Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 50 (2020) 93–97

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

18th International Conference Metal Forming 2020

Friction Stir Welding of Ti6Al4V complex geometries for aeronautical applications: a feasibility study

Davide Campanella, Gianluca Buffa*, Antonio Barcellona, Livan Fratini

University of Palermo, viale delle Scienze, 90128 Palermo, Italy

* Corresponding author. Tel.: +39-09123861869; fax: +39-09123861869. *E-mail address:* gianluca.buffa@unipa.it

Abstract

While Friction Stir Welding (FSW) of aluminium alloys can be considered a mature technology, even for complex joint morphologies, as T joints welded “in transparency”, welding of hard material still presents several open issues. In fact, welding of titanium alloys is a challenging process due to the chemical, mechanical and thermal characteristics of such materials which are subjected to atmosphere contamination resulting in joint hydrogen, oxygen and nitrogen embrittlement; additionally, due to the high melting temperature, large distortion and residual stress are found in joints obtained by traditional fusion welding processes as gas metal arc welding, electron beam welding and laser welding. In this way a solid-state process, as FSW, represents a valid choice in order to overcome problems related to the material melting. It should be noticed that FSW of titanium alloys is definitely more complex than the same process referred to aluminium alloys. In the proposed paper, a feasibility study on the production of Ti6Al4V T-joints in one welding pass, i.e. the so-called transparency welding, is presented. The main process parameters, i.e. tool rotation and feed rate have been fixed, and the main metallurgical and mechanical properties of the joint have been analysed. Macro and micro observations of the joints have been performed relating the final microstructure to the input process parameters utilized.

Keywords: Friction Stir Welding; Titanium alloys; T-joints.

1. Introduction

Titanium alloys, over the decades have drawn the attention of scientist due to their high strength, excellent corrosion resistance, and biocompatibility [1, 2]. Titanium and its alloys have become one of the most commonly used light alloys in industries that are more sensitive to performance than material cost [3]. However, titanium alloys present certain disadvantages in service. For example, as biomedical material, titanium alloy may present poor surface wear properties that will limit the performance and service life [2]. In addition, tiny particles on the surface will peel off as surface corrosion aggravates, which results in worse inflammation in soft tissues [4]. Another example is Ti-based shape memory alloys. Although most Ti-based shape memory alloys, such as TiNb, have a superior shape memory effect, pseudo-elasticity, corrosion resistance and biocompatibility, due to the difference in elastic modulus compared with human bones, their biomedical applications are still limited [5-7]. Therefore, appropriate measures are desired to realize control of both the microstructure and properties of titanium alloys to make them better meet requirements under various working environments.

Wide use of these alloys is made in the aerospace industry for which the continuous focus on reducing the buy-to-fly ratio is one of the key drivers.

In the last years, particular attention has been given by industry to Friction Stir Welding (FSW) because of the possibility to successfully weld similar and dissimilar lightweight materials such as aluminum alloys commonly used in the transportation field, including aerospace, aeronautics, automotive, naval and ground transportation. Aeronautical engineers have used the FSW process to weld materials that cannot be welded by conventional fusion welding, such as the aluminum alloys of 2XXX and 7XXX series [8] and also serve

2351-9789 © 2020 The Authors. Published by Elsevier B.V.

10.1016/j.promfg.2020.08.017

as a riveting replacement [9]. In the recent years, for a number of applications conventional TIG and MIG welds have been replaced by FSW process, owing to its provision of a significantly better corrosion resistance [10, 11] and fatigue properties [2], [12].

A number of papers can be found in literature on FSW of titanium alloys. Lee et al. [13] and Zhang et al. [14] investigated mechanical and metallurgical properties of FSW joints obtained from commercially pure titanium sheets of 5.6 mm and 3 mm respectively, finding the feasibility of the process for such materials and pointing out the main differences with the already known microstructure evolution phenomena occurring in FSW of aluminum alloys. Pasta and Reynolds [15] investigated the residual stress effects on fatigue crack growth also using numerical simulation taking into account Ti-6Al-4V titanium alloy; in particular, their numerical model was limited to the prediction of the crack growth rate and showed a good matching with experimental results

The studies carried out until now have been concerned with only two joint configurations, i.e. butt and lap. However, in various industrial applications, T-joint configuration (composed of skin and stinger sheets) is normally used [16]:

- ✓ *Aviation industries* for the reinforcement of fuselage.
- ✓ *Shipbuilding industry* for producing ship hulk, mast, etc.
- ✓ *Railways industry* for joining wagon components and floorboards.
- ✓ *Automobile applications* for the welding of car bodies, fuel tanks, back supports, bicycle as well as motorcycles frames, and
- ✓ *Construction industry* for connecting bridges, pipelines, window frames, etc.

The geometry of T configuration has important features in stiffness and strength of skin or stringer, which can be increased significantly without significant weight increase [17]. Such kind of geometry can be obtained by extrusion, riveting or by the conventional welding process. It should be known that the high manufacturing cost and limitations in size are not suitable to satisfy for high manufacturing volume. For example, in the aero-structure field, riveting increases the plane weight while adding the manufacturing procedure of the pre hole introduces stress concentration in the joint [18]. However, conventional fusion welding or laser welding have known disadvantages such as high residual stress, porosity, cracks, metallurgical defects as well as distortion, which significantly affect the mechanical properties [19]. For these reasons, only a very limited number of papers can be found in recent literature on fusion welding of Titanium alloys T-joints. The buckling and post-buckling behavior of laser welded titanium alloy T joints stiffened panels under shear load have been investigated using both experimental method and FE numerical simulation by Su et al. [20]. In particular, the authors implemented a parametric analysis using the Finite Element (FE) models to study the influence of the certain ranged stringer thickness and height on the behavior of the stiffened panels. Froend et al. produced T-joints between cp-Ti skin and Ti-6Al-4V stringer by laser beam welding to investigate the influence of welding parameters on the weld quality, shape, distortion, and defects [21]. In this paper 13 process parameters having an influence on the weld quality were identified by the authors.

In such cases, FSW can represent an effective solid-state joining technology for fabricating T-joints of titanium alloys. Technological parameters, as the tool rotating speed and the tool feed rate, have to be properly chosen, since they strongly influence the specific thermal contribution conferred to the joining edges. Detailed information on the influence of such parameters on the FSW process mechanics and on the performances of the welded joints can be found out for instance in Liu et al. [22], Rhodes et al. [23], Guerra et al. [24], and Barcellona et al. [25].

The present paper presents the results of a feasibility study on Ti-6Al-4V T-joints produced by FSW. A dedicated clamping fixture has been designed and a specially designed tool has been used to weld in “transparency” skin and stringer structures. The joints metallurgical and micro-mechanical properties have been investigated.

Nomenclature

FSW	Friction Stir Welding
SZ	Stir Zone
GTAW	Gas Tungsten Arc Welding

2. Experimental procedure

For the tests, titanium alloy Ti-6Al-4V sheets were used (the chemical composition and main mechanical properties are demonstrated respectively table 1 and table 2).

Table 1. Chemical composition of Ti-6Al-4V.

Chemical compounds	*Percentage [%wt.]*
V	*4.22*
Al	*5.48*
Sn	*0.0625*
Zr	*0.0028*
Mo	*0.005*
C	*0.369*
Si	*0.0222*
Cr	*0.0099*
Ni	*< 0.0010*
Fe	*0.112*
Cu	*< 0.02*
Nb	*0.0386*
Ti	*90.0*

Table 2. Main mechanical properties of Ti-6Al-4V.

Work material	Ti-6Al-4V
Ultimate tensile Strength [MPa]	887
Modulus of elasticity [x10^6 MPa]	11.3
Hardness [HV]	340

The tests were carried out using an ESAB LEGIO 3ST machine using a tilt angle (θ) of 2.5° and a tool plunge of 2.8 mm. In order to ensure the same plunge along the weld, a force control on the stirring head was set on the machine. Both the skin and stringer sheets, 2 mm thick, were reduced into rectangular specimens 100 x 100 mm in length and width respectively.

In Fig.1, the used clamping fixture is shown: steel plates, which were finished at the grinding machine, were used in order to assure a uniform pressure distribution on the specimens. Once the stringer was fixed between the vertical walls, the skin was placed and then clamped above it. Screw grains were used to ensure the pressure on the skin avoiding thus distortion during the process.

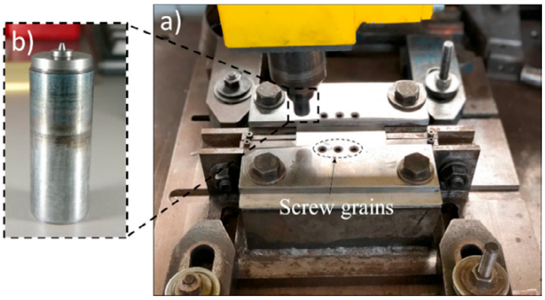

Fig. 1. (a) Clamp fixture; (b) Pin tool utilized.

The heat propagation on the stringer is crucial in this kind of configuration and proper values cannot be achieved only by changing the technological parameters. For the tests, a pin tool with double shoulder (fig.1b) was used according to a few studies carried out by some of the authors of the present work demonstrating that such geometry can resolve the heat-propagation problem [26], [27]. The tool was made in W-Re alloy characterized by a melting point of 3050°C and a recrystallization temperature near 1900°C. The geometrical parameters used are shown in table 3.

Table 3. Geometry of the utilized tungsten-rhenium tool.

Work material	Ti-6Al-4V
Shoulder diameter [mm]	14
Shoulder diameter [mm]	7
Shoulder height [mm]	1.2
Pin major diameter [mm]	2
Pin angle [°]	15
Pin height [mm]	1.2

As far as the process parameters are regarded, the tool rotation and the feed rate were respectively fixed to 800 rpm and 20 mm/min.

Micro Hardness measurements were carried out on the skin and on the stringer at mid thickness. The distance between two consecutive indentations was 0.5 mm. A 500 g weight was used for 30 sec.

3. Results

Figure 2 presents weld top surface characterized by 800 rpm and 20 mm/min.

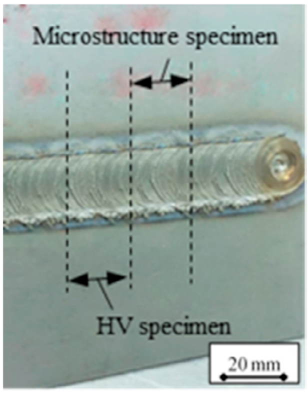

Fig. 2. Test carried out with 800 rpm and 200 mm/min.

With the aim to study the junction quality, two specimens were cut to analyze the microstructure and micro-hardness. In figure 3 the hardness result are shown. In particular, two different trends regarding skin (blue line, x axis) and stringer (orange line, y axis) micro hardness have been indicated.

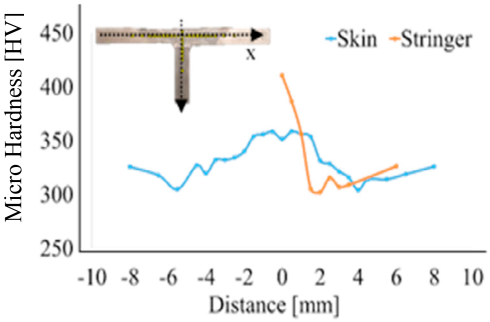

Fig. 3. Micro hardness for skin and stringer sheets.

In table 4 the average values measured in the three zones characterizing this process are demonstrated. In fact, as known in literature, the FSW process of Ti6Al4V is characterized only by three-zone instead of four, because there is no nugget as in the FSW of aluminum alloys, but rather a wider area, usually referred to as Stir Zone, including the “equivalent” nugget and Thermo-Mechanically Affected Zone.

Table 4. HV measurements for the medium heat input case study.

Indentation Nr	SZ	HAZ	PM
1	352.09	332.24	328.47
2	351.45	336.08	324.56
3	351.16	329.02	326.18
Mean values	351.56	332.33	326.40

It can be supposed that the increase of micro hardness is due to the martensitic transformation occurring in the weld bead. However, with the increase in the distance from the weld bead the micro-hardness values slightly return to those typical of the parent alloy. These values are consistent with the HV measurements carried out on Friction Stir Welded specimens of the same material, where the material undergoes analogous thermo-mechanical solicitation. Overall larger HV values are found with lamellar microstructure, i.e. were the heat flow given by the tool allowed to reach the beta-transus temperature, which, for the considered alloy, is about 980°C. The latter considerations explain why larger values with respect of the base material are found at the center of the welds while the minimum values, even smaller than the base materials, are found in the HAZ. Finally, it should be observed that micro hardness profile observed in figure 3 for the skin is extremely different from the ones known for aluminum alloys, where, as far as precipitation hardening alloys are regarded, a strong material softening is observed all along the joint transverse section due to the density reduction of the precipitates. The latter phenomenon is determined by the heat flux generated during the process resulting in local temperature levels larger than the solubilization thresholds of the precipitates. Such effect is partially limited in the nugget due to the reduced grain size influence

As mentioned above, the morphological analysis has been carried out on the joint.

The microstructure of the parent material, Ti6Al4V titanium alloy is characterized by a biphasic structure ($\alpha+\beta$) with α equiaxed grains and intergranular β phase. The specimen for the metallographic analysis was prepared according to ASTM E3-11 standard procedure and etched with 0.5% HF solution. In figure 5, a typical joint section found when a tool with the double shoulder is used has been highlighted.

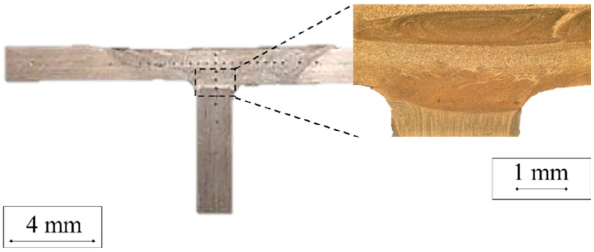

Fig. 4. Macro and micro observations in the stirring zone.

In figure 5, an observation with magnifications in three characteristic areas is shown where It can be seen the complex flow generating during the process. Two different stirring zones can be noticed in the skin (figure 5b) and in the stringer (figure 5a) respectively, due the combination of high temperature and high strain. The areas are characterized by similar micro hardness values. Furthermore, the material flow at the center of the skin results in large strain of the material, as inferred observing the vortex of material flow (figure 5b).

In figure 5c, the material flow seems to begin creating a hocking defect which however, does not results in material discontinuity.

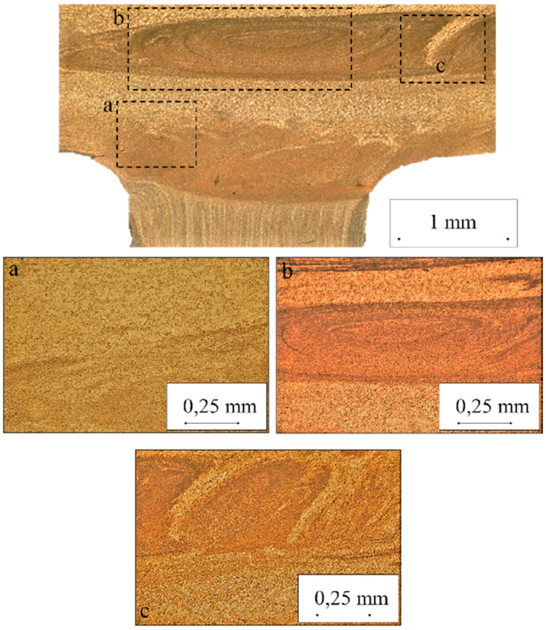

Fig. 5. Macro and micro observations in the two stirring zones.

4. Conclusions

In the paper, a feasibility study on the FSW of T joints made out of Ti6Al4V thin sheets is presented. A double shoulder Tungsten Rhenium tool was used to allow the heat to reach the bottom of the skin sheet, i.e. where the actual bonding has to take place. A sound weld could be obtained using tool rotation of 800 rpm and tool feed rate equal to 20 mm/min. From the observation of the joint metallurgy, it arises that two different Stir Zones can be found in the stringer and in the skin, respectively. This is due to the use of a double shoulder tool which results in two zones characterized by large temperature and deformation. In these areas, based on the increase in micro hardness measured, it can be inferred that the beta-transus temperature was reached and a lamellar structure was obtained.

Future developments include the carry out of a complete experimental plane with varying tool rotation and feed rate in order to investigate the effect of these process variables on the joints integrity.

References

[1] Wang L, Lu W, Qin J, Zhang F, Zhang D. Influence of cold deformation on martensite transformation and mechanical properties of Ti-Nb-Ta-Zr alloy. J Alloys Compd 2009. https://doi.org/10.1016/j.jallcom.2008.02.032.

[2] Wang X, Wang K, Shen Y, Hu K. Comparison of fatigue property between friction stir and TIG welds. J Univ Sci Technol Beijing Miner Metall Mater (Eng Ed) 2008. https://doi.org/10.1016/S1005-8850(08)60053-5.

[3] Liu X, Chu PK, Ding C. Surface modification of titanium, titanium alloys, and related materials for biomedical applications. Mater Sci Eng R Reports 2004. https://doi.org/10.1016/j.mser.2004.11.001.

[4] Rabadia CD, Liu YJ, Jawed SF, Wang L, Li YH, Zhang XH, et al. Improved deformation behavior in Ti-Zr-Fe-Mn alloys comprising the

C14 type Laves and β phases. Mater Des 2018. https://doi.org/10.1016/j.matdes.2018.10.049.

[5] Lin Z, Wang L, Xue X, Lu W, Qin J, Zhang D. Microstructure evolution and mechanical properties of a Ti-35Nb-3Zr-2Ta biomedical alloy processed by equal channel angular pressing (ECAP). Mater Sci Eng C 2013. https://doi.org/10.1016/j.msec.2013.07.010.

[6] Hafeez N, Liu S, Lu E, Wang L, Liu R, lu W, et al. Mechanical behavior and phase transformation of β-type Ti-35Nb-2Ta-3Zr alloy fabricated by 3D-Printing. J Alloys Compd 2019. https://doi.org/10.1016/j.jallcom.2019.03.138.

[7] Ahmed MMZ, Ataya S, El-Sayed Seleman MM, Ammar HR, Ahmed E. Friction stir welding of similar and dissimilar AA7075 and AA5083. J Mater Process Technol 2017. https://doi.org/10.1016/j.jmatprotec.2016.11.024.

[8] Cavaliere P, Nobile R, Panella FW, Squillace A. Mechanical and microstructural behaviour of 2024-7075 aluminium alloy sheets joined by friction stir welding. Int J Mach Tools Manuf 2006. https://doi.org/10.1016/j.ijmachtools.2005.07.010.

[9] Dracup BJ, Arbegast WJ. Friction stir welding as a rivet replacement technology. SAE Tech. Pap., 1999. https://doi.org/10.4271/1999-01-3432.

[10] Wadeson DA, Zhou X, Thompson GE, Skeldon P, Oosterkamp LD, Scamans G. Corrosion behaviour of friction stir welded AA7108 T79 aluminium alloy. Corros Sci 2006. https://doi.org/10.1016/j.corsci.2005.02.020.

[11] Maggiolino S, Schmid C. Corrosion resistance in FSW and in MIG welding techniques of AA6XXX. J Mater Process Technol 2008. https://doi.org/10.1016/j.jmatprotec.2007.06.034.

[12] Moreira PMGP, de Figueiredo MAV, de Castro PMST. Fatigue behaviour of FSW and MIG weldments for two aluminium alloys. Theor Appl Fract Mech 2007. https://doi.org/10.1016/j.tafmec.2007.06.001.

[13] Lee WB, Lee CY, Chang WS, Yeon YM, Jung SB. Microstructural investigation of friction stir welded pure titanium. Mater Lett 2005. https://doi.org/10.1016/j.matlet.2005.05.064.

[14] Zhang Y, Sato YS, Kokawa H, Park SHC, Hirano S. Stir zone microstructure of commercial purity titanium friction stir welded using pcBN tool. Mater Sci Eng A 2008. https://doi.org/10.1016/j.msea.2007.10.062.

[15] Pasta S, Reynolds AP. Residual stress effects on fatigue crack growth in a Ti-6Al-4V friction stir weld. Fatigue Fract Eng Mater Struct 2008. https://doi.org/10.1111/j.1460-2695.2008.01258.x.

[16] Krasnowski K. Experimental Study of FSW T-joints of EN-AW 6082-T6 and Their Behaviour Under Static Loads. Arab J Sci Eng 2014. https://doi.org/10.1007/s13369-014-1465-0.

[17] S.M.O. Tavares, P.C.M. Azevedo, B. Emilio, V. Richter-Trummer, M.A.V. Figueiredo PV and PMST de C. Friction stir welding of T-joints in dissimilar aluminum alloys. Proc. Int. Mech. Eng. Congr. Expo., 2008, p. 265–273.

[18] Zhou G, Yang XQ, Cui L, Zhang ZH, Xu XD. Study on the microstructures and tensile behaviors of friction stir welded T-joints for AA6061-T4 alloys. J Mater Eng Perform 2012. https://doi.org/10.1007/s11665-012-0154-y.

[19] Jesus JS, Gruppelaar M, Costa JM, Loureiro A, Ferreira JAM. Effect of geometrical parameters on Friction Stir Welding of AA 5083-H111 T-joints. Procedia Struct. Integr., 2016. https://doi.org/10.1016/j.prostr.2016.02.033.

[20] SU Y, GUAN Z, WANG X, LI Z, GUO J, HUANG Y. Buckling and post-buckling behavior of titanium alloy stiffened panels under shear load. Chinese J Aeronaut 2019. https://doi.org/10.1016/j.cja.2018.09.007.

[21] M.Froend, F.Fomin, S.Riekehr, P.Alvarez, F.Zubiri, S.Bauer, B.Klusemann NK. Fiber laser welding of dissimilar titanium (Ti-6Al-4V/cp-Ti) T-joints and their laser forming process for aircraft application. Opt Laser Technol 2017;96:123–31.

[22] Liu HJ, Fujii H, Maeda M, Nogi K. Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy. J Mater Process Technol 2003. https://doi.org/10.1016/S0924-0136(03)00806-9.

[23] Rhodes CG, Mahoney MW, Bingel WH, Spurling RA, Bampton CC. Effects of friction stir welding on microstructure of 7075 aluminum. Scr Mater 1997. https://doi.org/10.1016/S1359-6462(96)00344-2.

[24] Guerra M, Schmidt C, McClure JC, Murr LE, Nunes AC. Flow patterns during friction stir welding. Mater Charact 2002. https://doi.org/10.1016/S1044-5803(02)00362-5.

[25] Antonio Barcellona;, Buffa G, Fratini L. Process parameters analysis in friction stir welding of AA6082-T6 sheets. ESAFORM Conf., 2004, p. 371–4.

[26] Fratini L, Buffa G, Filice L GF. FSW of AA6082-T6 T-joints: process engineering and performance measurement. Proc IME B J Eng Manufact, 2006;220(5):669–76.

[27] Fratini L, Micari F, Squillace A, Giorleo G. Experimental Characterization of FSW T-Joints of Light Alloys. Key Eng Mater 2007. https://doi.org/10.4028/www.scientific.net/kem.344.751.