Meas. Sci. Technol. 18 (2007) 877–883 doi:10.1088/0957-0233/18/3/041

Temperature field acquisition during gas metal arc welding using thermocouples, thermography and fibre Bragg grating sensors

P M G P Moreira[1], O Frazão[2], S M O Tavares[1], M A V de Figueiredo[1], M T Restivo[1], J L Santos[2] and P M S T de Castro[1]

[1] IDMEC and Faculdade de Engenharia da Universidade do Porto, Porto, Portugal
[2] INESC Porto and Departamento de Física da Faculdade de Ciências do Porto, Porto, Portugal

E-mail: pmgpm@fe.up.pt

Received 23 October 2006, in final form 7 January 2007
Published 5 February 2007
Online at stacks.iop.org/MST/18/877

Abstract
The paper presents the application of temperature acquisition systems integrating thermocouples, a thermographic camera and fibre Bragg grating (FBG) sensors in gas metal arc welding (GMAW) process, MIG (metal inert gas) welding type. Efficient procedures to use FBG sensors and thermocouples were developed. The paper presents and compares measurements made in welded plates of aluminium alloy 6082-T6. Tests were performed in both plate surfaces and good agreement between the three techniques was found.

Keywords: metal inert gas welding, thermocouples, thermography, fibre optic Bragg sensors

(Some figures in this article are in colour only in the electronic version)

1. Introduction

This study was performed in order to develop effective systems of temperature acquisition during an aggressively high heat flux welding process such as gas metal arc welding (GMAW), MIG (metal inert gas) welding type [1]. The arc and the weld are protected from atmospheric contamination by a gas shield. An electric potential is established between the electrode and the work piece causing a current flow, which generates thermal energy in the partially ionized gas [2].

Three different temperature acquisition systems were analysed, integrating thermocouples, thermographic equipment and fibre Bragg grating (FBG) sensors. Two different sets of tests were carried out. In the first tests temperature was acquired on the plate surface opposite to the weldments using thermocouples and a thermographic camera. In the second set of tests temperature was acquired using thermocouples and FBG sensors on the arc weld side of the plate.

An effective technique to use FBG sensors during welding was developed. Two different types of thermocouples and techniques for their connection to the plates were also tested.

The literature on welding process monitoring includes the synergic use of different thermographic methods by Meola *et al* [3]. Camilleri *et al* studied the alternative simulation techniques for distortion of a thin plate due to fillet-welded stiffeners, where temperature gradients were measured with thermocouples and a thermographic camera [4]. Another example of the applicability of thermographic techniques in welding is presented by Doong *et al* [5], investigating the feasibility of using infrared sensing devices to measure the surface temperature variation near the molten pool and to correlate this temperature variation with the changes in welding parameters.

2. Welding process

Weldments were deposited on 10 mm thick 500 × 300 mm^2 aluminium alloy 6082-T6 plates. The MIG welding parameters used were as follows: 170 A, 26 V, 60 cm min^{-1} and argon at a 22 l min^{-1} flow. A filler wire with the designation ESAB OK Autrod 18.15 with a diameter of 1 mm [6] was used. Welds were performed using an automated welding robot, GMF ROBOTICS—Arc Mat Sr.

Different sets of tests were performed to acquire temperatures on the plate top and back surface. The top surface is defined as the surface where weldments were deposited, and the back surface is the opposite surface. Temperatures were only acquired at the surfaces in order to use these welded plates in future mechanical tests.

3. Thermocouples

Thermocouples are popular transducers used for temperature measurement due to their large temperature range, stability and low cost. Using thermocouples a large number of points can be monitored.

Thermocouples are often welded to a metal part or clamped under a screw. They can be manufactured, for example, by silver-soldering or welding. When the thermocouple wires are soldered together, a third metal can be introduced into the thermocouple circuit, but as long as the temperature of the junction is uniform an error is not introduced [7]. To reach a higher measurement temperature, the joint must be welded. Since commercial thermocouples are high cost sensors, they are welded on expensive machinery using a capacitive-discharge technique to insure uniformity; the thermocouples used in these tests were manufactured in our laboratory. To weld the thermocouples wires a capacitive-discharge was built and several manufacturing techniques, including oxyacetylene flame, were tested.

Type K thermocouples (chromel alumel) were used in all tests. They are the most commonly used thermocouples and support oxidizing atmospheres. Their working range is from –200 °C up to 1100 °C, although above 800 °C oxidation causes drift and de-calibration. Thermocouples of K type have a sensitivity of 40.44 μV °C^{-1}. Thermocouples with 0.2 mm and 0.08 mm diameter were tested.

The response time for a thermocouple is defined as the time taken for the thermal voltage to reach 63% of maximum for the temperature at the moment [8]. It is dependent on the thermocouples diameters and lengths, and tip configuration. Thermocouples with grounded junctions display response times some 20% to 30% faster than those with insulated junctions. Very good sensitivity is provided by fine gauge unsheathed thermocouples. With a conductor diameter in the range of 0.025 mm to 0.81 mm, response times in the region of 0.05 to 0.40 s can be realized.

In this work AD 594's ICs from Analog Devices are used as complete instrumentation amplifiers for thermocouples of K type with cold junction compensation and a gain of 247.3 (10 mV °C^{-1} divided by 40.44 μV °C^{-1}) for measuring and amplifying the thermocouple f.e.m. [9]. The signal from each thermocouple conditioning circuit is then the input signal in a PC using a Spider 8 system. The circuit that makes the interface between the thermocouples and the Spider 8 was built in our laboratory.

4. Thermography

Thermography gives an overall thermal picture of the welded plate providing a remote observation of surface temperature distribution [10]. The thermographic working principle is based on capturing infrared emission from the part under study [11]. It involves determining the spatial distribution of thermal energy emitted from the surface of an object. This technique allows mapping of the temperature distribution and can be used in conjunction with software analysis to provide quantitative information. Thermography is a non-intrusive technique that can show reasonably fine detail where the pattern of radiant energy from a prescribed area of the object in question is scanned continuously. The radiant energy is converted to an electrical voltage with a suitable detector and this voltage is then available for further processing. It can, however, be expensive and the uncertainty is a function of the knowledge of surface emissivity and the transmission path. The temperature range covered by thermal imaging systems is of the order of −40 °C to 2000 °C. The thermal energy radiated from a body is dependent on its temperature and its surface emissivity.

The aluminium plate surfaces were spray painted matt black prior to welding in order to have a radiating surface with a black body emissivity near unity (perfect absorber). A FLIR ThermaCam PM575 was used.

5. Temperature measurements in the plate surface opposite to weldments

Temperatures were acquired at three points on the plate surface opposite to weldments using thermocouples and a thermographic camera. These points were positioned just under the weldments line. Thermocouples were placed at the plate surface. For their connection to the plate a spring effect capable of preventing any displacement throughout the measuring process was created. Thermocouple 2 was placed at the middle length of the welding line and the other thermocouples (1 and 3) were placed at a distance of 15 mm before and after thermocouple 2.

A thermographic camera was positioned behind the plate with three spots located in the same place as the thermocouples. The result obtained with the thermographic camera when the heat source is under point 2 is presented in figure 1(*a*). The interpretation of the temperature distribution is achieved by post-processing and conversion to a three-dimensional (3D) plot presented in figure 1(*b*).

Thermocouples with two different diameters 0.2 mm and 0.08 mm were also used in this test. Thermocouples were manufactured in-house testing different techniques to fuse the thermocouple junction: oxyacetylene flame, and electrical discharge using different contact materials. Also, different solutions to connect the thermocouples to the plates were tested.

Firstly, thermocouples of 0.2 mm diameter were tested. With this type of thermocouple and testing several techniques to fuse the thermocouple junction the difference between maximum values obtained with the thermographic camera and

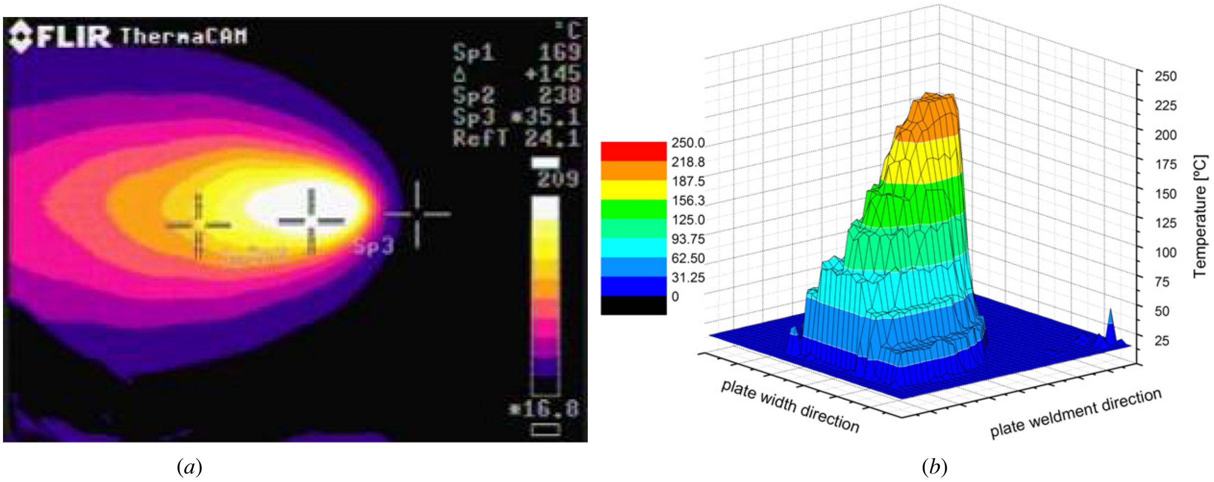


Figure 1. Thermographic temperature distribution at the second point: (*a*) thermographic plot, maximum temperature 238 °C; (*b*) 3D plot of temperature distribution.

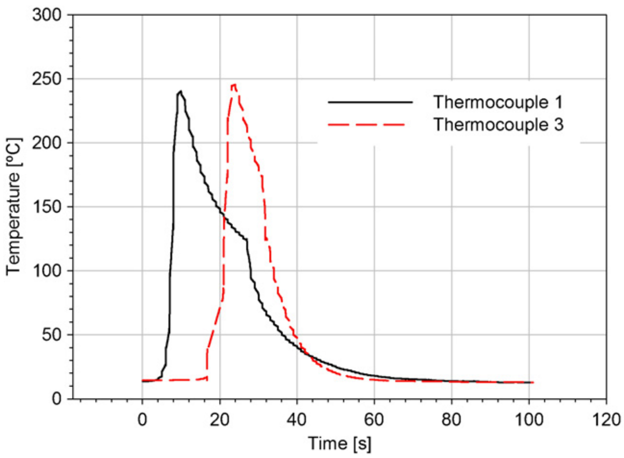


Figure 2. Temperature time function measured with thermocouples.

the thermocouples was of the order of 30 °C to 60 °C. This result can be explained by the high response time of these thermocouples. Their response time is too slow to follow the high rate temperature changes due to the welding process speed and to the high thermal conductivity of aluminium (170 W m^{-1} K^{-1}).

Thermocouples with 0.08 mm diameter gave better results. Electrical insulation of the thermocouple was achieved by protecting its measuring part with a thin cladding of cyanoacrylate glue. Since measurements were made at the plate surface, to compensate any measuring delay due to the cyanoacrylate glue, the thermocouple junction that was in connection with the plate were covered by a silver-based compound (silver, zinc oxide, aluminium oxide and boron nitride particles) with a reasonable conductivity (8.89 W m^{-1} K^{-1}). The technique to fuse (weld) the thermocouple junction that gave the best results was to weld the junction wires in a mercury bath by an electrical discharge.

The best results were obtained with thermocouples of 0.08 mm diameter covered with a silver-based compound. Temperature distributions at points 1 and 3 are presented in figure 2. The result of a thermocouple placed under point 2 was disregarded in this test due to lack of electrical insulation.

Table 1. Measured temperatures.

	Acquisition system (temperatures)	
Point	Thermography (°C)	Thermocouples (°C)
1	231	240
2	238	Disregarded
3	247	245.2

A comparison between maximum temperatures in each point acquired with termography and thermocouples of 0.08 mm diameter is presented in table 1. A good agreement between both techniques was found.

6. Fibre Bragg grating sensors

A FBG is a periodic modulation of the refractive index of the core of a single mode optical fibre [12]. Many FBGs with different resonance wavelengths can be inscribed in a single optical fibre, the number being only dependent on the spectral width of the optical source used. Current technology allows this number to be larger than 50. One major advantage of using fibre optic sensors in welding processes where electrical currents are present is their immunity to electromagnetic interference.

In a work by Suaréz *et al* [13] a FBG sensor and a thermocouple were used to monitor a TIG arc welding process. In that work the FBG sensor was placed on the side of the plate opposite to the welding line and some difficulties due to the connection of the sensor to the plate are described.

A study to develop feasible techniques to use FBG sensors to acquire temperatures in welding procedures was carried out. In a first study FBG sensors were placed at four different locations, schematically represented in figure 3 (two details presented in figure 4). It was found that all lead to unsatisfactory results, since the fibres became damaged in cases 1 and 4, and the location was found unsuitable in cases 2 and 3.

In a second study, placing the sensors on the weldment plate side, the minimum distance to the welding line from which temperatures could be acquired was evaluated. Since

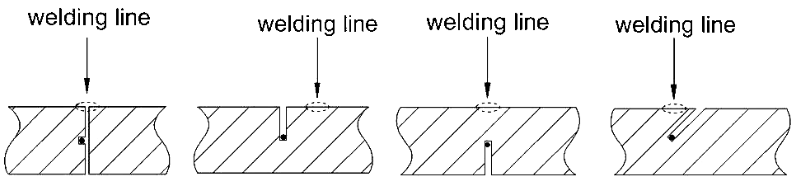


Figure 3. Locations where FBG sensors were placed in the first study (from left, cases 1 to 4).

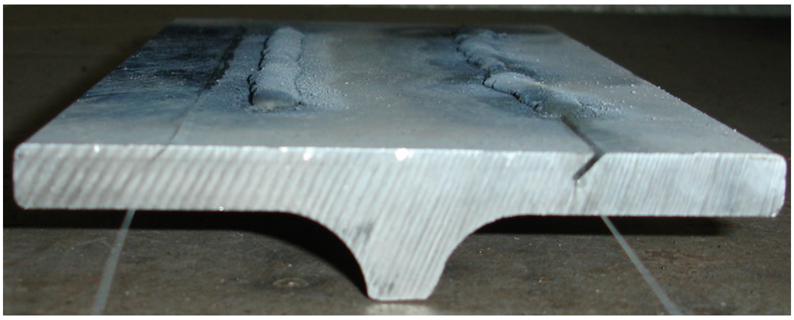
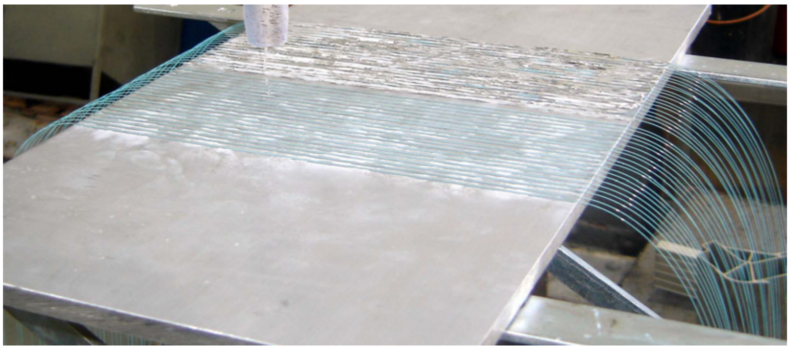
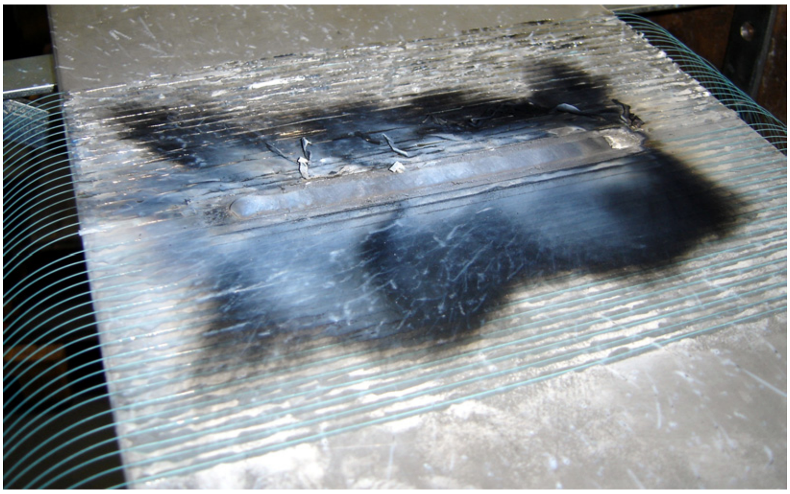


Figure 4. Example of a fibre placed at 10 mm parallel to the weld line and a fibre placed as in case 4 (figure 3).



(*a*)

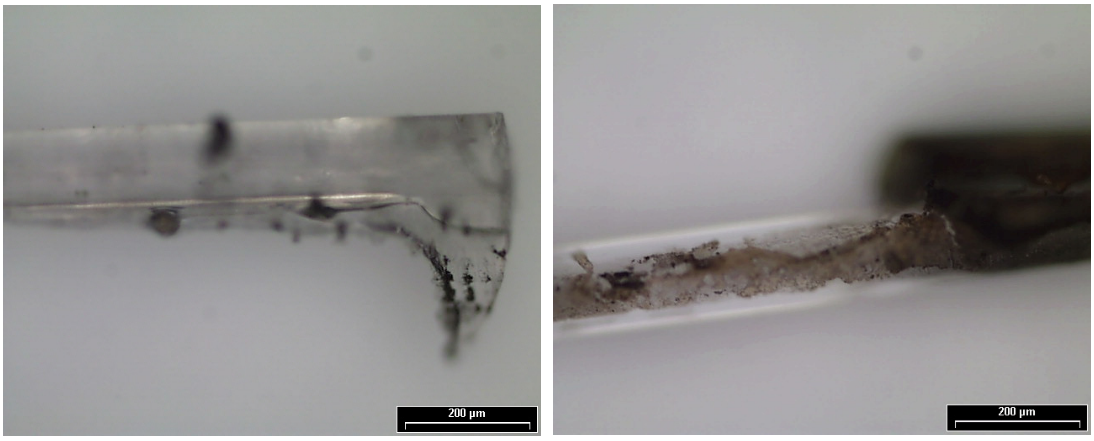


(*b*)

Figure 5. Welding test using epoxy glue and aluminium sheet stripes to protect the FBG sensors: (*a*) FBG sensors setup prior to welding; (*b*) FBG sensors setup after welding.

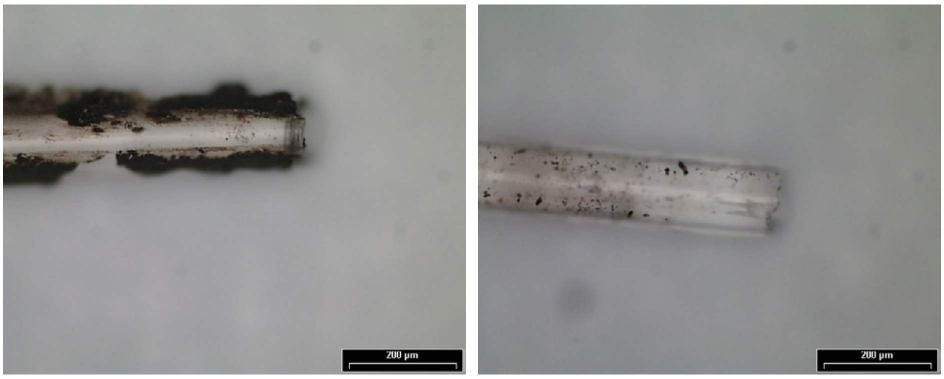
MIG is an arc welding process involving an aggressively high heat flux, unprotected and protected sensors using three different techniques were tested. The protection techniques were a cyanoacrylate glue, stripes of aluminium foil covering each sensor and a silicon based compound. The silicon based compound gave the best result. The result of a test using cyanoacrylate glue and stripes of aluminium foil is presented in figure 5.

In these tests, sensors were placed parallel to the weld line at distance multiples of 5 mm. With these



(*a*) (*b*)

Figure 6. Sensors protected with aluminium sheet stripes after welding: (*a*) damaged sensor (15 mm from welding line); (*b*) resistant sensor (15 mm from welding line).



(*a*) (*b*)

Figure 7. Sensors protected with cyanoacrylate glue after welding: (*a*) damaged sensor (10 mm from welding line); (*b*) resistant sensor (15 mm from welding line).

protecting techniques sensors were able to maintain integrity of measurement at a distance of 15 mm in the perpendicular direction to the weld line when covered with cyanoacrylate glue and aluminium stripes, and 10 mm when covered with the silicon based compound. Sensors placed near the weld line lost their measuring capabilities. A damaged (broken) and an undamaged sensor protected with aluminium stripes are shown in figure 6. A damaged and an undamaged sensor protected with cyanoacrylate glue are shown in figure 7.

In a third study, a silicon-based compound was used to protect the FBG sensors during welding. Tests where a silicon based compound was used gave the best results. Also, this technique permits a faster and easier test setup. A test setup using a silicon-based compound to protect the FBG sensors is shown in figure 8. In these tests the first sensor was placed parallel to the weld line at a distance of 15 mm and the following sensors were separated by 5 mm.

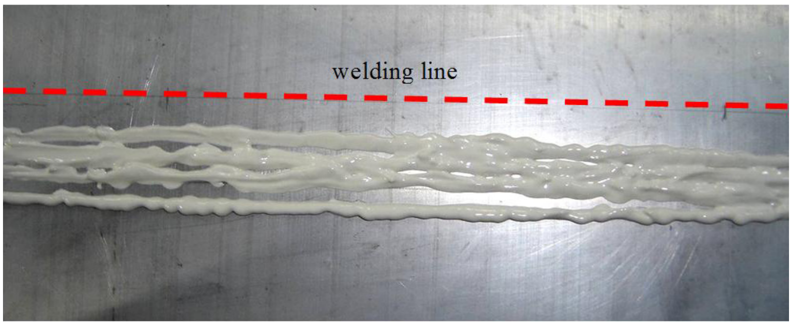
7. Temperature measurements in the plate-welded surface

After defining the best protecting technique for the FBG sensors, a benchmark exercise involving thermocouples and FBG sensors was performed. A weldment was deposited on a 500 × 300 mm and 10 mm thick aluminium alloy 6082-T6 plate and measurements were performed at a site at half of the welding line length. Temperature measurements in the welded plate side were performed at 15 mm in the perpendicular direction to the weldments. Thermocouples of type K with 0.08 mm of diameter protected by a silver-based compound were used. A covering layer of silicon-based compound was also used since temperatures were acquired at 15 mm from the weld line, as shown in figure 9. The brown stripes are used to create a spring effect which results in a permanent contact between the thermocouples and the aluminium plate.

The FBG sensors with a length of 30 mm were written in a hydrogen-loaded standard optical communication fibre (SMF 28) using an excimer laser. The Bragg wavelength peak at room temperature was at 1545 nm with reflectivity and spectral bandwidth at half maximum of ∼98% and ∼0.1 nm, respectively. FBG sensors were protected with the silicon-based compound.

A comparison of results obtained with both techniques is presented in figure 10.

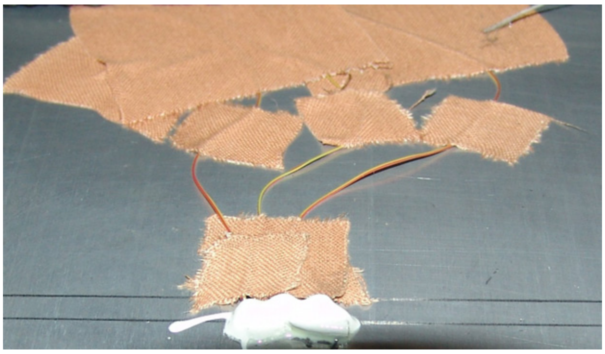
Results obtained with both measuring techniques present good agreement, particularly as concerns the maximum value. FBG results plotted in figure 10 correspond to one value



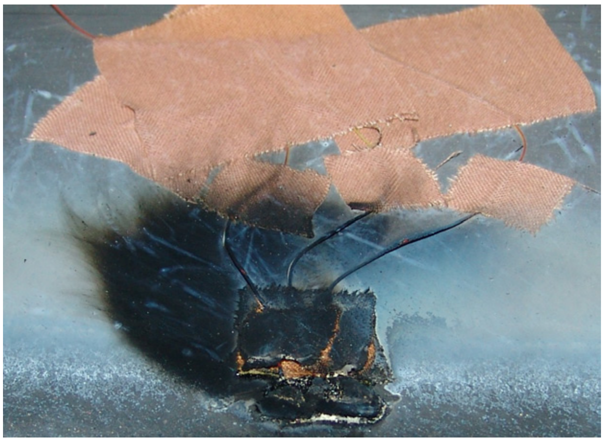
(*a*)

(*b*)

Figure 8. Welding test protecting FBG sensors with a silicon-based compound: (*a*) FBG sensors setup prior to welding; (*b*) FBG sensors setup after welding.



(*a*)



(*b*)

Figure 9. Thermocouple of 0.08 mm diameter covered with a silicone-based compound: (*a*) before a test; (*b*) after a test.

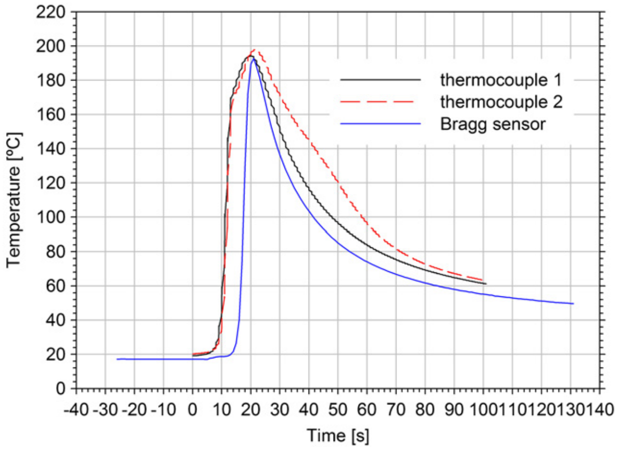


Figure 10. Temperature measured at 15 mm in a perpendicular direction to the welding line using thermocouples and FBG sensors.

per second, whereas thermocouple acquisition plots twenty values per second. Also, the FBG sensor grating was 30 mm long, implying that the presented result takes into account the difference in temperature along the 30 mm grating, which may justify the delay in the beginning of the acquisition. The results obtained suggest the possibility of using this new type of sensor to acquire temperature values in the aggressive conditions found in arc welding processes.

8. Conclusions

Three different temperature acquisition systems during GMAW welding were analysed: integrating thermocouples, a thermographic camera and fibre Bragg grating sensors. Weldments were deposited on 500 × 300 mm^2 and 10 mm thick aluminium alloy 6082-T6 plates.

Two different set of tests were carried out. In the first tests temperature was acquired on the plate surface opposite to the weldments using thermocouples and a thermographic camera. Thermocouples with 0.2 mm diameter and thermocouples with 0.08 mm were tested. Thermocouples with a diameter of 0.2 mm presented some 30 °C to 60 °C of difference with reference temperatures at around 250 °C. The best results were achieved with the 0.08 mm diameter thermocouples with their junction covered by thin cyanoacrylate glue cladding to insulate electrically the thermocouples from the plate. In this set of tests a comparison between maximum temperatures at each point acquired with thermography and thermocouples shows good agreement between both techniques.

In the second set of tests temperatures were acquired using thermocouples and FBG sensors on the weldments side of the plate. A feasible technique to use FBG sensors to acquire temperatures in welding procedures was developed. Sensors protected with cyanoacrylate glue, stripes of aluminium foil covering each sensor, and a silicon-based compound were able to maintain integrity of measurement at a distance of 15 mm in a perpendicular direction to the weld line. The silicon-based compound gave the best result and also permits a faster and easier test setup. Thermocouples were also used in these tests with effective measurements at 15 mm from the weld line. Results obtained with the FBG sensor and thermocouples present good agreement, particularly as concerns the maximum value. The results obtained suggest the possibility of using this new type of sensor to acquire temperature values in the aggressive conditions found on the arc weld side of the plate.

Acknowledgments

The work was partially supported by PhD scholarship FCT SFRH/BD/19281/2004 and FP6 project DaToN (contract no. AST3-CT-2004–516053 of the European Union).

References

[1] Air Products plc 1999 *Welder's Handbook, For Gas Shielded Arc Welding, Oxy Fuel Cutting & Plasma Cutting* Air Products plc, 3rd edn

[2] Wahab M A, Painter M J and Davies M H 1998 The prediction of the temperature distribution and weld pool geometry in the gas metal arc welding process *J. Mater. Process. Technol.* **77** 233–9

[3] Meola C and Carlomagno G M 2004 Recent advances in the use of infrared thermography *Meas. Sci. Technol.* **15** R27–58

[4] Camilleri D, Mollicone P and Gray T G F 2006 Alternative simulation techniques for distortion of thin plate due to fillet-welded stiffeners *Model. Simul. Mater. Sci. Eng.* **14** 1307–7

[5] Doong J L, Wu C S and Hwang J R 1991 *Int. J. Mach. Tools Manuf.* **31** 607–16

[6] ESAB Filler Materials 2003 *ESAB Welding Handbook—Filler Materials for Manual and Automatic Welding* 5th edn

[7] Kasap S 1990–2001 Thermoelectric effects in metals: thermocouples *Special Custom Published e-Booklet* S O Kasap, Materials and Devices Website for Scientists and Engineers (http://kasap3.usask.ca/)

[8] Labfacility 2004 *The Temperature Handbook* (Middlesex, UK: Labfacility Ltd)

[9] Analog Devices 1999 Monolithic Thermocouple Amplifiers with Cold Junction Compensation *Data sheet* Rev. c, C731g-0-11/99, USA

[10] ESDU 02006 2002 Temperature Measurement: Techniques

[11] Camilleri D, Gray T and Comlekci T 2004 Use of thermography to calibrate fusion welding procedures in virtual fabrication applications *InfraMation 2004: Proc. Infrared Camera Applications Int. Conf. held by Infrared Training Center and FLIR Systems, Inc. (Las Vegas, Nevada, 4–8 Oct. 2004)*

[12] Hill K O, Malo B, Bilodeau F, Johnson D C and Albert J 1993 Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask *Appl. Phys. Lett.* **62** 1035–7

[13] Suárez J C, Remartínez B, Menéndez J M, Güemes A and Molleda F 2003 Optical fibre sensors for monitoring of welding residual stresses *J. Mater. Process. Technol.* **143–144** 316–20