A BREAKTHROUGH IN THE ASSEMBLY OF AIRCRAFT COMPOSITE STRUCTURES

Rowan Paton*, Meng Hou**, Andrew Beehag**, Paul Falzon*
* Cooperative Research Centre for Advanced Composite Structures Ltd,
506 Lorimer Street, Fishermans Bend, Vic 3207, AUSTRALIA,
** Cooperative Research Centre for Advanced Composite Structures Ltd,
361 Milperra Road, Bankstown, NSW 2200, AUSTRALIA

Keywords: *assembly, composite structures, welding, TCW*

Abstract

Thermoset Composite Welding (TCW) is a new technology, developed by the Cooperative Research Centre for Advanced Composite Structures Ltd (CRC-ACS), for joining advanced composite components in aircraft. Carbon-epoxy laminates are laid up and cured with a special thermoplastic surface. Laminates are then welded together through these thermoplastic surfaces. Weld cycle times are approximately thirty minutes. Joint strength is excellent and the process is robust and very competitive.

1 Introduction

Joining technology for advanced composite components in aircraft has not advanced as rapidly as other aspects of advanced composites technology. Most carbon-epoxy aircraft components are still assembled using mechanical fasteners. While there has been considerable implementation of automated fastening machines, mechanical fastening is still comparatively slow, and requires expensive fasteners which add unnecessary weight. Since bearing strength in composites does not match that of metals, mechanical fasteners can be inefficient in transferring load between composite structures.

Adhesive bonding, which appears to be a natural way to join such structures, is not as widespread as might be expected. The adhesives themselves perform well, but an autoclave or oven curing step is usually required, usually with extensive tooling to support and locate the parts during bonding. Careful surface preparation is vital, and deficiencies in surface preparation procedures can lead to joints which appear to be satisfactory, and which satisfy current Non-Destructive Inspection (NDI) tests, but which fail at low loads because of surface contamination. Until the actual strength of the chemical bond at the adhesive interface can be reliably measured, certification authorities in particular will be cautious in accepting adhesive bonding.

The lack of progress in assembly technology has forced aircraft manufacturers to adopt techniques for the manufacture of heavily integrated co-cured structures. This strategy can reduce manufacturing costs significantly when all goes well, but involves complex tooling and difficult NDI procedures. Project risk is substantially increased.

Alternative, efficient joining procedures for advanced composite aircraft components are thus urgently needed. In response to this, CRC-ACS has developed an innovative welding process for advanced composite components, called Thermoset Composite Welding (TCW).

2 Process Description

Thermoset Composite Welding is a true welding process – it is *not* an adhesive bonding process with a name chosen by the marketing department. In order for TCW to be used, the composite laminates must be manufactured with a special thermoplastic polymer layer integrated onto the surface during cure (the co-curing stage). Components with such thermoplastic surfaces can then be welded together under moderate heat and pressure (the welding stage)

These two parts of the process are described separately in the following sections.

2.1 Manufacture of the Laminates

In most respects, the manufacture of carbon-epoxy laminates with a suitable thermoplastic surface is quite straightforward, and requires no procedures which would be unfamiliar to the prepreg layup technician. The prepreg plies are laid up as normal. The thermoplastic layer, normally a film around 0.1 to 0.2 mm thick, is laid up as an additional "ply" on one or both surfaces of a prepreg layup as shown in Figure 1 and "cocured" with the laminate. Generally the thermoplastic is laid up only at future assembly interface areas of the laminate surface. Multiple layers of thermoplastic can be laid up where higher surface layer thicknesses are required, as the film will weld to itself during curing. The film can be laid up on the bag side or tool-side of the laminate as required—bag-side surfaces are quite suitable for welding.

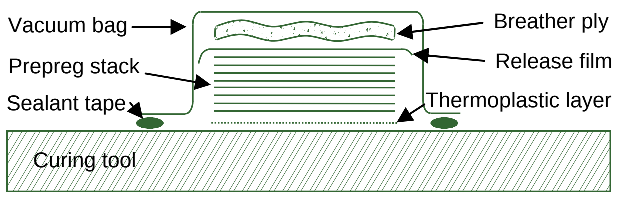

Fig. 1. Layup Including Thermoplastic Film

Normal bagging procedures are used in most cases. Many different standard release films and release agents have been used without problems in preparation of the laminates for TCW. However some tool release agents appear to transfer to the thermoplastic film surface, inhibiting the development of full strength in subsequent welds. In other respects, typical vacuum bagging materials such as breather, bagging and vacuum tape systems are used.

In work to date, the laminate has been cured using the prepreg manufacturer's recommended cure cycle. During heat up and curing, the thermoplastic and the epoxy resin become mutually soluble and some diffusion takes place across the interface. As the resin cures, a Semi-Interpenetrating Polymer Network (SIPN) is formed between the thermoplastic and the cured epoxy matrix, providing mechanical interlock between the epoxy and thermoplastic polymer chains. The thermoplastic surface is thus extremely well "bonded" to the carbon-epoxy laminate.

After curing, the laminates appear little different to standard laminates, and can be debagged, trimmed and put through standard ultrasonic NDT procedures. If the laminate is thin, and the thermoplastic layer is thick, the laminate is significantly asymmetric and thus may be warped to some extent.

2.2 The Epoxy-Thermoplastic Interface

The formation of the SIPN depends on diffusion across the interface during cure. It is necessary for the prepreg to be compatible with the thermoplastic film at the curing temperature for this to occur. Most 177°C-cure epoxy prepreg resin systems appear to be compatible, although joint strength can vary for different prepregs. Initial screening has been done with a number of prepreg and film infusion resins. Much of the development work on TCW has been done using one particular 177°C-cure plain-weave prepreg system, hereafter called the benchmark prepreg system, and joints between these laminates are very successful and well understood.

Diffusion, and thus SIPN formation, may also be sensitive to the initial level of cure of the composite resin, the heat-up rate and the cure temperature. Cocured laminates made with the benchmark prepreg system have been found to have strong interfaces when cured under the full range of processing conditions suggested by the manufacturer.

The compatibility of the thermoplastic with any epoxy resin system can be determined using physical tests (measuring the SIPN depth) or mechanical tests (lap shear strength). Procedures for assessing compatibility have been developed within CRC-ACS.

2.3 Welding

TCW can be done using a variety of heating methods. It can be conducted in an oven or autoclave, in a process very similar to the film adhesive bonding of aircraft structures. The direct weldline heating methods used for joining thermoplastic composites (such as resistance or induction heating) can also be used in TCW, and have been investigated briefly by CRC-ACS. However in many cases the most efficient heating method for TCW appears to be local contact heating through one of the laminates, combined with local pressure application. This process of applying local heat and pressure is referred to as Local Through-Thickness Heating (LTTH).

The welding process is rapid and robust, but in many ways is similar to film adhesive bonding. A key difference is that extensive surface preparation is not required, due to the difference between a welded and a bonded joint. For structural bonding using epoxy film adhesives, extensive cleaning and surface abrasion of the adherends can be required. This is necessary to provide sufficient sites for chemical bonding at the component surface, and prevent any chance of surface contamination. The adhesive attaches to a single surface plane, meaning that even minute amounts of contamination surviving poor surface preparation can be very detrimental to the performance of the joint.

TCW is naturally a more robust process. Welding of thermoplastic surfaces occurs through the intermingling of polymer chains in the adjacent surfaces – this process is known as the “healing” of the two thermoplastic surfaces. The original surface effectively disappears - the original surface polymer is absorbed and redistributed within the thermoplastic weldline during the healing process. The effect of any contamination is originally present on the surface of the laminate is much less than in adhesive bonding of composites.

Surface preparation consisting of no more than a precautionary solvent wipe (isopropyl alcohol is normally used) of the thermoplastic surfaces on the components to be welded has been found to be satisfactory.

In the work carried out to date, weld pressures in the range 100-150 kPa have been found to be quite adequate. (By contrast, bonding with film adhesive or welding of thermoplastic composite laminates usually requires 300-500 kPa for consistent joint formation.) Most experimental coupons have been welded under a vacuum bag. At lower pressures there may not be sufficient flow in the thermoplastic to bring the whole interface together, or the component surfaces may not be held together sufficiently to overcome small dimensional mismatches. Greater weld pressures can be used if desired, as it quite difficult to squeeze too much thermoplastic out of the joint. Scrims or other thickness-control materials are not required in the weldine to maintain a minimum weld material thickness.

The thermoplastic has moderate flow during processing: minor gaps between facing thermoplastic surfaces will fill with normal processing conditions, resulting in a full weld. Where additional gap filling is required, additional thermoplastic film can be included at the time of welding. Where welding conditions are correct, a small fillet should form on all borders of the joint. This demonstrates that sufficient flow has occurred to bring all the surfaces into contact and to allow healing.

The assembly is held together until the joint has cooled. Joint strength appears unaffected by the cooling rate in practical welding situations. Normal ultrasonic NDI methods can be used to inspect the individual components and the TCW joint. Initial work has been done on correlation between detectable defects in the thermoplastic and mechanical performance of welded joints.

Upper limits on welding temperature are determined by the thermal exposure limits of the cured carbon-epoxy laminates. In oven or autoclave welding, thermal exposure of the laminates is similar to that found in secondary bonding, although the exposure time at high temperature is much less. During welding in a shop-floor environment using LTTH, thermal exposure is dependent on component and joint geometry. This welding method is discussed in further detail below.

3 Welding Tooling and Equipment

The main drivers of the efficiency of the TCW process are the low pressures, modest temperatures and short welding times involved. These allow innovative tooling and heating arrangements to be used. In addition the process is quite robust, and is not expected to require clean-room conditions. This gives great flexibility in the design and scheduling of the assembly process.

The thermoplastic weld material has excellent chemical resistance and low water uptake, is difficult to contaminate and easy to clean. It is not sensitive to moisture – two components soaked under water for a week have been welded, with no drop in joint performance compared to control specimens. The thermoplastic surface should of course be kept clean; however contaminants only have a significant effect if there is substantial interruption of the thermoplastic healing process. Minor levels of particulates, such as dust and dirt, are generally absorbed within the thermoplastic. Other potential contaminants can be removed with a simple solvent wipe of the “adherend” surfaces. TCW appears to be a substantially more robust process than adhesive bonding, potentially allowing it to be routinely conducted outside highly-controlled, clean room environments.

The assembly of some sets of components by TCW, such as the assembly of cured wing stringers to a wing skin, would suit the use of oven-heating methods already common in curing of film adhesive joints. The assembly would be bagged and cooked in the usual way, with the advantage of considerably shorter autoclave cycles (at least two hours less) because the thermoplastic weld material does not have to cure.

For many other assemblies, it will be attractive to take advantage of the low pressures, modest temperatures and short welding times possible. The Local Through-Thickness Heating (LTTH) tooling philosophy illustrated in Figure 2 has been used on a number of demonstration assemblies at CRC-ACS, with satisfactory results.

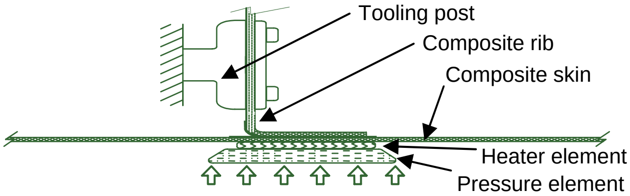

Fig. 2. Possible LTTH Arrangement for Welding a Rib and Skin by TCW

LTTH uses flexible heating elements and pressure application systems to provide heat and pressure only to the areas required. Because welds can be made in a relatively short time (10-15 minutes at the welding temperature is normally sufficient) and reasonable temperatures, LTTH allows fast and inexpensive welding operations for many smaller or lightweight structures.

LTTH transfers heat to the weld line through one or both of the cured carbon-epoxy components. The heater is placed in contact with the outer surface of the component which is thinnest or most accessible. Carbon-epoxy laminates conduct heat quite well, and the temperature drop across the laminate has been extensively modeled, as shown in Figure 3. The total laminate thermal exposure is acceptably low, due to the short welding time. Therefore LTTH can be used without degrading the mechanical properties of the laminate in contact with the heater element. Typical excursions to the required outer lamina temperature in typical laminates have been found to have no adverse effects on properties such as laminate T_g and open hole compression (OHC) strength.

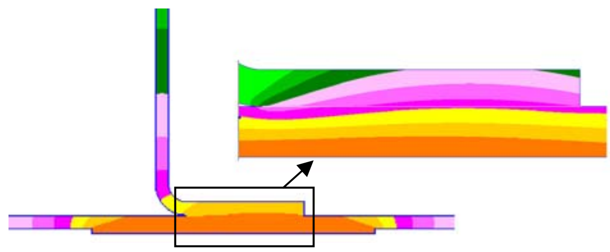

Fig. 3. Simulation of Temperature Distribution During LTTH.

LTTH is particularly applicable to assemblies where the laminate being heated is relatively thin. The temperature drop between the heater element and the weld line increases with the thickness of component being heated. The temperature drop can be reduced by adjusting the heat transfer conditions. CRC-ACS has conducted welding trials, thermal degradation tests and heat transfer modeling to predict the practical limits of LTTH. Naturally these limits are greater for some prepregs than others.

A key advantage of LTTH is that it is compatible with low-cost assembly-floor implementation of the TCW process. Since most of the structure is not heated, and the local temperatures and loads used are moderate, in many cases the composite components can be largely self-supporting during welding - they require little specific support tooling. Individual components may be located and held together using a small number of temporary or permanent fasteners if desired. Determinate assembly principles can be applied, with self locating and self-jigging features. It is expected that assemblies may be joined in the same area of the factory as that used for mechanical fastening, and using compatible light-weight tooling.

4 Mechanical Performance

The performance of TCW joints has been assessed in many types of tests. In most cases comparative tests have also been carried on adhesive-bonded joints made with a standard high-temperature epoxy film adhesive. Generally the adhesive used was Cytec FM 300K.

The mechanical properties of carbon-epoxy TCW joints have been found to be equivalent, or superior, to the adhesively-bonded joints. The single lap shear strength of the TCW coupons made from benchmark prepreg laminates has been tested at different temperatures from -55°C to 80°C. The results compare well with shear strength of the adhesively bonded coupons. Similar results for TCW joints have also been found with adherends made from other aerospace grade epoxy prepregs. The results shown in Figures 4 and 5 are from coupons with 12.5 mm overlaps.

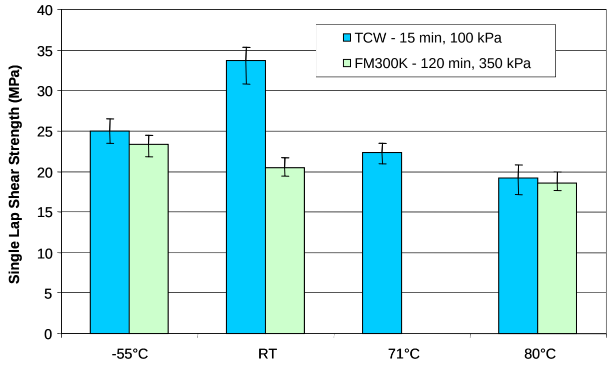

Fig. 4. Single-Lap Shear Strength of TCW and Adhesive-Bonded Coupons

Single-lap shear strength is consistently high over a wide range of weld material thicknesses (90-400 μm). Fatigue performance of single lap shear joints has also been found to be satisfactory compared to FM 300 joints.

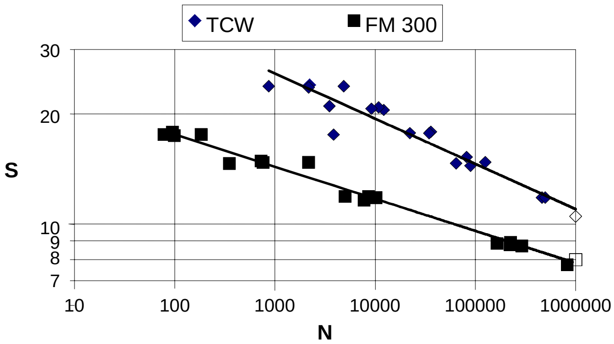

Fig. 5. Fatigue Performance of TCW and Adhesive-Bonded Coupons

5 Environmental Resistance

The thermoplastic used as the weld material in TCW is a tough, engineering thermoplastic that offers a good balance of properties. It is highly stable when exposed to harsh thermal, chemical, and ultraviolet environments.

The thermoplastic has good resistance to typical aerospace fluids. As shown in Figure 6, stress cracking resistance of TCW joints immersed in jet fuel and aviation fluid (Skydrol), and in the hot/wet condition, was found to be equivalent to that of the FM 300 adhesively-bonded joints. Immersion of lap shear coupons prior to testing shows that resistance to MEK is also excellent.

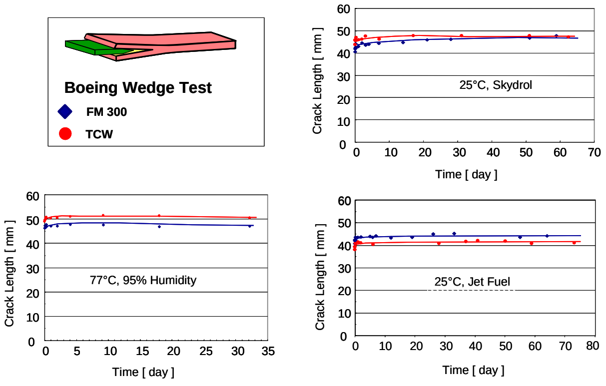

Fig. 6. Environment Resistance of TCW and Adhesive-Bonded Coupons

6 Demonstration Articles and Cost Studies

A number of demonstration articles have been made using TCW.

6.1 Blade-Stiffened Skin

An early example was a stiffened panel, shown in Figure 8, made by welding "T" stiffeners to a skin. Thermoplastic film strips were cocured onto the interface surfaces of a plain weave prepreg laminate, and on the lower surface of three T-stiffeners, as seen in Figure 7. All laminates were 2.3 mm thick.

The skin and T-stiffeners were welded together in an oven under a vacuum bag for 15 minutes.

The welding process was simple and rapid, and no significant problems were encountered. Ultrasonic C-Scans of the welds indicated good bonds. TCW appears ideally suited for the attachment of pre-cured stringers and stiffeners to skins.

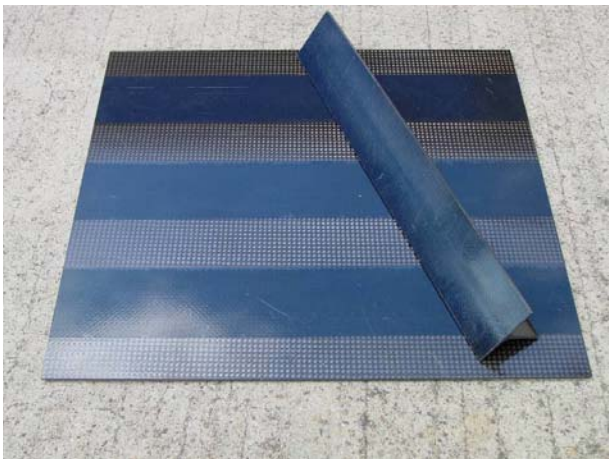

Fig. 7. Details Ready for Welding

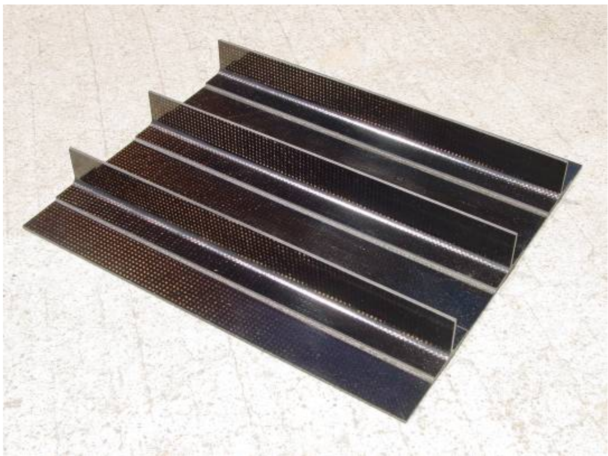

Fig. 8. Welded Stiffened Skin

6.2 Box Demonstrator

This box demonstrator, illustrated in Figure 11, consisted of two 2.3 mm panelised carbon-epoxy prepreg honeycomb-sandwich skins, two 3 mm carbon-epoxy "C" spars, and two machined aluminium ribs. The skins and spars were laid up with thermoplastic strips on the bag side surfaces at the future assembly interface locations.

Fig. 9. Welding of Demonstrator Box

The aluminium ribs and composite spars were first fastened together to complete the sub-structure. A reaction frame, shown in Figure 9, was used to apply local pressure to the skins, and through them to the lower flanges of the composite spar. A heated element contained within the frame was pressed against the skin to effect the weld. For this demonstrator box, each weld (there were four spar-skin welds in total) was conducted separately, with a cycle time of a little more than 20 minutes. With appropriate tooling, it would have been possible to weld all four joints simultaneously. Following welding, the aluminium ribs were mechanically fastened to the skin.

Fig. 10. Close-up of Welded Joint

Weld quality was assessed by thermography. The scan showed a high weld quality in all joints. Good weld quality was also indicated by the fillet at all joint edges, as indicated in Figure10, a sign of substantial shear flow and healing in the thermoplastic weld material.

Fig. 11. Completed Demonstrator Box

The joints in the rectangular box demonstrator are representative of those in many spar/rib/skin structures. The box successfully demonstrated the practicality of Local Through-Thickness Heating (LTTH). The joints were successfully welded without any support tooling restraining the spars or their flanges, showing that a similar substructure could be self-supporting during welding using LTTH. A similar welding, heating and tooling concept could be used to weld a complete substructure to the skins in the assembly of control surfaces.

6.3 Curved Control Surface

This structure, shown in Figure 12, is representative of the shape of a fighter aircraft flap. The ribs, spar, and skins were cured with thermoplastic film on the surface at interface areas.

Fig. 12. Partially-Completed Flap Structure

Fig. 13. LTTH/TCW Assembly Tooling

The composite ribs and spar were located on tooling posts as shown in Figure 13, and mechanically fastened together. The composite skin was then introduced to the substructure assembly. Welding was conducted using flexible heaters with multiple heater zones. Tooling posts were used to support the ribs during welding of the first skin, but were removed before welding of the upper skin. The flexible heaters used in this LTTH process were easily able to weld the curved ribs, the smallest of which had a flange radius of 282 mm.

6.4 Cost Studies

A range of assembly cost studies have been undertaken by CRC-ACS and other organisations. These have indicated savings in assembly costs of between 25% and 75%, as well as large reductions in assembly time.

7 Conclusion

An efficient new welding process has been developed to assemble carbon-epoxy aircraft components. The process requires the layup of one additional "ply", a thermoplastic film, on the surface of the carbon-epoxy laminate. After curing, the thermoplastic layer is very strongly bonded to the underlying carbon-epoxy laminate. Such laminates can then be welded together in a rapid, efficient process resulting in high-strength joints. The joints have good fatigue and environmental resistance.

Welding can be accomplished in under 30 minutes, using moderate temperatures and pressures. It has been shown that simple assembly tooling, using local through-thickness heating, can be used to join carbon-epoxy components. TCW has great potential for large cost and time savings in assembly of composite aircraft structures.