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Environmental Cracking Behavior of Submerged Arc-Welded Supermartensitic Stainless Steel Weldments

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Supermartensitic stainless steel welds produced by submerged arc welding were assessed for their microstructure and properties. Slow strain rate tests conducted on these specimens revealed that both the parent material and the weld metals are susceptible to cracking under conditions of hydrogen (H) charging.

Keywords hardness, hydrogen cracking, slow strain rate test, supermartensitic stainless steel, welding

1. Introduction

The oil and gas industry employs a wide variety of materials ranging from American Petroleum Institute (API) grade carbon/low alloy steels to highly alloyed stainless steels, especially for the flow lines and offshore structures. The recently developed supermartensitic stainless steels (SMSS) are gaining popularity over the current materials used in aggressive environments due to their better weldability, better elevated temperature mechanical properties, and superior stress corrosion cracking resistance.[1,2] The stress corrosion cracking behavior of SMSS base materials in sweet/sour environments has been investigated,[3,4] and the performance of weldments produced with non-matching duplex stainless steel fillers have also been addressed.[5,6] Efforts are being made to understand the mechanical and corrosion behavior of SMSS weldments obtained with matching supermartensitic stainless steel consumables.[7] The current work addresses the tensile behavior of SMSS weldments in the presence of hydrogen under slow strain rate test conditions.

2. Experimental

The current investigation used two grades of SMSS materials with the chemical compositions given in Table 1. Butt joint welds were produced with plates of SMSS of 20 mm in thickness by submerged arc welding (SAW) under optimized welding conditions using a supermartensitic stainless steel filler wire. The root pass was laid down with plasma arc welding, and the subsequent filling/capping passes were made with SAW, on a double V groove joint. The weldments were subjected to a post-weld heat treatment at 630 ± 10 °C for 30 min for relieving the stresses and also to accomplish tempering. For ease of referencing, the high grade and medium grade SMSS weldments are designated as HW and MW, respectively.

Metallographic specimens were prepared and etched in 50 ml HCl + 5 ml HNO_3 + 50 ml H_2O solution. Slow strain rate tensile tests (SSRTs) were performed using cylindrical specimens of dimensions, as shown in Fig. 1, to assess the tensile behavior in air and under conditions of hydrogen (H) charging. Specimens were polarized at a potential of −1200 mV versus Ag/AgCl in 0.1 M NaOH solution to provide hydrogen charging conditions, and the specimens were kept at a small pre-load of 0.5 KN (~25 MPa) for 24 h prior to start of tests. Reference tests in air and all SSRTs were performed at a strain rate of 10^{-6} s^{-1}. All the tests were evaluated following the ISO standard 7539-Part 7 "Slow Strain Rate Tests,"[8] and the fracture surfaces of the SSRT specimens were examined in a scanning electron microscope.

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3. Results and Discussion

The microstructure of the high and medium grade SMSS base materials (Fig. 2a and 2b) reveal tempered low-carbon martensite. Figure 3(a) shows an overview of the HW weldment comprising the weld metal, the heat affected zone, and the base material. Figure 2(b) shows that the coarse and fine-grained heat affected zones in this weldment had a tempered martensitic structure. The MW weldment also had similar features. Figure 4(a) and (b) indicate that the weld metal region of weldments HW and MW also had a fine tempered martensitic structure.

Table 1 Chemical Composition of SMSS Base Materials and Filler Wires (wt.%)

Material	C	Mn	Si	Cr	Ni	Mo	Cu	N
High grade	0.006	1.870	0.294	11.650	6.498	2.330	0.475	0.009
Medium grade	0.014	1.030	0.380	11.650	4.730	1.420	0.250	0.011
Solid wire electrode	0.013	0.670	0.500	12.370	6.370	2.650	…	0.002

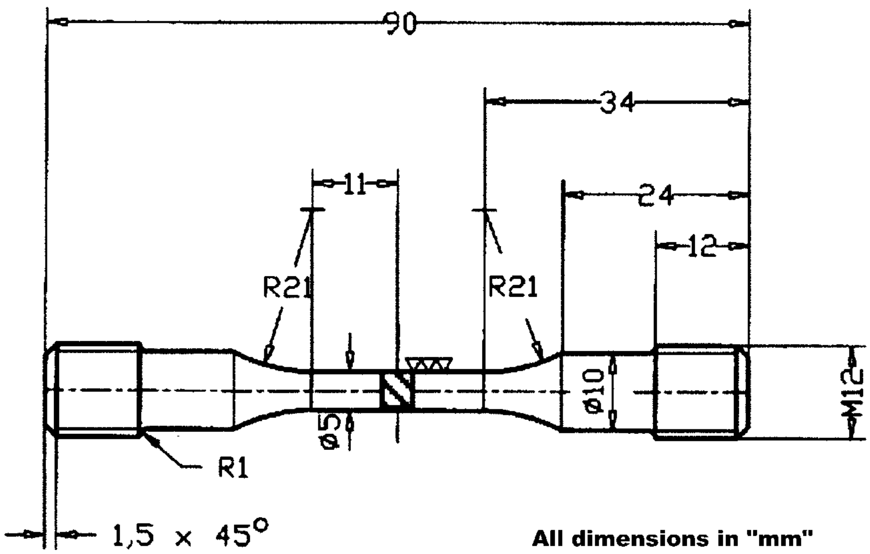

Fig. 1 SSRT test specimen configuration

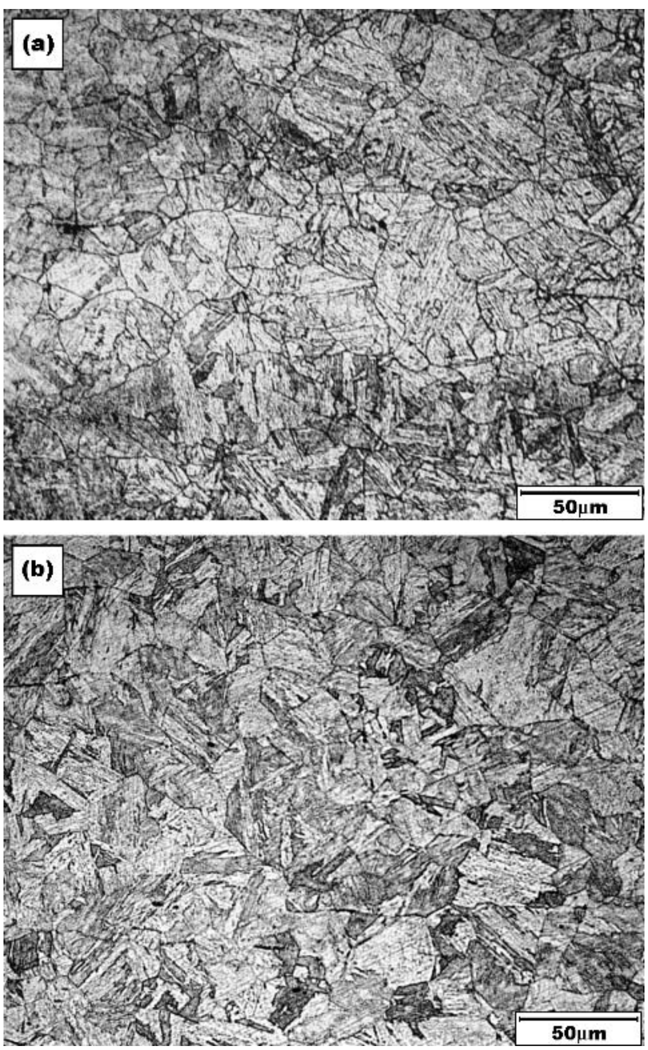

Fig. 2 Microstructure of SMSS base materials: **(a)** high grade, **(b)** medium grade

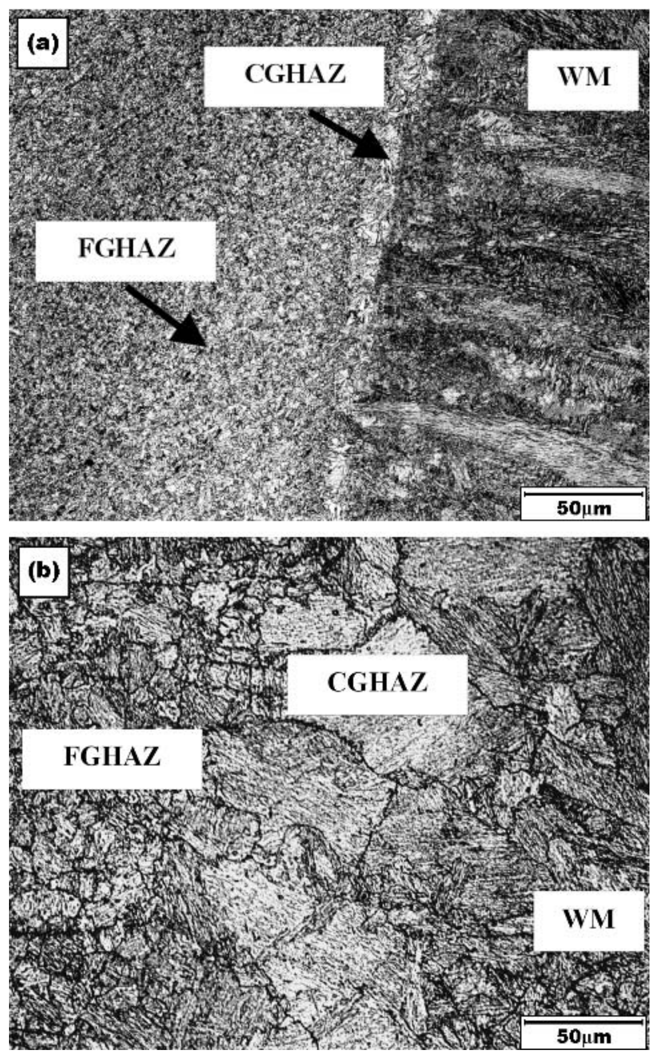

Fig. 3 Microstructures of the composite zone of weldment HW at different magnifications. WM, weld metal; FGHAZ, fine-grained heat affected zone; CGHAZ, coarse-grained heat-affected zone

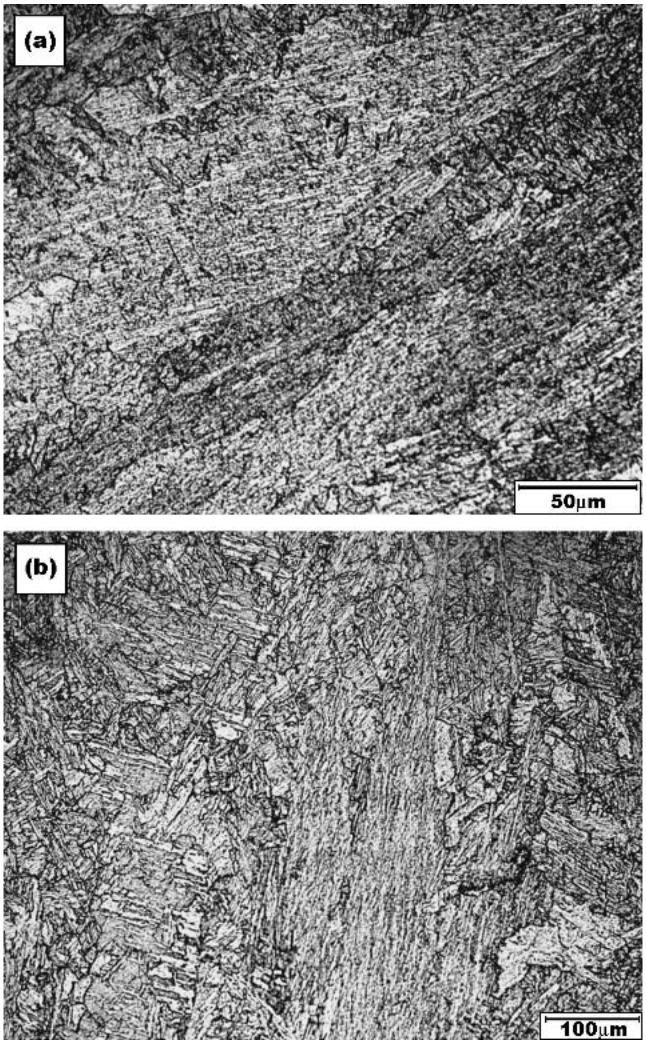

Fig. 4 Microstructural features of the weld metals: **(a)** high alloy, **(b)** medium alloy

Table 2 Tensile Properties of the SMSS Samples Tested in Air and Under Conditions of Hydrogen Charging

Sample	Test Medium	Reduction in Area, %	Tensile Strength, MPa
High-grade base material	Air	74.9	921
High-grade base material	0.1 M NaOH (a)	4.5	901
Medium-grade base material	Air	73.5	883
Medium-grade base material	0.1 M NaOH (a)	3.6	778
Weldment HW	Air	66.8	925
Weldment HW	0.1 M NaOH (a)	7.3	795
Weldment MW	Air	72.8	890
Weldment MW	0.1 M NaOH (a)	8.9	760

(a) Potentiostatic at −1200 mV versus Ag-AgCl

The macro hardness measurements on the weldments revealed that the weld metals had higher hardnesses than their base material counterparts. The hardness of the weld metals (HW and MW) were found to be around 315-325 HV_{20} in contrast to 275-290 HV_{20} in the base material counterparts, indicating that the welds are overmatched. The heat affected zones also had registered hardness values around 315-325 HV_{20}, which clearly illustrates the beneficial effect of post weld heat treatment in controlling the hardness in the weldment.

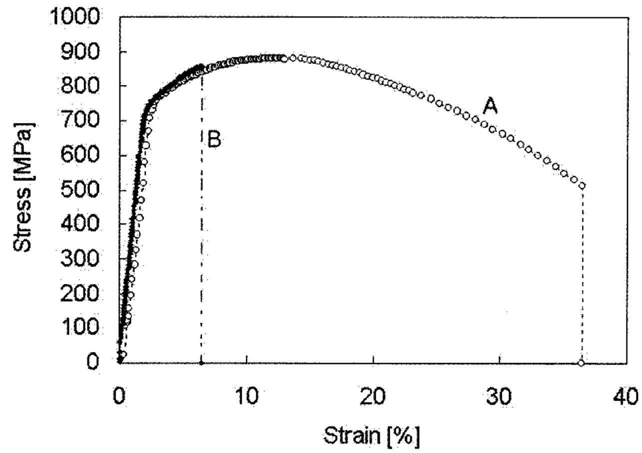

Fig. 5 Stress-strain behavior of medium grade SMSS base material in air and under conditions of H charging (SSRT tests): **(a)** in air, **(b)** under conditions of H charging

Representative stress-strain plots of the medium-grade SMSS base metal SSRT tested in air and under conditions of hydrogen charging are shown in Fig. 5. The SSRT test data of all the specimens are presented in Table 2. Under conditions of H charging, both the high-grade and medium-grade SMSS base metals showed brittle fracture with low ductility levels. Macro photographs of the high-grade base material tested in air and under conditions of H charging presented in Fig. 6(a) and (b), respectively, reveal the differences in fracture behavior. Both the high and medium-grade base material specimens SSRT tested in air had a dimpled fracture surface, as shown in Fig. 7(a), while the specimens tested under H charging conditions exhibited a mixed mode of transgranular/intergranular fracture, characteristic of environment-assisted cracking (Fig. 7b).

The weldment specimens failed in air in the low strength region (the base metal) and exhibited a ductile fracture mode. The percentage reduction in area of the two-weldment specimens was marginally lower than that of the base materials, which could plausibly be due to the different strain levels experienced in the gauge section in the composite nature of the weldment (weld metal + heat affected zone + base material). This was consistent with an earlier investigation, which found that the ultimate tensile strength of an all-weld metal SMSS specimen was higher than the SMSS base material, with an overmatch of around 5-7%.[9]

In contrast, the weldment specimens tested under conditions of H charging failed in the middle of weld metal, with a characteristic flat fracture. Testing under H charging conditions was associated with a considerable drop in ductility (assessed in terms of percentage reduction in area) and furthermore these specimens had a lower ultimate strength, and fractured at the same maximum stress level in a brittle fashion. The fracto-

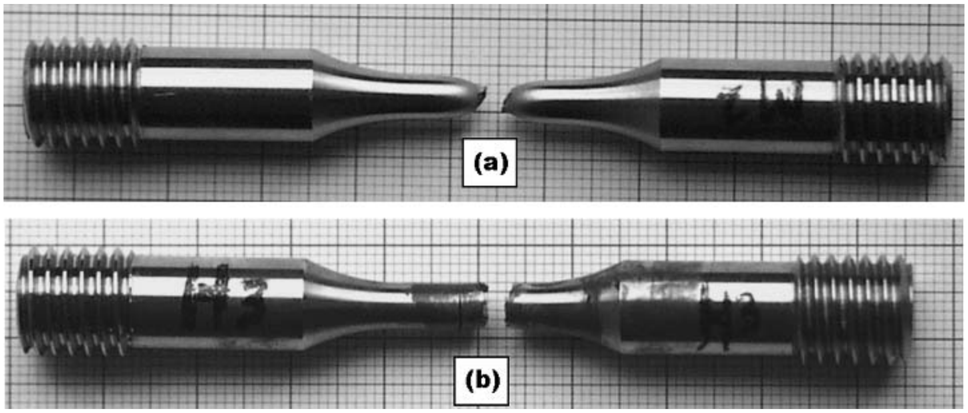

Fig. 6 Macro photos showing the features of the fractured SMSS base material tensile samples after SSRT tests: **(a)** in air, **(b)** under conditions of H charging

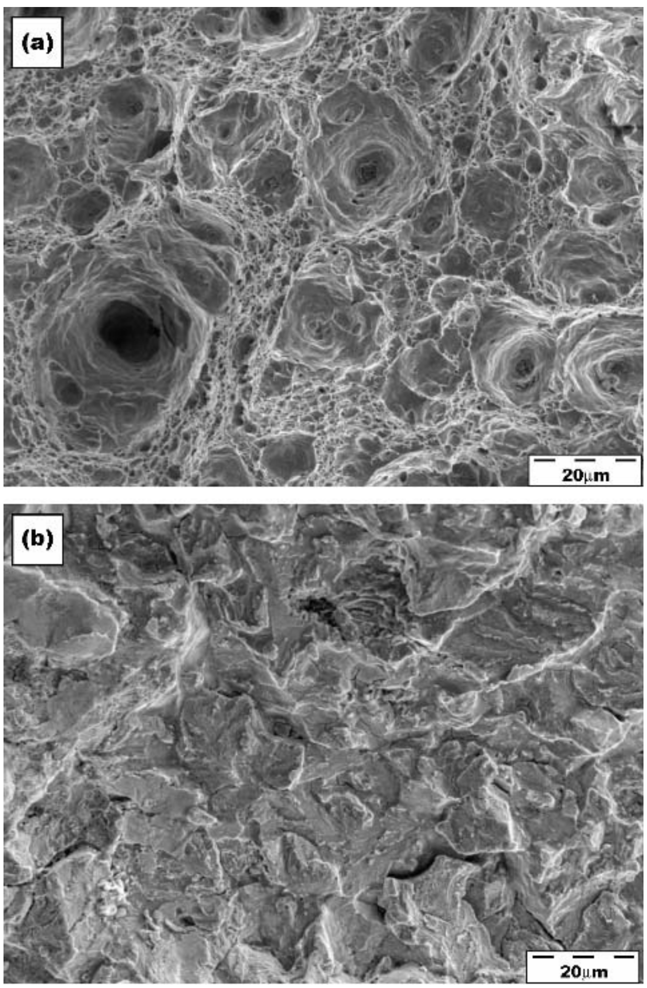

Fig. 7 Fractographs of SSRT tested high-grade SMSS base material: **(a)** in air, **(b)** under conditions of hydrogen charging

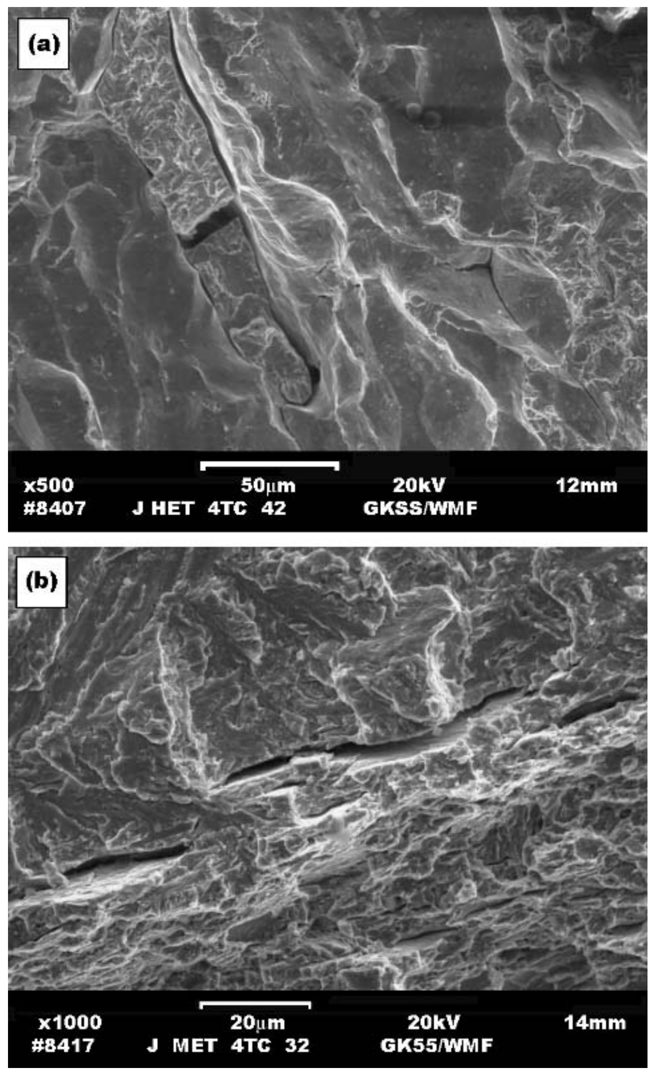

Fig. 8 Fractographs of the SSRT tested specimens under conditions of hydrogen charging: **(a)** weldment HW, **(b)** weldment MW

graphs of the weldment specimens HW and MW, shown in Fig. 8(a) and (b), respectively, revealed a mixed mode, inter-transgranular fracture. It is well known that high-strength materials used in sour/sweet environments may experience either dissolution-assisted or H-induced cracking depending on the service conditions. The dependence of H-induced cracking has also been reported to be a function of the local pH and also the potential of the H-generating environment, especially in wet H_2S environments.[10] Cracking under such conditions has been observed to be associated with the development of pits, which then become crack-initiation sites, with the adsorption of hydrogen at the crack tips, leading to crack propagation.

In this work, corrosion was eliminated completely by the selection of the appropriate test condition, and only the effect of H on the cracking behavior was studied. It has been stated that H-assisted cracking is feasible only when the H concentration in the material exceeds the threshold level.[10] The experimental conditions for H charging were chosen to simulate the over-protection condition of cathodic protection applied to these materials in oil and gas piping application. The applied potential of −1200 mV versus Ag/AgCl was sufficiently high to generate H, exceeding the threshold limit. The cracking could be explained by the decohesion theory, which suggests the migration of dissolved hydrogen into triaxially stressed regions, causing embrittlement of the lattice by lowering the cohesive strength between the metal atoms.

Though it has been stated in a recent work by Boellinghaus et al.,[11] that the H degradation markedly influences the ductility rather than strength in wet hydrogen sulphide environments, in this work there was a distinct drop in strength level, especially for the weldment specimens. It is well known that H damage is generally higher in regions of higher hardness and susceptible microstructures. Hence is it quite probable that in this case the higher hardness of the weld metals would have influenced the cracking behavior. However, it has been documented that the H diffusion coefficient in supermartensitic stainless steels differed up to three times with small variations in chemical compositions,[12] indicating that the cracking behavior is dependant on chemistry of the alloy, too. No quantitative analysis of H level was done to correlate that with the microstructure in this work. However, the above observations suggest that both the SMSS base materials and their overmatching weld metal counterparts are susceptible to cracking under conditions of H generation/charging even in the absence of aggressive corrosive environment.

4. Conclusions

1. Joining of supermartensitic stainless steels by SAW using matching consumable results in overmatched weld joints.
2. Though the weld metals are overmatched, they are equally susceptible to H induced stress cracking in hostile environments.

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