Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division II: , Fracture Mechanics and Structural Integrity

FRACTURE TOUGHNESS OF AN INDUSTRIAL ALLOY 182 WELD: EFFECT OF TEMPERATURE? SPECIMEN ORIENTATION AND PWHT

Inge Uytdenhouwen[1], Rik-Wouter Bosch[2], Frederic Somville[3], Séverine De Vroey[4] and Erich Stergar[5]

[1] Program manager, SCK CEN, Boeretang 200, 2400 Mol (Belgium) (iuytdenh@sckcen.be)
[2] Senior scientist, SCK CEN, Boeretang 200, 2400 Mol (Belgium)
[3] Mechanical Engineer, Tractebel, Boulevard Simon Bolivar 36, 1000 Bruxelles (Belgium)
[4] Medior Expert, Laborelec, rue de Rhode, 125 1630 Linkebeek (Belgium)
[5] Senior scientist, SCK CEN, Boeretang 200, 2400 Mol (Belgium)

ABSTRACT

A high Nickel based dissimilar metal weld (Alloy 182), known for its susceptibility to Primary Water Stress Corrosion Cracking (PWSCC), was investigated by fracture toughness tests in the ductile regime. One of the key inputs for the structural integrity evaluation of components is determined by the maximum acceptable defect size that is based on the crack growth rates from fracture toughness specimens. Extensive testing programs were carried out over the last years at SCK CEN and elsewhere and a large scatter of results is reported in literature. The scatter is related to the heterogeneous nature of the weld material, but no full explanation is available yet. An overview of the obtained results is given as a function of the test temperature, the specimen orientation in the weld and the post-weld heat treatment (PWHT).

EXPERIMENTAL

A dissimilar metal weld (Alloy 182) available from a RPV (Reactor Pressure Vessel) component that was never put into operation was selected. An overview of the component in the as delivered state can be seen in Figure 1a. The investigated weld is marked with a black arrow in Figure 1a. Figure 1b shows the metallographic cross-section of the investigated weld. The right side of the picture represents the RPV side and the left side the stainless steel safe end. Between the actual Alloy 182 weld and the RPV material a buttering layer was deposited on the carbon steel nozzle (slightly darker region between RPV and weld material in Figure 1b). The chemical composition of the investigated weld material is given in Table 1.

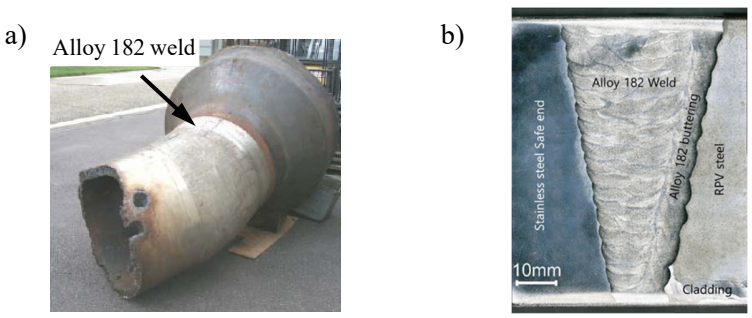

Figure 1. (a) component and (b) macroscopic view of the dissimilar welds, showing the weld beads and buttering layer after polishing and etching.

Table 1. Chemical composition of the investigated weld material in wt%.

	Fe	Cr	Mn	Ti	Nb	Ta	Si	Ni
Alloy 182	9.9	14.7	6.7	0.33	1.07	0.022	0.5	Bal.

Fracture toughness tests were performed according to the ASTM E1820 standard (ASTM 2018) with 0.5T-CT (Compact Tension) and mini-CT (0.16T) sized samples. A schematic view of sample extraction and orientation can be found in Figure 2. Figure 2a shows the extraction of 0.5T-CT samples from a slice of the component and Figure 2b shows the extraction of mini-CT samples from the larger 0.5T-CT sample.

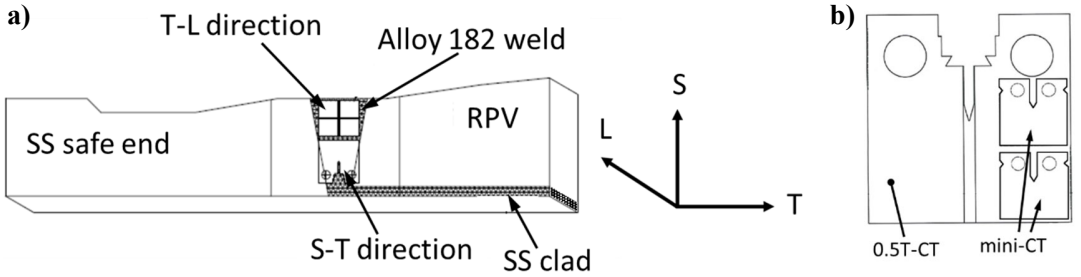

Figure 2. a) Schematic of sample extraction and orientations, b) extraction of mini-CT samples from 0.5T-CT sample.

Except for two samples, where the pre-crack was produced by a stress corrosion cracking (SCC) procedure, all samples were fatigue pre-cracked. After each fracture toughness test, the specimen was oxidized at 330 °C for four hours to create discoloration of the existing cracks. Subsequently, a post-test fatigue crack was created to clearly reveal the transition between the ductile extended crack front and the final rupture of the specimen. As a result the different cracking zones (fatigue pre-crack, ductile crack extension during testing, post-test fatigue crack, final rupture) could be clearly distinguished from each other. None of the tests showed a crack front that is completely straight. This is related to the fact that a specimen typically contains several weld beads and due to the heterogeneous nature of the weld metal the fatigue pre-crack can be irregular. Examples for such irregular pre-cracks can be found in Figure 3. For the fracture toughness analysis three techniques following the ASTM standard (unloading compliance (UC), potential drop (PD), the normalization data reduction (NDR)) were applied together with the SCK CEN in-house Energy normalization (EN) technique (Chaouadi 2004). The given fracture toughness values are the arithmetic average of all four methods. In some cases not all methods resulted in proper values. Then the average is calculated from the remaining values. Fractography on selected broken samples was done by using a Jeol 6610LV scanning electron microscope. The test temperatures were chosen so that they either represent ambient temperature during outage or elevated temperatures in the cold leg (~290°C) or hot leg (~330°C) water temperature during operation.

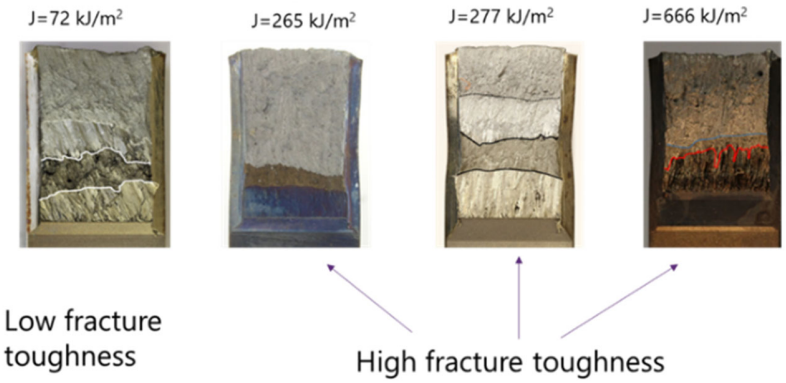

Figure 3. Typical fracture surface examples of side grooved CT samples with non-uniform pre-crack front for low and high fracture toughness values.

RESULTS

Figure 4 shows a summary of the gained ductile fracture toughness values J_Q as a function of the test temperature. At room temperature as well as at higher temperatures a significant scatter is obvious (Figure 4). Especially at room temperature this scatter is large and ranges from less than 100 kJ/m² to almost 1000 kJ/m². In the current work CT's with SCC pre-crack exhibit comparatively high toughness values (Figure 4). No significant difference between the mini-CT's and the 0.5T-CT specimens can be identified. Fracture toughness values of specimens which received a Post Weld Heat Treatment (PWHT) tend to be higher when compared to specimen without a PWHT. This could indicate towards a beneficial effect of PWHT. However, the available data at this point is not enough to make a statistical sound statement.
When only considering fatigue pre-cracked specimens, a small difference between the T-S and T-L specimen orientation can be noticed. Both at room temperature and at high temperature, the T-L oriented specimens exhibit a slightly higher ductile fracture toughness.

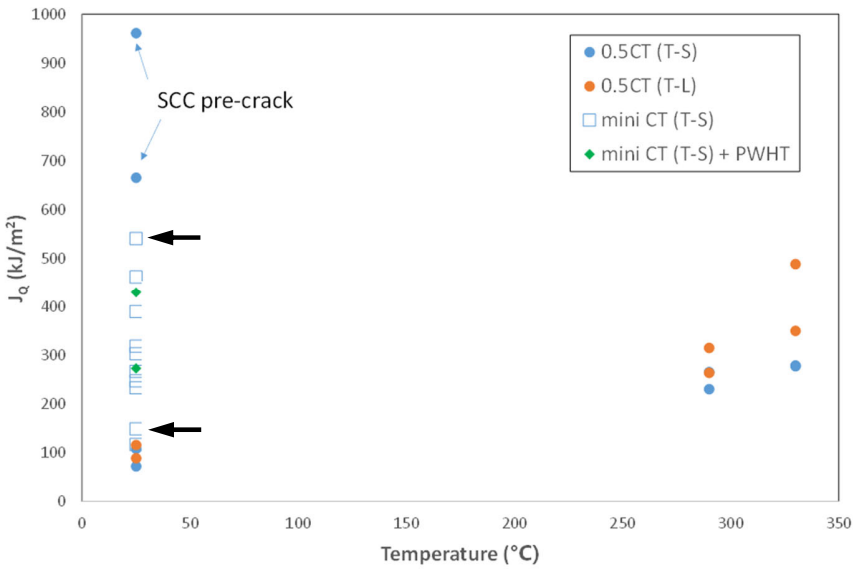

Figure 4. Fracture toughness (J_Q) of Alloy 182 as a function of the test temperature. Fracture surfaces of the samples marked with horizontal black arrows are shown in Figure 5.

In order to further investigate the reasons of the large scatter, the fracture surfaces of several broken samples were analysed with a scanning electron microscope. Figure 5 compares two representative fracture surfaces from a sample with high fracture toughness (a, J = 541 kJ/m²) and a sample with low fracture toughness (b, J = 117 kJ/m²). The sample with high fracture toughness shows a fully ductile fracture surface where the typical ductile dimples are clearly visible (Figure 5a). The sample with low fracture toughness shows in contrast mainly intergranular features with a minor amount of ductile (dimpled) fracture (Figure 5b) as shown by the white marked regions.

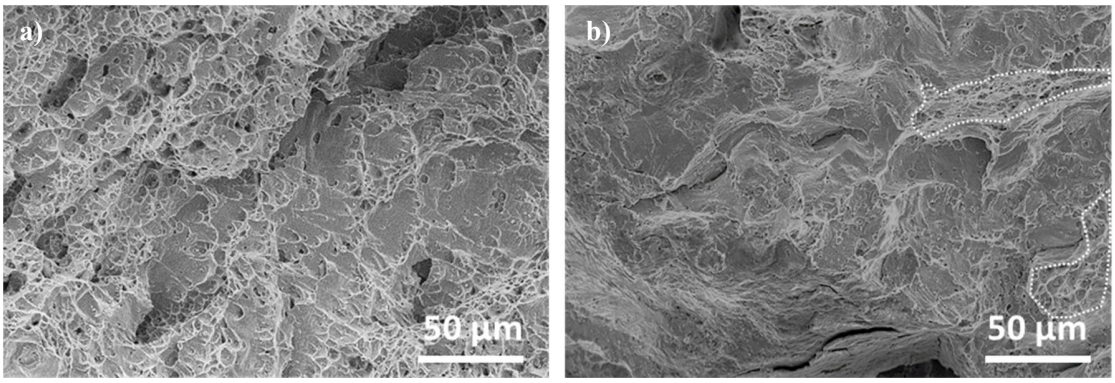

Figure 5. Comparison of fracture surfaces from a) a sample showing high fracture toughness (J = 541 kJ/m²) and b) a sample showing low fracture toughness (J = 117 kJ/m²). The white dotted lines mark regions with ductile dimples.

The graph in Figure 6 compares data from the current work with available literature data. Large scatter is observed at all test temperatures, albeit that the lowest fracture toughness values are only present at room temperature.

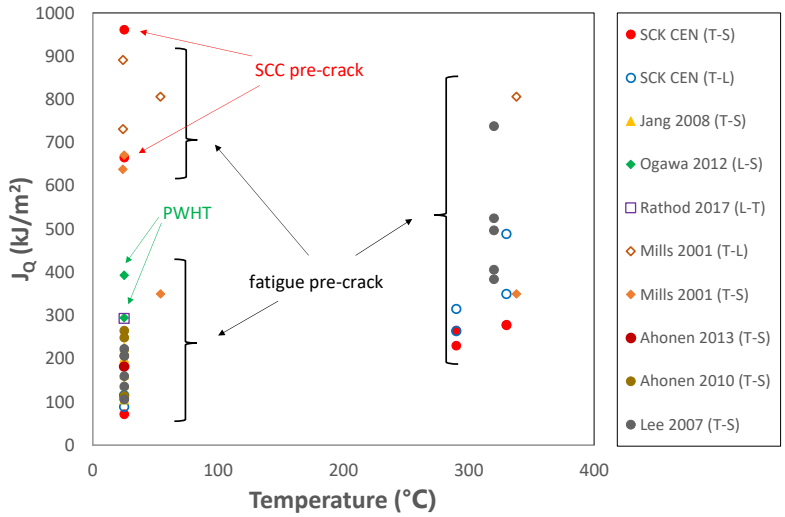

Figure 6. Comparison of fracture toughness data of Alloy 182 with data from literature at temperatures between 25 °C and 340 °C; the two red dots in the left upper corner represent tests results with SCC pre-crack; all the other results were obtained with a fatigue pre-crack (Jang, et al. 2008, Ogawa, et al. 2012, Rathod, et al. 2017, Mills und Brown 2001, Ahonen, et al. 2013, Ahonen, Ehrnstén und Hänninen 2010, J. Lee und Jin 2007).

CONCLUSION

Fracture toughness tests with 0.5T-CT and mini-CT specimens made from the weld metal Alloy 182 were carried out. The mini CTs were machined from the remains of prior tested 0.5T-CT specimen. The main aim of the work was to investigate a possible cause for the large data scatter in fracture toughness test results. From the gained data it can be concluded that the large scatter is most probably related to materials inhomogeneity often observed in weld metals. Although it seems that the dendrite orientation does play a role, a detailed explanation is not yet available and requires further investigations.

Alloy 182 is susceptible to a degradation phenomenon called Low-Temperature Crack Propagation (LTCP). This is associated with spurious hydrogen and can result in very low values of the fracture toughness. Hydrogen can be introduced in the material during Electro Discharge Machining (EDM). As all the specimens have been produced by EDM at least a significant portion of them should show low fracture toughness values. As this was not the case, LTCP is ruled out as possible cause for the measured low fracture toughness values.

For all the specimens that were exposed to a PWHT heat treatment, both the current data as well as from literature (Ogawa, et al. 2012), comparatively high fracture toughness values were found. However the total number of tests is too limited to substantiate this and more tests are required for a statistically sound statement.

No clear effect was found on the fracture toughness values with respect to the specimen position in the weld. The fracture toughness in the T-L orientation is slightly higher than in the T-S orientation. The fracture toughness values range between 72 and 1000 kJ/m² at room temperature, while the fracture toughness at temperatures above 300°C varies between 230 and 800 kJ/m². The PWHT is representative for the stress relief treatment applied to the reactor pressure vessels after welding of the safe-end welds. The PWHT specimens showed a significantly higher fracture toughness than non-heat treated samples.

References

Ahonen, M., U. Ehrnstén, and H. Hänninen. 2010. "Low Temperature Crack propagation (LTCP) susceptibility of Nickel based weld metals in hydrogenated PWR primary water." *FONTEVRAUD 7*.

Ahonen, Matias, Ulla Ehrnsten, Tapio Saukkonen, Olga Todoshchenko, and Hannu Hänninen. 2013. "Low temperature crack propagation (LTCP) susceptibility of nickel-based weld metals alloy 182, 152 and 52 in PWR primary water." *16th International Conference on Environmental Degradation of Materials in Nuclear Power Systems and Water Reactors, August 11-15, 2013, Ashville, North Carolina, USA*. 20.

ASTM. 2018. "ASTM 1820 Standard Test Method for Measurement of Fracture Toughness." West Conshohocken, PA, 19428-2959 USA: ASTM International.

Chaouadi, R. 2004. "An Energy-Based Crack Extension Formulation for Crack Resistance Characterization of Ductile Materials." Edited by R. E. Link DR Petersen. *Journal of Testing and Evaluation* (ASTM International) 32: 469–475. doi:10.1520/JTE11956.

Lee J., J. S. Kim, and T. E. Jin. 2007. "Mechanical Properties Evaluation in Inconel 82/182 Dissimilar Metal Welds." *Transactions, SMIRT 19 paper nr G04/4, Toronto.*

Jang, Changheui, Jounghoon Lee, Jong Sung Kim, and Tae Eun Jin. 2008. "Mechanical property variation within Inconel 82/182 dissimilar metal weld between low alloy steel and 316 stainless steel." *International Journal of Pressure Vessels and Piping* 85: 635–646. doi:10.1016/j.ijpvp.2007.08.004.

Mills, W. J., and C. M. Brown. 2001. "Fracture toughness of alloy 600 and an EN82H weld in air and water." *Metallurgical and Materials Transactions A* 32: 1161–1174. doi:10.1007/s11661-001-0126-6.

Ogawa, Takuya, Masao Itatani, Toshiyuki Saito, Takahiro Hayashi, Chihiro Narazaki, and Kentaro Tsuchihashi. 2012. "Fracture assessment for a dissimilar metal weld of low alloy steel and Ni-base alloy." *International Journal of Pressure Vessels and Piping* 90-91: 61–68. doi:10.1016/j.ijpvp.2011.10.012.

Rathod, Dinesh W., Sunil Pandey, P. K. Singh, and Suranjit Kumar. 2017. "Microstructure-dependent fracture toughness (JIC) variations in dissimilar pipe welds for pressure vessel system of nuclear plants." *Journal of Nuclear Materials* 493: 412–425. doi:10.1016/j.jnucmat.2017.06.038.