EVALUATION OF STRESS CORROSION CRACKING OF 316L STAINLESS STEEL IN SUPERCRITICAL WATER USING CONSTANT-LOAD C-RING SAMPLES

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Summary

The study of stress corrosion cracking in elevated temperature environments can be completed using a variety of methods from simple non-reproducible techniques to complex cryogenically sealed straining systems. Materials research for the supercritical water reactor (SCWR) provides a unique and extreme environment to investigate stress corrosion cracking using simple specimens to understand their response to different environmental variables. The following study uses ABAQUS CAE, a finite element program, to assess the constant-load c-ring technique in a supercritical water environment on 316LSS. This is a preliminary step into more detailed testing for SCWR materials selection.

1. Introduction

The Generation IV International Forum was established as a cooperative endeavour between twelve countries to foster research and development for the next generation of nuclear energy reactors. Canada has elected to research the Supercritical Water-cooled Reactor (SCWR) and the Very High Temperature Reactor (VHTR). Due to the extreme environments proposed for these reactors, extensive studies on the materials of construction are required to be conducted. The goal for this work is to assess the stress corrosion cracking (SCC) behaviour of various candidate materials in the SCWR environment.

The Canadian SCWR is anticipated to operate with a maximum temperature and pressure of 625°C and 25 MPa respectively; under these conditions, material selection poses unique challenges. SCC, of all the forms of corrosion, possesses some of the least understood mechanisms but most devastating failures. In SCC, depending on the numerous mechanical and electrochemical factors that play into its initiation and propagation, cracks are propagated into the materials. Unlike general corrosion where a slow loss of material can lead to wall thinning, SCC can result in complete failures of components.

Due to the extreme testing conditions posed in the SCWR environment, measurement of the cracking potential and material stresses is made more challenging. In order to evaluate the results from specimens exposed and strained in supercritical water and to create an accurate and reproducible technique for experimental testing, a finite element analysis (FEA) program, ABAQUS CAE, has been used to assess the expected stresses on the test specimen under various planned experimental conditions. The FEA on the test specimens can also be used to relate the mechanical nature of SCC to the anticipated failure sites.

As a first step to evaluate the SCC behaviour of 316L SS in SCW, a constant-load test experiment been selected. Otherwise known as "dead load," the constant-load test on a c-ring provides the unique ability to assess the SCC propensity of a metal in a reproducible manner. A common approach in SCC tests using c-rings is to utilize a constant-strain or "fixed-displacement" specimen. The challenges with either testing technique are that neither produces a true constant-stress during the test [5]. The fixed displacement test is simple but offers poor reproducibility, while the dead-load has the advantage of more control over the stress intensity but the specimen is likely to fail earlier.

During the testing, a constant-load specimen uses a spring to provide a stress at a constant level. The challenge becomes that, as the specimen begins to crack and propagate into the specimen, the load applied will become greater at the crack tip and will result in failure earlier with lower threshold stresses. A constant-strain specimen, unlike the constant-load, has no spring and, as the specimen begins to crack, the stress decreases across the specimen due to the interaction between microcracks and the elastic strain changing to the plastic in high strain locations [5].

A key element that has been indentified is to have the stresses as controlled as possible. In the desired testing conditions of 500°C and 25 MPa, the specimen will experience thermal expansion, creep and other stress inducing factors. The constant-strain technique in the stress condition will result in a specimen that will be stressed plastically as it expands against its stressing bolt and relieves its stresses, which is undesirable. By applying the load through a spring, a relationship can be derived for expected expansion and attempt to constrain the strains to the elastic region.

2. Experimental Setup

A constant-load c-ring technique will be applied to test the SCC propensity of metals in a SCWR environment. The main challenges posed by the c-ring test will be to develop a technique that is reproducible and accurate. Due to the environmental conditions and lack of suitable measuring equipment in the high temperature environment, no in-situ evaluations of corrosion potential can take place at this time. Thus, it is important to develop a FEA model to determine the expected stresses induced by the extreme testing conditions under the initial load of the specimen at room temperature. The FEA model will also give rise to areas that may result in the highest likelihood of failure due to SCC.

The actual test setup will use a 300 mL, Inconel 625 static autoclave with a coupon support tree placed in the vessel that can hold 21 test specimens, each being stressed simultaneously at a level determined before insertion into the autoclave. Initially, the autoclave will be operated under the supercritical water conditions of 500°C and 25 MPa. The vessel will be purged to maintain a controlled oxygen concentration at or below 25 ppb. A ceramic washer will be used on either end of the specimen to inhibit galvanic corrosion effects. Disc springs, constructed of 300 series stainless steel, will be used to apply a constant-load to the c-ring. The discs used are 2.77 mm ID, 9.52 mm OD, 0.051 mm thick. At flat load the springs are capable of applying, based upon their geometry, 50 MPa to the ceramic washer. The disc springs are fabricated to DIN 2093:2006-03, series C [2]. The discs can be stacked either in parallel or in series to configure the desired spring constant. Figure 1 depicts the configuration of the apparatus once fully loaded.

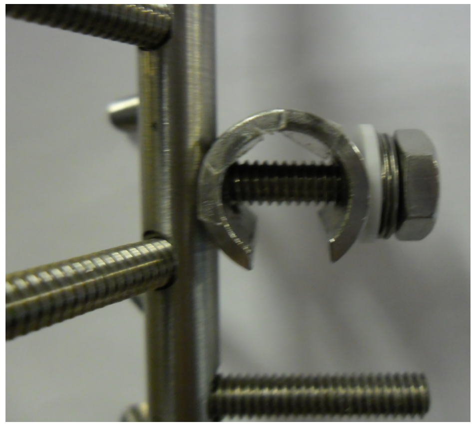

Figure 1 Loaded specimen and support tree

The c-ring test specimens were fabricated according to ASTM G38-01 [1]. Specifications for the specimens are an outer diameter (OD) of 12.7 mm, inner diameter (ID) of 9.15 mm and a length of 12.5 mm. The test specimen used is 316LSS which was fabricated according to ASTM A213/A269/A511. The c-rings will be stressed according to the National Association of Corrosion Engineers (NACE) Standard TM0177-96, which is 100% of the 0.2% offset yield strength of the tested material [4]. The resultant strains in the c-ring will be plastic but it is expected that this is a conservative engineering estimate [1]. From various Slow Strain Rate Tests (SSRT) and constant load tests at similar SCWR conditions, the test duration will begin at 500 hours [6].

3. Results and Discussions

As discussed earlier, the finite element program is key to the success of this testing because without it, one can only guess at the actual stresses present in the SCW environment. Most c-ring experiments utilize a constant-strain technique for simplicity but at the process conditions, bench top approximations of stresses are insufficient to account for the variety of thermomechanical interactions taking place within the testing condition. Figure 2 shows the results of the FEA modeling depicting the relieving of some of these stresses from the low temperature to the high temperature conditions. The ceramic washers were not shown in the analysis as to focus on the results of the C-ring. The ring was situated between two washers and given no movement constraints. A stress of 2.5 MPa was applied along the x-axis and allowed the specimen to deflect. Heat was applied in the second step, as seen in the right diagram. It can be noted that the system was allowed to expand with a constant-load applied, as in the expected experimental conditions. As expected, it was found that the deflection of the initial stressing will be removed by the thermal expansion and creep of the material in the high temperature environment resulting in a lower stress intensity than originally applied. However, having this knowledge is crucial to formulating representative and meaningful SCC tests using the c-ring technique.

The highest stresses can be found on the underside of the specimen but the stresses of interest are on the apex of the c-ring. It is anticipated that the SCC initiation will be most prevalent at the areas with the highest stresses. The Von Mises stress at the apex has a maximum of 149 MPa. Room temperature yield and tensile strength for 316L SS is 232 MPa and 544 MPa respectively. At temperature, the yield and tensile strength is 141 MPa and 417 MPa respectively. These results show that a stress of 2.5 MPa results in high local stresses at the apex but can be controlled based on desired stresses. Future experimental testing will involve strain gauges to confirm expected stresses and in environment testing to confirm if the stresses will result in SCC initiation and failure sites of highest observed stress.

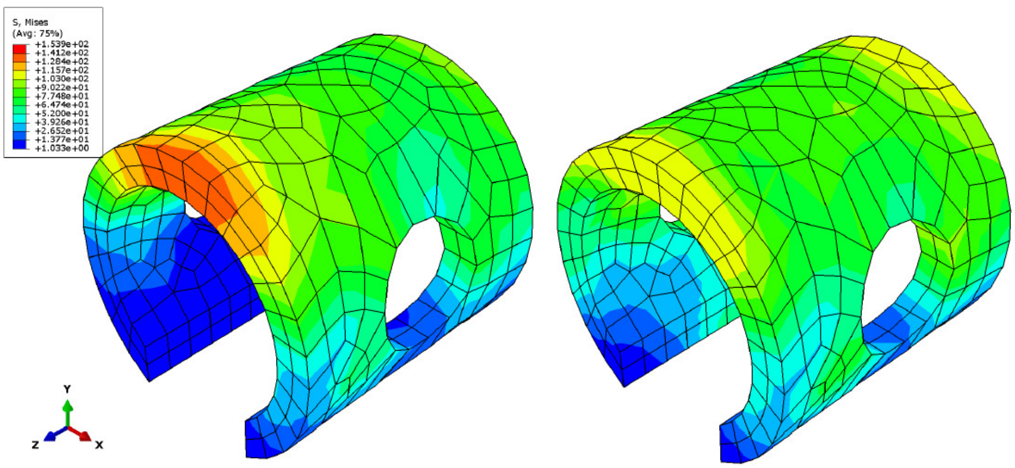

Figure 2 Stressed C-ring 25°C (left), stressed C-ring 500°C (right) – MPa

The disc springs have a substantial impact on the results of the experiment. Their ability to survive the testing environment will affect whether the testing conditions remain consistent and, thus the results reproducible and reliable. The durability of the disc springs will be subject to the loading condition and material selection. SCC and stress relaxation propensity of the disc springs is of concern but there currently exists limited data on these behaviors of disc springs in high temperature environments. The data that is available fails to make the connection with temperature, material and stress. It can be expected that with the Series C disc springs, as defined by Deutsches Institut für Normung (DIN) 2093: 2006-03, the stress relaxation will be a non-influencing factor due to applied stresses being substantially below previous relaxation testing [3]. For the purpose of examining the potential mechanical effects of the disc springs, a FEA on the disc springs was developed to analyze the mechanical and thermal effects that the disc springs would experience, Figure 3. The disc springs are assumed to be fabricated of 316L SS.

For this analysis with ABAQUS CAE, the disc spring was constrained against a backing washer, its image being suppressed for this presentation. The disc on the left shows the stressed case at room temperature and the diagram on the right shows the spring heated to a process temperature of 500°C. The bodies were constrained using a general contact setup between the disc springs and backing washer. An applied load of 489 N was set across the surface of spring to achieve flat load conditions. Plasticity effects were neglected to complete the simulation under the extreme conditions. The FEA results show that the highest stress concentration will be located at the inner diameter of the disc. At the 489 N applied load, the spring is anticipated to be at flat load. From the image, it is clear that at the at temperature conditions the inner diameter will experience stresses above its fracture stress. The disc will need to be utilized well below the flat load condition and hence will be capable of surviving the experiment but further experimental work will be required to ensure its durability in actual test conditions and determine plasticity effects.

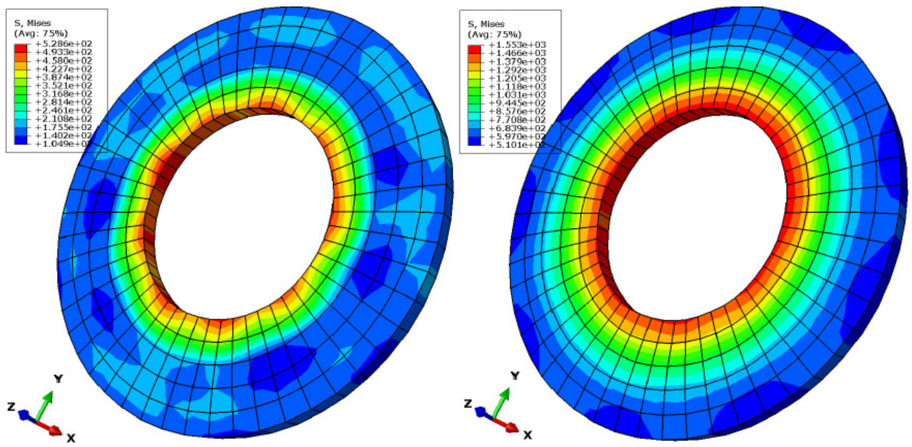

Figure 3 Stressed Disc Spring 25°C (left), Stressed Disc Spring 500°C (right) - MPa

4. Conclusion

SCC is an important phenomenon observed in materials but especially critical in the development of material selection for the SCWR program. The dangers posed by the failure of equipment through the variety of mechanisms posed by SCC are real and must be assessed critically to obtain the most prudent solution. The results from the ABAQUS CAE FEA software show that the c-ring specimens should experience cracking behavior at the apex near the edges of the c-ring based on a constant-load application of 2.5 MPa applied at room temperature. The FEA and associated research also demonstrates that the loading mechanism, the disc spring, should be mechanically suitable to survive the testing conditions, even at an extreme loading of 489 N. Further experimental testing will be conducted to prove the validity of the technique at 500°C and 25 MPa.

5. References

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