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RESEARCH ARTICLE

Investigation of the heat affected zone by thermal cycle simulation technique

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Abstract

The heat generated during welding induces a large temperature gradient in and around the welded area. In the arc welding process, three main different zones have been recorded in the welded joint: the fusion zone, the heat affected zone and the base metal. The objective of this article is to present the thermal cycle simulation technique and its usefulness for the study of the heat-affected zone. Rapid heating and cooling treatment was applied in specific simulation equipment. The most published research on using thermal cycle simulation to understand the heat affected zone is presented. A case study is also presented. An X70 steel was chosen to undergo thermal treatment cycles using the simulation equipment. It has been shown the importance of this technique for the study of HAZ. It was found that the microstructure of HAZ depends on the heating temperature.

1. Introduction

Welding is a process of joining materials into one piece. The heat generated during welding induces a large temperature gradient in and around the welded area. Three main different zones were observed in the welded joint: the fusion zone (FZ), the heat affected zone (HAZ) and the base metal (BM). The HAZ is a region between the FZ and the BM which is thermally affected by the welding treatment. The HAZ is the part of the base metal whose mechanical properties and microstructure have been altered by the heat of welding. HAZ is subject to a thermal cycle (sudden heating followed by rapid cooling) in which all temperatures in the melting range of steel down to relatively much lower temperatures are involved and HAZ therefore consists of a series of graduated structures surrounding the weld bead. Therefore, the HAZ generally contains a variety of microstructures. Knowledge of the HAZ sub-zones is important from a practical point of view, since, as indicated in [1], the fine-grained sub-zone is at a critical location in terms of creep resistance and to thermal fatigue.

The main difficulty associated with welding is the prevention of unexpected deterioration of properties as a result of the microstructure evolutions which reduce the resistance to brittle fracture in the heat-affected zone (HAZ) [2]. Properties of the HAZ are different from those of the base material. It was concluded that by improving the microstructure of the HAZ, the properties of the welded joint can be improved. For example, excessive heat input could result in a wide HAZ with low impact resistance [3]. The ZAT is responsible for the microstructural and mechanical changes in the welded joint, due to the heat generated during the welding process and, generally, due to the large grain size, the ductility and toughness of this area are poor. Therefore, the heat input being the most important factor among those that affect HAZ [4].

According to the literature, the HAZ is the most problematic area in the high strength steels weld. For this reason, many research works investigated this critical zone in welded joint. However, the investigation of the HAZ in the real welded joint is not easy, because it is not possible to obtain an appropriate specimen at very narrow locations in the HAZ [5, 6]. To evaluate the HAZ's properties, thermal cycle simulation is one the best approaches for the investigation of HAZ. It gives more information about changes in the temperature and different microstructures obtained in HAZ caused by welding [7]. In addition, weld thermal cycle simulation can be used for optimizing the welding technology since it enables some mechanical testing for properties that cannot be made on real welded joints because of small width of HAZ [8]. For example, in our previous contribution to understanding the different microstructures in welded joints of the Inc 738 LC superalloy using thermal cycle simulation [9], we found that the microstructures obtained by welding thermal cycle simulation correspond to those observed in the same area of the real welded joint produced by TIG welding. Moreover, in our recent works [10], we found that the HAZ in the 2014 aluminum alloy, studied by a thermal cycle simulation, is not a homogeneous zone but it is composed of different sub-zones.

The objective of this article is to present some published research on the use of thermal cycle simulation to understand the heat affected zone. The thermal cycle simulation technique is also presented with a real application on X70 steel.

2. Thermal cycle simulation technique

Simulator tests Smitweld TCS 1405 is presented in Figure 1. This device allows studying the microstructural variations appearing during heat treatments in metal alloys, in particular during welding. The power sources are provided by electro resistance and electro induction that facilitate and control heating rates. Figure 2 illustrates the applied heating and cooling cycles. The first step of the cycle consists of a rapid heating (from *To* to *Tm*) followed by the cooling step (from *Tm* to

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ambient temperature). The heating takes place by the Joule effect (from 0 to 1300 C, linearly). The heating speed is fast (100 K/s), and the cooling speed is also fast. The thermocouple is a Chrome/Alumel was used to measure the temperature of the specimen during the thermal cycle. This element is fixed in the central point of the standardized test specimen (100 x 10 x 12 mm) (Figure 3). The selected specimen for this experience is X70 steel. Table 1 presents the chemical composition of X70 steel. The Smitweld TCS1405 simulator is equipped to carry out computer-controlled temperature cycles that consist of a rapid heating followed by a cooling treatment. The heat treated specimens by the Smitweld thermal cycle simulator were polished and etched by Nital to reveal the microstructure. The etched specimens were observed by optical microscopy.

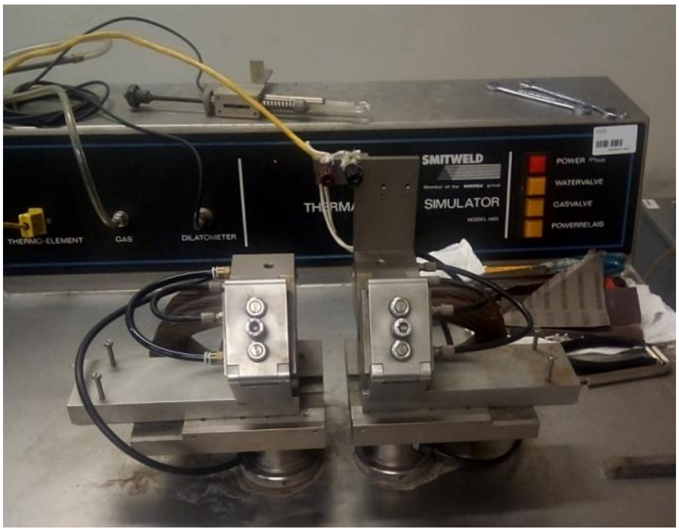

Figure 1. Smitweld thermal cycle simulator

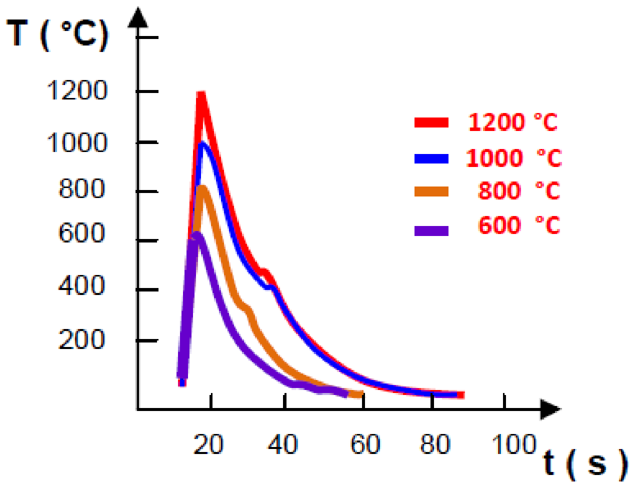

Figure 2. Thermal cycles applied to the specimen.

Figure 3. Fixing of the thermocouple on the standardized test specimen

3. Case study

In this part of this work, an investigation by thermal cycle simulation of X70 steel is presented. First of all, the microstructure of the base metal (Fig.4) consists of finer ferrite grains (white) and dispersed colonies of pearlite (black).

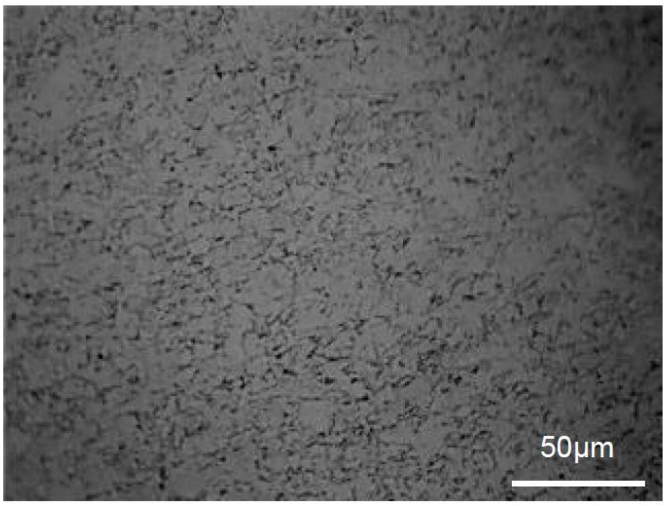

Figure 4. Microstructure of the base metal (X70 steel)

Figure 5 shows the heating effect on X70 steel during one thermal cycle from 25 C to 1200 ºC. By increasing the temperature, the appearance of the specimen changes to the red color. However, the opposite behavior of the specimen can be observed in figure 6 during the cooling process.

Table 1. The chemical composition of the base metal (wt %).

C	Si	Mn	P	S	Cr	Ni	Cu	Al	N	Mo
0.066	0.210	1.520	0.016	0.001	0.060	0.194	0.030	0.032	0.006	0.136

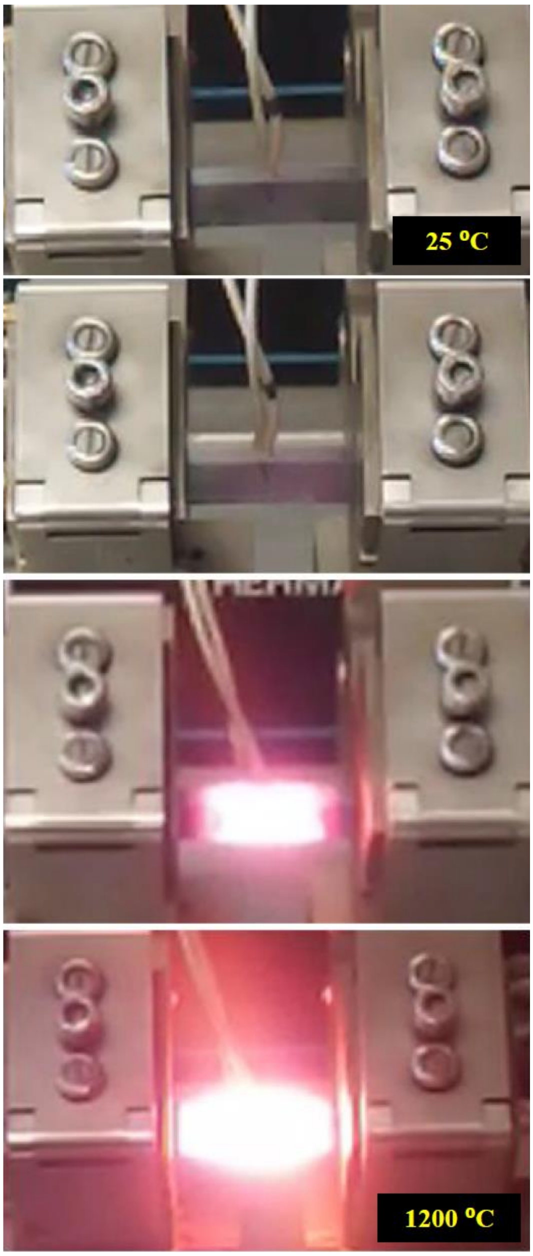

Figure 5. Effect of heat treatment on specimen of X70 steel during heating from 25 ºC to 1200 ºC

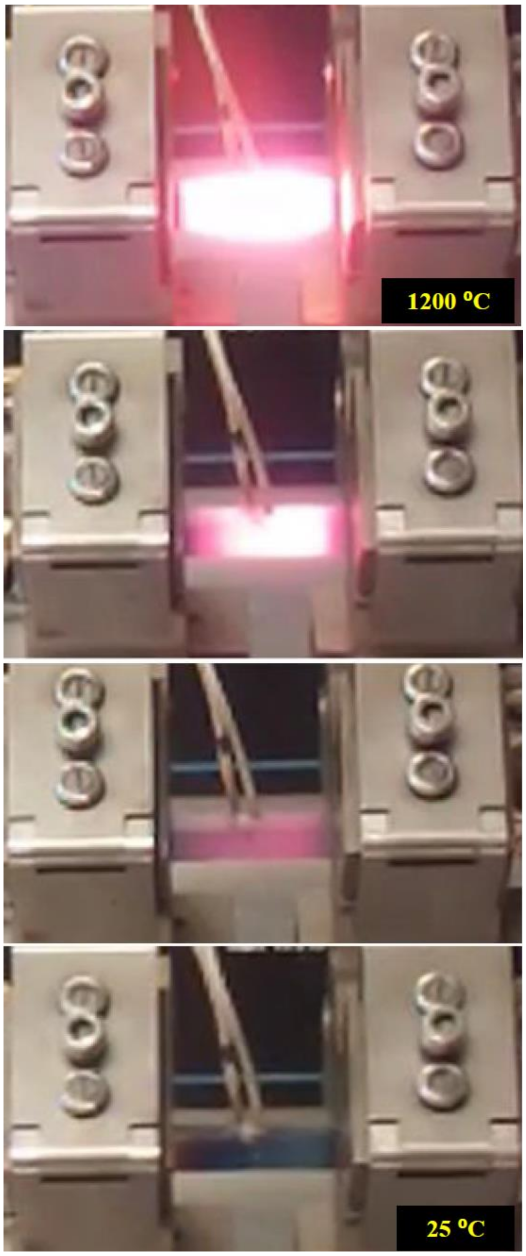

Figure 6. Thermal behavior of X70 steel during cooling process from 1200 to 25 °C

This thermal cycle is repeated and applied for other specimens at different temperatures to simulate the temperature distribution in HAZ. In our case, we have chosen four temperatures (600, 800, 1000 and 1200 °C), which correspond to four thermal cycles. The choice of these four temperatures is based on bibliographic data which indicate that the temperature of HAZ in ordinary steel welded by conventional processes varies from 400 °C to 1400 °C [11]. In our case, our temperatures are within this temperature range. Figure 7 shows macro views of the specimens of X70 steel after different thermal cycle (600, 800, 1000 and 1200 °C), with their microstructures. The effect of heating temperature on the microstructure can be observed:

At 600 °C, the microstructure of the heated specimen corresponds to the initiation of the recrystallalization reaction. Against the temperature of 600°C, complete recrystallization was developed. By increasing the temperature up to 1000°C or 1200 °C, a new microstructure is formed which is characterized by the formation of the acicular ferrite.

According to some published works [5, 8] and to our previous investigations [9-11], the thermal cycle simulation technique gives more details about the microstructure of the HAZ. For example, Hamdi et al. [12], investigated the heat affected zone (HAZ) in X60 steel by thermal cycle simulation. They found that the HAZ in welded X60 steel is formed with different sub-zones, and each zone has its own microstructure; i.e., as it has been reported, the HAZ is not homogenous zone, but different sub-zones can be distinguished [13, 14]. This result is confirmed in the present case study.

However, it is important to indicate that the HAZ is often the cause of future damage of many devices in which welding technology was applied for their repair. In order to reduce the negative effect of the HAZ on welded joint, some heat treatments can be proposed such as annealing treatment after welding process [15].

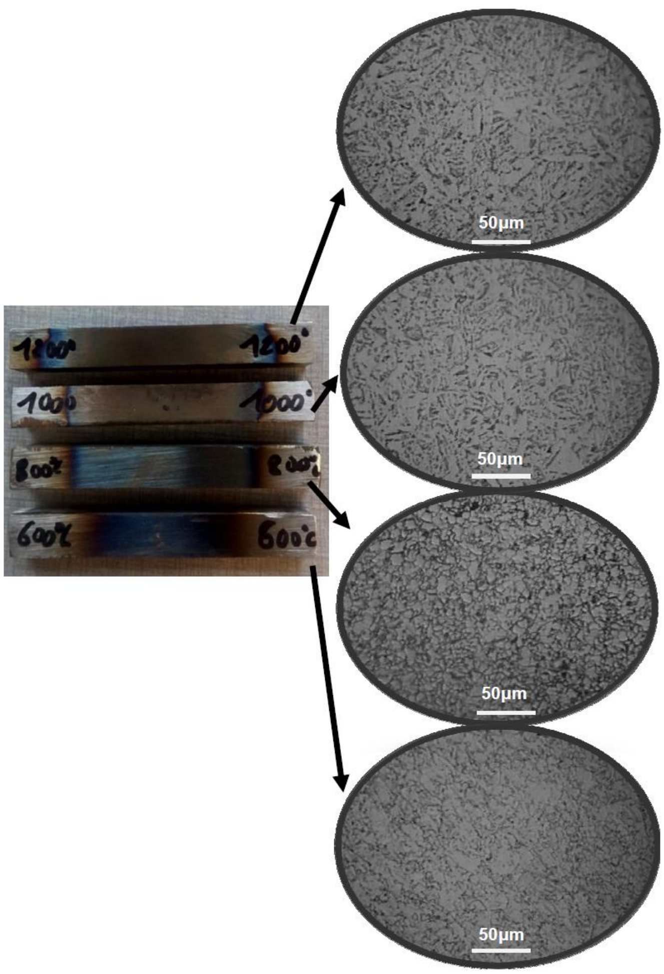

Figure 7. View of X70 steel specimens after different thermal cycles (600, 800, 1000 and 1200°C) with their microstructures

4. Conclusion

Heat affected zone in welded joint is an area in which some structural changes in the welded material take place as the result of experienced temperature. The investigation of the HAZ in the real welded joint is not easy. The use of the thermal cycle simulation technique is the appropriate solution. This technique is based on a rapid heating followed by a cooling treatment of the base metal. This technique has been applied for some metallic materials such steel and aluminum alloy. A case study is presented by the application of this technique in X70 steel. We have showed that the heat affected zone of welded joint is not homogenous zone. This zone is made up of several sub-zones and this is linked to the temperature to which each sub-zone has been subjected. According to our microstructural observations, it was found a beginning of recrystallization at 600°C, a complete recrystallization at 800°C, and a new ferritic structure at 1000°C and 1200°C.

Author contributions

Zakaria Boumerzoug: investigation, simulation, writing the original draft, methodology, supervision, review & editing

Fabienne Delaunois: resources, visualization, reviewing

Oualid Beziou (PhD student): metallographic acquisition, funding acquisition, writing the original draft.

Ines Hamdi: Visualization

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