Fracture Toughness of STS 304 Stainless Steel at Low Temperatures

Do-Sik Kim, B. O. Yoo, S. J. Baik, K. H. Kim, Y. S. Choo, K. P. Hong
Korea Atomic Energy Research Institute, Irradiated Materials Examination Facility,
150, Yusong-Ku, Dukjin-Dong, Taejeon, 305-353, kimds@kaeri.re.kr

1. Introduction

AISI Type 300-series stainless steels are used widely in cryogenic applications because of their excellent low temperature properties. Among these properties, fracture toughness is the measure of a cracked material's resistance to tearing and fracture. In this study, the fracture toughness tests of the cold-worked STS 304 stainless steel plate were conducted in the temperature range of 111K (-162°C) to 293K (20°C). The dependence of low temperature on fracture toughness was experimentally examined.

2. Experimental Procedure

2.1 Material and Apparatus

The material used in this study was a 2mm thick plate of cold worked STS 304 stainless steel produced by POSCO in Korea. All *J*-integral tests were conducted on servo-hydraulic testing system with cryostat, and began after the temperature had stabilized at 111K (-162°C), 153K (-120°C), 193K (-80°C) and 293K (20°C). A thermocouple was positioned near the crack growth path on the compact tension (CT) specimen. The fracture surface of the CT specimen was observed by using SEM.

2.2 Elastic-plastic fracture toughness test

The *J*-integral tests were performed using CT specimens with a 2mm thickness and a 40mm width (W). The notch was machined in the *L-T* orientation. All specimens were fatigue precracked with a sinusoidal waveform at room temperature to an a/W ratio of 0.60. To prevent out-of-plane displacement, antibuckling plates were fitted to either side of the specimen.

3. Results and Discussion

3.1 Load versus load-line displacement curves

Figure 1 shows typical load and load-line displacement curves at room (293K) and low temperature (111K). The pop-in does not occur at each unloading point during testing. This indicates that the crack tip blunting and the stable crack growth occur until the specimen is totally fractured. Thus, in this study, the microvoid coalescence is believed to be the dominant cracking mechanism at all the test temperatures.

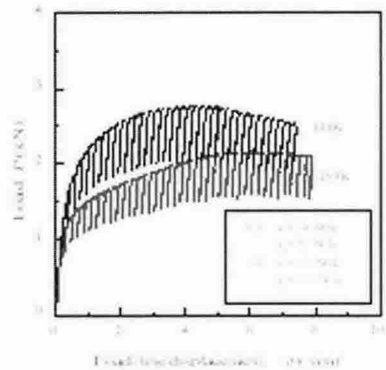


Figure 1. Typical Load vs. Load-Line Displacement curves.

3.2 Temperature dependence of fracture toughness

Initiation fracture toughness (J_c) and tearing modulus (T_{mat}) [1] are shown as a function of temperature in Figures 2 and 3, respectively.

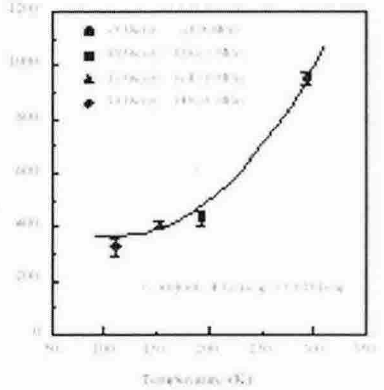


Figure 2. The Effect of Temperature on J_c.

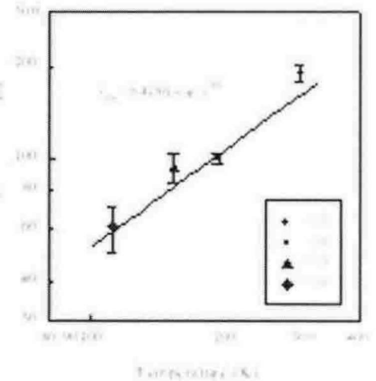


Figure 3. The Effect of Temperature on T_{mat}.

In Figure 2, J_c considerably decreases as the temperature decreases to 193K and it does not change noticeably between 193K and 111K. On the other hand, Figure 3 indicates that the T_{mat} linearly decreases with a decrease in temperature. The fracture toughness degradation with decreasing temperature is associated with an increase in tensile strength due to increasing strain hardening. Therefore, we examined the relationship between the initiation fracture toughness (J_c) and the effective yield strength (σ_{flow}). The variations of J_c are plotted as a function of effective yield strength (σ_{flow}) in Figure 4, and the empirical relationship is indicated in this figure.

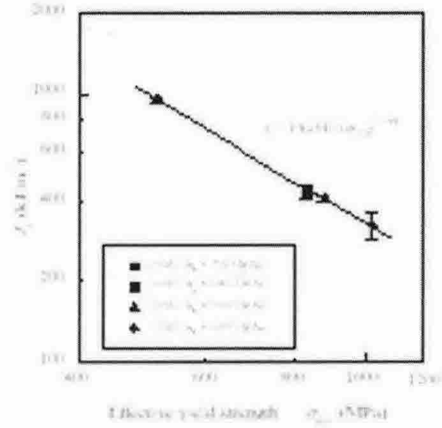
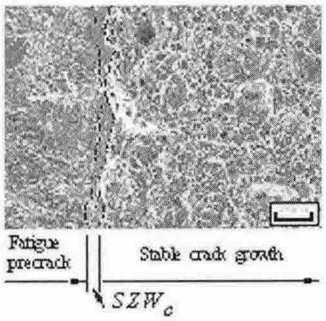


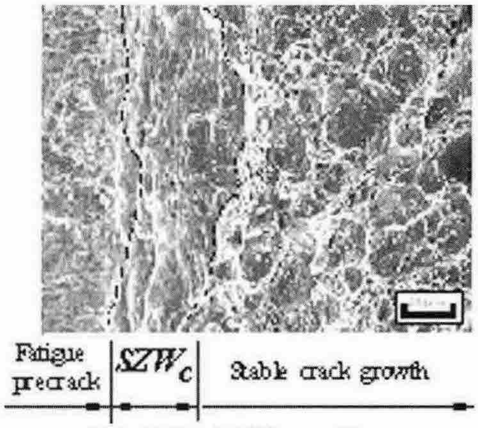
Figure 4. The Correlation between J_c and σ_{flow}.

3.4 Correlation between fracture toughness and stretch zone width

When a fatigue precracked specimen in metal is loaded, the crack tip blunts, and the stable crack growth initiates at the critical stretch zone width (SZW_c)[2,3]. Figure 5 shows typical SEM fractographs of the fracture surface at the midpoint of the specimen thickness after J-integral testing at room (293K) and low temperature (111K). In this figure, the SZW_c at room temperature is about three times as large as that at 111K. The J-test fracture surface at 111K exhibits relatively small dimples compared with that at room temperature. Through the fractographic examination, therefore, it is known that the degradation of J_c and T_{mat} with decreasing temperature results from the decrease in the SZW_c and the size of dimple with decreasing temperature.



(a) 111K, $(SZW_c)_{ave.} \approx 10\mu m$



(b) 293K, $(SZW_c)_{ave.} \approx 33\mu m$

Figure 5. Fracture Surfaces of CT Specimens.

4. Conclusion

The fracture toughness of cold-worked STS 304 stainless steel plate was experimentally invetigated at low temperatures. The main conclusions are as follows:

1. Initiation fracture toughness (J_c) considerably decreased as the temperature decreased to 193K, and it did not change noticeably between 193K and 111K. In addition, the tearing modulus (T_{mat}) linearly decreased with a decrease in temperature.
2. Initiation fracture toughness (J_c) was inversely related to the effective yield strength (σ_{flow}).

$$J_c = 1.820E7\ (\sigma_{flow})^{-1.580}$$

3. Fractographic examination revealed that the critical stretch zone width (SZW_c) at room temperature was about three times as large as that at 111K. This indicates that the variation in fracture toughness according to temperature corresponds to the decrease in SZW_c with decreasing temperature.

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