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D2: Executive Summary
Friction Stir Welding (FSW) of Titanium Silicon Carbide Composites for Xenon Tank Applications

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TWI Endorsement

This report has been reviewed in accordance with TWI Policy

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Contents

1 Introduction

Titanium matrix composites have been identified as a potential route to component mass reduction in a range of space systems. Pressure vessels and propellant tanks have been identified as an area of interest for space craft and launchers and are the subject of a number of previous and on-going programmes in ESA and elsewhere. Tubular structures such as struts, actuators and robotic limbs (booms) are also of interest due to the low density, high mechanical performance and other characteristics of titanium composites. The range of opportunities for titanium composites to enhance system performance can be further extended through cost effective and flexible fabrication processes. This could include the development of an optimised process for welding composite or monolithic attachment features to simple geometry composite parts.

The European Space Agency (ESA) initiated a programme in March 2016 to investigate the capability of Friction Stir Welding (FSW) as a manufacturing method for joining titanium and silicon carbide based MMCs known as TiSiC, for Xenon tank applications for its future space programmes. ESA Ref: AO/1-8223/15/NL/RA. This TR (Technical Research) programme of work is aimed at increasing the options for fabricating titanium composite components and in particular pressure vessels and propellant tanks. The project aimed to assess the feasibility of using FSW to join TiSiC without damaging the reinforcing fibres and overall properties.

The general principle of this project was to develop an optimised set of parameters for a friction stir weld between TiSiC and TiSiC or monolithic titanium plates. The term optimised covers two aspects:

- The joint must be optimised so that the weld zone reaches similar mechanical properties to a conventional monolithic to monolithic titanium alloy friction stir weld.
- The joint thickness, separation between the weld and fibre and any monolithic overlap of the composite region must be optimised to eliminate fibre damage and enable load transfer between composite and monolithic regions. The performance of the monolithic material is lower than the composite and therefore, the greater the monolithic material needed for a robust joint, the greater the mass and bulk of the welded part.

2 Welding of TiSiC

The stationary shoulder friction stir welding (SSFSW) technique was developed for joining thin section (~2.7mm thickness) monolithic titanium alloy Ti-3Al-2.5V with TiSiC. The TiSiC plates consisted of Ti-3Al-2.5V matrix and 8 ply SiC fibres (diameter 140µm), manufactured using the hipping process. A 0.4mm thick monolithic cladding was present on each side of the plates. During pre-weld checks, which included X-ray, it was identified that the precision of the SiC reinforcement position, relative the FSW probe was insufficient for the requirements of the current study. After considerations by all partners, a plate rectification plan was established and TISIC Ltd reprocessed the panels with the goal of increasing the precision of the SiC positioning. Further X-ray inspections confirmed that the position of the SiC reinforcement in the reworked plates was now sufficiently consistent.

The welding trials were carried out using W-25%Re probes and Si_3N_4 stationary shoulders to explore process conditions (Figure 1). The FSW process parameters for three different tool rotation speeds and a constant traverse speed were explored to establish the best process parameters. The welds were characterised through metallography, hardness profiles and tensile testing. A tool rotation speed of 900rpm was selected for production of the characterisation welds as this parameter resulted in the highest UTS and excellent weld surface quality; full process parameters are listed in Table 1.

The control over dimensional accuracy of TiSiC plates is critical to the successful performance of the SSFSW process. However, because of multiple processing, the flatness of each panel had been compromised, thus requiring a small region of each plate surface had to be machine flat prior to friction stir welding. This local machining at the top and bottom surface of both the monolithic and TiSiC plates reduced distortion and taper present at the butted edges. The result was a welded plate with a 25mm margin of undercut at the joint, with a local plate thickness of 2.65mm and a reduction in monolithic width to 6mm on the TiSiC plates as shown in Figure 2.

Figure 1 TWI's FSW machine and the FSW tool probe in the stationary shoulder welding head.

Table 1 The process parameters selected for characterisation welds

Parameter	Value
Rotational Speed	900rpm
Welding Speed	100mm/min
Downforce	11.5kN
Pilot Hole Diameter	8mm
Pilot Hole Depth	1.1mm
Probe Length	1.3mm
Argon Flow	10L/min
Dwell	2Sec
Ramp Distance	33mm

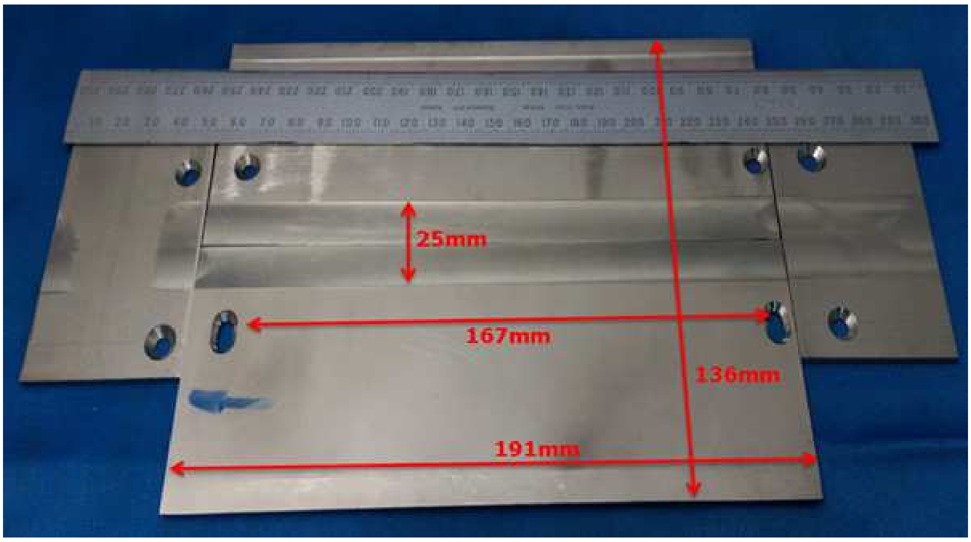


Figure 2 A pair of monolithic Ti-3Al-2.5V and TiSiC plates illustrating the local machining of reworked TiSiC and monolithic Ti-3Al-2.5V plates. The run-on and run-off tabs along with screw holes to mount plates into fixture are also visible.

3 Weld Characterisation

Friction stir welded joints between TiSiC and monolithic Ti-3Al-2.5V plates have been characterised using a range of tests, including; visual inspection, microstructure, microhardness, non-destructive inspection, tensile, fatigue, fracture toughness, fatigue crack growth rate, and residual stress. Stress corrosion crack (SCC) testing was not performed as per the original objective as the baseline test data gap analysis identified that such test data was already available to ESA via a prior study conducted between ESA, TISICS and AAC.

The FSW joints, welded using 100mm/min and 900rpm, appeared visually consistent, with little discoloration, a smooth surface finish, and no surface signs of cracking or porosity. Some plate surface discoloration was present on the root side of the weld. Each plate was subjected to X-ray NDI prior to destructive testing, with no signs of significant internal defects (cracks, pores) observable.

Sample metallography (Figure 3) confirmed the weld HAZ to be approximately 12mm wide at the top surface and 10mm near the root. At the widest portion, the HAZ just brushed the top fibre reinforcement ply, thus suggesting that a 2mm gap between the fibre reinforcement and a 10mm diameter FSW probe is just on the acceptable limit. Using the current setup, the temperature profile induced by the welding process (i.e. time at temperature) was not sufficient to cause significant thermal damage to the fibre reinforcement. Microhardness profiling indicated a slight elevation within the first 3mm of the fibre reinforcement end. Through the bulk of the FSW, the average hardness was 290Hv, slightly higher than that measured in the as-HIPed parent region at 270Hv.

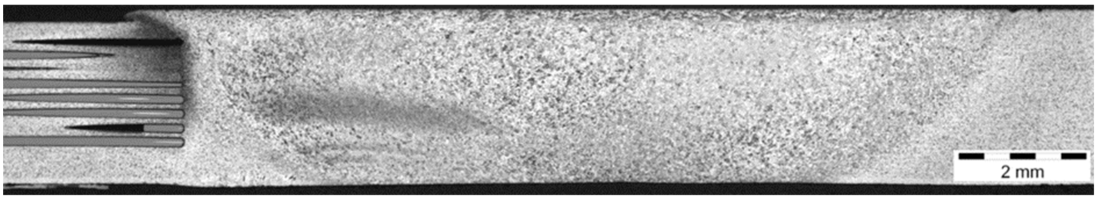


Figure 3 Macrograph of FSW at 900rpm and 100mm/min.

The FSW joint strength was shown to have an average UTS 5.89% higher than that of the parent as-HIPed alloy, whilst the strain to failure was 43% lower. This result is gauge length dependant due to the variations in microstructure along the gauge length. The fatigue performance of the FSW was also shown to be consistent with that of the as-HIPed parent alloy (Figure 4), both with respect to stress vs cycle response and fatigue crack growth rate measurements. With respect to fracture toughness, the data available suggested an 18.5% increase for the FSW (137.14MPa√m) joints vs the comparable diffusion bond (115.75MPa√m), although it is recommended that a greater number of specimens be tested in future studies. Five residual stress measurements were performed in the weld nugget, HAZ and parent material of a Ti-3Al-2.5V flat plate friction stir weld. The highest tensile residual stresses were measured in the weld nugget. These measured between 312MPa and 318MPa in the longitudinal direction and 25MPa and 67MPa in the transverse direction. Residual stress measurements in the HAZ and parent material were low, the maximum principal stresses measured between -23MPa and 16MPa.

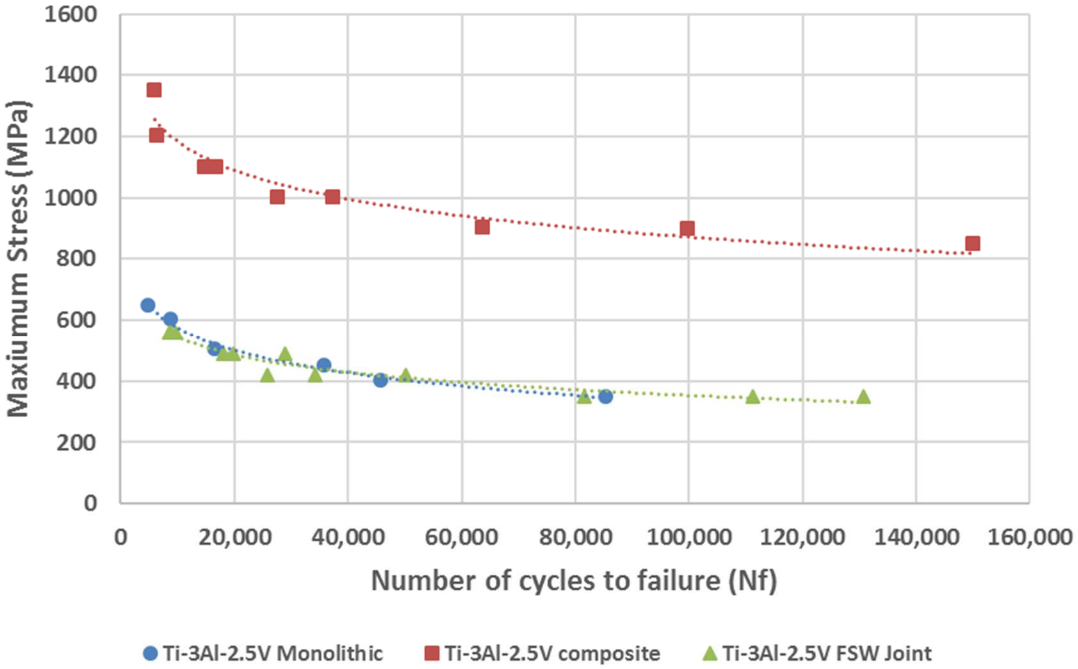
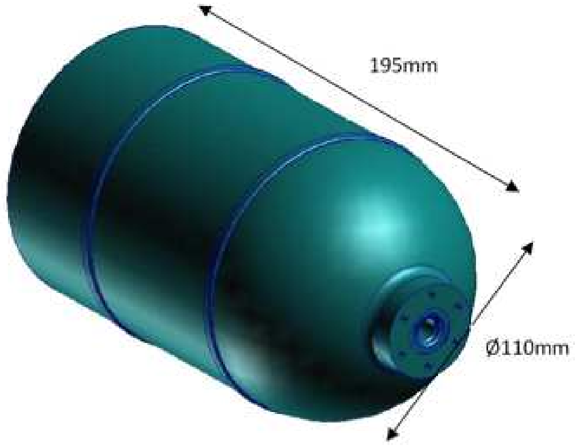


Figure 4 Comparison of the fatigue behaviour for friction stir welded Ti-3Al-2.5V joints vs as-HIPed alloy and composite materials.

4 Structural Component Comparison

A Xenon tank was selected as the target structural component (Figures 5 and 6). As a minimum, the material performance of the FSW joint as implemented into the structural component should meet or exceed that of the current technology (i.e. diffusion bonding). As such, the structural component performance requirements are the same as the diffusion bonded, i.e. baseline material performance.



- 195mm (8”) high x 110mm ($4^1/_2$”) diameter
- 3mm ($\sim^1/_8$”) wall
- 1.1ltre capacity

Figure 5 Surry Satellite Technology Ltd pressure vessel front view.

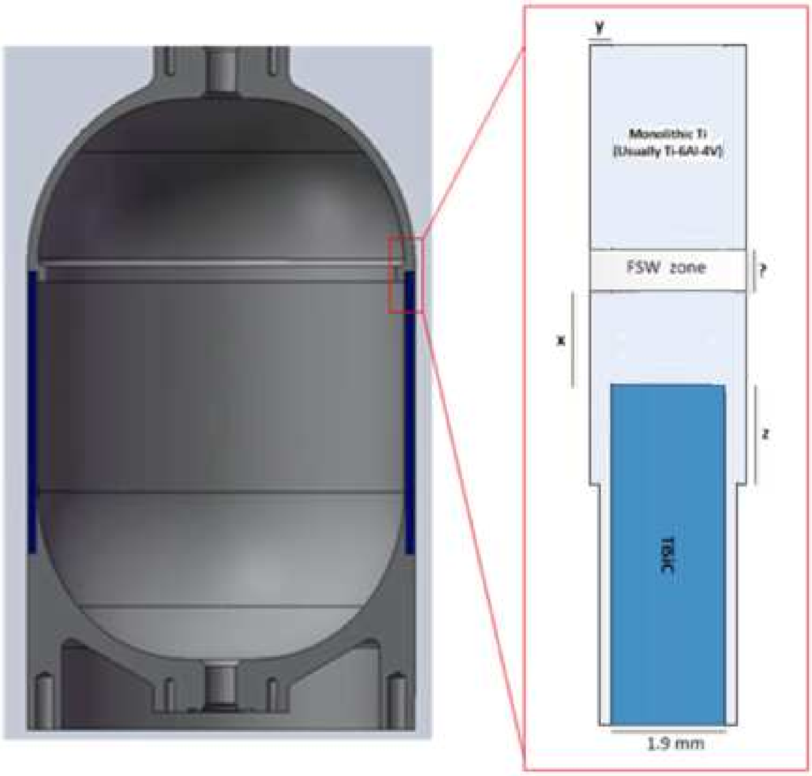


Figure 6 Pressure vessel cross section view alongside schematic of joint variables.

As a minimum, the material performance of the FSW joint as implemented into the structural component should meet or exceed that of the current technology (i.e. diffusion bonding). As such, the structural component performance requirements are the same as the diffusion bonded, i.e. baseline material performance. Table 2 presents both the baseline and FSW joint performance data for comparison. The FSW joint meets or exceeds the diffusion bond in all aspects apart from strain to failure, therefore, the FSW joint can be considered to satisfy the structural component requirements in each of these areas. When considering the strain to failure, the structure itself will consist of both a composite body and monolithic ends. Given that the composite has a strain to failure of 1%, despite the FSW joint being 50% that of a diffusion bond, in absolute terms a strain to failure of approximately 10%, as with the FSW joint, would be satisfactory.

Table 2 Comparison of WP5 results against the baseline and structural component requirements

Parameter	Parent Baseline	FSW	TISICS Baseline	Target Component Requirement	Acceptable
Visual	Seamless	Slight distortion	Seamless	Properties dictate	N/A
Microstructure	Homogenous, coarse grains	Non-homogenous, fine grain	Non-homogenous	Properties dictate	N/A
Micro-hardness (Hv)	280	290	295 [3]	Non-critical	Yes
Ultimate Tensile (MPa)	679	719	1650	Same or higher	Yes
Yield Strength (MPa)	576	613	576	Same or higher	Yes
Strain to Failure (%)	20%+	~10%	~1%	>1%	Yes
Youngs modulus (GPa)	115	129	200	Same or higher	Yes
Fatigue	100,000 cycles @ 400MPa	100,000 cycles @ 400MPa	100,000 cycles @ 900MPa	Same or higher	Yes
Fracture Toughness (MPa√m)	115	137	N/A	Same or higher	Yes
Fatigue Crack Growth Rate	1×10^{-3} @ 30 MPa√m	6×10^{-4} @ 30 MPa√m	2×10^{-4} @ 30 MPa√m	Same or higher	Yes
Residual Stress (MPa)	11	318	200-450	Up to 450MPa	Yes

The structural component requirements set out in TN1 also stipulated the need for additional clarification with regards to 3 geometrical parameters; x- welding distance from fibre ends, y – monolithic surface cladding, z- monolithic transition length. The quantitative property values obtained for the FSW joint can now be used in future studies to help select the appropriate thickness of the monolithic regions. Since the performance of the FSW has been shown to be comparable or superior to that of a diffusion bond, there is no specific requirement for an additional knockdown factor to account for the presence of the FSW. In other words, the thickness of the monolithic regions (i.e. geometrical parameters y & z) do not need to be increased beyond what is required for a diffusion bonded joint, which would normally be sized to match the TiSiCs region. In addition, the process development trials have identified that a 2mm probe to fibre distance is satisfactory when welding 3mm thick material with a 10mm diameter probe.

Figure 7 shows an illustration of the recommended configuration for FSW of TMC, based on the experience gained throughout the current programme. To maximise the strength of the joint, the goal is for the failure to occur through the stronger composite material. As such, the weaker monolithic regions will have to be sufficiently thickened. Future developments can now use the test data summarised in Table 2 to generate specific component joint designs.

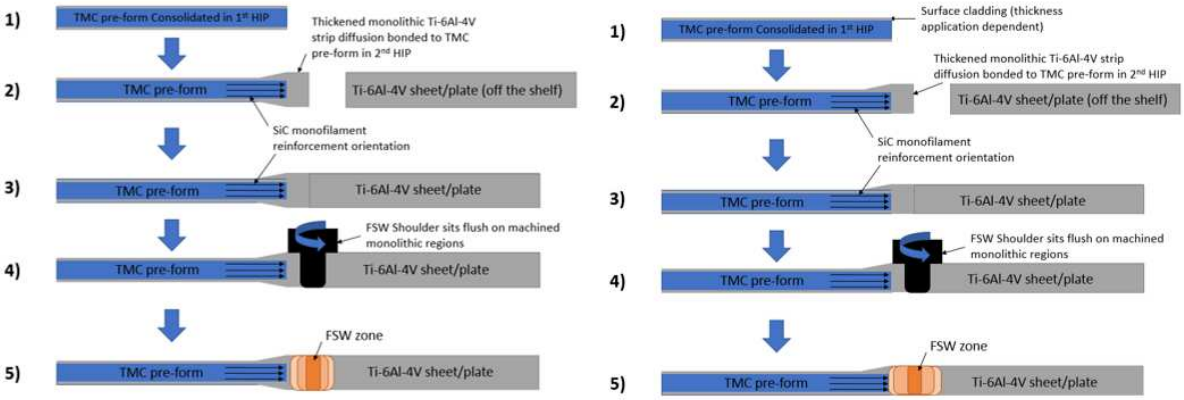


Figure 7 Recommended TMC panel configuration for FSW: Option 1 double taper; b) Option 2 single taper.

5 Summary of Lessons Learned

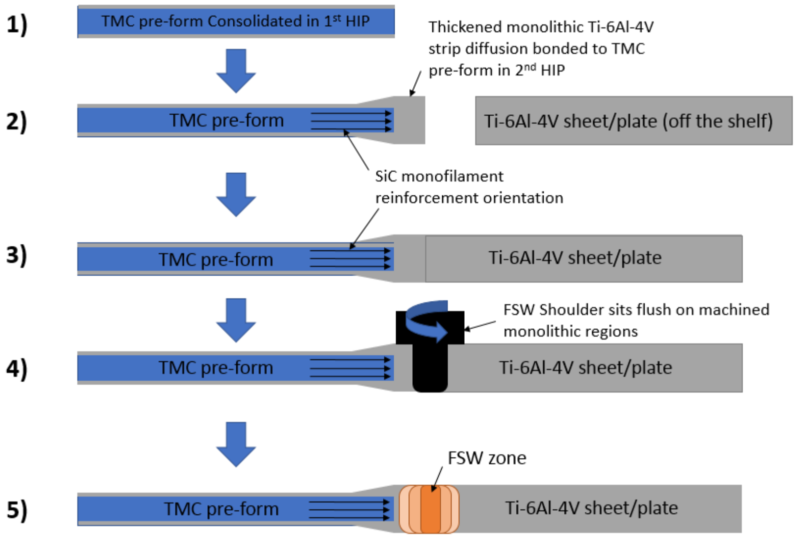
5.1 Material manufacture

Processing all TiSiC plate material in a single batch provides little scope to make corrective action when things go wrong. Future project plans should assume TiSiCs material is supplied in a series of smaller sequential batches. Panel sectioning should be performed after release agent removal, thus enabling better marking of cut lines, and more anomalous surface features to be identified pre-sectioning. Wire EDM should be used for precision TISICS panel sectioning, even if this means delaying delivery. Mechanical cutting should only be used if the precision requirements are low. Future panel manufacture for SSFSW should assume that a finish machining operation will be required to ensure panel fit. Run-on and run-off plates do not have to be integral to the panels being welded, so long as the fixturing is sufficient. This same approach may also apply to the welding if 3D structures. For panels, this significantly simplifies the TiSiC panel manufacturing requirements and allows the fibre termination position to be visible pre-weld. Programme characterisation tests showed how steps on the test specimen surface could artificially constrain failure into the weld HAZ (often stronger than the parent alloy). Useful for identifying actual weld strength, but not consistent with test standards, as such, the steps need to be removed prior to specimen testing.

5.2 Recommended panel manufacturing method

TISICS Ltd should use a 2-step manufacturing route to diffusion bond a monolithic Ti-6Al-4V strip onto the edge of a pre-consolidated TiSiC panel. The TiSiC preform should be wire eroded for controlled fibre termination and position control. The thickness of the Ti-6Al-4V monolithic strip should be greater than that of the bulk TiSiC plate, with a gradual taper leading from the TiSiC plate to the maximum monolithic thickness. The thickness increase will be such that the tensile failure load of the monolithic region will exceed that of the higher strength TiSiC plate. The Ti-6Al-4V monolithic plate for welding should be purchased from commercial suppliers. Any run-on and run-off required should be provided by separate monolithic plates as demonstrated in the current programme.

Two weld configurations are available, the first is to have a double taper, where there is a transition to a thicker monolithic region on both faces of a TiSiC plate. This is a more balanced configuration, but the initial plate manufacture and fixturing would be more complex. Option 2 is to have a sufficiently large taper on only one of the TiSiC panel faces, this isn’t symmetrical, but would be easier to manufacture and fixture during the FSW process (see Figure 8).



a)

Figure 8 Recommended TMC panel configuration for FSW:
a) Option 1 double taper.

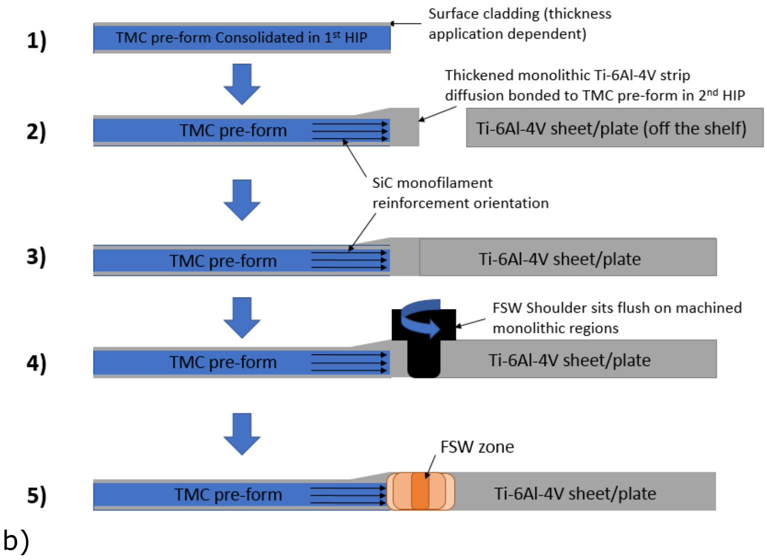


Figure 8 (continued) Recommended TMC panel configuration for FSW:
b) Option 2 single taper.

This above approach overcomes several issues encountered within the current programme; namely being able to precision machine the oversized monolithic strips flat, without any risk of reliving residual stresses or hitting the TiSiC reinforcement. Since the stationary shoulder would never rest on the TiSiC plate, the as-HIPed plate condition would no longer be relevant. There would also no longer be a requirement to remove steps form the test specimens post welding.

6 Conclusions

- The SSFSW technique successfully produced sound welds in monolithic Ti-3Al-2.5V to TiSiC plates, with highest ultimate tensile strength of 768MPa achieved.
- The monolithic width of 6mm on the abutting edge of TiSiC plates is sufficient to avoid any damage to SiC fibres during welding.
- The control over dimensional accuracy of TiSiC plates is critical to the successful performance of the SSFSW process.
- Friction stir welded joints between TiSiC and monolithic Ti-3Al-2.5V plates have been characterised using a range of tests. The FSW results were comparable or higher than the baseline (i.e. diffusion bond) in every metric tested apart from strain to failure, which was approximately 50% that of the baseline.
- A comparison between The FSW performance was compared to target structural component performance needs for a Xenon tank. The structural component requirements are based on the baseline performance thus, as expected, the FSW results satisfied the necessary criteria in every tested metric. This also included strain to failure because, although the FSW was approximately 50% that of a diffusion bond, given that the TiSiCs material has a strain to failure of 1%, a strain to failure higher than this would still be satisfactory.

TWI Ltd Management System

TWI operates a certificated Management System designed to ensure that Customer requirements are met and that all work carried out is conducted in a planned and controlled manner. Customer satisfaction is a key measure of the success of TWI, which remains committed to delivering world-class solutions. To this end:

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The Management System operated by TWI includes the following features that are particularly relevant to ensuring successful projects:

- Close and frequent contact with the Customer by the Project Leader throughout the project. In particular, any changes in key personnel involved in the project or equipment availability will be discussed together with any potential project delays or contractual changes.

- Regular management reviews are held throughout the life of a project and upon its completion. These cover project finances, technical progress and adherence to schedule.

- Project Customers are formally contacted on project completion to determine their satisfaction with the work carried out. Moreover, TWI senior management welcomes Customer feedback on project progress at all times during the course of the work. Significant lapses in service will be subject to a structured management review so that inadequate procedures can be identified and improved.

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