FRACTURE TOUGHNESS CHARACTERIZATION OF 316L STAINLESS STEEL WELDED PLATES AT LIQUID NITROGEN (77 K) AND LIQUID HELIUM (4 K) TEMPERATURES

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Abstract

In the framework of a collaborative project between ASME, NASA, and NIST, quasi-static fracture toughness tests were performed at liquid nitrogen temperature (77 K, or 196 °C) and liquid helium temperature (4 K, or -269 °C) on precracked SEN(B) specimens extracted from the centers of four separate lots of welded 316L stainless steel plates. Although the plates were produced in accordance with the same specifications from the same material (316L), large differences in fracture toughness have been observed, with the toughest weld exhibiting almost twice the critical toughness of the least tough at 77 K (219 kJ/m^2 vs. 113 kJ/m2), and about seven times the critical toughness of the least tough at 4 K (146 kJ/m^2 as compared to 21 kJ/m^2). Charpy absorbed energies previously obtained at 77 K for three of the four welds were found to be strongly linearly correlated with fracture toughness at both test temperatures, with an exception represented by the fourth weld, which provided the highest impact toughness and the second lowest quasi-static fracture toughness. Dynamic toughness measurements at impact loading rates were also performed on precracked SEN(B) specimens, in order to deconvolute the roles of strain rate and notch sensitivity on the fracture properties of the investigated welds.

1. Introduction

Currently, both ASME Boiler and Pressure Vessel Code (BPVC) Section VIII and ASME Piping Code B31.12 Hydrogen Piping and Pipelines require performing Charpy impact tests at liquid nitrogen (LN2) temperature, i.e., 77 K (-196 °C), to assess the fracture performance of austenitic stainless steels at liquid helium (LHe) temperature, i.e., 4 K (269 °C).

Charpy testing provides a relatively inexpensive measurement of the impact toughness of a material, quantified by absorbed energy. However, due to adiabatic heating occurring at high strain rates during Charpy impact testing, measuring impact toughness at temperatures below 77 K is not technically feasible by Charpy testing. The temperature rise during the transfer of the specimens from the cooling medium to the impact position is also a concern at temperatures below 77 K. These infeasibilities call into question the technical justification of using Charpy impact toughness values measured at LN2 temperature to assess the reliability of quasi-static fracture toughness tests conducted on single-edge bend (SEN(B), Charpy type) specimens at LHe temperature. While actions have been proposed to mitigate the temperature increase due to specimen transfer, the heat generated within the specimen during high strain rate deformation and fracture cannot be avoided and is significant.

The main objective of this investigation is to evaluate the use of 77 K Charpy test results to assess material properties at 4 K, with specific focus on crack propagation through welded sections of 316L stainless steel pipes. The weld sections of four unique lots in welded 316L plates, covering a representative range in welding process, chemical content, and delta ferrite fraction, had been previously characterized by tensile testing (77 K and 4 K) and Charpy testing (77 K). Within this paper, we present the results of quasi-static fracture toughness tests performed on precracked Charpy-type specimens at 77 K and 4 K, extracted from the same four lots of welded 316L plates.

2. Results and Conclusions

The most significant findings of this investigation were the following.

(a) At both test temperatures (77 K and 4 K), the same two welds resulted in the toughest and the least tough, respectively, based on both critical toughness at crack initiation and resistance to crack propagation. The toughest weld also exhibited the lowest scatter of toughness properties at both temperatures.

(b) In most of the tests performed, tearing (ductile) instabilities were observed, corresponding to large crack "jumps", which were clearly observed on the fracture surfaces of the tested specimens. In some cases (8 tests out of 43), the earliest tearing instability occurred before stable crack initiation, and the corresponding value of J integral represented the critical toughness value for that particular specimen. The only test condition that did not experience any tearing instability was weld W2 tested at 77 K.

(c) The toughest weld was the only one produced using gas tungsten arc welding (GTAW) for both root and subsequent cover passes, with the final layer (weld cap) created using the most passes (four) when compared to other welds. The number of passes in the final layer (weld cap) inversely correlated with toughness. The ferrite content in the weld covers also likely played a role in toughness, such that the welds containing the least amount of ferrite exhibited the highest toughness.

(d) For all welds, quasi-static fracture toughness was significantly reduced from 77 K to 4 K, with a strong linear correlation observed between critical toughness at 77 K and 4 K. While ductile behavior (microvoid coalescence) was observed on the fracture surfaces of all welds tested at 77 K, some instances of brittle failure (cleavage) were observed on the surfaces of the specimens tested at 4 K. Fractography showed the least amount of cleavage for the toughest weld and the highest amount for the two least tough welds, as well as revealing worm hole porosity on the fracture surfaces of the worst weld, likely cause by contaminated flux core materials.

(e) Average critical toughness values, J_Q, at 4 K reasonably correlated with Charpy absorbed energies measured at 77 K, but only for three of the investigated welds. The correlation broke down for one of the welds, which absorbed the highest energy in Charpy tests at 77 K, but resulted the second least tough weld at both 77 K and 4 K. The relationship between Charpy (77 K) and fracture toughness (4 K) results is shown in Fig. 1.

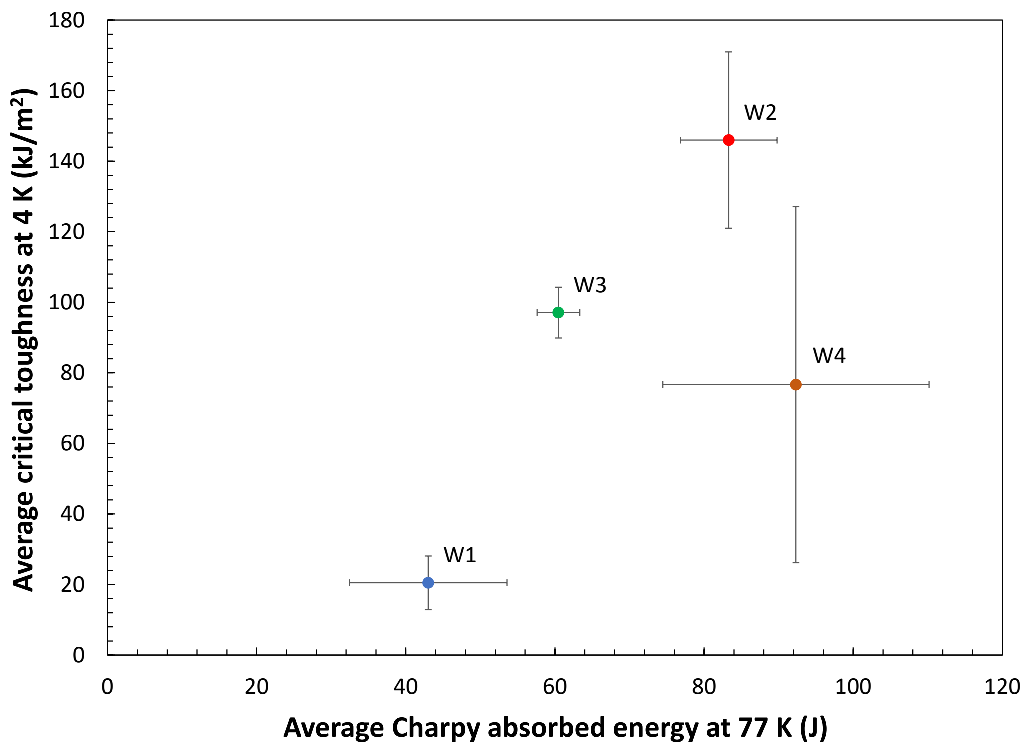

Fig.1 – Correlation between critical toughness at 4 K and Charpy absorbed energy at 77 K (average values and ±1 SD error bars).

(f) Apparent negative crack growth, caused by material stiffening in the plastic zone around the crack tip during the blunting phase, was observed in 40 of the 43 tests performed. This seemingly non-physical phenomenon, however, is currently not acknowledged by the ASTM E1820-21 test standard, which was used to establish critical toughness values and crack resistance curves.

The results of these fracture toughness tests, as well as those of the tensile and Charpy tests previously conducted, can be applied in energy and aerospace industries.

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