A HEGESZTÉSI HŐCIKLUSOK VARRATTULAJDONSÁGOKRA GYAKOROLT HATÁSA 500 MPa FOLYÁSHATÁRÚ OFFSHORE ACÉLNÁL

THE EFFECT OF WELDING THERMAL CYCLES ON WELD PROPERTIES OF 500 MPa GRADE OFFSHORE STEEL

Marcell Gáspár
Institute of Material Science and Technology, University of Miskolc, 3515 Miskolc-Egyetemváros, Hungary
marcell.gaspar@uni-miskolc.hu

Judit Kovács
Institute of Material Science and Technology, University of Miskolc, 3515 Miskolc-Egyetemváros, Hungary
judit.kovacs@uni-miskolc.hu

Johannes Sainio
SSAB Europe Oy, Raahe, 92180, Finland
johannes.sainio@ssab.com

Henri Tervo
University of Oulu, Faculty of Technology, Materials and Mechanical Engineering, Oulu, 90570, Finland
henri.tervo@oulu.fi

Vahid Javaheri
University of Oulu, Faculty of Technology, Materials and Mechanical Engineering, Oulu, 90570, Finland
vahid.javaheri@oulu.fi

Antti Kaijalainen
University of Oulu, Faculty of Technology, Materials and Mechanical Engineering, Oulu, 90570, Finland
antti.kaijalainen@oulu.fi

Absztrakt – A tengeri acélszerkezeteknek ellenállniuk kell a sarkvidéki régió zord környezeti viszonyainak, amelyek üzemelésére a negatív hőmérsékleti tartomány mellett általában dinamikus terhelések is hatással vannak. Ezért az előírások különleges követelményeket támasztanak a tengeri alkalmazásokhoz használt acélok szövetszerkezetére és mechanikai tulajdonságaira vonatkozóan. Bár ezek az acélok általában jól hegeszthetők, az ömlesztő hegesztő eljárások által kifejtett hőhatás károsan hat a kedvező mechanikai tulajdonságokra. Jelen cikkben a többrétegű varratokban előforduló egyes varratsorok által kiváltott hőhatás következményeit vizsgáljuk fizikai szimulációval 500 MPa szilárdsági kategóriájú offshore acél esetén. A hegesztési hőciklusokat a reprodukálhatóság érdekében Gleeble 3500 fizikai szimulátorral állítottuk elő 70×10×10 mm-es próbatesteken, amelyeket 16 mm vastagságú acéllemezek fedettívű hegesztéssel készült kötéseiből munkáltunk ki keresztirányban. A fedettívű hegesztés alkalmazásának célja az volt, hogy egy rétegben elő lehessen állítani egy akkora, viszonylag homogén, varrattérfogatot, amely elegendően nagy fizikai szimulációs próbatestek kimunkálására. A hegesztett kötések elkészítéséhez ESAB OK 13.24 (EN ISO 14171-A: S3Ni1Mo0,2) huzalelektródát és nagy bázicitású salakot eredményező ESAB OK Flux 10.62 fedőport használtunk. Az illesztési rés 3 mm, az élszalag 4 mm, a leélezési szög pedig 40° volt. A fizikai *szimulációk elvégzésének célja a többrétegű varratokban előforduló lehető legkedvezőtlenebb szövetszerkezet létrehozása volt. Ezért szakirodalmi ajánlások és az adott acélra jellemző átalakulási hőmérsékletek alapján a hegesztési varratban kialakuló durvaszemcsés hőhatásövezeti sáv (CGHAZ-W) szimulálására 1350 °C csúcshőmérsékletet, az interkritikus hőhatásövezeti sáv (ICHAZ-W) előállítására pedig 815 °C-ot alkalmaztunk. Az interkritikus durvaszemcsés sáv (ICCGHAZ-W) szimulálására a két hőciklus kombinációját állítottuk be. A vizsgált $t_{8/5}$ hűlési időintervallum az ívhegesztési folyamatok hegesztési hőbeviteli tartományát figyelembe véve 5…30 s között volt. A többrétegű hegesztési varratban kialakuló hőhatásövezeti zónák tulajdonságait makrovizsgálattal, optikai mikroszkópos vizsgálattal és keménységvizsgálattal elemeztük.*

Kulcsszavak: offshore acélok, fizikai szimuláció, hegesztés, keménység, szövetszerkezet

Abstract (in English) – Offshore steel structures need to withstand harsh environmental conditions in the arctic region. Besides the negative temperature range, dynamic loads also affecting the operation of these marine structures. Therefore, special requirements are set by the standards for the microstructure and the mechanical properties of the steels for offshore applications. Although these steels generally have good weldability, the heat effect of fusion welding processes can destroy the outstanding mechanical characteristics. In present paper the effect of multipass welding thermal cycle on 500 MPa grade offshore steel weld is investigated by physical simulation. A Gleeble 3500 physical simulator is used to produce the welding thermal cycles on 70×10×10 mm samples manufactured in transversal direction from a submerged arc welded (SAW) joint of the examined 16 mm thick base material. The purpose of using SAW was to produce a large, relatively homogeneous, weld seam volume in one layer, which is sufficient to produce physical simulation specimens. An ESAB OK 13.24 (EN ISO 14171-A: S3Ni1Mo0,2) filler material and a high basicity bonded ESAB OK Flux 10.62 was used for the preparation of the welded joints. The root gap was 3 mm, the edge width was 4 mm, and the bevel angle was 40°. The aim of the physical simulations was to produce the possible most unfavourable multipass weld microstructure. Therefore, 1350 °C peak temperature was selected for the simulation of the coarse-grained heat-affected zone forming in the weld metal (CGHAZ-W), and 815 °C for the intercritical heat-affected zone (ICHAZ-W) considering the recommendation of the literature and the transformation temperatures of the given steel. For intercritically reheated coarse-grained zone (ICCGHAZ-W) the combination of these heat cycles was applied. The examined $t_{8/5}$ cooling time interval was between 5…30 s considering the relevant welding heat input range of arc welding processes. The properties of the HAZ subzones forming in the multipass weld metal was examined by macro test, optical microscopic test, and hardness test.

Keywords: offshore steels, physical simulation, welding, hardness, microstructure

1. Introduction

Offshore steels are typically used for oil drilling platforms, marine foundations, structural elements of offshore wind farms and shipbuilding, where the structures are exposed to harsh weather conditions and increased mechanical stress [1, 2]. Therefore, these steels need to have good strength and excellent toughness properties. The new generation of offshore steels in the medium strength (R_{eh}=400…500 MPa) category are produced with low carbon content and relatively low carbon equivalent which results a ferritic-bainitic microstructure, in which the formation of acicular ferrite has a crucial role to achieve the demanded mechanical properties [2, 3]. The chemical composition of these steels leads to good weldability properties, which can be predicted by the Graville diagram in which these offshore steels fall into the 1st area resulting low cold cracking sensitivity [4]. Nowadays, numerous research investigates the heat-affected zone (HAZ) characteristics of offshore steels and the formation of acicular ferrite on toughness properties, however there is less focus on weld characteristics [5, 6]. Present examination aims to analyse the weld properties of multipass welded joint by physical simulation in the relevant $t_{8/5}$ cooling time range of the industrially applied arc welding technology.

2. Materials and methodology

2.1 Base and filler materials

The chemical composition of the applied 500 MPa grade base and ESAB OK 13.24 (EN ISO 14171-A [7]: S3Ni1Mo0,2) filler materials are summarized in Table 1. The filler material is a nickel- and molybdenum alloyed, copper-coated wire for submerged arc welding (SAW), which is tested by CTOD. With the recommended OK Flux 10.62 excellent toughness values can be achieved. This filler material and flux combination is developed for low temperature steels and fine-grained steels in ship building and offshore industries.

Table 1. Chemical compositions of the applied base and filler materials (%)

Material	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
Base material	≤0.14	≤0.6	≤1.7	≤0.02	≤0.01	Cr+Mo≤0.65		≤2,00
Filler material	0.067	0.184	1.33	0.015	0.0078	0.053	0.187	0.784
Weld*	0.053	0.366	1.46	0.011	0.0058	0.061	0.201	0.893
Material	**Nb**	**V**	**Ti**	**Cu**	**Al**	**B**	**CEV**	**CET**
Base material	Nb+V+Ti≤0.26			≤0.55	≥0.02	N/A	N/A	N/A
Filler material	0.003	0.003	0.003	0.058	0.014	0.002	0.49	0.27
Weld*	0.024	0.006	0.007	0.202	0.022	0.0002	0.42	0.25

*OES analysis

2.2 Experimental circumstances

The experiments were performed by a Gleeble 3500 thermomechanical physical simulator which is frequently used for the HAZ tests [5, 8, 9]. By the equipment the desired subzones of the welded joint can be precisely and homogeneously created in a volume sufficient for the further material tests. The specimen size was 70×10×10 mm. In contrary to the conventional application of the simulator the present investigations aimed to analyse the

effect of multipass welding heat cycles on the weld properties. Therefore, SAW joints were prepared from the examined 16 mm thick offshore steel. The purpose of using SAW was to produce a large, relatively homogeneous, weld seam volume in one layer, which is sufficient to produce physical simulation specimens. An ESAB OK 13.24 (EN ISO 14171-A: S3Ni1Mo0,2) filler material and a high basicity bonded ESAB OK Flux 10.62 was used for the preparation of the welded joints. The root gap was 3 mm, the edge width was 4 mm, and the bevel angle was 40°.
The aim of the physical simulations was to produce the possible most unfavourable multipass weld microstructure. Therefore, 1350 °C peak temperature was selected for the simulation of the coarse-grained heat-affected zone forming in the weld metal (CGHAZ-W), and 815 °C for the intercritical heat-affected zone (ICHAZ-W). For low CEV steels the A_{c1} temperature can be considered as 765 °C, and the recommended peak temperature for intercritical simulation is A_{c1}+50 °C. The combination of these two heat cycles were used for the simulation of intercritically reheated coarse-grained zone (ICCGHAZ) which is often the most brittle local subzone in multipass welded joint. The examined $t_{8/5}$ cooling time interval was between 5…30 s considering the relevant welding heat input range of arc welding processes. Rykalin-3D model [10] was used for producing the HAZ cycles considering the following thermophysical properties of the investigated 500 MPa guaranteed yield strength steel: density δ = 7.7 g/cm^3, specific heat c_p = 0.46 J/g°C and thermal conductivity λ = 0.50 J/cms°C.

3. Materials tests and discussion

3.1 Optical microscopic tests

Optical microscopic (OM) examinations were carried out using the Zeiss Axio Observer D1m optical system. Gleeble specimens were perpendicularly cut to their longitudinal size at the thermocouples. The samples were grinded, sanded and polished. Then they were etched with 2% Nital (a 2% alcoholic solution of nitric acid). The OM images of the different weld subzones in the function of $t_{8/5}$ cooling time are summarized in Figure 1.
The original weld microstructure consisting of acicular ferrite nucleated from the oxide inclusions is still visible after the thermal cycles. However, as a result the acicular ferrite laths have become finer. This is shown especially in CGHAZ-W with the $t_{8/5}$ cooling time of 5 s. In ICHAZ-W and ICCGHAZ-W samples it is seen that carbon has diffused at the prior austenite grain boundaries forming carbon-rich constituents. This tendency is expected to increase along with the increasing cooling time, although not clearly visible in the images. Ferrite side-plates can be observed at the prior austenite grain boundaries in all cases.

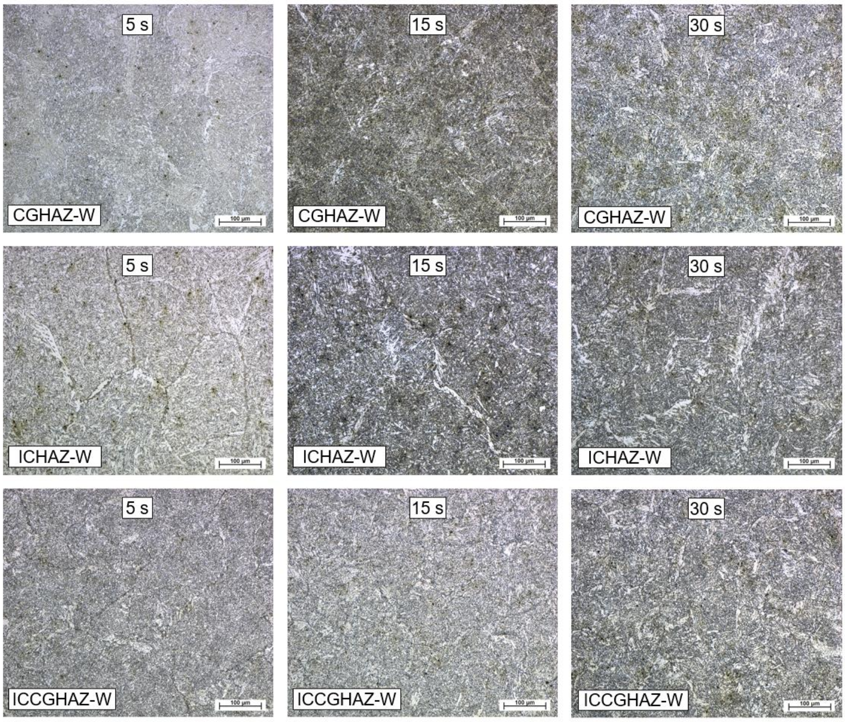

Figure 1.
Optical microscopic images of the simulated weld subzones, M=200×, 2% Nital

3.2 Hardness tests

A Reicherter UH250 universal macro-hardness tester was used for the hardness measurements. Evaluation was performed according to the EN ISO 15614-1 standard [11], which permits HV_{max} = 380 HV10 for the non-heat-treated welded joints (including HAZ) of thermomechanically rolled structural steels belonging to the 2nd group of CEN ISO/TR 15608 [12]. The transversal hardness distribution on the Gleeble specimen is illustrated together with the macro image on Figure 2. The weld has nearly equal hardness to the base material due to the selected matching wire electrode, however approximately 10% softening occurs in the HAZ.

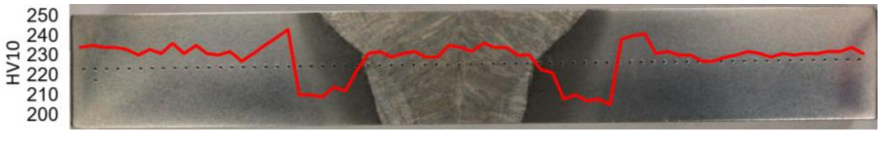

Figure 2.
Macro image and hardness distribution on the Gleeble specimen

Five measurements were done on the cut surface of Gleeble samples. The average macro hardness values of the simulated subzones are presented in Figure 3. Slight hardening only occurred in the short (5 s) cooling time which values were safely under the permitted 380 HV10 value of the governing standard. The medium 15 s cooing time resulted almost equal hardness with the base material, while a minimal softening occurred in the CGHAZ-W and ICGHAZ-W at 30 s. In general, the hardness has reduced by the increasing cooling time in all subzones.

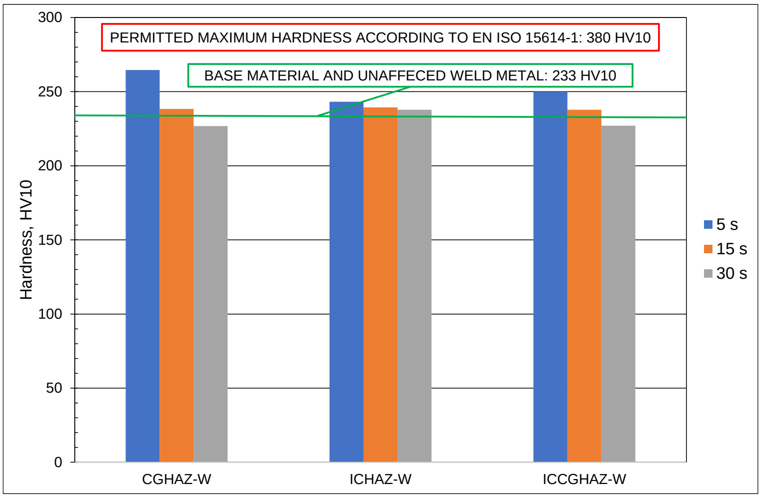

Figure 3.
Hardness of the simulated weld subzones

.4. Summary

1. The critical heat-affected subzones within the weld of multipass welded joint were physically simulated.
2. Neither significant hardening nor softening was observed in the simulated CGHAZ-W, ICHAZ-W and ICCGHAZ-W.
3. The $t_{8/5}$ = 15 s cooling time resulted nearly same hardness as the unaffected weld metal.
4. Microstructures of all simulated HAZ-W samples consisted of acicular ferrite. The ferrite laths had become finer and carbon-rich constituents had formed at the prior austenite grain boundaries due to the thermal cycles.

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