DEVELOPMENT OF AN EXPERIMENTAL PROCEDURE TO ANAYLSE THE TEMPERATURE FIELD IN THE WELDED JOINT OF STRUCTURAL STAINLESS STEEL

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Abstract

In this work, an experimental procedure to determine the temperature distribution in sheet butt-welded joints has been established. Related to light structures, the experiments are focussed on stainless steel elements welded by GTWA procedure. The proposed methodology lets the authors analyze the influence of welding parameters on the heat affected zone. The experimental method can be applied to other types of structural steels and arc welding processes.

Keywords: Temperature field, electric arc welding, metal structure, stainless steels

1. Introduction

The metallic structure is a design and construction alternative which over the last few decades has been developing into a structural solution. Nowadays its use has been fully consolidated. The variety of industrial applications of welding systems have led them to substitute the traditional nuts and bolts and rivets in the construction sector, not just because welding is an easier and faster operation, but also because the draughtsman can combine sheets, plates, bars, tubes, profiles etc. limitlessly, to apply a great number of design possibilities which will enable to improve the relation between resistance/weight and stiffness/weight with greater economic viability (Benhayon, 1994).

Stainless steels are very important in the construction of equipment for the process industry as well as for building. These steels are used instead of conventional ones due to their excellent properties, such as: resistance to corrosion, hardness as low temperatures and good properties at high temperatures.

The high resistance to corrosion of stainless steels is due to the passivation which they go through with the formation of a surface film of impermeable chrome oxide which isolates the steel from the corrosive medium.

Stainless steels have a thermal conductivity lower than that of carbon steels, which leads, in comparative terms, to more pronounced temperature gradients and greater permanent deformation. Applied to the welding operations, a slower diffusion of the heat through the base metal represents that the welded zone will remain hot for a longer time and permits the possibility of precipitation of chromium carbides on the grain edges if the transition from 800ºC to 500ºC during cooling is not carried out sufficiently rapidly. Moreover, due to the greater concentration of the heat in the zone of the bead, less heat is required to produce the fusion, as compared to the welding of ordinary construction steels; which means that in similar conditions, the welding speed can be greater (Gomez de Salazar, 2003).

In relation to the coefficient of thermal dilatation, this is much higher in stainless steels than in carbon steel, which generates a greater complication for their welding, from the point of view of deformations and residual tensions after cooling (Mazur et al., 2002).

In electric arc welding processes, the energy is applied in a localized zone, reaching temperatures far superior to the fusion temperature of the base material. The large temperature differences which are established between the zone where heat is applied and adjacent zones, together with the good thermal conductivity, in general, which the metals to be welded show, originates an important thermal flow which conditions the behavior of the welded structures, modifying the properties which result, both in the weld bead as well as in the zones near to it. When the harmful effects that the thermal cycle of the welding can produce in the welded piece are analyzed, the interest does not lie necessarily in the zone of fusion or the bead, but also in the zone near to this, denominated the heat affected zone (HAZ), which usually presents a greater degree of weakness in its mechanical properties than the bead itself. Therefore, knowledge of the evolution of the temperature in the vicinity of the weld bead, during the welding process and in the cooling process, is essential in order to determine the degree to which the material is affected and serves to establish strategies which minimize these thermal effects, such as using preheating, post-welding thermal treatments, the positioning of hot points, etc.

The principal results that can be determined with the experimental thermal analysis are the evolution over time of the temperature field in any point of the pieces to be welded, as well as the isothermal map of any instant during the welding process. The corresponding effects of the temperature on the material are quantified in different conditions (González et al,2006; Mazur et al, 2002; Alhama et al, 2005).

The present study analyses the results of the temperature field of a welded joint of AISI 304 structural stainless steel by means of the TIG technique without the contribution of material.

2. Materials

The material tested experimentally is AISI 304 austenitic stainless steel, X5CrNi18-10 according to the UNE norm (Aenor, 2006). The fusion point for this steel is estimated to be at 1400º C and the chemical composition of the steel tested is indicated in table 1. In tables 2 to 4 the physical properties are shown (Aenor, 2007); the variation in mechanical properties with the temperature; and the thermal properties at different temperatures. The test-tubes used for the tests are 75 mm long and 30 mm wide, the thickness varies depending on the test carried out.

	I	N				R	I
.07 %	%	%	.045 %	.015 %	.11 %	8 %	%

Table 1: Composition of the AISI 304 steel.

Density	Thermal Conductivity	Thermal Capacity	Electrical Resistivity	Magnetizable
7.9 kg/dm^3	15 W/m K	500 J/ kg K	0.73 Ω .mm^2/ m	No

Table 2: Physical properties of the AISI 304 steel.

Temperature (º C)	20	100	200	300	400	500
Elasticity Modulus(GPa)	200	194	186	179	172	165

Table 3: Values of the elasticity modulus for the AISI 304 steel at different temperatures.

Temperature º C	100	200	300	400	500
Thermal Dilatation C.(10^{-6} K^{-1})	16	16.5	17	17.5	18

Table 4: Thermal dilatation coefficient of the AISI 304 steel at different temperatures.

3. Welding Procedure

The welding procedure used is that of electric arc with protection by inert gas and non-consumable electrode or TIG procedure, also denominated GTWA, habitually utilized for the welding of stainless steels. As the protection gas, commercial argon C-50 has been selected, supplied by Carburos Metálicos. The volume of gas utilized is 12 l/min., and the welding has been done without contribution material. The welding has been carried out "in position", that is to say, in a horizontal position. The electrode employed is made of thorium-lanthanum of 1.6 mm in diameter, with a fusion point estimated to be at 4000ºC. The type of current selected is continual with direct polarity. At all moments the point of the electrode has been guaranteed to be sharp according to the established norms for the type of current employed to maintain the arc stable. A small electrode diameter has been selected in order to concentrate the arc and obtain a reduced fusion bath. The zone of the welded joint was superficially prepared with a brush with stainless steel bristles to eliminate any type of surface oxidation which might complicate the stability of the electric arc during the welding. Finally, to eliminate possible

traces of dirt from the base material, acetone was used to clean the area to be welded. Due to the thickness of the plate, the welding could not be carried out without preparing the edges.

The welding variables considered are indicated in table 5.

I	A	Intensity of the current
V	V	Voltage
e	mm	Thickness of the plate
v	m/s	Lineal velocity of welding

Tabla 5.Experimental welding variables.

4. Description of equipment and instrumentation

4.1. Thermocouples

Initially, type K thermocouples were used encased in a sheath of stainless steel, figure 1, although finally the measurements were made with type K thermocouple wire to increase the response speed. To improve the contact between the tip of the thermocouple and the base material, the plate was drilled to insert the wire, as can be seen in figure 2.
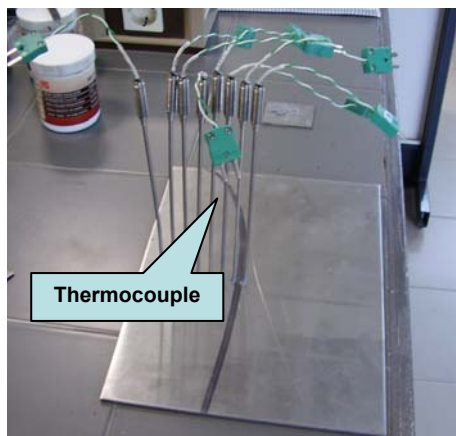
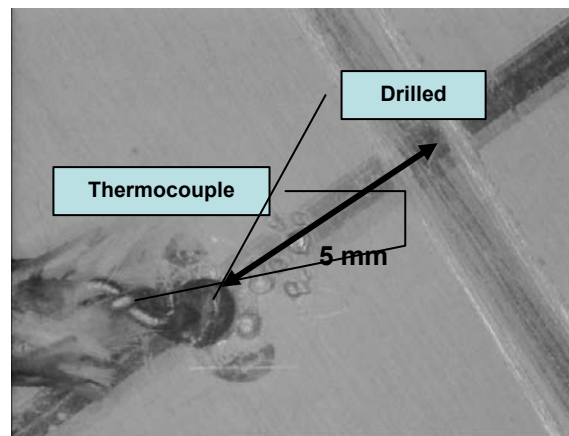Figure 1: Encased thermocouples.   Figure 2: Thermocouple Position.

To measure the real distance between the drills made on one side of the bead, a profile projector has been used. Figure 3 shows three drills of 1 mm made in one of the tests to insert the thermocouples.

4.2. Temperature logger

For the measurement of the plate temperature a USB TC-08 logger for thermocouples has been employed, connected to a PC which permits compiling, analyzing, and visualizing the data from eight channels. Moreover, the data logger offers connection through USB port. To log all

the temperature data that are registered with the TC-08, we utilized Picolog commercial software for Windows 5.15.6. It has a wide range of temperature scales, with a vertical resolution of 20 bits.
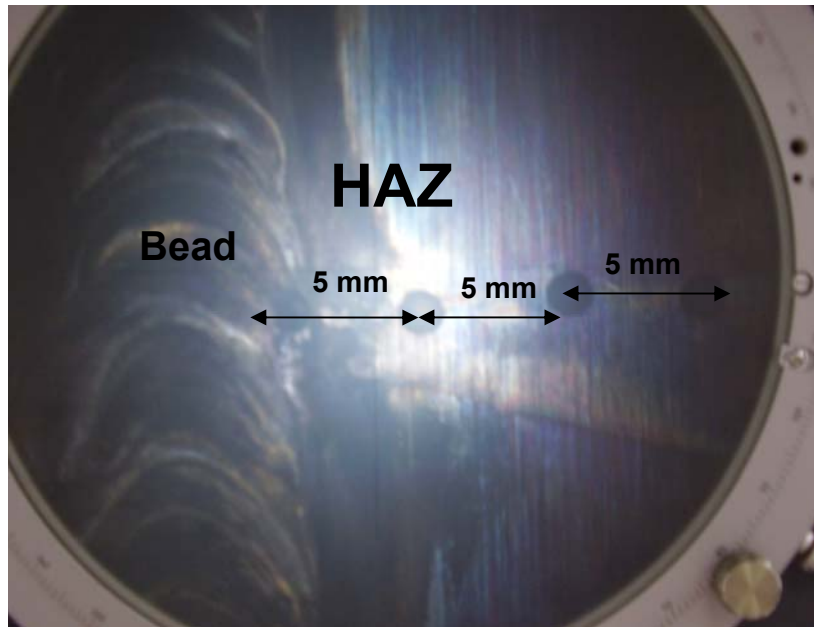

Figure 3: Distance thermocouples-bead.

4.3. Welding equipment

The equipment employed (figure 4) is a transformer-rectifier; model MAGIC WAVE 2600, made by Fronius. This equipment permits the execution of manual TIG welding, as well as with coated electrodes and allows the possibility of choosing the type and polarity of the current. The electricity tension is rectified by means of transistors and the control is Fuzzy type.

4.4. Control of the welding speed

To maintain a constant welding speed a milling machine has been used with a tool made expressly to house the welding machine's torch fitted into the head. In this machine we can select several forward velocities and thus consider that as a test variable (figure 4).

4.5. Support for the base material

To carry out the tests a wooden support has been produced to hold the plate and thus avoid deformations during the welding. The support is housed on the milling machine table. Wood has been chosen for the support in order to avoid the existence of heat losses by conduction.

5. Description of the test method

The tests are initiated with the preparation of the base metal to be welded, as indicated in section 2. The following step consists in positioning the thermocouples in the base metal. It must be ensured that the thermocouple remains in contact with the base metal in order to

guarantee the correct measuring of the plate temperature at all times. Different methods have been adopted for the positioning of the thermocouples but finally that indicated in figure 1 has been selected. To guarantee the contact during the initial manipulation of the plate, adhesive resin has been employed.
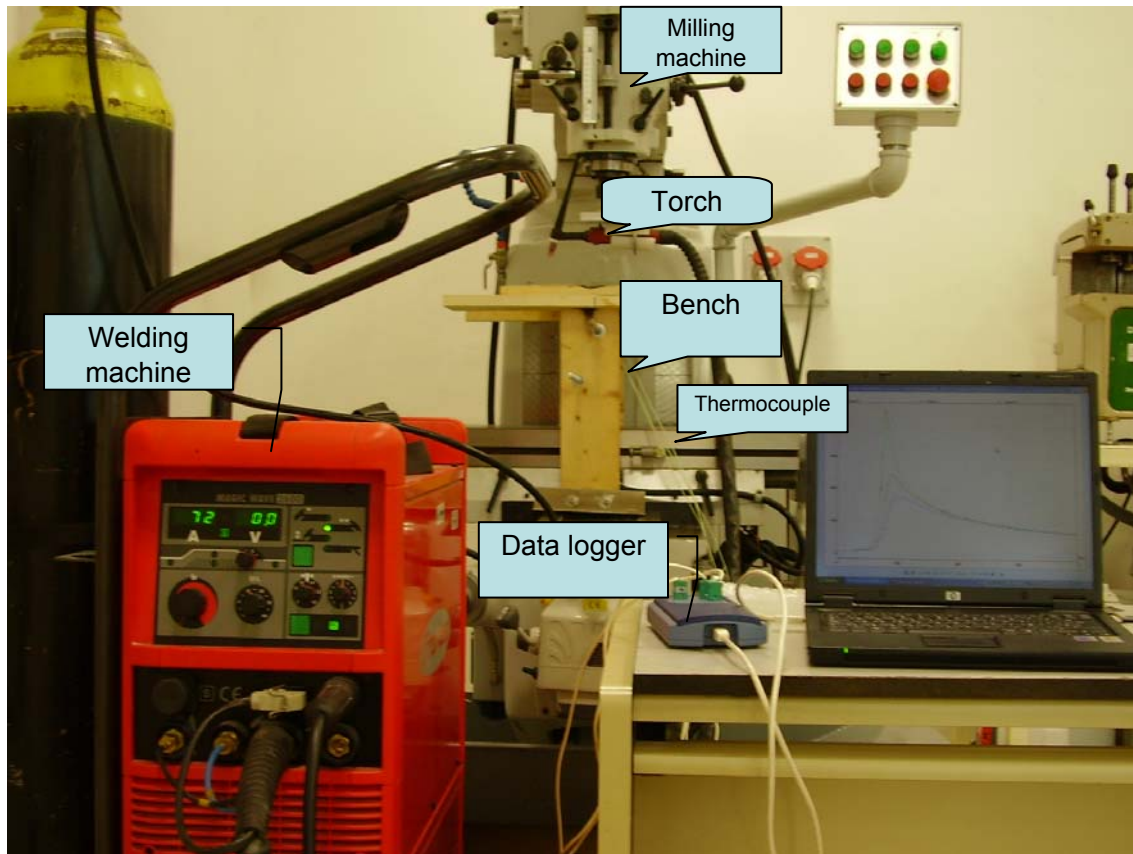

Figure 4. Experimental equipment.

Next, the base metal is placed in the wooden support and held in place by clamps to thus avoid deformation of the plate. All this is then finally placed on the milling machine table and bolted into place.

Following that, the TIG torch is positioned by means of the corresponding tool to the head of the milling machine. Then the mass clamp is placed on the metal to be welded, the gas volume and the intensity of the welding current are regulated, the velocity of movement of the milling machine table is programmed, and finally the thermocouples are connected to the data logger, which is in turn connected to the PC.

Once the test set is prepared, the arc is charged, the feed velocity is switched on (milling machine table) and the test commences. While the weld bead is made the temperatures are recorded. Finally, the data obtained are exported to a spreadsheet for later analysis.

6. Results and Discussion

6.1. Preliminary Tests

To fine-tune the test method, initially the first experiments were carried out with eight thermocouples encased in a sheath of stainless steel. With this system it was detected that the

thermocouples furthest from the weld bead scarcely varied in temperature and that, moreover, the highest temperature registered by said thermocouples did not surpass 500º C, as can be seen in Figure 5.
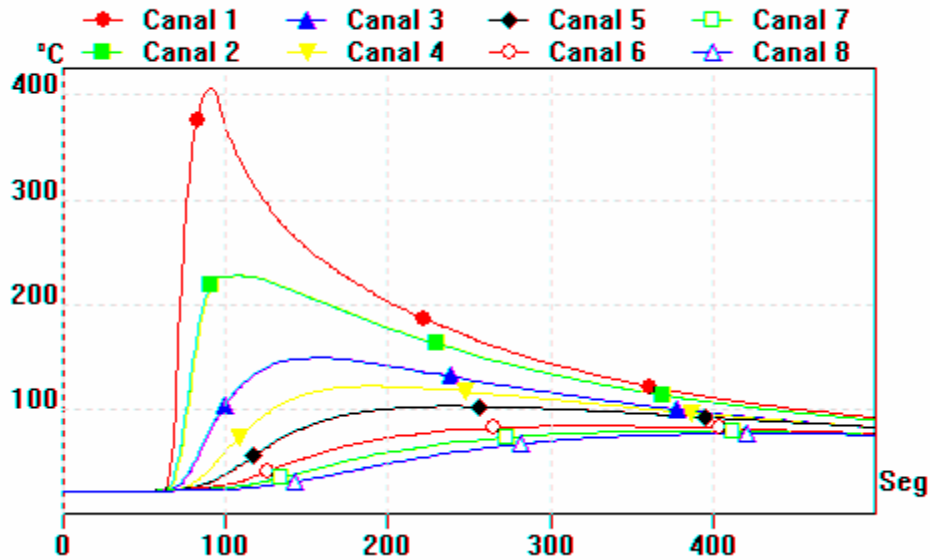

Figure 5. Result of the test with 8 thermocouples (preliminary tests). Registers temperature-time.

In addition, in order to be able to move the plate towards the encased thermocouples, a tool was designed made in aluminium (figure 6). This tool was excessively rigid and did not allow for compensating the deformations which are produced in the plate during the welding process. Thus, contact between the thermocouples and the plate was lost, and non-real temperate readings were obtained.
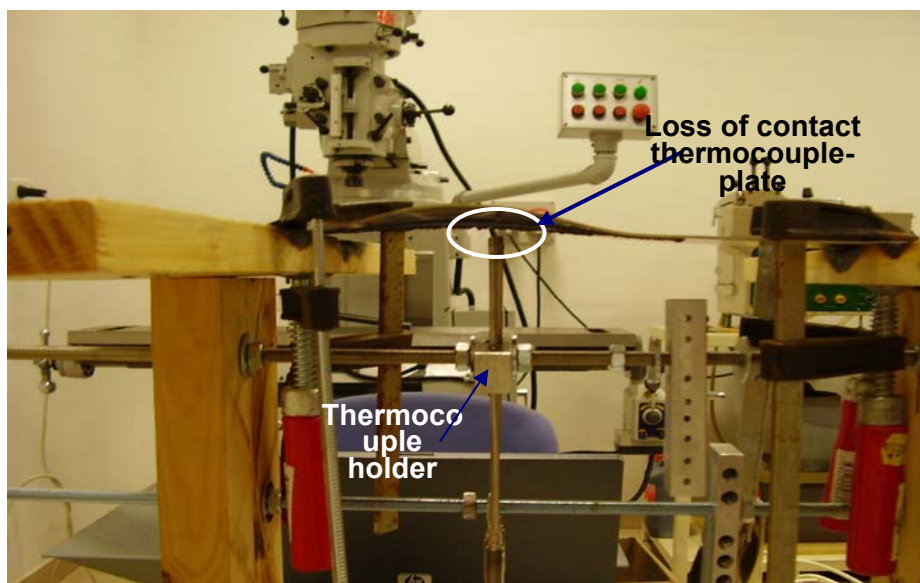

Figure 6: Tool used to hold the encased thermocouples (preliminary tests).

6.2. Final tests

Table 6 indicates the welding variables considered in the two tests carried out with the final procedure.

	Test I	Test II		Description
I	79	120	A	Intensity of the current
V	15	20	V	Voltage
η	0.7	0.7		Yield of heat contributed
EBA	3.485	5.263	kJ/mm	Gross Energy Contributed
e	2	4	mm	Plate thickness
v	0.0034	0.0034	m/s	Lineal weld velocity

Table 6. Experimental welding variables.

In figure 7 the temperature values registered according to time at 5, 10 and 15mm distance from the axle of the bead and the weld are represented. A cooling time of 200 s is considered, which corresponds to the time in which the temperatures at the different points become the same.
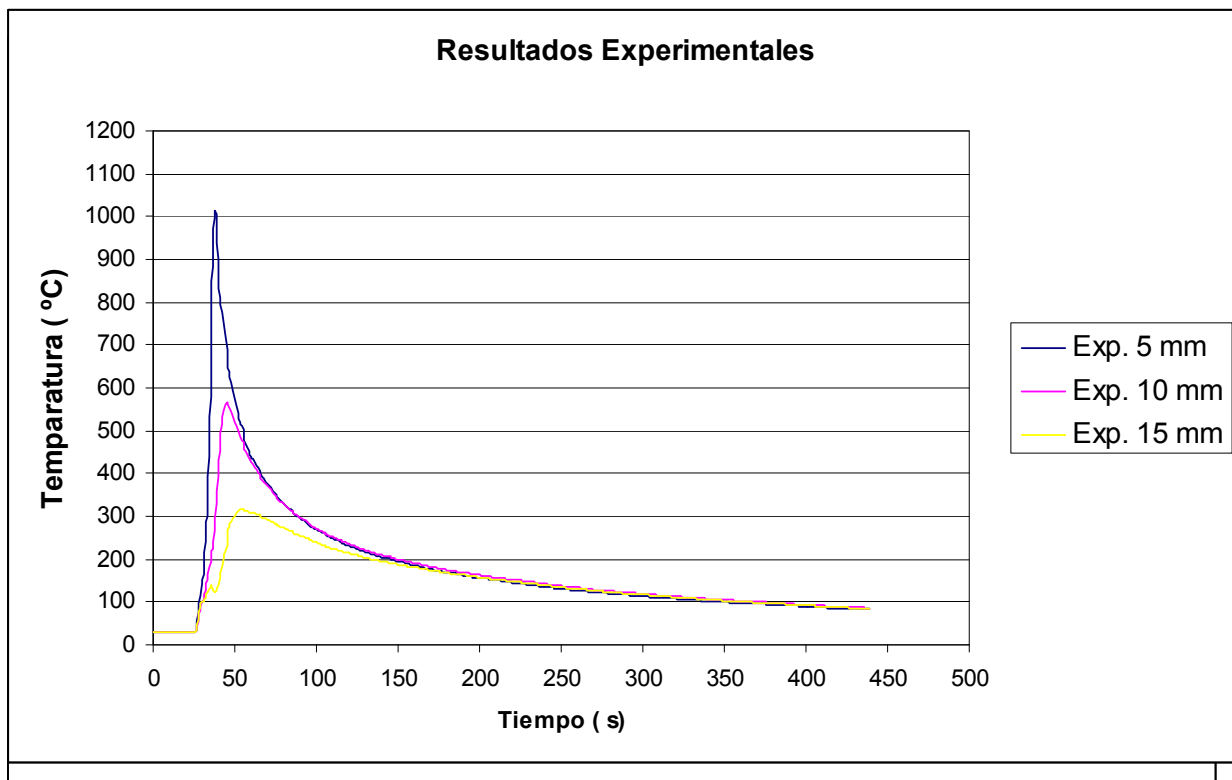

Figure 7. Experimental results test 1.

One of the important parameters to determine in welded joints of stainless steels is the time taken between the temperatures of 800 and 500ºC during cooling, that is to say, the well-known t $_{8/5}$. The determination of this parameter is shown in figure 8.
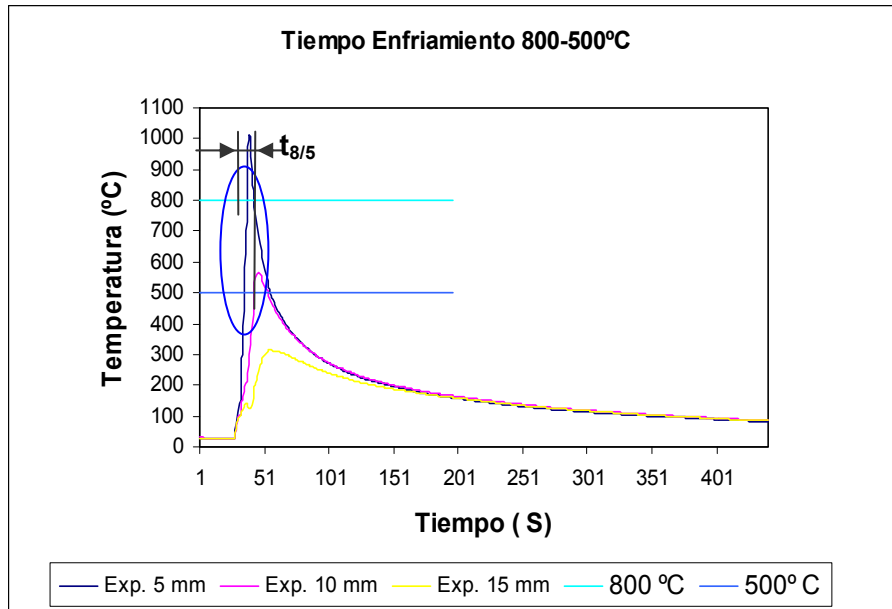

Tiempo Enfriamiento 800-500ºC

Figure 8. Determination of the parameter t $_{8/5}$.

The tests allow to also determine the variation of the temperature with the distance from the weld bead, as is indicated in figure 9.
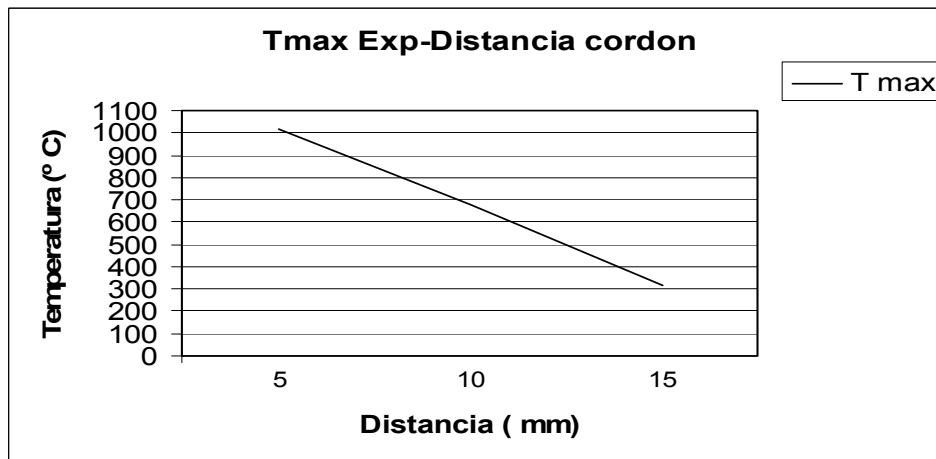

Tmax Exp-Distancia cordon

Figure 9: Variation of the values of maximum temperature with the distance to the weld bead.

In figure 10 the experimental results from Test II can be seen, according to the parameters from table 6. In this test, the thickness of the plate and the intensity of the current have been modified. It can be observed that, although the intensity employed has been greater than in the previous test, the maximum temperature reached is considerably lower. This demonstrates the sensitivity of the phenomenon to the plate thickness, which, being greater in this case,

generates greater thermal dissipation acting as a thermal cooler. In this last case one more thermocouple has been considered, so that a greater distance to the main bead has been analyzed (fourth thermocouple).
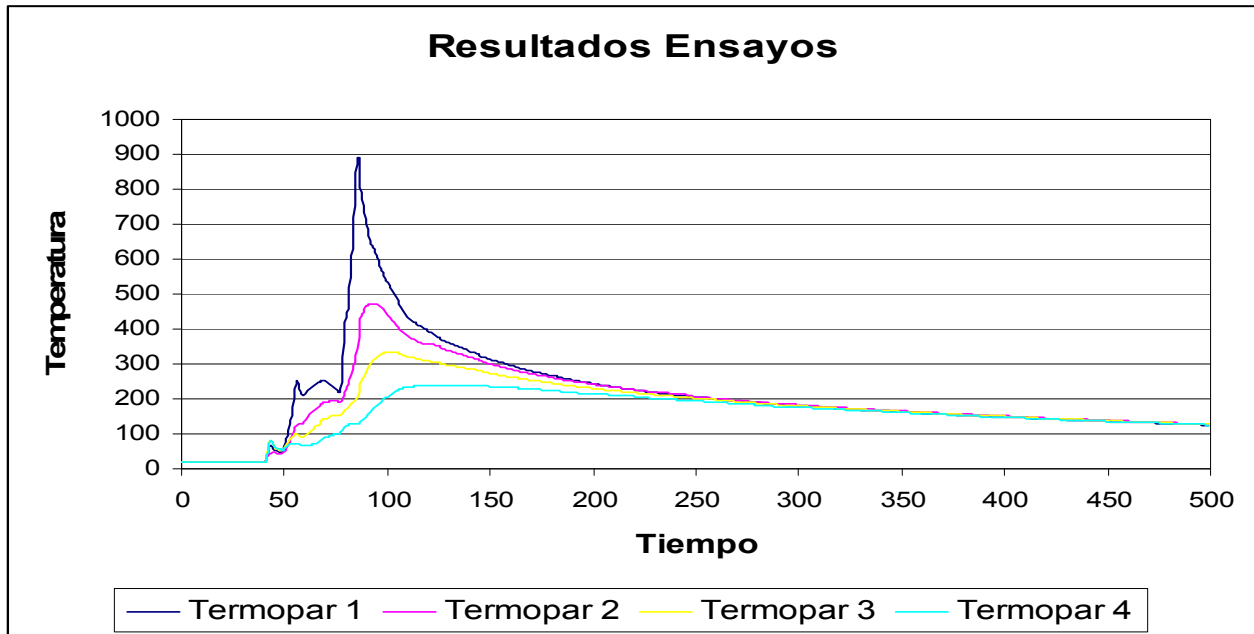

Figure 10. Registers for temperature time for an intensity of current of 120 And a plate thickness of 4 mm.

7. Conclusions

An experimental procedure has been designed to calculate the distribution of temperatures in the zone adjacent to the weld bead of a structural stainless steel.

It has been seen that it is more adequate to measure the temperatures in the zone of the weld bead by means of type K thermocouple wire, since thermocouples encased in a sheath of stainless steel do not provide good results due to the elevated thermal inertia of the cover.

During the welding time an important increase occurs in the temperature in the zone of the joint, this produces a deformation of the base material. With this experimental analysis the temperature in the HAZ can be calculated in order to reduce the deformation of the base material.

By means of this analysis of the temperature field, the dimension of the HAZ can be calculated.

The data obtained with these tests can serve to validate the calculation of the HAZ with a numerical method.

This experimental procedure can be used for other types of steel and for other welding procedures by electric arc such as MIG/MAG.

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