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Experimental Analysis of HSLA Steel Welded Joint Fracture Behaviour

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Abstract

In order to assess the integrity of welded pressure vessel containing a crack, the behavior of three-point bending specimens made of HSLA steel welded joint are tested at -40 °C, and their fracture behaviour analyzed, as a conservative measure of crack resistance. Specimens were made of low-alloyed steel NIONIKRAL 70, welded by SAW process. Surface notches were machined by the electro-erosion method in the parent metal (PM), heat affected zone (HAZ) and weld metal (WM). The highest resistance to cracking was in PM, and the lowest one in WM, due to so-called pop-in behaviour.

Keywords: HSLA, SEM micrographs, welding, fracture

1. Introduction

The most important advantages of high-strength low alloy (HSLA) steels compared to other construction steels are reduction in structures' weight, increase in load capacity, service life extension and lower production costs. Because of their good weldability, HSLA steels are progressively used for fabricating of welded structures intended for demanding exploitation conditions. However, Gliha et al. (2004) point at one disadvantage of this type of steels, their susceptibility to brittleness during multi-pass welding because the fact that existence of local brittle zones reduces the load-carrying capacity of the welded joint (WJ) and may compromise the integrity of the whole welded structure.

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Bearing in mind that in practice there is no WJ without any imperfection, acceptance criteria that serve to evaluate the significance of the imperfections in welded structures, have been elaborated and are used in the design (EPRI, R6, SINTAP etc). A designer should always keep in mind that the calculation methods of a homogeneous structure in the presence of the crack is different from the calculation methods for stresses occurring in a heterogeneous welded structure. Zhang et al. (1997) stated that because of microstructural and mechanical heterogeneity of WJ, the mismatched geometry and weld metal (WM) properties have significant effect on toughness, crack driving force and fracture assessment of welded structures. Read and Petrovski (1992), Petrovski and Koçak (1994) and Kim and Schwalbe (2001) among others, dealt with the fact that the accurate estimation of mismatch yield loads is essential for assessing cracked welded constructions integrity. For adequately overmatched WJ (weld metal yield strength higher than that of the parent metal - PM) in combination with relatively small flaws, plastic strains in WM will be small even in presence of cracks. In such situation, low plastic strain in WM near the crack generate a low fracture driving force. When welding constructions made of HSLA steels, the overmatched WJ are more often performed, Gubeljak (1999). Yet, in some cases, undermatched WJ are preferred. Satoh and Toyoda (1975), investigated WJ in welded structures of HSLA steel heavy plates, having weld metal yield strength lower than the PM (undermatching), which has been found effective for preventing cold cracks in WM. In case of undermatching of HSLA steels with yield strength above 700 MPa, fracture of transverse butt joints in general occurs in the WM due to concentration of the plastic strain in WM and the WJ behaviour is governed by the fracture toughness of the WM, Petrovski and Koçak (1993). Sedmak and Petrovski (1992) investigated HSLA steel with ultimate tensile strength of 800 MPa from which the highly stressed penstock of the Bajina Bašta reversible hydroelectrical power plant was made. Some test results of WJ behaviour have shown higher value of yield strength of the weldment produced by submerged arc welding with undermatched WM than the yield strength of proper WM. This meant that a WJ could be stressed to higher level than WM yield strength, which could be explained by existence of constrained soft interlayer effect. Similar to that were conclusions in couple of papers on mismatching effects in HSLA steel welded joints, both for undermatching, Adziev et al. (2002), Adziev et al. (2003) and Adziev et al. (2008), and overmatching effect, Doncheva et al. (2015). Few other references also considered different fracture mechanics properties in welded joints made of high temperature steels, P22 and P91, Jovanovic et al. (2020), Camagic et al. (2017), Camagic et al. (2014)

In this paper, one part of extensive investigation of HSLA steel grade NIONIKRAL 70 is presented. Several papers were published, presenting obtained results. The investigation included determination of tensile properties, impact energy, fracture mechanics parameters, microstructural characterization and low-cycle fatigue testing of parent steel and its welded joints, in order to gain insight into its behavior during exploitation. Grabulov et al. (2002) showed two methods for the evaluation of static and dynamic *J-R* curves on precracked Charpy specimens made of NN-70. In order to study the influence of plasticity, i.e., the condition for slow steady tearing, Milovic et al. (2011 and 2019) presented the concept of determine the crack growth resistance using the contact between crack driving force curves and crack resistance curves. The behavior of the parent NN-70 steel and its coarse-grained heat affected zone obtained by thermal simulation, exposed to low-cycle fatigue was described in Aleksic et al. (2019), while the behavior of NN-70 weldments exposed to low cycle fatigue was presented by Bulatovic et al. (2014). The impact test results performed on NN-70 PM and its WJs was presented by Bulatovic et al. (2021).

Here, the results of microstructural response of different subregions of the welded joint specimens exposed to three-point bending at operating temperature -40 °C, are presented and discussed.

2. Material

High strength low-alloyed (HSLA) steel (0.106% C, 0.209%Si, 0.220% Mn, 0.05% P, 0.017% S, 1.26% Cr, 2.361% Ni, 0.305% Mo, 0.246% Cu, 0.01%Nb, 0.019%Co) used in the present investigation was produced in a high-frequency electric furnace, casted in ingots, rolled in slabs and then into 18 mm thick plates. Heat treatment regime was selected after determine transformation temperatures (A_{C1}=723.7 °C, A_{C3}=818.6 °C, A_{r1}=633.5 °C and A_{r3}=708 °C. Heat treatment involved water quenching from 890 °C followed by tempering at 660 °C. The tempering time was 9 minutes/mm thickness.

This particular HSLA steel, named NIONIKRAL 70 (NN-70), was intended for welding of ships and pressure vessels for operating at low temperatures. At room temperature, ultimate tensile strength of 824 MPa and yield strength of 780 MPa, both parallel to rolling directions, with elongation of 19%, were obtained.

3. Experiment

Steel plates, 18 mm thick, made of NN-70, was butt welded by Manuel Metal Arc (MMA) welding process with basic low hydrogen stick covered electrodes, with undermatched WM. Multi-layered asymmetric double-V groove welded joint was fabricated under conditions that can best simulate the stress distribution of the real structure, Zrilic et al. (2007). The chemical composition and mechanical properties of the used electrodes are selected to obtain an under-matched weld deposit with the yield stress of about 700 MPa compared to parent steel yield stress of 780 MPa, which gives 10% under-matching. Data about weldability of the investigated NN-70 steel and its cracking sensitivity are described by Zrilic et al. (2007).

Experimental work was carried out to determine the fracture behavior of welded joints made of NN-70 steel. To investigate its static behavior in the presence of a crack, the fracture mechanics tests were done on fatigue pre-cracked three-point bending (TPB) specimens, see Fig. 1, with geometry shown in Fig. 2. Crack propagation resistance was measured at three locations of the WJ of NN-70. A starter notch for the cracks was introduced in the PM, heat affected zone (HAZ) and WM subregions of the WJ. The pre-cracking was done on the universal testing machine AMSLER.

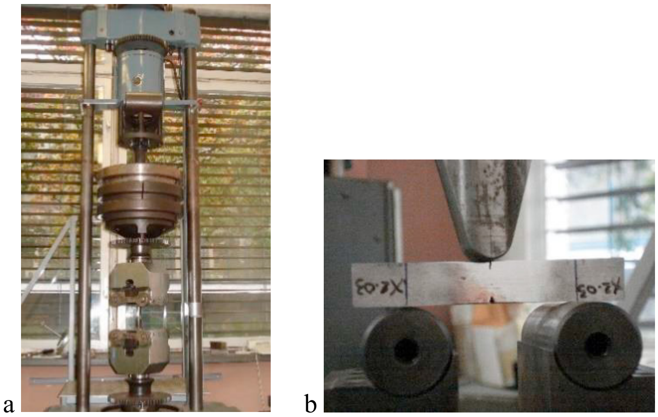

Fig. 1. (a) Universal testing machine Amsler; (b) Fatigue precracking of TPB specimen with the starter notch in WM

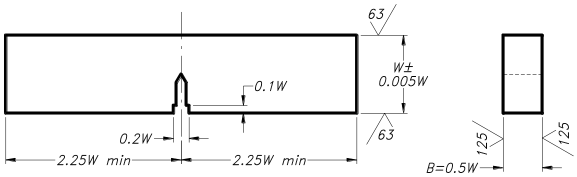

Fig. 2. Geometry of 3PB specimen used for Fracture mechanics tests.

Fracture mechanics tests were done on 3PB specimens with previously made fatigue pre-crack. The basic diagram, see Fig. 3, is a record of the load vs. crack mouth opening displacement (CMOD), obtained by successive loading and partial unloading at test temperature of -40 °C.

4. Results and discussion

Typical plots load vs. CMOD of fatigue pre-cracked PM, HAZ and WM TPB specimens obtained at low operating temperature are shown in Fig. 3. The shape of obtained load vs. CMOD curves depends on crack location. In PM the dimple type of fracture micromechanism was observed, with the presence of dimples of ductile tearing. Point A, see Fig. 4, corresponds to the region next to the stretch zone in PM, where the maximum load value is reached, while point B indicates the appearance of fracture in the crack propagation region. The fracture took place in dimple type fracture mode, i.e., by the ductile microvoid coalescence as the fracture micromechanism.

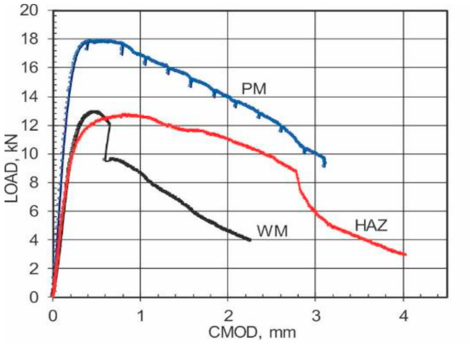

Fig. 3. Load vs. CMOD curves of fatigue pre-cracked PM, HAZ and WM specimens tested at -40 °C.

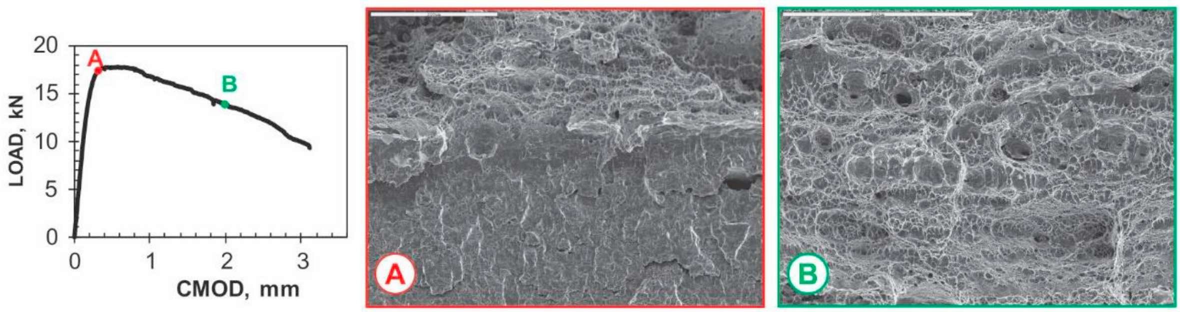

Fig. 4. Smooth Load vs. CMOD curve for PM, with micrographs of fractured crack surfaces tested at -40 °C: (A) and (B), observed by SEM.

When it comes to WM specimen, Fig.5, the diagram was obtained with the drop in load corresponding to the sudden crack propagation. Point A indicates the fracture surface appearance next to the stretch zone shortly before reaching the maximum load while point B shows the fracture surface appearance shortly after maximum load. Point C shows the presence of pop-in instability with intergranular fracture surface look. We will consider it a crack-arrest, meaning the crack came across some weak point such as cavity or impurity, i.e., the crack grew suddenly and then stopped. Then crack passed that brittle zone and entered ductile zone, so the fracture micromechanism exhibit a dimple fracture type, only dimple size was larger than in case of PM. Point D indicates also the dimple micromechanism of fracture.

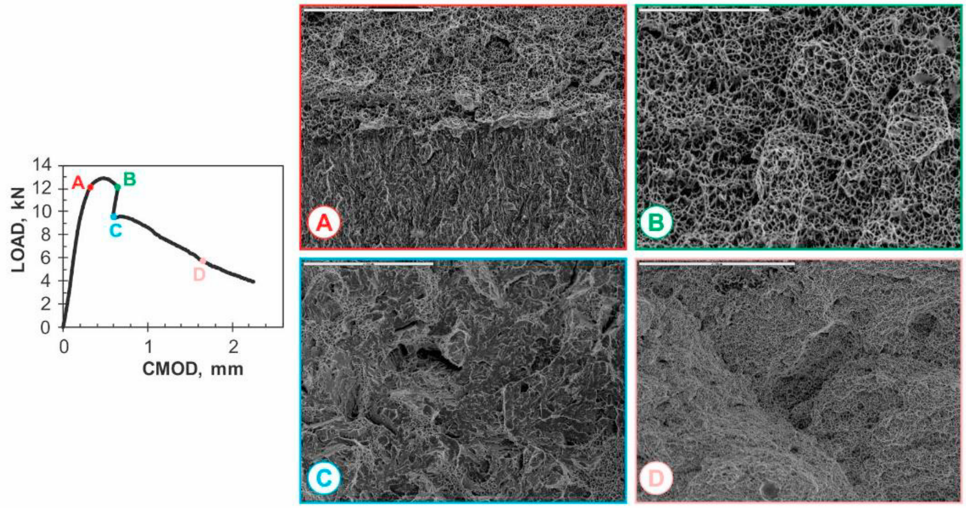

Fig. 5. Load vs. CMOD curve for WM, with micrographs of fractured crack surfaces tested at -40 °C: (A), (B), (C) and (D), observed by SEM.

SEM micrographs taken on the fracture surface of HAZ specimen, see Fig. 6, shows stretch zone just before reaching maximum load, point A, fracture surface for crack propagation after maximum load-point B. Points C and D, where there was a load drop, denote some instability, where the presence of mixed mode fracture, dimple and transcrystalline fracture types, was observed.

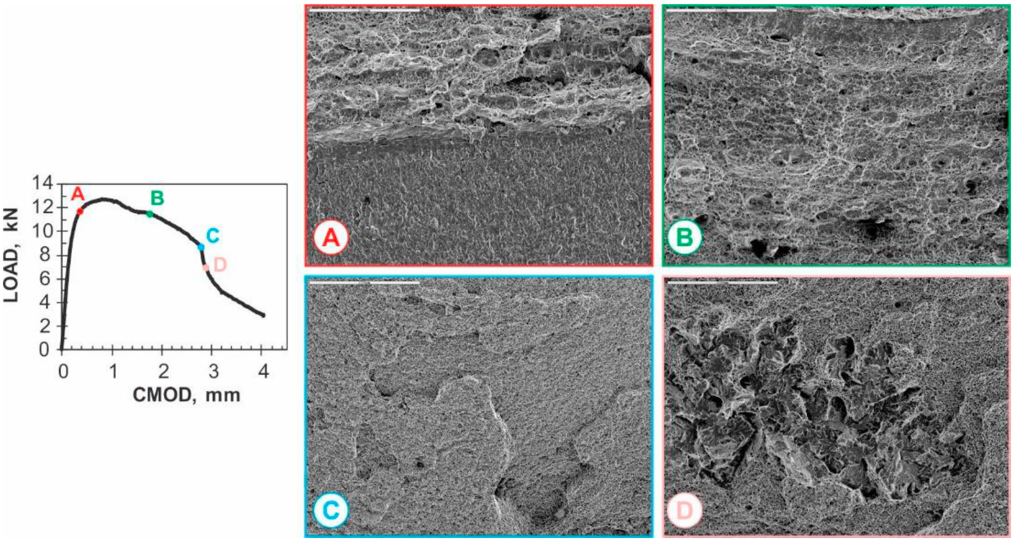

Fig. 6. Load vs. CMOD curve for HAZ, with micrographs of fractured crack surfaces tested at -40 °C: (A), (B), (C) and (D), observed by SEM

5. Conclusion

Based on presented experimental results, following conclusions can be made:

- In case of all tested PM specimens, smooth load vs. CMOD diagram was obtained. Dimple cleavage fracture mode was observed which is favorable to high fracture toughness of NIONIKRAL 70 steel.
- In case of some specimens with fatigue pre-crack positioned in WM, diagrams with decreasing applied load during crack propagation were obtained. This can be explained by local brittle zones in WJ, like voids, inclusions or impurities, so the crack grew rapidly and then slowed down after entering a ductile region.
- In all specimens taken from three different WJ subzones, the presence of dimples corresponding to the stable crack growth, was detected. In some places where the pop-in occurred, in addition to dimple fracture, transcrystalline brittle fracture is also present.

Acknowledgements

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