WARM PRE-STRESS EFFECTS ON CLEAVAGE FRACTURE IN CENTER CRACK SPECIMEN

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ABSTRACT
The apparent fracture toughness of cracked components can be increased for some materials by a loading procedure called warm pre-stressing (WPS). The procedure creates a region of compressive residual stresses around the crack tip and hence allows larger service loads to be tolerated by the cracked specimen. Numerical modeling of this procedure in the past has been conducted only for high-constraint specimens. In this paper the warm pre-stress procedure is simulated for a center crack specimen using finite element method. Different values of the lateral load are considered in the preloading stage to provide different levels of crack tip constraint. It is shown that a compressive lateral load in the preloading stage increases the fracture load whereas a tensile lateral load decreases the fracture load.

1 INTRODUCTION

Proof test is a common method for ensuring the integrity of mechanical components like pressure vessels. In this test, the component is subjected to a testing load, 20 to 50 percent higher than the service load. If the test is done at a temperature higher than the service condition, and the component's material displays enough toughness transition with temperature, the procedure is called warm pre-stressing (WPS). The WPS test can be used not only for validating the integrity of component, but also for improving fracture toughness of the material [1].

One of the most conventional methods for warm pre-stressing is called LUCF (Loading, Unloading, Cooling, and Fracture). In this method, a cracked specimen is subjected to a mechanical load at an elevated temperature in the same direction as the service load. Then, the specimen is unloaded and the temperature is decreased to the operational condition. At the end, it is reloaded to its fracture load. In the preloading stage, a plastic zone is created around the crack tip. The size of the plastic zone depends on the magnitude of the load. When the component is unloaded, a region of compressive residual stress is produced around the crack tip. The load bearing capacity of the cracked component is improved due to the presence of the residual stress.

Many researchers have attempted to study the effects of warm pre-stressing on the fracture resistance of cracked specimens. Succop et. al. [2], Smith [3], Nakamura et. al. [4] and Harris et. al. [5] are to name a few. However, almost all of the theoretical and experimental studies in the past have been conducted on high constraint specimens like three-point bend specimen (see for example [2,3]) or the compact tension specimen [4]. Betegon and Hancock [6] and O'Dowd and Shih [7] have shown that the crack tip constraint is high only in specimens having zero or positive T-stress.

The finite element method is used in this paper to investigate the effect of LUCF procedure on cleavage fracture in a centrally cracked specimen made of a ferritic steel alloy (A533B). The T-stress is altered by changing the load applied parallel to the crack. Therefore, the effects of T-stress on warm pre-stressing can be studied in general for the same material. It is assumed that during the whole process, the specimen is under mode I loading.

2 FINITE ELEMENT MODELING

The finite element code ABAQUS was used to analyze the LUCF procedure in a square specimen containing a center crack. The dimensions of specimen are given in Table 1 and Figure 1. The crack length ratio a/W was 0.5 where 2a is the crack length and 2W is the specimen width. The loading history in LUCF was obtained from earlier experimental studies performed on A533B steel alloy by Fowler [8]. The material is considered to be elastic-plastic with kinematic hardening behavior in unloading. The stress-strain curves for A533B at 20 ^oC and -170 ^oC were obtained from reference [8]. As shown in Figure 1, the specimen is subjected to two perpendicular mechanical loads applied uniformly along the specimen edges: S_y normal and S_x parallel to the crack direction. Eight-noded plane strain elements were employed to simulate the specimen. The path independent J-integral was calculated directly by ABAQUS using the virtual crack extension techniques. In the whole analyses, it was confirmed that the J-integral was path independent over a considerable range ahead of the crack tip.

Table 1: Dimensions of the center cracked specimen

Description	Value
2H (Specimen Length)	200 mm
2W (Specimen Width)	200 mm
2a (Crack Length)	100 mm
B (Specimen Thickness)	25 mm

The RKR model is adopted here for predicting cleavage fracture in the specimen. According to this model, cleavage fracture takes place when the hoop stress in front of the crack tip and along the crack line (σ_{yy}) reaches a critical magnitude σ_f at a critical distance r_c from the crack tip. The critical stress σ_f and the critical distance r_c are often considered to depend only on the material properties. Earlier studies [9], [10] suggest that for A533B the value of r_c is about 1^{mm}. Two models are needed to study the effects of preloading on cleavage fracture in the center cracked specimen. The first model, which corresponds to the as-received specimen without any preloading effects, is used to determine the critical stress σ_f from the finite element results. In this model, the specimen is subjected to equibiaxial load and the load is increased till the J-integral attains its critical value corresponding to the experimentally determined fracture toughness K_{Ic} at -170 ^oC [8]. For such loading conditions the T-stress is zero and the singular stresses are adequate to describe the stress field near the crack tip [6]. The critical stress σ_f is calculated from the value of σ_{yy} at the critical distance of $r_c=1^{mm}$ from the crack tip.

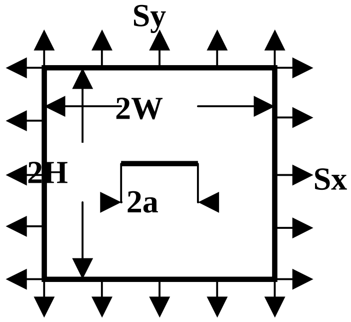

Figure 1: Center crack specimen.

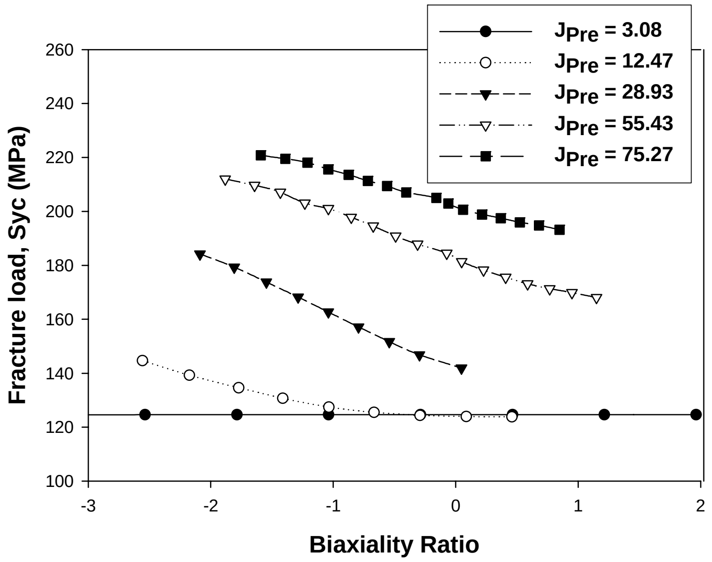

Figure 2: Effect of T-stress in preloading stage on fracture load.

In the second model, the specimen is first subjected to biaxial preloading (normal and parallel to the crack directions) at 20 ^{o}C. Then it is unloaded in the same temperature. Because of the elastic-plastic behavior of the material, a residual stress field is produced around the crack tip after unloading. The specimen is finally reloaded uniaxially at a lowered temperature of -170 ^{o}C. The load is increased until σ_{yy} along $\theta = 0^{o}$ reaches the critical stress σ_f which was obtained in the first model. This load is introduced as the fracture load limit after WPS. By changing the magnitude of lateral load S_x in the preloading stage, the effect of T-stress on the WPS procedure can be investigated. In each set of analyses, the value of lateral load varies relative to the normal load S_y but the loads S_x and S_y are increased until the J-integral reaches a given value.

3 NUMERICAL RESULTS

Based on the test results presented by Fowler [8], the average value of the as-received fracture toughness at –170^{o} for A533B steel is taken as K_{Ic} =65.6MPa$\sqrt{m}$ (or equivalently J_c=18.91MPa.mm). Using the first model, the critical stress was determined from the finite element results. For the preloading stage in the second model, nine different values of the lateral load were applied individually to the specimen. Thus, the effect of T-stress on the WPS could be studied for a wide range of negative and positive values of T. Numerical values of the lateral loads applied are: $S_x = -200, -150, -100, -50, 0, 50, 100, 150, 200\,MPa$. For each of these values, five different levels of normal load (S_y) were considered. The normal loads were adopted in a way that five fixed J-integrals ($J_{\mathrm{Pre}} = 3.8, 12.47, 28.93, 54.43, 75.27$ MPa.mm) could be produced in the specimen for each value of S_x . The maximum size of the plastic zone in the preloading stage was always less than half of the specimen ligament for any considered combinations of S_x and S_y. By such an arrangement it was confirmed that full plasticity does not take place in the specimen and that there is always an elastic region surrounding the near crack tip area.

To show the ratio of T-stress relative to the stress intensity factor K_I, the T-stress is normalized as

$$\beta = \frac{T\sqrt{\pi a}}{K_I} \tag{1}$$

The dimensionless parameter β is called the biaxiality ratio. The T-stress and the biaxilaity ratio were determined for each loading configuration, using the procedure described in [11] and eqn (1). Figure 2 shows the variations of fracture load with the biaxiality ratio for different values of J in the preloading stage J_{pre}. Similar results are shown in Figure 3 but for the critical values of J-integral J_c after WPS procedure. It is seen from both Figures that the load bearing limit of the component is improved for lower values of the biaxiality ratio in preloading.

4 DISCUSSION

As described before, because of highly concentrated stresses near the crack tip, preloading develops a plastic zone in this area. Due to unrecoverable plastic strains, subsequent unloading and temperature reduction produce a region of residual stresses near the crack tip. The finite element results showed that the distribution of residual stresses depends significantly on the load applied parallel to the crack S_x. For example, Figure 4 shows how the residual stress σ_{yy} ahead of the crack tip varies for different values of the lateral load S_x. The stresses shown in Figure 4, correspond to a fixed value of J_{pre} =55.43MPa.mm in the preloading stage. It is seen from Figure 4 that for r<2mm, the hoop stress ahead of the crack tip is always compressive. This compressive hoop stress enhances the load bearing capacity of the specimen in the reloading stage. The magnitude of compressive hoop stress increases when the lateral load S_x decreases from 200MPa towards -200MPa. A similar trend was observed for other values of J_{pre} in the preloading stage.

The shape and size of the plastic zone developing around the crack tip in the preloading stage, depend upon the loading conditions. Our finite element results showed that for a fixed value of J-integral, the size of plastic zone decreases when the lateral load S_x increases relative to the normal load S_y. This is consistent with earlier studies by Miller and Kfouri [12] and Al-Ani and Hancock [13]. The dependency of plastic zone size on the loading conditions can be related to the sign and magnitude of the T-stress. Al-Ani and Hancock [13] suggest that due to the loss of crack tip constraint, the plastic zone is larger for specimens having a negative T-stress.

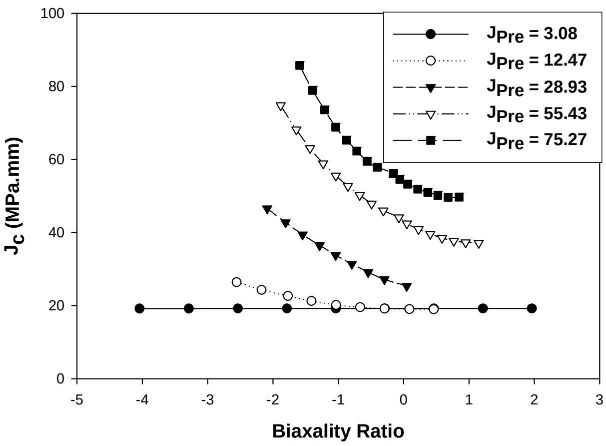

Figure 3: Effect of T-stress on the J-Integral at fracture load, J_c.

It can be suggested that the significant effect of β on LUCF is mainly because of its influence on the shape and size of the plastic zone. Larger plastic zones in the preloading stage are associated with larger plastic strains. Larger plastic strains cause more considerable residual stresses upon unloading and an increase in the apparent fracture toughness in reloading. Therefore, the fracture load for a negative T-stress in preloading is expected to be larger than the fracture load for a positive T-stress. This is consistent with finite element results shown in Figures 2 and 3.

It is also observed in Figure 3 that as the preloading J-integral (J_{pre}) increases, the J-integral at fracture (J_c) becomes more dependent on the T-stress. For instance, when J_{pre}=55.43 MPa.mm and β= -1, the value of J_c is about 1.5 times J_c in the case J_{pre} is the same and β= +1. But for a low J-integral in preloading like J_{pre}=12.47 MPa.mm the variation of J_c with the biaxiality ratio is not considerable.

According to the linear elastic fracture mechanics (LEFM), the lateral load S_x has no effect on the stress intensity factor in a center crack specimen. In small scale yielding (SSY), plastic deformation near the crack tip is often neglected and the linear elastic relations are considered to be applicable with a good approximation. For moderate scale yielding, the area of plastic region cannot be neglected, and hence the use of elastic-plastic relations is inevitable. In this case, the J-integral is used instead of the stress intensity factor. According to the classical theories of fracture mechanics, a single parameter is sufficient to describe the stresses and strains near the crack tip. Therefore, it is assumed that different cracked specimens of identical J-integral should always have similar stresses near the crack tip and inside the plastic region [14], [15]. However, constraint based fracture mechanics suggests that at least a second parameter like T or Q is required to characterize fully the crack tip fields. While previous studies dealing with constraint effects are confined mainly to monotonic loading, similar results were found in this research for the effect of constraint on the WPS procedure. This implies that in a center crack specimen, the crack tip stresses after warm pre-stressing depend not only on the value of J-integral, but also on the T-stress. For example, it can be observed in Figure 2 that for a specified J-integral in the preloading stage, the fracture load decreases when the T-stress or the biaxiality ratio is increased.

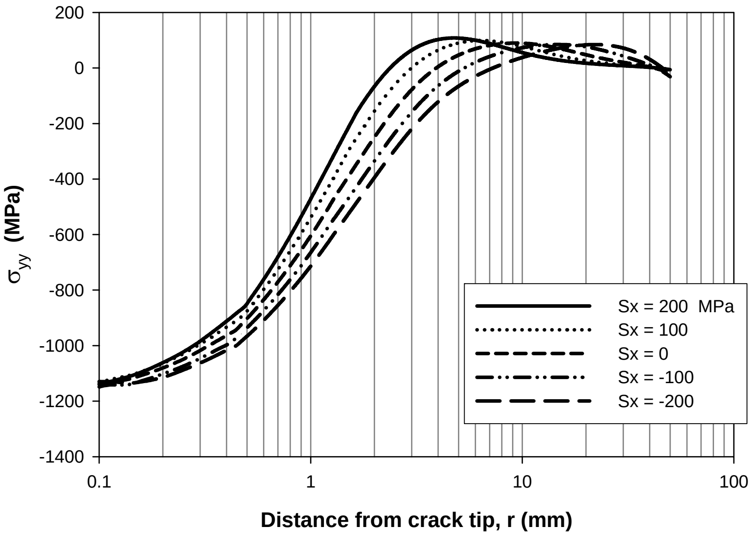

Figure 4: The hoop stress ahead of the crack tip after unloading.

5 CONCLUSIONS

1- The biaxiality ratio β influences significantly the size of plastic zone near the crack tip in the preloading stage.

2- Different sizes of the plastic zone in preloading cause different levels of residual stress upon unloading. More compressive lateral loads or more negative T-stresses produce larger compressive hoop stresses ahead of the crack tip.

3- A negative T-stress (or a negative β) in preloading leads to an increase in the critical J-integral corresponding to cleavage fracture. The apparent fracture toughness is decreased when the lateral load in the center crack specimen is tensile or more specifically when the T-stress in the specimen is positive.

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