Physical Simulation of Heat-Affected Zones in a Weld Metal Used with 500 MPa Offshore Steel

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Abstract: Offshore steels are engineered to have an outstanding combination of high strength and toughness to withstand extreme conditions needed in offshore and marine applications. Multiple welding passes may be needed when welding thick steel sections. In this case, microstructures of pre-existing passes are affected by the thermo-cycles caused by the subsequent passes. These heat-affected zones (HAZ) in the weld metal are less studied than the HAZs in the base metal next to the weld. HAZs after real welding process are relatively narrow and that way challenging to study and test reliably. Physical simulation provides an opportunity to produce different kinds of HAZs on sufficiently large area for various types of microstructural and mechanical properties characterization. Moreover, the effect of different welding methods and parameters can be easily studied by adjusting the simulation settings. Therefore, the aim of this study was to produce the coarse-grained (CGHAZ-W), intercritical (ICHAZ-W) and intercritically reheated heat-affected zones of the weld metal (ICCGHAZ-W) using physical simulation. Submerged arc welding (SAW) method was used to produce the original weld. HAZs with 2 different cooling times from 800 °C to 500 °C ($t_{8/5}$ = 5 and 30 s) were simulated utilizing Gleeble 3500 thermomechanical simulator. Microstructures were characterized using a Zeiss Sigma field emission scanning electron microscope. The results indicated that the original weld metal contained acicular ferrite nucleated on oxide inclusions, and thermal cycles induced microstructural changes in the weld metal, with each simulation variant resulted in distinctive features. Microstructures obtained by the physical simulation were supported by the numerical simulation results carried out by JMatPro software.

Keywords: simulation, steel, weld, microstructure, Gleeble, JMatPro, heat-affected zone

1. INTRODUCTION

High strength offshore steels are developed for demanding conditions where both high strength and toughness are required from the materials and structures manufactured of them. Some of the typical applications for such steels are offshore oil drilling platforms, wind power mills and ships body. For example, some parts of Valhall oil drilling platform in Norway were constructed using 500 MPa offshore steels (Willms, 2009).

As a result of thermomechanically controlled hot rolling process, the microstructure of 500 MPa offshore steel usually consists of fine-grained bainite and ferrite. However, the original microstructure is altered when steel is welded. The thermal cycles originating from the welding process cause different types of heat-affected zones (HAZ) depending on the peak temperature and cooling rate of each location in the steel. Additionally, welding of thick steel sections may require multiple passes causing additional thermal cycles on already altered microstructure as well as on the weld metal produced during previous passes.

The most important HAZs where the properties are expected to change are coarse-grained (CGHAZ), intercritical (ICHAZ) and intercritically reheated heat-affected zone (ICCGHAZ). Each of these zones is usually relatively narrow making it challenging to characterize their microstructures and mechanical properties reliably.

Physical simulation provides a way to produce microstructures imitating those of the different types of HAZs on sufficiently large area for mechanical tests and microstructural examination. It also makes it possible to study the effect of different welding methods and parameters by adjusting simulation parameters. Consequently, physical simulation is nowadays rather common way to study the HAZ microstructures and properties (Afkhami et al., 2022; Gáspár, 2019; Gáspár et al., 2019, 2015; Kovács et al., 2024; Laitinen et al., 2013; Mičian et al., 2020; Sisodia et al., 2019; Henri Tervo et al., 2020; H. Tervo et al., 2020; Tervo et al., 2021; Węglowski et al., 2013). However, there are less studies where the physical simulation has been applied on studying HAZs on weld metal caused by subsequent welding passes, referred as ”reheated zones” there (Kang et al., 2018; Tezuka et al., 1995).

Therefore, the aim of this study was to simulate different types of HAZs on the weld metal for enabling further investigation of them. The microstructures obtained by the physical simulation were compared with the numerically simulated microstructures calculated by the JMatPro software.

2. MATERIALS AND METHODS

The studied base material is a 16 mm thick 500 MPa offshore steel that was welded by single-pass submerged arc welding (SAW) method. The filler material is ESAB OK 13.24, a Ni- and Mo-alloyed, Cu-coated wire for SAW. The flux used with the filler material is OK Flux 10.62. The chemical composition of the base material and the filler material are presented in Table 1. The following welding settings were applied: the root gap 3 mm, the edge width 4 mm, and the bevel angle 40°.

Table 1. Chemical compositions of the studied base metal and filler metal.

	C	Si	Mn	Cu	Cr	Mo	Ni
Base	≤ 0.14	≤ 0.6	≤ 1.7	≤ 0.55	Cr+Mo ≤ 0.65		≤ 2.00
Filler	0.07	0.18	1.3	0.06	0.05	0.2	0.78

70 × 10 × 10 mm^3 specimens were machined keeping the welded joint nearly in the middle with 1 mm offset from the weld centerline in order to eliminate the effect of segregation. These specimens were used for the HAZ-W simulations. Example of the specimen is shown in Fig. 1.

Thermomechanical simulator Gleeble 3500 was used to produce coarse-grained (CGHAZ-W), intercritical (ICHAZ-W), and intercritically reheated heat-affected subzone on the weld metal (ICCGHAZ-W). The time and temperature points of thermal cycles were determined based on the Rykalin-3D model (Rykalin et al, 1971) and the GSL programs were manually written. This 3D model characterizes the temperature field generated by a moving point-like heat source on the surface of a semi-infinity body (Fig. 2). In this case 3D thermal conductivity is dominant while surface heat transfer is negligible. This model was selected considering the investigated 500 MPa steel is in the medium and heavy plate thickness (16 mm) where the Rykalin 3D model provides more precise result. Furthermore, this equation is independent from the plate thickness, therefore reduced number of variables needs to be considered. Each of the HAZ was simulated using two different cooling time from 800 °C to 500 °C ($t_{8/5}$ = 5 and 30 s) to represent the typical welding parameter variation. With regard to the selection of peak temperatures the motivation was to generate the most critical parts of the selected subzones, having the lowest toughness. Peak temperature of the CGHAZ-W simulations was 1350 °C, whereas in the ICHAZ-W simulations it was 815 °C defined by determining the A_{c1} temperature of the steel by using a dummy sample and adding 50 °C to it. The ICCGHAZ-W simulations were performed by combining the previously mentioned simulations. Simulation was based on Rykalin-3D model.

Microstructure of the simulated HAZ-Ws was characterized using field emission scanning electron microscope (FESEM, Zeiss Sigma). The acceleration voltage was 5 kV and the working distance varied approximately between 4 and 6 mm. The samples for microstructural characterization were cut from the Gleeble specimens keeping the simulation region in the middle. The samples were placed in specimen holders, grinded, polished and Nital-etched before the FESEM examination.

Hardness (HV10) was measured using a Reicherter UH250 universal macro-hardness tester according to the EN ISO 15614-1 standard.

Microstructures of the weld metal were also simulated numerically by calculating the continuous cooling transformation (CCT) and time-temperature transformation (TTT) diagrams using JMatPro (v12.2) software. The input for

Fig. 1. Specimen for the physical simulation of the heat-affected zones with the original weld metal in the middle.

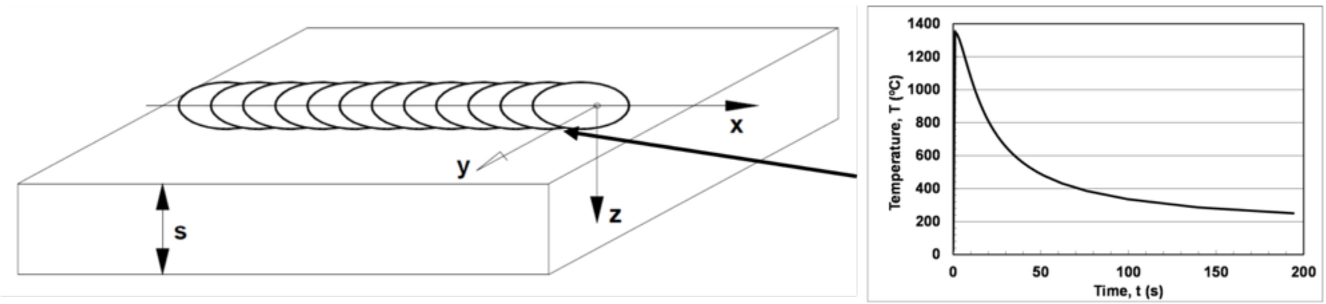

Fig. 2. CGHAZ-W thermal cycle based on the Rykalin-3D model.

the calculation is the fraction of each element present in the chemical composition of the steel in wt.%, estimated grain size and austenitization temperature. Outputs include the microstructure and hardness of the steel after various cooling rates.

3. RESULTS AND DISCUSSION

The simulated heat-affected zones on the weld metal as well as the original weld metal were examined by the FESEM to observe the changes in the microstructure due to the thermal cycles. The original single-pass weld metal consisted of acicular ferrite (AF). AF is a type of intergranular ferrite nucleating on certain type of non-metallic inclusions inside the prior austenite grains. AF consists of chaotically oriented needle-like grains with the width and length of approximately 1–3 μm and 5–15 μm, respectively. These grains form a complex interlocking structure, which efficiently prevents the fracture propagation, assisting to improve the toughness of the steel (Loder et al., 2016; Xiong et al., 2015). The original weld metal microstructure of the studied steel is presented in Fig. 3.

Intercritical heat-affected zone of the weld metal (ICHAZ-W) was simulated using the peak temperature 815 °C. The steel is partly austenitized in this temperature, so some changes in the microstructure are expected. The applied cooling times from 800 °C to 500 °C ($t_{8/5}$) were 5 s and 30 s to simulate the practical heat input range of the arc welding processes. Figures 4(a) and (b) show the ICHAZ-W microstructures.

The peak temperature for the coarse-grained heat-affected zone of the weld metal (CGHAZ-W) simulation was 1350 °C. Therefore, the steel was fully austenitized. In this case, it is expected that the prior austenite grain growth occurs. The transformation microstructure depends on the cooling rate. Using high heat input, the cooling rate slows down (cooling time increases), and the resulting microstructure is less hardened than with low heat input welding. Therefore, a significant difference in the hardness values between the samples simulated with $t_{8/5}$ = 5 s and 30 s was observed. The CGHAZ-W microstructures are presented in Figs. 4(c) and (d).

Intercritically reheated coarse-grained heat-affected zone of the weld (ICCGHAZ-W) combines the thermal cycles of CGHAZ-W and ICHAZ-W, in this order. Firstly, the steel is fully austenitized at 1350 °C, prior austenite grain size increases and the transformation microstructure becomes more or less hardened depending on the cooling rate. Secondly, the heat-affected microstructure experiences another thermal cycle, this time peaking at 815 °C, partly austenitizing the steel. As a result, coarsened prior austenite grains together with other microstructural changes are expected. The ICCGHAZ-W microstructures are shown in Figs. 4(e) and (f).

Weld metal microstructures were also simulated numerically by JMatPro software. Continuous cooling transformation (CCT) and time-temperature transformation (TTT) diagrams are presented in Figs. 5(a) and (b), respectively.

Based on the calculations from the CCT and TTT diagrams, it is evident that pearlite formation is highly unlikely, with ferrite and bainite being the predominant microstructures expected to form. Considering the cooling rates applied in this study, ferrite remains the primary microstructure. These results are in line with the obtained microstructures by the physical simulation.

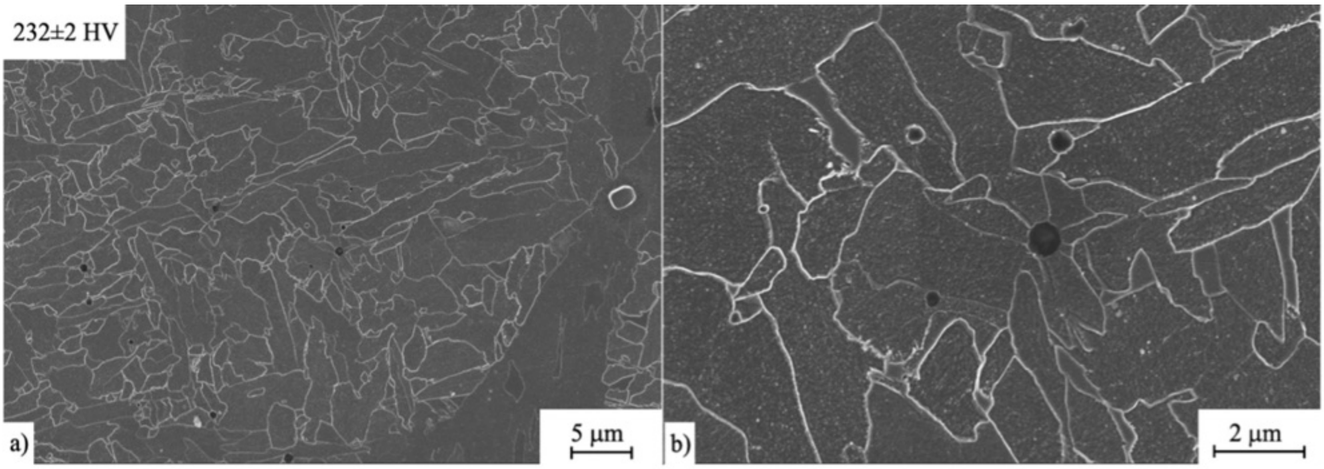

Fig. 3. FESEM images and the average hardness of the original weld metal taken with the magnification of 5000x (a) and 20000x (b). 95% interval for the mean hardness was determined using the student-t method.

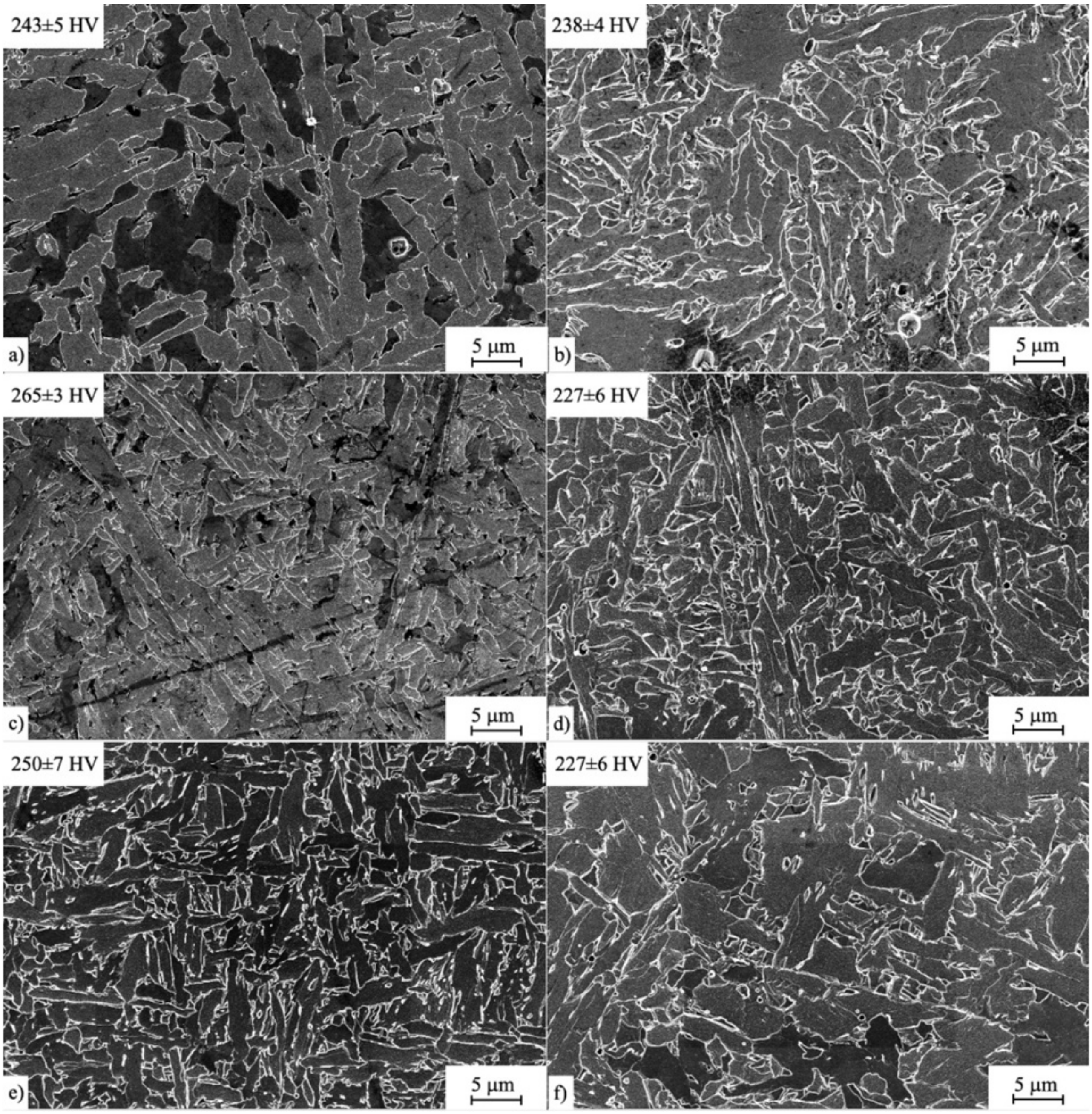

Fig. 4. FESEM images and the average hardness of the simulated ICHAZ-W (a) and (b), CGHAZ-W (c) and (d), ICCGHAZ-W (e) and (f) using the $t_{8/5}$ = 5 s and 30 s, respectively, taken with the magnification of 5000x. 95% intervals for the mean hardness's were determined using the student-t method.

4. CONCLUSIONS

Physical simulation was performed by Gleeble 3500 thermomechanical simulator to produce heat-affected zones on the pre-existing weld metal bonding two pieces of a 500 MPa offshore steel. The aim was to simulate the effect of multiple welding passes on the original single-pass weld microstructure. Following conclusions were made:

- Coarse-grained (CGHAZ-W), intercritical (ICHAZ-W), and intercritically reheated coarse-grained heat-affected zones (ICCGHAZ-W) were successfully simulated on the weld metal using two different cooling times ($t_{8/5}$ = 5 and 30 s) to be able to study the microstructures in each variant.
- The original weld metal consisted of acicular ferrite nucleated on oxide inclusions.
- As a result of the thermal cycles of the physical simulation, changes in the weld metal microstructure were observed. CGHAZ-W, ICHAZ-W and ICCGHAZ-W simulations all were seen to cause their characteristic features in the microstructure.
- Numerical simulation of the microstructures by JMatPro supported the results obtained by the physical simulation.

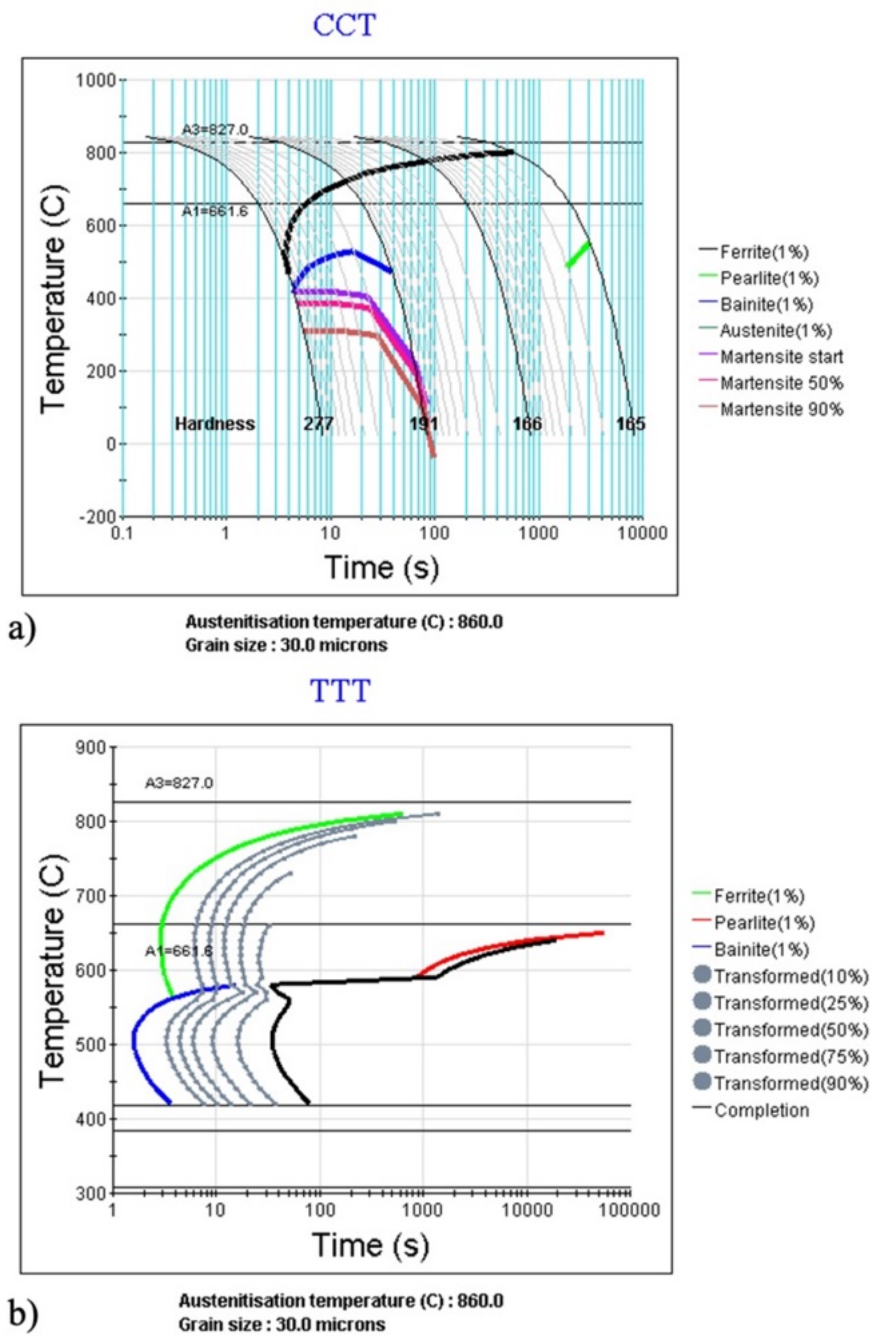

Fig. 5. Continuous cooling transformation (CCT) (a) and Time-temperature transformation (TTT) (b) diagrams of the weld metal calculated using JMatPro software.

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