International Journal of Advancements in Mechanical and Aeronautical Engineering– IJAMAE
Volume 2: Issue 1 [ISSN : 2372-4153]

Publication Date : 30 April, 2015

Monitoring System of Temperature Field in Pipeline Subjected to Multi-Wire Submerged Arc Welding

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***Abstract*— The investigation focuses on particular aspects and features related to the spatial measurement of temperatures, in the case of longitudinal multiple-wire submerged arc welding of pipelines. The research methodology is based on the combination of traditional measuring methods of temperature, such as thermocouples and digital pyrometers, with modern methods, like infrared thermography technique. The infrared thermography method provides the temperature field distribution on the welded plate surface, while numerical methods give information on temperature in the entire welded joint, including on the plate thickness. The authors propose a dual monitoring system of temperature measurement in longitudinal welded pipelines which comprises K-type thermocouples and an infrared thermo-camera. The temperatures values are recorded through four devices (recorders) with different number of channels which continuously monitor the temperature in the welded joint. The thermo-camera is used to acquire the instantaneous values of the temperature and to visualize the heat field distribution on the bottom surface of the pipeline. The system is designed to be used in industrial applications for temperature monitoring of and further to predict the microstructural changes that determine important degradation of mechanical properties in welded pipelines.**

***Keywords*—submerged arc welding, pipelines, temperature, monitoring, thermography, thermocouples**

I. Introduction

Nowadays, the international trends in the construction field are to perform larger welded metallic structures using advanced high strength steels. Larger weight structures and increasingly efficiency of the welding procedures lead to a demand of better performances of the materials used in industry. A balance between the weight of metallic structure and higher strength of the materials is one of the most important objectives for the economical and modern design in all industrial sectors. Gas pipelines used in infrastructure strategic projects must satisfy the economical and technical conditions to achieve safety in exploitation, sustainable development and environment protection.

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The most important requirements for the pipelines used in the petroleum products transport are connected to the strength, plasticity and security in exploitation at extreme temperatures, different altitudes and depths.

Welding is the main joining technique used in pipelines fabrication and is applied in order to produce large-scale pipes for long distance transportation of oil or natural gas under high pressure. During conventional fusion welding processes, pipeline steels are often subjected to mechanical and metallurgical changes, such as a significant loss of strength and toughness in the welding joint area. The microstructure of the joint is deeply affected due to the high energy introduced in the pipeline during the welding process [1], [2]. From this point of view, the welded joints represent the structural weakness in most of the cases and hence, they must be strongly monitored in order to ensure structural integrity of the final products [3].

Thermography is a modern technique used in non-destructive evaluation of the material proprieties in many applications from manufacturing processes. Non-destructive techniques consist in the possibility of inspecting large areas in faster and safer conditions without needing the access to all sides of the components. Nevertheless, infrared thermography is limited to the inspection of surfaces, since it is affected by 3D heat diffusion [4], [5]. The temperature measurements using infrared thermography are also quite difficult and uncertain; the uncertainty is caused by the temperature dependent emissivity and reflectivity of the seam areas. Improved accuracy and minimum errors are achieved by an appropriate calibration of the systems, adapted to the industrial applications of the welding process.

In order to have an overview of the entire welding process in situ, a complex system should be designed for ensuring the accuracy of the temperatures data acquired during the joining process. The authors propose a dual monitoring and measurement system of temperatures, induced in the submerged double-arc/double-wire (SDAW/SDWW) welding process of pipelines, comprising K-type thermocouples and an infrared thermo-camera [6].

The longitudinally welded pipeline steel is X52M/L360M-PSL2, having the diameter of 914 mm and thickness of 15.88 mm. The monitoring system measures temperatures during the welding process through several K-type thermocouples longitudinally and transversally placed to the welded joint axis. Also, the system provides an analysis of thermal cycles in different points located in the weld and heat affected zone (HAZ). An infrared thermo-camera is positioned under the welded joint in order to acquire the instantaneous values of the temperature in the contact region of the thermocouples and to visualize the temperature field distribution on the bottom surface of the longitudinally welded pipeline.

II. Experimental Procedure

Traditionally, temperature field distribution is acquired on the materials surfaces, by using infrared thermography, while the temperatures from the rest of the welded joint regions are analytically determined or by applying numerical methods to simulate the heat transfer [6], [7].

Currently, worldwide, different variants of temperature monitoring systems and weld quality are developed, as well as joint tracking using infrared temperature measurements and Laser based systems. Taking into account the state of the art, the authors intend to explore the possible development of a joint tracking and weld geometry measurement technique, based on infrared temperature measurement.

The experimental research was conducted in a Romanian company, specialized in pipelines manufacturing. A pipeline made of a typical grade steel (X52M/L360M-PSL2) with 914 mm diameter and 15.88 mm thickness and previously subjected inside to SDAW/SDWW process was selected for investigation. The welding parameters applied for performing the outside weld are presented in Table I. It can be noticed that the first welding arc (WA1) is characterized by a lager heat input for obtaining a proper penetration and an overlapping of the root pass, while the second welding arc (WA2) ensures the deposition rate and qualitative weld geometry due to the increased welding voltage. The filler materials couple used in experiments were AS35 electrode wire of 4mm diameter and AS 461/WPS-EN907 welding flux.

TABLE I. WELDING PARAMETERS USED IN EXPERIMENTS

Welding Arc	Welding current	Amperage [A]	Voltage [V]	Welding speed [cm/min]
WA 1	DC	883	34.0	100
WA 2	AC	696	40.0	

Temperature history - Temperature vs. time - registered in different points of the outside welded joint has been plotted by processing all data collected through a monitoring system with nineteen K-type thermocouples positioned in different spots of the welded joint. In order to choose the optimum arrangement and disposal of the thermocouples in the experimental phase, a macrostructure of a pipeline welded in similar welding conditions was analysed (Figure 1).

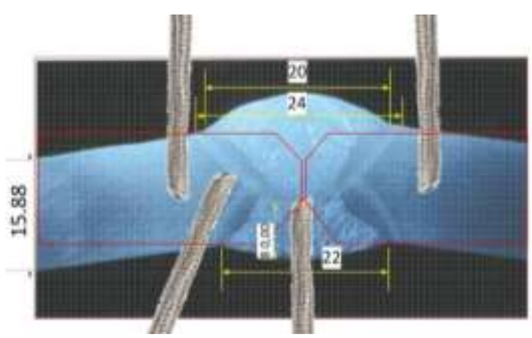

Figure 1. The disposal of thermocouples in the weld and HAZ [6]

TABLE II. WELDING PARAMETERS USED IN EXPERIMENTS

TC	Thermocouple Type	d_{mt} [mm]	d_{ai} [mm]	d_{im} [mm]	α [^{0}]	On pipe positioning
TC1	grounded inserted	230	0	8	0	inside
TC2	grounded with lug	227	0	0	0	
TC3	grounded inserted	230	17	12	60	
TC4	grounded inserted	630	0	8	0	
TC5	grounded with lug	627	0	0	0	
TC6	grounded inserted	630	17	12	60	
TC7	grounded inserted	1030	0	8	0	
TC8	grounded with lug	1027	0	0	0	
TC9	grounded inserted	1030	17	12	60	
TC18	grounded inserted	- 15	0	12	0	
TC10	grounded inserted	230	17	6	0	outside
TC11	grounded with lug	227	23	0	0	
TC12	grounded inserted	630	17	6	0	
TC13	grounded with lug	627	23	0	0	
TC14	grounded inserted	1030	17	6	0	
TC15	grounded with lug	1027	23	0	0	
TC16	grounded with lug	230	17	0	0	
TC17	grounded with lug	1030	7	0	0	
TC19	grounded without lug	230 630 1030	23	0	0	

The thermocouples positioned *inside* the pipeline were disposed in three measurement areas consisting of three sets of three thermocouples (T1-T9), with 400 mm distance between them (Table II). The thermocouples mounted *outside* the pipeline were distributed into three sets of two thermocouple (T10-TC15), arranged on the same direction like the thermocouples positioned inside pipeline. Besides, two lug thermocouples, T16 and T17, were positioned, symmetrically with TC10 and TC14, at distance of 230 and 1030 mm to the edge of the pipeline sheet, respectively. The positioning of thermocouples was determined taking into account the distance from the edge of the pipeline (d_{mt}), the distance from welded joint axis (d_{ai}), the sloping angle to the joint axis (α) and the thermocouple insertion depth (d_{im}). The temperatures were recorded using two Lutron BTM-4208SD devices with 12-channel recorders, a Testo 175 data logger and Testo 845 infrared thermometer with measurement point marking [8], [9], [10]. The thermocouples layout and disposal inside and outside pipeline, in cross section, is presented in Figure 2.

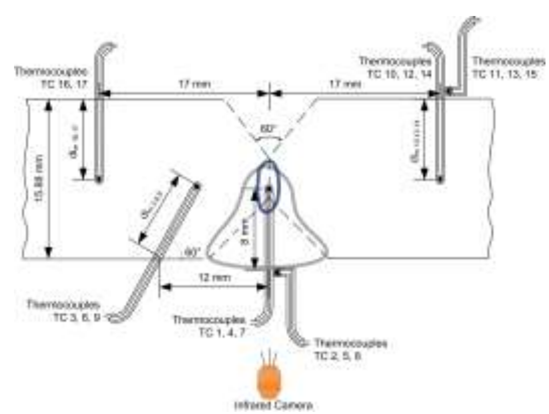

Figure 2. Sketch of thermocouples positioned inside and outside the pipeline

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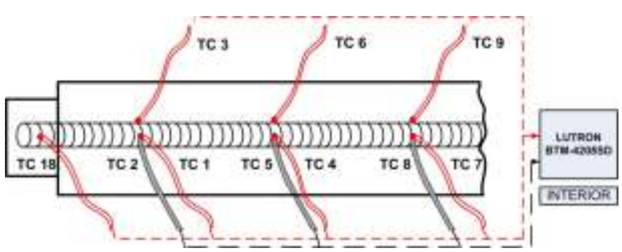
The layout of thermocouples positioned on the longitudinal direction, inside and outside the pipeline, is shown in the figure 3 (*a* and *b)*. Their positioning is carried out through threaded holes.

It can be noticed the positioning of the thermocouples inside (TC1...TC9, TC18) and outside (TC10...17) the pipeline, which are symmetrically arranged to the interior weld at distances of 230, 630 and 1030 mm from the edge of the pipeline and end-plate.

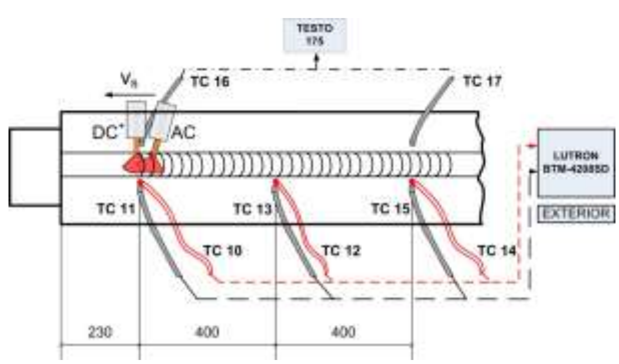
The dual monitoring system comprises Omega thermocouples, K 163 type, with (0 -1100°C) measuring range [8], [9]. One measuring system registers the temperature values of the thermocouples TC1 to TC9 and TC18 inside (Figure 3a) and the other provides the temperatures of TC 10 to TC15 thermocouples outside the pipeline (Figure 3b).

The temperature values of TC16 and TC17 thermocouples have been achieved by using a 2-channel Testo 175 data logger with a probe for the external K-type connector, compatible with OMEGA thermocouples. The measurement accuracy of this device is 0.7%, in the temperature range of (70 ... 1000 °C), and resolution of 0.1 °C.

Testo 845 infrared thermometer with measurement point marking has been chosen for obtaining the temperatures measured by the T19 grounded thermocouple without lug. This IF thermometer is a temperature measurement device with infrared laser cross sighting. The measurement was remotely achieved, in real time, focusing on the contact probe. The accuracy of the last device is ± 0.75 °C, having the scanning speed of 100 ms.



a)



b)

Figure 3. Thermocouples positioned inside and outside the pipeline

Figure 4 presents the location and the arrangement of the thermocouples mounted outside the pipeline, the connection of the recording systems comprising K-type thermocouples and the electronic devices used for the temperature values recording by data loggers, Testo 175, LUTRON BTM-42087SD and pyrometer TESTO 845 [11]. Figure 5 illustrates the measurement system used for monitoring of temperature variation inside the pipeline subjected to SDAW/SDWW process. It can be noticed the position of the infrared camera under the weld with the aim of surface temperatures monitoring during the exterior weld performing. The images and data, provided by Flir AM20 infrared camera, related to simulation of heat transfer and modifications of temperature field in time, have been used for validation of finite elements models developed and reported by the authors [1], [2].

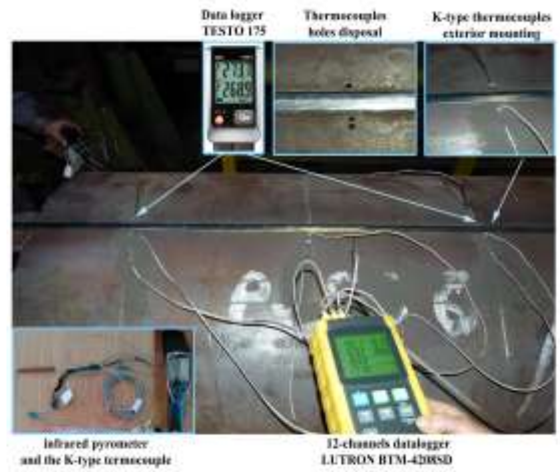


Figure 4. Temperature measurement system outside the pipeline

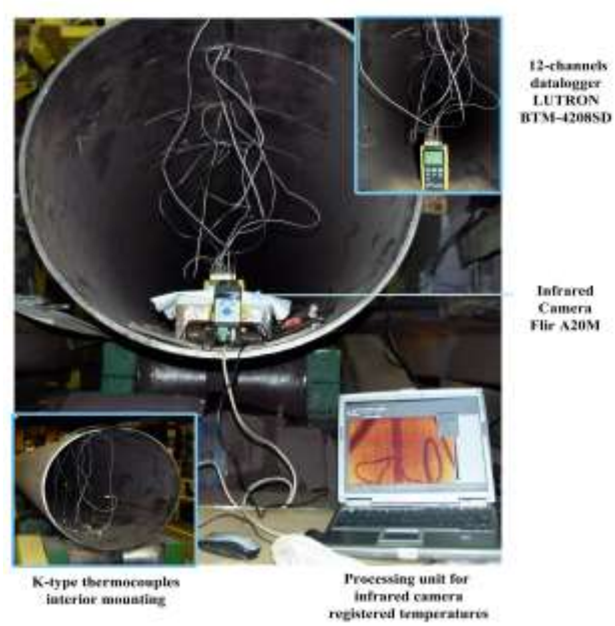


Figure 5. Temperature measurement system inside the pipeline

III. Results and Discussions

Temperature vs. time achieved at multiple-wire submerged arc welding of pipeline, by using the thermocouples system described in the table 2, is clearly illustrated in Figures 6 to 8. For instance, figure 6 shows the thermal history recorded by TC1 – TC9 and TC18 thermocouples positioned inside the welded pipeline. Figure 7 illustrates the thermal history recorded by TC10 – TC14 thermocouples, positioned outside the pipeline, and by TC15 thermocouple located on the end-plate. Due to different distances to groove axis and different depths of thermocouples positioning, the inside and outside thermocouples record different temperatures, including different peak temperatures.

Thermal history recorded by T16 and T17 thermocouples, placed outside the pipeline, at the beginning and the end of the joint, respectively, at distance of 230 and 1030 from the edge of the pipeline is presented in Figure 8.

Because of the welding flux existence, that covers the joint's regions, the temperature could not be recorded in the areas of the thermocouples. This is the reason of positioning the infrared camera inside the pipeline, at distance of 0.7 m under the weld as figure 5 shows, with the aim of monitoring the temperature field continuously changed during the weld performing outside the pipeline [10].

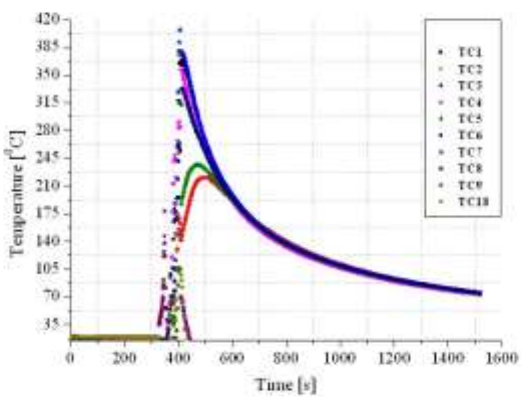


Figure 6. Temperature vs. time recorded by the thermocouples positioned inside the pipeline

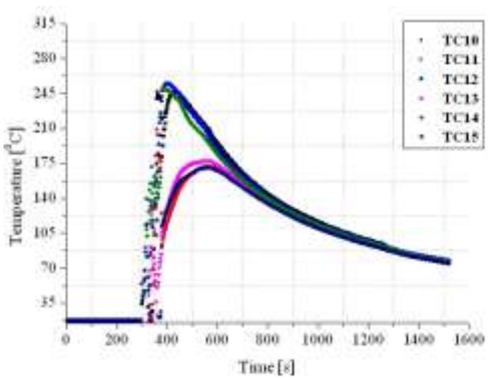


Figure 7. Temperature vs. time recorded by the thermocouples positioned outside the pipeline

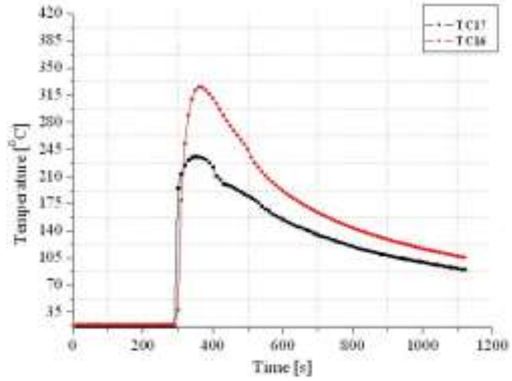


Figure 8. Temperature vs. time recorded by T16 and T17 thermocouples positioned outside the pipeline at the beginning and the end of joint

The thermograms captured with the infrared camera, at different moments of the SDAW/SDWW process, illustratates the weld performing outside the pipeline and are presented in figure 9.

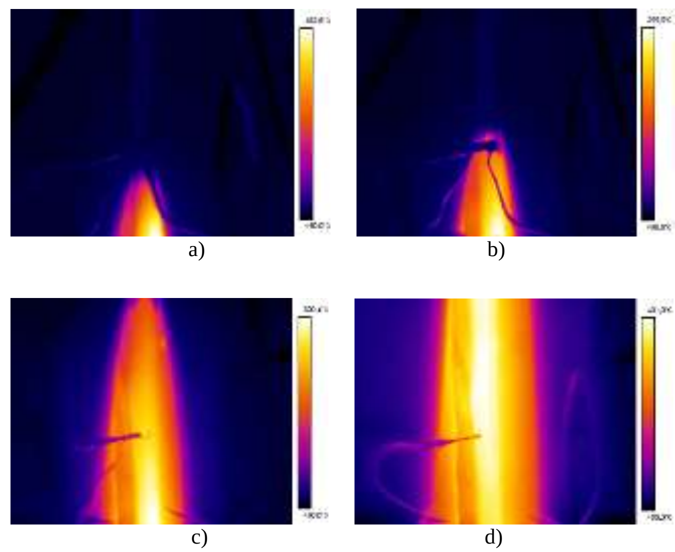


Figure 9. Temperature field achieved at the multi-wire SAW process

A deep analysis of the experimental results was made and several features have been noticed and described below:

- a strong influence of the magnetic field, produced by the welding arc, on the temperature measurements obtained through thermocouples system has been remarked, regardless the thermocouple type or positioning area (outside or inside the pipeline);
- the peak temperature is up to 410^{O}C and was measured by the TC3 thermocouple. Lower values of temperature were recorded by the TC6 and TC9 thermocouples, positioned at the interior of the pipeline, close to the weld root;
- a similarity of heating and cooling charts shape has been noticed both the outside and inside the pipeline. Still, because of different positions of thermocouples inside and

outside the pipeline, an increase of $150^{O}C$ of temperature was recorded in the interior of the pipe;

- a comparative analysis between the temperature values achieved by using the infrared camera and those recorded by the TC2, TC5, TC8 thermocouples, positioned inside the pipeline, reveals errors of 15% in the temperature measurements. These errors are caused either of wrong setting of the emissivity value of infrared camera or because of the thermocouple lug positioning in the concave shape surface of weld.

IV. Conclusions

The investigation addressed the following objectives:

- analysis of three-dimensional temperature variation experimentally achieved through measurements, both inside and outside the pipeline during the multi-wire submerged arc welding;
- finding appropriate solutions for thermocouples positioning in the optimal areas of the welded pipeline, in order to obtain accurate temperature measurements, so that a reduced number of thermocouples could be used for calibration of the infrared camera;
- investigation of alternatives measurements systems of temperature in order to improve the monitoring technique in industrial applications of the welding process.

Experimental results revealed relevant conclusions highlighted below:

- temperature measurements through the thermocouples, with or without contact, with lug fasteners and/or immersion revealed that an appropriate calibration of the infrared camera should be performed by using contact thermocouples with rod. The thermocouple positioning should be made close to the end-plate;
- in the case of K-type thermocouples positioned in holes, it is recommended:
    - the use of thermocouples with reduced diameters and unprotected junction, which provide a faster response time;
    - their assembling should be made in electrical and thermal insulated holes. The electrical contacts (short-circuit) should be carefully tested with ohmmeters in order to achieve a proper contact with the measured surface.
- the errors produced by inadequate emissivity values can be reduced by using pyrometers with laser converging spot, self calibration (automatically sets the emissivity value), wave-length of 1.6μm, in the measuring range of $490\text{-}2000^{O}C$;
- in order to obtain temperature values close to $1100^{O}C$ and to analyse the cooling rate, which determine the nature of metallurgical changes, wolfram thermocouples should be used and positioned in the weld pool. Because the fusible tip will remain after solidification of the melted metal inside the weld, uch experimental tests can be conducted only in research laboratories.

Acknowledgment

This work was supported by a grant of the Romanian National Authority for Scientific Research, CNDI–UEFISCDI, project number PN-II-PT-PCCA-2011-3.1-1057.

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