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Experimental Determination of Temperature During Rotary Friction Welding of AA1050 Aluminum with AISI 304 Stainless Steel

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Abstract: *The purpose of this study was the temperature monitoring at bonding interface during the rotary friction welding process of dissimilar materials: AA1050 aluminum with AISI 304 stainless steel. As it is directly related to the mechanical strenght of the junction, its experimental determination in real time is of fundamental importance for understanding and characterizing the main process steps, and the definition and optimization of parameters. The temperature gradients were obtained using a system called Thermocouple Data-Logger, which allowed monitoring and recording data in real-time operation. In the graph temperature versus time obtained, the heating rates, cooling were analyzed, and the maximum temperature was determined that occurred during welding, and characterized every phases of the process. The efficiency of this system demonstrated by experimental tests and the knowledge of the temperature at the bonding interface open new lines of research to understand the process of friction welding.*

Keywords: *Friction Welding, Aluminum, Stainless Steel, Dissimilar Materials, Temperature.*

INTRODUCTION

The rotary friction welding (RFW) is a special process that occurs in the solid state. It provides high productivity, excellent repeatability, low cost, and its greatest application is found in the production of dissimilar materials joints used in aerospace, nuclear, marine, and automotive fields. All process happens at temperatures lower than the melting point of the materials involved and the joints produced are of excellent quality, featuring superior mechanical properties of the metals that were joined.

In the RFW, one part is fixed and rotated by a motor unit to a predetermined speed, and the other is positioned, aligned, and moved by a hydraulic piston to touch the part that is spinning. After that, a P_1 pressure is applied for a given time (t_1), the machine is braked until it reaches zero speed, and P_2 pressure is applied during a t_2 time, finishing the welding (Alves, 2010a).

Parameters of welding (rotational speed = rotation per minute (RPM), P_1 and P_2 pressures, t_1 and t_2 times) are defined by welding procedures established for each material or materials and according to the type of the equipment employed. Figure 1 shows the phases of the process.

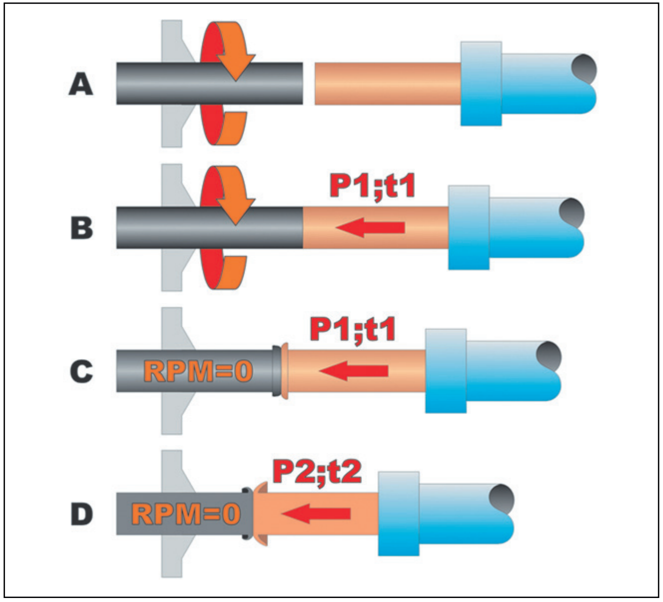

Figure 1. Phases of conventional friction welding process. A: period of approximation; B: P_1, t_1, application; C: end of P_1, t_1, and breaking of the machine (RPM=0); D: P_2, t_2 application and finish welding (Alves, 2010a).

Figure 2 shows the basic layout of RFW equipment, whose flawless performance and timing are of fundamental importance in the quality of joints obtained by this process.

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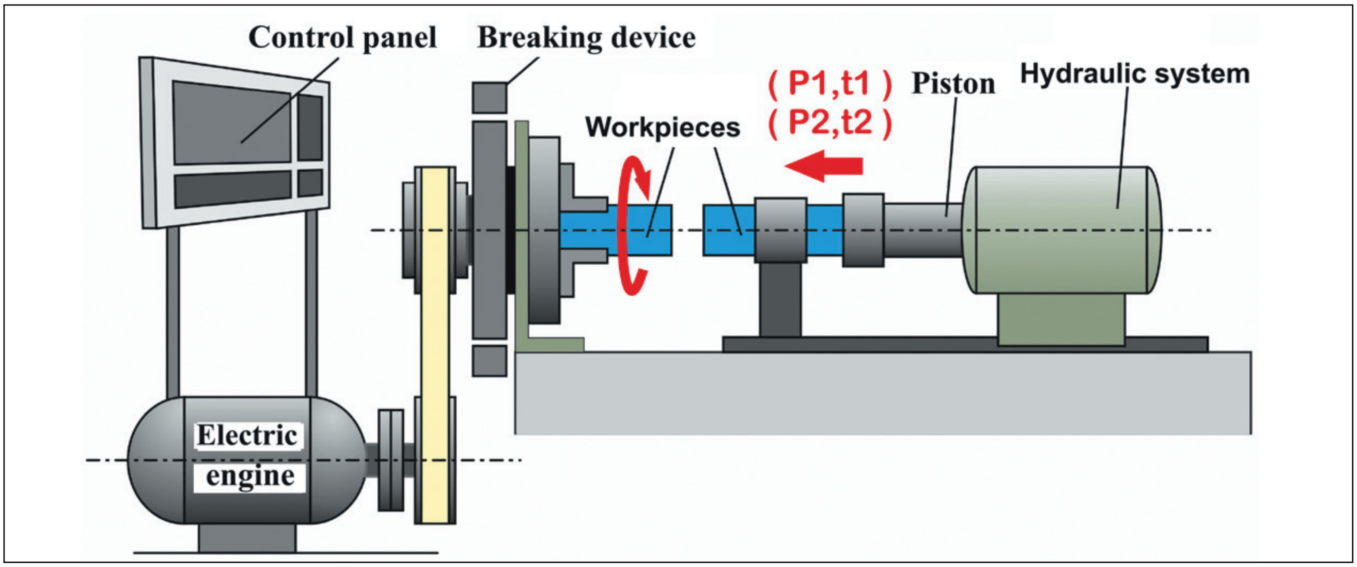

Figure 2. Equipment of RFW (Alves, 2010a).

When using this process to the union of two materials, it is very important to know the temperature in the bonding interface, because it directly interferes with the formation of the crystal structure of the heat affected zone (HAZ), influencing the mechanical and metallurgical properties of the welded joint (Alves, 2010a).

All the heat necessary for welding is produced by the direct conversion of mechanical energy into the thermal one. It is a complex metallurgical process, which involves a series of variables, such as pressure, time, travel speed, rotational speed, accompanied by physical phenomena: heat generation by friction, atomic diffusion, plastic deformation and formation of intermetallic compounds. During the relative motion of surfaces, a significant amount of heat is dissipated causing temperature increase, even with small values of loads and sliding speeds (Burakowiski and Wierzchon, 1998).

In friction welding, the heat generation occurs differently from conventional welding processes for fusion, however there is a similarity in the temperature distribution on the joint of union of base metals (Alves, 2010a). The amount of heat generated at the bonding interface or heat input in RFW is a consequence of the friction and work of plastic deformation due to the relative motion between both materials.

The temperature at the surface depends on the applied pressure, rotational speed, thermal conductivity, and also on the coefficient of friction. Heat dissipation is an automatic process since friction and adhesion occur in places where micro welds cause an increase in the rate of heat dissipation, which contributes to an increase in micro welds and bond of two surfaces (Burakowiski and Wierzchon, 1998).

There are many published studies on RFW and on its thermal effects through experimental and analytical methods, which were conducted by researchers in different countries according to their importance in understanding the mechanisms that involve the process.

Vill, 1962; Ylbas *et al*., 1994; Sahin, 2004; Chalmers, 2001; Zepeda, 2001; Nikolaev and Olshansky, 1977; Aritoshi and Okita, 2003; Ambroziak *et al*., 2007; Isshiki *et al*., 2008; Kusçu *et al*., 2007; Sluzalec, 1990; Lee, 2003; Kimura *et al*., 2010; Ochi *et al*., 1998; Banker *et al*., 2002, conducted several studies involving the joining of dissimilar materials. These authors wrote articles on the mechanical properties and on the metallurgical and thermal effects of the welded parts of the RFW.

In this study, a method for monitoring the temperature in the bonding interface in real-time operation, called Thermocouple Data-Logger (TDL), was used (Alves, 2010a). Through this system, we can monitor, determine the beginning and end of each stage of welding, analyze the different heating rates and cooling, and characterize all stages of the process through time versus temperature curves.

TEMPERATURE AT BONDING INTERFACE

When two dissimilar materials are joined, such as AA1050 aluminum and AISI 304 stainless steel, with different properties by this process, the heat generated by friction between the two materials is spread differently in each material. The thermal conductivity of aluminum is three times higher than in stainless steel, influencing directly the rate of heating and cooling that occur during the process. The surface roughness of the interfaces that will be attached can also change the heating rates in the initial stages of the welding operation and influence the diffusion mechanism, which occurs mainly in the first phase of welding (heating phase).

The temperature gradient and thermoplastic deformations determine microstructural changes, diffusion phenomena, and mechanical properties of the final product (Lindemann *et al*., 2006). During the welding of aluminum with stainless steel, the rise of temperature in the bonding interface causes a large plastic deformation and flash formation in AA1050 aluminum. Part of the heat is dissipated into the flash and into the contacts of the materials with the components of the welding equipment.

As can be seen in Fig. 3, during the welding of AA1050 aluminum with stainless steel AISI 304, the initial temperature is higher in the peripheral region due to the higher tangential velocity, and then it extends to the centre of interface increasing with the heating time (t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9). After a given time, the difference between the temperatures is going to be very small, especially on the aluminum side that has a high thermal diffusivity (Lindemann *et al*., 2006). When the material reaches the critical temperature *Tc*, the material begins to undergo severe plastic deformation leading to formation of the flash, which dissipation is also responsible for part of the of heat generated by the process.

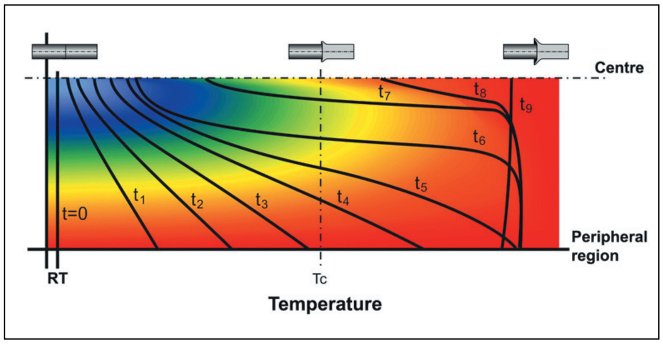

Figure 3. Distribution of temperature on the bonding interface: RT: room temperature; *Tc*: critical temperature. Source: Adapted from Fukumoto *et al*., 1997.

EXPERIMENTAL PROCEDURE

Materials and surfaces preparation

The materials used in this study were: AA1050 aluminum (commercially pure aluminum, 99.5%) and AISI 304 austenitic stainless steel. Both materials were machined with a diameter of 14.8 mm and lengths of 100 and 110 mm, respectively. After machining, they were subjected to be cleaned with acetone in order to remove organic contaminants, such as oils, greases, and so on. Tables 1 and 2 present chemical compositions and mechanical properties of the materials.

Friction welding equipment

A rotary friction welding machine, GATWIK brand, was used with fixed rotational speed of 3,200RPM, P_1=2.1MPa, t_1=32 seconds, P_2=1.4MPa and t_2=2 seconds. These parameters refer to welding procedures by friction between the related materials described in a previous paper (Alves, 2010a), optimized and qualified with the fracture occurring in the AA1050 aluminum, away from the bonding interface with the mechanical resistance superior of AA1050 aluminum (Alves, 2010b). Temperature in the bonding interface was also monitored with the heating time t_1 extended to 52 seconds for analysis and comparison of the curves and rates of warming and cooling during welding. The materials were placed as shown in Fig. 4.

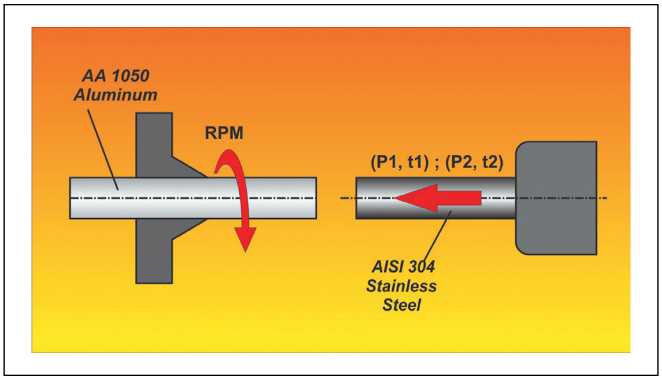

Figure 4. Schematic view of the materials placed before welding.

Table 1. Nominal chemical compositions of materials.

AA1050 Aluminum	Si(wt%)	Fe (wt%)	Cu (wt%)	Mn (wt%)	Mg (wt%)	Cr (wt%)	Zn (wt%)	Ti (wt%)
	0.07	0.26	< 0.001	-	< 0.001	-	< 0.002	< 0.007
AISI304 Stainless Steel	Si (wt%)	S (wt%)	P (wt%)	Mn (wt%)	C (wt%)	Cr (wt%)	Ni (wt%)	-
	0.38	0.024	0.036	1.67	0.054	18.2	8.0	-

Table 2. Mechanical properties of materials.

	Strenght σ (MPa)		Elongation ε (%)		Modulus of elasticity E (GPa)
	Yield	Maximum	Maximum	Fracture	
AA1050 Aluminum	44.70	78.48	21	43	59.12
AISI304 Stainless Steel	354.69	643.79	48	63	177.10

Temperature monitoring during friction welding process

Temperature is the most important parameter of a joint in the solid state by controlling the kinetics of thermally activated processes involved in diffused junctions. In the joints that occur at high temperatures, the atomic mobility increases and helps the movement displacement of atoms through the bonding interface (Bagnato, 2002).

As the temperature in the interface is directly related to the characteristics of the HAZ and with the strength of joints obtained by the RFW, its monitoring on a trial is extremely important for understanding the characteristics of this process.

For data acquisition, the TDL system was used, coupled to a notebook that provided real-time graph of the temperature during the process. We used a thermocouple type K (cromel-Alumel) measured and calibrated, ECIL brand, positioned on the pin of AISI 304 stainless steel, axial region, at a distance of 0.12mm of the interface (Fig. 5) and a data logger, brand NOVUS, with 16k of storage capacity, which allowed the collection of data in 0.5 second intervals during all the process. It was also used thermal paste of brand IMPLASTEC to improve the area of contact between the thermocouple tip and the surface of stainless steel pin. A total of five measurements was realized during the welding operation.

The TDL system was settled up by software in a Windows environment and it provides resources for collecting, plotting, analyzing, and exporting logs. Communication between the data logger and the notebook is realized in a few seconds via infrared optical non-contact (Alves, 2010a).

Figure 5 shows an illustration of the TDL system used for temperature monitoring in real-time (Alves, 2010a).

RESULTS

In welding tests, which were performed with temperature monitoring by the TDL system, the pins of AISI 304 stainless steel showed changes in the color of the surface near the bonding interface due to displacement of heat flow. Pins made from the AA1050 aluminum also show displacement of heat flows, but they are not visible on the surface due to the characteristics of the material.

The thermocouple fixed in the axial region of the cylindrical pin of AISI 304 stainless steel (Fig. 5) recorded a maximum temperature of 376 °C during the welding process in real-time of 34 seconds (Approach + t_1 + t_2), shown in Fig.6 (Alves, 2010a).

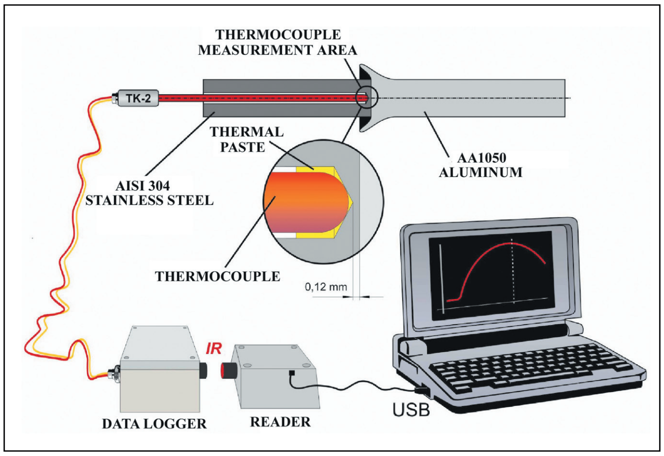

Figure 5. TDL system composed of K-type thermocouple, data logger, infrared (IR) reader IR, and notebook to monitor the temperature.

In the graph obtained, all phases of the welding process, the approach with a time of ten seconds, the first phase of heating with application of pressure (P_1=2.1MPa) at the time of 22 seconds, the second phase of forging with application of pressure (P_2=1.4MPa) at the time of two seconds, and the completion of welding were characterized.It was observed that when the rotational speed was stopped at the end of the first phase (point A – 376 °C), a drop in temperature during the forging phase (B – 350 °C) occurs, finishing the welding. Hence, the phase of cooling to room temperature starts.

This type of cooling does not interfere in the characteristics of the HAZ and the mechanical properties of the junction between the materials involved, mainly because the AA 1050 aluminum is not heat-treatable and has high purity (minimum 99.50% Al), which was proven by the results of the analysis and testing in this study. However, in the case of welding

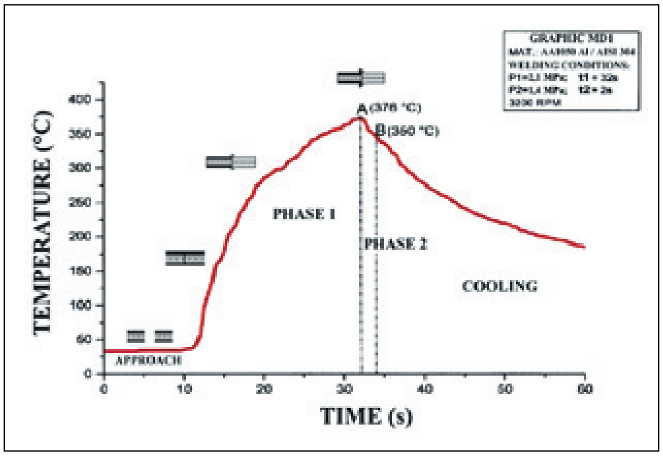

Figure 6. Graph temperature versus time – AA 1050 aluminum and AISI 304 stainless steel with total time of 34 seconds.

AISI 304 stainless steel with heat-treatable alloys (series 2XXX, 6XXX and 7XXX), the slow cooling can change the characteristics of the HAZ, as the proximity of the temperature values obtained in the bonding interface with the values used for heat treatment of solubilization and aging of these alloys (Alves, 2010a).

With time t_1 extended to 52 seconds, the process temperature with total time of 62 seconds (approach=eight seconds; t_1=52 seconds; t_2=2 seconds), using the same welding parameters of P_1 and P_2, there is an increase of temperature during the heating phase, and over time it was stabilized to the temperature of 410°C, point "A". After applying the pressure P_2 and the time t_2, the welding was completed with a temperature of 392°C, point "B". The air cooling performed at room temperature (30°C) showed similar cooling rates to the previous example (total time of 34 seconds). Figure 7 (Alves, 2010a) shows all process phases and temperatures monitored during welding of AA1050 aluminum with AISI 304 stainless steel.

Another important result of the analysis performed is that the maximum temperature monitored is within the range of the hot forging temperature of the alloy AA 1050, between 315 to 430°C (ASM, 1993). This knowledge allows the default parameters of RFW for a given diameter using data supplied by the graph, which allows to eliminate a series of preliminary stages in obtaining parameters for the welding of dissimilar materials.

In our observations, we found that although each welding parameter individually has its importance, the relationship between them and their subsequent phases result in the formation of a joint with good mechanical properties and ideal for an application.

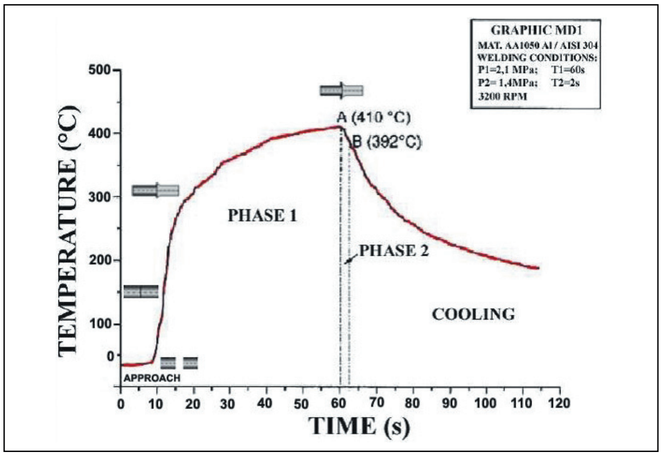

Figure 7. Graph temperature versus time – AA 1050 aluminum and AISI 304 stainless steel with total time of 62 seconds.

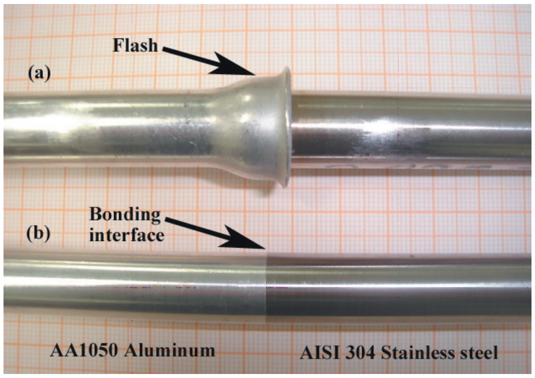

Figure 8. (a) shape of the flash in RFW; (b) bonding interface after machining (samples on graph paper)

In the heating phase, the relationship among the parameters (P_1 pressure, t_1 time, travel speed and rotational speed) aims at increasing the temperature at the bonding interface through the friction between the contact surfaces. This rapid increase in temperature with the constant application of pressure promotes a severe plastic deformation and removal of oxides and impurities through the flash, providing ideal conditions for the occurrence of the phenomenon of diffusion. In the early phase of forging, the temperature at the interface should have reached a certain level so that with the application of forging pressure P_2 in the time interval t_2, the union between the materials was successfully completed. If this relationship does not occur satisfactorily in the heating phase, and between it and the forging phase the cycle of welding ends, the layers of oxides and impurities can not be removed completely from the surfaces. The temperatures necessary for the occurrence of diffusion and forging may not be enough for the perfect union of the materials involved, resulting in a junction with poor mechanical properties. Figure 8 shows the flashes formed by plastic deformation and the bonding interface after the machining.

As the temperature at bonding interface is directly related to the mechanical resistance of the junction, prior knowledge can be used to optimize processes and parameters, reducing operating times and production costs, which are the key factors for growth and development of industries working with high productivity in an increasingly globalized world.

CONCLUSIONS

The temperature monitoring interface in real-time connection with the TDL system proved to be very efficient, because the results of this study showed the importance of characterization of all phases of the process in real-time by means of curves time versus temperature.

The temperature monitoring during welding tests as used parameters recorded the maximum temperature of 374 °C. This result confirmed that the temperature at the bonding interface during welding coincides with the range of hot forging of AA1050 aluminum (315-430 °C), as quoted in the literature (ASM, 1993).

The highest rates of heating occurring in the first ten seconds of the first phase of welding (heating phase) tend to stabilize as a function of deformation and plastic flow of the AA 1050 aluminum.

Knowing the temperature curves for certain joints between dissimilar materials, they can be used to obtain optimization and qualification of parameters, reducing stop times for equipment set up in different tests that involve RFW, machining, and mechanical testing.

The results of this study were of fundamental importance for understanding and comprehending the RFW, allowing the characterization of the different phases that involve this process and observation of heating and cooling rates. This knowledge will allow the opening of new lines of research, optimization, cost reduction, and increased productivity.

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