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The influence of hydrogen charging on the notch tensile properties and fracture behaviour of dissimilar weld joints of advanced Cr–Mo–V and Cr–Ni–Mo creep-resistant steels

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The influence of hydrogen charging on the room-temperature tensile properties and fracture behaviour of two dissimilar weld joints has been investigated. The weld joints were either ferritic/ferritic (T91/STN15128) or ferritic/austenitic (T91/TP316H). The tensile tests were carried out using the samples with a circumferential notch. The position of notch was individually located in different weld joint regions, either in the heat-affected zones (HAZ) or weld metal (WM). The application of hydrogen charging had detrimental effect on strength and plasticity of the weld joint T91/STN15128. The most significant deterioration of the notch tensile properties was measured for the STN15128 HAZ. The hydrogen charging had only small influence on the strength of the weld joint T91/TP316H but remarkable detrimental effects on the plasticity. In the PWHT state (without hydrogen charging) all regions of the studied weld joints fractured by ductile dimple tearing. The failure initiated on the secondary phase particles and/or inclusions as well. In contrast, the failure after hydrogen charging initiated in the vicinity of sizeable particles and showed a transition from the ductile dimple tearing to the transgranular cleavage and/or quasi-cleavage fracture mode.

1. Introduction

Advanced creep-resistant steels are used for constructing of different parts of steam boilers in energy industry [1]. The structural parts working at different operating conditions are joined by dissimilar welds [2–4]. In many cases, the used filler materials differ vastly from both welded base materials. Such dissimilar welds are commonly denoted as transition welds [2,5,6].

The creep-resistant steels and their weld joints are often subjected to the presence of hydrogen during operation of power plants. The hydrogen effects at high temperatures and pressures may cause the destabilisation of carbides in microstructure of the steels [7]. Moreover, the hydrogen absorbed on dislocations promotes the occurrence of hydrogen embrittlement (HE) at low temperatures [8]. The coarse-grained HAZ in the welds of Cr–Mo–V ferritic steels is known to be the most susceptible region to the HE. The embrittling effects are typically manifested by a significant decrease of plastic properties such as fracture toughness and ductility [7,9]. The coarse-grained HAZ exhibits generally the highest hardness and the lowest toughness in these welds. At the presence of hydrogen and tensile stresses after cooling, the brittle fracture occurs by hydrogen induced cracking (HIC) [8–10].

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Generally, the Cr–Ni–Mo austenitic stainless steels possess a good resistance against the HE. However, after the precipitation of some secondary phases during thermal exposure, the toughness of these steels may also be lowered at the presence of hydrogen [11–15].

The aim of this work is investigation of the effects of hydrogen charging on the room-temperature tensile properties and fracture behaviour of ferritic/ferritic (T91/STN15128) and ferritic/austenitic (T91/TP316H) dissimilar weld joints. The investigation is focused on the critical parts of the weld joints, specifically the HAZ regions and weld metals.

2. Experimental procedure

The tubes (38 mm outer diameter, 5.6 mm wall thickness) of dissimilar steels were circumferentially welded by classical TIG method using different filler materials. In the case of T91/STN15128 ferritic/ferritic weld joint the filler metal was based on T24 steel composition, whereas for the welding of T91/TP316H weldment the Ni-based filler metal (Thermanit Nicro 82) was used. The chemical compositions of the materials used for the production of the weld joints are given in Tables 1 and 2.

After the welding, the post-weld heat treatments (PWHT) were carried out subcritically (i.e. below Ac1 temperature), with respect to the lower-alloyed steels of the studied weld joints. Thus, the holding PWHT temperatures were 720 °C and 750 °C for the weld joints T91/STN15128 and T91/TP316H, respectively. In order to avoid thermal stresses, the heating and cooling rates were controlled to be maximally 150 °C/h. After the performed PWHT regimes, the tubular weldments were longitudinally cut by spark erosion into the cross-weld (c-w) blocks (see Fig. 1). One of the cut blocks was used for the metallographic examination. For the etching of dissimilar materials the different etching solutions were used (see Table 3). From the other c-w blocks the cylindrical tensile samples (4 mm body diameter, 40 mm gauge length, M6 head thread) were machined by turning. The body surface of the prepared c-w tensile samples was etched in order to visualise their HAZ regions. Afterwards, the specimens were circumferentially notched. The position of notch was located alternately in different parts of the c-w samples (i.e. either in WM or the first HAZ or the second HAZ). Prior to tensile tests, the notched samples were electrolytically charged with hydrogen in the solution of 1 M HCl + 0.1 N NH_2SO_4 (hydrazine sulphate) at the current density of 200 A m^{-2}. After the hydrogen charging, the tensile specimens were put into the container with liquid nitrogen and transported to the tensile testing machine. The period between hydrogen charging termination and conduction of the tensile tests took at most 30 min. The room-temperature tensile tests were carried out at loading rate 0.5 mm min^{-1}. From the performed tensile tests the values of notch strength (Rm_V) and reduction in area (RA) were determined. The fracture surfaces of broken tensile samples were fractographically analysed by scanning electron microscopy (SEM).

3. Results and discussion

3.1. Weld joint T91/STN15128

Fig. 2 shows light optical microstructures of different regions of the dissimilar T91/STN15128 ferritic/ferritic weld joint in PWHT state. The HAZ region of T91 steel (Fig. 2a) is formed of highly tempered martensite within coarsened prior austenite grains. Fig. 2b represents the tempered bainitic–martensitic microstructure of T24 steel based weld metal. Despite a strong tempering effect, the microstructure still preserves its columnar features. The HAZ region of STN15128 steel (Fig. 2c) consists of mixture of tempered martensite and/or bainite and the grains of proeutectoid ferrite.

The results of tensile tests of the notched samples of the weld joint T91/STN15128 without and with hydrogen charging are documented in Fig. 3. After the initial hardening effect of hydrogen a rapid decrease of strength occurred at longer charging duration (see Fig. 3a). Regarding the plasticity (Fig. 3b), hydrogen caused a gradual decrease of RA values with increasing charging duration. Consequently, it can be stated that the hydrogen charging of the weld joint T91/STN15128 resulted in deterioration of strength and plasticity of all tested regions (i.e. both HAZ regions and weld metal). The increasing detrimental effects of hydrogen charging on the tensile properties of the weld joint T91/STN15128 were found to be in the following order of regions: T91 HAZ, T24 WM, and STN15128 HAZ.

The susceptibility of different regions to hydrogen embrittlement depends on their chemical composition (differences in Cr and C contents), state of microstructure affected by welding and subsequent PWHT conditions (size and distribution of precipitated carbides) and the amount of absorbed hydrogen which invokes the plastic instabilities during loading [16–18]. The important factor which also affects the resulting tensile properties is the local stress state at the notch position. It is known that the presence of notch induces a triaxial stress state which intensifies the hydrogen embrittling effects by tensile loading due to the migration of hydrogen towards the stress concentrator [17–19].

Table 1
Chemical composition [wt%] of the materials used for the production of the ferritic/ferritic weld joint T91/STN15128.

Material	C	Si	Mn	S	P	Cr	Ni	Mo	V	Ti	Nb	B	Fe
T91	0.1	0.38	0.49	0.001	0.02	8.5	–	0.94	0.23	–	0.069	–	Balance
STN15128	0.14	0.33	0.54	0.005	0.018	0.45	–	0.57	0.25	–	–	–	Balance
T24	0.055	0.65	0.65	0.007	0.012	2.36	0.06	0.95	0.25	0.072	–	0.002	Balance