ISSN online 2066 – 8570 Volume **8**, Number **2**/**2016**

EFFECT OF PRE-HEAT TREATMENT ON MECHANICAL PROPERTIES OF Ti-6Al-4V WELDS

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Rezumat. *Articolul prezent se referă la optimizarea procesului de sudare prin frecare şi deplasarea sculei (FSW). Obiectivul este acela de a studia influența anumitor parametri utilizați în producerea îmbinărilor sudate prin FSW. Cei mai importanți parametri sunt viteza de rotație şi viteza de avans a sculei. Efectul tratamentului de preîncălzire pe plăcile de sudat este de asemenea studiată folosind metoda planului de experiențe. Aceste tratamente de preîncălzire conduc la o modificare a proprietăților mecanice ale plăcilor care urmează să fie sudate, dar, de asemenea, a microstructurii lor. Experimentele au fost realizate în conformitate cu un plan fracționar de experiențe tip Taguchi cu 16 linii.*

Abstract. *The work presented here is related to the optimization of the Friction Stir* ***Welding (FSW) process. The objective is to study the influence of some parameters used*** *in the production of welded joints by FSW. The most important parameters are the welding speed and the rotational speed of the tool. The effect of pre-heat treatment on the plates to be welded is also studied by the design of experimental methods. These pre-heat treatments result not only in a change of mechanical properties of plates to be welded, but also of their microstructure. The experiments were performed following a 16 lines fractional Taguchi table.*

Keywords: friction stir welding, design of experiments, heat treatment, microstructure.

1. Introduction

Titanium is a metal discovered in 1791. Its wide use is due to its good resistance to corrosion, high strength despite its low density and its biocompatibility. It has applications in several domains such as aeronautic, medical science and automobile. Due to its good mechanical properties, manufacturing processes applied to titanium remain a difficult task. Especially, welding titanium by conventional welding methods usually leads to a loss in mechanical properties. To overcome these problems, a solid state welding method namely Friction Stir Welding is used to maintain enhanced mechanical properties.

Friction Stir Welding (FSW) is a solid state welding process invented in 1991 by The Welding Institute (TWI). The FSW process has not only the advantage of reducing the weight but also of avoiding solidification defects associated with other welding methods. The non-consumable tool (fig. 1a) is composed of a shoulder and a pin.

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As shown on fig. 1, the process consists of three phases: (b) rotating tool plunging in the work piece, (c) tool displacement along the joint line and (d) tool removal from the work piece.

After microscopic observations of a FSW weld, it can be divided in five different zones (figure 2):

- The base metal (BM): it is the most distant part from the welding centre. It does not undergo any significant modification. Its thermo-mechanical properties remain unchanged.

- The Heat Affected Zone (HAZ): It undergoes a change of microstructure due to the increase of the temperature. There is no plastic strain in this zone, but fractures often occur there during tensile tests [1].

- The Thermo-Mechanically Affected Zone (TMAZ): This area undergoes plastic deformation. In the case of titanium welds (or its alloys), this area is often absorbed by the nugget; both zones then form the Stirred Zone (SZ).

- The nugget: it is the centre of the weld. The strains are greater there and usually exceed 10 [2]. Temperatures in the nugget of Ti-6Al-4V FSW welds often reach 1500 K [3].

- The flow arm: it is a forged zone just below the tool shoulder. Its mechanical properties are similar to those of the nugget.

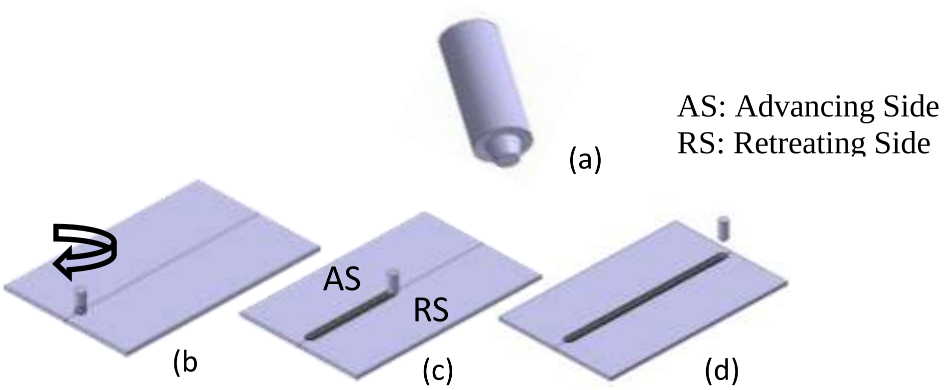

Fig. 1. Representation of the FSW process: (a) FSW tool
(b) tool plunging (c) welding (d) tool removal.

Many studies have been conducted on mechanical properties of Friction Stir Welds. The materials commonly welded are metals such as aluminium alloys, titanium alloys and steels. In this paper, we will present the effect of different friction stir welding parameters on Ti-6Al-4V titanium alloy welds by design of experiments (DOE) method.

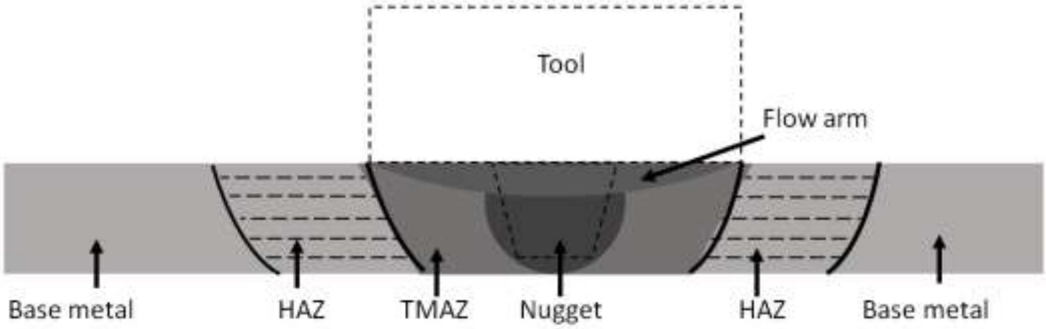

Fig. 2. Decomposition of the welded zone.

2. A review on previous FSW studies

In FSW, DOE method usually helps to study the effect of welding parameters on the mechanical and structural properties of the welds.

Kasman investigated on multi response optimization for dissimilar friction stir butt welding of AA6082-T6/AA5754-H111 [4]. He reported that the welding speed, the tool rotational speed and the shoulder diameter to pin diameter ratio (D/d) have a significant effect on ultimate tensile strength and elongation.

Zhang et al. studied the microstructural and mechanical properties of Ti-6Al-4V weld joints for different welding and rotational speeds. They found that high rotational speeds lead to lower hardness and tensile strength [1]. In the stirred zone, they observed a fully lamellar microstructure and a duplex structure in the heat affected zone.

Other researchers studied the effect of rotational speed on the microstructure of Ti-6Al-4V welds [5].

Their welds showed two different microstructures in the stirred zone, consisting of lamellar and equiaxe structures.

Liu et al. investigated the microstructural characteristics and mechanical properties of friction stir welded joints of Ti–6Al–4V titanium alloy [6].

The welds exhibited a duplex structure in the stirred zone. Hardness and tensile strength in the welded zone were lower than in the base material.

Edwards and Ramulu determined experimentally peak temperatures during friction stir welding of Ti–6Al–4V with thermocouples [3].

By varying the welding and rotational speeds, they concluded that rotational speed has the dominant effect on the peak temperature and the welding speed has control on exposure time at peak temperatures.

3. Experimental work

The received Ti-6Al-4V plates were 5 mm thick annealed with an equiaxe structure (fig. 3a). In order to study the effect of a pre-heat treatment, three different heat treatments were applied. Many heat treatments can be applied to metallic materials. The most common for titanium alloys are annealing and solution treatment. Solution treatments are done above the phase change temperature called *beta transus*. The *beta transus* temperature of Ti-6Al-4V alloy is ~995°C [7]. Three heat treatments were done, giving rise to three microstructures (fig.3b-d) with different mechanical properties.

The first one is a solution treatment at 1050° during 35 minutes followed by air cooling. This treatment gave rise to a fine lamellar structure with a higher Vickers Hardness than the equiaxe one. The second heat treatment is a solution treatment at 1050° during 35 minutes followed by furnace cooling. A coarse lamellar structure was obtained with the lowest Vickers Hardness. The last treatment is an annealing at 950°C during 15 minutes air cooled followed by aging during 4 hours and air cooled. This treatment led to a duplex structure.

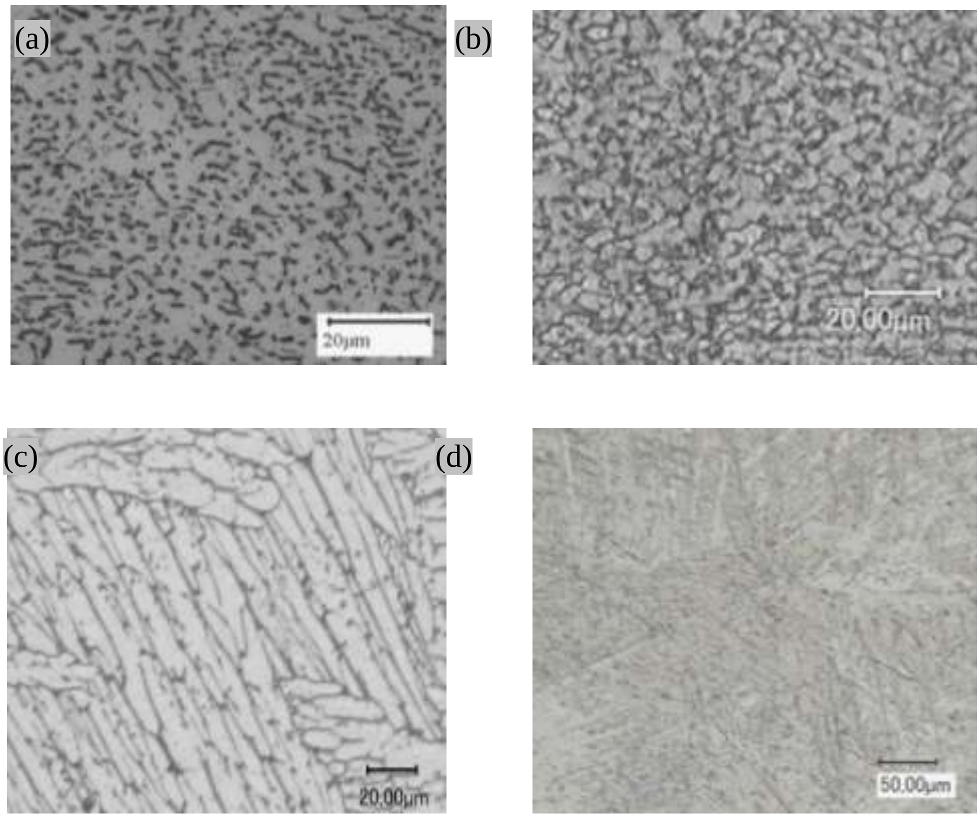

Fig. 3. Different microstructures obtained: (a) fine equiaxe, (b) duplex, (c) coarse lamellar, (d) fine lamellar.

In order to study the effect of welding speed and rotational speed on the properties of the welds, different values of these parameters were used.

The design of experiments method was employed to reduce the number of experiments. We used the well-known Taguchi method [8] with a $L_{16}(4^5)$ table. Some calibration tests were made in order to determine an adequate range for each parameter. Finally, the experimental design matrix used is given in table 1.

The FSW machine used in this study has a water cooling system to keep the temperature of the spindle and the tool as low as possible.

Argon gas was used as shielding gas to prevent the welds from oxidation. Before welding, the plates were clamped to a stainless steel backing plate. A W-25Re tool with a concave shoulder and a conical pin was used to make full matter penetration.

Table 1. Experimental design matrix

Sample	Microstructure (A)	Speed (B) (mm/min)	Rotation (C) (rpm)
1	1	50	400
2	1	65	420
3	1	80	440
4	1	95	460
5	2	50	420
6	2	65	400
7	2	80	460
8	2	95	440
9	3	50	440
10	3	65	460
11	3	80	400
12	3	95	420
13	4	50	460
14	4	65	440
15	4	80	420
16	4	95	400

Microstructures:
1= Fine equiaxe, 2 = Coarse lamellar, 3 = Fine lamellar, 4 = Duplex.

4. Results and discussion

Vickers hardness (figure 4) measured across the welded section at mid thickness shows that the hardness is not the same in each welding zone.

In the HAZ, it is smaller than in the BM.

The highest hardness is observed in the SZ.

This result is in good agreement with those obtained by other authors [1], [9].

There is no significant difference between the advancing side and the retreating side of the joints.

This variability in hardness results from significant microstructural changes that occurred during the FSW process.

The High hardness in the stirred zone should be attributed to a fine microstructure.

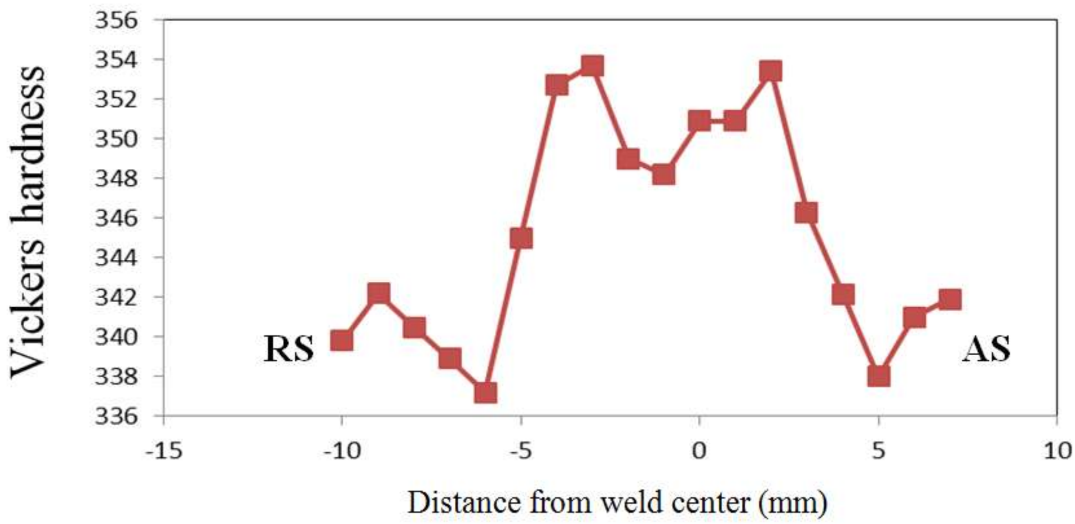

Fig. 4. Hardness profile in a sample welded in condition 1.

Conclusions

In this study, a design of experiment has been established to investigate the effect of various welding parameters on mechanical properties of FSW weld joints.

Different heat treatments were made on Ti-6Al-4V plates in order to investigate the influence of the initial microstructure on

(a) the ease of welding and

(b) the hardness profile.

A hardness test made across the weld showed a non-uniform profile due to drastic changes in microstructure.

Future work has to be done to characterize more in detail the different welding joints, i.e. microstructural observations and mechanical tests.

Acknowledgment

This project has received support from the State managed by the French National Research,

The Agency (ANR) under the program Future Investments Excellence Initiative IdEx Bordeaux and bearing the reference ANR-10-IDEX-03-02.

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