ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

MECHANICAL PROPERTIES EVALUATION OF FRICTION STIR PROCESS OF TITANIUM TI-6AL-4V ALLOY

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Abstract. *This research addresses the application of Friction Stir Welding (FWS) of titanium alloy Ti-6Al-4V. Friction stir welding is a recent process, developed in the 90's for aluminum joining. This joining process is being applied increasingly in many industries from basic materials such as steels alloys to high performance alloys such as titanium. It is a process in great development and has its economic advantages when compared to conventional welding. For high performance alloys such as titanium, a major problem to overcome is the construction of tools that can withstand the extreme process environment; in the approaching literature the possibilities are only few tungsten alloys. When using as a process the best term to its definition becomes Friction Stir Processing (FSP). Rather than joining the two sheets process is used in a single plate in order to improve the characteristics of the material. Early experiments with tools made of tungsten carbide (WC) showed optimistic results consistent with the literature. Mechanical properties as micro-hardness and residual stress were evaluated in order to understand the influence of the process parameters (tool rotation and feed) on the final condition of the process. It was observed that a lower condition of tool rotation resulted in a lower condition of residual stress. The metallographic analysis of the welds did not show primary defects of voids (tunneling) or similar internal defects due to processing, only defects related to tool wear which can cause loss of weld quality. The severe tool wear caused loss of surface quality and inclusions of fragments inside the joining, which should be corrected or mitigated by material replacement of tungsten carbide alloys by tungsten alloys as found in the literature.*

Key words*: Friction Stir Welding, Friction Stir Processing, titanium, WC tools, Residual Stress*

1. INTRODUCTION

Friction Stir Welding (FSW) is a joining process in the solid state, which eliminates problems associated with material melting and solidification, such as cracks, residual stresses and distortions generated during conventional welding. It was invented in 1991 at TWI (The Welding Institute) in the UK initially for aluminum joining. Among the most important advantages of FSW are: ease automation, less distortion, lower residual stress and good mechanical properties in the joining region. FSW is a recent approach to the metals joining and although originally intended for aluminum alloys, it is investigated in a variety of metallic materials. Despite the qualities initially observed, for certain applications such as superplastic forming (SPF), the analysis of mechanical properties resulting from FSW is of major importance for the correct process application. One example is found in Figure 1, where a difference is observed between the superplastic ability on the base original material and a region which has undergone a FSW.

A question that arises from Figure 1 is what will be the ideal parameters for FSW or FSP processing? These parameters will greatly influence the further processing on the resulting structures. The thesis related to this project is that knowledge of the process dynamics, their fixed and variable parameters involved in the FSP can be taken into account when developing a model to predict the mechanical properties with higher precision. The issue of tool wear resistance should also be exploited for a correct conclusion on the relevant factors involved in the final modeling.

ISSN 2176-5480

Figure 1 - In (a) processed region is more superplastic than the base material, and (b) the processed region is less superplastic than the base material (EDWARDS e RAMULU, 2009).

2. LITERATURE REVIEW

2.1. Friction stir welding

The basic concept of FSW is a rotating tool, made of non-consumable material, especially designed with a geometry consisting of a pin and recess (shoulder). This tool is inserted spinning on its axis at the adjoining edges of sheets or plates to be joined, and then it travels along the joining path line. Figures 2, 3 and 4 illustrate the process and have settings for the tool and the plate.

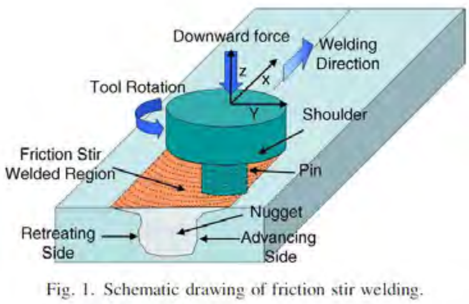

Figure 2 – FSW settings and definitions (MISHRA AND MA, 2005).

Figure 3 shows the process typical steps of the process: i) downward motion to penetrate the material; ii) penetrating the material; iii) time for the heat generation for deformation; iv) linear movement on the part toward the processing direction; v) end of processing and tool retraction.

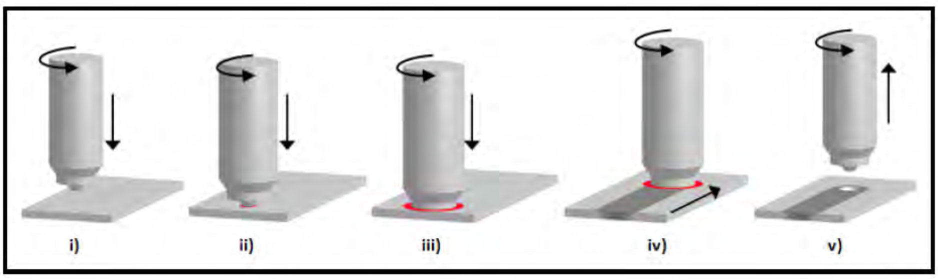

Figure 3 – FSW process steps (MASHININI, 2010).

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The tool rotation axis defines with the components to be welded an angle of inclination. This angle is used for receiving the material to be processed at the tool base and promote the gradual forge effect imposed by the shoulder during the passage of the tool. This prevents the material plastic flow, ensuring weld closure on the back of the pin.

2.2. Titanium

Some properties such as the unique relationship of high strength and low weight, good formability and fatigue resistance leads the use of titanium in various special applications where high demands (physical, chemical and / or mechanical) restrict the use of conventional materials. Titanium and its alloys are used in aerospace, marine, chemical, petrochemical, engineering and biomedical applications because of its amazing range of properties (JOSHI, 2006).

The high strength of titanium alloys combined with its metallurgical stability at high temperatures and its low flow rates, makes them favorable for jet engine components such as blades and disks, aerospace applications such as components for rocket engines and fuel tank. They are also used in aircraft fuselage structures because of its good relationship strength/weight ratio, such as landing gear, beams, hydraulic lines, wing boxes, spacers and screws. In marine applications where corrosion resistance is required because of sea water and acidic hydrocarbon atmospheres. In the biomedical field applications, titanium also displays a great advantage in medical use, is fully biocompatible, titanium is one of few materials that are inert to corrosion by any human body fluids and tissues, a major requirement for implantation in human body. It is used in prosthetic devices for bone and joint implants, heart valves and dental implants. These are made from commercial pure titanium, Ti-6Al-4V alloy or recently developed alloys such as Ti-6Al-7Nb. Currently over one hundred titanium alloys are known, which however, only twenty to thirty are commercially produced. Of these, the Ti-6Al-4V alloy covers more than 50% of use. Another 20% to 30% use is for pure titanium (LEYENS and PETERS, 2003).

2.3. Materials for FSW tooling

Tungsten based alloys have been used in FSW of nickel-aluminum alloys and titanium alloys. According to Fuller (SANDERS, RAMULU, *et al.*, 2010, p. 7-35) and Mashinini (2010) four materials with tungsten alloys were cited specifically for tools building: WC, W+25%Re, Densimet (PLANSEE, 2012) and W+1%LaO_2. Tools from tungsten-rhenium has a high operating temperature, but its construction is difficult because the need of grinding machining (more difficult than the conventional machining), and an important issue is that rhenium and tungsten materials have a high cost for production. Densimet consists of small tungsten spheres of carbide bound in a matrix containing one or other material such as nickel-iron or nickel-copper. The alloy does not have high operating temperature (compared with other tungsten alloys), however, unlike other tungsten alloys (for example tungsten-rhenium), Densimet is easily machined by conventional process and it has a lower cost. Another tungsten-based alloy is W+1% LaO_2, which has cost and workability of Densimet and the temperature range of tungsten-rhenium alloy.

Figure 5 shows the basic geometry for a FSW tool for titanium where:

R_s: shoulder radius

R_p: pin base radius

R_{pt}: pin point radius

L_{pin}: pin height

α: tap angle

According to Edwards and Ramulu (2009) a conical tool is needed because of the low thermal conductivity of titanium. A cylindrical pin tool is not indicated for titanium because heat generated in the shoulder is not able to flow to the root of the joint and allow the mixing of material in the lower plate

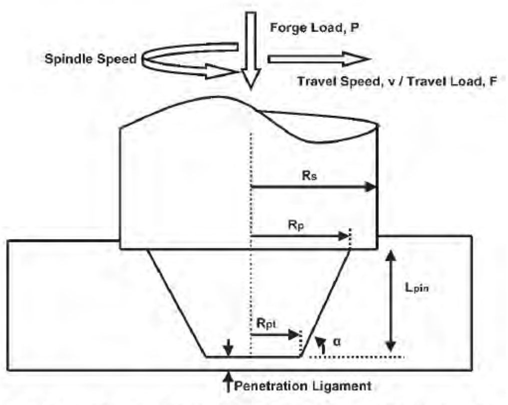

Figure 5 – Basic geometry for FSW tool (EDWARDS e RAMULU, 2009).

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Simple geometries are generally used on pins tool for titanium alloys such as in Figure 5. One reason for this is the difficulty in machining complex shapes in tungsten alloys tools.

3. EXPERIMENTAL DETAILS

3.1 Material

3.2. Screening test

For data approximation and first contact with the process, screening tests helps planning the initial knowledge of what conditions will really should be explored in greater detail in future trials. For this reason a DOE ½ fraction fractional factorial without replication plus a central point ($2^{(3-1)} + 1_{ax}$) to study the initial levels was defined, appropriate to generate superplasticity ranges, resulted in 5 trials. This plan sought to assess initial results for weld residual stress and internal condition of the structure.

3.3. Conditions

- **Parameters and variable conditions:**

Table 1 shows the resulting matrix for the preliminary planning, the array is in random sequence between the test and standard sequence and a_p is the depth of penetration. Although it was performed a factorial design, analysis of all results X conditions could not be raised for reasons of measuring equipment availability.

Table 1 – Matrix for preliminary planning.

Test Sequence	Rotation [RPM]	feed [mm/min]	a_p [mm]
1	1100	40	1,65
2	1000	50	1,65
3	1200	50	1,60
4	1200	60	1,65
5	1300	60	1,65
6	1000	40	1,60
7	1600	50	1,65
8	1550	50	1,65

- **Fixed conditions**

a) Tool tilt angle : 0,5°
b) Machine : Machining Center - CNC manufacturer MAZAK model FJV 35-60

- **Samples geometries**

Titanium alloy material Ti-6Al-4V with 2mm thick, Fig. 6 shows samples geometry.

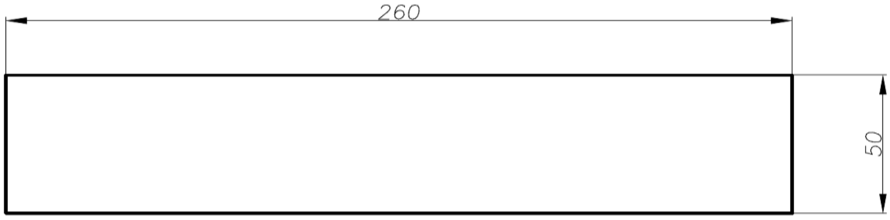

Figure 6 – Samples geometry, dimensions in millimeters.

- **Tool Material**

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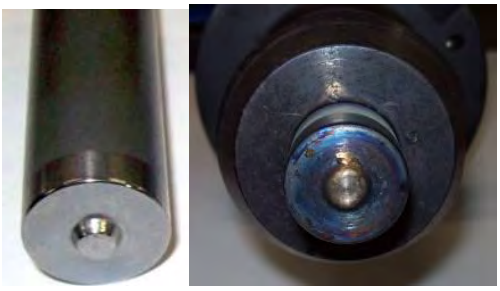
Aiming at the goal of developing a tool material that supports the FSW processing of titanium sheets, two tools were prepared with dimensions of 20mm diameter shoulder, 5mm diameter tapered pin with a 30° angle in the tungsten carbide (WC) material. This alloy is successfully used in the processing of holes in metal sheet at the automotive industry for the housing and screw clamps vehicle assembly. It was chosen as the first choice because the processing temperatures involved are in the order of 900°C to 1000°C. Preliminary tests were performed with this tool to define the initial parameters window and specific tests for wear resistance.

3.4. Test execution

The values in Table 1 were chosen in order to prevent extreme conditions, preliminary conditions that would induce unwanted interactions between the parameters. Basically the intention is to know and understand the process for obtaining a crystal structure of grain to be used in superplastic tensile testing. Another important factor is to perform an evaluation of the tool design and the WC used alloy, the testing tool should be able to make the joining without wearing and without breaking.

The test was conducted without any cooling at the tool in order not to decrease the process temperature. To minimize vibrations and to provide an initial guide for the tool pin a previous pilot hole was made with a twist drill in a depth of 1.60 mm. The drill diameter (4.8 mm) was selected so as to be smaller than the tool tip (5.0 mm), therefore the tip of the tool, while executing the penetration, will generate friction with the lateral of the hole supplying heat to the initial process.

Titanium FSW process input the tool under severe strain, friction and temperature, the latter estimated at up to 900°C (Mashinini, 2010), which limits the use of most available materials. Despite being used in manufacture of tools where friction and temperature are high, the WC tool had marked wear. Figure 9 (a) shows a new tool shoulder with a diameter of 20mm and Figure 9 (b) shows the same tool after the FSW process. It is remarkable the wear on the tool tip which resulted in a poor surface finish of the sample as shown in Figure 10.



(a) (b)

Figure 9 – (a) new tool, (b) tool after FSW.

Due to process conditions, tool fragments disengaged causing scratches at the workpiece surface, within the weld detachment of tool particles was also found, these staying within the plate. In addition to the uneven surface, there was an excess of burrs resulting in further surface processing of cleaning.

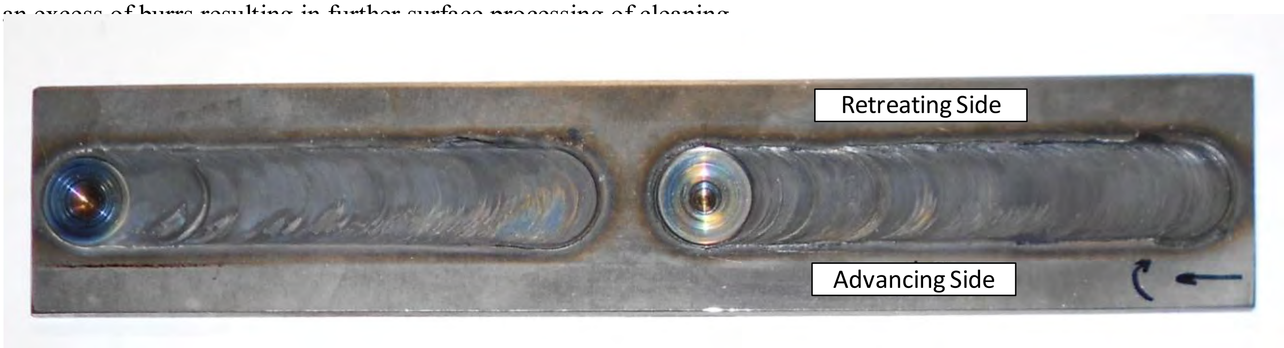


Figure 10 – Sample Ti-6Al-4V (260mmx50mm) after FSW process, AS: advancing side of the tool, RS: retreating side of the tool.

3.5. Residual Stress Measurements

In order to provide experimental data for comparisons with the model being implemented latter by finite elements, the condition of residual stress and the processed region metallographic evaluation were raised. Residual stress measurements were performed at the samples with X-ray diffraction equipment from Shimadzu XRD-7000. Measurements were performed at the bottom of the plate to prevent surface defects caused by the tool which could interfere with the results.

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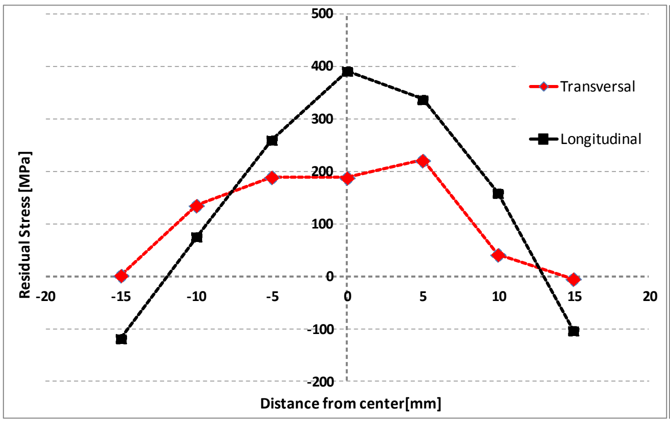
3.6. Microhardness Measurements

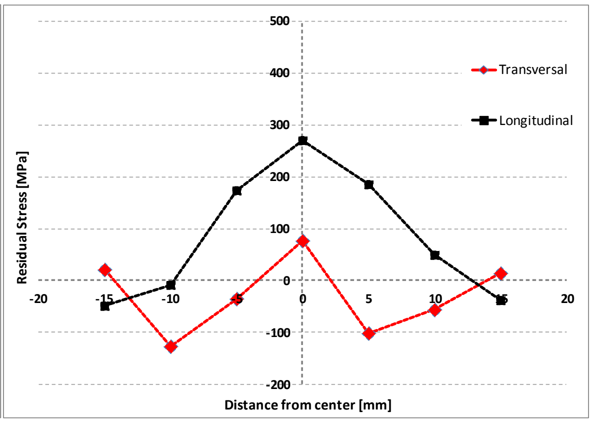
Vickers hardness measurements were carried out along transversal direction with load of 9,807 N, 15 measurements were performed in all conditions.

4. RESULTS AND DICUSSION

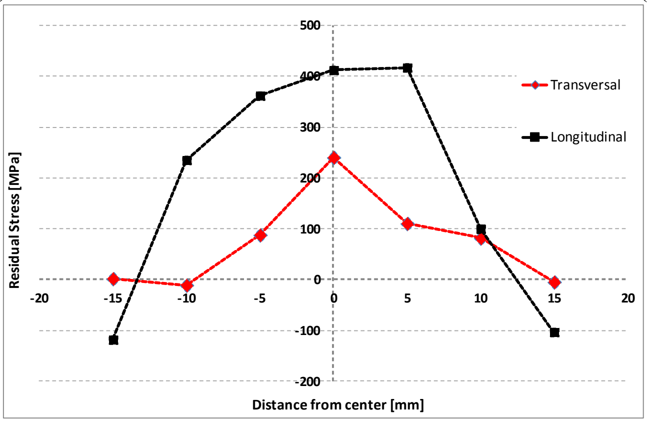
Figure 11.b shows the measurement results of two samples. The residual stress was measured in transversal and longitudinal direction and also in 45° angle direction (see Figure 10) in order to verify the principal stress resulting from the process. The main residual stress values resulting T1 processed in the area is coincident with the longitudinal direction of the sample, the longitudinal direction is where the tool has performed its linear path. It can be seen that different processing conditions results in different values of residual stress. The rotation tool (RPM) showed to be more significant, for the same feed of 40mm/min, the sample processed with 1100 RPM presents a maximum residual stress of about 400MPa while a 1000 RPM processing resulted in a maximum of 280MPa. The maximum residual stress was located at the center of the processed region for each condition.



(a)



(b)



(c)

Figure 11 – Residual stress at conditions 1 (a) 1100 RPM and feed 40 mm/min; condition 5 (b) 1000 RPM and feed 40 mm/min and condition 3 (c) 1200 RPM and feed 50 mm/min.

Figure 12 reports hardness as a function of position along transversal direction for all conditions. These plots clearly show a hardness increase on friction stir processed region, except condition 8, 1550 RPM and feed 50 mm/min, Figure 12 (h). In this case the hardness is constant and no grain refinement was observed on friction stir processed region. Additionally, it is apparent that advancing side showed higher hardness than retreating side for the conditions 3, 4, 5 and 7 due a heterogeneous microstructure.

Figure 13 show different microstructures observed along the transversal direction for the condition 7 where the hardness measurements was realized. In general, 4 microstructures was observed (i) base metal, bimodal structure, Figure 13 (b); (ii) refined bimodal structure, Figure 13 (c); (iii) Widmanstatten structure, Figure 13 (d), (f) and part of (c); and finally (iv) Martensitic structure, Figure 13 (e).The regions showed on Figure 13 were observed on all conditions however with different proportions. It is noteworthy that each microstructure is associated with a different hardness value. The conditions 2 and 6, rotation 1000 RPM and feed 40 e 60mm/min respectively, resulted in a more homogeneous microstructure with grain refined region on the center of the friction stir processed region.

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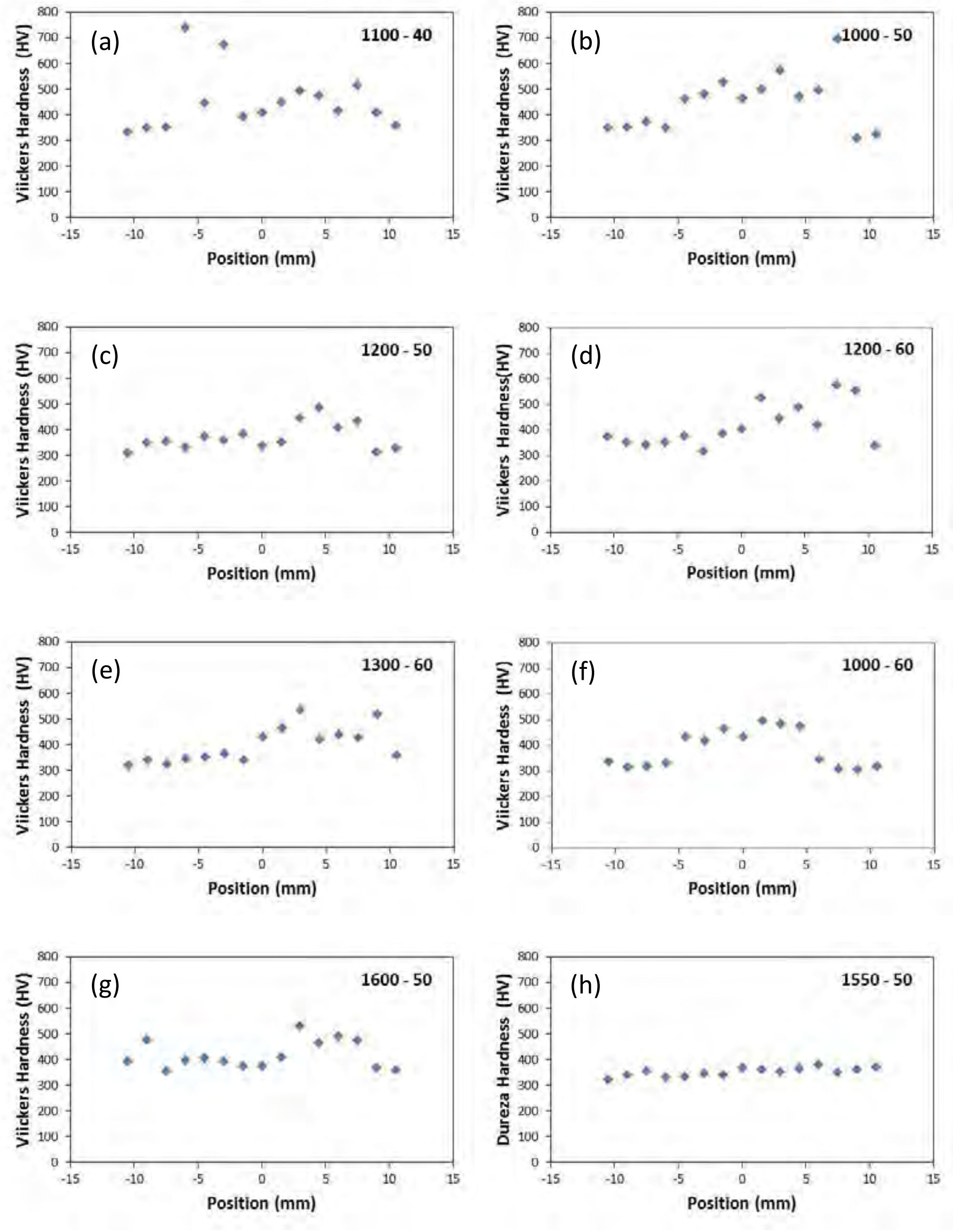

Figure 12 – Vickers hardness as a function of position along transversal direction at conditions 1, 1100 RPM and feed 40 mm/min (a); 2, 1000 RPM and feed 40 mm/min (b); 3, 1200 RPM and feed 50 mm/min (c); 4, 1200 RPM and feed 60 mm/min (d); 5, 1300 RPM and feed 60 mm/min (e); 6, 1000 RPM and feed 60 mm/min (f); 7, 1600 RPM and feed 50 mm/min (g); 8, 1550 RPM and feed 50 mm/min (h).

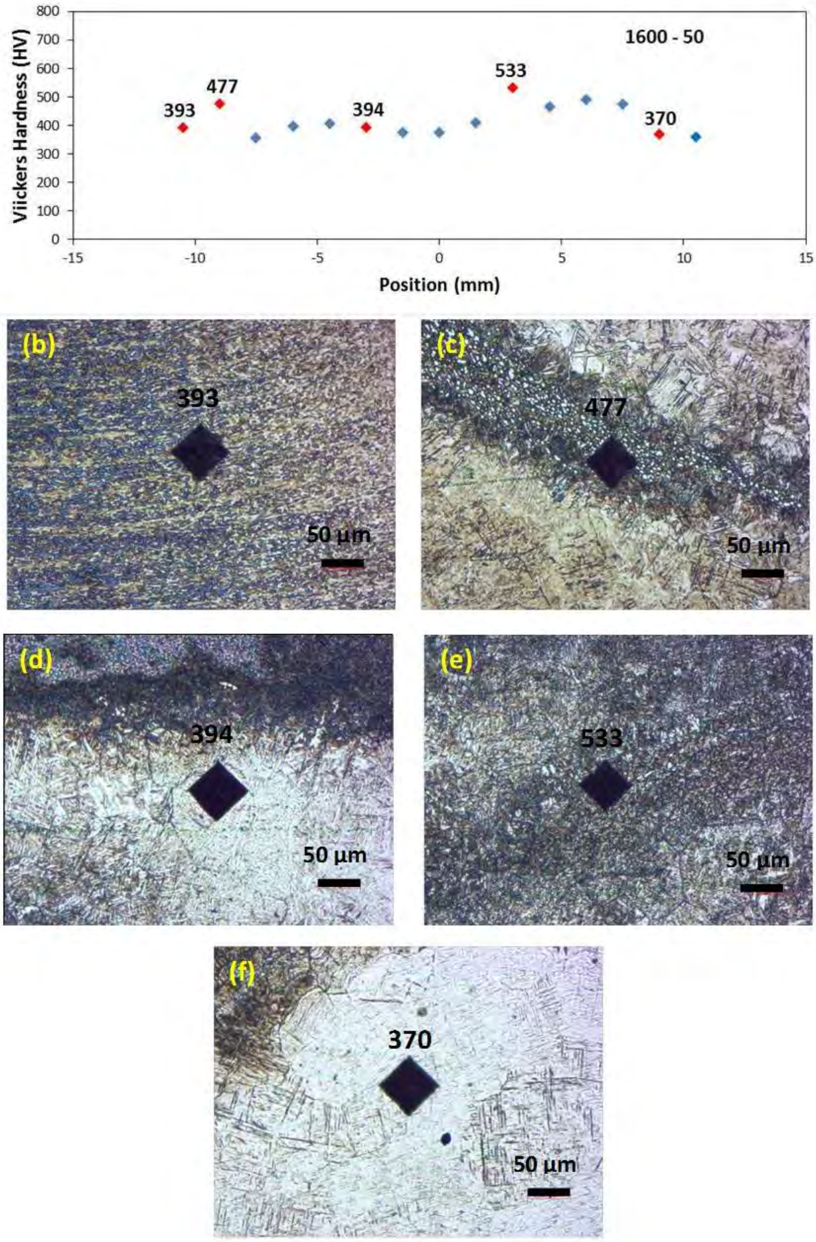

Figure 12 – Vickers hardness as a function of position along transversal direction at condition 7, 1600 RPM and feed 50 mm/min (a);

5. CONCLUSIONS

Mechanical properties as micro-hardness and residual stress were evaluated in order to understand the influence of the process parameters (tool rotation and feed) on the final condition of the process. It was observed that a lower condition of tool rotation resulted in a lower condition of residual stress. The metallographic analysis of the welds did not show primary defects of voids (tunneling) or similar internal defects due to processing, only defects related to tool wear which can cause loss of weld quality. The severe tool wear caused loss of surface quality and inclusions of fragments inside the joining, which should be corrected or mitigated by material replacement of tungsten carbide alloys by tungsten alloys as found in the literature.

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