DEPENDENCE OF MODE I AND MIXED MODE I/III FRACTURE TOUGHNESS ON TEMPERATURE FOR A FERRITIC/MARTENSITIC STAINLESS STEEL - H. Li (Associated Western Universities--Northwest Div.), R. H. Jones (Pacific Northwest Laboratory), J. P. Hirth (Washington State University), and D. S. Gelles (Pacific Northwest Laboratory)

OBJECTIVE

To investigate the dependence of mode I and mixed mode I/III fracture toughness on temperature in the range of -95°C to 25°C for a low activation ferritic/martensitic stainless steel (F82-H).

SUMMARY

Mode I and mixed mode I/III fracture toughnesses were investigated in the range of -95°C to 25°C for a F82-H steel heat-treated in the following way; 1000°C/20 h/air-cooled (AC), 1100°C/7 min/AC, and 700°C/2 h/AC. Mode I fracture toughness (J_{IC}) was determined with standard compact tension (CT) specimens, and mixed-mode I/III fracture toughness (J_{MC}) was determined with modified CT specimens, which resulted in 0.41 ratio of $P_{iii}/(P_{iii} + P_i)$. The F82-H was very tough at room temperature (RT), giving a J_{IC} value of about 284 kJ/m^2. Mixed-mode I/III loading dramatically lowered fracture toughness. The J_{MC} value was only 150 kJ/m^2 at RT. J_{IC} values exhibited a strong temperature dependence and decreased rapidly with decrease of temperature. J_{IC} at -90°C was only 30 kJ/m^2. On the other hand, J_{MC} values depended much more weakly on temperature. J_{MC} at -95°C was 50 kJ/m^2, about 70% higher than J_{IC} value at -90°C. At RT the mode I specimens fractured by microvoid coalescence. Mixed mode specimens also fractured by microvoid coalescence, but tortuosity and void size on fracture surfaces were significantly less than those in mode I specimens. Interestingly, at -90°C, a crack in a mode I specimen initiated and grew by quasi-cleavage fracture; but a crack in mixed mode specimen initiated and propagated a short distance (0.5 mm) by a mixture of intergranular fracture and ductile tearing. Then the crack turned to mode I and fractured by quasi-cleavage failure. Our results indicate that crack tip plasticity was increased by mixed mode loading, and suggest that at low temperature, mode I fracture toughness is the critical design parameter, but at temperatures above RT, especially concerning fatigue and creep-fatigue crack growth rate, a mixed mode loading may be more harmful than a mode I loading for this steel because a mixed mode loading results in lower fracture toughness and higher crack tip plasticity (or dislocation activity).

PROGRESS AND STATUS

Introduction

In tough materials, which fail primarily by a microvoid nucleation and growth mechanism, the presence of a mode III loading component lowers the J_{MC} (total J-integral from mode I and mode III components) values considerably from their mode I values. The J_{MC} values pass through a minimum at a position between mode I and mode III on a plot of J_{MC} vs crack inclination angle. J_{IC} (mode I J-integral) turned out to be the highest fracture toughness value. For brittle materials such as ceramics and brittle steels, on the other hand, J_{IC} values are the lowest fracture toughnesses. The introduction of a mode III loading component increased J_{MC} values in brittle materials. More generally, materials can be divided into three categories according to their process zone size as presented by J_{IC}/σ_Y and the ratio of J_{MC} (at crack angle of 45°) to J_{IC}, as shown in Fig. 1 [1]. The materials in Region I are brittle and sensitive to mode I loading and, consequently, mode I fracture toughness is the lowest as compared with mixed-mode I/III

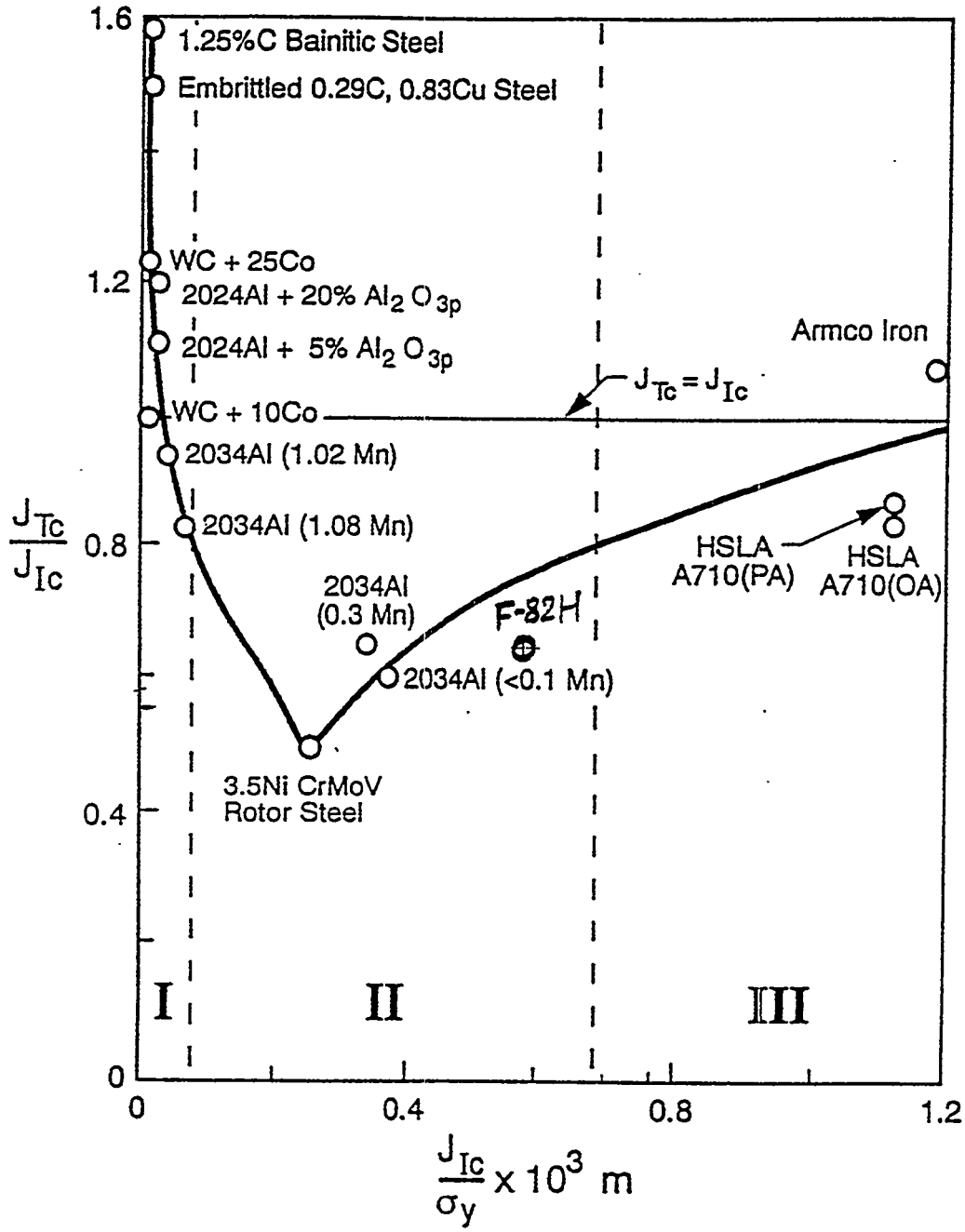

Fig. 1. J_{TC}/J_{IC} vs J_{IC}/σ_y for different materials; where J_{TC} is mixed-mode I/III J-integral at $\sigma_{iii}/\sigma_i = 1$, and σ_y is yield strength. The materials in Region I, II, and III are low toughness, tough, and ductile/tough materials, respectively.

fracture toughnesses. Therefore, for such materials, mode I fracture toughness is properly used for design. Materials in Region II are tough and sensitive to mixed-mode I/III loading, mode I fracture toughness is no longer the lowest, and the minimum mixed-mode J_{MC} is recommended as a design criterion. For the

materials in Region III, mode I and mixed-mode fracture toughness levels are similar and the mode I value can be used for design with small uncertainty. We have reported [2,3] that F-82H steel is a tough material which falls in Region II in Fig. 1. The presence of mode III stress component lowers its fracture toughness significantly. It is well known that a ferritic/martensitic steel will experience a ductile to brittle transition as temperature is lowered. However, the dependence of J_{MC} on temperature has not been reported. In this study, the dependence of J_{IC} and J_{MC} values was investigated in a temperature range of -95°C to 25°C.

Material

The F-82H steel plate used in this study was supplied by the Nippon Kokan Steel Company (NKK) in Japan. The chemical composition of the plate (as provided by NKK) is (by wt%): 0.096C-7.71Cr-2.1W-0.18V-0.04Ta-0.003P-0.003S. Specimens used in this study were cut in the T-L orientation as specified in ASTM E399-90 and were given a heat-treatment of 1000°C/20 h/AC, 1100°C/7 min/AC, and 700°C/2 h/AC. This heat treatment produced smaller grain size and higher strength than those produced by 1050°C/0.5 h/AC and 760°C/5 h/AC. The resulting microstructure was tempered martensite. The mean intercept grain size was 25 μm. The heat-treatment resulted in a yield strength (σ_y) of 648 MPa, an ultimate tensile strength (σ_{uts}) of 735 MPa, an elongation of 16.7%, and a reduction in area of 70%.

Experimental Methods

The geometries of a standard compact tension (CT) specimen and a modified CT specimen are shown in Fig. 2. The specimen shown in Fig. 2a was used for determination of mode I stress intensity (K_{IC}) at temperatures below -40°C. K_{IC} values then were converted to critical J-integrals (J_{IC}) by means of Eq. 1. Modified CT specimens were used for mixed-mode I/III testing. The magnitude of a mode III loading component can be varied by changing the crack slant angle Φ. As Φ increases, the mode III component increases owing to $P_{iii} = P_{appl} \sin\Phi$, where P_{appl} is the applied load. The crack-inclination angles used in this study were 0 and 35°, respectively. A 0° specimen represents mode I loading and the geometry of a 0° specimen becomes the standard CT specimen with side grooves as specified in ASTM standard E813-89, which was used for mode I J-integral testing at RT. A 35° specimen gives a ratio of mode III loading component to the total load $[P_{iii} /(P_{iii} + P_i)]$ 0.41. This specimen was used for both mixed mode J- and K-tests. Side grooves of 20% reduction of total thickness were used to increase the stress triaxiality at the specimen surfaces and constrain the advancing crack on the original crack plane. Calculating mixed-mode I/III J-integral (J_M) requires measuring both the vertical displacement (δ_v) and horizontal displacement (δ_h) of the load points. A standard crack opening displacement (COD) gage was positioned on the knife edges. We found that the δ_h increased with δ_v in a linear manner. Hence δ_hs were calculated approximately using a relation of $\delta_h = \alpha \times \delta_v$, where $\alpha = \delta_{hmax} / \delta_{vmax}$.

ASTM E813-89 was used to determine critical J-integrals and ASTM E399-90 was used to determine the critical stress intensity factor. The single-specimen technique was used in this study, which allows a J-R curve (J vs crack extension Δa) to be generated with one specimen. At least 40 pairs of J-Δa data were used to construct a J-R curve. J_{MC} values at -95°C were calculated from mode I K_{ic} and mode III K_{iiic} components by means of Eq. 2. Subzero temperatures were achieved by means of a refrigerator and controlled to within ±5°C during testing.

$$J_{IC} = \frac{K_{IC}^2 (1 - v^2)}{E} \tag{1}$$

where E is Young's modulus and ν is Poisson ratio.

$$J_{ic} = \frac{K_{ic}^2 (1 - v^2)}{E} \tag{2a}$$

$$J_{iiic} = \frac{K_{iiic}^2 (1 + v)}{E} \tag{2b}$$

$$J_{MC} = J_{ic} + J_{iiic} \tag{2c}$$

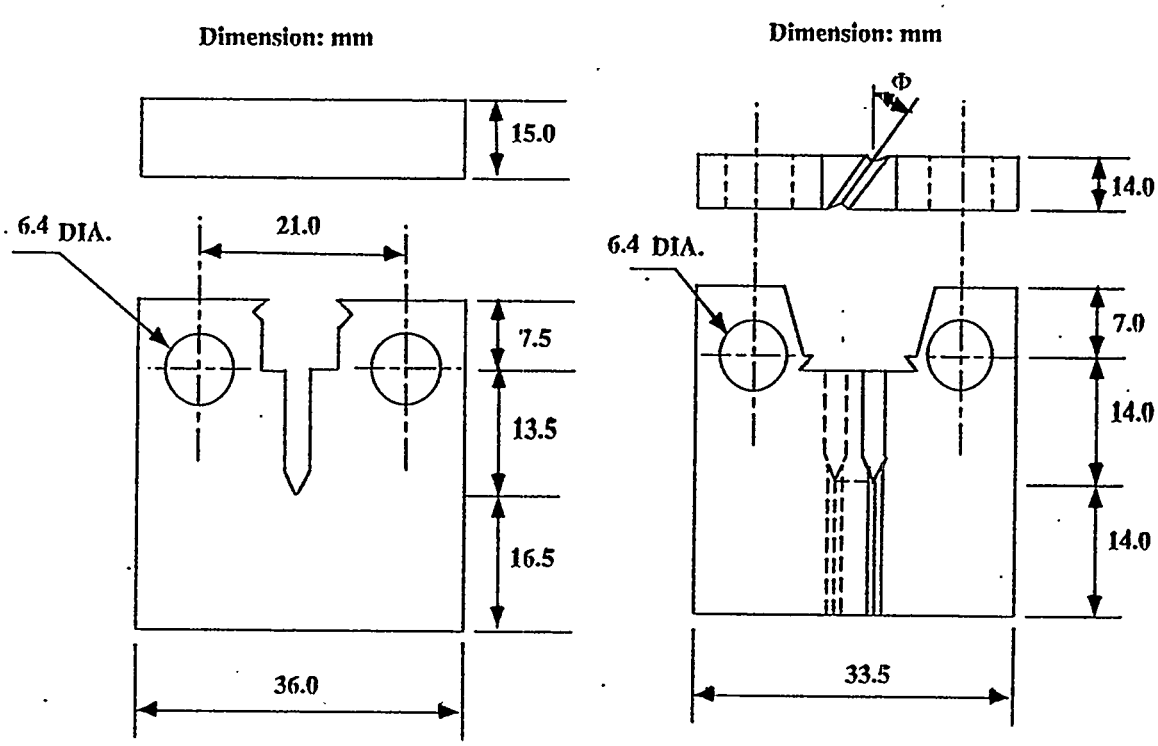

Fig. 2. The geometry of a compact tension specimen (2a) and a modified compact tension specimen (2b).

Results

At RT, the F-82H steel is very tough, J_{IC} is 284 kJ/m^2. The addition of a mode III loading component reduced J_{MC} dramatically, from 284 for mode I to 150 kJ/m^2 for mixed mode. Both mode I and mixed mode specimens fractured by microvoid coalescence, as shown in Fig. 3. However, the introduction of a mode III loading component reduced the tortuosity of the fracture surface and void size greatly, indicating lower energy dissipation during crack initiation and propagation. Consequently, mixed mode loading resulted in significantly lower critical J-integral.

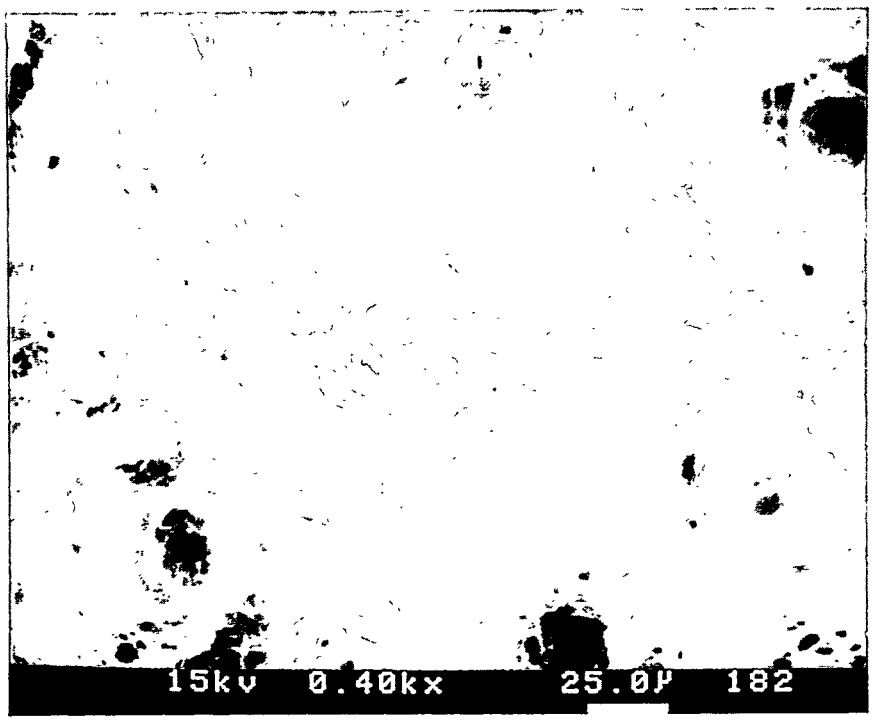

Fig. 3. SEM fractograph showing the microvoid coalescence nature fracture surfaces of a mode I specimen tested at room temperature.

The effect of temperature on fracture toughness (J_{IC} and J_{MC} values) and fractography is summarized in Table 1, and also shown in Fig. 4. It is evident that temperature has a much stronger effect on J_{IC} values than on J_{MC} values. At -90°C, J_{IC} is only 30 kJ/m^2, but J_{MC} is 50 kJ/m^2, about 70% higher. Fractographic investigation with SEM revealed that at -90°C, a mode I crack initiated and propagated by quasi-cleavage fracture (Fig. 5), indicating brittle characteristics consistent with a low J_{IC} value. On the other hand, a mixed mode crack tested at -95°C initiated and grew a short distance (0.5 mm) along the original crack plane, then changed to a mode I crack, as shown in Fig. 6. SEM investigation showed that the mixed mode crack propagated by a mixture of intergranular fracture and ductile tearing (Fig. 7). However, when the crack changed to mode I, it propagated by quasi-cleavage (Fig. 8). The information from the fracture surface of the mixed mode specimen suggests that mixed mode I/III loading increase crack tip plasticity, resulting in a higher fracture toughness.

Table 1. The dependence of fracture toughness and fracture surface appearance on temperature

	Mode I		Mixed Mode	
Temp. (°C)	J_{IC} (kJ/m^2)	Frac. surface	J_{MC} (kJ/m^2)	Frac. surface
25	284	dimple	150	dimple
-55	60	quasi-cleavage		
-90	30	quasi-cleavage	50	dimple & I.G.*

* I.G.: intergranular fracture.

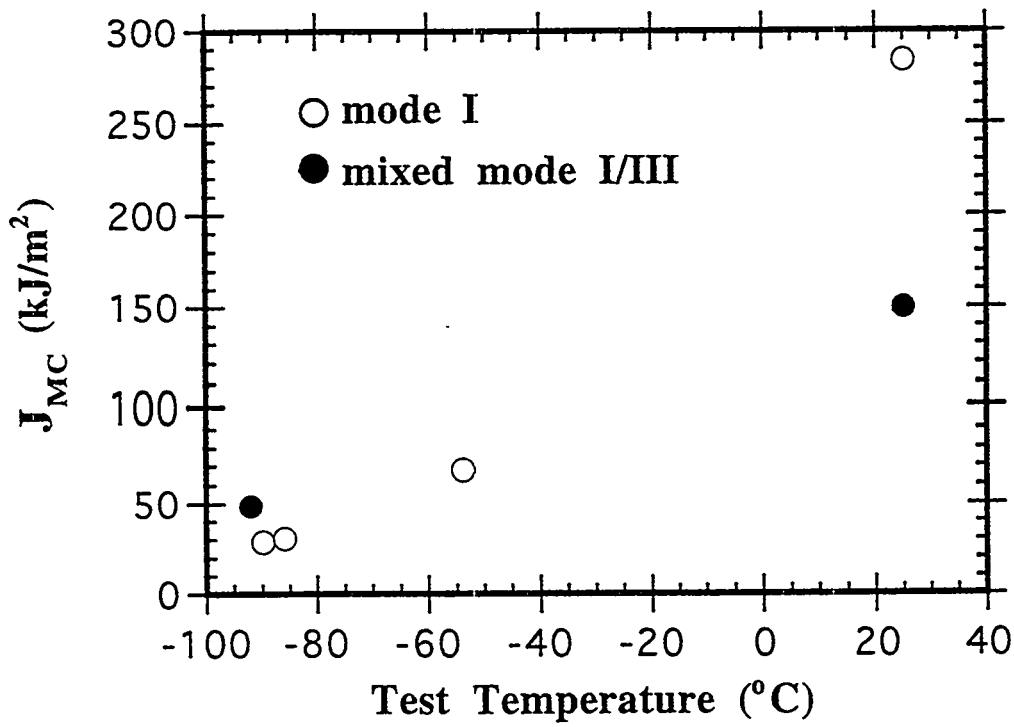

Fig. 4. The dependence of J_{IC} and J_{MC} values on testing temperature.

Discussion

The addition of a mode III loading component to mode I loading could increase, decrease, or have little or no effect on the J_{MC}, depending on the material toughness, as shown schematically in Fig. 9. For brittle materials (class A), such as glass [4], 0.29C-0.83Cu and 1.25C bainitic steels [5-7], where fracture was controlled by tensile stress and local crack-opening displacements, the addition of mode III loading components had little or no effect on the J_{ic} value (mode I J component of J_{MC}), but tended to increase the J_{MC} value. For those materials with intermediate toughness (class B), such as AISI 1090 steel [8], the introduction of a mode III loading component decreased J_{ic} values moderately, and had little effect on J_{MC}. For tough steels (class C), such as a high purity rotor steel [9] and the F82-H steel [2,3], which failed primarily by microvoid coalescence, the addition of a shear stress resulted in plastic shear localization

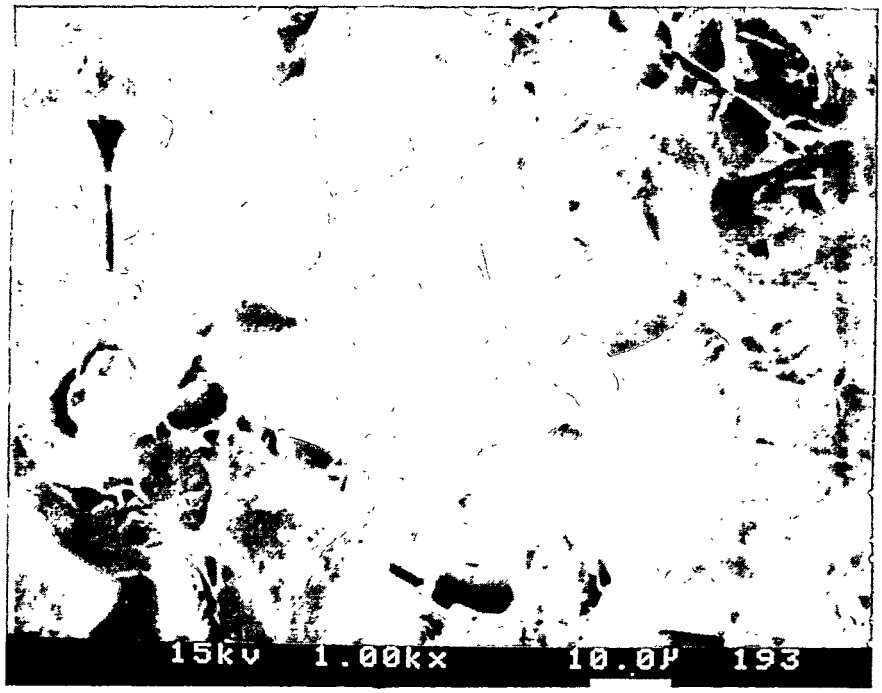

Fig. 5. SEM fractograph showing the quas-icleavage nature fracture surfaces of a mode I specimen tested at -90°C.

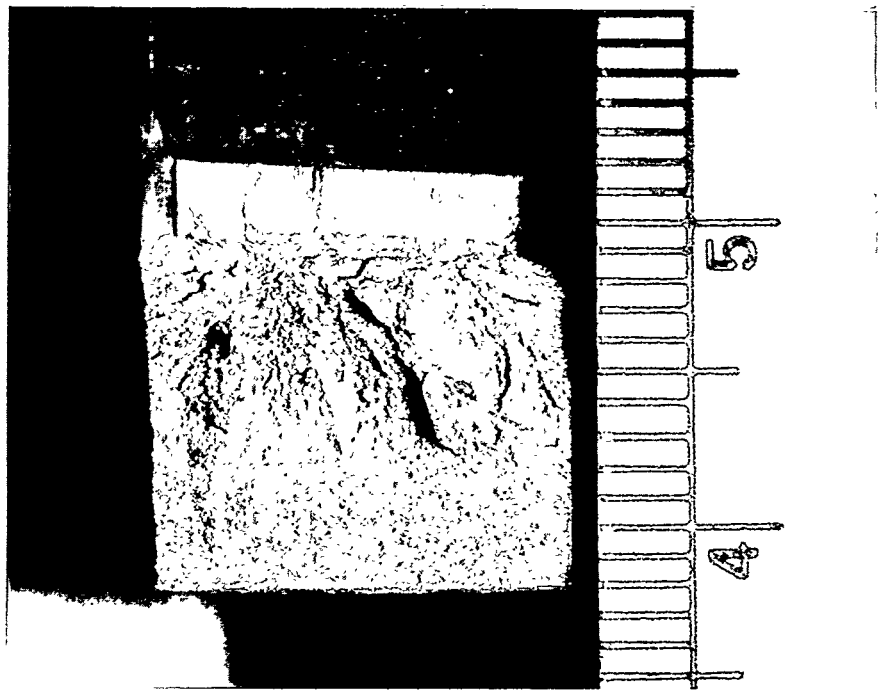

Fig. 6. An overview of a mixed mode I/III specimen tested at -95°C, showing the crack grows in mixed mode for about 0.5 mm and then switched to mode I.

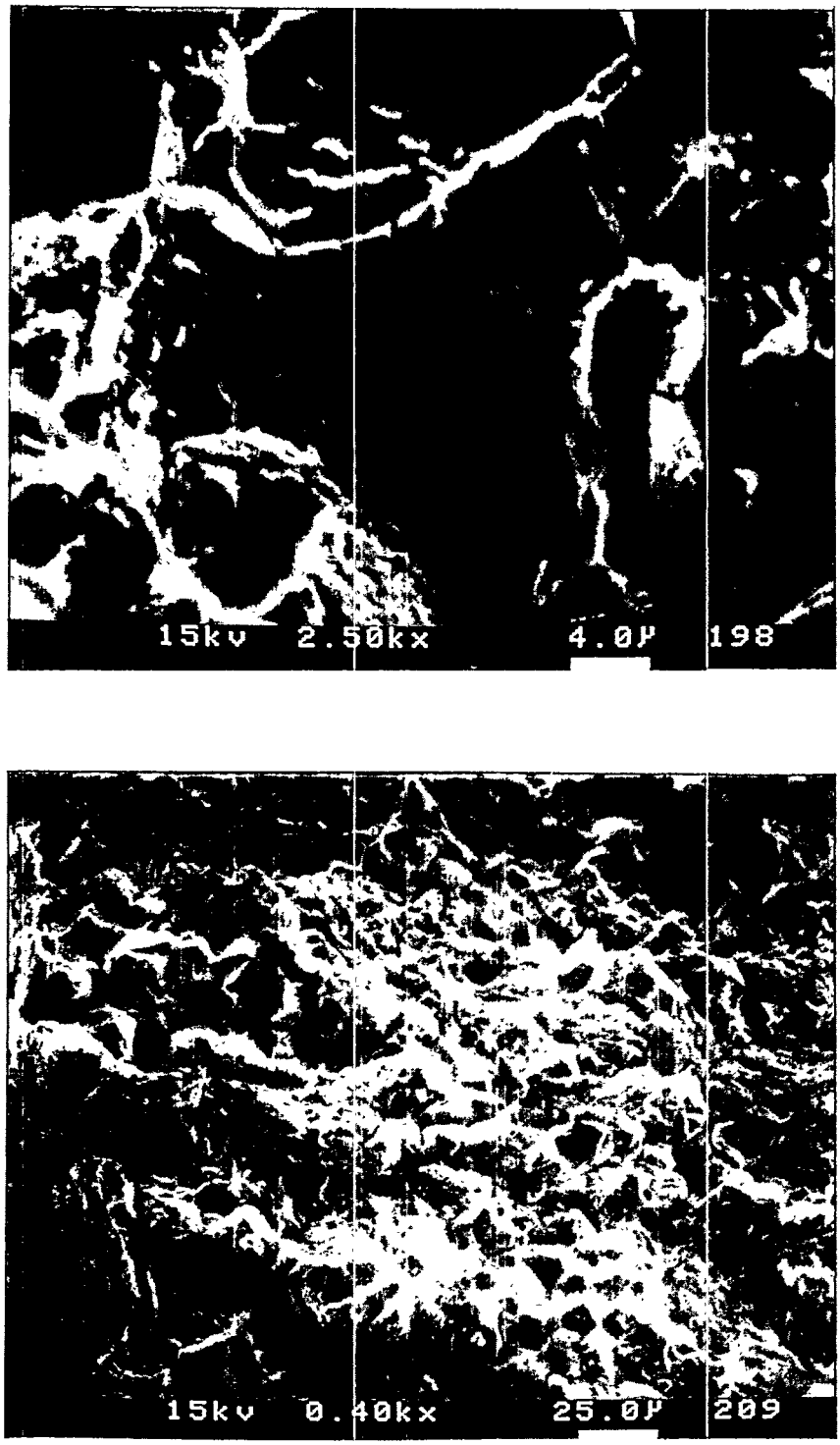

Fig. 7. SEM fractographs of intergranular facets and plastic tearing on the fracture surface within 0.5 mm from original crack tip where the crack is in mixed mode in a mixed mode specimen tested at -95°C. a. lower magnification; b. higher magnification.

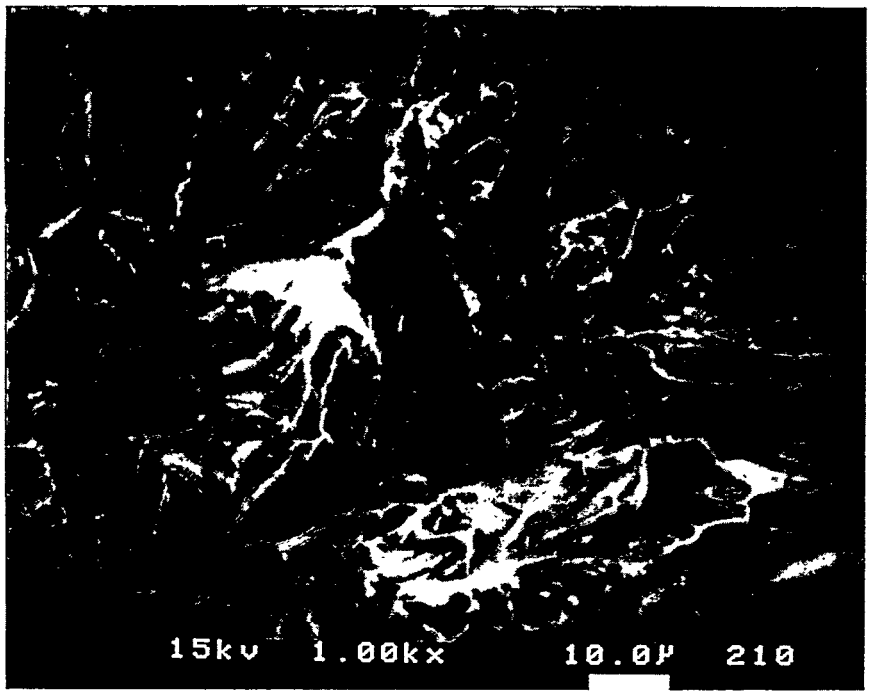

Fig. 8. SEM fractograph of cleavage surface in a mixed mode specimen tested at -95°C after the crack mode becomes mode I.

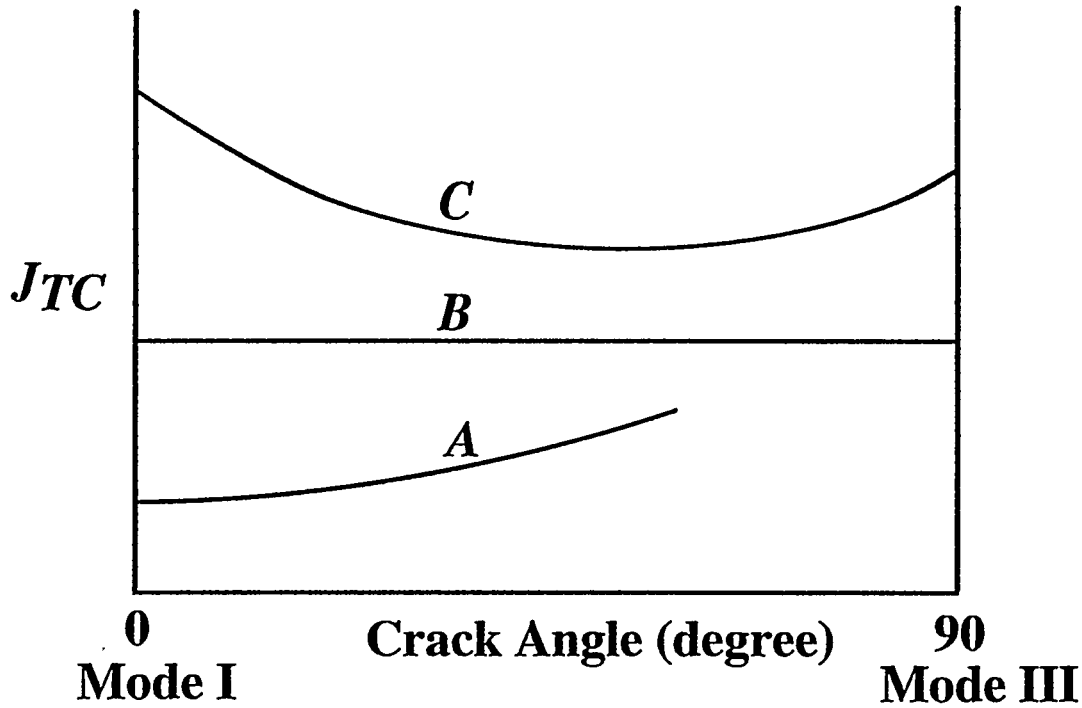

Fig. 9. Dependence of mixed I/III *J*-integral toughness for various structural materials on crack inclination angles. Brittle materials, intermediate tough materials,and tough materials follow curve **A**, curve **B**, and curve **C**, respectively.

ahead of the crack tip in the trajectory of the crack plane. Large stress concentrations emerge at hard particles in the path of such a sheared region because of strain incompatibility [10], which promotes either the decohesion of particles from the matrix or particle fracture (shear damage), and, therefore, void initiation. Continuum mechanics models [11,12] show that the presence of voids further promotes shear localization. Thus, an autocatalytic process of voids promoting shear localization and shear localization promoting voids follows. This process leads to void formation that limits the mode I plastic flow field and causes premature cracking by the coalescence of closely spaced voids under the action of the mode I stress. Accordingly, tough materials exhibit lower fracture toughness for a mixed-mode crack than that for a mode I crack.

The F-82H steel is a very tough steel at RT, and very sensitive to incompatibility stresses at the particle/matrix interface caused by the mode III component. Introducing a mode III loading component (shear stress on the crack plane) dramatically decreased toughness, from J_{IC} (284 kJ/m^2) to J_{MC} (150 kJ/m^2). As temperature decreased, the F82-H steel became brittle and sensitive to mode I loading, resulting a lower J_{IC} value. The result is consistent with the prediction of the mixed mode I/III fracture mechanics theory. However, that mixed mode loading contributes to both enhanced crack tip plasticity and intergranular fracture in the steel at low temperature has not been reported, and the mechanism is not clear yet.

The present results indicate that crack tip plasticity was increased by mixed mode loading, and suggest that at low temperature, mode I fracture toughness controls the performance of the steel, but at temperatures above RT, especially concerning fatigue and creep-fatigue life, the mixed mode loading should be addressed because it lowers fracture toughness and increases crack tip plasticity.

CONCLUSIONS

1. At RT, F-82H steel is a very tough steel. J_{IC} is about 284 kJ/m^2. Mixed-mode I/III loading dramatically lowered the fracture toughness. With a crack angle of 35°, where the ratio of $P_{iii}/(P_{iii} + P_i)$ is 0.41, the J_{MC} is only 150 kJ/m^2.

2. At RT, loading modes did not change the fracture mode (microvoid coalescence). However, the mode III loading component reduced fracture surface roughness and void size significantly.

3. At about -90°C, J_{MC} (50 kJ/m^2) was greater than J_{IC} (30 kJ/m^2).

4. At -90°C, mode I crack initiated and grew by quasi-cleavage fracture; but at -95°C the mixed mode I/III crack initiated and propagated a short distance (0,5 mm) by a mixture of intergranular fracture and ductile tearing. When the mixed mode crack switched to mode I, it fractured by quasi-cleavage.

FUTURE WORK

To complete the tests and investigate the effects of loading modes on fracture behavior at low temperatures.

ACKNOWLEDGEMENTS

The assistance of Mr. J. L. Humason at Pacific Northwest Laboratory in developing the test methods is gratefully acknowledged. This research was supported by the Office of Fusion Energy of the U. S. Department of Energy under Contract DE-AC06-76RLO 1830 with Battelle Memorial Institute.

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