“Microstructure and mechanical characterisation of titanium alloy linear friction welds”

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Abstract

The increasing use of composite materials in new aircraft builds leads to a significant demand for titanium alloy structural parts. The increasing costs and popularity of this material, together with restrictions in supply and processing, are driving the aerospace industry to make increasingly efficient use of available material.

Linear Friction Welding (LFW) is a rapid, high integrity, solid-state forging process that has the potential to decrease the buy-to-fly ratio, production time and time to market of aerostructure components. Its dependability has already been proven for the production of key components in some of the latest generation aero engines.

The LFW process is yet to be used for aerostructures. This is primarily due to the LFW process not being widely known, but also due to a lack of performance data on aerostructures manufactured by LFW being available to the supply chain and design community.

To address this issue, a large series of titanium alloy weldments was produced and assessed via metallographic examinations and mechanical testing in both as-welded and post-weld heat-treated condition. The matrix of experiments was able to capture the LFW process window of this titanium alloy, and to measure the impact of the parametric conditions.

Metallographic examination revealed a high integrity weld free from contaminants and oxides at the weld interface; with a characteristic recrystallised Widmanstätten martensitic Beta weld centre zone microstructure, in as welded condition, and a fine-grained equiaxed recrystallised to alpha-beta microstructure in post-weld heat-treated condition.

As-welded joints were tested under tensile and alternating fatigue conditions to provide an extended set of joint performance data. Joints demonstrated tensile performance equivalent to that of the parent material in all cases, with near-parent fatigue properties and improved (reduced) fatigue scatter in the post-weld heat-treated condition.

Introduction

Background

Air travel and commercial aviation is booming. Despite uncertainties, air traffic has doubled in the last 15 years, and this trend is expected to continue over the next 15 years, with world passenger traffic and cargo growing 4.8 % annually [1]. The increasing use of composite materials observed in new aircraft builds leads to increased demand for titanium alloy structural parts. Due to limited global manufacturing capacity for titanium structural parts and the use of inappropriate processing routes, the buy-to-fly, or material utilisation ratio, can be as poor as 20:1 and is rarely as good as 4:1 [2]. This is symptomatic of components being machined from oversized ingots, forgings or extrusions. There is a need for a manufacturing route that reduces costs and achieves greater efficiency of titanium utilisation. Linear friction welding (LFW) can help to address this issue by joining smaller workpieces to produce a preform, which is subsequently machined to size, resulting in significant material and cost savings.

Linear Friction Welding

The LFW process is not widely known, and it is not yet used by the aerostructure community. However, LFW is a qualified production process for critical titanium alloy aeroengines compressor components called Blisks [3] and this is a clear indicator of the capabilities, potential and relevance of LFW to titanium aerostructures. Linear friction welding is a solid-state joining process, meaning that the material is bonded in a plastic state, not molten; resulting in a forged microstructure. LFW works by oscillating two workpieces relative to each other, while under a normal compressive force of sufficient magnitude, to induce expulsion of

plasticised material out of the weld interface. The LFW process is self-regulated by the change in material properties as friction heating occurs, and pre-set parameters allow control of a LFW cycle through its phases, described Fig 1 [4] and [5].

Fig. 1: LFW process a) Initial phase b) Transition phase c) Burn-off phase d) Forging phase (deceleration)

Aims and Objectives

This article aims to demonstrate the advantages of the LFW process for producing Ti-6Al-4V aerostructures. To achieve this, a series of experimental welds were produced so that the impact of the processing conditions on the tensile and fatigue behaviour could be characterised. The experimental welds were also analysed to understand the weld interface microstructure. Furthermore, it is inconceivable to propose a technological innovation to the aerospace industry sector without considering its economic implications. An economic assessment was designed to determine and take account of all arising expenses for producing a demonstrator using conventional and current methods of machining from solid, to the new approach of near-net-shape manufacture using LFW, in order to identify cost savings.

Material and Experiments

Equipment used

TWI's latest linear friction welding machine, internal designation FW34, a Kuka E20 model of 250kN capacity, was used to produce the welds for this programme. It is a stored energy hydraulic machine of modular design consisting of an oscillator half and a forge half. It is emphasised, that a major benefit of machine tool based welding processes for production applications, such as LFW, is reproducible weld quality; which as evaluated by a series of repeat welds with measurements provided for intrinsic position and repeatability.

Material

The material was specified as Ti-6AL-4V alloy, Grade 5, 25.4mm thick plate, of AMS4911 specification. The work carried out in this programme was done on symmetrical butt joint coupon weldments, with workpieces of 40mm x 25mm faying area and 75mm body length (plate longitudinal grain direction).

Welding experiments methodology

These coupon welds were first assessed via in-process quality monitoring. The pressure was first varied under a high rubbing velocity, to determine the minimum forging pressure required for stable frictional heating, as well as noting when cold deformation occurred due to excessive pressure. The amplitude and frequency (energy input) were studied and the forge duration was finally defined from the thermal behaviour using thermocouples placed up to 2mm away from the interface. Repeat trials were run to assess the impact of welding with and without a protective argon shield. Table 1 lists the parameter ranges used.

Table 1: Envelope of key parametric conditions observed

	Amplitude	Frequency	Pressure	Forge duration	Atmosphere
High envelope	± 3mm	75Hz	240MPa	60s	Air
Low envelope	±1mm	20Hz	5MPa	0s	100ppm O ₂

Post-weld heat-treatments

A selection of industry standard [6] post-weld heat-treatments, such as stress relief, mill, ELI, or duplex annealing, as well as a custom solution treatment and aging, were applied to a series of weldments to assess their impact on joint performance.

Metallographic preparation

Selected weld coupons were prepared for metallographic examination. Sections were wet ground down to 2400 grit on silicon carbide grinding wheels and finally polished to 0.03 μ m using colloidal silica in a vibratory polishing machine. The sections were etched in Kroll's reagent and the weld zone examined using optical microscopy.

Tensile testing

Round cross weld tensile test specimens, 8.0mm nominal diameter with a gauge length of 40mm, were cut out and machined from selected weldments. Cross weld tensile tests were carried out at ambient temperature according to BS EN ISO 6892-1:2009 A.

Fatigue testing

Fatigue specimens were machined and tested under alternating fatigue loading using methods described in ASTM STP 566EB. These specimens had a nominal neck diameter of 3.2mm and had the weld centreline displaced slightly (0.4mm) from the minimum neck diameter to position the weld at the maximum stress location.

Results and discussions

Relative workpieces position

The repeat nominal welds were measured and their intrinsic position and repeatability were found to present positioning tolerance on par with the manufacturing accuracy of most mechanical components, 0.1mm; well beyond the expectations for a welding process. Parallelism and symmetry deviation between workpieces returned values within the measurement equipment's own variation of repeatability.

Effective LFW process window

In-process weld monitoring was used across the entire test matrix to assess the impact of the parametric conditions. Table 2 details the effective weld parameter envelope identified. At high rubbing velocity, Ti-6Al-4V successfully welded at all the pressures applied, and displayed a wide tolerance to process parameters, as demonstrated in Fig. 2a. Initial, transition and burn-off phases combined, the low pressures offered durations up to 6.3s, the medium parametric range were taking typically 1.0s to 1.75s, and the high pressures took as little as 0.7s to complete the friction cycle.

Amplitude and frequency were controlled most effectively during the medium to high rubbing velocity welds. The measured thermal gradients can be seen in Fig. 2b. Thermal gradients as great as 3600°C/s were observed during the 'initial' and 'transition' stages of the welding cycle. This graph also shows that it took around 12s for the joint interface to cool to 300°C, the temperature at which oxidation starts to occur for this alloy [6], and less than 25s for the interface to drop below 200°C. This results in typical welding cycle durations of less than 30s.

Table 2: Process window of some of the parametric conditions observed

	Amplitude	Frequency	Pressure	Forge duration	Atmosphere
High envelope	± 3mm	60Hz	150MPa	25s	Air
Low envelope	± 2mm	30Hz	50MPa	6.5s	Air

Fig. 2: a) Characteristic burn-off rates at various pressures; b) Weld interface temperature for friction and forge

Performance of the post-weld heat-treatment

Out of the post-weld heat treatments trialed, only the custom solution treatment and aging proved to be efficient in recovering parent material properties in Rp 0.2% proof stress, ultimate tensile (max) stress, low cycle fatigue (LCF) and high cycle fatigue (HCF). The results presented below discuss the performance of as-welded and solution treated and aged “PWHT” welds.

Metallographic observations

The as-welded micrographs of the samples studied showed that all joints made with an average rubbing velocity of 250mm/s or more had successfully welded regardless of the pressure used. All bore a characteristic fine-grained equiaxed microstructure while displaying differences in formation of weld centreline and thermo-mechanically affected zones as shown Fig. 3. These differences helped to determine a suitable process window. High integrity welds were consistently produced in an unprotected atmosphere. Optical metallographic examination revealed them free from surface contaminants and alpha case ingress within the weld line; with only the outside of the welds and flash showing traces of oxidation. Protective gas shielding during LFW production may therefore be unnecessary, assuming the expelled weld flash and outer joint areas are fully machined post weld.

Fig. 3: Weld joint cross micrographs for high rubbing velocity and a) low; b) medium; c) high pressure joints.

Tensile test results

Cross-weld tensile samples were prepared from selected weldments run with mid-matrix parametric conditions, without and with PWHT. The tensile tests all failed in the parent material, away from the weld zone, and the results, Fig. 4, reflect this behaviour. No significant reductions in tensile performance were observed, with proof stress, maximum stress and elongation returning close to parent material values. The only slight variation was a minor reduction in the cross-sectional area (RA%) of the

fracture surfaces in the as welded condition, which could be explained by a different necking behaviour due to the presence of the weld. PWHT specimens displayed a recovery of the RA%, presumably due to the weld centre zone exhibiting properties closer to the parent material.

Fig. 4: parent material and cross-weld tensile testing results of as welded and PWHT LFW specimens.

Fatigue test results

The test carried out in this programme revealed that all the welded and parent material low cycle fatigue (LCF) and high cycle fatigue (HCF) specimens were above their respective minimum fatigue allowable data [7]. The lowest LCF as-welded LFW specimen recorded showed a comparative drop in performance of 27.9% on average from the lowest parent material specimen, see Fig. 5. The HCF as-welded LFW specimens and parent material populations showed identical minimum values. The PWHT specimens, thanks to their processed and recrystallised microstructure exhibited less scatter in the population both for LCF and HCF, and a higher minimum fatigue performance in both cases. The level of performance in the as-welded condition is very high, and certainly more than satisfactory for static components. The improved performance of the PWHT welds permits fatigue applications to be considered. It is probable that the performance of these joints may be further enhanced through refinement of the parametric conditions and additional post-weld heat-treatment investigations.

Fig. 5: Low cycle alternating load fatigue and high cycle alternating load fatigue results of parent material, as welded and PWHT LFW specimens

Techno-economic assessment of a representative structural airframe component

Comparing the 'LFW route' against an aggressive machined 'from solid' route

When an established route for component manufacture is challenged by a new process, it is likely that the current part producer would seek ways of making their production process more efficient and competitive. The CNC 'from solid' production route was therefore defined with competitive figures in mind, with a three shift staff rotation and full machine utilisation, lean solid material block volumes, and a material removal rate based on the latest tool wear management practices. This assessment also took into account recurring and non-recurring costs. Recurring costs included materials, consumable tooling, energy usage, labour, maintenance, and building costs. Non-recurring costs included machines and non-consumable fixture investments. Non-recurring costs and depreciation estimates were amortised over a credible lifespan to provide realistic values for comparison.

The down-selection process looked at the geometrical intricacies, manufacturing complexities and the number of welds required when forming near-net-shape blanks. Stanchion parts were considered suitable target components for this alternative manufacturing solution. A generic demonstrator, shown in Fig. 6a, was designed for the purposes of this case study and to aid dissemination. The generic demonstrator had external dimensions of 300x92x60mm. LFW workpiece plate dimensions were extrapolated from the finished part drawing, Fig. 6b, as was the minimal volume of solid titanium plate required to machine the part from solid, Fig. 6c.

Fig. 6 a) Generic demonstrator b) Near-net-shape by LFW c) Volume used by the machining route

Potential savings by the LFW near-net-shape manufacturing route

It became apparent during the demonstrator down-selection process that LFW could be applicable to a large proportion of modern titanium aerospace components. The generic near-net-shape manufacturing route of joining gussets and a boss to a baseplate reduced the raw material usage by 66%, compared to the manufacturing from solid solution, improving the reduced buy-to-fly ratio from 10.9:1 to 3.7:1. This also translates in a reduction of 49.9% in production time and an estimated 23.3% savings in production costs.

Conclusions

The manufacture of linear friction welded near-net-shape aerospace components is an effective and lean manufacturing approach with a mature readiness level, supported by clear economic benefits.

- The LFW process window was identified for Ti-6Al-4V Grade 5 AMS4911 on 25mm thick plate;
- All the weldments that completed their burn-off exhibited forged microstructures free from oxides and contaminants;
- The as-welded and post-weld heat-treated LFW cross-weld tensile performance was effectively equal to that of the parent material;

- The alternating load LCF and HCF minimum performance of the as welded LFW specimens exceeded the minimum design allowable for AMS4911. The use of these type of joints for static loaded aerostructure components can be considered;
- The alternating load LCF and HCF minimum performance of the PWHT LFW specimen exceeded that of the parent material and design allowables for AMS4911. The use of these type of joints for fatigue loaded aerostructure components can be considered.

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