

Stationary Shoulder Friction Stir Welding of Ti-6Al-4V; Process and Evaluation

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Friction Stir Welding (FSW) is now an established production technology for aluminium components, and work is continuing on the development of FSW for high temperature materials including titanium alloys. Titanium is one of the more challenging materials to weld by this process. Recent developments at TWI have led to significantly improved results in the FSW of titanium alloys, particularly in the areas of process control and stability. In particular, the development of stationary shoulder friction stir welding tools, (which give more uniform heating through the thickness) have had a profound effect on weld quality and ease of weld production.. This paper describes the principles of the process, and gives examples of the weld quality that can be obtained. In particular, one development weld has been subjected to a very detailed metallurgical assessment, and this has given very valuable information on the nature of the microstructure and textures, and how they vary in different parts of the weld. This valuable information will provide a standard against which future improvements to the welding process can be compared.

Keywords: titanium (Ti), friction stir welding, EBSD, texture

1. Introduction

Friction stir welding (FSW) is an established process for Al alloys, but application to Ti alloys has been hampered by its physical and mechanical properties. Poor thermal conductivity of alloys such as Ti-6Al-4V means that heat distribution in the weld is not uniform, and since heat is generated mostly at the upper surface when conventional tools are used there is a significant temperature gradient through the thickness. FSW is primarily a hot working process, and unlike Al alloys, the hot working temperature range of Ti is limited. Therefore, an even temperature distribution is essential for the best results. Tool technology has also presented a significant challenge. Ti alloys retain significant strength at the hot working temperature. Tool materials must not only be able to withstand the high welding forces and torque levels but must also be inert to Ti at high temperature (typically 1100-1200°C).

This work describes an alternative approach to FSW of Ti, in which the method of heat generation has been radically altered. The paper describes some preliminary experiences with the new approach, and gives details of the microstructures of a weld made in Ti-6Al-4V.

2. Conceptual design

It was apparent that obtaining a more uniform heat generation profile would require radical changes to tool design. Since the rotating shoulder on conventional tools generates the majority of the heat at the upper surface, experiments were carried out with some alternative approaches, one of which was the stationary shoulder approach. The welding mechanism consists of a rotating pin located in a non-rotating shoulder component, which slides over the surface of the material during welding. An inert gas shroud is provided by a specially made chamber fixed to the welding head which protects the welding region and trailing edges during welding. Other components for the stationary shoulder welding head are illustrated by the cross sectional view in Figure 1).

During Stationary Shoulder FSW (SSFSW), a tool probe (component 11) rotates through a non-rotating shoulder, which is held within a sliding shoe (components 7 and 10). The shoulder components do not directly contribute to the heat generated during welding. This

approach enables the process to produce focussed heat input around the tool pin, and eliminates the problem of surface overheating. SSFSW generates a consistent linear heat input throughout the weld cross-section, which is particularly suitable for the welding of low conductivity materials. The SSFSW head is shown in Figure 2. A very smooth “polished” weld surface is reliably produced for over 1m long weld runs, as shown in Figure 3.

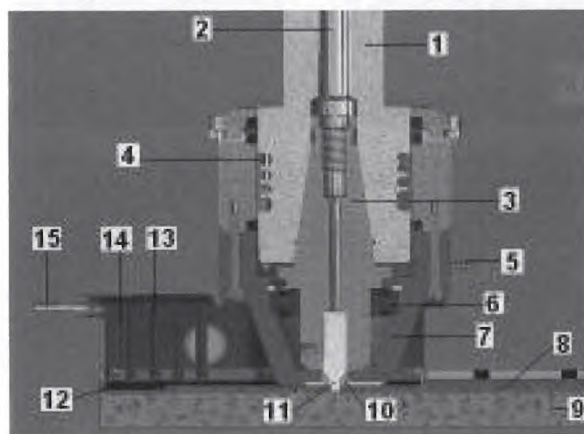


Figure 1. Stationary shoulder FSW mechanism

(1) Rotating spindle (2) Draw bar (3) ISO 50 Tool holder
(4) Water cooling jackets (5) Argon input (6) Support bearing
(7) Stationary tool head (8) Ti workpiece (9) Backing plate
(10) Sliding shoe (11) Rotating pin (12) Sliding seal
(13) Argon supply (14) Gas chamber (15) Inert gas input

3. Results

Initial trials on 6.35mm Ti-6Al-4V showed very encouraging results. The process was remarkably stable, and the weld surface appearance was very smooth, and much better than found in conventional friction stir welds.

Welds were made under a variety of conditions. Good results were obtained with speeds of 60-80mm/min, using rotation speeds of 400-500rev/min. Force control was used to maintain a constant pressure on the welding tool. Clearly the non-rotating shoulder will experience very high stresses and temperatures, and research on the optimum material for this component is continuing. Mechanical properties, as measured by room temperature cross weld tensile tests are as expected. 100% joint

efficiency can be obtained, although there is a reduction in ductility when failure occurs close to the weld zone. In many samples, the failure was remote from the weld, in which case elongation equalled parent plate values. The status at the moment is that of a successful technology demonstration, and further studies are in hand to optimise a number of aspects of the process.

A macro section of a typical weld (Figure 4) shows that the weld is defect free, but that the thermal profile was not quite parallel, due to a small taper on the probe, and to the heat loss through the tool bed. This profile is considered satisfactory, and a major improvement on welds made without a stationary shoulder.

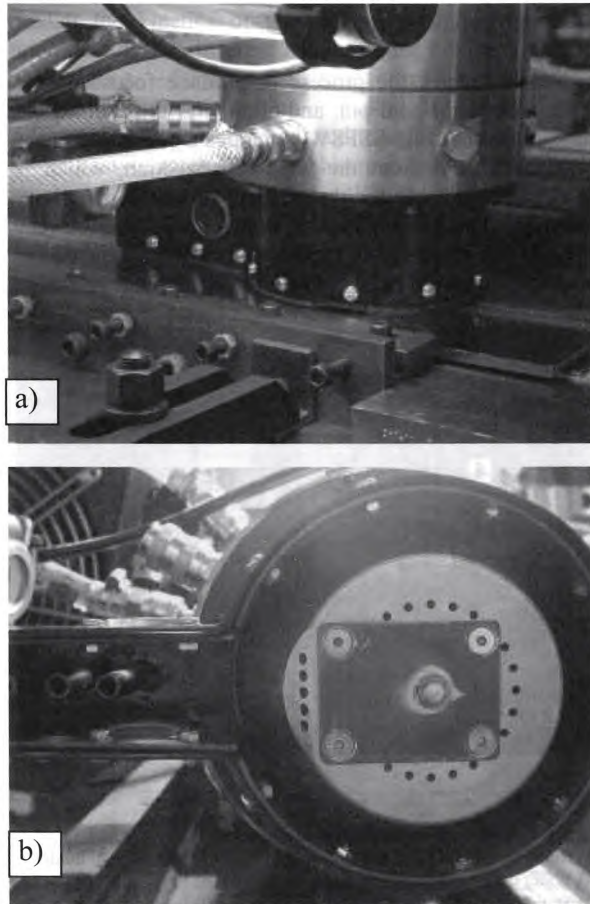


Figure 2. The SSFSW welding head. (a) external view. (b) underneath.

A detailed microstructural examination of a weld made at 400rev/min and 60mm/min using high resolution electron backscattered diffraction (EBSD) is shown as an orientation image map in Figure 5a. The EBSD data were acquired using a 3 μ m step size in the plane perpendicular to the travel direction with an FEI Sirion FEGSEM equipped with an HKL Nordlys CCD camera controlled by HKL Channel 5 acquisition software. The map, which covers the top 4mm of the whole weld, shows distinct orientation regions across the weld which are labelled A to K and a surface layer labelled L. Regions A and K in parent material contain a strong rolling texture and a

spheroidised α microstructure. There is slight coarsening of the microstructure on both sides of the weld as the weld is approached, but no evidence of deformation. This is confirmed by the texture in Region J (retreating side) which is almost identical to that of the parent material. Just beyond J there is a subtle orientation change that is approximately 250 μ m wide (Region I). The pole figure here has changed but similarities with the parent material suggest that this region has been heated above the β transus, (\sim 990 $^{\circ}$ C), but without deformation.

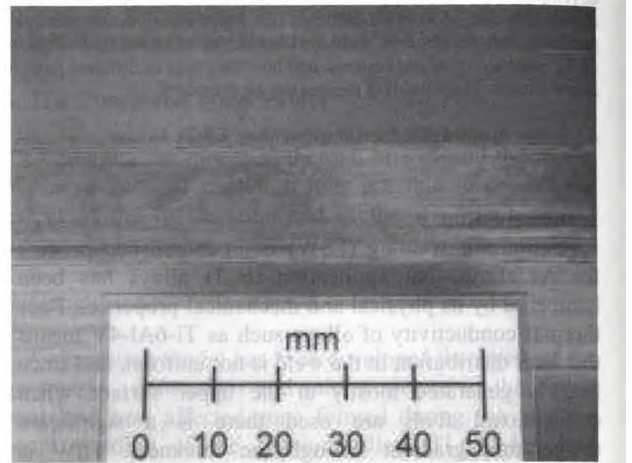


Figure 3: Surface appearance of a typical weld

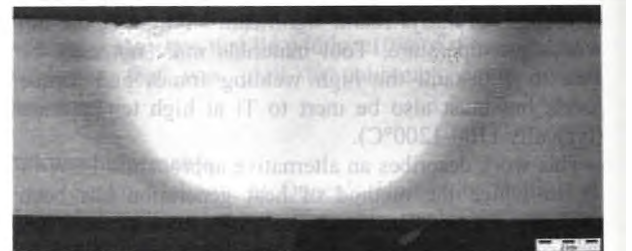


Figure 4. Macro section of a weld made at 500rev/min and 80 mm/min travel speed.

To examine this further the map in Figure 5a has been plotted (Figure 5b) showing only boundaries with a misorientation greater than 12 $^{\circ}$ and which also do not correspond to a misorientation between α transformation variants from the same β grain²⁾. This highlights the position of the prior β grain boundaries. Thus it can be concluded from Figure 5b that Region I has experienced significant β grain growth.

This is further confirmed by high resolution maps of Regions I and J shown in Figures 6a and 6b. These maps clearly show the as-rolled microstructure in Region J and a fully acicular α structure transformed from large equiaxed β grains in Region I. The adjoining region, H, has a similar transformed microstructure but the texture has become diffuse suggesting that the prior β grains have been slightly plastically deformed before transformation

back to α . Hence, we believe Region H defines the edge of the thermo-mechanically affected zone (TMAZ). A similar situation exists on the advancing side (the detailed analysis is not shown in Figure 5) although the equivalent regions are slightly larger. Work is ongoing to confirm these observations with emphasis on stationary heat treatments above and below the β transus of the parent material to identify the textures of heat affected only material. For material closer to the weld centre the microstructure again consists of an acicular α microstructure but the width of the similarly orientated regions is of the order of 2mm. In all cases these regions have relatively distinct textures clearly different from the parent but with intensities at the same level of the parent's texture. It is unclear if these textures are transforming from deformed or recrystallised β grains. Work is ongoing to reconstruct the β morphology and texture to gain evidence for distinct TMAZ (non-recrystallised β) and nugget (recrystallised β) zones.

Information already in hand (Figure 5b) shows the β grain size is relatively uniform at about $50\mu\text{m}$ throughout the whole cross-section of the weld suggesting there are no major regions of accelerated grain growth within the weld. For material at the surface of the weld, Region L, there is a distinct change in texture from the bulk shown by a strong transverse basal texture to a maximum depth of about $250\mu\text{m}$. The microstructure is also changed with a considerable reduction in prior β grain size. This surface layer extends beyond the pin affected region of the weld to fit exactly the area underneath the stationary shoulder and we believe this layer has its origin in the shear force generated by the forward motion of the stationary shoulder. Moreover, below this layer the texture immediately returns to the textures described previously indicating that the effect of the stationary shoulder on microstructure evolution is limited to a relatively thin surface layer.

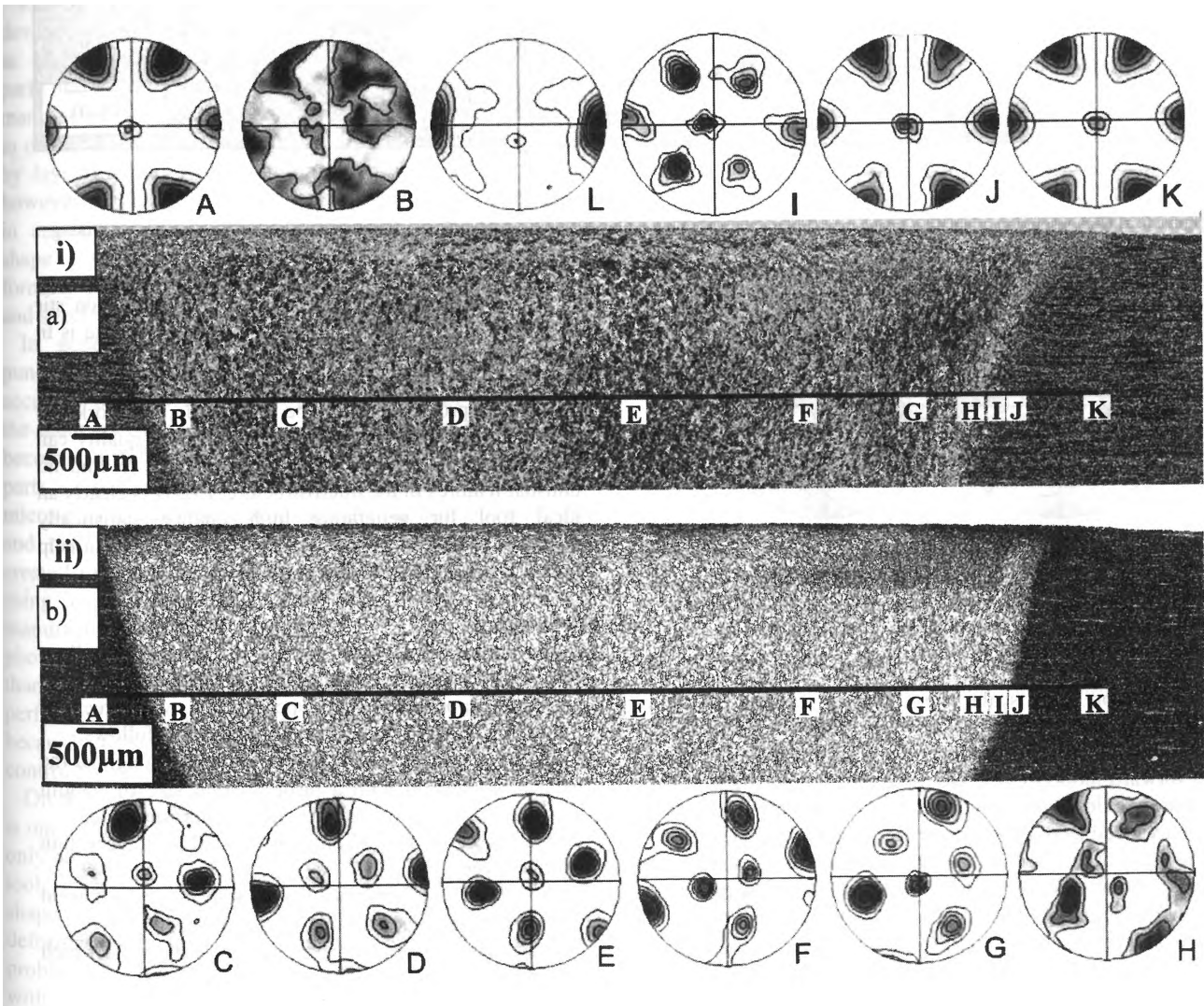


Figure 5. a) An Euler contrast orientation image map and b) a β grain boundary construction map using Burgers misorientation. $\{0002\}$ pole figures represent α phase textures in the regions highlighted in the map. Pole figure L is the texture for the surface layer of the weld. Each contour in the pole figures represents $1 \times$ random intensity. Regions A and K are on the advancing and retreating side, respectively.

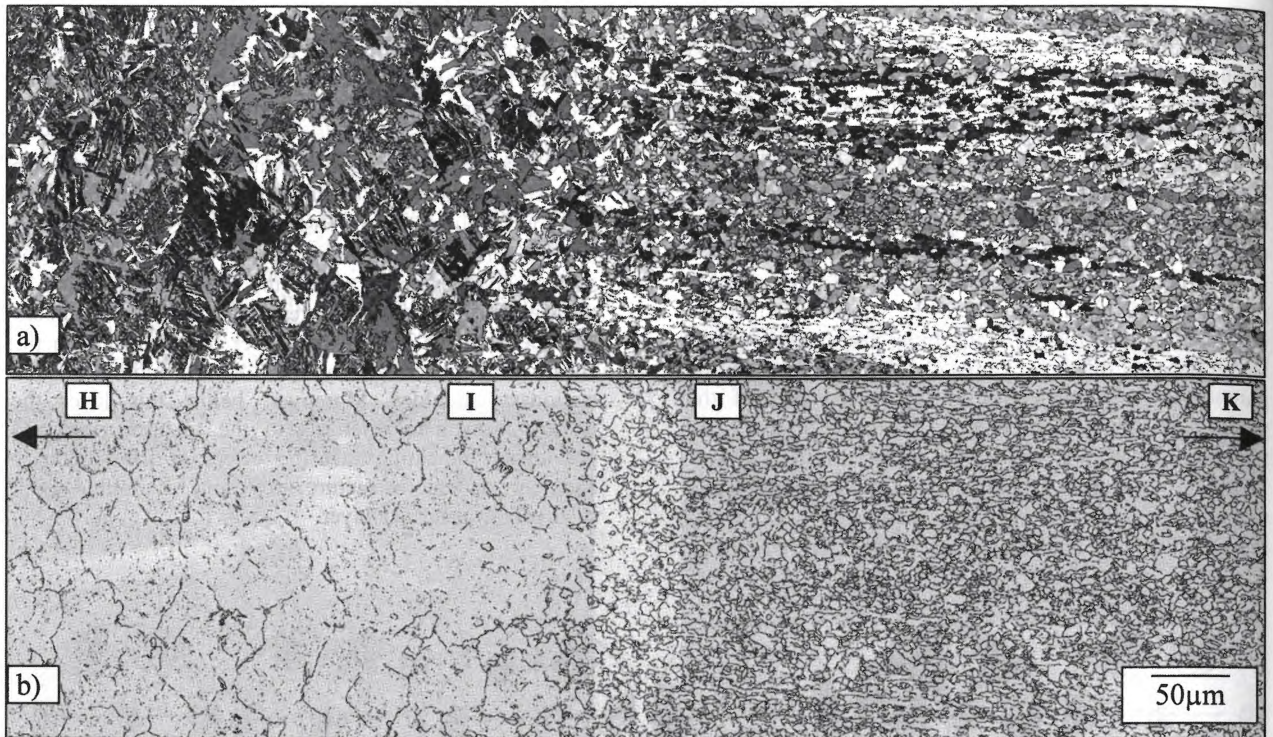


Figure 6. a) High resolution orientation image map (Euler contrast) of retreating side of the weld in Figure 5. b) β grain boundary construction of a) using Burgers misorientation. Highlighted boundaries represent a misorientation $>12^\circ$.

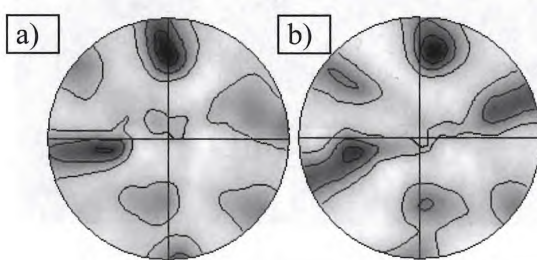


Figure 7. {0002} pole figures of a) advancing side and b) retreating side of weld looking from behind the acquisition plane and rotated 30° about the vertical direction of the weld.

On a more bulk scale, the complete textures of the advancing and retreating sides have been analysed and show an interesting symmetry relationship. If there was no forward motion in the weld then the advancing side's texture would be the same as the retreating side's texture when viewed from the opposite face of the viewing plane. This was not the case for the current weld but the textures were similar and they were made nearly identical, as shown in Figure 7, by a rotation of about 30° about the vertical direction of the weld. A deeper analysis of these relationships will determine if these texture symmetries can be related to a macroscopic symmetry within the welding process itself.

The weld examined here is a development weld, and modifications to the tool/process design and/or welding parameters may result in differences in microstructure. It

is arguably the most detailed analysis of a friction stir weld in Ti-6Al-4V, and further analysis of the data is in progress. It is a valuable exercise to take a good development weld and use it as a yardstick against which possible improvements can be measured. The work has demonstrated that friction stir welds of high quality can be made in Ti-6Al-4V, and it is reassuring to find no unusual features in the microstructure. EBSD is clearly an ideal tool for generating high quality statistically quantitative data of benchmark microstructures in to help in the development of this technology.

5. Summary

The stationary shoulder variant of FSW for Ti alloys has been described, as well as its advantages over more traditional approaches. Key aspects of the microstructures found in Ti-6Al-4V have been highlighted as follows:-

- 1) the microstructure is relatively uniform throughout the weld cross-section with a prior β grain size of $\sim 50\mu\text{m}$ producing a fine transformed acicular microstructure.
- 2) the effect of the shoulder is limited to a very thin surface layer.
- 3) the TMAZ/HAZ interface most likely occurs in a weld section with temperature above the β transus.
- 4) there are distinct texture zones across the weld which are approximately 2 mm thick.

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