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Study of the temperature distribution on welded thin plates of duplex steel to be used for the external clad of a cask for transportation of radiopharmaceuticals products

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ABSTRACT

The clad material for a proprietary transport device for radiopharmaceutical products is the main focus of the present work. The production of 99Mo-99mTc transport cask requires a receptacle or cask where the UNS S32304 duplex steel sheet has shown that it meets high demands as the required mechanical strength and the spread of impact or shock waves mitigation. This work reports the experimental efforts in recording the thermal distribution on autogenous thin plates of UNS S32304 steel during welding. The UNS S32304 duplex steel is the most probable candidate for the external clad of the containment package for the transport of radioactive substances so it is highly relevant the understanding of all its physical parameters and its behavior under the thermal cycle imposed by a welding process. For the welding of the UNS S32304 autogenous plates the GTAW (gas tungsten arc welding) process was used with a pure argon arc protection atmosphere in order to simulate a butt joint weld on a thin duplex steel plate without filler metal. The thermal cycles were recorded by means of K-type thermocouples embedded by electrical spot welding near the weld region and connected to a multi-channel data acquisition system. The obtained results validate the reliability of the experimental apparatus for the future complete analysis of the welding experiment and further comparison to numerical analysis.

1. INTRODUCTION

This paper presents the experimental set up and measurements of the transient temperature field during a GTAW welding pass, on a UNS S32304 duplex stainless steel plate intended to be used as a clad material, for radiopharmaceutical products containment transport vessels. It is proposed here the analysis of the thermal history in UNS S32304 steel plates during the welding process of butt joint without filler metal. The results are to be linked to other studies being carried out on the residual stress in these plates after the welding process in order to assure better quality to the fabricated parts [1,2]. The increased reliability in materials and process for applications in the nuclear industry and the transport of radioactive products endorse this work.

The welding technology is known to be the most reliable, practical and efficient method of joining metals. It is widely used in nuclear, aerospace and automotive industries around the world. Despite the great advantages there are also some limitations generated during exposure the materials to high welding temperatures. The thermal cycles of the processes can affect important parameters such as residual stresses, deformations and altering the mechanical properties within the parent metal [3]. However, careful about these failures are even greater when dealing with the transportation of nuclear products.

Modern duplex stainless steels have excellent corrosion resistance and good mechanical properties. This combination has boosted its use in highly aggressive environments [5]. Duplex steels have a microstructure essentially of about 50% ferrite and 50% austenite, which combines the properties of both phases [5]. Its application is becoming more common in industrial products that involve welding operations. The modern stainless steels have been developed thinking in its weldability.

Murugan et al (1998) [6] measured the temperature distribution in AISI type 304 stainless and low carbon steel using eight thermocouples. They showed that the temperature distribution in the measured points were clearly dependent on the welding conditions. In a study by Kasuya et al (2000) [7] it was proposed an analytical heat conduction model for the prediction of the temperature histories on bidirectional multi-pass welding samples with short weld bead lengths, and validates the model with experimental results obtained with the use thermocouples. In another article by Zhu and Chao (2004) [8] the temperature transient was associated to the residual stress during the friction welding of 304L stainless steel plates. Deng et al (2006) [9] experimentally obtained the temperature distribution on butt-welded piping joints using thermocouples and compared the results with a finite element simulation. Liang et al (2008) [10] investigated the temperature field in AZ31B magnesium alloy welding obtaining cooling curves using thermocouples by non-contact measurements.

Attarha et al in 2011 [3] measured the transient temperature distribution in GTAW welded plates of carbon steel, stainless steel St37 and AISI S304. The temperature curves were obtained with the use of K type thermocouples. A work written by Machado et al (2014) [11] shows the effect of the shielding gas composition on the residual stress distribution in UNS S32304 duplex stainless steel welded by the GTAW process. The work describes residual stress distribution induced by the GTAW welding process for various weld bead lengths on the thin plates.

The proposal for the new Brazilian Multipurpose Nuclear Reactor (RMB) and the short period withdrawal of one of the major producers of radiopharmaceutical products from the market arose the need of proprietary transport device to accomplish for high demands in the production of radiopharmaceuticals. The containment receptacle or cask (see Fig. 1) for transport of substances of high radioactivity sources requires high thermo-mechanical protection, mainly the tungsten/tungsten alloys or depleted uranium shielded devices are used for the transport of the 99Mo with activity above 0.6 TBq (16.2Ci). The International Atomic Energy Agency (IAEA) standards regulating the transport of radioactive material were adopted by Brazil and the National Commission of Nuclear Energy is the authority responsible for its regulation and implementation within the country. The CNEN-NE-5.1 [12] standard defines the key safety parameters for the design, project and validation tests of transport devices in order to guarantee an adequate level of control of the potential exposure of people, property and the environment to ionizing radiation [13].

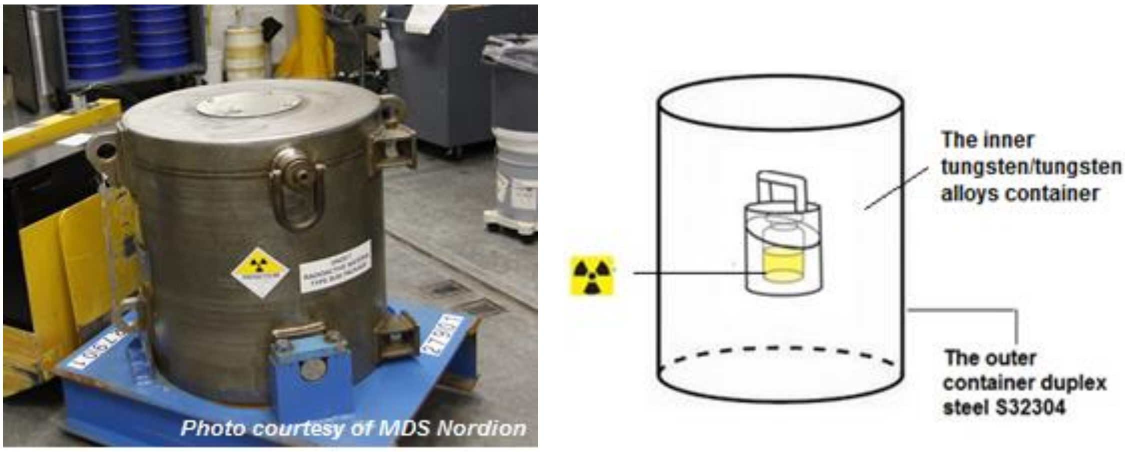

Figure 1. Left hand side container currently used by MDS Nordion in Canada. Right hand side schematics of a container [14].

2. EXPERIMENTAL

The experiment was carried out using the GTAW welding process on two autogenous UNS S32304 steel plates. Table 1 shows the chemical composition of UNS S32304 duplex stainless steels used in the experimental work. The alloy chemical composition was certified by the commercial supplier (APERAM Inox South American S.A.) based on energy dispersive X-ray fluorescence spectrometry (EDXRFS).

Table 1. Chemical composition (mass %) of UNS S32304 steel

C%	Mn%	Si%	P%	S%	Cr%	Ni%	Mo%	N_{ppm}	Ti%	Cu%	Co%
0.016	1.4	0.25	0.023	0.001	22.2	3.52	0.255	1030	41	0.4171	0.09

Duplex stainless steel strips with a thickness of 1.8 mm were cut with the aid of a continuous strip-shearing machine in order to avoid the influence of stresses originating from the shearing process, in 51 mm dimension. The welding GTAW parameters are summarized on Table 2, which describes the experimental butt-welded joint and the locations of the thermocouples regarding the distance from welding nugget.

The temperatures were measured and recorded using type K thermocouples attached to a data logging system. Three thermocouples were positioned and fixed by electrical spot welding at different distances, along a line transversal to the weld bead as seen schematically in Fig. 2. Mechanical restriction blades were used in order restrain the movement of the thermocouple wires and to avoid mechanical stresses.

Table 2. Summary of the experimental butt-welded joints and the locations of thermocouples regarding the distance from welding nugget

Experiment	Thickness	Plate material	Thermocouples		
			1	2	3
W1	1.8 mm	UNS S32304	20 mm	10 mm	20 mm

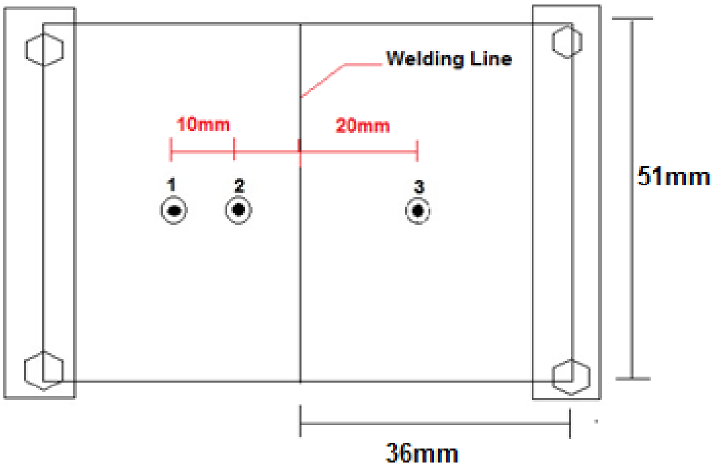

Figure 2. Welding scheme with thermocouple positions regarding the distance from the welding bead.

The signals obtained originated from the three thermocouples were acquired through a HBM QuantumX MX840B - 8 channel universal data acquisition system (DAQ) amplifier using MX Board - PT1000 for room temperature automatic conditioning. According to the HBM, the total error limit at 22 ° C ambient temperature is ± 1K and the temperature drift (type K) it is used K/10K ratio where the uncertainty is ≤ ± 0.5. For data logging and processing the catman Enterprise software suite version V3.5.1 was used to display the thermal curves. Logging was performed using a sample rate of 50 Hz. The welding was carried out with only one weld pass without addition of filler metal. The obtained sample piece was obtained from two autogenous plates welded together by the GTAW process. During welding, pure argon gas was used as the shielding gas, see Table 3 for the used welding parameters.

Table 3. Welding parameters used for the GTAW using dc current and direct polarity

Voltage	Current	Speed	Arc efficiency	Shielding gas Ar	Heat input
8.8 V	55 A	2.3 mms^{-1}	50%	10 $Lmin^{-1}$	0.105 $kJmm^{-1}$

The electrical current and voltage values were obtained for a single weld pass. A welding movie was recorded and then the welding speed was calculated from the measured weld length and from the weld pass elapsed time obtained from the movie. Through the voltage (*V*), current (*I*) and the welding speed (*v*) along with 0.5 arc efficiency (η) for the GTAW welding, the welding heat input per mm (*Qw*) could be calculated using Eq. 1.

$$Qw = \frac{\eta VI}{v} \tag{1}$$

The average current, voltage and speed were 55 A, 8.8 V, 2.3 mms^{-1}, respectively, and the calculated heat input was 0.105 $kJmm^{-1}$, see Table 2. In the next section the temperature variation on each point distant from the weld pool duplex steels are shown in detail.

3. RESULTS AND DISCUSSION

The sample welded can be seen through Fig. 3 where is also possible to check the HAZ and molten zone and also thermocouple locations. Fig. 4 shows the temperature distributions for the 3 thermocouples. Thermocouple 1 and 3 were placed 20 mm away from the weld bead. The curves for both thermocouples are plot in grey and blue and exhibits temperature peaks close to 262 °C and 263 °C, respectively. This result is important for the validation of the measures and experimental apparatus, since both temperature curves behavior are very close.

The thermocouple 2 was embedded at 10 mm from the center of the weld bead and is plotted in red in (see Fig. 4). The highest temperature was close to 460 °C, being the highest among the 3 thermocouples. Again it was an adequate behavior since it was the closest thermocouple to the weld bead. An important observation is that the temperature decreases non-linearly against the time for all 3 thermocouples [9]. The reason for this is associated to an increased localized heat by the welding torch and the nonlinear variation of material properties with respect to the temperature [15].

Figure 3. Welded sample plate showing thermocouples positions and distances from the weld bead.

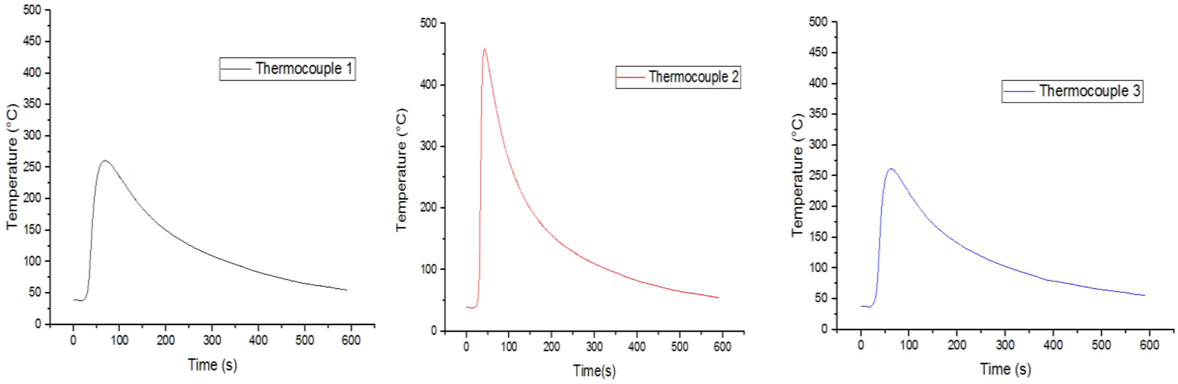

Figure 4. Thermal variation for each thermocouple for the UNS S32304 duplex steel, 1.8 mm thick plate, while being welded.

From the observation of the welded sample image (Fig. 3) it can be seen that the heat-affected zone (HAZ) is 7.3 mm wide and the molten zone is approximately 2.6 mm wide. It is still possible to observe that the thermocouple 2 exhibits the highest temperature and was placed 3.7 mm away from the limit of the HAZ.

In Fig. 5 the temperature of the 3 thermocouples was plotted against time and describes the behavior in three points of the material. Thermocouples 1 and 3 are at equal distances from the weld bead and thermocouple 2 (red), which showed higher temperature than the others thermocouples was due to its smaller distance to the weld pool.

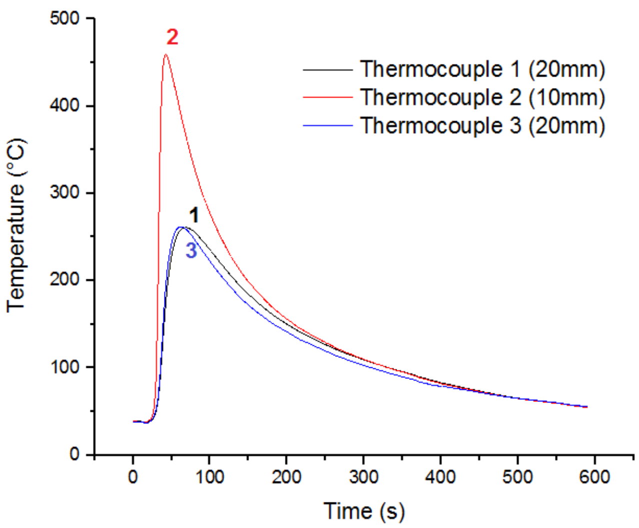

Figure 5. Temperature curves profiles for 3 thermocouples placed at different distance from the weld bead.

The temperature curves suggest possible relations with the residual stresses profiles studied by Machado et al [11]. In this mentioned work, the residual stresses showed significant values of tractive tension in the melted zone and the heat affected zone between 0 and 10 mm from the weld bead, a region where there has been a major incidence of heat. Through the cooling rate at each distance from the weld pool one can propose the microstructure of the heat-affected zone (HAZ) [11].

4. CONCLUSION

The experimental results obtained for the temperature distribution during welding of thin plates duplex steels UNS S32304 using the GTAW welding process validate the reliability of the experimental apparatus for the future complete analysis of the welding experiment and further comparison to the numerical analysis.

It was observed that in order to obtain the best temperature distribution resolution in the 10 mm width zone by the weld bead that the thermocouple placing is critical as was as its own size on the plates, because this is the zone where the residual stresses profiles shows its influence. So, the validation of the thermal symmetry of the experimental apparatus is of fundamental importance.

Referring to Fig. 5, the very close temperature peaks of the two symmetrically positioned thermocouples may be used as a validation parameter to the measurements performed in the experimental apparatus and procedures. Again referring to Fig. 5, the shape coincidence of the two temperature distribution curves indicates that the thermocouples may be positioned either sides with equal results, despite small differences in the experimental arrangement. This behavior allows a better experimental planning with more and better spaced thermocouples on the sheets within the 10 mm zone by the weld bead.

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