Report No: 24736-Ex/1v1/16

December 2016

For: European Space Agency, M&P Division

Executive Summary
Friction Stir Welded Low-cost Titanium Propellant Tank for the Space Industry

TWI Ltd, Granta Park, Great Abington, Cambridge CB21 6AL, United Kingdom. Tel: +44 (0)1223 899000

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(See inside back cover TWI Management System.)

TWI Report: Executive Summary

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Prepared for: European Space Agency, M&P Division

Contact: Andy Norman

Authors: Dick Andrews, Naveed Iqbal, Khalid Nor and Alex Robelou

TWI Endorsement

This report has been reviewed in accordance with TWI Policy

Project Leader ....
(Signature)

Print name: Dick Andrews

Technical Reviewer ....
(Signature)

Print name: Kathryn Beamish

Approved by ....
Product Manager
(Signature)

Print name: Adrian Duncan

Approved by ....
Group Commercial Manager
(Signature)

Print name: Andrew Carey

Administrator ....
(Signature)

Print name: Helen Everson

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1 Introduction

A propellant tank is a container in space vehicles, where liquid propellant is stored prior to actual use. Propellant tanks vary in construction and are quite sophisticated since high strength and low weight is a premium. The space industry is increasingly interested in lighter weight, highly reliable, less complicated and cost effectively manufactured propellant tanks for advanced satellite launchers. Aluminium and titanium alloys are usually used to fabricate such tanks, and the search for new tank designs along with high performance metallic materials and advanced manufacturing processes is always in the forefront of designer's minds.

The standard on-board spacecraft propellant is hydrazine, contained in propellant tanks fabricated by forging and machining of hemispheres and cylinders of titanium alloy Ti-6Al-4V. The components, which have a shell thickness between 1 and 4mm, and an outer diameter between 0.5 and 2 metres, are typically joined (girth weld) together by electron beam (EB) or Tungsten Inert Gas (TIG) welding. The examples of such propellant tanks include 104, 177 and 218 Litre Hydrazine Tanks: A typical propellant tank is shown in Figure 1.

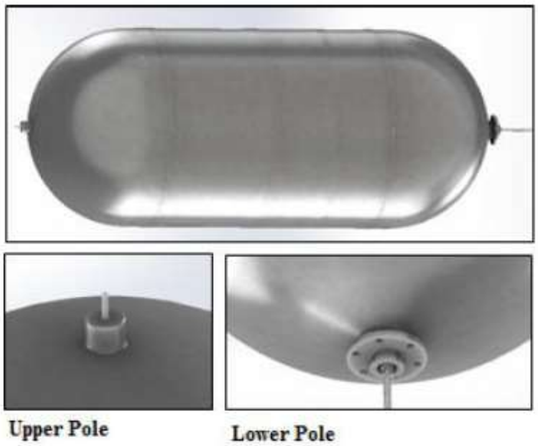


Figure 1 E3000 Tank – Typical propellant tank.

The titanium propellant tanks are usually manufactured from oversized forgings from which the excess material is then machined. This manufacturing method is very wasteful of material leading to high 'buy-to-fly' ratio, high costs along with long manufacturing times. Therefore there is a need for more sustainable, robust and cost-effective manufacturing route for these tanks. On the welding side, although EB welding is currently used to make the girth weld in propellant tanks, there are a number of associated limitations due to this fusion based weld process. This is mainly associated with the formation of defects such as pores and cracks, which are potentially detrimental to the mechanical integrity of the tank structure.

FSW of high strength, high temperature materials like steel, titanium and nickel based alloys has received increasing interest worldwide. However, welding these materials requires FSW tools with a high strength at elevated temperatures. The tool must also be resistant to fatigue, fracture, mechanical wear and chemical reactions with both the atmosphere and the work piece material. Up to now ceramic polycrystalline cubic boron nitride (pcBN) and refractory metal or tungsten-based tool materials show promising weld results, but they are reported to exhibit a short lifetime.

2 Development

In 2014 the European Space Agency (ESA) initiated a programme consisting of seven work packages (WP 1-7) to investigate the capability of friction stir welding (FSW) as a manufacturing method for making titanium propellant tanks for future space programmes.

TWI, in partnership with Airbus Defence and Space in Stevenage, developed a proposal to conduct a feasibility study of Stationary Shoulder Friction Stir Welding (SSFSW) for titanium alloys suitable for launch vehicle propellant tanks.

The main aim of this programme was to raise the technology readiness level of SSFSW of titanium alloys from TRL3 to TRL6 in conjunction with a potential reduction of costs against the current conventional approach for manufacturing propellant tanks. The two-year project comprised of two phases of work:

1. Develop, characterise and validate the SSFSW process and system required for welding titanium alloy(s).
2. Manufacture titanium demonstrator tanks using the SSFSW process (Figure 2). The manufacturing process will be compared with current conventional technical approaches in terms of cost, reliability, efficiency and environmental impact.

Figure 2 Demonstrator propellant tank design.

Current fabrication methods for propellant tanks have several drawbacks:

- High-cost forging
- Long delivery time for forging
- High-cost machining process
- High buy-to-fly ratio
- Fusion-based welding process limitations

TWI and Airbus worked together to undertake an extensive review of materials and manufacturing routes and taking into consideration the limitations identified above, associated with the current manufacturing route there were two main issues to resolve as follows:

- How to reduce the cost and delivery time of the currently forged and machined hemispheres and cylinders from which propellant tanks, such as the Eurostar family are manufactured?
- What alternative welding process has the potential to reduce the incidence of porosity and/or cracking?

In the early stages of this project, suppliers with a known capability for the manufacture of propellant tank components (forged and machined) were asked to provide quotations to supply sufficient parts for manufacturing five tanks. However, it quickly became clear the purchase of these parts (particularly from Mecachrome) would absorb more than 50% of the total project budget, combined with a six month delivery lead-time. This cost and timescale were not acceptable for a welding technique development programme, in terms of the funding available, or the project duration. In fact, if this route had been pursued it is likely that demonstrator tanks would not have been produced before the current project completion date of the end of 2016.

This information fully justified the previously mentioned statement regarding the need for a 'more sustainable, robust and cost effective method of manufacturing the tanks'. In parallel with the procurement exercise for forged and machined parts, two spin forming companies were asked to provide quotations (SpinCraft UK and Keystone Spinform USA). In both cases the budget required to produce sufficient hemispheres was similar to the forge and machine costs, as were the timescales, which again was considered to be unacceptable. Neither company could quote for manufacture of the cylinders and thus the machine from solid or forge and then machine route would have to have been used, further adding to the procurement costs. The spin forming route now looked to be far less attractive as a viable alternative manufacturing route, in terms of the objectives of this project, than had originally been suggested.

Although discussed at the outset of this project, the use of cast Ti-6Al-4V alloy components had been addressed with some caution, because of the expectation of casting flaws such as porosity, solidification cracking and a large grain size. However, contact with Casting Technology International Ltd UK (CTI), a state-of-the-art casting specialist, revealed that it would be possible to produce near-net shape castings using spin casting in Ti-6Al-4V alloy with metallurgical and mechanical properties within the Airbus Defence and Space task material operating specifications.

As the prices for components manufactured by the traditional forge and machine and also the spin forming route were considered unacceptable for this programme, a qualitative trade-off study was carried out as shown in Table 1. The table shows that the casting route had the potential for realising the overall project aims of developing a production route for the manufacture of lower cost propellant tanks within the available project budget and timescale. On this basis, the cast material was investigated in more detail. Following this review wrought and cast Ti-6Al-4V alloy was procured for welding trials and mechanical property assessment.

A representative demonstrator tank design was developed and agreed with ESA and Airbus and is shown in Figures 2 and 3.

Table 1 Qualitative trade-off between the Ti-6Al-4V alloy propellant tank component procurement/manufacturing options for this project

Decision Matrix				**Tank Component Manufacturing Options**			
Criteria		Weight	Scale	Spin forming	Forging	Casting	Machining from solid
Delivery time		30	5=least time 1= most time	2	2	5	2
Component cost		30	5= least cost 1= most cost	2	1	5	1
Mechanical properties compared to minimum acceptable data	Tensile strength	10	5= most cost 1= least cost	4	5	3	4
	Yield Strength	10		4	5	3	4
	Fracture toughness	10		3	3	5	3
Novelty		10	5= novel 1= least novel	4	3	5	5
Weighted total in %		100		54	50	92	50

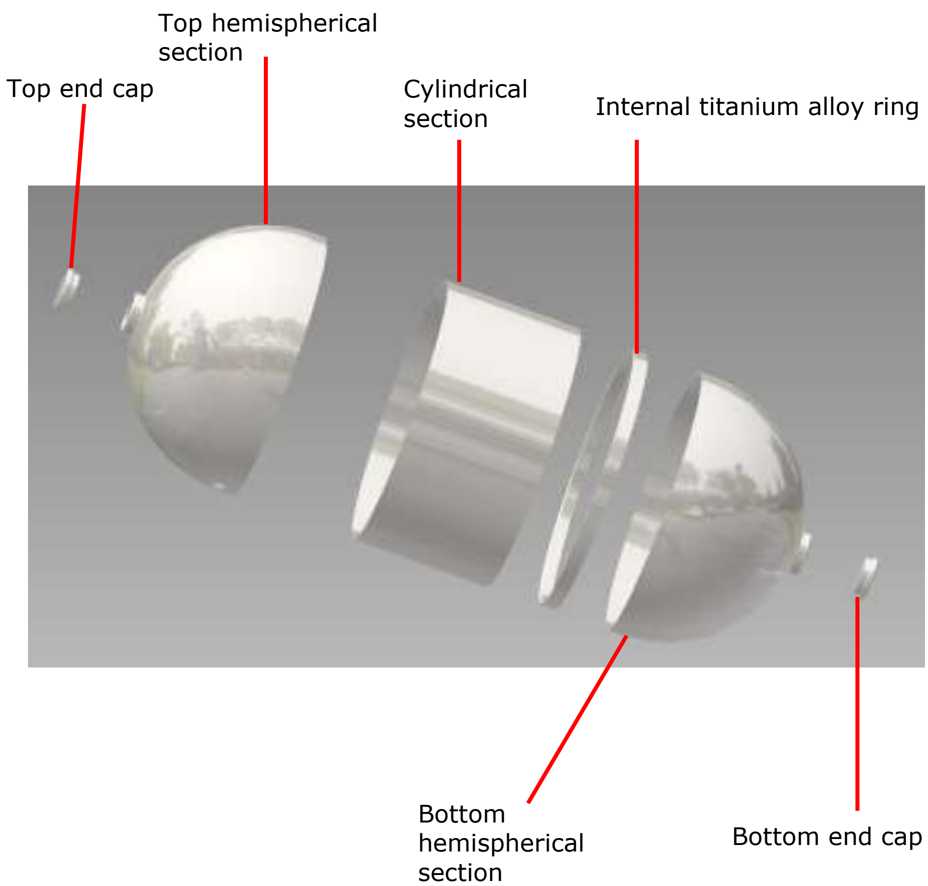


Figure 3 Exploded view of the titanium alloy demonstrator tank.

2.1 FSW Machine

In this project, all welding trials during the development study were to be carried out using TWI's ESAB SuperStir gantry-type machine. This machine is equipped with both high and low rotational speed welding heads. The high speed welding head was used in this study.

The SuperStir machine can be controlled in the position and force control modes. When operating in position control, the height of the rotating tip of the FSW probe above the tool bed (z-axis position) is monitored by a linear transducer and a set position is maintained using a feedback loop. The z-axis force is automatically adjusted as necessary to keep the FSW tool in the required position. Figure 4 shows the ESAB SuperStir machine.

TWI Neg No: D002131_01

Figure 4 TWI's ESAB SuperStir machine.

2.2 SSFSW

Although other Research and Technology (R&T) organisations have developed equipment, FSW tools and procedures for welding titanium alloys, TWI has continued with the use of SSFSW particularly for propellant tank application. This technique has been found to be suitable for the propellant tank application for the following reasons:

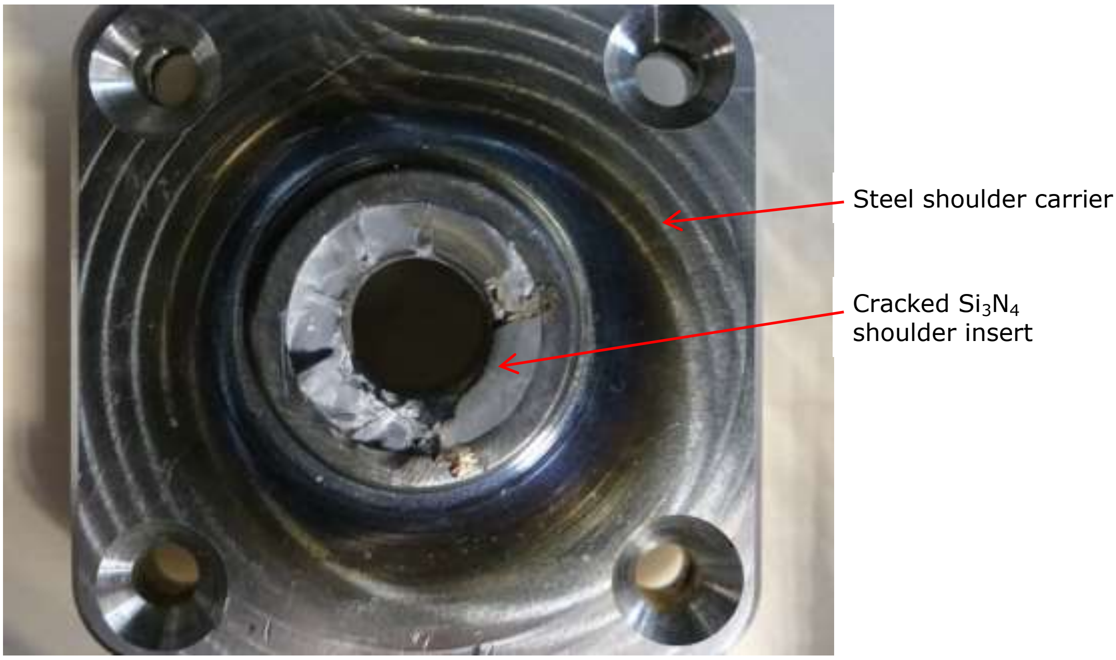
- Conventional FSW uses a rotating shoulder and probe in combination to produce frictional heating and material softening and it has proved difficult to produce a homogeneous microstructure through the thickness of a titanium plate or sheet.
- The lack of microstructural homogeneity is associated with the relatively low thermal conductivity of titanium and its alloys. It has been found to be difficult to establish FSW parameters that can produce a good plate/sheet top surface appearance and good weld quality as well as a flaw free weld root. When using welding conditions that produce a good top surface appearance and microstructure, poor thermal conductivity prevents sufficient frictional heating reaching the weld root. Alternatively, if welding conditions are used to produce a good quality weld at the root, the plate/sheet top surface becomes overheated resulting in surface breaking flaws.
- The SSFSW technique uses a rotating probe only, which generates through thickness weld microstructure homogeneity, because there is not the excessive heat input resulting from the rotating shoulder when using conventional FSW.
- The probe diameter to length ratio (D:L) for SSFSW of titanium alloy is very favourable when welding 2.4mm thick sheet at 1:0.13. This permits the rotating probe to withstand a high traverse (x-axis) force, without the

danger of premature failure. The heating and mixing action of FSW tools extends for a certain (material specific) distance below the tip of the tool probe. The ceramic coated backing bar used in this programme prevented significant heat loss to the backing bar, maximising heating efficiency. It was thus possible to produce a through thickness weld in the 2.4mm thick sheet with a probe sticking out from the stationary shoulder by only 1.3mm.

2.3 Ceramic Stationary Shoulder/Shoe

Various geometries and dimensions of sliding shoe/shoulder were designed and manufactured for improved lifetime when producing ~1.5m circumferential tank welds. The material selected was the so-called "flexible" ceramic silicon nitride (Si_3N_4), which has high wear resistance and toughness.

The original ceramic stationary shoulder/shoe design that had been progressively developed for welding titanium alloys was assessed. It was clear from this earlier work that the small silicon nitride (Si_3N_4) shoulder inserts were not sufficiently robust to produce welds 1.3m long (circumference of the demonstrator tanks) and greater, as illustrated by the extensive cracking in Figure 5.



TWI Neg No: P1050168

Figure 5 An example of the cracking experienced when using the earlier design Si_3N_4 small shoulder insert.

TWI developed a solution, working with industry suppliers to overcome this problem. A stationary shoulder made in a high quality grade of Si_3N_4 as a one piece part was designed because utilising the increased volume of material provided greater strength to withstand the applied welding forces. In addition, fracture of the shoulder was reduced.

2.4 Backing bars

It is very important to use a backing bar that is inert to hot, softened Ti-6Al-4V alloy (does not become part welded, which occurs with steel backing bars). In addition, for the production of good weld quality the SSFSW process relies on minimal heat transfer away from the weld zone into the backing bar and support tooling. The method devised for limiting heat transfer was the use of solid ceramic backing bars, such as alumina (Al_2O_3) and syalon but these materials are extremely prone to cracking via thermal expansion and contraction and also thermal shock.

Although the use of a solid ceramic backing bar was ideal for demonstrating the capability of the SSFSW process for producing high quality welds in titanium alloys, it could not be practically considered for the manufacture of Ti-6Al-4V alloy propellant tanks. The reason being, that the manufacture of a large annular (~1.3m diameter) internal backing bar containing solid ceramic segments with a curved profile would be complicated and costly. Also, following the welding process, cracked expensive solid curved ceramic segments would have to be replaced prior to further welding.

With the production application in mind, steel backing bars with a thin ceramic coating were selected as a more durable, less costly, practical solution. These ceramic coatings applied to steel backing bars were shown to prevent the Ti-6Al-4V alloy becoming attached to the backing bar and also acted as a thermal barrier to assist weld formation. This was an important milestone in the programme as it considerably reduced the complexity associated with a circumferential backing bar which had to incorporate a ceramic outside diameter. Solid ceramic inserts would have had to be diamond ground to size and interfaced with a suitable internal sub-structure.

2.5 Weld development – wrought and cast coupons

Initial welding trials using TWI's recent developments in stationary shoulder friction stir welding (SSFSW) tools demonstrated excellent results, producing high-quality welds and, importantly, demonstrating a meaningful extension in the lifetime of the tool.

The work commenced with weld trials on wrought Ti-6Al-4V alloy flat plate to define the optimum process parameters as shown in Figures 6-8. These welds underwent preliminary testing, allowing identification of the optimised process window for this application.

TWI Neg No: X256178

Figure 6 Setup for wrought flat plate SSFSW trials.

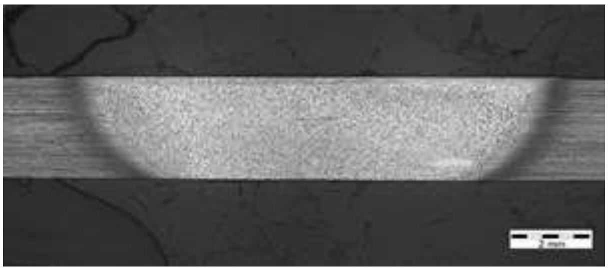


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Figure 7 Transverse metallographic section cut through SSF welded wrought Ti-6Al-4V alloy plate.

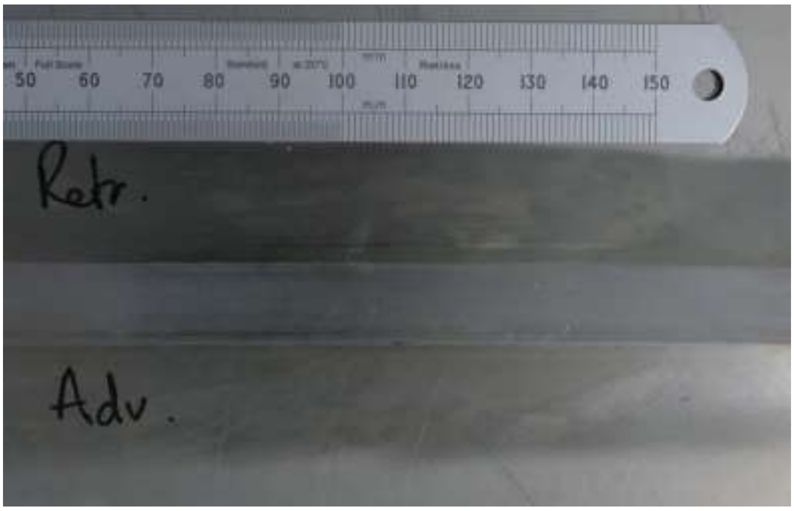

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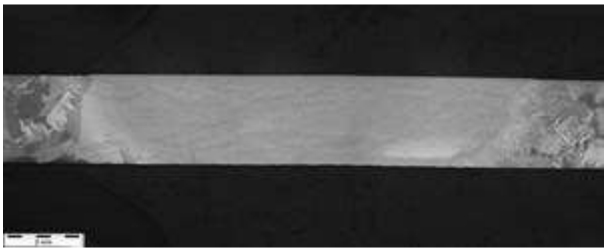
Figure 8 Smooth surface finish on SSFSW wrought Ti-6Al-4V alloy plate.

Following completion of initial trials TWI progressed to verify the welding parameters on cast flat-plate coupons. Welds were produced to confirm the process conditions were comparable from wrought plate to cast material, with the result that no further weld parameter development was required. The surface finish of a weld in cast plate and a transverse metallographic section are shown in Figures 9 and 10 respectively.

TWI Neg No:P1070474

Figure 9 Cast Ti-6Al-4V alloy surface finish



TWI Neg No:S42768

Figure 10 A transverse metallographic section through SSFSW welded cast ti-6Al-4V alloy plate

2.6 Circumferential welding

During the flat plate welding trials, TWI established the required tools, fixtures and jigging, shown in Figure 11, to enable the welding of curved coupons representative of the final demonstrator.

TWI Neg No:P1090981

Figure 11 TWI developed tooling to support circumferential FSW trials.

TWI undertook the first curved weld trial, making a full circumferential weld to join two 420mm diameter cylinders to form a barrel, as shown in Figures 12 and 13. Following successful completion of the weld, it was subjected to non-destructive testing (NDT) and mechanical testing to determine its quality and properties.

TWI Neg No: P1090837

Figure 12 Welding underway on the cylinder-cylinder

TWI Neg No: P1090902

Figure 13 First full circumferential weld.

A cylinder-to-hemisphere circumferential weld was made to complete the weld development work package. The weld was completed using the same welding parameters and was a full circumferential weld on the 420mm diameter cylinder configuration representing a significant improvement in the tool life in the application of FSW for titanium alloys.

2.7 Testing

A comprehensive testing regime assessed the performance of SSFSW of cast titanium. Visually, the welds produced in the cast material were very similar to those in wrought material. No top surface breaking flaws or bottom surface root flaws could be detected visually.

TWI Neg No:24788_1_16_59

Figure 14 Cylinder-cylinder set up for X-ray

2.7.1 NDT examination

Non-destructive testing was carried out on 15 titanium welded plate coupons and 1 cylinder to cylinder weld using:

- Ultrasonic Immersion Testing.
- Digital X-ray radiography.
- X-Ray Computed Tomography (for verification).

2.7.1.1 NDT of development welds

During weld development, ultrasonic testing was able to detect a cluster of micro-voids in a forged FSW plate (produced using welding parameters outside the weld parameter tolerance envelope) which correlated well with the micro-sectioning results. Further to this, radiography revealed that the micro-voids contained tungsten-rhenium alloy deposits from the SSFSW probe.

Ultrasonic testing detected weld cracking at the weld root in a cast plate and again there was a good correlation with the micro-sectioning results. Radiography established a portion of the ceramic coating on the backing bar had become impressed into the partially welded flaw. Following identification of these indications, the team optimised parameters and undertook a study of potential backing bar coatings in order to achieve improved results.

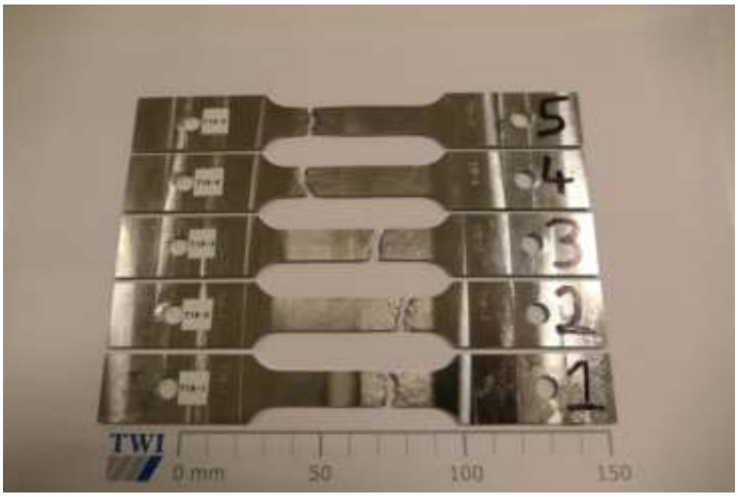
Digital radiographic inspection of a full circumferential cylinder to cylinder weld was carried out and no volumetric defects were identified (Figure 14).

2.7.2 Tensile testing

Tensile tests undertaken on the cast material welds revealed a weld efficiency of 93% (Table 2). All specimens tested failed in the parent metal (Figure 15).

Table 2 Average cross weld tensile test values for cast Ti-6AL-4V plate

Specimen identity	Proof stress Rp 0.2% N/mm^2	Maximum stress N/mm^2	% Elongation
Parent material	854	951	7.7
Weld T18	899	910	5



TWI Neg No:P1090026

Figure 15 Cast Ti-6Al-4V Alloy FSW - Tensile tests

Further tensile testing was undertaken on specimens taken from the cylinder-cylinder welded assembly. The results, shown in Table 3 were considered to be encouraging.

Table 3 Average cross weld tensile test values for the first cast cylinder to cylinder weld

Specimen identity	Proof stress Rp 0.2% N/mm^2	Maximum stress N/mm^2	% Elongation
A	845	930	3.7
B	845	933	5
E	855	943	4.3
H	843	953	5
Parent cast flat plate	854	951	7.7

2.7.3 Fracture Toughness

The fracture toughness results for the parent material and the weld were consistent, with the parent material having a higher average value of fracture toughness (340kJ/m^2 and 181kJ/m^2 respectively). Figure 16 shows a cast Ti-6Al-4V Alloy SSFSW sample after testing. The calculated values of fracture toughness are comparable with values taken from the literature for similar Ti-6Al-4V material.

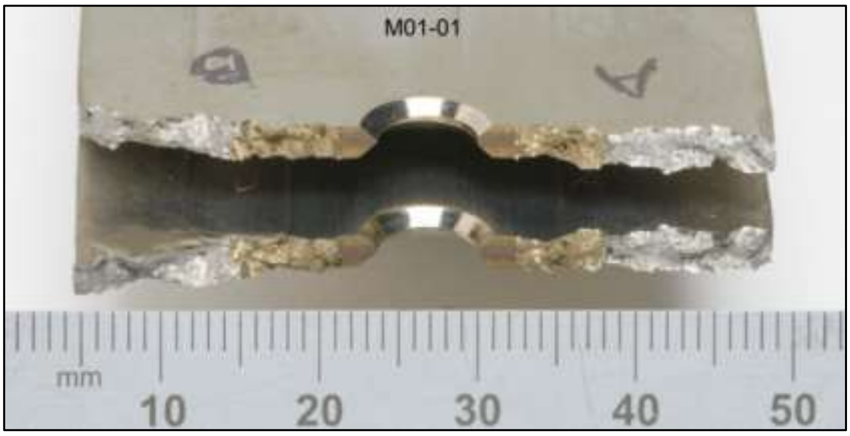


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Figure 16 Cast Ti-6Al-4V Alloy FSW - Fracture toughness testing.

2.7.4 Stress Corrosion Cracking

ECSS-Q-ST-70-37C(1) assigns three classes of material stress corrosion cracking susceptibility. No specimens failed during the thirty days of exposure. Mechanical testing of the stressed specimens showed an average tensile strength of 934MPa which was well above 90% of that of the unstressed specimens (90% of unstressed UTS average of 931MPa is 840MPa). No stress corrosion cracks were observed in any of the samples tested during the programme. The welded material therefore can be classified as Class 1: High resistance to stress corrosion cracking.

2.7.5 Microhardness survey

Hardness surveys were carried out at the centre line of the specimens taken from the cast cylinder-cylinder weld. A comparison between hardness surveys carried out on SSFSW weld cast Ti-6Al-4V and mill annealed (MA) wrought Ti-6Al-4V alloys are shown in Figure 17.

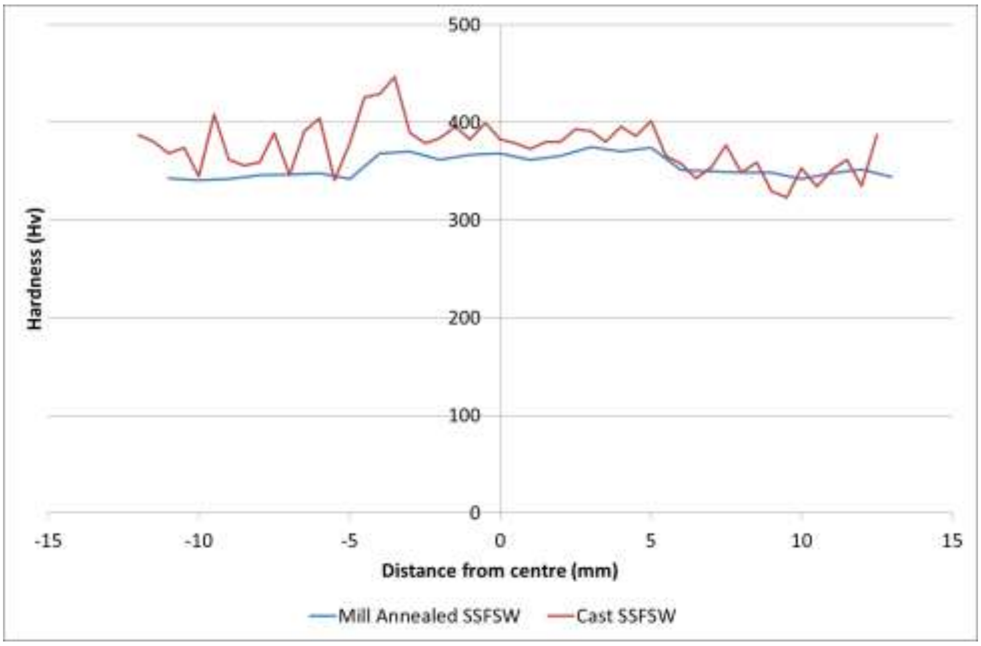

Figure 17 Typical variation of micro hardness across the weld and at the centre of 2.4mm thickness Ti-6Al-4V MA alloy and Ti-6Al-4V cast alloy.

2.8 Demonstrator tank

Following completion and verification of the welding parameter development, TWI successfully welded the first FSW demonstrator propellant tank (Figure 18), which were finish machined by CNC Rotherham. The tank is now on display at the European Space Agency (Figure 19).

TWI Neg No:P1100848

Figure 18 Fully welded assembly on fixture.

TWI Neg No:P1110492

Figure 19 The first FSW cast Titanium alloy propellant tank demonstrator.

Production of further demonstrators is anticipated and it is hoped that follow-on work will be undertaken to further test and assess the performance of the FSW assemblies.

3 Summary of Lessons Learnt

This summary of lessons learnt throughout this development programme to manufacture demonstrator propellant tanks in Ti-6Al-4V alloy using SSFSW is given in Table 4. The main issues that had to be overcome or improved are briefly mentioned.

Table 4 Summary of lessons learnt

Testing	Project Start	Project End
Standards	Wrought material thickness below minimum quoted in fracture toughness standard ECSS-Q-ST-70-45C	EFAM GTO 02 (GKSS, 2002) applied and results compared well with literature data.
	Wrought material thickness below minimum quoted in fatigue crack growth standard ASTM E647	BS 12108 applied, although material thickness insufficient to avoid out of plane deflection.
Materials	Limited supply chain for material procurement	Supply chain established for procurement of cast Ti-6Al-4V tank parts
	Wrought material most suitable but not available in wide range of dimensions	Cast material suitable for manufacture of demonstrator tanks

Manufacture	Project Start	Project End
Fixtures	W1 fixture possible. Steel expanding or segmented mandrel.	Required ceramic coating on working surface. Reaction processed ceramic made it possible to produce circumferential tank welds.
	W2 fixture – extremely difficult to extract mandrel through end cap hold – only 60mm diameter.	A number of concepts devised but the collapsible, reusable mandrel is a unique design which made it possible to complete a closure weld.
Tool design	The state-of-the-art stationary shoulder (Si_3N_4 ceramic) had a short life limiting weld length	Several versions of a longer life shoe design tested and improved grade of Si_3N_4 enabled 1.4m long welds to be made. 4m lengths have been welded with no shoulder cracking or spalling.
Coatings (for tooling/backing bar)	How to replace solid ceramic backing bars with steel internal support mandrel for circumferential welding was a challenge.	Various ceramic coating techniques were evaluated and tanks could be produced using RPC (Cr_2O_3) which has superior bond strength. PVD coatings may be superior.
Welding	300mm long flat plate welds could be produced with confidence but circumferential welds in Ti-6Al-4V alloy had not been attempted.	Circumferential welding required development of process parameters to accommodate the thermal mass of the tank and fixtures. The improved shoulder life also improved the W25%Re alloy tool probe life.

Procurement	Project Start	Project End
Casting	The cost to produce the parts for 5 tanks by the traditional route absorbed more than 50% of the project budget. The casting route offered cost savings but a reduction in mechanical properties.	The casting route has the potential of reducing the cost of parts by approximately 80%. The grain size of the cast material was much larger, as would be expected, but the mechanical properties, although lower, were within current material specifications.
Machining	Alternative routes for machining were required to stay within the project budget.	CNC Rotherham did not have the expertise developed by Mecachrome over many years but what they achieved was sufficient for making demonstrator tanks. Improved tooling required.

4 Conclusions

In line with the project objectives an SSFSW procedure has been developed for both wrought and cast 2.4mm thick flat Ti-6Al-4V alloy sheet and when subjected to a range of tests described in this report has confirmed the production of high quality welds.

Thus the main conclusion of this project is that the results generated indicate that the SSFSW process and cast Ti-6Al-4V alloy hemispheres and cylinders could potentially provide a lower cost manufacturing route for propellant tanks compared to current procedures.

TWI Management System

TWI operates a Management System designed to ensure that customer requirements are met and that any 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:

- All technical activities are controlled by a management system that complies with the general requirements of the BS EN ISO 9000:2008 series of standards.
- Project management, examination and training services are audited by LRQA as complying with BS EN ISO 9001:2008 and software development in accordance with TickITplus, Certification Number 0925004.
- TWI is a UKAS accredited testing laboratory No. 0088. Specific details are given on the UKAS Schedule of Accreditation, available at www.ukas.org. Reports may contain information not included in the TWI schedule of accredited tests. Enquiries concerning accreditation of tests should be directed to the Quality and Safety Group.
- Examination activities are assessed by PCN to BINDT requirements and by TWI Certification Ltd to CSWIP requirements.
- TWI is certificated by LRQA to BS EN ISO 14001:2004, certificate number LRQA 4000756.
- TWI's Occupational Health and Safety Management System is certificated to BS OHSAS 18001:2007 by LRQA, certificate number 4004571.

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

- Close and frequent contact with the customer is requested of the Project Leader throughout the project. In particular, changes in personnel involved in the project or equipment availability are discussed together with any project delays or contractual changes.
- Regular management reviews of projects are held throughout the life of a project and upon its completion. These cover finance, technical progress and adherence to schedule.
- Project sponsors are formally contacted on project completion by senior TWI management to determine their satisfaction with the work carried out. Moreover, TWI management welcomes feedback on project progress at all times during the course of the work. Significant lapses in service are subjected to a structured management review so that inadequate procedures are identified and improved.

TWI Ltd
Granta Park, Great Abington
Cambridge CB21 6AL
United Kingdom

Tel: +44 (0)1223 899000
Fax: +44 (0)1223 892588
Web: www.twi-global.com

VAT Number GB 700 1708 89

Registered Number 3859442 England