Material Properties of a Dissimilar Metal Weld Inconel 600/ Inconel 82 Weld Filler/ Carbon Steel (Gr. 106 B)

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Summary

Inconel 600 pipes welded to Carbon-Steel are used in CANDU nuclear reactors. Fracture of these welded pipes has important consequences in term of safety, and therefore their mechanical properties need to be better understood. In this study, the weld region was analyzed at various length-scales using optical microscopy, micro hardness testing, small and large scale tensile testing, and Digital Image Correlation (DIC). Micro-hardness profiles showed variations across the weld and through thickness and were justified in terms of residual stresses. Local stress-strain curves were built using DIC and showed good agreement with stress-strain curves obtained from miniature tensile samples.

1. Introduction

A dissimilar metal weld (DMW) is a weld used to connect two different metals. In nuclear power plants, these welds are often used to connect Stainless Steel or superalloys such as Inconel to low alloys steels. Failure of these DMW could lead to costly reactor shut down (for repair) and release of radioactive heavy water. Various experimental techniques have been used to characterize dissimilar metal welds and to understand their deformation and fracture properties. The most widely used technique is the tensile test, which provides information on where the weld would fail upon straining [1, 2]. However DMWs show spatial variation due to the welding process. Therefore, it has been recognized that macroscopic testing of DMW is not sufficient to capture details of the deformation and fracture processes. Another widely used method to characterize welds is the hardness test, which provides the advantage of revealing local properties. A pattern of indents can be placed on the sample surface to obtain a map of the local strengths as shown in Figure 1 [1, 3, 4, 5, 6, 7]. This technique is very useful and inexpensive but lacks information compared to the typical tensile test. A hardness test only provides the hardness value at a point (which can be related to the strength of the material at that point) while a tensile test can provide the whole stress vs. strain curve of the material. To overcome this problem, miniature tensile samples have been extracted from various locations in the weld region and have been tested in tension. The result is a full stress strain curve from a local region in the sample [2, 5, 8]. The drawback of this technique is the difficulty in extracting samples from different regions in the weld and the size of these samples which will still provide an average stress-strain curve. The most recent approach used to tackle the last problem is to use Digital Image Correlation (DIC). DIC is based on tracking features on the sample surface as it deforms and uses software to obtain a strain map on the sample surface. From this strain map, the stress strain curve of the sample can be extracted at virtually any spatial resolution, with the only limitation being the resolution of the DIC measurement [7, 9, 10, 11, 12, 13].

The purpose of this research is to obtain quantitative information on the mechanical properties of Inconel and Carbon Steel based dissimilar metal welds using a combination of experimental techniques. This information will be essential in building robust damage models to predict fracture in dissimilar metal welds and to improve the design guidelines of welded pressure tubes.

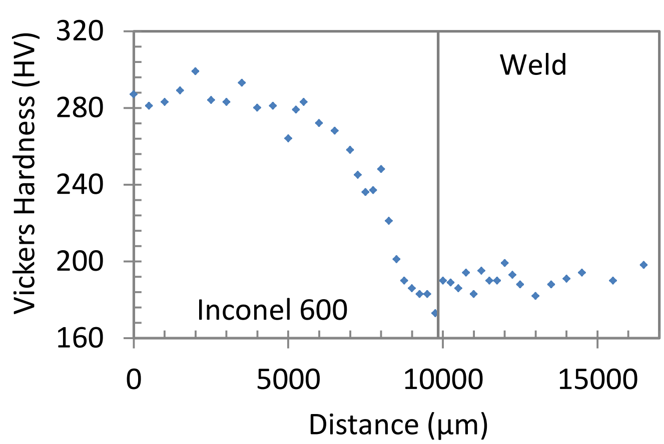
2. Experimental Procedure

The dissimilar metal weld used in this research project was completed using Tungsten Inert Gas (TIG) Welding (also called GTAW) and provided by Atomic Energy of Canada Ltd. The weld microstructure was first revealed by polishing down sections of the weld to a mirror finish using a 0.05 µm colloidal suspension. To characterize the variations in strength in the weld region, Vickers micro-hardness indents were placed across and through the weld thickness using a 500 g load. Hardness indents provide insight into the local strengths of the material but do not provide the whole plastic flow behavior. The flow behaviour was seen during tensile tests on large tensile dog-bone shaped samples that were machined normal to the weld line. Tensile tests were performed on these samples in-situ with a digital image correlation (DIC) system. DIC is done by recording images during the tensile test which, upon processing, provide the strain field at the sample surface and the local material properties. Small tensile samples were extracted from different areas in the weld region using a femtosecond laser, in order to obtain local material properties for comparison with the DIC results.

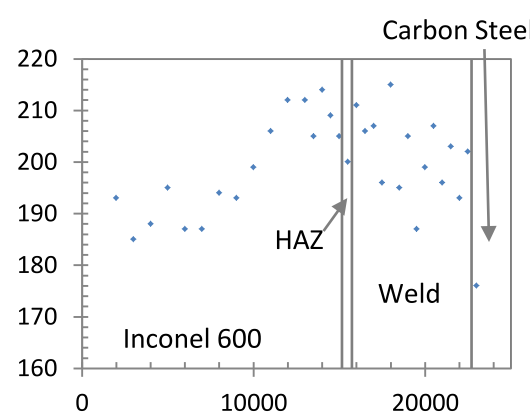
3. Results and Discussion

3.1 Hardness Tests

To understand how the material properties change across the weld and through the weld thickness, hardness tests were carried out. The first hardness test was performed in the Inconel region away from the weld. The hardness at the inner diameter of the tube started at around 180 HV and increased to almost 300 HV near the outer surface. This increase in hardness is most likely due to the residual stresses and plastic deformation created when machining the pipe out of a solid block of Inconel.



[A]



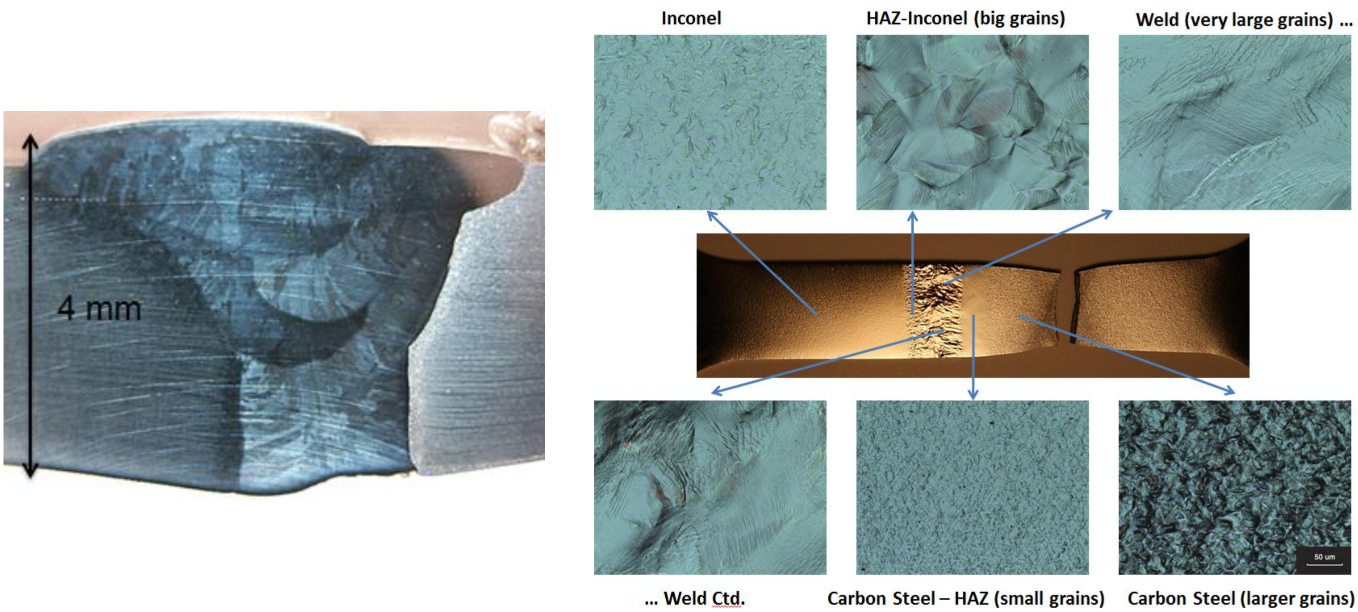
[B]

Figure 1 [A] Hardness Test 0.3 mm from the Outer Diameter [B] Hardness Test 7 mm from the Outer Diameter (≈ 1 mm from ID)

Tests were then performed across the weld. A first line of indents was completed 300 µm from the outer diameter. The test showed a very large decrease in hardness within the heat affected zone of Inconel. It can be predicted that the decrease is due to a release of residual stress and a recovery of the dislocation structure when the material is heated during the welding process. Three more tests were done at thicknesses closer to the inner diameter. The test closest to the inner diameter saw an increase in hardness within heat affect zone of Inconel. Since there was very little deformation at this location, the heat didn't have any stresses and dislocations to anneal. Instead it is possible that the heat led to the formation of carbides which could explain the observed increase in hardness.

3.2 Microstructure

Figure 2A is an image from an optical microscope showing the 7 weld passes needed to create a weld as thick as the pipe. Very large grains can be observed within each pass. The grains within the heat affected zone of Inconel are significantly larger than those in the unaffected zone (Figure 2B). The opposite can be said about the grains within the heat affected zone of carbon steel; where the grains are significantly smaller than the unaffected zone.

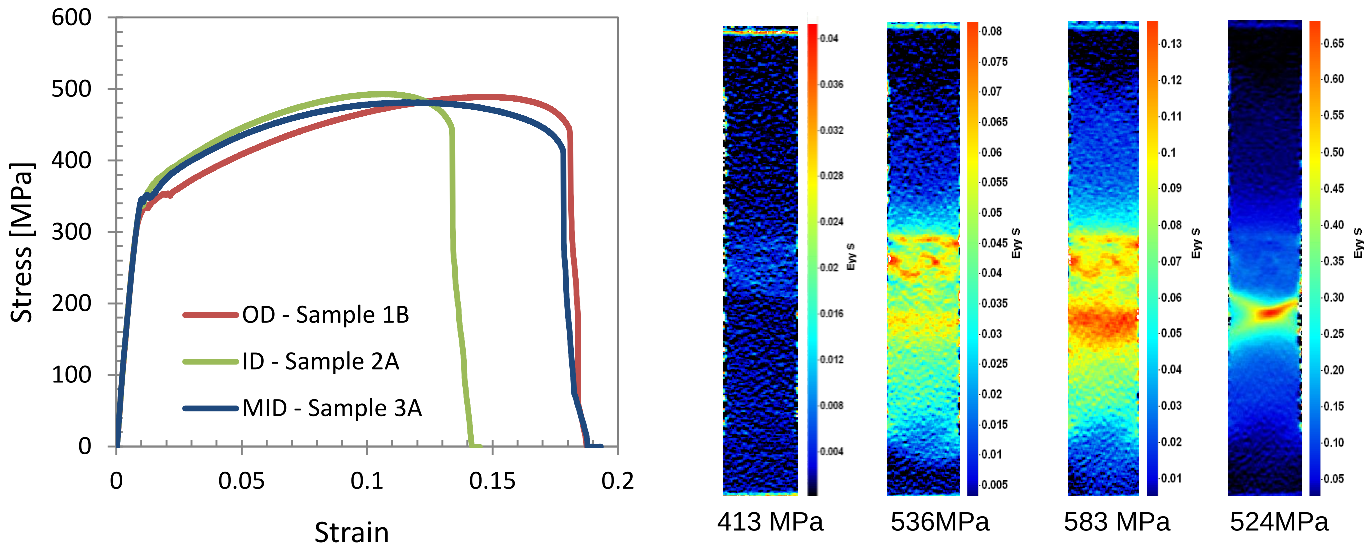


[A] [B]

Figure 2 [A] Whole Weld Cross-Section Polished and Etched (Left to Right: Inconel 600, Inconel 82 Weld Filler, Carbon Steel (Grade 106 B) [B] Microstructure after tensile test (Scale in bottom right valid for all images)

3.3 Tensile Tests

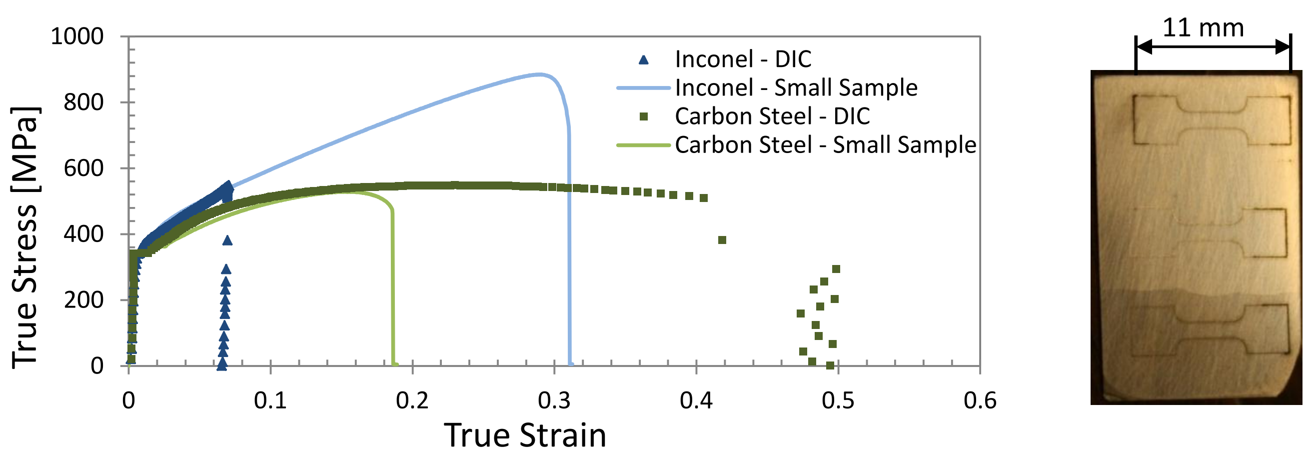
The large tensile samples were tested at three different thickness locations. The large tensile sample began as a smooth surface and became rough during testing (Figure 2B). As the sample is tested, grains re-orient themselves to accommodate the tensile deformation. The larger the grains, the more the change in orientation is visible at the surface. Slip steps are clearly visible in the large grains (above 25 μm) in the weld and Inconel regions. The regions with small grains (under 10 μm) see little overall deformation. Figure 3A shows the stress-strain curve of samples taken from the outer diameter, middle and inner diameter regions of the weld. Samples did not show significant variations in strength but they did differ in failure strains. The total amount of strain is proposed to be directly proportional to the width of the weld in the sample. The inner diameter has the smallest weld and deforms the least which results in low failure strains (Figure 3A).



[A] [B]

Figure 3 [A] Stress-Strain Curves for Large Tensile Samples, [B] Digital Image Correlation Results: Local Strain vs. Engineering Stress

The Digital Image Correlation (DIC) results show strain first accumulating in the weld region. The maximum strain value then varies in location between the weld and the carbon steel regions, before isolating at the final fracture location in the carbon steel. The stress obtained during the tensile test can be coupled to the local strain from the DIC result in order to obtain local stress-strain curves. These results were then compared to stress-strain curves obtained from the miniature tensile specimens (Figure 4A).



[A] [B]

Figure 4 [A] Stress-Strain Curves for DIC and Miniature Tensile Tests, [B] Miniature Samples

The total strain is higher in the miniature tensile sample for Inconel because the Inconel region did not reach fracture in the large tensile test and it did fracture in the miniature test. The strain seen in the DIC results of Carbon Steel is larger because DIC is able to track the local strain in the neck of the sample, whereas the strain in the miniature test is the average strain over the entire sample. These results show that DIC can provide accurate stress strain curve and that miniature tensile sample complement the information provided by DIC.

4. Conclusion

The mechanical properties of an Inconel to Carbon steel dissimilar metal weld were investigated. Large grains were observed in the weld region with smaller grains in the Inconel and Carbon Steel base metals. Micro-hardness profiles showed variations across the weld and through thickness. They were justified in terms of residual stresses and plastic strain accumulated in the in the sample during machining. Large tensile samples were extracted normal the weld line and were used to identify the material in which fracture initiated. Local stress-strain curves were built from digital image correlation (DIC) data and compared to stress-strain curves obtained from miniature tensile samples extracted from the Carbon Steel and Inconel regions. The results demonstrate the advantage of using DIC for extracting local material properties in dissimilar weld systems. Finally, the variations in the materials stress-strain curves though-thickness emphasize the need for obtaining a complete map of the mechanical properties in the weld region for predictive models to be accurate.

5. References

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