using
- glue gun with white hot-melt adhesive
- table jig, accuracy .05″
- black hot melt adhesive tape

Melt Black Adhesive
- Light Oven for 10 minutes
- forced ventilation to cool frame

Assemble Spar Caps
- carbon adhesive tape
- with sandwich skins, glue cap to inner CFRP sheet

Assemble Sandwich Skins
- Vacuum Mold, accuracy .003″
- CFRP + pressure sensitive adhesive
- foam + pressure sensitive adhesive
- CFRP + pressure sensitive adhesive
- vacuum bag

Assemble Wing
- insert frame and hinge upper & lower skins together, accuracy .004″
- glue cools completely in 10 minutes

Thermal cycle (optional)
- in heated mold

Finish
- trim excess glue
- fill leading edge seams
- cover with acrylic