Key Engineering Materials
ISSN: 1662-9795, Vol. 981, pp 43-50
doi:10.4028/p-4rSwBo

Submitted: 2023-03-26
Revised: 2023-09-09
Accepted: 2023-09-22
Online: 2024-05-14

Thermal Cycle Simulation of Heat Affected Zone in the Welded Mild Steel

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Keywords: mild steel, welding, thermal cycle simulation, heat affected zone, microstructure.

Abstract The aim of this work was to study the microstructure evolution of simulated heat affected zone in mild steel using thermal cycle simulation and it was compared to the heat affected zone in the real welded joint. The optical microscopy, micro-hardness measurements, X-ray diffraction were used as characterization techniques. The microstructures and mechanical properties of the simulated heat affected zone were also determined. The use of the thermal cycle simulation technique revealed in detail the different microstructures in the heat affected zone (HAZ) of the welded joint. Some similarities were observed between the heat affected zone obtained by the thermal cycle simulation technique and the heat affected zone observed in the real welded joint. The thermal cycle simulation technique revealed more details about the microstructure and mechanical behavior of the heat-affected zone. The HAZ microhardness values were lowest hardness in the welded joint. Moreover, the lowest hardness value is obtained for the HAZ simulated at 850°C.

Introduction

Mild steel is a type of carbon steel that contains a low level of carbon with a carbon mass percentage of 0.05 % to 0.29 %. This is why it belongs to the family of mild steels. Mild steel is an inexpensive material with properties suitable for most general engineering applications. Its high melting temperature means that mild steel is more suitable for welding. Mild steel is typically used for pipe manufacturing and has been in common use since the 1940s [1].Welding is one of the most important steps in the pipeline construction process, usually performed by one of the arc welding processes. The arc welding process is based on melting steel at the weld joint. Consequently, cyclic heating during the welding process will change the microstructure of the base metal [2].The welded joint is made up of three zones: a central zone which is the fusion zone (FZ), followed by the heat-affected zone (HAZ) then the base metal (BM).

The heat affected zone (HAZ) formed during welding is an area in which some structural changes in the welded material occur due to the temperature experienced [3, 4]. Microstructural changes in these zones depend on the level of thermal exposure and vary with distance from the weld metal zone. Properties of the HAZ are different from those of the base material. According to the literature [4], the HAZ is the most problematic area in the high strength steels weld. To assess HAZ properties and indicate areas of the joint where instability occurred, the thermal cycle simulation technique is one of the best approaches, as it gives more information about temperature changes and different microstructures obtained in the HAZ caused by welding [4].

According to the literature [5,6], the HAZ can be subdivided into different sub-zones: coarse grained heat affected zone (CGHAZ), fine grained heat affected zone (FGHAZ), inter-critical heat affected zone (ICHAZ) and sub-critical heat affected zone (SCHAZ). The temperature range of each sub-zone has been determined. In the CGHAZ sub-zone, the steel was heated between1100°C and the melting point. In the FGHAZ sub-zone, the steel was heated to temperature above A3 (900 ≤ T_{max}≤1100°C). In ICHAZ zone, it was heated into temperature above A1, in the range A1-A3

(700 ≤ T_{max}≤ 900°C). Finally, in SCHAZ sub-zone, the steel was heated below A1 in the range (600≤T_{max}≤ 700°C) [4].
There is good agreement that the ICHAZ is the “weak point” of the weld from the low carbon steels and in most cases, the welds are broken in that area. In addition, Jambor et al. [7] found that the ICHAZ is the most critical part of the HAZ in high strength steels welds. However, the authors in [8] reported that the local brittle zone exists in CGHAZ in the welds of high strength low-alloy steel, and similarly in [9-11] the authors found that the impact strength and ductility of CGHAZ were deteriorated after one welding thermal cycle. It can be concluded that the HAZ is a critical area of the welded joint that requires further investigation.
The aim of this work is to study the microstructure evolution of the heat affected zone in C45 steel used in pipeline construction. To achieve our objective, a thermal cycle simulation method was used. The microstructures and microhandness were given for each subzone of the HAZ, and compared to the real welded joint of C45 steel.

Experimental Methodology

Table 1 presents the chemical composition of the experimental material. For the real welding, E6013steel electrodes were used to deposit the welds using the shielded metal arc welding process.

Table 1. Chemical composition of the experimental material C45 (Wt.%)

C	Fe	Mo	Cu	Ni	Mn	Cr	V	Si	P
≤0.22	99.10	0.005	0.044	0.026	0.573	0.048	0.003	0.189	0.008

A microstructure representative of an HAZ was produced using thermal cycle simulation technique and which was characterized by optical microscopy and microhardness measurements.
For the thermal cycle simulation study, 10 mm thick 10× 12 mm^2 test specimens of C45 steel were heat treated by tests on a Smitweld TCS 1405 (Fig. 1) simulator (simulator Lincoln Smitweld BV, SMITWELD Thermal Cycle Simulator (TCS) 1405, Netherlands), for temperatures between 325 and 1200˚C. The heating cycle for the six base metal samples consists of heating at an average rate of 100°C/s to the chosen temperature followed by cooling in air at a rate of approximately 10°C/s.
The dimensions of the real welded specimens are 10 mm thick 10 × 40 mm^2. Welding experiments were carried out using the metal inert gas technique with a speed of 0.028 mm min^{-1}, where the inputs were 42 V and (80 –150) A.
Specimens used for optical microscopic observations were polished with SiC paper to grade 2000 and with 0.3µm diamond paste, and etched with 4% Nital solution. For this purpose, an optical microscope was used (Hirox, KH-8700 Digital Stereo Microscope, Japan). The Vickers microhardness testing machine (MITUTOYO, HM 200, Japan) was used to measure the hardness of the specimens with a load of 200gf using the Autovick hardness tester. Five measurements were taken for each sub-zone in the HAZ and the mean values were calculated. X-ray diffraction characterization of the samples was carried out with a SIEMENS device (SIEMENS, D5000, Germany) using a Cu Kα line at λ = 0.1540 nm in the 2θ range between 10° and 100°.

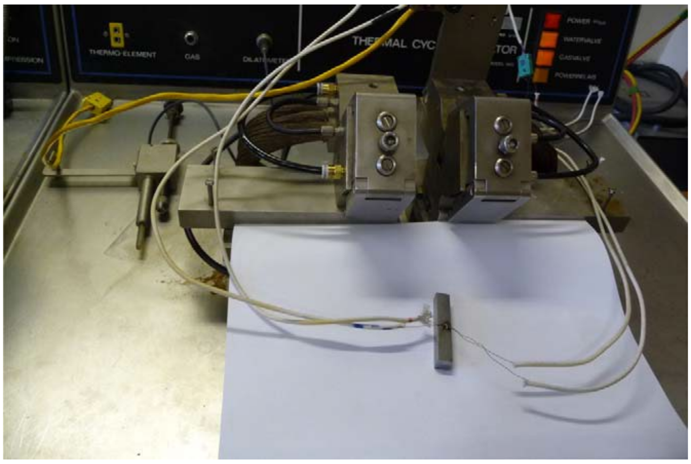

Fig. 1. Smitweld TCS 1405 thermal cycle simulator.

3. Results and Discussion

3.1. Microstructure

The optical micrographs of heat treated at different temperature (325,475, 660, 850, 1090 and 1200°C) of the base metal in simulator are shown in figure 2. The microstructure of C45 steel heat treated at325, 475 and 660 °C corresponds to the microstructure of the base metal, i.e. the microstructure is formed with ferrite and pearlite (Fig.2a, b and c). For this temperature range (325-660), the microstructure does not change compared to the initial microstructure. At 850°C, the microstructure of the alloy begins to change; a refined granular structure is observed which leads to improved mechanical properties [12]. However, the annealing of C45 steel up to 1090C will lead to the formation of a totally different microstructure from the previous ones, because different ferritic phases are observed with pearlite such as, Widmanstätten ferrite (α_w), Massive ferrite (α_m) (marked with circles).By increasing the annealing temperature of C45 steel to a higher temperature (1200 C), the development of a coalescence reaction of the previous phases formed at 1090 C is observed (Fig. 2 f). Based on these microstructural observations, it can be concluded that the HAZ is formed by four different sub-zones, which shows the interest of using of the thermal cycle simulation technique. This result is in agreement with our previous work [13-14], where it was found that the HAZ is not a homogeneous structure but it is formed with different subzones.

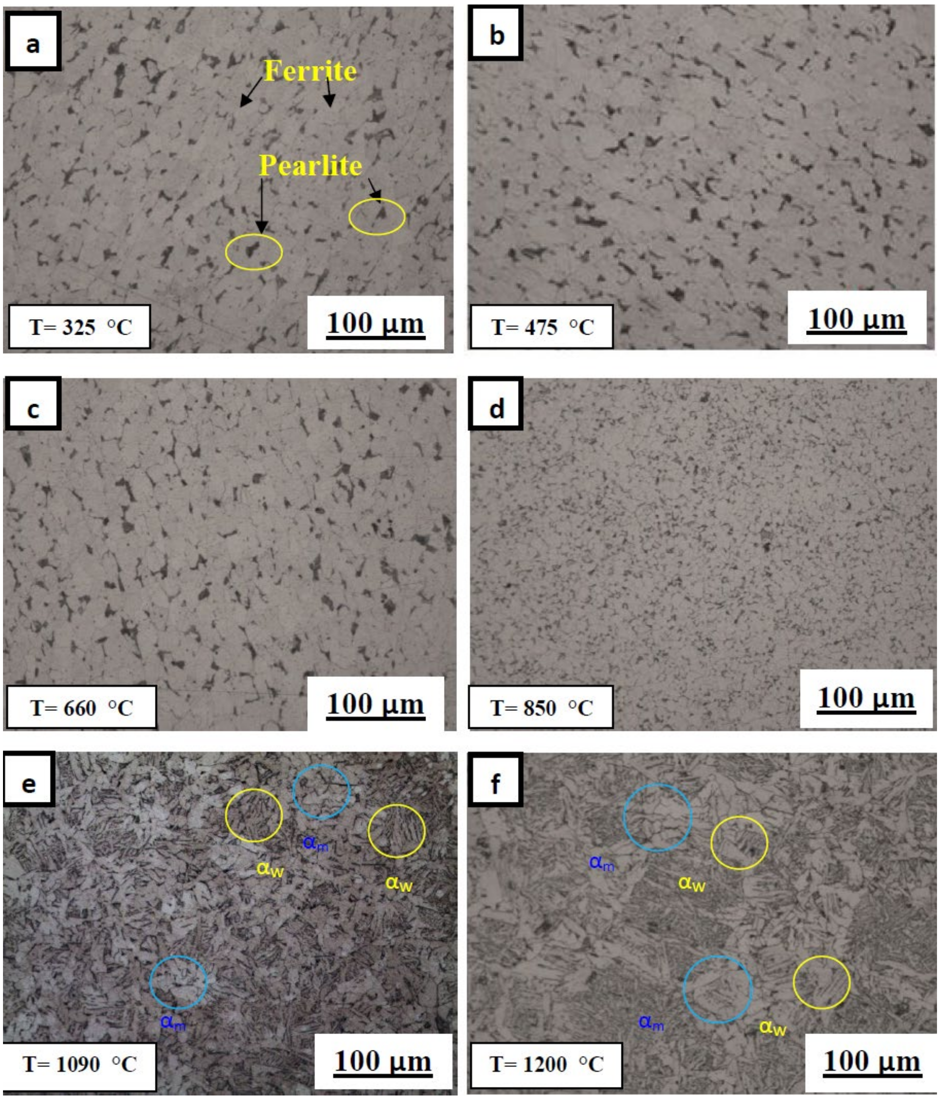

Fig. 2. Microstructures of C 45 steel after simulation welding process and their plotted temperature.

In order to see whether there is an analogy between the simulated HAZ and the real HAZ, the microstructure of the real welding joint of C45 steel is shown in figure 3. This figure shows the microstructure the base metal (BM) (Fig.3a) the HAZ (Fig.3b and c) and FZ (Fig.3d) of the real welded joint of the C 45 steel. As can be seen, the microstructure changes along the welded joint. The base metal has a microstructure containing a ferritic matrix with pearlitic colonies (Fig.3a). On the other hand, the HAZ is composed of two main zones of different microstructures. The first zone (Fig.3b), which is the least heated zone and close to the base metal, presents a microstructure containing colonies of pearlite inside the ferritic matrix and isolated Widmanstätten ferrite (α_W).The microstructure of this first zone of the HAZ of the real welded joint is similar to that observed in the simulated HAZ (Fig. 2e).The second zone, close to the fusion zone and which is the most heated zone of the HAZ, has a coarse-grained microstructure and this is due to the effect of high temperature in this area. The latter can be considered as the sub-critical heat affected zone (SCHAZ) zones [5]. In addition, traces of Widmanstätten ferrite (α_W) were also observed. Finally, the fusion zone is similar to a typical fusion zone as seen in many welded steels [15], as it is formed of elongated ferritic grains as indicated by the yellow circle and Widmanstätten ferrite (α_W). As mentionned by Fajt et al.[16] the microstructure in fusion zone which has been heated above the liquidus temperature is characterized by a typical casting structure.

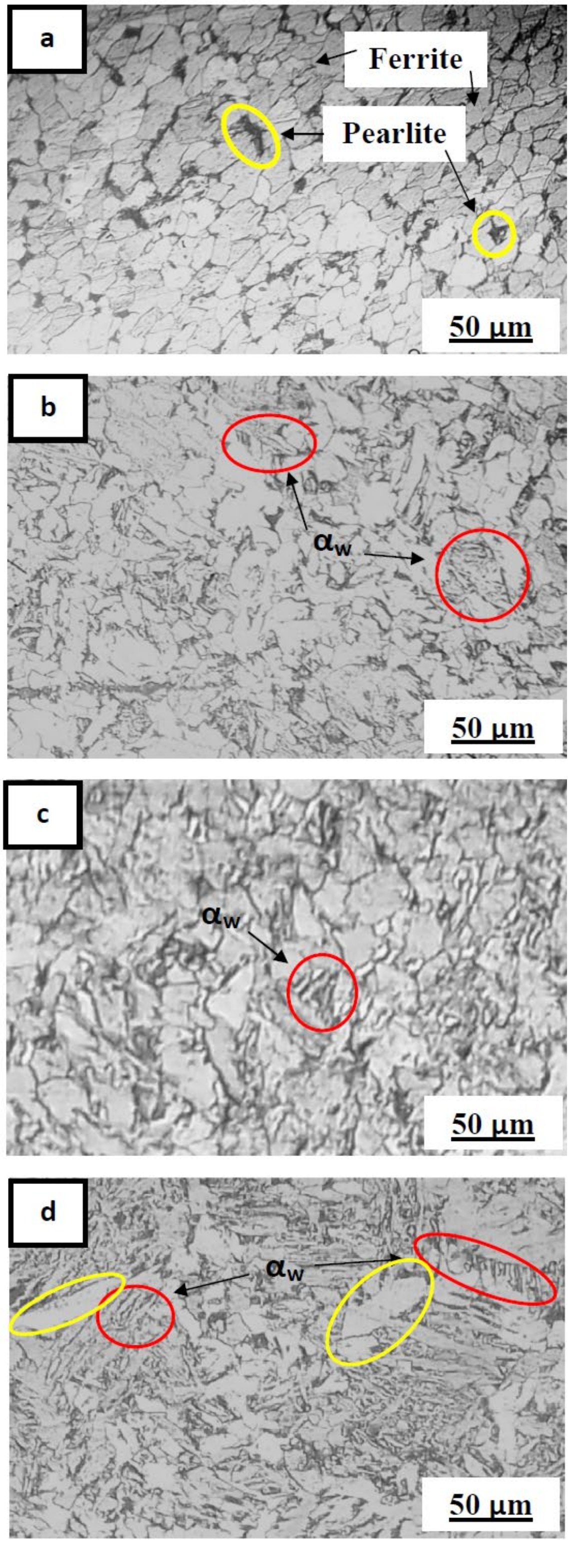

Fig. 3. Microstructures of real weldedC45steel.
(a) BM, (b) HAZ1, (c) HAZ2, and (d) FZ

3.2. X Ray diffraction analyses

Figure 4 presents the X-ray diffractograms obtained after heating the base metal in the simulator up to (325,475, 660, 850, 1090 and 1200°C). It can be observed that all the X-ray diffractograms reveal the peaks of the α-ferritic phase. It can be concluded that there has been no phase change or occurrence of a new phase, since only the ferritic peaks are present after the various thermal cycles. It can be also concluded that the HAZ in the welded joint of mild steel does not contain a new phase compared to the base metal.

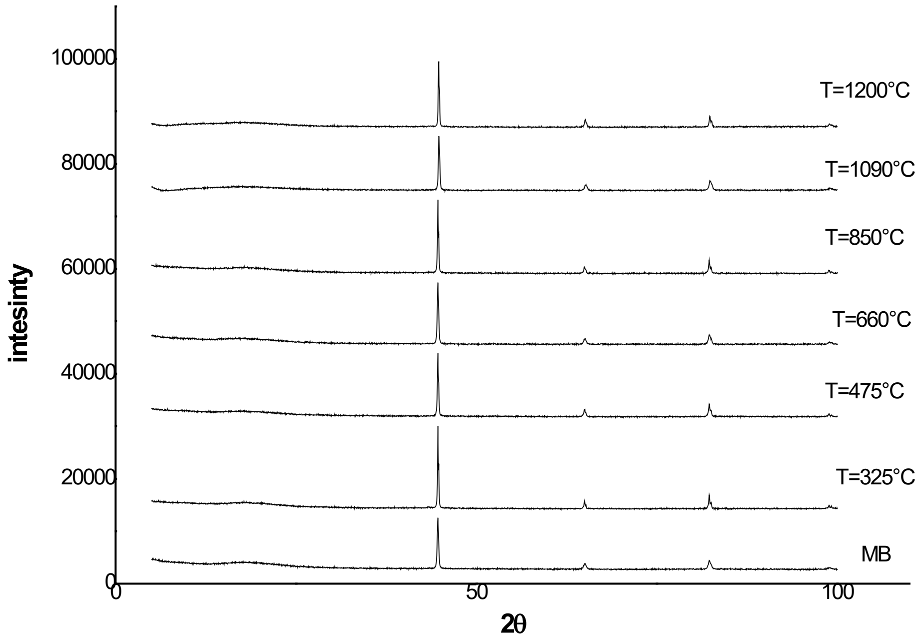

Fig.4. X-ray diffractograms obtained after heating the base metal in the simulator up to (325,475, 660, 850, 1090 and 1200°C).

3.3. Microhardness measurements

The hardness values measured after each thermal cycle applied to the C45 steel are represented in figure 5. On the other hand the hardness values measured through the real welded joint of the C45 steel are represented in figure 6. It can be concluded that the hardness curve in figure 5 is similar to part of the curve in figure 6 (indicated by a red circle).Overall, the hardness of the HAZ is low either in the real welded joint or in the simulated HAZ [17]. The hardness values of the simulated HAZ, at 325, 475 and 660 °C, change from 230 to 245 Hv. These values are similar to the hardness values of the HAZ measured on the real welded joint. However, with the increase of temperature, at 850 °C, the hardness HV decreases to the lowest value (175 Hv). After that, when the temperature increases to 1200 °C, the HV hardness increases again.This increase in hardness can be attributed to the development of new phases such as Widmanstätten ferrite (α_w) and massive ferrite (α_m). It can be deduced that the hardness of the HAZ change with the change of temperature. Khalaji et al. [18] also found that the hardness of HAZ in a tool steel increases with increasing temperature. This result indicates that the HAZ is not a homogeneous structure but that it can be divided into successive subzones and that each subzone is subject to a specific temperature.

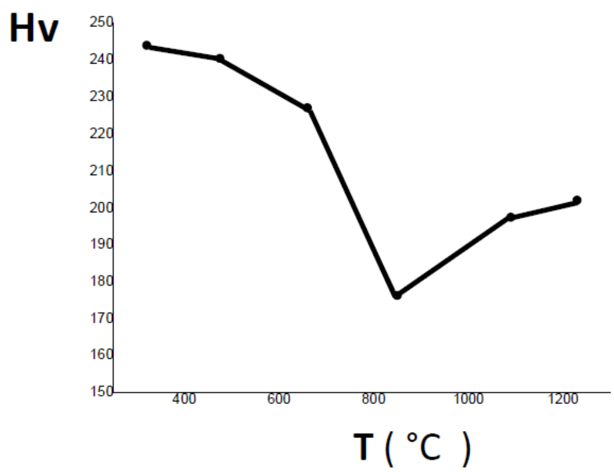

Fig. 5. Curve of measured hardness values corresponding to different thermal cycle simulation of C45 steel.

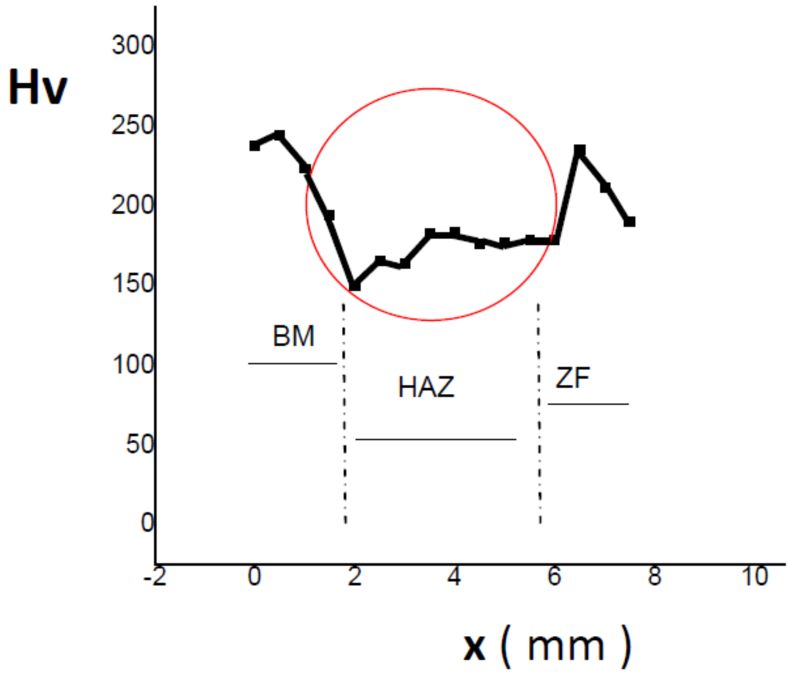

Fig.6 Hardness curve across the real weld joint of C45 steel.

Conclusion

The simulated HAZ of the welded C45 stainless steel was investigated by the thermal cycle simulation technique and compared to the HAZ obtained from the real welded steel. The following conclusions can be deduced:

• The microstructures obtainedfrom the heat-treated mild steel by the simulation technique revealed differents sub-zones in the heat-affected zones. The HAZ microstructure of the real welded joint is composed of two main subzones of different microstructures. However, the HAZ microstructures obtained by thermal cycle simulation revealed different sub-zones, where massive ferrite (αm) and Widmanstätten ferrite (αw) were observed by increasing temperature. Consequently, the thermal cycle simulation technique has given more details

• The HAZ has the lowest hardness in welded joint.

• The HAZ hardness values measured in the real welded joint are not different from the values measured in the specimens treated by thermal cycle simulation.

•The hardness values obtained by the thermal cycle are more precise than the hardness values measured on the real welded joint.

• The ICHAZ zone is the weak point of the weld from the mild carbon steels.

• Analysis by X-ray diffraction on the samples treated by the simulation technique did not reveal the formation of a new phases.

Acknowledgements

We thank the DGRSDT for its financial contribution to this research work.

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