Understanding internal defects formation by the heat generated during friction-stir welding

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ABSTRACT

One of the most important factors during friction stir welding is the amount of heat generated during welding process. In most cases, joint will benefit certain amount of heat generated during the process. The amount of heat generated during friction-stir welding depends on several operational variables, such as the tool rotation and its advancement, tool geometry, shoulder plunge deep, tilt angle, welding machine, type and thickness of material to be welded, among others aspects. However, as soon as the materials to be welded, the machine and the tool have been chosen, the heat quantity is mainly subjected to rotation and advancement of the tool. On one hand, the pseudo heat index is considered, in a certain mode, as an indicator of relative quantity of heat produced during the joint. This index is related to the rotation and advancement of the tool. On the other hand, both lack and excess heating during welding, cause union defects known as wormholes or porous network. Therefore, this study was carried out to understand the rationale behind the generation of such defects; a major probability to select better conditions to weld, mainly focused on tool rotation and its advancement to bond materials by friction-stir. The images from scanning electron microscopy of AA7075-T651 aluminum alloy welded with three PHI values, allowed to analyze the wormholes and voids, which resulted due to lack of and excess heating respectively and, to interpret the physical-metallurgical phenomena involved in their formation.

Key words: Internal defects, friction stir welding, AA7075-T651, heat generation.

INTRODUCTION

In industry, in general, the friction stir welding (FSW) could represent savings in manufacturing time, reduction of parts complexity and consequently, a reduction of the finished structures weight, which causes a reduction in production costs (Biro et al., 2012). These advantages are being exploited by the transport industry, where it is being demonstrated that this welding produces joints with a mechanical resistance of more than double as compared with that obtained with a joint using rivets and, at least, the same resistance to fatigue (Christner, 2003). More so, the traditional defects of the traditional fusion welds are eliminated (Priya et al., 2009), because the FSW is in plastic state. The FSW is a welding technique developed in 1991 by the Welding Institute of Cambridge, England (Sidhu and Chatha, 2012). This technique uses a non-consumable rotary tool that generates heat due to friction and plastic deformation of the material to be welded (Bahemmat et al., 2010; D’Urso et al., 2009; Hattingh et al., 2008). The amount of heat generated during welding depends, to a large extent, on the revolution per minute (rpm) of the tool and the transverse speed thereof, known as welding speed (Arora et al., 2012; Grujicic et al., 2011). The heat increases the temperature of the material, leading to its plastic state, which allows it to be forged by the tool shoulder pressure. Several researches have shown that the temperature reaches values between 0.7 and 0.9 of the
melting point of the material to be welded (Murr, 2010; Thomas and Nicholas, 1997). This means that the weld is produced at lower temperatures than the materials melting point (Bitondo et al., 2011; Lertora and Gambaro, 2010); that is, in plastic state. Due to the plastic materials bonding, the characteristic defects of the metallurgical fusion-solidification process inherent to other welding technologies are avoided (Esmaili et al., 2011; Garware et al., 2010; Grujicic et al., 2011; Lotfi and Nourouzi, 2014; Rajakumar et al., 2011). Thus, the amount of heat by friction and material plastic deformation received an emphasis because it is the medium that favors the union trough the material flow and forging (Grujicic et al., 2011; Gupta et al., 2012). However, there are internal FSW defects, the best known are: pin holes, wormholes or tunnels, voids in several sizes, and kissing bonds (Ramulu et al., 2013).

According to studies, as soon as the tool geometry is fixed, it is stipulated that the tool rotation and welding speed are the main parameters in the generation of heat in the FSW, for being the variables that have the main participation in the friction and plastic deformation of the material, caused mainly by the shoulder (Prasanna et al., 2010) and to lesser extent by the pin (Grujicic et al., 2011; Kumar and Kailas, 2008). There is evidence that the tool rpm generates heat proportionally and, its translation speed is inverse to the heat generation (Cam and Mistikoglu, 2014; Grujicic et al., 2011). These variables, between others, determine the relative character of the hotness or coldness of this joint process (Mishra and Ma, 2005). Thus the tool rpm is the key parameter to temperature control (Lombard et al., 2008). Regarding the type of material to be welded, the tool geometry and the variables of machine assembly where the material will be welded (with all being fixed), the optimum amount of heat generated during welding by proper selection of tool RPM and welding speed will result in a sound weld (Azimzadegan and Serajzadeh, 2010; Dubourg et al., 2010; Gupta et al., 2012; Lotfi and Nourouzi, 2014; Rafi et al., 2010; Soundararajan et al., 2007). The key is to generate the adequate amount of heat in the whole welding established system. Otherwise, there is a high probability of obtaining a defective union and as such, it is relevant to understand the mechanism of formation of joint defects. Several researchers have shown one or more mathematical relationships between the tool RPM and its speed of transverse advancement (Jana et al., 2010; Plasari and Villermaux, 2010; Radisavljevic et al., 2013; Saeid et al., 2008) given the name of pseudo heat ratio (Sanders et al., 2010) or simply rotation per feed (KLOBČAR et al., 2014). Thus other mathematical models include the geometric configuration of the tool (Querin and Schneider, 2012). In these proposed mathematical equations, the units have no meaning, since it is a mathematical relation designated as an indicator relative to the heat generated during the FSW process. The first indicator used as reference was named "pseudo heat index (PHI)" and its mathematical formula is: \[ \text{PHI} = \frac{\text{RPM}^2}{10000} \]

Once the tool geometry is defined, the material flow is fixed for this fact (Cam and Mistikoglu, 2014), but in general terms, the material flow, to a major extent, has influenced on advancing by the vortex velocity boosting up the plasticized material. That is because the velocity fields move in the direction of the advancing side (Zadpoor et al., 2010). This causes internal defects when the weld conditions do not generate the heat amount required. Moreover, when the material passes around the advancing side of the weld, it remains there, due to the absence of force promoting its movement back into the volume stirred by the rotating tool (Azimzadegan and Serajzadeh, 2010). So, if there is a poor stirring of the material, a defect is formed mainly in this side.

The FSW is able to join metals of the same or different chemical composition, including composites. At present, the general consensus establishes that the FSW has advanced to the feasibility of being applied in the commercial and military aeronautical industry, cases where metallic materials with low melting point and relatively low specific gravity are the main demand (Sinko et al., 2010), such as aluminum, magnesium and lithium alloys (Aye et al., 2008; Lertora and Gambaro, 2010). The features that meet the AA7075-T651 aluminum alloy have found applications in the air transport industry. For example, in aircraft, it is used in the main internal structure and in lower part of the wings; that is, in areas of the airplane subject to high strengths, especially in the moments of takeoff and landing (Aye et al., 2008). Hence, the importance of understanding the formation of defects on the FSW by considering the PHI as an indicator.

MATERIALS AND METHODS

Three pairs of plates of the aluminum alloy AA 7075-T651 with dimensions of 240 × 50 × 6.35 mm, were welded with three PHI conditions (Table 1). The brand welding machine used was a Kryle CNC. The welding seams were cut according to AWS D1.2 / D1.2M: 2003. The first 2.54 cm was discarded, one zone was sliced for stress test and then another for microscopic analysis and so on. According to ASTM E8-04 standard, five specimens were machined from each of the three joints and from the base material for the stress test. The mechanical tensile strength tests were performed on an Instron universal machine model 4482. The sections for microscopic analysis were mechanically mirror polished and chemically attacked with Keller's reagent. Finally, a fracture analysis of the specimens stress tested was done. For the microscopic analysis, a microscope Hitachi model SV 3500 was used. The average value of the mechanical strength was calculated from the ultimate tensile strength results. The
Table 1: Welding parameters.

<table>
<thead>
<tr>
<th>Weld number</th>
<th>V (inch/min)</th>
<th>RPM</th>
<th>PHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>500.0</td>
<td>2.50</td>
</tr>
<tr>
<td>2</td>
<td>3.34</td>
<td>615.0</td>
<td>11.30</td>
</tr>
<tr>
<td>3</td>
<td>2.95</td>
<td>615.0</td>
<td>12.82</td>
</tr>
</tbody>
</table>

Figure 1: Specimens cutting (A) and machining (B) for stress test and microscopic analysis.

Figure 2: Specimens polished and chemically etched. (A) With a PHI of 2.5 showing a wormhole defect in the advancing side. (B) Using a PHI of 11.30 there is no visible defects and, (C) With a PHI of 12.83 there are defects, such as voids and tunnels.

RESULTS AND DISCUSSION

Welds

Figure 1 shows one of the welds obtained and its cutting conferring to AWS D1.2 / D1.2M: 2003 and the stress test specimens machined according ASTM E8-04 standard. Figure 2 shows the specimen polished and chemically etched for microscopic analysis.

Ultimate tensile strength and welds efficiency

Table 2 shows the means values of the mechanical Properties of each of the three welds and their efficiency,
Table 2: Tensile strength and weld efficiency of the welds and its PHI, respectively.

<table>
<thead>
<tr>
<th>Weld number</th>
<th>PHI</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Weld efficiency (%)</th>
<th>Fractured zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.50</td>
<td>207.0</td>
<td>35.0</td>
<td>Nugget</td>
</tr>
<tr>
<td>2</td>
<td>11.30</td>
<td>435.0</td>
<td>73.4</td>
<td>Base Material (advancing side)</td>
</tr>
<tr>
<td>3</td>
<td>12.82</td>
<td>352.4</td>
<td>59.4</td>
<td>Nugget</td>
</tr>
</tbody>
</table>

respectively. The tensile strength mean value of the base material was 592.8 MPa.

The specimens fractured in the nugget zone had a rapid failure, while the weld fractured in the base material had a progressive failure, indicating plastic deformation before the fracture.

Fracture microscopic analysis

The images were obtained from the weld number one with a PHI of 2.5. Figure 3 shows in the advancing side of the seam, a wormhole caused by an abnormal material flow. There is a lack of material, because, the pin do not carry enough amount of material from the front and retreating side to the advancing side. Also, by the insufficient material plasticity, the axial force is not able to forge it, thereby avoiding the defect formation. This kind of defects reduce the mechanical properties of the joint as shown by the weld efficiency obtained in this study.

The joint with a PHI of 11.3 showed a sound weld. This means that the heat amount generated during this welding is within the proper range. Figure 4 shows the microstructure of such weld. In the fracture analysis of magnifications, no visible defect in the weld is observed. As a result, a high weld efficiency is reached.

Figure 5 shows the fracture of the joint with a PHI of 12.83. There are defects that reduce the mechanical strength of the weld, such as tunnel and voids. More so, zones with melted-solidified material are observed. The fusion of the material is caused by the excessive heat generated through the operational conditions used during this weld. Thus, the characteristics of the weld defects of fusion-solidification process are presents in the seam.

Conclusion

The analysis of defects in this study shows that, to avoid internal defects in welds of this kind during FSW, it is
necessary produce the quantity of heat required for the given weld system, considering that there is a range of temperature that needs to be determined for each combination of the operational variables of the FSW. Since PHI is only an indicator, it should be taken as such and not an absolute value.

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