FRICTION STIR WELDING OF Ti-ALLOYS FUTURE PERSPECTIVES

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Abstracts

Friction stir welding (FSW) of aluminum alloys is nowadays a well developed and almost mature technology with wide application in the aerospace industry and in the near future in the automotive industry. However, the FSW of higher melting temperature alloys as steel, stainless steel, Ni-base alloys and Ti alloys is well behind, mainly because of technical difficulties. Technical problems associated with the tool and the economics of this joining process limits its applicability to these harder materials to high-end products. However, there is an alloy system, for which the metallurgical advantages of FSW and the material cost make this joining process a very attractive alternative. These alloys are the Ti alloys, which are extensively used in the aerospace, oil, chemical, medical, and high-end consumer goods industry. The metallurgical advantages of friction stir welding or processing of Ti alloys are discussed in the light of a work with the commercial Ti-6Al-4V alloy.

Key-words: Friction stir welding; Titanium alloys; Ti-6Al-4V; TMAZ; Alpha globularization; Secondary alpha.

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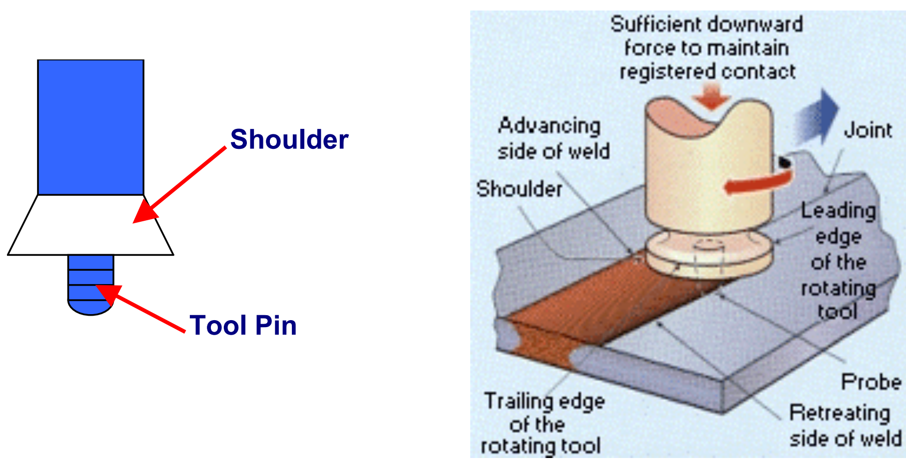
1. INTRODUCTION

The friction stir welding (FSW) process was developed during the early 1990's at The Welding Institute (TWI) in Cambridge-UK [1]. This is a solid state welding process where a cylindrical and shouldered tool with an extended pin is rotated and gradually plunged into the joint between the pieces to be welded and the non-consumable, rotating tool is translated along the aligned joint, producing a weld. See Fig. 1. The combination of the frictional heat produced by the stir rod shoulder against the plate and the intense deformation imposed by the tool pin produces a local forging/stirring effect which produces a high integrity metallurgical bond. This combination of heat and deformation results on a particular joint structure with the differentiated macro-regions presented schematically in Fig. 2:

- Stir zone (SZ): Where intensive stirring and deformation occurred.
- Thermomechanically affected zone (TMAZ): Where substantial deformation and heating occurred but not stirring.
- Heat Affected zone (HAZ): Where substantial heating occurred but none deformation.
- Base material (BM): The material that has been unaffected by heat or deformation.



a. b.

Figure 1: Schematic of the (a) Stir rod and the (b) friction stir welding process (courtesy of TWI).

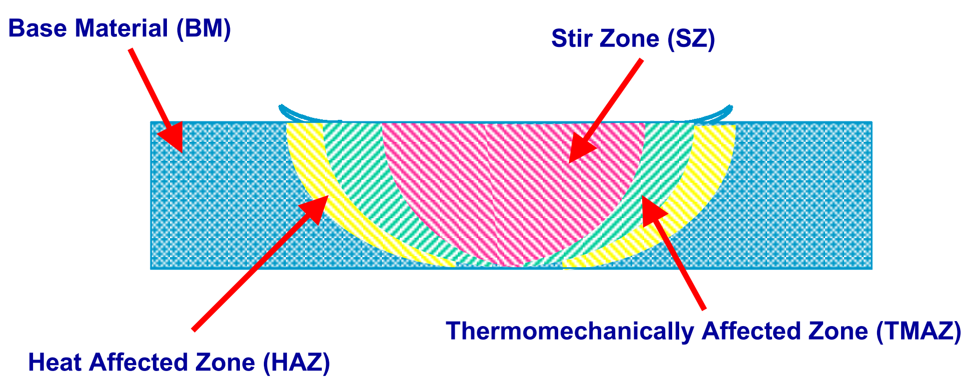


Figure 2: Schematic of a friction stir welded joint regions.

FSW is now a commercially available technology, with extensive use mainly in the aerospace industry, for the joining of aluminum alloys. This joining technique consistently produces excellent quality welds in some alloys that are otherwise difficult to weld by fusion welding techniques. The possibility of producing solid state joints in plate and sheet material has driven the expansion of this technology to higher melting temperature materials such as mild steels, stainless steels, nickel base alloys and titanium alloys [2, 3, 4, 5]. However, there are several challenges to be addressed and overcame before the commercial application of FSW to high melting temperature and strength alloys becomes a reality. Among these challenges are the relationship among the joining process, the resultant microstructures and ultimately the properties of the welds.

There are several reasons that made FSW of Ti-alloys a very attractive technology. For this reason, several important companies and research institutes as EWI (Edison Welding Institute), TWI (The Welding Institute) and General Electric are putting a lot of effort on developing FWS of Ti-alloys. Table 1 presents a parallel between fusion and friction stir welding of Ti-Alloys. Most of the potential on FSW of Ti-alloys resides on the possibility of tailoring microstructures by the thermo-mechanical processing associated with the stir process. This is especially important for Ti-alloys because the variety and complexity of microstructures that can be produced on α/β Ti-alloys controlling the deformation temperature and the following cooling rate. Fig. 3 presents a schematic diagram with the possible microstructures attainable on Ti-6Al-4V alloys with processing conditions.

Table 1: Parallel between fusion and friction stir welding of Ti-alloys [6].

Fusion Welding	Friction Stir Welding / Processing
Porosity – Solidification cracking	No liquid related defects
Solidification segregation	No segregation
Coarse grain joint microstructure	Refined joint microstructure
High residual stresses (fatigue problem)	Lower residual stresses
PWHT to relive residual stresses and temper α'- Low temperature HT	PWHT may be necessary to relieve stresses
Severe risk of contamination (O, N, H)	Severe risk of contamination (O, N, H, tool material)
Joint microstructure (properties) may be partially tailored by the cooling rate control	Extensive potential for joint microstructure (properties) tailoring by friction stir thermo-mechanical processing
Extensive commercial applications Processes and techniques well developed	No commercial applications. Processes and techniques need to be developed
Joining - Worried about final properties	Joining/Processing - Improving properties

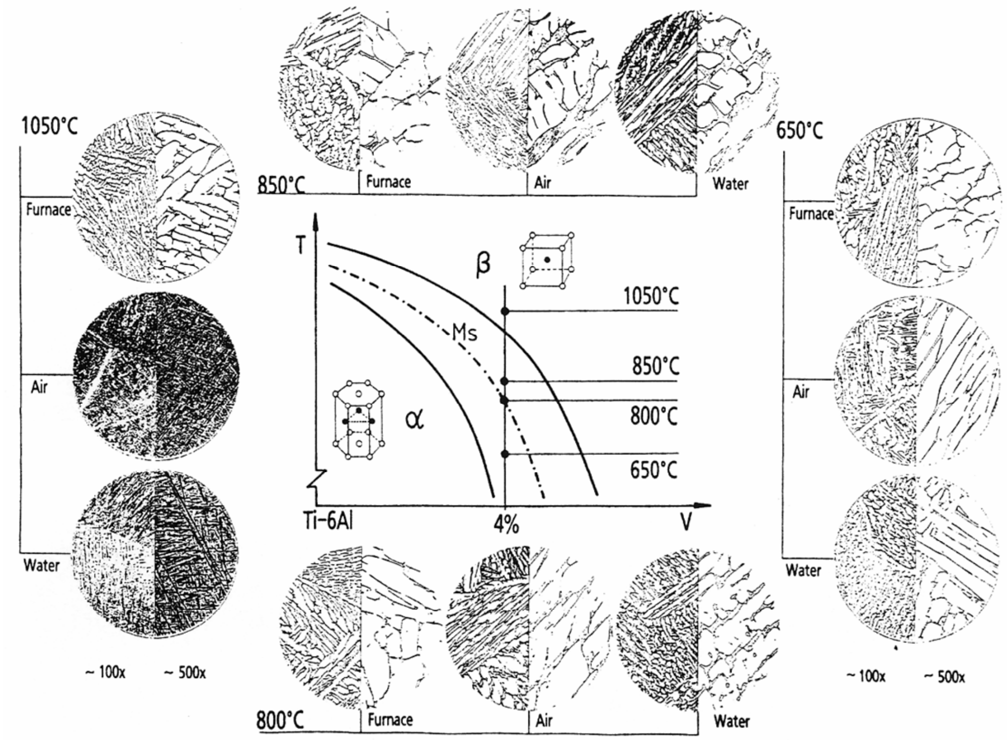


Figure 3: Ti-6Al-4V alloy microstructures developed with different heat treatment conditions [7].

However, FSW of Ti alloys brings several important technological challenges as:

- The process happens at higher temperatures than the usual FSW of Al alloys. This condition puts serious constraints on the stir rod material and design.
- As a consequence of the high temperatures achieved during the process, environment contamination becomes a concern. In addition, the tool material by become a contamination source that should be accounted for during the process development.
- The residual stresses built during the FSW process are a smaller than the ones produced during fusion welding [4]. However, they may be still a concern for highly solicited parts.
- Finally, the real challenge for friction stir welding or processing of Ti-alloys is on the possibility of tailor the microstructure by the friction stir joining or processing, as proposed by Ramirez and Juhas [6]. To achieve this point is necessary to fully understand and control the FWS process for these alloys and mainly to understand the microstructural changes imposed by the process and their relationships with the process variables.

Thus, this work presents an update on the studies being developed by the authors on the microstructural evolution during the FSW of Ti-6Al-4V in the mill and β annealed conditions.

2. MATERIALS AND PROCEDURES

Mill annealed (723 °C/ 30 min) and β annealed (1038 °C/30 min + 732 °C/2 hr) 609 x 15 x 6 mm plates of Ti-6Al-4V (6.3 Al - 3.9 V - 0.14 Fe - 0.16 O - 0.005 N - 0.018 C) alloy supplied by TIMET were friction stir welded at EWI (Edison Welding Institute) using a square-groove butt joint with no root opening. Fig. 4 presents a picture of the weld.

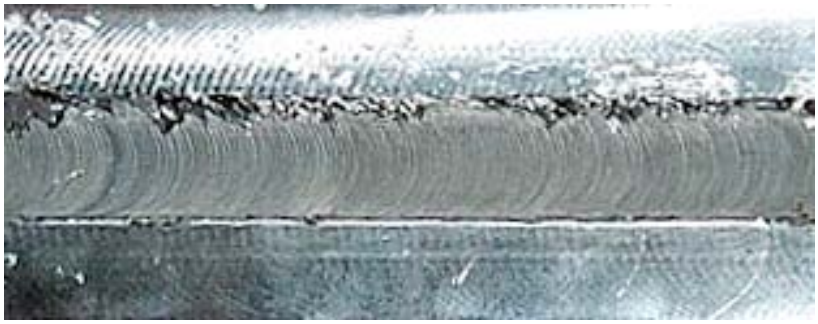


Figure 4: Top view of the FSW on the mill annealed Ti-6Al-4V plate.

The welds were performed on a 50 HP Kearny-Trecker milling machine using a smooth steel backing plate. The friction stir process as performed at a travel speed of 1.6 mm/s using a W-based alloy tool tilted 3.5° and rotating at 275 rpm.

Transverse sections of the welds were cut, polished and etched using the Kroll's reagent (2 vol% HF, 4 vol% HNO_3 in water) for the SEM examination. A Philips Sirion field emission gun (FEG) SEM was used to characterize the microstructures. For the transmission electron microscope (TEM) sample preparation, transverse sections (0.5 mm thick) of the welds were cut, ground to a thickness of 200 μm and etched using Kroll's reagent to identify the regions of the weld. 3 mm disks were punched out from specific regions of the welds and thinned to electron transparency by ion milling. The TEM analyses were performed using a Philips CM-200 with X-ray energy-dispersive spectrometry (XEDS) capabilities.

In addition to the advanced microstructural characterization results that are presented in this document, residual stresses, micro-hardness mapping and orientation image microscopy studies were performed and reported elsewhere [4].

3. RESULTS AND DISCUSION

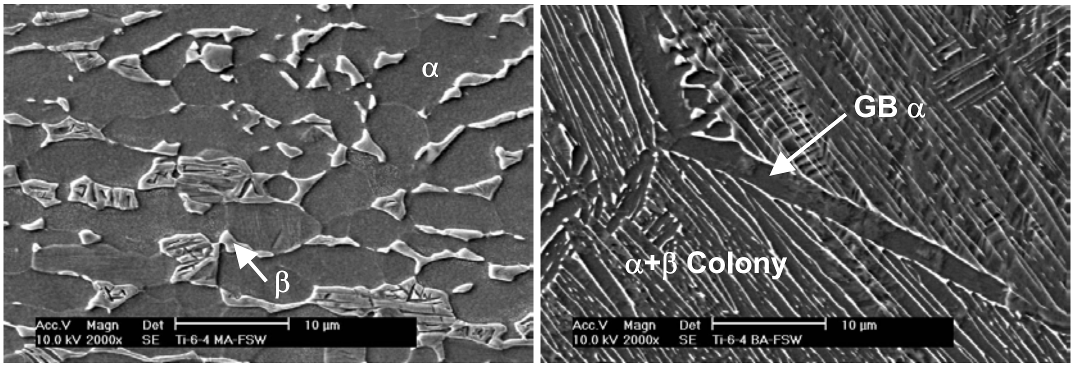
Both the SEM and TEM microstructural analyses were performed in the base material, stir zone and TMAZ of the FSW joint, as presented in Fig. 2 were analyzed.

3.1 Base Materials

The microstructures of the Mill Annealed (M-A) and β-Annealed (β-A) materials are presented in Fig. 5. The M-A plates contain a bimodal microstructure formed by bands of α grains (about 2 μm thick and 5 - 10 μm long) and colonies of transformed β which is typical of a Ti-6Al-4V alloy rolled in the α+β temperature range, then annealed below β transus followed by air cooling. In contrast, the β-A plates contain large prior β grains with the original β grain boundaries decorated by grain boundary α, as indicated in the figure. The interior of the grains are a lamellar structure of the α+β colonies which developed during the rapid cooling from above the β transus temperature. Due to the large prior β grain size (500 μm) in the β annealed material, Fig. 5.b shows only a fraction of prior β grain boundary, decorated by grain boundary α, and regions of lamellar α+β colonies. The TEM study of these samples revealed the expected low dislocation density of an annealed structure. Two different types of lamellar α/β colonies were observed on the β-A alloy, as presented in Fig. 6. The chemical composition of the phases as measured by XEDS was:

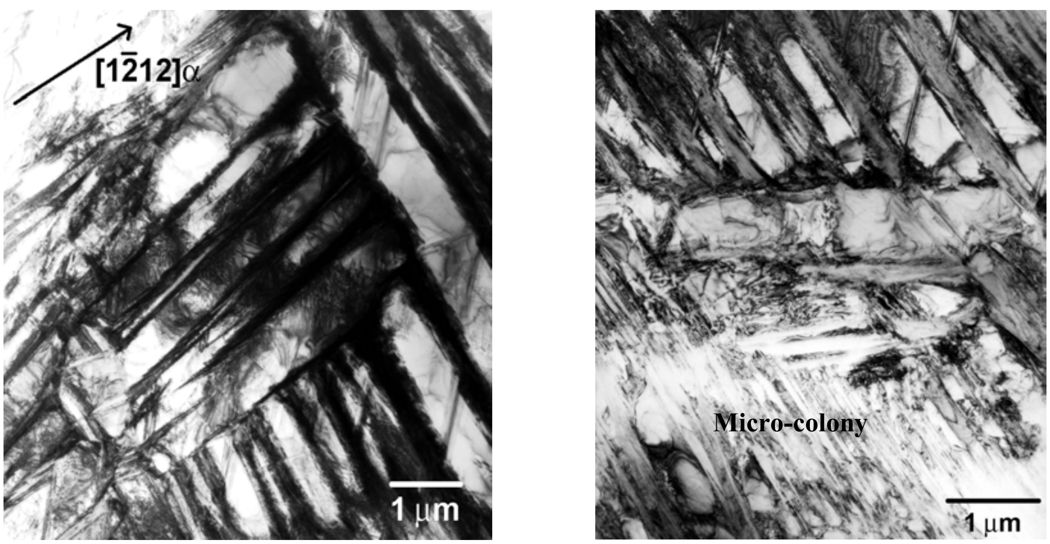
M-A α: 9.0 Al – 2.0 V – 89.0 Ti
 β: 3.7 Al – 16 V – 79.1 Ti

β-A α: 8.2 Al – 2.7 V – 89.1 Ti (β was not measured due to its small size)



a. b.

Figure 5: Mill Annealed (a) and β-Annealed (b) base materials microstructure. SEM images



[1$\bar{2}$1$\bar{3}$]

Figure 6: β-Annealed base material. TEM images.

3.2 Stir Zone (SZ)

The microstructure of the stir zone (SZ) varied depending on the region. In the central region of the SZ the developed microstructure did not depend on the initial stage of the plate, i.e. M-A or β-A. As shown in Figure 7, the microstructures were characterized by small prior β grains (~ 10 μm) with fine grain boundary α and transformed β within the grains in the form of fine lamellar α+β colonies, microstructure with expected good fracture toughness. These microstructures reveal that the material in the central region of the SZ exceeded the β-transus temperature.

This microstructure was controlled by the deformation and temperature imposed during the stir process. The small β grain size is thought to be the result of severe deformation restricted grain growth and/or a dynamic recrystallization process during the stirring. In addition, the short dwell time above the β-transus temperature plays an important role. The decoration of the prior β grain boundaries by grain boundary α suggests that the cooling rate in the central region of the SZ was not high enough to restrict its formation, which may be advantageous for fracture toughness purpose [8]. However, the cooling rate was high enough to promote the formation of stacking faults in the α, as presented in observed in the TEM [9-10].

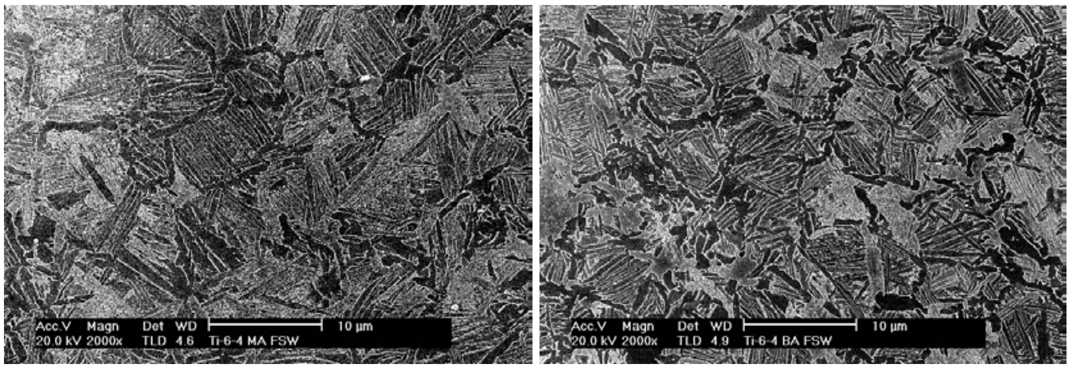


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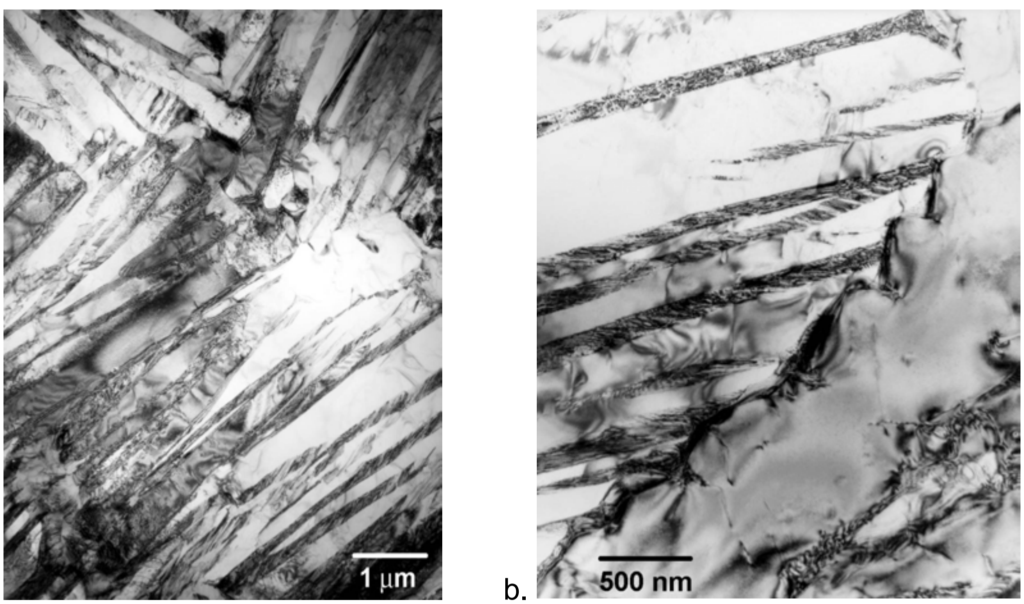
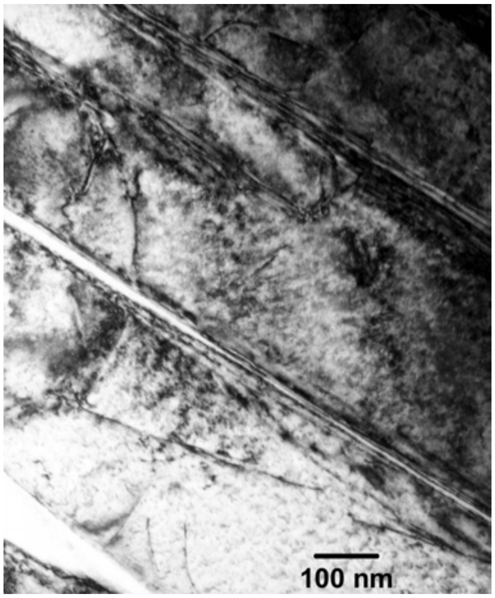
Figure 7: Central region of the stir zone of (a) Mill Annealed and (b) β-Annealed plates. SEM images.



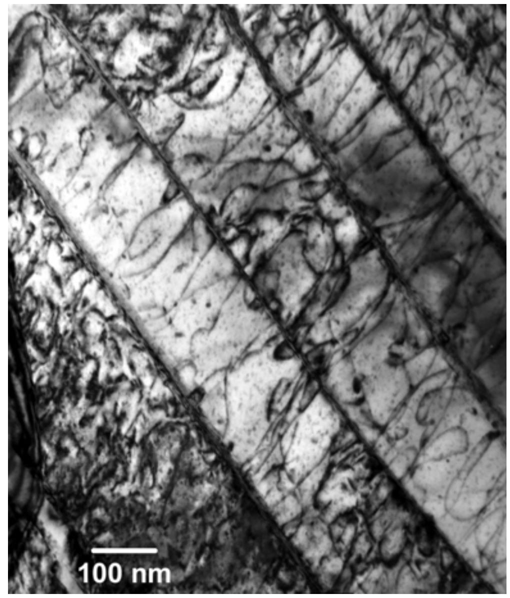
a. b.

Figure 8: β-Annealed stir zone microstructure. In (a) fine α/β colonies and in (b) grain boundary α and α/β colonies. TEM images.

It is anticipated that the development of new tool materials [11] or process modifications which may allow higher flexibility in travel speeds and joint heating, will provide an invaluable method of controlling the stir zone microstructures and optimize mechanical properties.



a.



b.

Figure 9: Highly deformed a/β colonies in (a) β-Annelaed and (b) Mill annealed near to TMAZ stir zone. TEM images.

The region of the SZ adjacent to the TMAZ is characterized by distinctive features, which is common to both M-A and β-A materials. Some highly deformed regions are observed, as shown in Fig. 9. As previously reported [4, 12], small equiaxed α grains (about 1 μm), as presented in Fig. 10.b, were observed. The similar size of these equiaxed α grains for both materials may suggest that their formation does not depend on the initial microstructure and is strictly controlled by the stirring process and the thermal cycle. However, this is not the case, as will be discussed in the TMAZ section which follows.

3.3 Thermomechanically Affected Zone (TMAZ) – Near Stir Zone (NSZ)

The change from the stir zone to the TMAZ is not abrupt. Actually, there is a continue decreasing on the stir effect and maximum reached temperature from the central stir zone to the TMAZ. Consequently, it is extremely difficult to identify the where the SZ ends and the TMAZ starts. For this reason the authors have defined a region called near stir zone, which still appears to be SZ, but it has a differentiated microstructure from the central SZ due to the lower imposed deformation and reached peak temperature. Depending on the initial state of the material, it may be possible to differentiate between these two regions.

The TMAZ formed on these Ti-alloys was extremely narrow (~ 10 μm wide) and had a common feature to both initial conditions. Extensive presence of equiaxed α was observed in the TMAZ and the near SZ of both material conditions. Fig. 11 shows the TMAZ of the M-A material, where the primary α bands have undergone further recrystallization. Because of the history of the base material, no deformation was available in the material to drive this recrystallization. Thus, the thermal conditions and the deformation imposed by the stirring process in the near SZ and the TMAZ were enough to drive the dynamic recrystallization (DRX) of the large primary α bands, to form small equiaxed α (about 1 μm). In the M-A material is very difficult to recognize between the NSZ and the TMAZ. The size and fraction of the α/β colonies is larger in the TMAZ-NSZ when compared with the original (BM) microstructure of the M-A plates. The high temperatures reached by this region during the FSW process resulted on the growth of the β phase fraction, as evidenced by the larger size and fraction of the α/β colonies that formed by the decomposition of this high temperature β phase.

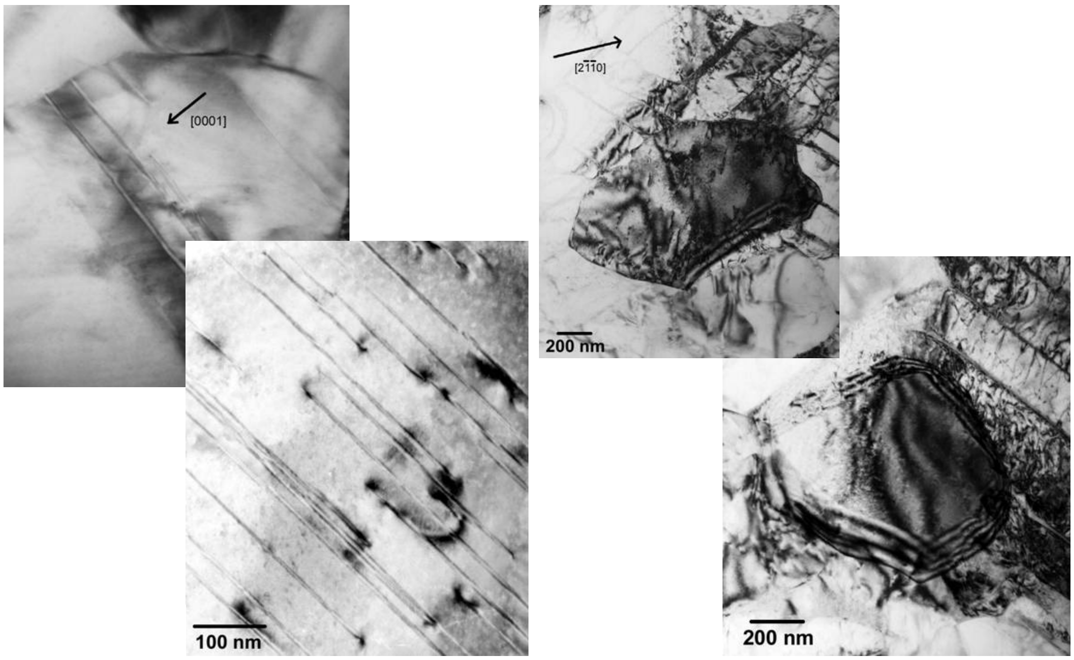


Figure 10: Stir zone of Mill and β annealed plates. In (a) stacking faults within the α and in (b) equiaxed α. TEM images.

The recrystallization process becomes more evident in Fig. 12, where the near stir zone (NSZ) and TMAZ of the β-A material are shown. As is revealed in this figure, the α lamellae within the α+β colonies in the TMAZ have undergone DRX, forming small equiaxed α grains (about 1 μm). This process of lamellar α recrystallization is known in the α+β Ti alloy literature as α globularization [13].

The low dislocation density observed in these equiaxed α grains, as shown in Fig. 13, supports the DRX explanation. This elucidates how the region in the near SZ of both materials, with a profusion of equiaxed α grains, is the result of an intense deformation process that triggers DRX in a region which did not exceed the β-transus temperature. The similar thickness of primary α bands in the M-A material and the α lamellae in the α+β colonies of the β-A material resulted in formation of equiaxed α particles of approximately same size (about 1 μm) in both materials.

Another notable microstructural feature observed in the TMAZ of the M-A material was the formation of acicular particles within the larger β particles. These particles were only observable in the TEM due to their small size. Fig. 14 presents bright field images of β particles with acicular second phase particles precipitated within it. These acicular particles were identified as secondary α by STEM study reported elsewhere [14]. The large prior β grains grew and became depleted in V during exposure to temperatures slightly below β-transus. Thus, when the TMAZ cooled at a rate that inhibited β dissolution over appreciable diffusion distances, the large β grains remained in the microstructure. Since the β phase was unstable at room temperature, acicular secondary α nucleated within the prior β grains upon cooling.

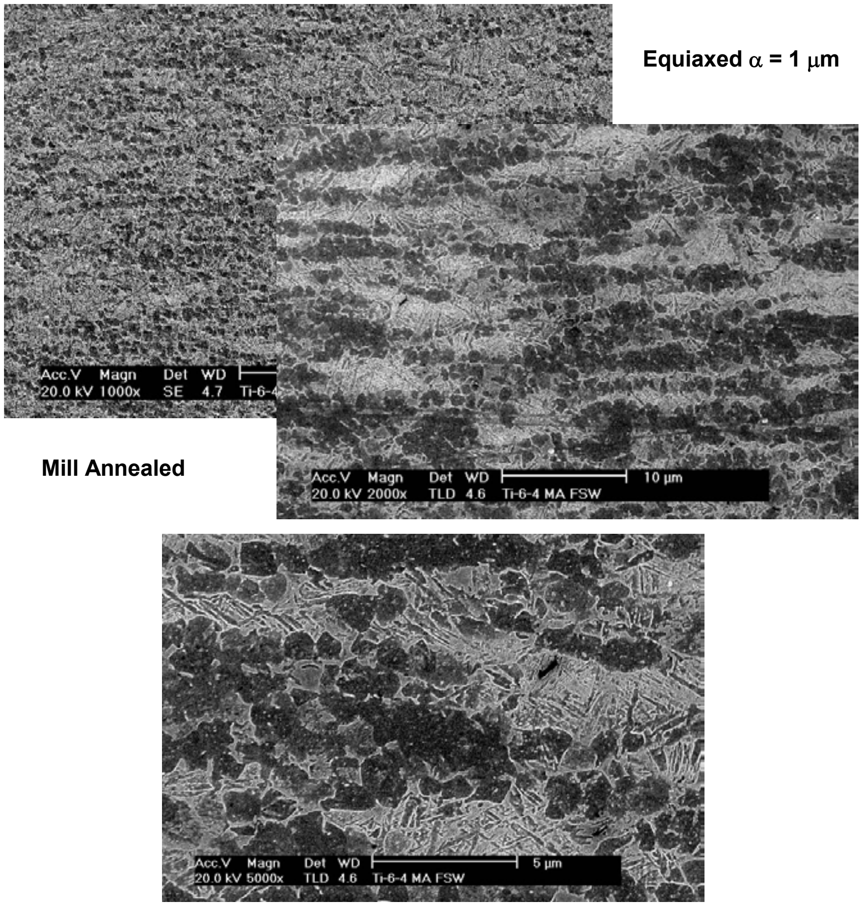


Figure 11: TMAZ – Near SZ in the mill annealed material. SEM images.

4. SUMARY

For the given welding conditions, the SZ temperature of the mill annealed and β annealed Ti-6Al-4V alloys exceeded β-transus, however, the prior β grain growth in this region was limited by the severe deformation and short dwell time above β-transus. The final microstructure obtained in this region was prior β grain boundaries decorated by grain boundary α and lamellar $\alpha+\beta$ colonies within the prior β grains. The presence of grain boundary α reveals that the cooling rate was not high enough to preclude its formation, but was high enough to induce the formation stacking faults on basal planes in the α phase. The presence of equiaxed α particles within the TMAZ and the NSZ is explained by the DRX induced by the intense deformation and high temperature in these regions, which did not exceed the β-transus temperature. Thus, the equiaxed α grains are the result of the recrystallization of α bands in the M-A base material and globularization of lamellae from the β-A base material. The low dislocation density observed in these grains supports the hypothesis of recrystallization. Another microstructural feature observed in the TMAZ of the M-A plates was the precipitation of secondary α within the β particles.

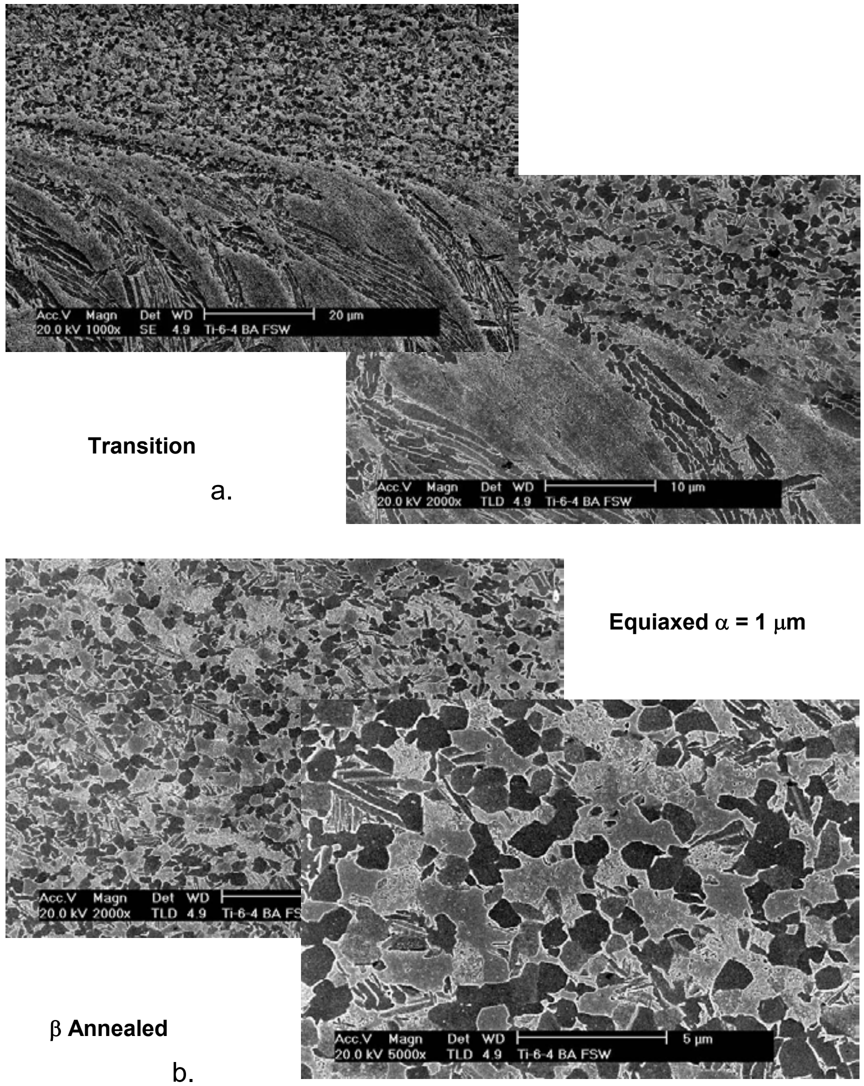


Figure 12: TMAZ – Near S.Z in the β Annealed material. In (a) transition from the near SZ to the TMAZ and in (b) the so-called near stir zone (NSZ). SEM images.

The detailed microstructure characterization in Ti alloy friction stir welded joints is extremely important to understand the evolution and metallurgical phenomena involved in this process. The understanding of the microstructural evolution will permit the adjustment of welding parameters to obtain the appropriate microstructures for optimized weld performance, which should be the goal of FSW and friction stir processing of Ti alloys. For example, it would be possible to cast Ti-alloys obtaining large β grain (β-A like) microstructures, which have good crack growth properties but poor fatigue life and friction stir process. Furthermore, the cast surface can be friction stir processed to obtain a small β grain structure, which will have a better fatigue life. The FSW permits to obtain ultra-refined microstructures with for example small acicular α particles or even finer secondary α colonies precipitated with the β phase, which may be preferred to certain applications, as fatigue.

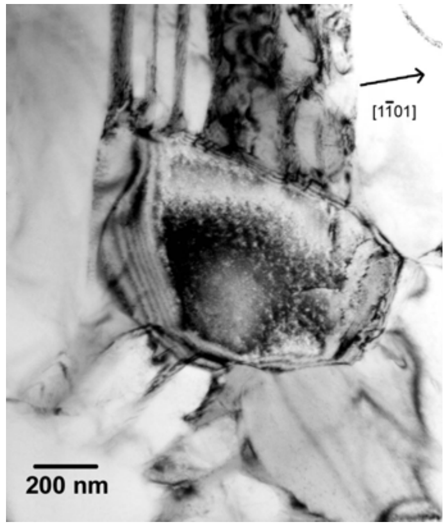


Figure 13: Equiaxed α particle in the near stir zone of the M-A material.

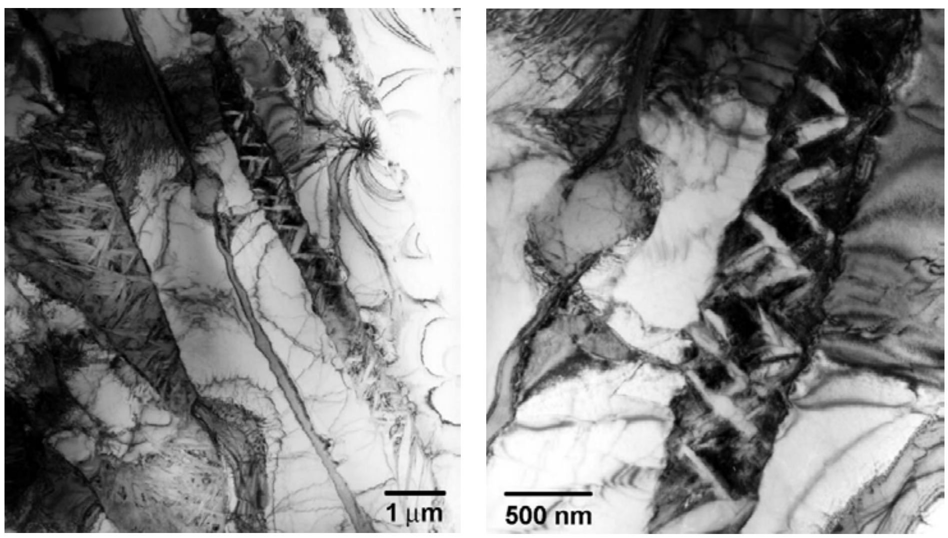


Figure 14: Secondary α at the TMAZ of the M-A material.

Once the microstructural evolution during the friction stir process and their relationship with the process parameters become well understood it may be possible to developed different level of microstructural refinement for different applications. At this moment would be possible to friction stir weld or process tailoring the material properties.

5. ACKNOWLEDGMENTS

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RESUMO

A soldagem por atrito com pino (SAP) (friction stir welding - FSW) de ligas de alumínio é uma tecnologia já bastante difundida e amadurecida com importantes aplicações na industria aeroespacial e no futuro próximo é esperada sua entrada em outros segmentos como a industria automobilística. Porém, o desenvolvimento da SAP de ligas com temperatura de fusão elevado como os aços carbono e inoxidáveis, as ligas de níquel e as ligas de titânio está bem incipiente e ainda não existem aplicações comerciais. Tanto fatores técnicos (material do pino), como fatores econômicos limitam a aplicação deste processo de união para materiais "duros" à produção de bens com elevado valor agregado. Em especial as vantagens metalúrgicas e mecânicas da SAP fazem este processo bastante atrativo para soldar ligas de titânio, as quais são amplamente utilizadas nas industrias aeroespacial, química, medica, petróleo e outros produtos de consumo de alto valor. Este trabalho discute as vantagens metalúrgicas da soldagem ou processamento por atrito com pino de ligas de Titânio, na luz de trabalho experimental com a liga comercial Ti-6Al-4V.

Palabras-Chave: Soldagem por atrito com pino, Ligas de Titânio, Ti-6Al-4V, Zona Termo-Mecanicamente afetada, Globularização de fase Alfa, Fase Alfa Secundária.