Australian Government
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Defence Science and
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Standard Operating Procedure - Manufacture of Carbon Fibre Reinforced Plastic Waveguides and Slotted Waveguide Antennas, Version 1.0

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Air Vehicles Division
Defence Science and Technology Organisation

DSTO-TN-0937

ABSTRACT

Slotted Waveguide Antenna Stiffened Structure (SWASS) is a type of conformal load-bearing antenna structure where the top-hat cross-section stiffeners used to reinforce thin skins, or blade stiffeners in sandwich panels, serve the dual purpose of acting both as structural stiffeners and radiofrequency waveguides. Slotted waveguide antenna arrays are created by cutting slots through the outer skin and into these waveguide stiffeners. Development of the SWASS concept requires the production and evaluation of representative test specimens, one of which is a rigid rectangular waveguide. This report details Version 1.0 of a Standard Operating Procedure for the production of slotted waveguide antenna arrays manufactured from aerospace grade carbon fibre reinforced plastic (CFRP) prepreg.

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Executive Summary

Conformal Load-Bearing Antenna Structure (CLAS) offers the potential to enhance dramatically the operational effectiveness of military platforms by improving the performance of radiofrequency (RF) systems such as communications, radar and electronic warfare. CLAS may be distributed over a larger portion of the external skin of a platform than conventional antennas, thereby allowing substantially larger individual antenna elements and antenna arrays. Such arrays would have increased gain, decreased beamwidth and lower operating frequencies when compared to traditional aircraft antennas.

One promising CLAS concept, developed jointly by DSTO and the United States Air Force Research Laboratory, is the Slotted Waveguide Antenna Stiffened Structure (SWASS). In SWASS the top-hat cross-section stiffeners, commonly used to reinforce thin skins, or blade stiffeners in sandwich panels, serve the dual purpose of acting both as structural stiffeners and RF waveguides. Slotted waveguide antenna arrays are created by cutting slots through the outer skin and into these waveguide stiffeners. The slots are filled with a RF transparent cover to create an aerodynamic exterior.

The validation and development of the SWASS concept is assisted by the production and evaluation of specimens at the coupon, structural element and design detail level. The results of tests on such specimens may be correlated with analytical and numerical simulations to facilitate the development of a simulation based design methodology, without the expense of testing full-scale components.

Waveguides, with and without slots, are the fundamental functional unit of SWASS. They support structural loads as well as transmitting RF waves. Thus the rigid rectangular waveguide is a structural element level specimen.

A method has been developed to manufacture rigid rectangular waveguides using aerospace grade carbon fibre reinforced plastic (CFRP) prepreg tape and fabric. This report details Version 1.0 of a Standard Operating Procedure for this manufacture.

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Contents

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1. Manufacture of Carbon Fibre Reinforced Plastic (CFRP) Waveguides

1.1 Background

Conformal Load-Bearing Antenna Structure (CLAS) offers the potential to enhance dramatically the operational effectiveness of military platforms by enhancing the performance of radiofrequency (RF) systems such as communications, radar and electronic warfare. One promising CLAS concept, developed jointly by DSTO and the United States Air Force Research Laboratory, is the Slotted Waveguide Antenna Stiffened Structure (SWASS). In SWASS the top-hat cross-section stiffeners commonly used to reinforce thin skins, or blade stiffeners in sandwich panels, serve the dual purpose of acting both as structural stiffeners and RF waveguides. Slotted waveguide antenna arrays are created by cutting slots through the outer skin and into these waveguide stiffeners. The slots are filled with a RF transparent cover to create an aerodynamic exterior.

The validation and development of the SWASS concept is assisted by the production and evaluation of specimens at the coupon, structural element and design detail level. The results of tests on such specimens may be correlated with analytical and numerical simulations to facilitate the development of a simulation based design methodology, without the expense of testing full-scale components.

Waveguides, with and without slots, are the fundamental functional unit of SWASS. They support structural loads as well as transmitting RF waves. Thus the rigid rectangular waveguide is a structural element level specimen.

1.2 Introduction

This Standard Operating Procedure (SOP) describes the materials, processes and techniques that may be used to produce rigid rectangular waveguides and slotted waveguide antennas, up to 350 mm long, with internal dimensions of 22.86 mm x 10.16 mm, from aerospace grade carbon fibre reinforced plastic (CFRP) prepreg. These dimensions match that of rigid rectangular WR-90 waveguides.

The production of waveguides with different internal dimensions and/or materials will require modification of this SOP. This version of this SOP does not cover such alternatives.

1.3 Prepare mandrels

1.3.1 Acquire mandrels of appropriate material and dimension.

Material — Mandrels may be any material that (i) can be formed to the desired dimensional tolerance, (ii) is compatible with the materials and (iii) maintains dimensional tolerances during the autoclave curing process. If aluminium is used then it is preferred that MIC 6 ® (Alcoa) aluminium be used because it is cast and does not distort during machining or autoclave curing. However, standard commercial grade aluminium has also been used successfully.

Dimensions 400 mm x 22.51 mm x 9.86 mm mandrels can be used to produce CFRP waveguides that are up to 350 mm long and have an internal cross-section of 22.86 mm x 10.16 mm. This matches that of a standard WR-90 rigid rectangular waveguide. The undersize mandrel cross-section is required to accommodate the thickness of the super-slick Teflon tape as described in Step 1.2.2.

1.3.2 Wrap a single ply of super-slick Teflon tape (Saint Gobain, R Series, Skived PTFE tape, Product R253, McMaster Carr Item 6305A18) lengthways around the mandrels. Ensure the seams are as close to a perfect butt joint as possible. The tape is supplied as a 2″ wide strip. If this is not wide enough to fully wrap one mandrel then, if possible, wrap two mandrels using three strips of tape, as shown in Figure 1, in order to conserve tape.

1.4 Prepare outer tools

1.4.1 Wrap two plies of green flash break tape lengthwise on tooling surfaces of outer tools (400 mm x 24.1 mm x 11.4 mm angle section). Ensure there are no seams on the tooling surfaces.

1.4.2 Fasten a 400±5 mm long x 150±5 mm wide piece of non-porous Teflon to the short edge of one outer tool as shown in Figure 2 with 1″ wide flash break tape. Repeat for the number of outer tools to be used in the cure run.

1.5 Prepare prepreg

1.5.1 Remove prepreg from freezer. Allow to thaw and equilibrate at room temperature. Open bag.

1.5.2 Cut prepreg pieces so that, when wrapped around the mandrels, they produce perfect butt joints. Use the coordinates specified in Figure 3.

The following ply sizes have been found suitable when using aerospace grade CFRP prepreg unidirectional tape (ply thickness approximately 125 μm) over 22.51 mm x 9.86 mm mandrels prepared in accordance with Section 1.3. These ply widths will need to be adjusted for plies with different thickness (such as woven fabric) and/or mandrel dimensions.

Four ply lay-up

Ply # 1 (inner ply)	350 mm long x 67 mm wide
Ply #2 and 3 (as one piece)	350 mm long x 136 mm wide
Ply #4 (outer ply)	350 mm long x 70 mm wide

Two ply lay-up

Ply # 1 and 2 (as one piece)	350 mm long x 137 mm wide

1.5.3 Rebag unused prepreg, seal and return to freezer.

1.6 Lay-up

1.6.1 For Waveguides with Ply Seam along the waveguide broad-wall

Place aligning marks on mandrel as shown in Figure 4.

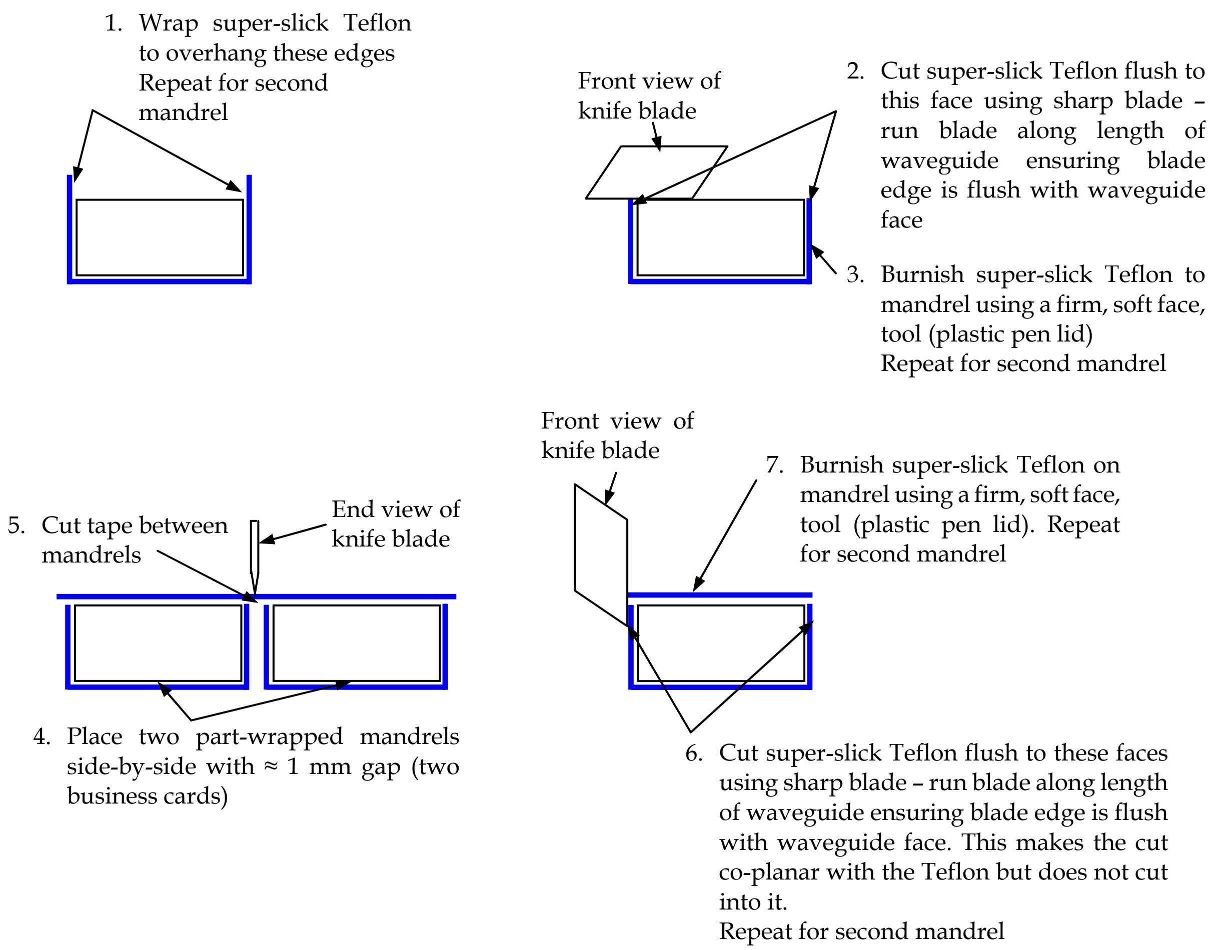


Figure 1: Diagram of mandrel cross-sections and the seven step process for wrapping with super-slick Teflon tape

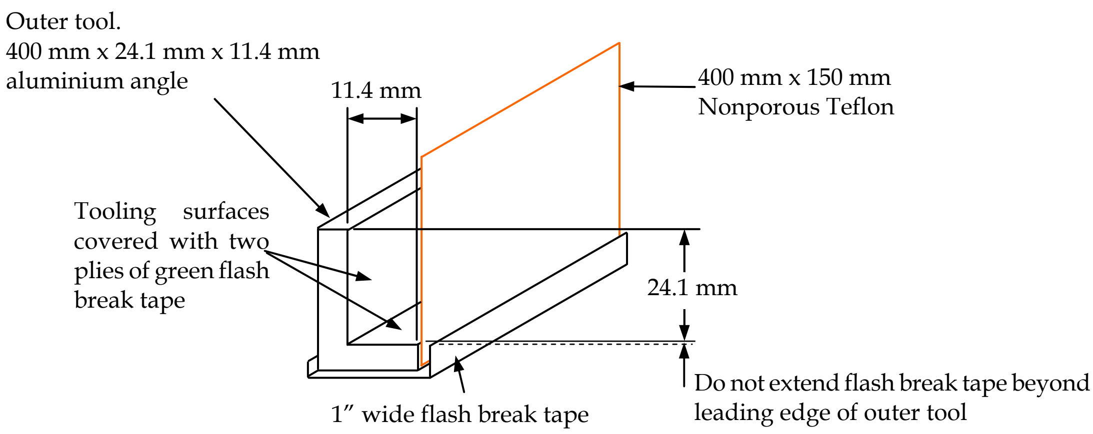


Figure 2: Diagram showing the location of the nonporous Teflon and flash break tape on the outer tool

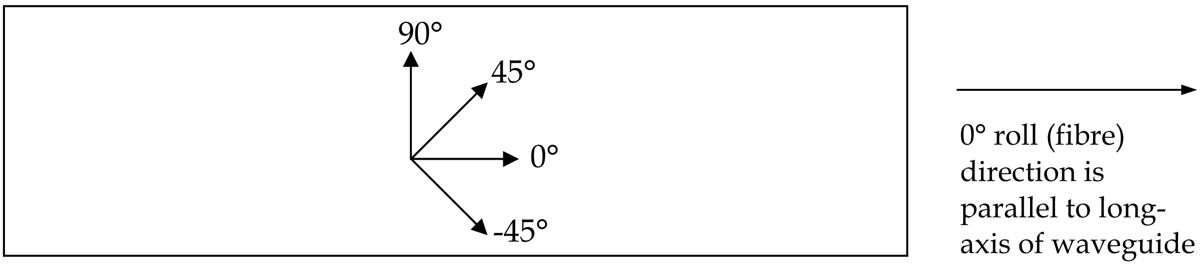


Figure 3: Diagram of a prepreg roll showing the ply coordinate system

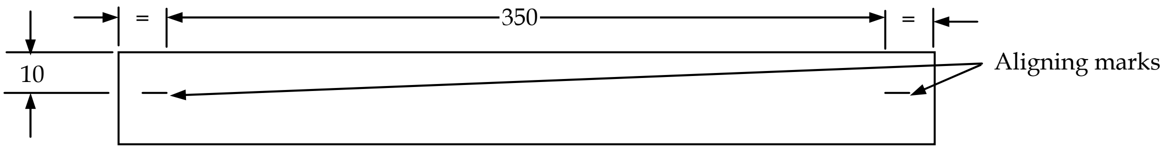


Figure 4: Diagram of the location of aligning marks on mandrel

Peel the backing paper off the prepreg ply.

Using the aligning marks, locate the ply on the mandrel as shown in Figure 5. Burnish this ply against the broad-wall of the mandrel using a tool that is soft enough not to damage the ply or the underlying Teflon tape.

Working one wall at a time wrap the inner ply fully around the mandrel and burnish it down against the mandrel. Use the 400 mm x 24.1 mm x 11.4 mm outer tool as a former and pulling on the nonporous Teflon to achieve tight wrapping of the ply. The goal is for the ply to contact the mandrel on all faces and the seam to be a perfect butt joint (no gap or overlap) as shown in Figure 6.

Locate both outer tools over the wrapped mandrel, with the nonporous Teflon wrapped once around the mandrel. Pull the nonporous Teflon tight to assist keeping the ply firmly pressed against the mandrel. The configuration is shown in Figure 7.

Hold the outer tools to the mandrel using flash break tape. Wrap with breather cloth and hold with flash break tape. Place in vacuum bag. Vacuum debulk for five minutes.

For the next ply, place aligning marks on the mandrel as shown in Figure 4, however mark the opposite broad-wall of the mandrel to that containing the seam from the previous ply.

Place the next ply in position as shown in Figure 5 and burnish this ply onto this broad-wall.

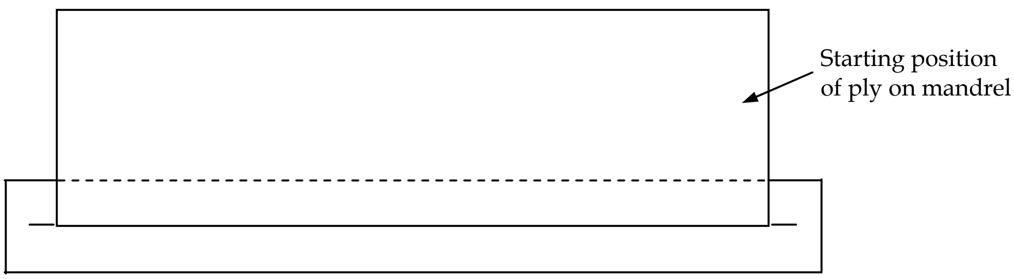


Figure 5: Diagram of the location of first ply on mandrel relative to aligning marks

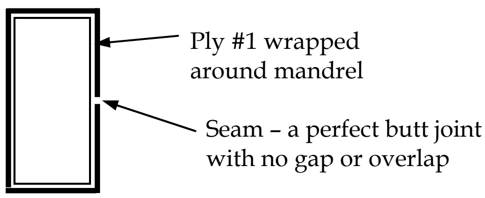


Figure 6: Diagram of the cross-section of a well wrapped mandrel

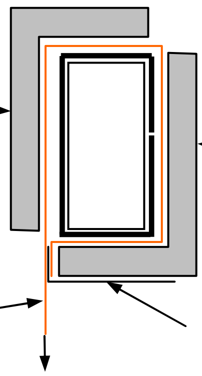


Figure 7: Diagram of the cross-section of tool setup for vacuum debulking

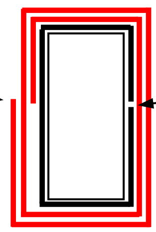


Figure 8: Diagram of the cross-section of a wrapped mandrel (with the outer piece constituting two plies) showing the opposing seam positions

Working one wall at a time, using the outer tool as a former and pulling on the nonporous Teflon to achieve tight wrapping of the ply, wrap the ply fully around the mandrel and burnish it down. For pieces of prepreg that are:

Single plies	the aim is for the seam to be a perfect butt joint (no gap and no overlap) and be parallel to the longitudinal axis of the waveguide, as shown in Figure 6 (except for the additional ply).
Multiple plies	the aim is for the end and start of the piece to finish at the same location and be parallel to the longitudinal axis of the waveguide, as shown in Figure 8.

Locate outer tools over the wrapped mandrel, with the nonporous Teflon wrapped once around the mandrel. Pull the nonporous Teflon tight to assist keeping the ply firmly pressed against the mandrel. The configuration is shown in Figure 7 except for the additional ply.

Hold the outer tools to the mandrel using flash break tape. Wrap with breather cloth and hold with flash break tape. Place in vacuum bag. Vacuum debulk.

Repeat this step as necessary, with the seams of each subsequent ply located on alternating broad-walls, to obtain the specified laminate stacking sequence.

1.6.2 Lay-up – For Waveguides with Ply Seam along Narrow-wall

Tape the ends of the non-porous Teflon down to the outer tool as shown in Figure 9.

Place aligning marks on the nonporous Teflon taped to this outer tool as shown in Figure 10.

Peel the backing paper off the prepreg ply then, using the aligning marks, locate the ply onto the nonporous Teflon as shown in Figure 11.

Place the broad-wall of the mandrel onto the ply, aligning the mandrel with the aligning marks on the nonporous Teflon as shown in Figure 12. Burnish the face of the ply against the mandrel.

Fold the prepreg up against the narrow-wall of the mandrel, using the nonporous Teflon and any other convenient item for support to prevent the prepreg tearing. Burnish the face of the ply in contact with the mandrel against the mandrel. Continue burnishing until the ply adheres to the mandrel. It has been found that holding fingers against the prepreg for ten to thirty seconds provides sufficient warmth for the prepreg to hold against the mandrel. A diagram of the final position of the prepreg on the mandrel is shown in Figure 13.

Peel the prepreg off the nonporous Teflon taking care not to separate the prepreg off the mandrel. Position the mandrel/prepreg against the corner of the outer tool in the position shown in Figure 14.

Working one wall at a time, and using the outer tool as a former and pulling on the nonporous Teflon to achieve tight wrapping of the ply, wrap the inner ply fully around the mandrel and burnish it down against the mandrel. The goal is for the ply to contact the mandrel on all faces and the seam to be a perfect butt joint (no gap or overlap) as shown in Figure 15.

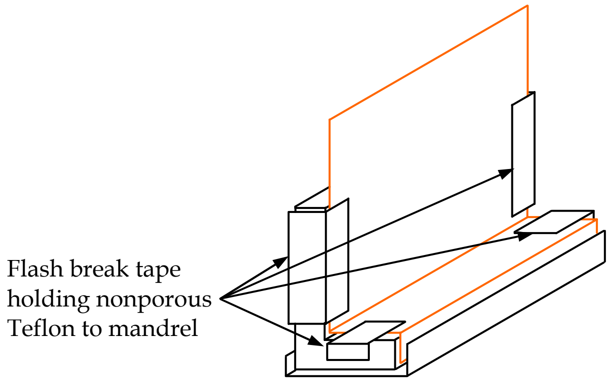


Figure 9: Diagram showing the location of the nonporous Teflon and flash break tape on the outer tool

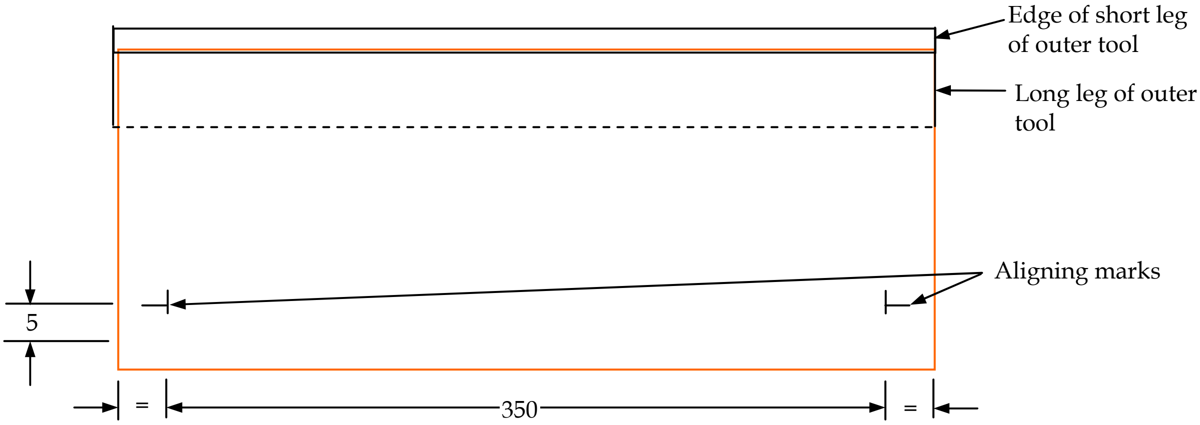


Figure 10: Diagram of the location of aligning marks on the nonporous Teflon taped to the outer tool

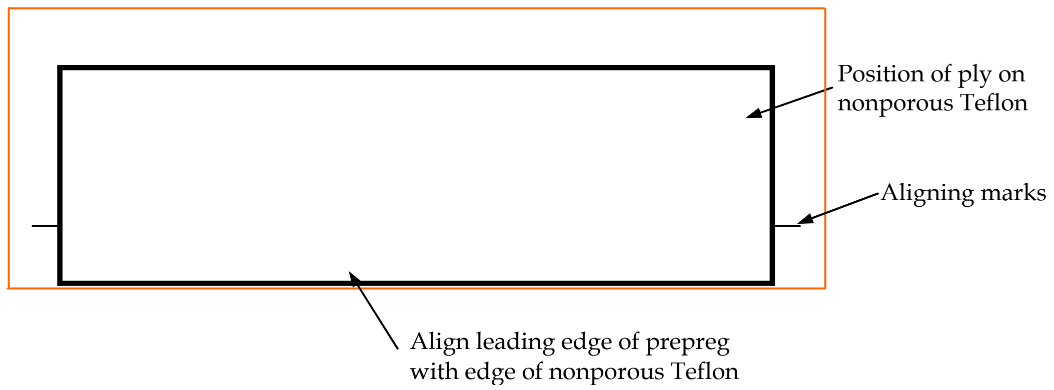


Figure 11: Diagram of the location of first ply on nonporous Teflon relative to aligning marks

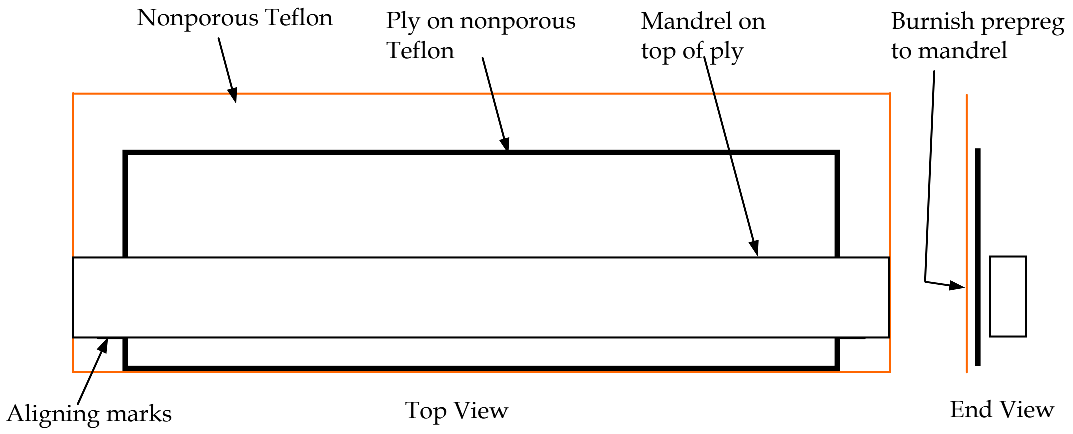


Figure 12: Diagram of the location of the first ply on nonporous Teflon

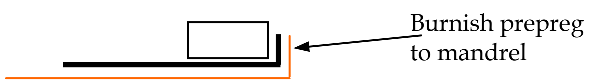


Figure 13: Diagram of the location of the first ply against narrow-wall of mandrel

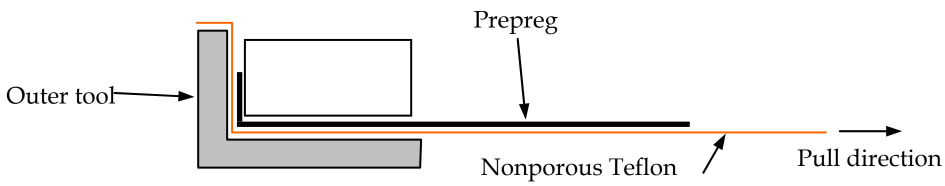


Figure 14: Diagram of the cross-section after mandrel/prepreg have been located against the outer tool

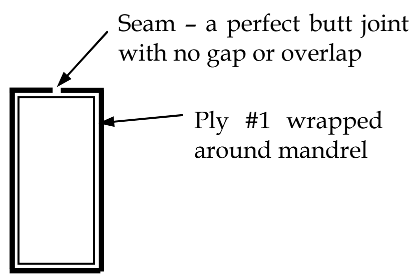


Figure 15: Diagram of the cross-section of a well wrapped mandrel

Locate both outer tools over the wrapped mandrel, with the nonporous Teflon wrapped once around the mandrel. Pull the nonporous Teflon tight to assist keeping the ply firmly pressed against the mandrel. The configuration is shown in Figure 16.

Hold the tools to the mandrel using flash break tape. Wrap with breather cloth and hold with flash break tape. Place in vacuum bag. Vacuum debulk.

Locate the next ply onto the nonporous Teflon using the aligning marks, as shown in Figure 11.

Place the broad-wall of the mandrel onto the ply with the seam from the previous ply on the opposite side of the short protruding end of the current ply. Align the mandrel with the aligning marks on the nonporous Teflon as shown in Figure 12. Burnish the face of the ply against the mandrel place aligning marks on the mandrel as shown in Figure 13.

Working one wall at a time, using the outer tool as a former and pulling on the nonporous Teflon to achieve tight wrapping of the ply, wrap the ply fully around the mandrel and burnish it down. For pieces of prepreg that are:

Single plies — the aim is for the seam to be a perfect butt joint (no gap or overlap) and be parallel to the longitudinal axis of the waveguide, as shown in Figure 15.

Multiple plies — the aim is for the end and start of the piece to finish at the same location and be parallel to the longitudinal axis of the waveguide, as shown in Figure 17.

Locate outer tools over the wrapped mandrel, with the nonporous Teflon wrapped once around the mandrel. Pull the nonporous Teflon tight to assist keeping the ply firmly pressed against the mandrel. The configuration is shown in Figure 16.

Hold the tools to the mandrel using flash break tape. Wrap with breather cloth and hold with flash break tape. Place in vacuum bag. Vacuum debulk.

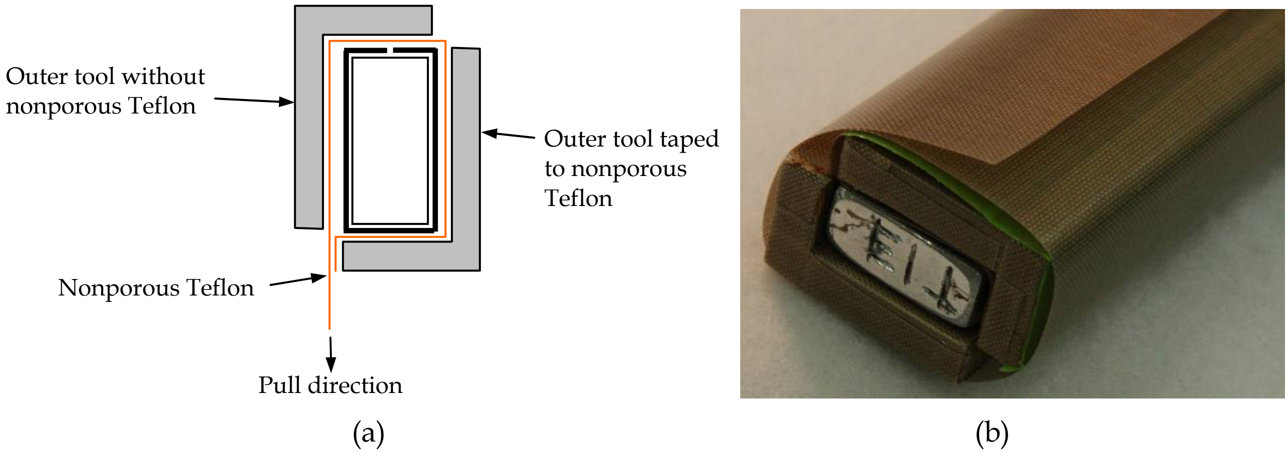


Figure 16: (a) Diagram and (b) photograph of the cross-section of tool setup for vacuum debulking

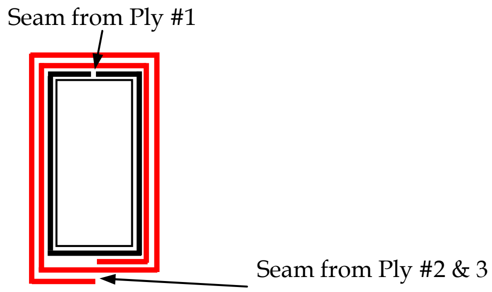


Figure 17: Diagram of the cross-section of a wrapped mandrel (with the outer piece constituting two plies) showing the seam position

Repeat this step as necessary (with the seams on each subsequent ply being on alternating narrow-walls) to obtain the specified laminate stacking sequence.

1.6.3 Upon the completion of ply wrapping, wrap the tool assembly with breather cloth. Ensure that no tool edges are exposed as these may perforate the envelope bag. Hold breather cloth with flash break tape.

1.6.4 Seal the tool in an envelope bag suitable for autoclave curing.

1.7 Cure

1.7.1 Cure the waveguide(s) using the specified cure cycle, typically the manufacturers recommended cycle. The cycle for some common CFRP prepreg materials are shown in Figure 18 to Figure 21.

1.8 Release

1.8.1 After curing, cut the breather and bagging film away from the outer tools. This may require some effort if resin has bled between the mandrel and outer tools into the breather cloth.

Peel the outer tools and nonporous Teflon away from the cured waveguides.

Slide the cured waveguide sticks out of the mandrels. This may require some force. If it is not possible to withdraw the mandrel from the waveguide manually (by holding the waveguide stick and pulling the mandrel) then additional force may be exerted by pressing one end of the mandrel against a fixed post of less than 10 mm diameter and approximately 100 mm long.

CAUTION: The edges of waveguide sticks are extremely sharp. Appropriate PPE (heavy gloves) and care must be taken to avoid damaging cured waveguide sticks and lacerating hands on these edges during withdrawal.

1.8.2 Remove super-slick Teflon tape from mandrels.

If there is any adhesive residue then remove it by soaking the mandrels in mineral turpentine for at least 15 minutes then scraping with a tool that does not damage the surface of the mandrel, such as a wooden stick. Clean up with a turpentine soaked rag.

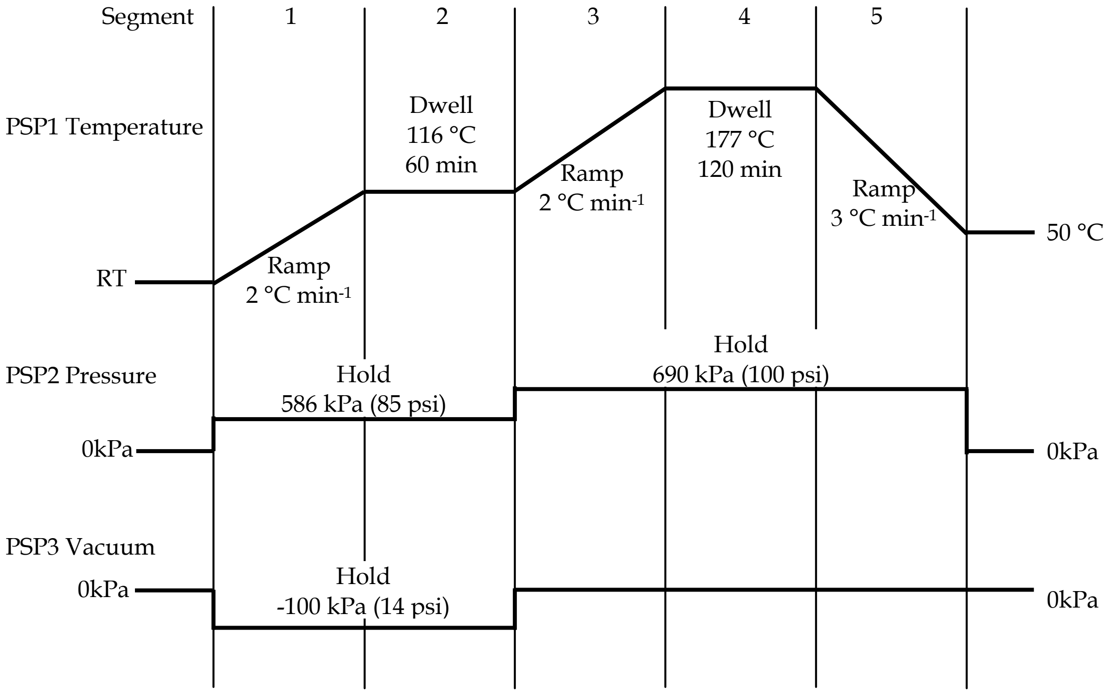


Figure 18: Autoclave cure cycle for AS4/3501-6

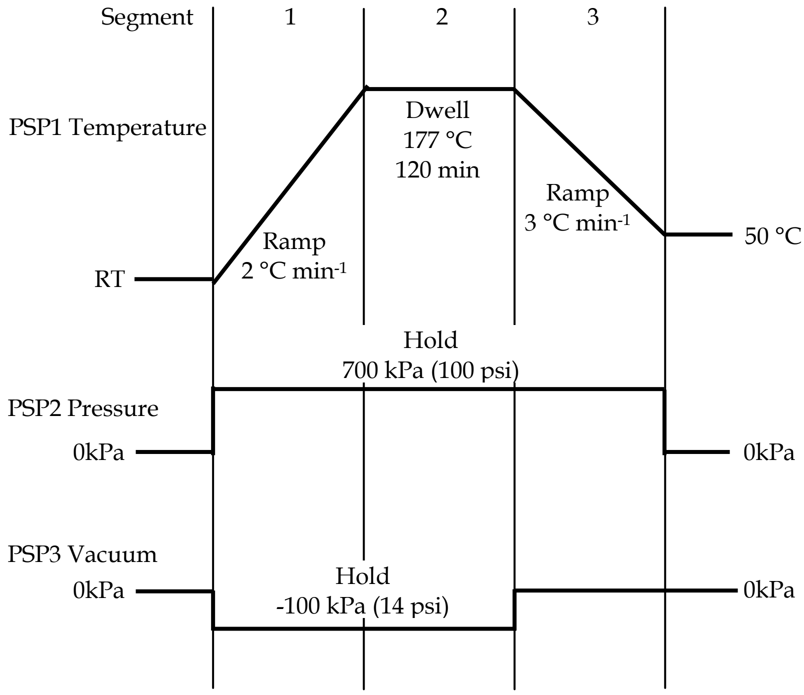


Figure 19: Autoclave cure cycle for Hexply M18-1-42%/G947

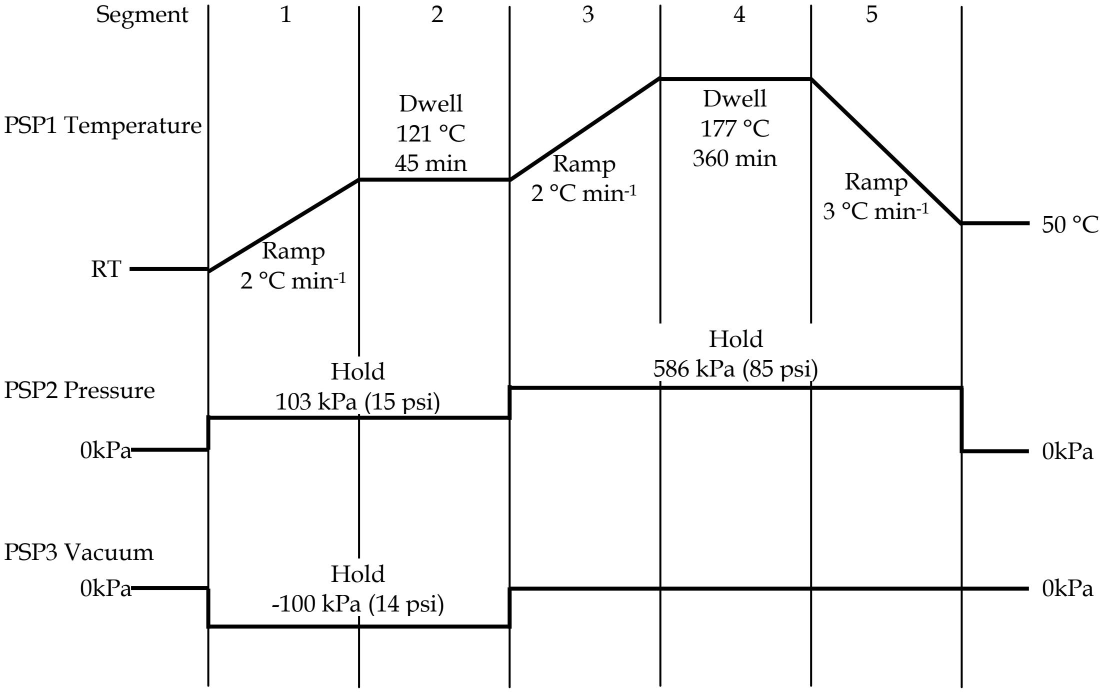


Figure 20: Autoclave cure cycle for Cycom IM7/5250-4

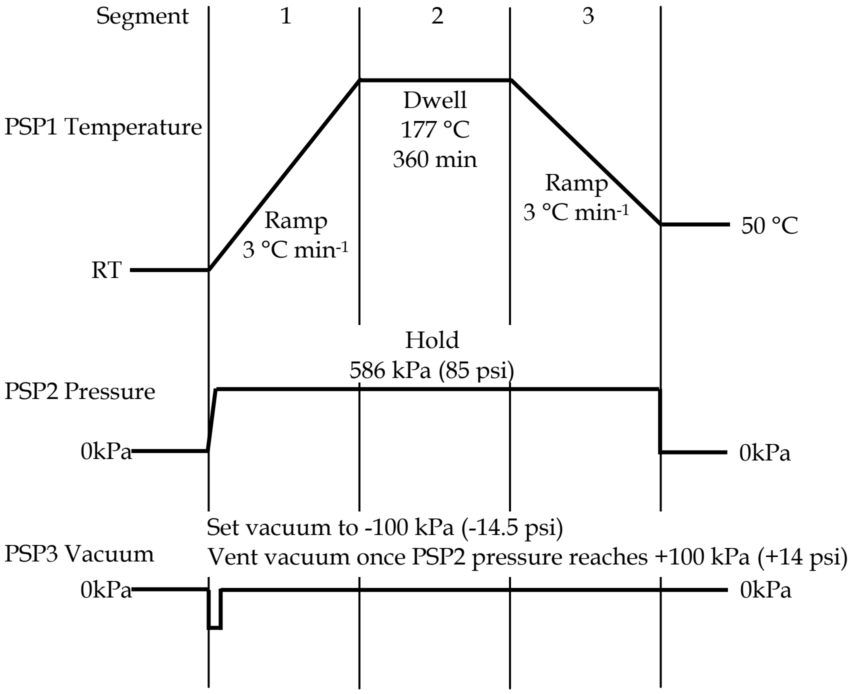


Figure 21: Autoclave cure cycle for Cycom IM7/977-3

1.9 Postcure and cleanup

1.9.1 Postcure the cured CFRP waveguide if required. For example Cycom IM7/5250-4 requires a freestanding postcure in an air-circulating oven at 227°C for 360 min. Heat and cool at 3°C min^{-1}.

1.9.2 Remove sharp edges from waveguides using 300-400 grit wet/dry paper.

1.9.3 Cut the waveguides to the specified length using a diamond saw with water lubricant.

CAUTION: The dust from machining composites may be hazardous if inhaled.

Operations that may produce composite dust are to be conducted in appropriate facilities (DSTO Melbourne, Integrated Composites Facility, IC.028) by approved operators using approved procedures.

Wet machine wherever possible to trap any dust in water.

Wash all specimens and equipment before they have dried until there is no visible sign of carbon dust. In IC.028, flush contaminated water down the designated drains.

1.10 Slots and flanges

1.10.1 Cut slots, if required, in accordance with Section 2.

1.10.2 If flanges are required then bond them to the waveguide ends in accordance with the following procedure:

Obtain flanges (UG 135-U MB flanges have been used for WR-90 waveguides), waveguides, adhesive and tools as shown in Figure 22 (a).

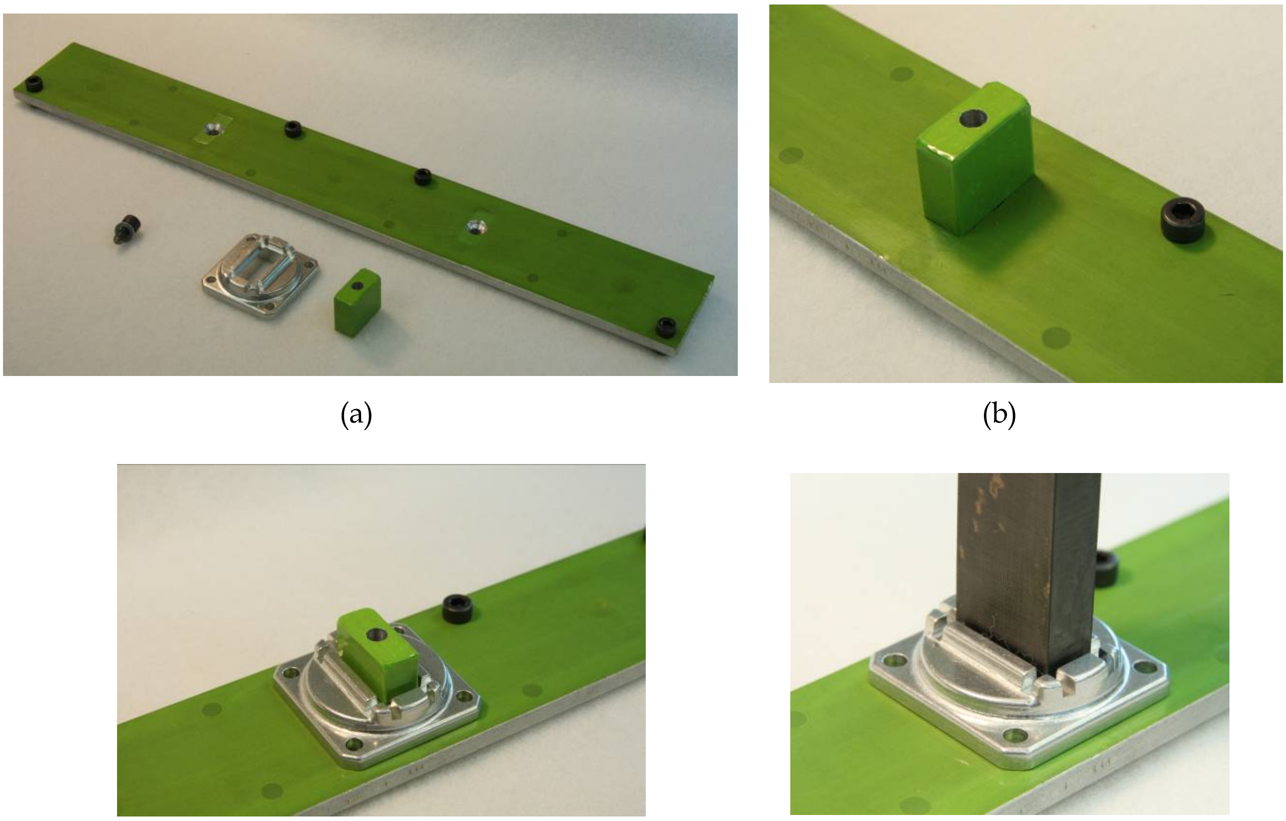
Clean all residues from the 22.6 x 10.0 x 25.4 mm aluminium aligning blocks. There are sufficient blocks to bond up to five flanges per batch.

Wrap a single ply of green flash break tape around the aligning blocks. Orient the tape so that it will not be rolled off the block when it is pulled out of the waveguide stick.

Fasten the aligning blocks to the base-plate as shown in Figure 22 (b).

If a conductive adhesive is to be used between the waveguide end and flange then run a small continuous bead of the adhesive around the mating surface of the waveguide flange using a wooden spatula. If a conducting adhesive is not required then do not treat the waveguide flange. Slide the flange over the aligning block and down to the baseplate as shown in Figure 22 (c).

Slide the CFRP waveguide stick over the aligning block until it presses onto the mating surface of the flange as shown in Figure 22 (d).



(a) (b) (c) (d)

Figure 22: Photographs showing the setup for bonding flanges to CFRP waveguides, (a) the tooling, (b) an aligning block covered with flash-break tape and fastened to the baseplate, (c) flange located on aligning block, and (d) waveguide located over the flange.

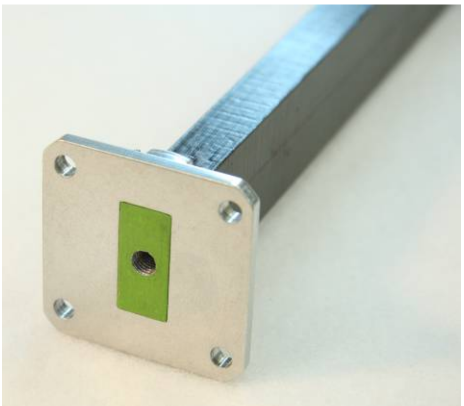
If conductive adhesive has been used then ensure a positive connection between the waveguide and flange and a continuous bead of adhesive around the waveguide/flange joint. Fill the fillet between the waveguide and flange, or overlay the conductive adhesive fillet, with a thick continuous bead of cyanoacrylate adhesive.

Allow the cyanoacrylate to cure and, if necessary, repeat application until cured cyanoacrylate covers the entire periphery of the waveguide/flange joint.

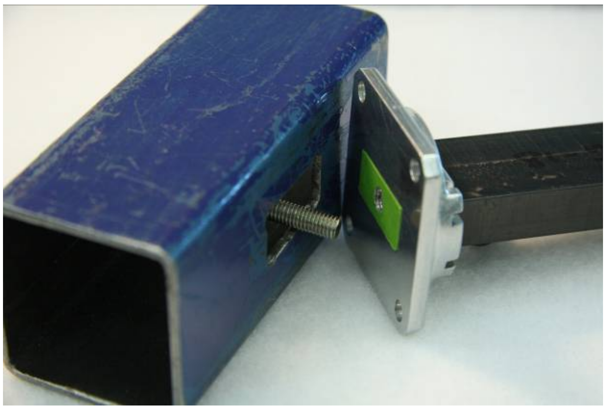
Unscrew the aligning block from the base-plate. The aligning block will be trapped in the waveguide as shown in Figure 23 (a). Use the puller shown in Figure 23 (b) to pull the aligning block out of the waveguide/flange. Removal may require a moderate amount of force if the adhesive has extruded into the waveguide section and partially bonded to the flash break tape on the aligning block.

Clean the flash break tape and any adhesive residue off the aligning block.

Abrade any adhesive residue from the inner wall of the waveguide/flange using coarse then medium grade sanding sticks. Continue abrading until there is a smooth, debris-free, transition between the flange and waveguide as shown in Figure 24.



(a)



(b)

Figure 23: Photographs showing (a) an aligning block trapped in the end of a waveguide, and (b) the puller used to separate the aligning block from the waveguide/flange

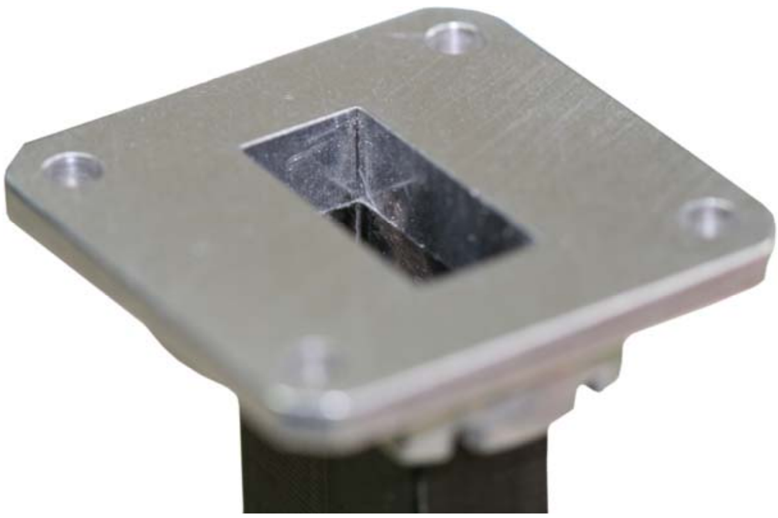


Figure 24: Photograph of the waveguide/flange joint after cleanup

Repeat this bonding procedure if a flange is required at the opposite end of the waveguide stick.

2. Cutting Slots into Composite Waveguides

2.1 Prepare waveguide

2.1.1 Cut the CFRP waveguide(s) to the desired length using a diamond saw with water lubricant. Upon completion of cutting, wash-down the waveguides, diamond saw and floor area around the saw until all visible signs of carbon dust have been removed.

2.1.2 Dry the waveguides, diamond saw and surrounding area.

2.1.3 If necessary, mark the waveguide with a clearly visible mark of the required accuracy to show the slot position.

2.2 Prepare vice

2.2.1 Slot cutting may be performed by any machine that can rotate the tool with sufficient speed and follow the desired slot shape. In this work a Multicam M-I CNC Router was used. Fasten vice to bed of Router.

2.2.2 Align vice with Router Y-axis by first affixing a dial gauge to the X-axis gantry. Then position the dial plunger perpendicular the fixed face of the vice.

2.2.3 With the Router on the slowest slew speed, move the cutting head along the Y-axis and note the variation on the dial gauge.

2.2.4 Adjust the position of the vice and repeat step 2.2.3 until the dial indicates a difference of less than 0.01 mm across the length of the fixed face of the vice.

2.3 Install waveguide in vice

2.3.1 Clamp the waveguide to the vice as shown in Figure 25.

2.4 Rout slot

2.4.1 Install the desired router bit.

It has been found that some router bits “kick” as they penetrate the surface and leave a rounded offset at the end of the slot. In these cases it has been necessary to use a router bit that produces a slot narrower than the desired slot size and cut the slot in multiple passes, starting with the centre and moving out to the final size.

2.4.2 Adjust the X- and Y- position of the router head to the desired start point.

The position of the router cutter must be performed visually as implied by Figure 26. In some cases it will be sufficiently accurate to align the tip of the cutter with a mark made on the waveguide. There is limited visibility of the precise cutter location and it is estimated that this technique is accurate only to within 0.25 mm.

Figure 25: An aluminium waveguide clamped in vice on the Multicam M-I CNC Router bed

Figure 26: Adjusting the X-Y position of the router cutter bed

If greater accuracy is required a hard datum or optical alignment method will need to be developed.

2.4.3 Rout the slot(s) using suitable machine settings. The settings specified in Table 1 have been found to produce acceptable slots.

Table 1: Parameters used in cutting slots into CFRP waveguide

Parameter	*Value*	*Multicam Function numbers*
Feed speed (mm min^{-1})	20	1
Spindle speed (rpm)	15,000	2
Plunge (mm min^{-1})	20	15
Peck retract (mm)	0	15
Depth per pass (mm)	0.2	Set in RhinoCam

2.4.4 After the slot has been cut and the router program completed, loosen the vice and remove the waveguide.

Clean any carbon dust off the waveguide, vice and Router and dispose of dust in accordance with authorised safety procedures.

2.4.5 Inspect slot(s) to ensure that the location, shape, dimensions and smoothness of slot(s) are in-accordance with the design tolerances. If these conditions are not satisfied then the waveguide must be discarded and the slotting repeated on a fresh waveguide.

It may be necessary to observe the slot walls through a binocular microscope at moderate magnification. There must be no evidence of delaminations on the slot walls.

2.4.6 Repeat Steps 2.4.2 to 2.4.5 for the desired number of waveguides.

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Antenna design, Antenna Construction, Carbon fibre reinforced composites, Composite structures

19. ABSTRACT
Slotted Waveguide Antenna Stiffened Structure (SWASS) is a type of conformal load-bearing antenna structure where the top-hat cross-section stiffeners used to reinforce thin skins, or blade stiffeners in sandwich panels, serve the dual purpose of acting both as structural stiffeners and radiofrequency waveguides. Slotted waveguide antenna arrays are created by cutting slots through the outer skin and into these waveguide stiffeners. Development of the SWASS concept requires the production and evaluation of representative test specimens, one of which is a rigid rectangular waveguide. This report details Version 1.0 of a Standard Operating Procedure for the production of slotted waveguide antenna arrays manufactured from aerospace grade carbon fibre reinforced plastic (CFRP) prepreg.

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