
Experimental Thermal Analysis in Rotary Friction Welding of Dissimilar Materials

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ABSTRACT: Rotary friction welding process (RFW) is one of the most used processes in the world for manufacturing bimetallic components that require high mechanical strength. All process occurs in solid state at temperatures below the melting point of the involved materials, having as the main bonding mechanisms the diffusion and mechanical mixture. The purpose of this work was to carry out an experimental thermal analysis of the dissimilar joint AA6351 T6 aluminum and AISI 304L stainless steel during the friction welding operation through system of thermocouples. Gradients of temperature obtained had their data analyzed and recorded. Results of the experimental thermal analysis showed the behavior of the temperature in the bonding interface, how the dissipation occurs in the radial and longitudinal direction, heating rates, cooling, maximum temperatures reached, its relationship with the different stages of the process and the influence on mechanical properties of welded joint. This study is of great importance for relating the temperature distribution in the bonding interface with atomic diffusion and mechanical resistance of junction.

KEYWORDS: Friction welding, Temperature, Dissimilar materials, Thermocouples.

INTRODUCTION

The joining of materials with different physical and chemical properties on a permanent basis, with structural quality that meets design requirements for applications in aerospace, aviation, nuclear, military and automotive areas, has been a challenge for engineering in the last years. The rotary friction welding (RFW) process provides high productivity, repeatability and low cost. It produces dissimilar joints such as aluminum-stainless steel, aluminum titanium and copper-aluminum with great quality and mechanical properties better than the lowest resistance material used in the junction.

All heating responsible by the union is mechanically generated by friction between the parts to be welded. The friction between the surfaces enables a rapid increase in temperature in the bonding interface, causing the mass to deform plastically and to flow depending on the application pressure and centrifugal force creating a flash. This process causes the removal of impurities and oxides from the surfaces, promoting the creation of a surface with excellent physical and chemical adhesion (Alves *et al.* 2010). The temperature increase and constant application of pressure in the bonding interface for a determined time enables the atomic diffusion among the main elements of the two materials, and hence their union.

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In friction welding of dissimilar materials, the temperature generated in the bonding interface is directly related with the weld strength and its interface properties. The non-uniform heat generation in the bonding interface generates the formation of intermetallic compounds, unbold zones, and insufficient plastic deformation to total removal of layers of oxides and other contaminants in the bonding interface. High temperature increases the intermetallic compound forming and, consequently, the thickness of intermetallic layer that affects the heat affected zone (HAZ) (Khan 2011).

Due to the relevance of the topic, there are many experimental and analytical studies published by researchers from different parts of the world: Wei and Sun (2018), Dawood *et al.* (2017), Ratkovic *et al.* (2017), Rombault (2011), Aritoshi and Okita (2003), Khan (2011), Kuchuk-Yatsenko and Zyakhov (2002), Basher (2013), Yilbas and Sahin (2014), Fukumoto *et al.* (2010), Nikolaev and Olshansky (1977), Seli *et al.* (2010), Maldonado-Zepeda (2001), Cenk *et al.* (2012), Moarrefzadeh (2012), Faizal *et al.* (2014), Li *et al.* (2012), Ruma *et al.* (2013), Singla (2010), Kimura *et al.* (2010) and Bouarroudj *et al.* (2017), Burakowski and Wierzchon (1998).

Experimental analysis of temperature on bonding interface is of fundamental importance to the knowledge and understanding of the phenomena occurring in the formation of dissimilar joint obtained by RFW. Analytical calculations carried out until the time to temperature modeling are complex and do not allow obtaining precise values due to the large number of variables involved.

ROTARY FRICTION WELDING PROCESS

The process of friction welding is classified by the American Welding Society (AWS) as a solid state joining process in which bonding is produced at temperatures lower than the melting point of the base materials (Maldonado-Zepeda 2001). In the rotary friction welding, one of the pieces is fixed and submitted to a particular rotation by a motor drive (RPM), and the other is positioned, aligned and powered by a hydraulic piston up to touch the part in rotation. After this, P1 pressure is applied by a certain time (t_1), followed by the braking of rotation (RPM = 0) and subsequent application of P2 for a time t_2 , finishing the welding. The main stages of the process can be observed in Fig. 1 (Alves 2016).

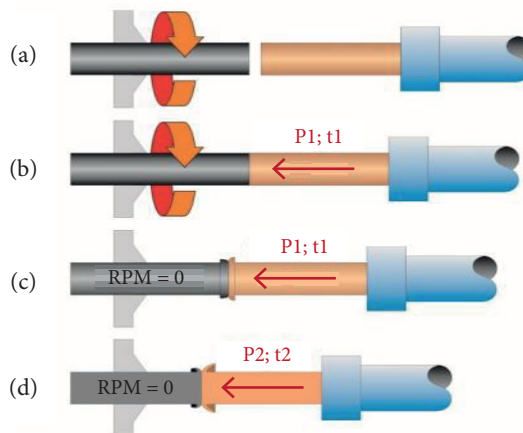


Figure 1. (a) Period of approximation; (b) P1, t_1 application; (c) End of P1, t_1 application and braking of machine (RPM = 0); (d) P2, t_2 application and finishing welding.

FRICTION WELDING EQUIPMENT

Dissimilar welded joints samples were carried out using a rotary friction welding machine, mark GATWICK, with relative speed (RPM) 3200 RPM, fixed pressure ($P_1 = 300$ MPa; $P_2 = 1200$ MPa), time ($t_1 = 5$ s; $t_2 = 2$ s), and constant piston displacement

speed. These parameters used for the trials were obtained previously in a study conducted by Alves (2016), whose results have confirmed the rupture away from the bonding interface in AA 6351-T6 aluminum alloy. The materials were placed as shown in Fig. 2.

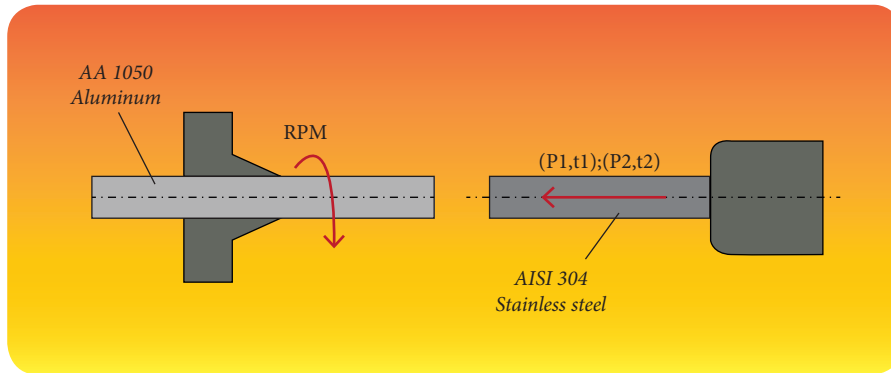


Figure 2. Schematic view of the materials placed before welding.

MATERIALS AND METHODS

Cylindrical pins used in this work were machined in conventional lathe with 14.8 mm diameter and 100 mm length (AISI 304 L stainless steel) and 110 mm (AA 6351-T6 alloy) with 3.2 μm surface roughness, value obtained with the use of common tools for the machining process. Aluminum pins were manufactured with two different geometries in one of its ends, regular geometry and conical geometry (Fig. 3). Tables 1 and 2 present chemical compositions and mechanical properties of the materials.

Table 1. Nominal chemical compositions of materials.

Material	Elements (wt %)								
AA 6351-T6 Aluminum	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni
	0.96	0.22	0.02	0.46	0.58	0.005	0.006	0.02	< 0.010
AISI 304 L Stainless steel	Si	S	P	Mn	C	Cr	Ni	Mo	Ti
	0.47	0.006	0.035	1.87	0.016	18.0	8.7	0.21	-

Table 2. Mechanical properties of materials used in present study.

Base Material	Tensile Strength (MPa)	Yeld Strength (MPa)	Elongation (%)
AA 6351-T6 Aluminum	323.68	297.25	14.0
AISI 304 L Stainless steel	643.79	354.69	63.0

Thermal analysis of the process was carried out by thermocouples used the MGC-PLUS system-HBM, model TG001D and thermocouples of type “J”. To achieve the thermal testing it was manufactured pins in AISI 304L stainless steel with special holes for attachment of thermocouples in three different configurations (with four monitoring points): radial measurement; longitudinal measurement to 7.4 mm deep; and longitudinal measurement the 4.3 mm deep. All setting measurements were carried out in stainless steel pins (Fig. 3b).

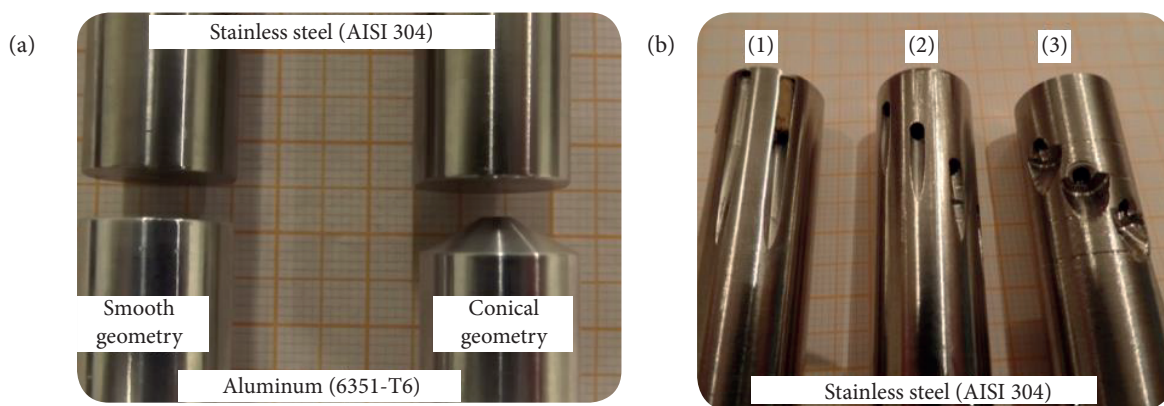


Figure 3. (a) Details of the aluminum pins geometry; (b) Steel pins with different holes for attachment of thermocouples.

RESULTS AND DISCUSSION

The analysis by thermocouples of dissimilar joints welded by RFW enabled a quantitative understanding of the process. There were performed 30 essays, being 15 for each sample type and parameters (P1, P2, t1 and t2) adopted were the resulting joints with higher resistance to traction. To eliminate and reduce the influence of external variables to the process, the tests were performed in a single day in sequence, under the same conditions. Figure 4 shows the equipment and thermocouples attached to the sample before and after welding.

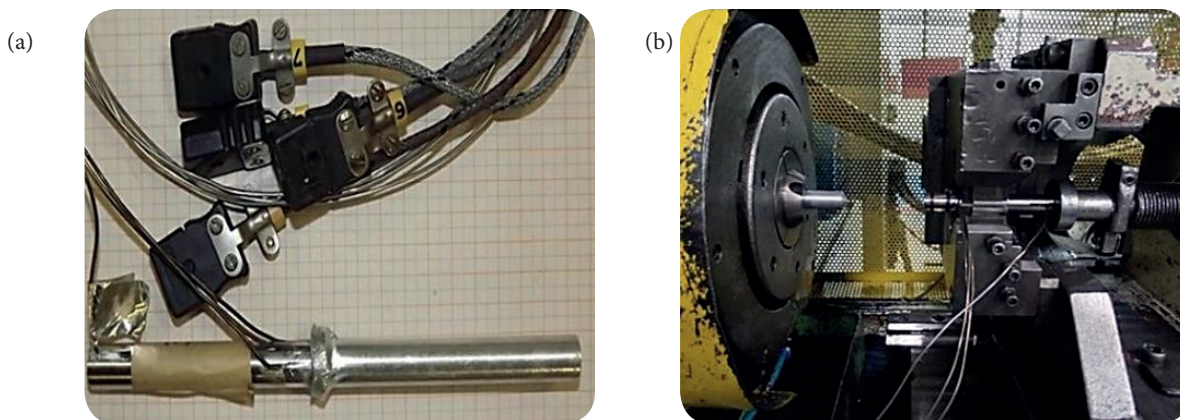


Figure 4. (a) Thermocouples fixed on the stainless steel pin after the welding finished; (b) Welding equipment moments before performing the test.

RADIAL TEMPERATURE PROFILE

Friction welding tests for measuring the temperature variation in the radial direction used the setting of the thermocouples shown in Fig. 5. The thermocouple in position 0.0 mm is in the center of the pin, and the thermocouple in the 5.8 mm position lies in the region known as medium radius (higher temperature).

Figure 6a shows the radial temperature profile for welding with aluminum pins regular geometry, the highest temperature values found refer to the thermocouples attached to a distance of 5.8 mm from the centerline of the samples (medium radius). Figure 6b shows the radial temperature profile for welding with aluminum pins with conical geometry, where higher temperature values were observed in the central region of the sample.

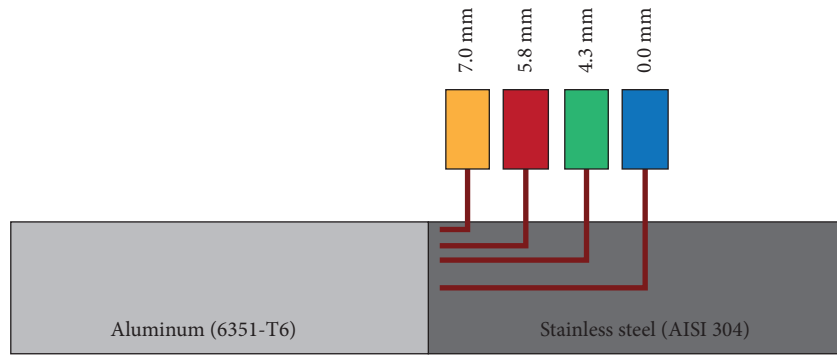


Figure 5. Configuration of the thermocouples for radial temperature profile.

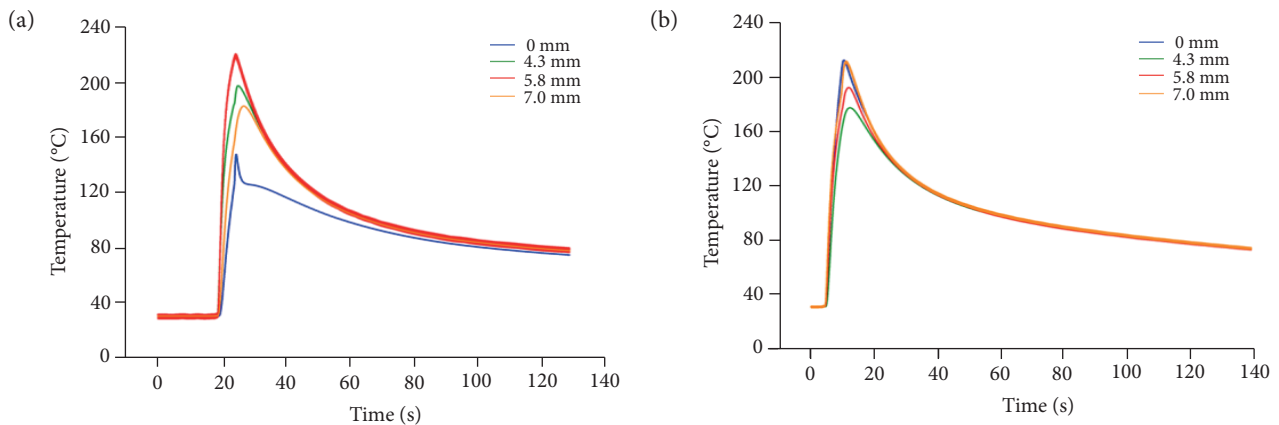


Figure 6. Radial temperature profile (a) aluminum pins with regular geometry; (b) Aluminum pins with conical geometry.

Analyzing the graphics of $T \times t$, it was noted that in tests conducted with aluminum pins with conical geometry (Fig. 6b), the highest elevation in temperature occurred in the central region of the bonding interface since the start of the welding operation. Already in tests with aluminum pins with regular geometry (Fig 6a), the highest elevation in temperature occurred in the medium radius and then dissipated to other parts of the interface, which enables us to say that changing the geometry of pin from regular to conical caused the displacement of the region of highest temperature from the medium radius to the central region.

The conical geometry of the aluminum pin caused the heat flux at the bonding interface shift from the central region (higher temperature region) to the peripheral regions of the samples. This made possible a homogeneous diffusion in the contact surfaces, enabling better removal of layers of oxides and impurities present in these surfaces by plastic deformation.

LONGITUDINAL TEMPERATURE PROFILE

Figure 7 shows the thermocouple configuration used for testing of longitudinal profile with two different depths, 7.4 mm and 4.3 mm, and with variable distances of bonding interface of 5, 10, 15, and 20 mm.

Figures 8 and 9 present the longitudinal profiles of temperature with depths of fixing of thermocouples of 7.4 mm and 4.3 mm, respectively.

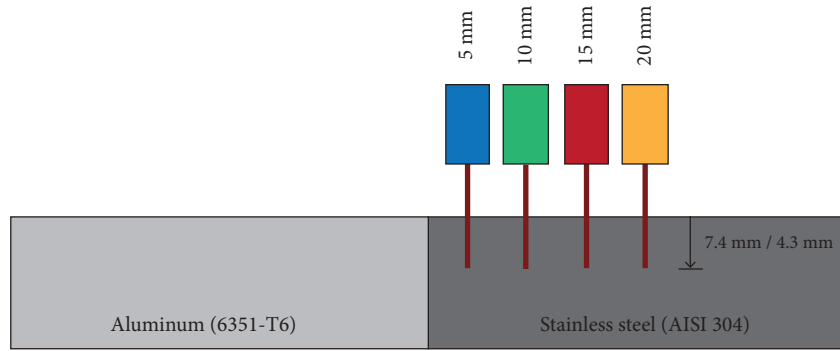


Figure 7. Configuration of the thermocouples for temperature longitudinal profile with depth of 7.4 mm and 4.3 mm.

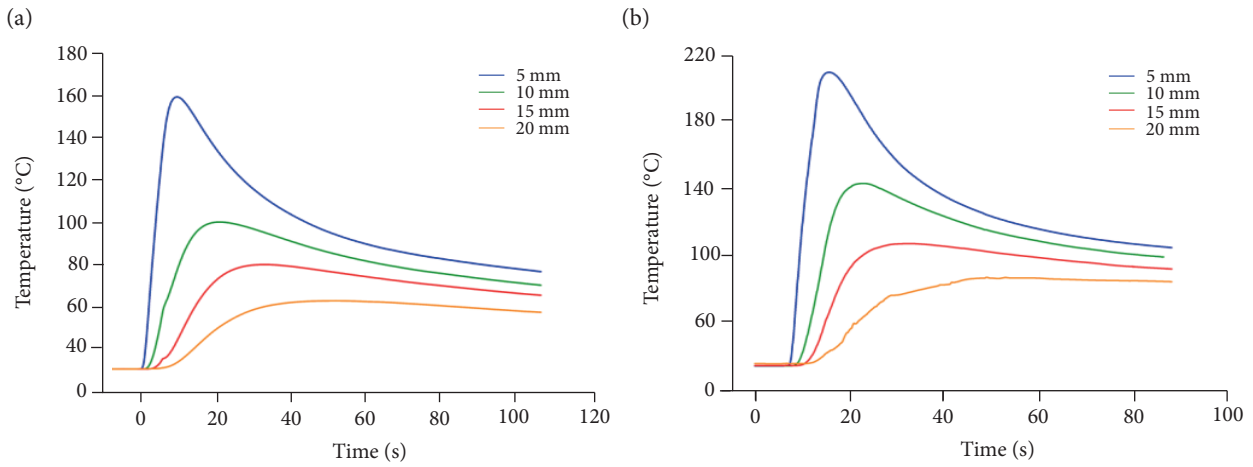


Figure 8. Temperature longitudinal profile with depth of fixing of 7.4 mm: (a) Aluminum pins with regular geometry; (b) Aluminum pins with conical geometry.

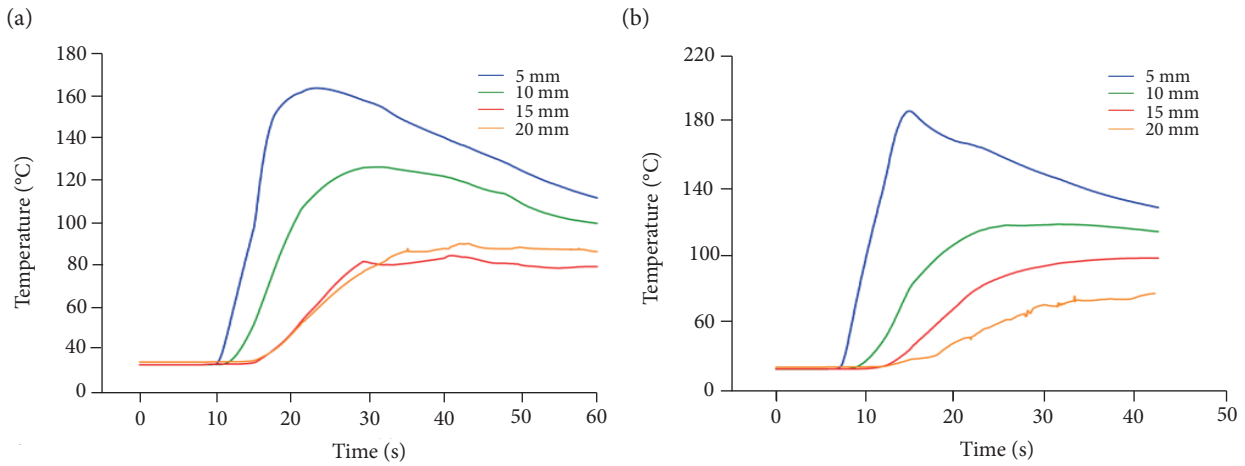


Figure 9. Temperature longitudinal profile with depth of fixing of 4.3 mm: (a) Aluminum pins with regular geometry; (b) Aluminum pins with conical geometry.

The results of monitoring of the heat flux displacement in the longitudinal direction of the stainless steel pins with depths of 7.4 mm and 4.3 mm and different geometries of the aluminum pins showed similar curves. The highest temperature recorded was 210 °C at a distance of 5.0 mm of bonding interface, sense of the length of the stainless steel with thermocouple fixed a depth of 7.4 mm, using aluminum pin with conical geometry. During the welding operation, the aluminum pins with conical geometry have undergone a reduction in their length (LR), exceeding the pins with regular geometry.

Tension tests performed on samples considering the two aluminum cylindrical pin geometries showed that the use of cylindrical pin with conical geometry allowed an increase of mechanical resistance of the junction of 12% to 15%. In the tension test number 2 (aluminum pins with conical geometry), the rupture occurred in the aluminum, away from the bonding interface. Table 3 shows the results of the tension tests.

Table 3. Results of tension tests carried out using aluminum cylindrical pins with regular and conical geometry.

Aluminum pins with regular geometry						
N°	P1 (MPa)	t1 (s)	P2 (MPa)	t2 (s)	LR (mm)	Tensile strenght (MPa)
1	300	5	1200	2	12	292
2	300	5	1200	2	13	297
3	300	5	1200	2	13	283
4	300	7	1200	2	14	278
5	300	7	1200	2	12	255
Aluminum pins with conical geometry						
N°	P1 (MPa)	t1 (s)	P2 (MPa)	t2 (s)	LR (mm)	Tensile strenght (MPa)
1	300	5	1200	2	14	315
2	300	5	1200	2	14	327
3	300	5	1200	2	13	318
4	300	7	1200	2	14	288
5	300	7	1200	2	15	285

Comparing the data obtained in this work with the referenced articles, we verify that the temperature is always cited as an important element in the system. Regardless of the dissimilar materials to be joined by RFW, if the cylindrical pin of lower mechanical strength presents conical tip geometry, it will provide better temperature distribution in the bonding interface, welds with good quality and great mechanical resistance.

CONCLUSIONS

Measurements and temperature monitoring with use of thermocouples are of extreme importance for analysis of the temperature distribution on the bonding interface seen its efficiency and large data collection capacity during friction welding. Tests conducted with two different pin geometries showed that the biggest rise in temperature occurs in the first three seconds of the process, independent of geometry. Pins with regular geometry have a higher temperature rise in the so-called medium radius away from the central region, while pins with conical geometry had the central region with highest elevation in temperature allowing better heat distribution in the bonding interface during welding.

The use of aluminum cylindrical pins with conical geometry in dissimilar joints involving aluminum alloys and stainless steel enables better temperature distribution on the surface of contact materials, favors activity of bonding mechanisms, generates a HAZ more homogeneous and increases mechanical resistance of the junction produced by friction welding process.

Obtaining dissimilar joints where the rupture of the tension specimen occurs outside the bonding interface is a great indication that there was perfect distribution of temperature in the contact areas of the materials during the friction welding operation. When the rupture occurs in the bonding interface, usually the defects encountered are related to the poor distribution of temperature.

AUTHORS' CONTRIBUTION

All the authors contributed equally for the manuscript.

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