INFLUENCE OF RESIDUAL STRESSES ON BRITTLE FRACTURE OF FERRITIC STEELS

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ABSTRACT

An experimental and numerical study is presented which demonstrates the significant effect of tensile residual stress fields on the brittle fracture of ferritic steels. A residual stress field was introduced into laboratory specimens, specifically single edge notched bend, SEN(B), and round notched bars, RNB, using in-plane compression. In-plane compression consists of applying a compressive load along the longitudinal axis of a specimen containing a shallow notch and then unloading at room temperature. The specimens were then cooled to a temperature of -150^{o}C and reloaded to fracture after introduction of a sharp notch. Numerical analyses utilizing ABAQUS finite element code were carried out to simulate the process of in-plane compression. The numerical studies demonstrated that a high tensile residual stress region was created at the notch tip. A considerable decrease in fracture stress and fracture toughness was observed as a result of in-plane compression. The results emphasise the significant role of residual stresses in the fracture behaviour of ferritic steels.

1 INTRODUCTION

Residual stress fields have significant effect on the fracture load of structures [1]. Welding is one of the major causes of residual stresses. The magnitude of weld residual stress can be as high as the yield strength of the material [2]. The tensile residual stress field can be combined with in-service stresses and promote failure [2,3]. This can be detrimental in the case of brittle fracture, since the tensile residual stress is more effective when there is a low level of plasticity at fracture. A review of the treatment of residual stresses in the defect assessment of welded structures has been discussed by Budden [4]. Understanding how residual stress affects the subsequent in-service loading will assist in establishing more accurate structural integrity assessments codes. The purpose of this paper is to understand the influence of residual stress fields on the fracture behaviour of two types of ferritic steels, A508 and A533B at low temperature. These steels are commonly used in the power generation sector. Tensile residual stresses were introduced in laboratory specimens at room temperature and their fracture behaviour was studied at -150^{o}C. Decreasing the temperature increases the likelihood of a brittle fracture mechanism in the ferritic steel.

In order to study the effect of residual stresses, different methods have been used to generate tensile residual stress fields in laboratory specimens [1,5,6]. Harris [6] applied a compressive preloading on four point bend specimens which generated a tensile residual stress field ahead of a notch. Generally, tensile preloading of fracture specimens, known as warm pre-stressing produces a compressive residual stress field and inhibits the fracture [7]. Harris observed a strong effect of residual stress on the low temperature fracture load of A533B steel. Another method to introduce a residual stress field into laboratory specimens is local compression, or side punching [5]. This method has been extensively studied by Mahmoudi [8]. Local compression consists of punching two opposite sides of the specimen with rigid punching tools. The local compression method has been used to generate a tensile residual stress field at the notch tip of compact tension specimens made of Aluminium and A508 steel. Considerable decreases in the fracture toughness of the materials following local compression were observed.

Spindler [9] applied a compressive load in the longitudinal direction to a single edge notched bend , SEN(B) specimen. A combination of bending moment and compression produced a tensile residual stress field at the notch tip. In this paper the same procedure was followed to introduce a tensile residual stress in SEN(B) specimens. Moreover, a number of round notched bar, RNB, specimens were compressively loaded in their axial directions. Here, the term in-plane compression is used to describe this preloading for both SEN(B) and RNB specimens.

In the following section experimental results are presented. Due to the scatter of low temperature fracture data in ferritic steel, a statistical comparison was made to investigate the effect of residual stress fields created by in-plane compression. A brief summary of the in-plane compression technique is described in section 2.1. In section 3 the finite element studies which include a simulation of the in-plane compression technique and a prediction of the residual stress field are presented. Finally, conclusions are drawn in section four.

2 EXPERIMENTS

A total of sixteen RNB and thirteen SEN(B) specimens were tested in two different conditions, as received and containing residual stresses. As-received corresponds to the specimens being tested without any residual stress. These specimens initially had a sharp notch. The in-plane compression method used to generate a residual stress field in the other set of specimens. In these specimens a sharp notch was created after preloading.

The RNB specimens were made of A508 steel. Nine out of sixteen test results from the RNBs in the as-received condition came from an earlier test programme of Mirzaee-Sisan [10]. The RNB configuration of this study is similar to that in the previous work. The RNB specimens contained a sharp notch of 0.07 mm radius with an inner diameter of 8 mm and an outer diameter of 14 mm. In this study, seven extra RNB specimens were fabricated. Figure 1 shows the dimensions of the RNB specimens. The notch root of these specimens had a shallow notch with radius of 1.25 mm. A sharp notch created using the electro discharge machining, EDM, process was introduced after a residual stress field had been generated. The final inner diameter was therefore 8 mm, with a sharp notch similar to the as-received specimens. The specimens were subsequently loaded to fracture at low temperature.

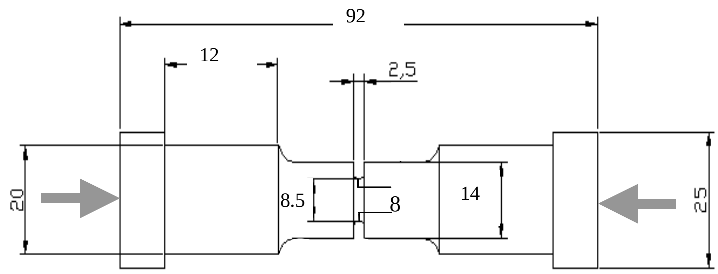

Figure 1: A round notched bar specimen. All dimensions are in mm. The arrows show the direction of pre-loading.

Thirteen SEN(B) specimens were made of A533B ferritic steel. Figure 2 illustrates the configuration of the specimens. The SEN(B) specimens had dimensions of 250 x 50 mm with a thickness of 10 mm. The length of span for the subsequent three point bending was chosen as 192 mm. Five specimens had a shallow notch of R=12.5 mm. A sharp notch of 0.1 mm was created in the specimens after preloading. The length of the EDM notch was 2.5 mm, which meant a/W=0.3. They were then loaded to fracture at low temperature. In the next section the in-plane compression technique is described briefly.

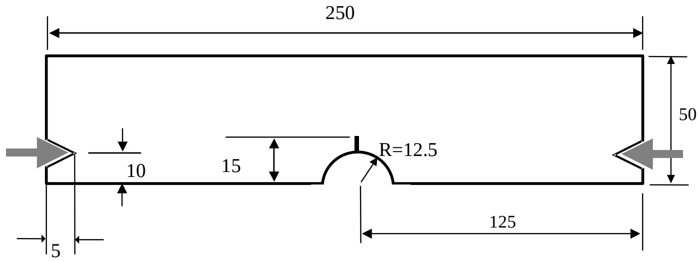

Figure 2: A single edge notched bend, SEN(B), specimen. All dimensions are in mm. The arrows show the direction of pre-loading.

2.1 In-plane compression

Spindler [9] used in-plane compression to introduce a tensile residual stress field at the notch root in SEN(B)specimens. A similar configuration of SEN(B) to that described previously was used in this study. The specimens had a shallow notch and a special design was made in order to apply a compressive load to the notch tip. The notch tip radius was R=12.5 mm. Two 'V' notches were grooved at the longitudinal ends of the beam. The SEN(B) specimens were subjected to in-plane compression at room temperature. The loading direction is shown in Figure 2. A compressive load of -73 kN was applied at the grooved sides at room temperature. The specimens were then unloaded. This cycle of loading and unloading generated a residual stress field which was tensile at the notch tip. A 250 kN servo-hydraulic rig was used in displacement control at room temperature and with a loading rate of 0.003 mm/s. To determine the fracture toughness of the specimens at low temperature, a sharp notch of length 2.5 mm was introduced at the notch root using the EDM process. The specimens were then fractured at -150^{o}C and the data compared to the as received data.

A similar process was applied to the RNB specimens. The RNBs were compressively loaded to an average net section stress of 910 MPa in the axial direction. The initial radius of the RNB was 1.25mm. A non-uniform deformation at the net section due to bending and compression loads generated a residual stress field which was tensile at the notch tip and compressive in the centre of the round notched bars. The EDM process was then used to introduce a circumferential sharp notch at the mid-section of the bars and they were then cooled to -150°C before being reloaded to fracture.

2.2 Summary of results

SEN(B) specimens in the as-received (AR) condition, and containing residual stress fields were cooled in a chamber to -150^{o}C by liquid nitrogen and subjected to three point bend loading. A loading rate of 0.003 mm/sec was used. The results, in terms of fracture toughness against probability of failure, are shown in Figure 3a. The loading cycle to which the specimens were subjected is termed CUCF – compression, unloading, cooling and loading to fracture. The probability of failure for the experimental results is based on the following estimate [11],

$$P_f = \frac{i-0.5}{N}, \quad (1)$$

where N represents the sample size and i the order number. The statistical distribution of the experimental results demonstrates that the average fracture toughness of the material reduces by approximately 40 % after a CUCF cycle.

The RNBs containing a residual stress field were also fractured in tensile loading at -150 °C. The earlier as-received data [10] and the current data are shown against the probability of failure, obtained using equation 1, in Figure 3b.

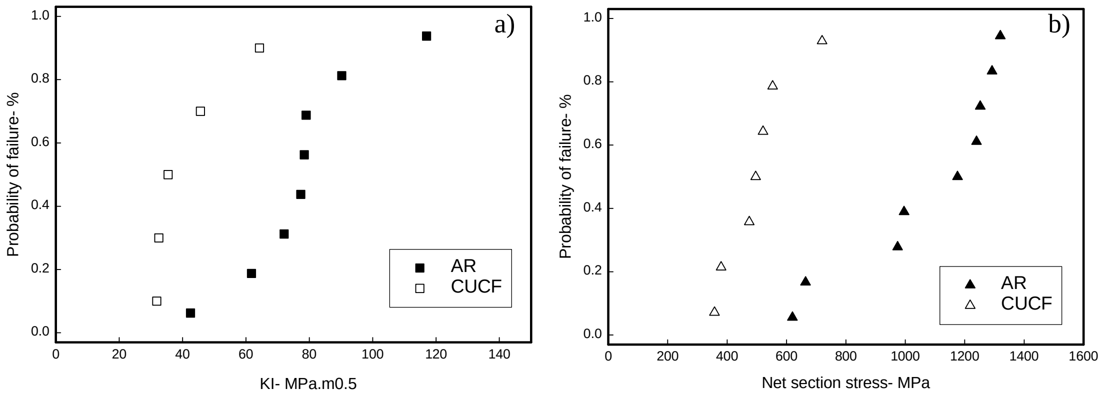

Figure 3: Experimental results of (a) SEN(B)s and (b) RNBs in the AR and CUCF condition

The net section stress was found by dividing the fracture load by the cross sectional area. The cross sectional area was determined by measuring the fracture surface diameter of the bars. The results from the RNB tests also show a high level of reduction in net section stress. The minimum and maximum net section stresses in the RNBs had decreased from 620 to 357 MPa and 1319 to 719 MPa respectively. The mean value also showed a reduction of about 50 %.

The fracture surface of the specimens indicated that the mechanism of failure in the specimens at -150°C was cleavage. To understand how the residual stress was generated in a CUCF cycle, finite element analyses were carried out. This will be explained in the next section.

3 FINITE ELEMENT SIMULATION

ABAQUS /CAE 6.3 [12] finite element code was employed to simulate the in-plane compression method of generating residual stress fields. An elastic-plastic, isotropic hardening, material model was used. For A533B steel the yield strengths were 470MPa and 625MPa at 20°C and -150°C respectively. A508 steel had the yield strengths of 430MPa at 20°C and 695MPa at -150°C. An axi-symmetric model of the RNB specimens and a 3D model of the SEN(B) specimens was created. An axi-symmetric 8-noded quadrilateral element, CAX8R, with reduced integration was used for the RNB specimens. A three dimensional 8-noded linear brick element, C3D8R, with reduced integration was used for the SEN(B) specimens. Due to the existence of two planes of symmetry, only a quarter of the SEN(B) and one quarter of the RNB specimens was modelled.

The simulation of in-plane compression consisted of a cycle of compression, unloading and introduction of a crack. The simulation was carried out in three different steps. The first step modelled the compression of a SEN(B) containing a shallow notch and loading the specimen in the axial direction to -73 kN, using room temperature material properties for the A533B material. The second step consisted of removing the applied load. The residual stress field created after in-plane compression is shown in Figure 4a. The stress normal to the notch tip is plotted against the distance from notch tip. The third step of the finite element simulation was to introduce a sharp notch. This was achieved by changing the boundary condition at the symmetry plane. The constraint in symmetry plane was released for 2.5 mm. Figure 4a demonstrates that tensile residual stress fields were created at the edges of the SEN(B) with compressive stresses in the centre.

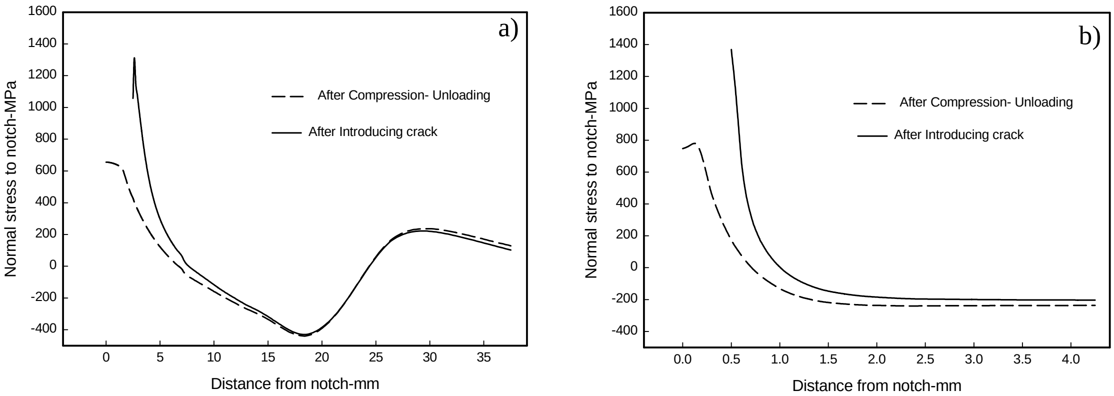

Figure 4: Residual stress distributions in (a) SEN(B) and (b) RNB after being subjected to in-plane compression

The same steps were repeated for the RNB specimen. The specimen was compressively loaded to achieve 900 MPa net section stress. Then the load was removed. Figure 4b shows that a high tensile region was created at the notch tip. A sharp notch was introduced by changing the boundary condition by releasing the constraints in the symmetry plane to achieve a final diameter of 8 mm. Figure 4b explains why the loading capacity of the specimens dramatically decreased. The high tensile residual stresses normal to the notch tip promoted brittle fracture of the specimens.

4 CONCLUDING REMARKS

This work has investigated the effect of residual stress fields on brittle fracture of ferritic steel at low temperature. First, a residual stress field was created in RNB and SENB specimens at room temperature. Then a sharp notch was introduced into the residual stress field. The technique used for introducing residual stresses was in-plane compression. The experimental results have shown that tensile residual stresses can dramatically reduce the material strength. The results highlight the significant role of a residual stress field on the fracture behaviour of specimens.

5 ACKNOWLEDGMENT

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