Corrosion behaviour of bonded steel bars by means of transient liquid phase bonding technique

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Abstract

In many areas of engineering industries there are necessary to bond steel, where traditional bonding processes such as welding and brazing are neither efficient enough nor possible. Alternative technique is transient liquid phase bonding (TLPB). In this study, carbon steel (IRAM 1010/1040) have been welded using transient liquid phase bonding method with Fe-B amorphous as filling material. The joints were performed by induction heating with argon flux, set pressure and different temperature and bonding times. The welded bars were then analysed using optical and scanning electronic microscopy (SEM).

The bars with good microstructures and optimal parameters were then tested with galvanostatic corrosion test against each other and non-welded bar to study the corrosion behaviours. The study shows that the IRAM 1010 steel corroded slightly faster than the IRAM 1040 but comparing with the non-welded bars, still consider having good corrosion resistance.

In this study, TLP bonding shows to be a relevant method to weld low and medium carbon steel, regarding to the microstructure of the weld, corrosion behaviour, bonding time and temperature.
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1. Introduction

This report is the conclusion of a Master thesis project performed at the Departamento de Ingenieria Mecanica, Buenos Aires. The aim of the project was to investigate the corrosion behaviour of carbon steel bars, welded with transient liquid phase bonding technique.

1.1. Structures of the thesis

The project report is organized in ten chapters, which gives the reader a complete but brief overview of the work. This work is divided into two parts. First part is about creating the weld with TLP bonding and the second part is about the corrosion test. After each part there are a result and discussion chapter.

This chapter introduce the work and gives the background of this work.

The second chapter gives an introduction of transient liquid phase bonding and an understanding of the concept.

Chapter three is based on the previous research on similar work on TLPB and corrosion test.

The chapters’ four to six are dedicated to the bonding of the carbon steel bars using TLPB and chapter 8 is on the experimental part of the corrosion test.

The chapters seven and nine is the results and discussion of part one respectively part 2.

Finally, chapter ten is the conclusion of this work and results.

1.2. Background

In this study, the application of transient liquid phase bonding (TLPB) is use to weld carbon steel with an amorphous Fe-B metal as the interlayer. The applied method is an article to the patent of Paulonis et al in 1971 [1], with moderate pressure and adjustment to the joint during the bonding.

In many areas of engineering industries there are necessary to bond steel, where traditional bonding processes such as welding and brazing are not efficient enough in many applications, e.g. bonding super alloys. The resistance of high temperatures means that welding and brazing do not possess the adequate elevated temperature mechanical or physical properties [2]. A method which has shown promising results for joining steels is solid state diffusion bonding. This process is attractive but the need for high bonding pressure, exactly mating surface preparation and the difficulty of making parts of complex geometry can make the process uneconomical and even impossible in many situations [3]. A process which alleviates these difficulties and is not depending on high bonding pressure is transient liquid phase bonding, TLPB [2]
TLPB is an ancient process; that has received increased attention in recent years. As early as sixteenth century it was a method for attaching decorative gold beads for ceremonial articles [4]. In this process copper oxide is painted on the article and then gold balls are attached. The article is then placed in a reducing flame which causes the oxide to reduce to copper and then react and form a eutectic with gold which disappears by diffusion [4]. Nowadays TLPB has been applied to join nickel based super-alloys, titanium, boron-aluminium composites and semi-conductor materials. The interlayer composite is selected to minimize bonding time, provide adequate wetting and avoid the formation of intermetallic inclusions [4].

Prior studies of bonding steel rods using TLPB have been scarce; most studies have been using TLPB to join super-alloys. In this work steels unions of commercial carbon steel of IRAM 1010 and IRAM 1040 were made using filler metal of amorphous Fe-B. The importance of different parameters such as temperature, pressure and heating time will be studied. In order to analyse how they affect the quality of the welded union and determine the required welding times the get proper microstructural continuity. The microstructures were analysed by optical metallography and with SEM-EDX. A galvanostatic corrosion test will be done on the un-bonded and bonded IRAM 1010 and IRAM 1040. The results obtained in this work can also be of great interest for future research on the application of the method in other steels. Considering that carbon steel is the base material, where many mechanical constructions are made of.

1.3. Purpose of this project

The purpose of this project is to analyse the corrosion behaviour of welded carbon steel made by TLP bonding technique. To be able to do it, these experiments will be done:

I. To produce welded bars using IRAM 1010 and IRAM 1040 steel rods with TLP bonding, both with amorphous Fe-B as the interlayer

II. To analyse the metallography of the welded bars and evaluate which welded bars to make the corrosion test.

III. To make a galvanostatic test of the chosen welded bars and compare them with the un-bonded bars.

2. The concept of transient liquid phase bonding

The general concept using TLPB to bond end faces of materials such as steel bars and steel pipes is that an insert material such as an amorphous metal (B), is lower in melting point (T_B) than the materials to be bond (A). The bonding temperature T_B should be reached as fast as possible [4]. T_B<T<A.

The interlayer must meet the following criteria:

- Must has at least one melting point depressant, MPD
- Must solve in the base metal
- Must have significant diffusivity at the bonding temperature, to ensure reasonable bonding times
- Must not be detrimental to the physical and mechanical properties of the base metal

The TLPB process can be described in 5 simplified steps:

1. The end faces are attached such as in figure 1. The substrates of material ‘A’ are attached with an interlayer ‘B’. See Figure 1.

   ![Figure 1](image)

   **Figure 1** An outline of the end faces of the material (A) and the insert material (B)

2. The attached portion is heated and raised to a temperature higher than the melting point of the insert material, $T_b < T_i < T_a$. According to MacDonald et. al. [4] the time require for this step is estimated to be in order of seconds. The joining process should be in either vacuum or oxygen free environment to prevent oxidation. In this experiment argon gas is used.

3. The widening of the bonding area. Causing by the melting interlayer. The widening process requires times in the order of minutes [4].

4. The melting forms a transient liquid phase and which subsequently re-solidifies at a certain temperature as a result of constituent inter-diffusion, continued heat treatment providing a homogeneous solid-state diffusion bond. This is the most important step as it requires the greatest amount of time and it is dependent on the width of the liquid interlayer formed and the rate of the diffusion into the bulk [4]. See Figure 2.

5. The last step is the homogenization process and is dependent on the time at the bonding temperature. The kinetics of the process is controlled by solid state diffusion into the material to be joined.
Figure 2. Nominal stages in TLPB process: a) initial condition; b) dissolution; c) isothermal solidification; d) completion of isothermal solidification; e) solid state homogenisation; f) final condition [6]
3. State of the art

3.1. TLP bonding

Transient liquid phase bonding is a bonding process that was developed to improve existing bonding technologies, such as welding, brazing etc. This process was patented by D.F. Paulonis et al. in 1971 [1] to overcome the difficulties of contemporary bonding techniques in joining Ni-based super-alloys. The bonding process is described where:

- A thin interlayer alloy of specific composition is placed between the substrate to be bonded.
- A rapid heating to the bonding temperature and keep the temperature until the bond is complete
- The bonding should be in vacuum, argon or any oxygen free environment to prevent oxidation.

The TLP bonding technique is still considered as a relatively new bonding process, which is still in development, even though a big spectrum of materials (substrates and interlayers) has been successfully bonded [14]. Suggested interlayers for low carbon steel are and Fe-B-Si and BNi-2.

3.2. Interlayer

An important feature of the TLP bonding process is the composition and physical characteristics of the interlayer placed between the surfaces to be joined. The interlayer must melt at a temperature below the melting point of the base metal. Its composition and amount must be such that the bond region will solidify at the bonding temperature and become as chemically and microstructural homogeneous with the base metal as is necessary in a practical annealing time. Economically and practically it is obviously more preferable to have an annealing time as short as possible for a satisfied bonding.

In the work of D.F. Paulonis [1] various melting point depressants such as boron, silicon, manganese, columbium and titanium have been evaluated to be used in the thin interlayer. Several combinations of these elements produce interlayers with satisfactory melting points. However, with the rich nickel-base super-alloys all except boron also produce unwanted stable phases at the joint interface. Consequently, only boron is utilized in the TLP Bonding Process. The boron content is controlled to obtain an optimum balance between the melting point and the ease of subsequent homogenization.

In the work of T.I Khan et. al. from 2004, an interlayer of Fe-B-Si is used to bond micro-duplex stainless steel (see Table 1 and 2). The results show that with bonding time of 5 min a distinct bond-line was visible along the length of the joints. By increasing the bonding time to 30 min, the bond-line was removed and became indistinguishable from that of the parent alloy.
However, the micrograph shows distinct changes in the grain morphology within the joint region after 30 min. One example of this is that isothermally solidifies to produce a ferrite joint when the Fe-B-Si interlayer is used. The presence of Si contributes to this phase stabilization, which is unwanted, as ferrite increases the corrosion rate [15].

**Table 1**: Composition of the interlayer [15].

<table>
<thead>
<tr>
<th>Fe (wt %)</th>
<th>B (wt %)</th>
<th>Si (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>

**Table 2**: Composition of the duplex stainless steel [15].

<table>
<thead>
<tr>
<th>C (wt %)</th>
<th>Si (wt %)</th>
<th>Mn (wt %)</th>
<th>P (wt %)</th>
<th>S (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018-0.02</td>
<td>0.5-0.55</td>
<td>1.5</td>
<td>0.02</td>
<td>0.005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cr (wt %)</th>
<th>Ni (wt %)</th>
<th>Mo (wt %)</th>
<th>Cu (wt %)</th>
<th>N (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.9-22</td>
<td>5.4-5.5</td>
<td>2.9-3.1</td>
<td>0.2</td>
<td>0.17</td>
</tr>
</tbody>
</table>

The work by C. Epelbaum et. al. [7] further shows that Si as an element in the interlayer for TLP bonding of steels is unwanted. TLP bonding was made on low carbon tubes with a Fe-Si-B glassy metal as interlayer filling material (see Table 3 and 4). Induction heating was used as a heating source under moderate pressure and argon flux. The bond was then analysed with SEM, an energy dispersive X-ray and electron probe microanalysis. The result from the analysis shows that the diffusion coefficient is significantly larger for boron than that of silicon, which means that the time needed to homogenize the chemical concentrations along the joint will be determined by the diffusion of silicon.

**Table 3**: Composition of the interlayer [7]

<table>
<thead>
<tr>
<th>Fe (wt %)</th>
<th>B (wt %)</th>
<th>Si (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.35</td>
<td>13.3</td>
<td>8.45</td>
</tr>
</tbody>
</table>

**Table 4**: Composition of the low carbon steel tubes [7].

<table>
<thead>
<tr>
<th>C (wt %)</th>
<th>Mn (wt %)</th>
<th>Si (wt %)</th>
<th>Ni (wt %)</th>
<th>Cr (wt %)</th>
<th>Mo (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>0.47</td>
<td>0.26</td>
<td>0.038</td>
<td>0.05</td>
<td>0.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V (wt %)</th>
<th>Cu (wt %)</th>
<th>Sn (wt %)</th>
<th>Al (wt %)</th>
<th>Ti (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.102</td>
<td>0.008</td>
<td>0.03</td>
<td>0.002</td>
</tr>
</tbody>
</table>
The thermal cycles consist of a rapid heating to 1220 °C, an isothermal stage (performed under 1, 3 and 5 min.) and a controlled cooling to room temperature. Metallographic observations in an optical microscope were taken at a depth of 3/4 of the thickness of the wall of the tubes relative to the external surface and at an increasing distance from the joining zone. The metallographic for 1 min isothermal heating shows a clear defect/separation of the bonding in the joining zone. The longer the bonding time, the less sharp the separation in the joint.

In the joining zone a 100 μm fringe of ferrite phase could be observed and around that ferrite fringe a region with coarse grain was produced. Some of them also showed Widmanstätten structure. This is observed up to 1 mm from the joints. The Energy dispersive X-ray analysis show that the Si concentration is in the joining zone. As the bonding time increase the Si concentration in the joining zone decrease. Far away from the joining zone the Si concentration tends towards the Si nominal concentration in steel.

The Electron probe microanalysis shows that boron is mainly localized in the remaining of the glassy metal and also in grain boundaries. A uniform distribution of boron is spread over the sample area. The silicon on other hand was observed to be localized in a frame at the joining zone. As a consequence of the slower diffusion constant of silicon, the time needed to homogenize the chemical concentration of the alloying elements along the joined samples is determined by the diffusion of silicon.

### 3.3. Bonding parameters

The parameters in the bonding procedure are:

- The dwell time
- Pressure
- Temperature during the isothermal stage.

Previous research shows that the most common pressure used in experiments with TLP bonding are between 1-10 MPa [14] and the temperature during the isothermal stage can vary. It depends on the combination of the substrate component and the choice of the interlayer material. The bonding temperature will affect the dwell time, but common for all systems is the relation $T_r < T_b < T_s$ based on an equilibrium phase diagram. Ideally there would be a temperature which would melt the interlayer fully without changing too much of the substrate structure and as low dwell time as possible. In the work of Epelbaum et. al. times of 1, 3 and 5 minutes are used as dwell time and bonding temperature of 1220 °C. At 1 min, the joint was not full bonded and with 3 and 5 min the joint was fully bonded. In the work of Khan et. al. a slightly different substrate material was used (see above), but the similar interlayer material (Fe-B-Si). The bonding time needed was 30 min, and the increased bonding time tends to form ferrite grains, which is unwanted.
3.4. Corrosion

In the previous research by W. Nimmo et. al. [8] three different corrosion tests of welded steel were made. The different tests were a long-term immersion test, an accelerated galvanostatic test and a scanning vibrating probe (SVP) technique. The results show that all three methods show to be useful in the corrosion behaviour of welded steels, with both pros and cons. Long term immersion test is the simplest, but needs constant control and was very slow. The accelerated galvanostatic test is simple and there is no need of expensive equipment. The method does not need tight control but in some cases, the high acceleration rate could lead to a different corrosion rate and behaviour than the one seen in service. The current density used in the experiment was 0.88mA/cm². The SVP technique is the most complicated of the three methods and mainly a laboratory method. It needs a lot of control and calibration. The results show that the accelerated galvanostatic test is the most useful in most welds. But the SVP is a great a compliment. A pitting corrosion test was made in a project by T.I. Khan et. al. which shows that the parameters used in the TLP bonding affect the resistance of the corrosion rate. The results show:

- The TLP bonded samples have lower corrosion resistance than the parent alloy
- TLP bonding with Fe-B-Si interlayer shows that presence of austenite grains have greater corrosion resistance than ferrite grains.
- Corrosion resistance increases with shorter bonding time. In this case, 5 min compared to 30 min.

4. Materials and methods for bonding of carbon steel SAE 1010/1040 with TLP bonding method

4.1. Modelling of the method of bonding carbon steel bars using amorphous metal interlayer

In this paper, the TLPB method for bonding round steel carbon bars of 6.35 mm in diameter was applied, using an amorphous metal interlayer of Fe-B eutectic composition as filler. The bars were cut into pieces of 65 mm in length and the ends were polished. The polished ends were put together with the amorphous material in between and a small axial pressure applied which was adjustable. This was made with a device constructed for that purpose. The joint was heated by induction under argon flow to prevent oxidation. See figure 3
When the merge of the interlayer material occurs, due to the set pressure, excess liquid is expelled out of the joint and solid-solid contact of the steel bars are produced in some points, while the liquid is filling the gaps. Since the process is controlled by diffusion, the effect of pressure would improve the contact between the surfaces and decrease the amount of filler by expelling the liquid out of the joint.

4.2. Characteristics of the joined bars

For this experiment, commercial carbon steels of round bars of 6.35 mm diameter were used, IRAM 1010 and IRAM 1040. They were produced by the company Acindar SA.

The steel corresponds to what established by the IRAM-IAS U 500-600 [10] standards, which is consistent with the designation established by the SAE J403 standards. Table 5 is the chemical composition allowance of the steel in this work.

Table 5. IRAM-IAS U 500-600 [10] standards for the chemical composition allowance of the steels used in this study (wt %).

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAM 1010</td>
<td>0,08 – 0,13</td>
<td>0,30 – 0,60</td>
<td>0,040 max.</td>
<td>0,050 max.</td>
</tr>
<tr>
<td>IRAM 1040</td>
<td>0,37 – 0,44</td>
<td>0,60 – 0,90</td>
<td>0,040 max.</td>
<td>0,050 max.</td>
</tr>
</tbody>
</table>

Analyses of the chemical composition of the bars used in this work were made using an optic emission spectrometer. To make sure the steels are within the standards. The results, see Table 6, confirms that the compositions of the steels are within standards.

Table 6. Results of the analysis of chemical composition of bars used in this study (wt %).

<table>
<thead>
<tr>
<th>Steel</th>
<th>Batch</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAM 1010</td>
<td>1</td>
<td>0,115</td>
<td>0,578</td>
<td>0,155</td>
<td>0,010</td>
<td>0,007</td>
</tr>
<tr>
<td>IRAM 1010</td>
<td>2</td>
<td>0,101</td>
<td>0,456</td>
<td>0,165</td>
<td>0,012</td>
<td>0,009</td>
</tr>
<tr>
<td>IRAM 1040</td>
<td>1</td>
<td>0,438</td>
<td>0,658</td>
<td>0,205</td>
<td>0,014</td>
<td>0,010</td>
</tr>
<tr>
<td>IRAM 1040</td>
<td>2</td>
<td>0,399</td>
<td>0,609</td>
<td>0,162</td>
<td>0,012</td>
<td>0,007</td>
</tr>
</tbody>
</table>
4.3. Characteristic of the interlayer material for TLPB

An important feature of this process is the composition and physical characteristic of the interlayer places between the surfaces to be joined. The interlayer must melt at a temperature below the melting point of the base metal ($T_A$) and which the base metal can be exposed without experience harmful effects. Yet its composition and amount must be such that the bond region will solidify at the bonding temperature and become as chemically and microstructural homogeneous with the base metal as is necessary in a practically annealing time. To promote bond homogeneity, the interlayer composition must be reasonably close to that of the base metal being joined. A melting point depressant is added to this basic composition in order to produce a satisfactory melting temperature, while certain elements normally present in the base metal are purposely excluded from the interlayer because they can form harmful phases during bonding [1].

In the work of Epelbaum [7], an amorphous metal ribbon Fe-B-Si was used to join tubes of low carbon steel (0.19 wt%) and observed that the time necessary to homogenize the chemical composition of the alloying elements through the welded joints was determined by silicon diffusion, because the diffusion coefficient of boron in the austenite is significantly greater than that of silicon. Subsequently, Di Luoizzo et al [9] used as well, an amorphous foil Fe-B eutectic composition with satisfactory results. Boron is used due to its effectiveness as a melting point depressant and its fast diffusivity in austenite, allowing completion of the homogenization step in the solid state in a relatively short time. Furthermore, the amorphous nature of the sheet filler is not a necessary condition for the process TLPB, but due to the higher toughness of the Fe-B alloy in the amorphous state, it is possible to use very thin films, which reduces the time of the bonding process. Besides its firmness, it allows manipulating and easily cut into the required geometry [7].

Consequently, for the present work, an identical filler sheet specification is used as by Di Luoizzo et al [9]. Is an amorphous metal ribbon 20 µm thick and 10 mm wide whose chemical composition is detailed in Table 7.

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass %</td>
<td>96.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Atomic %</td>
<td>83</td>
<td>17</td>
</tr>
</tbody>
</table>

In the phase equilibrium diagram of Fe-B, it is observed that this corresponds to the eutectic composition and that its melting point is 1174 ° C, being the lowest of the alloy system. See Diagram 1.
The filler was provided by Dr. Peter Svec Institute of Physics, Slovak Academy of Science.

5. The experimental equipment

5.1. The bonding device

For making the bond in this work, a device was designed and built. The device keeps the bars correctly aligned during the joining operation and is able to apply an axial compressive force of at least 200 N, which is adjusted by a compression spring. It is also equipped with a multiple conduit for injecting argon, which provides a protective atmosphere around the joint and thus prevents the oxidation of the steel junction. The assembly is completed with the induction coil used for heating the ends. The current generator is connected by high frequency behind the device by passing through two holes made in the confinement enclosure. See Figure 4.
5.2. The construction for the gas supply

In the base consists of the floor and the rear wall of the cabin rest on a table. In the rear wall there are two holes through which pass the ends of the induction coil and the induction generator device connected behind (see Figure 5 and 6). The subset also features multiple conduits of four outputs, built with aluminium tubes 5/16 inch in diameter, leading the argon around the joint. The argon flow rate is regulated by a valve that is part of the pressure regulator assembly directly connected to the gas pipe and connects to the manifold through a hose, also behind the device. The cabin is closed with a removable cover glass. An elastic gasket helps improve the seal.

Figure 5 & 6. Photographs of the gas construction (without the glass booth) and detail of the multiple blowing passage of argon and the induction coil.
5.3. Experimental determination of the spring constant of the spring

The clamping device comprises a steel compression spring to exert axial pressure to the welded joint adjustment. Adjusting the pressure exerted is accomplished by varying the spring length.

To determine the force exerted by the spring, it is considered ideally linear elastic, responding to Hooke’s Law (see Figure 7):

\[
F = -k \cdot \Delta l = -k \cdot (l - l_0)
\]

(Hooke’s Law)

Where:
F: force exerted by the spring, in N.
k: spring constant of the spring, in N / mm.
l: spring length in mm.
l₀: spring length when unloaded (natural length) in mm.

To experimentally determine the spring constant (k), the spring was placed vertically, among the disks spring holder guided by the stem (as it operates on the device) and axially loaded it on employing four weights two pounds each, eight kilos total (see Figure 8). Load for each separation distance between the plates was measured using a calliper holder springs calliper type with an accuracy of +/- 0.05 mm.
The measurement results were as follows (see Table 8):

**Table 8. Results of the spring constant.**

<table>
<thead>
<tr>
<th>M (kg)</th>
<th>F (N)</th>
<th>l (mm)</th>
<th>( \Delta l ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>44.7</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>19.62</td>
<td>43.6</td>
<td>-1.1</td>
</tr>
<tr>
<td>4</td>
<td>39.24</td>
<td>42.6</td>
<td>-2.1</td>
</tr>
<tr>
<td>6</td>
<td>58.86</td>
<td>41.5</td>
<td>-3.2</td>
</tr>
<tr>
<td>8</td>
<td>78.48</td>
<td>40.4</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

Series of data measured by least squares with a straight line adjusted. The spring constant of the spring is determined as the negative of the slope of the fitted line (see Diagram 2). The spring constant thus obtained was (1):

\[
k = (18.3 \pm 0.5) \frac{N}{mm}
\]  

*Diagram 2. Graph of the line fitted to the measurement points of the spring length according to the applied data*

Given that the bar diameter was (d) of 6.35 mm and therefore a cross section (S) gives 31.67 mm², it is possible to calculate the set pressure (p) depending on the length spring (l) using the expression:
\[ p(l) = \frac{k}{S} (l_0 - l) \quad (2) \]

Numerically:

\[ p(l) = \frac{18.3 \text{ N}}{31.67 \text{ mm}^2} (44.7 \text{ mm} - l) \]

\[ p(l) = 0.5778 \frac{\text{MPa}}{\text{mm}} (44.7 \text{ mm} - l) \quad (3) \]

By expression (3) is possible to calculate the pressure adjustment for the spring length in millimetres. For the realization of all the samples, 40.5 mm in length was fixed, resulting in a set pressure \( p \) of 2.43 MPa. The pressure is within the most common set pressure.

### 5.4. Temperature measurement

A pyrometer EDG brand, model PIR-100 was used for temperature measurement. The instrument has a lens to focus towards the body whose temperature you wish to measure. The measurement value is read directly from a small LCD screen (see Figure 9a and 9b). To make the pyrometer measurements started at a constant distance of 350 mm from the confining enclosure of the device, focusing towards the centre of the board of the bars to unite through the opening between the central turns of the induction coil (see Figure 9c).
5.5. *Induction heating system*

The joints were heated by induction. The employed high frequency generator has the following specifications (see Figure 10):

- **Manufacture**: GH Electrotermia SA
- **Model**: 12PM
- **Year**: 2001
- **Source**: Valencia, Spain.
- **Rated power**: 12 kW
- **Output voltage**: 500 V
- **Frequency range**: 25-40 kHz
The induction coil used was constructed with an internally cooled copper tube with demineralized water, and has the following specifications:

- Pipe diameter: 4 mm
- Number of turns: 4
- Inner diameter of the coil: 18 mm
- Length: 27 mm

6. Experimental procedure

6.1. Preparation of bars

The bars were cut into pieces of 65 mm in length by a hand saw for metallographic samples perpendicular to the axis. Taking special care that overheating does not occur during cutting that could oxidize or modify the original properties of the steel. The ends of each piece of rod was polished with sandpaper up to 1000 grit in grain size and finally fine polish with automatic polish sheet machine with alumina 3. The whole bar was then cleaned with acetone. The finished surface was similar to that of the samples for metallographic observation.
6.2. *Bonding procedure*

To make the welded joints, the following procedure was followed:

I. A piece of square amorphous metal tape supply side of 10 mm cut, approximately.

II. The ends of the bars were properly prepared and the ends are cleaned with a cotton ball soaked in acetone to ensure cleanliness of the surfaces.

III. The joined bars in the clamping device were put between the tapes. The correct alignment of the assembly is checked, as illustrated in Figure 11.

IV. Through the nut, the spring length is obtained to the required pressure.

V. The bar is aligned with the axis of the induction coil, placing the board in the middle of it so that its position coincides with the higher temperature during thermal cycling.

VI. The glass cabin is closed and argon is circulated for one minute before beginning the heating, in order to displace as much air as possible. The exhaust air is performed to decrease the concentration of O2 and prevent oxidation of the steel.

VII. Its thermal cycle begins. Two people are require for this operation, one operating power control of the induction generator, and another, timing and taking
The limitations imposed by the manual control of temperature allowed for deviations experiences +/- 10 °C above the temperature of the process established for the sample.

VIII. During the heating stage, a few tens of degrees before reaching the wanted temperature, the argon flow rate is reduced to reduce the convective heat loss caused by the impingement of the cold.

IX. The thermal cycle is ended; the generator power is cut, and during the cooling, the continuous argon flow will continue with the cabin closed until the welded bars are cooled down (for about one minute).

X. Removal of the bars

6.3. The thermal cycle

To heat the samples for bonding, an induction heater is used, because of its ability of quick and concentrated heating. In this case, a coil of 4 turns is used to reach the sufficient temperature, T °C. The induction heater generates a power of 12 kW and a frequency of 34 kHz, which is depending of the size and geometry of the bar.

The heating procedure can be divided into three parts (see Figure 12):

I. Heating up to the process temperature. The heating time (t_c) lasted about 60 seconds.

II. The time keeping the temperature at 1200 °C (+- 5 °C)

III. Power-off and cooling to room temperature under argon flow. The cooling time (t_e) lasted about 60 seconds.

Figure 12. Schematic graph of the thermal cycle applied during the bonding process the bars.
During the entire welding procedure the experiment is in argon environment to prevent oxygen. The oxygen will start the unwilling process of oxidation.

6.4. The parameters

The parameters in the bonding process were as follows:

- Union temperature ($T_B$)
- Dwell time ($t_p$) to union temperature
- Carbon content of the metal bars. Steel used are of two different compositions, IRAM 1010 and IRAM 1040, with a nominal carbon content of 0.10 and 0.40% (by weight) respectively.
- The same axial pressure (p) for all experience, 2.43 +/- 0.07 MPa was applied

Five sets of samples were run. In each series, experiments were conducted by varying the residence time and keeping the other parameters. The parameters adopted for each series are listed in Table 9.

<table>
<thead>
<tr>
<th>Serie</th>
<th>Steel IRAM</th>
<th>T_B (°C)</th>
<th>p (MPa)</th>
<th>0</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
<th>240</th>
<th>300</th>
<th>360</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1010</td>
<td>1400</td>
<td>2,43</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<td>•</td>
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<td>•</td>
</tr>
</tbody>
</table>

The numbers that are called sample series respond to the chronological order in which they were made and have no other significance.

The method of TLP bonding imposes physical limits to the range of temperatures in which experiences can be made. The melting point of the filler material, which in this case is 1174 °C is lower limit, while the upper limit is the solidus temperature ($T_s$) of the steel, because
above it, it will start to melt. Solidus temperature of the steel used is determined from the phase equilibrium diagram, meta-stable Fe-C (see Table 10. and Figure 13):

Table 10. Solidus temperature of the steel

<table>
<thead>
<tr>
<th>Steel</th>
<th>% C</th>
<th>T_s (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAM 1010</td>
<td>0,10</td>
<td>1495</td>
</tr>
<tr>
<td>IRAM 1040</td>
<td>0,40</td>
<td>1450</td>
</tr>
</tbody>
</table>

The bonding temperature in series 1 and 2 was 1400 °C, which is about 95 to 50 °C below the solidus temperature of IRAM 1010 and IRAM 1040 respectively. This junction temperature proved to be a practical upper limit for welding steel IRAM 1040 (Series 2) with a set pressure of 2.43 MPa. As several attempts to make the samples of this series, results in the bars to collapse during the execution of the welds, due to adjusting the pressure exceeded the strength of the bar at that temperature (see Figure 14). For this reason and in order to prevent collapse during welding, one of the sample of this series (with t_p = 30 s) was performed at temperature 1380 °C, 20 °C below the set temperature (70 °C below the corresponding T_s).

Figure 13. Phase diagram of Fe-C [12] indicating the melting temperatures of IRAM 1010 and IRAM 1040 steels.
The bonding temperature in the third series, IRAM 1010 were made from steel that was 1460 °C, about 35 °C below the solidus temperature of the steel. This series was conducted in order to establish a temperature difference similar to the IRAM 1040 steel solidus in series 2. Then performed a comparison of the behaviour of both steel in comparable thermal conditions and thus assess effect of chemical composition of steel in the bonding process. In this series there were problems of collapse.

The series 4 and 5 were performed at 1230 °C, which is about 55 °C above the melting temperature of the filling material, 265 and 220 °C below the temperature corresponding to the IRAM 1010 and IRAM 1040 steel respectively. The temperatures chosen for the samples are close to the physical limits of the method. Indeed, close to the upper limit of series 1, 2 and 3; while near the lower limit of series 4 and 5. This allowed comparisons which show the influence of junction temperature on the quality of the joints and the time required to achieve them.
6.5. Designation of the samples

In order to simplify the identification of the samples, a naming system consisting of a 3 digit code was adopted: Sample No. A-BC

Where each digit means the following:
A: Series to which it belongs.
BC: Indicate the residence time, so that: $t_p = BC \times 30$ (seconds)
For example; the sample No. 2-03, belongs to series 2 with 90 s residence time.
In Table 11 the parameters used in each of the samples are expressed.

Table 11. Parameters used in each sample

<table>
<thead>
<tr>
<th>Serie</th>
<th>Sample No.</th>
<th>Steel</th>
<th>IRAM</th>
<th>$T_B$</th>
<th>$t_p$</th>
<th>p</th>
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<td>240</td>
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<td>1010</td>
<td></td>
<td>1230</td>
<td>360</td>
<td>2,43</td>
</tr>
</tbody>
</table>

(1) The sample 2-01 was made at 20 °C below the rest of the series, due to bond collapse at higher temperature.
6.6. Sample preparation

In order to make the metallographic analysis of the joints, the samples were prepared as explained below (see Figure 15):

I. The welded bars were cut into pieces of 20 mm long, 10 mm to each side of the joint.

II. The pieces were then cut longitudinally along the central axis.

III. The samples were included in the polymer at a temperature of 170 °C.

IV. Grinding and polishing was performed with water sandpaper, successive decreasing in grain size.

V. The final polishing cloth was made with alumina slurry of 0.3 mm in a polishing disc

![Figure 15. The sketch of the cuts and inclusion in polymer sample.]

6.7. Metallographic analysis

For metallographic analysis of the samples, an optical microscope equipped with an ocular amplification factor 10x objective was used with amplification 8x, 32x, 65x. This results in an overall amplification of 80x, 320x or 650x, depending on the lens used. Through the eyepiece photographs were taken with a 6 megapixel digital camera. Nital reagent 3 was used (reagent No. 74 ASTM E-407 [13]) to reveal the metallographic structure, comprising:

- 3 ml of concentrated nitric acid
- 100 ml of ethyl alcohol

To perform measurements on micrographs, graduated scales on them were inserted. For this, images of a reference plate having a pattern engraved divisions of 100 mm (see Figure 16), used with different magnifications were taken. On these scales reference images which were then inserted in the micrographs.
7. Results and discussions part 1

7.1. Metallographic observation

The welded joint of all TLP bonding experiments were observed with optical microscope in order to determine the quality of the microstructure. Micrographs were taken on the longitudinal section of the joined bars.

7.2. General considerations of the joints

In order to establish a clear and uniform criterion to determine the quality of the joints, the following classification is applied to all experiments made, based on the optic lens with 80x (see Figure 17):

7.2.1 Union quality

• Quality A: bonding is continuous along the section of the bar and the microstructure is uniform across the board, so it is not possible to determine their exact position by metallographic observation. This joint quality is considered complete.
• Quality B: no metal binding along the section of the bar and the microstructure is uniform across the board, however, inclusions aligned along the board indicating that the process are not yet fully completed.

• Quality C: no metallic bond along the bar section but the joint coincides with grain boundaries, so that the microstructure is not uniform and the location of the seal is clearly discernible. Inclusions aligned along the board are also observed.

• Quality D: discontinuities in the metallographic structure along the seal, solidified molten filler metal is observed.

![Figure 17. Schematic microstructures of the board, representing different qualities of the attachment.](image)

**7.3. Quality of the joints obtained by TLPB**

In Table 12 is the result of the analysis of the samples. The quality of the joints obtained in each TLP bonding experiment with bonding parameters used in each case. “A” to “D” means the different quality of the bond. “A” as the highest quality, and “D” as the lowest. See 7.2. for definitions.
Table 12. Summary of joint quality obtained by the TLPB experiments

<table>
<thead>
<tr>
<th>Steel IRAM</th>
<th>T_b (°C)</th>
<th>p (MPa)</th>
<th>Serie</th>
<th>tp (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>1010</td>
<td>1230</td>
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<td>D</td>
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<td>B</td>
</tr>
<tr>
<td>1040</td>
<td>1400</td>
<td>2,43</td>
<td>2</td>
<td>C</td>
</tr>
</tbody>
</table>

7.4. Analysis of the samples

7.4.1 Series 1

Samples from Series 1 were performed with the following parameters:

- Steel: IRAM 1010
- T_b: 1400 °C
- p: 2,43 MPa
- t_p: 0, 30, 60, 90 and 150 s.

The minimum time necessary to achieve microstructurally sound bonding throughout the section of the bar with quality "A" was 60 seconds.

For shorter bonding times, the internal discontinuities together with solidified molten material, indicates that the bonding time was insufficient to get complete isothermal solidification. With longer dwell times, the joints were complete within the bar and it is impossible to distinguish the precise location of the joint by optical microscope. See Figure 18.
In the samples with \( t_p \) 90 to 150 s, aligned inclusions near the surface of the joint can be observed. These defects can be attributed to a possible deficiency in the flatness of the bonding surface, due to the method used in their preparation. That tends to round the edges. These undesirable rounding causes the gap between the bonding surfaces is greater near the edge. This will increase the bonding time needed to finalize the bond. This means that probably the 90 s and 150 s are better bonds.

7.4.2. Series 2

Samples from Series 1 were performed with the following parameters:

- Steel: IRAM 1040
- \( T_{B'} \): 1400 °C
- \( p \): 2.43 MPa
- \( t_p \): 0, 30, 60, 90 and 150 s.

The minimum time to achieve microstructurally sound bonding throughout the section of the bar with quality "A" was 30 seconds. In the joint made without permanence bonding temperature (\( t_p = 0 \) s), starting the cooling immediately after reaching the \( T_{B'} \), was observed that the ferrite grain boundary is aligned
with the board in most of the bond. It was possible to clearly determine the bond location (see first picture in Figure 19), and the aligned inclusions at the joint were observed. For more dwell times, the joints were complete within the bar and it was impossible to distinguish the precise location of the joint. See Figure 19.

The minimum time to achieve a bond with microstructural continuity was lower for IRAM 1040 than IRAM 1010.

![Figure 19. Micrographs of different samples of series 2. In all cases, the board is located in the centre of the image.](image)

7.4.3. Series 3

Samples from Series 1 were performed with the following parameters:

- Steel: IRAM 1010
- $T_b$: 1460 °C
- $p$: 2.43 MPa
- $t_p$: 0, 30, 60, 90 and 120 s.

For all dwell times used, including the joint made without permanence bonding temperature ($t_p = 0$), the joints were complete within the bar and impossible to distinguish
the precise location of the joint by metallographic observation. All joints were quality "A". This indicates that the solidification was completed during heating. See Figure 20. The increase in temperature by 60 °C comparing to the series 1, has reduced the time by more than 60 s to make a bond with microstructural continuity throughout the section.

![Figure 20. Micrographs of different samples of series 3. In all cases, the board is located in the centre of the image but it is impossible to identify.](image)

7.4.4. Series 4

Samples from Series 1 were performed with the following parameters:

- Steel: IRAM 1040
- \( T_b \): 1230 °C
- \( p \): 2,43 MPa
- \( t_p \): 120, 180, 240, 300 and 360 s.

The minimum time necessary to achieve microstructurally sound bonding throughout the section of the bar with quality "A" was 300 seconds. With shorter time spent on \( T_b \), aligned inclusions can be observed. At the first 3 pictures, the bond can be observed, which show an incomplete weld. For longer dwell time, the joint was complete within the bar and it was impossible to distinguish the precise location of the bond. See Figure 21.
The minimum time required to achieve microstructural joints continuity for IRAM 1040 steel bars at a temperature of 1230 °C was considerably higher than for the same steel at 1400 °C with the same pressure adjustment. This result is reasonable considering the dependence of the diffusion rate with temperature.

7.4.5. Series 5

Samples from Series 1 were performed with the following parameters:

- Steel: IRAM 1010
- T_B: 1230 °C
- p: 2.43 MPa
- tp: 120, 180, 240, 300 and 360 s.

The time necessary to achieve microstructurally sound bonding to achieve quality "A", was 240 seconds. For shorter tp, the bond had internal discontinuities aligned with the joint. Ferrite grains on the joint. At the first 2 pictures, the bond can be observed, allowing it to clearly distinguish its location. This means an incomplete weld. At the dwell time 180 s, these discontinuities
in the union are reduced. For longer time, the joint was continuous across the board inside the bar and it was impossible to distinguish the precise joint location by optical microscope. See Figure 22.

Reducing the junction temperature of 170 °C compared to the Series 1 samples, made with the same steel and the same contact pressure. This resulted in about 180 s increase in the time required to achieve continuity in the microstructural throughout the section.

![Figure 22. Micrographs of different samples of Series 5. In all cases, the board is located in the centre of the image.](image)

### 7.5. Effect of the bonding temperature

In the table 13, the minimum bonding times are summarized together with the temperature difference (between melting temperature of the base metal and the bonding temperature) needed to obtain a quality “A” bond. The melting temperature for IRAM 1010 is 1495 °C and for IRAM 1040 1450 °C
Table 13. Shortest time (s) that were needed for each steel for quality "A" bond and the difference between melting temperature and bonding temperature (T_A - T_B).

<table>
<thead>
<tr>
<th>T_B</th>
<th>IRAM 1010</th>
<th>IRAM 1040</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>T_A - T_B (°C)</td>
<td>tp min. (s)</td>
</tr>
<tr>
<td>---</td>
<td>----------</td>
<td>--------</td>
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<tr>
<td>1230</td>
<td>265</td>
<td>240</td>
</tr>
<tr>
<td>1400</td>
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</tbody>
</table>

The results verified that the increase in temperature significantly reduce bonding time required to complete the bond. This dependence was more significant in the steel IRAM 1040 than in IRAM 1010. An increase of 170 °C, reduce the time with about 270 s for IRAM 1040 and 180 s for IRAM 1010. However, it should be noted that this temperature variation was closer to the melting temperature for 1040 steel than for the IRAM 1010.

The bonding process is based on the diffusion of the atoms of the filler material in the steel to be joined at an elevated temperature, which may be near the melting temperature of the steel. At high temperatures, changes may occur in the microstructure such as grain growth, which change the relationship between the volume occupied by the grains and the grain boundaries. This can generate changes in the diffusion mechanism.

When trying to reduce the time spent (t_p) to zero for a union of quality "A", the temperature should be high and close to the melting temperature of the steel. The process was very complex at the temperatures close to a critical temperature, which was close to the melting temperature of the steel, due to the biggest changes in the diffusion mechanisms. In addition, it was where the system varies chemically the most and makes it extremely difficult to modelling the TLPB process. However, correlations can be made and use of macroscopic observations, in order to obtain better control of the process.

Since the process was performed at the temperatures close to the critical temperature. To obtain correlations which can be applied to other steel, it was reasonable to consider a variable to control the process temperature difference between the melting temperature and the bonding temperature (T_A - T_B). Thus, in Figure 23 bonding times are plotted to obtain a quality joint "A", depending on the temperature difference (T_A - T_B).
Figure 23. Comparison between the bonding time of the two steels, required to complete the bonding as a function of the difference between the starting and melting temperature of each steel ($T_A - T_B$).

It is observed that the time required for obtaining quality "A" with the same temperature difference ($T_A - T_B$), are generally lower for IRAM 1010 than for IRAM 1040. This can be explained by the Fick’s first law, by the lower concentration of interstitial solute (carbon) in the IRAM 1010 than 1040, which would cause the higher diffusion rate of boron.

7.6. **Choosing samples for the galvanostatic corrosion test**

Series 1: it took 60 s to make the bond, but the 90 and 150 s were better in the structures.

Series 2: Same $T_B$ as series 1 and needed 30 s to make the bond, but the 90 and 150 s were better in the structures.

Series 3: Higher in $T_B$ and made the bond very fast. Little bit too fast to be able to know more precise what it takes to create the bond.

Series 4 & 5: Took very long time ($t_p$) to create the bond for quality “A”

Samples 1 & 2 with $t_p = 150$ s will be used in the galvanostatic corrosion test comparing the corrosion speed against the un-bonded samples. The samples have good bonds in a decent time and can be compared, due to the parameters. $t_p = 150$ s is still consider a short bonding time and to have the margin to make sure the bond is as good as it gets before we do the corrosion test.
8. Galvanostatic corrosion test

8.1. Purpose of the study

The aim with the corrosion test is to see how resistance and the behaviour of the welded bars were comparing to the non-welded steel bars. A galvanostatic corrosion test will be used, similar to the one by Nimmo et. al. [8] and the bonded steel for the test will be from sample 1 and 2. With \( t_p = 150 \) s.

8.2. Experimental procedure

8.2.1 Materials

The un-bonded carbon steel (IRAM 1010/1040) and the bonded carbon steel (IRAM 1010/1040) worked as anodes. The un-bonded steels will be called 1010b and 1040b. AISI 308 carbon steel works as a cathode and ASTM seawater as the electrolyte solution. ASTM seawater is a mixture of distilled water and NaCl (3.5 weight %).

Potenciostat/Galvanostat EG&G from Princeton Applied Research.

8.2.2. The experiment

Un-bonded and bonded carbon steel bars were cut into the size of 0.64 cm² (8*8 mm²). Prior to the electrochemical experiments, the samples were polished with sandpaper up to 1000 grit and fine polished with automatic polish sheet machine with alumina 3 (0.3 µm particle diameter). The samples were then point welded with AISI 308 to a wire of stainless steel, AISI 308 to form the anode (see Figure 24). The wire was then consisted in a cylindrical glass pipe with the sample on top; fasten with poxipol (an adhesive). The poxipol helped to cover the sample surface to make sure of identic expose area of the 4 samples, which was 0.20 cm² (4*5 mm²).
Figure 24. Setup of each experiment

The cathode was larger than the anode to make the corrosion more efficient and an expose area of 3 cm$^2$ was chosen. The cathode had a radius of 0.04 cm.

Length (L) of the counter electrode:

$$A = 2\pi rl = 3cm^2$$

$$L = \frac{3cm^2}{2*\pi*0.04cm} = 12cm$$

The experiment was held in room temperature, about 22 ºC. The current density used in the experiment according to Nimmo et al. was 0.88 mA/cm$^2$, and with an expose area of 0.20 cm$^2$, the current applied is:

$$\delta = 0.88mA/cm^2$$

$$A = 0.20cm^2$$

$$\delta = \frac{I}{A} \Rightarrow I = \delta * A = 0.88 * 0.20 = 0.176mA = 176\mu A$$

The current connected in series as can be seen in Figure 25
The experiment lasted totally for six days. The samples examined with an optic microscope after 5 minutes, 6 days and 6 days with the oxide removed with phosphoric acid. The ASTM seawater was changed after 3 days.

9. Results and discussions part 2

The galvanostatic corrosion test was performed according to an experiment by Nimmo et al. The aim of the test was to see if there are any differences in corrosion rate between the bonding zones of the samples and to study the behaviour. The samples used in the test were un-bonded IRAM 1010/1040 as a reference and bonded IRAM 1010/1040 with 150 s bonding time. The current was 0.88 mA/cm² and the environment was ASTM seawater.

Before the corrosion test, the bonded samples were examined with optic microscope and SEM. In the optic microscope no significant difference in the bonding quality could be seen. Both samples had defects in the border of the bonding zone, see Figure 26 and 27). These defects can be attributed to a possible deficiency in the flatness of the bonding surface, due to the method used in their preparation. That tends to round the edges. These undesirable rounding causes the gap between the bonding surfaces is greater near the edge.

The observations with SEM (Quanta 200, Fei Company) show small un-bonded spots (size of 10 μm) on the 1010, while the same spots could not be seen in the 1040. These small spot may affect the corrosion rate and give rise to crevice attack.
After 5 minutes
Already after 5 minutes the samples have corroded significantly and it was possible to draw the first conclusion. The 0.88 mA/cm² was too strong for the samples and would not last 15 days as the experiment by Nimmo et. al. [8] Observations in optic microscope after 5 minutes did not show any particular corrosion pattern, the samples seems to be randomly attacked, see Figure 28.

After 6 days
After 6 days, the samples were totally corroded and the surface was covered with oxide. The observation with optic microscope did not show any significant difference between samples when it comes to corrosion rate, they all seems to be randomly corroded, see Figure 29.
After 6 days with the oxide removed
The oxide on the 6 days samples was removed with phosphoric acid (10%) and examined with an optic microscope. In the Figure 30 and 31 it can be seen that the bonding zone for bonded IRAM 1010 corroded faster than the rest of the samples. For the other samples no difference in corrosion rate could be seen. The faster corrosion rate in the bonding zone of IRAM 1010 could be a result of the spots founded with SEM.
10. Conclusion

The results provided in this study lead to the following conclusions:

10.1. Microstructure and properties

For IRAM 1010, 60 s is needed to make a complete bond with 1400 °C and set pressure of 2.43 MPa. At temperature 1230 °C, bonding time is 240 s. Furthermore, at temperature 1460 °C, the bond is complete during the heating to the bonding temperature. For IRAM 1040, 30 s is needed to complete the bond with 1400 °Cs. At the temperature 1230 °C, the bonding time is 300 s. The temperature of 1400 °C and set pressure of 2.43 MPa prove to be the practical upper limit for the bonding with this steel, as several samples is collapsing with theses parameters.

The dwell time decreases significantly for obtaining a quality "A" bond (see 7.2.1. for definition) with increase bonding temperature. It is also noted that, in general, IRAM 1010 requires lower bonding time than IRAM 1040 for an equal temperature difference between the solidus temperature (Tₛ) and the bonding temperature (Tᵦ). This can be explained by the Fick’s first law, the lower concentration of interstitial solute (carbon) in the IRAM 1010 than 1040, which would cause the higher diffusion rate of boron.

10.2. TLPB method for bonding of carbon steel

The results in this work show that transient liquid phase bonding by using amorphous Fe-B as interlayer has great potential for technological applications in joining steel with low and medium carbon. The method can make bonds with microstructural continuity in less than a minute, which make this method competitive against other welding methods. The method can especially be useful for performing bonds in serial production lines of steel parts, requiring bonds with excellent microstructural continuity. Where it is possible to design automate devices keeping the pieces correctly aligned, control the thermal cycle and ensure repetitiveness in the surface finish of the bonding sections.

10.3. Galvanostatic corrosion test

A galvanostatic corrosion test of un-bonded 1010/1040 carbon steel bars and bonded 1010/1040 carbon steel bars bonded for 150 s were performed. The test environment was ASTM seawater (3.5 % NaCl) and a current of 0.88 mA/cm².

The bonding of 1010 and 1040 are considering good quality bonds, due to the metallographic observations from part 1. The samples for the galvanostatic corrosion test were the bonded 1010/1040 with 150 s bonding time. Both samples are consider similar, only on SEM it could observe that 1010 has some small spots of defect which cannot be observe in 1040. It was possible after 6 days to see difference in the bonding rate between the samples.
The bonding zone of 1010 corrodes little faster than the rest of the samples. It can be the influence of the spots found with SEM, while bonded 1040 corrode in a same rate as the un-bonded ones. This means that the TLP bonding method with low/medium carbon steel can both make bonds with microstructural continuity within minutes and in the same time have good corrosion resistance.

10.3.1. Suggestions for further research

It would be interesting to make further research to get more correct and precise results, to know why the bonding zone of 1010 corrodes faster than 1040. This can be done by doing more welds to see if it will be spots on the “new” IRAM 1010 ($t_p$) content and use of lower anodic current density to make the test more sensible. Also investigate the exact metallographic composition of the bonding, draw a polarization curve to see the characterization of the electrodes and find a more suitable environment and more exact current for the samples.
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Nomenclature

TLPB Transient Liquid Phase Bonding
1010 Carbon Steel with 0.10 % carbon content
1040 Carbon Steel with 0.40 % carbon content
SAE The Society of Automotive Engineers
MPD Melting Point Depressant
SVP Scanning vibrating probe
B Amorphous metal
A Base metal
T_E Melting temperature of amorphous metal (°C)
T_A Melting temperature of base metal (°C)
T_B Bonding temperature (°C)
C_L Liquidus composition
C_S Solidus composition
C_R Room temperature solubility of element B in substrate A
D_B^A Diffusion coefficient of B in A
P % of total power of the induction heater
p Pressure (Pa)
T Temperature (°C)
T_amb Atmosphere temperature
t_c Heating time (s)
t_p residence time (s)
t_c Cooling time (s)
SVP Scanning vibrating probe
A Area (m^2)
d Diameter (m)
r Radius (m)
F Force (N)
L Length (l)
dl Displacement from equilibrium position of the spring (m)
k spring constant (N/mm^2)
SEM Scanning Electron Microscopy
HAZ Heat Affected Zone
NILS Non Isothermal Liquid Solidification
References


Patents


