Experimental Characterisation of Fatigue in Next-Generation Welded Steel Catenary Risers

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Abstract. Welded connections are a fatigue sensitive location for offshore steel catenary risers. The refined microstructures necessary to attain the balance of high strength, toughness and weldability required in next generation line pipe steels are significantly degraded by welding thermal cycles in the heat affected zone; resulting in reduced strength and toughness.

This work presents a full-scale instrumented and automated girth weld on X100Q, a next-generation line pipe steel. A parallel programme of Gleeble thermomechanical simulation is implemented to develop microstructurally uniform heat affected zone specimens. The girth weld and simulated heat affected zone are characterised through a programme of nanoindentation, tensile and low cycle fatigue testing on parent material, weld metal, cross-weld and simulated heat affected zone specimens.

Introduction

There is a drive towards the use of higher strength line pipe steels in the offshore oil and gas industry, where recent projects, such as the Shell Stones field [1], are pushing to sea depths greater than 3,000 m. Floating production facilities and steel catenary risers (SCRs) are typically used in such deep or ultra-deepwater locations. The use of higher strength steels for SCRs is particularly appealing, as it provides the potential for significant weight reductions, and thus reductions in buoyancy requirements. However, the degradation of material properties in the heat affected zone (HAZ) and geometrical discontinuities at the weld result in the potential for fatigue hot spots at welded connections [2].

In this work experimental characterisation of the constitutive and fatigue behaviour of an API 5L X100Q girth weld is presented. A representative full-scale automated SCR girth weld is conducted, with thermocouple and strain gauge instrumentation to capture the thermal and strain history in the weld zone. Gleeble thermomechanical simulation is implemented using representative thermal cycles for the HAZ to create microstructurally uniform simulated HAZ test specimens. The constitutive and fatigue behaviour of the X100Q girth weld and simulated HAZ specimens are then characterised through a programme of nanoindentation, tensile and low cycle fatigue (LCF) testing on parent material (PM), weld metal (WM), cross-weld (CW) and simulated HAZ specimens.

Results

The experimental apparatus and instrumentation used during the root pass of the X100Q girth weld is shown in Fig. 1 (a). An image of the completed X100Q girth weld is shown in Fig. 1 (b). The weld was completed in 14 passes, with 1 surface tension transfer root pass, 11 spray-transfer gas metal arc welding (GMAW) fill passes and 2 spray-transfer GMAW cap passes. An etched cross-section of the girth weld is shown in Fig. 1 (c). The CW sample which was extracted from the girth weld for microstructural analysis and nanoindentation is shown inset.

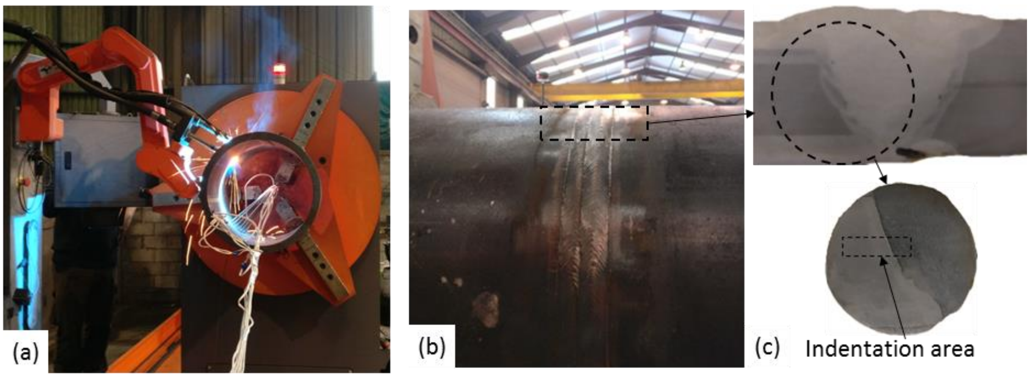

Figure 1 (a) Welding in progress using the Rotoweld 3.0 at Glenfield Engineering Ltd., (b) the completed X100Q girth weld, and (c) an etched cross section of the girth weld with the CW nanoindentation sample shown inset.

Two thermal cycles representative of the fine-grained HAZ (FGHAZ), with a peak temperature of 950°C cooling rates of 10°C/s and 30°C/s were identified for Gleeble thermomechanical simulation. Typical comparisons between the target simulated HAZ thermal cycles and the thermal cycles measured during Gleeble thermomechanical simulation are shown in Fig. 2.

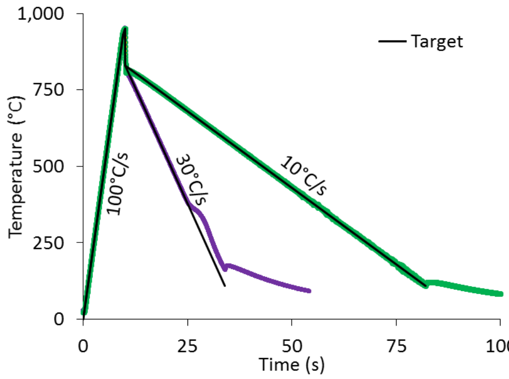

Figure 2 Typical comparison between the targeted HAZ thermal cycles and the thermal cycles measured during Gleeble thermomechanical simulation.

The tensile stress-strain responses obtained for the PM and the simulated HAZ specimens are shown in Fig. 3 (a). The elongation at failure of the PM is higher than the simulated HAZ specimens, but the ultimate tensile strengths of the simulated HAZ specimens are increased with respect to the PM. The first cycle stress-strain responses of the PM, WM and simulated HAZ for the 1.2% strain range LCF tests are shown in Fig. 3 (b). The yield points of the PM and the simulated HAZ specimens are quite close, but a higher level of strain hardening was shown in the simulated HAZ specimens than the PM, resulting in a greater stress range. The yield point of the WM is lower than that of the PM or the simulated HAZ specimens. The WM exhibited essentially perfectly plastic behaviour with a yield plateau in the first quarter cycle of the LCF test, and strain hardening for further tensile and compressive loadings.The stabilised half-life stress-strain responses of the PM, WM and simulated HAZ specimens, based on a half-life criterion, are shown in Fig. 3 (c). The stress range for the PM specimen cyclically softened by 30% at the half-life cycle, while the extent of cyclic softening in the WM, 10°C/s and 30°C/s cooling rate simulated HAZ specimens was approximately half that of the PM. The half-life stress-strain responses of the PM and the WM were almost identical for the 1.2% strain range test.

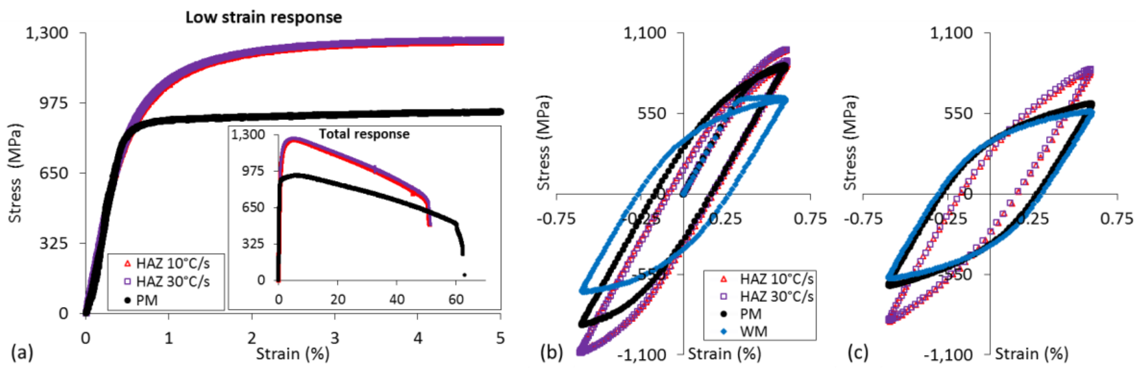

Figure 3 (a) The tensile stress-strain curves obtained for the X100Q PM simulated HAZ specimens, (b) the 1st cycle stress-strain responses of the PM, WM and simulated HAZ specimens, and (c) the stabilised stress-strain responses of the PM, WM and simulated HAZ specimens for 1.2% strain range tests.

Conclusions

The correlation between tensile strength, hardness and average grain size observed for the PM and simulated HAZ specimens follows a Hall-Petch type relationship. The hardness of the simulated FGHAZ specimens was greater than that observed in the FGHAZ of the CW sample manufactured from the girth weld. This has been attributed to the tempering effect of the multipass weld process.

The fatigue performance of the simulated HAZ specimens was shown to superior to the PM, WM and CW specimens. Fatigue failure was observed in the ICHAZ of CW specimens; a region of reduced strength in the weld which has been identified through microscopy and nanoindentation.

References

[1] R. Cunningham, *The Stones Development: A New Vision in the ultra-deepwater Gulf of Mexico*, PennWell Custom Publishing, Houston, TX (2017)

[2] R. J. Devaney, P. E. O'Donoghue, and S. B. Leen, *Experimental characterisation and computational modelling for cyclic elastic-plastic constitutive behaviour and fatigue damage of X100Q for steel catenary risers*, Int. J. Fatigue, vol. 116, pp. 366–378, Nov. 2018.