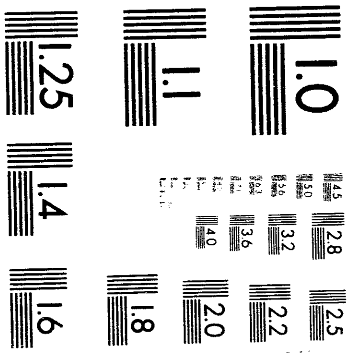
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EFFECT OF LOADING MODE ON THE FRACTURE TOUGHNESS OF A REDUCED ACTIVATION FERRITIC/MARTENSITIC STAINLESS STEEL

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EFFECT OF LOADING MODE ON THE FRACTURE TOUGHNESS OF A REDUCED ACTIVATION FERRITIC/MARTENSITIC STAINLESS STEEL

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ABSTRACT

The critical J integrals of mode I (J_{IC}), mixed-mode I/III (J_{MC}), and mode III (J_{IIIC}) were examined for a ferritic stainless steel (F-82H) at ambient temperature. A determination of J_{MC} was made using modified compact-tension specimens. Different ratios of tension /shear stress were achieved by varying the principal axis of the crack plane between 0 and 55 degrees from the load line. The results showed that J_{MC}s and tearing moduli (T_M) varied with the crack angles and were lower than their mode I and mode III counterparts. Both the minimum J_{MC} and T_M occurred at a crack angle between 40 and 50 degrees, where σ_i/σ_{iii} was 1.2 to 0.84. The J_{min} was 240 kJ/m^2, and ratios of J_{IC}/J_{min} and J_{IIIC}/J_{min} were about 2.1 and 1.9, respectively. Morphology of fracture surfaces was consistent with the change of J_{MC} and T_M values. While the upper shelf-fracture toughness of F-82H depends on loading mode, the J_{min} remains very high. Other important considerations include the effect of mixed-mode loading on the DBT temperature, and effects of hydrogen and irradiation on J_{min}.

1. Introduction

Since the late 1970s, ferritic/martensitic Cr-Mo steels have been considered as the alternate candidate structural materials to austenitic stainless steels for first wall and blanket structure applications. Irradiation studies [1,2] in fast reactors showed these steels were superior to austenitic steels in several aspects, such as swelling resistance, higher thermal conductivity and lower thermal expansion, and compatibility with potential breeder and coolant materials. Reduced-activation ferritic steels have been developed since the mid 1980s by replacing Mo in conventional Cr-Mo steels with V and/or W. Among these steels, martensitic steels with 7 to 9% Cr have been favored over 12% Cr steels, because it is difficult to eliminate δ-ferrite in a 12% Cr steel without increasing C or Mn for austenite stabilization. Delta-ferrite can lower toughness, and Mn promotes chi-phase precipitation during irradiation, which can cause embrittlement. For a potential material used as first wall or blanket, fracture toughness is an important mechanical property. However, fracture-toughness data are limited for either the unirradiated or irradiated conditions. The critical values of the J integral are used as an engineering estimate of fracture toughness near the initiation of slow stable crack growth of a pre-existing crack in tough metallic materials.

Traditionally, mode I fracture has been used to study elastic-plastic fracture mechanics. However, in recent years, mixed-mode fracture has become a focus of many studies because many observed failures included shear components [3-11]. Fracture characteristics have been found to differ from one another when subjected to mixed-mode I/III loading, depending on microstructure, strength, and toughness level of materials. In low-toughness high-strength alloys, such as 0.29C-0.83Cu steel, and 1.25C bainitic steel [9-12], mode III contributions to mode I loading had little or no effect on the overall value of J_{iC} and the mode I component J integral for mixed-mode crack initiation, and tended to increase J_{totC}, the total J integral for mixed-mode crack initiation. In tougher materials (such as 3.5NiCrMoV steel, A710A, and a high-purity rotor steel (HPRS) [3-11], which failed primarily by a microvoid nucleation and growth mechanism) mode III contributions lowered the J_{totC} values considerably from their mode I values. The J_{totC} values passed through a minimum at a position between mode I and mode III on a plot of J_{totC} vs crack inclination angle.

A steel with 0.1C-8Cr-2W-0.2V-0.04Ta (designated as F-82H) has been developed as a reduced activation ferritic/martensitic steel by Japanese scientists and considered as one of the candidates for the first-wall material of a fusion reactor. Preliminary J integral data [13] obtained from three point bending specimens showed that F-82H is a very tough steel. It is possible that introducing mode III components to mode I loading would also lower the total J integral of F-82H as in the case of HPRS. Hence, investigation of the effect of mixed-mode loading on fracture toughness of F-82H is critical if the steel is to be used as first-wall material.

2. Material and experimental methods

2.1. Material

The F-82H plate used in this study was supplied by Nippon Kokan Steel Company (NKK) in Japan. The chemical composition of the plate 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 orientation of T-L as specified in ASTM E399-90 and were heat-treated using 1000°C/20 h/air cooling (AC), 1100°C/7 min, AC, and 700°C/2 h/AC. The microstructure was tempered martensite. The average intersection distance grain size was 25 μm (ASTM #7.5). The heat-treatment resulted in a yield strength (σ_y) of 648 MPa, ultimate tensile strength (σ_{uts}) of 735 MPa, elongation of 16.7%, and reduction of area of 70%.

2.2. *Experimental methods*

The geometry of modified compact-tension (MCT) specimens used for mixed-mode I/III testing is schematically shown in Fig. 1. The magnitude of mode III components can be varied by changing the crack slant angle Φ. A degree of 0 represents mode I loading and the geometry of a 0-degree specimen becomes the standard compact-tension (CT) specimen as specified in ASTM standard E813-89. As Φ increases, the contribution of mode III components increases. The crack-inclination angles used in this study were 0, 10, 20, 30, 40, 45, 50, and 55 degrees. Side grooves of 20% reduction of total thickness were incorporated in all specimens. These side grooves can increase the triaxiality at the edges of a growing crack and constrain the advancing crack in the original crack plane. Calculating the J integrals in mixed-mode I/III requires measuring both vertical displacement (δ_v) and horizontal displacement (δ_h) of load points. A pair of knife edges was secured to the front face of a specimen. A standard clip crack opening distance (COD) gage was positioned on the knife edges. The load-line δ_vs were calculated from the front face δ_vs with the method proposed by Saxena and Hudak, Jr. [14]. It was found that the δ_h increased with δ_v in a linear mode [3,5]. Hence δ_hs were calculated approximately using a relation of $\delta_h = \alpha \times \delta_v$, where $\alpha = \delta_{hmax} / \delta_{vmax}$.

An electric discharge machine (EDM) was used to make thin cuts with a small radius (radius = 0.051 mm) and approximately 1.3 mm long. The cuts were used as a substitute for a pre-fatigued-crack (PFC) because a PFC tended to grow out of the original crack plane in mixed-mode specimens. The fine EDM cut was found identical to a PFC [6]. The EDM cuts were made after final heat-treatment, and specimens with cuts were heated at about 100°C for 24 h in a vacuum oven (10^{-3} Pa) to outgas possible hydrogen introduced by EDM cutting [15]. 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. During testing, the specimen was frequently and partially unloaded, and the partial unloading compliances were used to calculate the corresponding crack lengths following the procedure described in E813-89 and Ref. 14. Values of J matching those crack lengths were also calculated by means of Eq. (1) in the next section. At least 12 pairs of J-Δa data were used to construct a J-R curve.

The triple-pantleg like specimens [5-7,16] were used to determine J_{IIIC}. The specimens had two cracks that led to a symmetric loading and minimized an out-of-plane bending [6]. Two 1.3-mm EDM cuts were also made as the substitutes of PFCs. Indirect crack-length monitoring techniques, such as the electrical potential drop method or unloading compliance, are affected by the contact of the asperities on the two specimen surfaces during mode III (shearing) deformation. Hence, the multiple-specimen (five specimens) technique was adopted, and the crack lengths were measured after breaking open the specimens.

3. Data analysis

The mode I integral J_I and mixed mode I/III integral J_M were calculated from the area under the load vs load-line-displacement curve by means of Eq. (1) [17]:

$$J = \frac{2}{B_{net}\, b_o} \int_0^{\delta_v} P\, d\, V \tag{1}$$

where

B_{net} = 0.8B/cosΦ (the net crack front width excluding the 10% side grooves on each side)

B = the overall specimen thickness

Φ = the crack-inclination angle

b_o = W - a_o (the initial unbroken ligament)

W = the specimen width

a_o = the initial physical crack length.

To construct J-R curves and determine critical J values (J_{IC} and J_{MC}), ASTM E813-89 was used. The slope of the blunting line for mixed mode I/III was calculated using Eq. (2):

$$m_{i/iii} = \frac{m_i \cos\Phi + m_{iii} \sin\Phi}{\sin\Phi + \cos\Phi} \tag{2}$$

where $m_i = (\sigma_y + \sigma_{uts})/2$ and $m_{iii} = (\sigma_y + \sigma_{uts})/4$, which are blunting line slopes of pure mode I and mode III, respectively. When Φ equals 0 and 90, $m_{i/iii}$ is equal to m_i and m_{iii}, respectively. A best straight line was also made using the J-Δa data between the upper and lower exclusion lines, and the slope of the straight line was taken as the unnormalized tearing modulus (T_I or T_M) for each specimen. The critical mode I and mode III J components (J_{iC} and J_{iiiC}) in mixed mode specimens could also be calculated in terms of the corresponding resolved loads and displacements. The calculations of resolved mode I and mode III load and displacement and the determinations of J_{IC} and J_{iiiC} have been reported in detail in Ref. 8, 9, and 16.

Due to two cracks in the "triple-pantleg" specimen, Eq. (1) needs to be divided by a factor of 2. Due to the 20% side grooves on each side, $B_{net} = 0.60B$. The slope of the blunting line is $J_{III}/\Delta a = 2\tau_f$, where $\tau_f = (\sigma_y + \sigma_{uts})/4$. The values of J_{IIIC} and T_{III} were determined in the same way as that used in mode I and mixed mode I/III tests.

4. Results

4.1. Critical J values

The effect of crack angle, i.e. the ratio of tension to shear stress on J_{totC} (the total critical J values) was demonstrated by Fig. 2, where J_{totC} at $\Phi = 0$ and 90 degrees were equal to J_{IC} and J_{IIIC}, respectively, and J_{totC} at $0 < \Phi < 90$ degrees was equal to the corresponding J_{MC}. A solid circle was used for J_{IIIC} in Fig. 2 because a different specimen geometry and different technique, compared to the CT and MCT specimens, were used to determine J_{IIIC}. While the J_{totC} data have some scatter, the trend is clear. As the crack inclination angle Φ increases, i.e. the mode III component increases, the J_{totC} decreases to a minimum at a angle between 40 and 50 degrees. Curve fitting showed that the change of J_{totC} with Φ could be presented by a polynomial function of order 2, as shown in Fig. 2. Calculations from the best fit curve indicated that J_{IC} and J_{IIIC} were about 511 and 490 kJ/m^2, respectively. The minimum J value (J_{min}) was about 245 kJ/m^2 and occurred at a crack angle between 40 and 50 degrees. The J_{min} was only 48% of J_{IC} and 50% of J_{IIIC}, respectively. The J_{MC} trends in F-82H were similar to the other tough steels [7-9], where adding a mode III stress to mode I loading caused a dramatic drop in the J values in tough steels. However, F-82H steel was more sensitive to combined stress loading, and accordingly the reduction of J values was more pronounced than a Ni-Cr-Mo-V rotor steel (HPRS) [7]. For example, J_{totC} at $\Phi = 15$ degrees was 83% of J_{IC} for HPRS, but only 68% of J_{IC} for F-82H steel. The J_{min} of HPRS was 54% of J_{IC} and 85% of J_{IIIC}, respectively.

Combined mode I/III loading decreased not only the energy for crack initiation (J_{totC}), but also the resistance to stable crack growth, which can be evaluated by the total tearing modulus (T_{tot}). The unnormalized tearing moduli corresponding to crack angles are shown in Fig. 3. The variation of T_{tot} with Φ was also found to obey a polynomial function of order 2 (see Fig. 3). Furthermore, the T_{tot}-Φ data had much less scatter than those of J_{totC}-Φ. From Fig. 3, it is apparent that 360 kJ/m^2 is needed for a mode I crack to grow 1 mm and 295 kJ/m^2 for a mode III crack, but only 110 kJ/m^2 for a mixed mode I/III crack (Φ = 40 degrees).

4.2. Fractography

The crack fronts of all specimens remained in their initial orientation during J testing. All specimens exhibited a microvoid-coalescence type of fracture. However, the roughness of the fracture surfaces and the size as well as uniformity of the voids varied significantly with Φ. Generally, as the mode III component increased, the fracture surfaces became smooth, and the size of the voids became more uniform and smaller. The most dramatic change of fracture surfaces occurred between Φ = 10 and 30 degrees, where large drops in J_{totC} and T_{tot} occurred. The fracture surfaces of the specimens with $\Phi = 10$ and 55 degrees are shown in Fig. 4. The fracture surface of the 10-degree specimen (Fig. 4.a) consisted of very small voids along the tearing ridges where final rupture occurred and larger voids where nucleation and substantial growth of voids occurred before the final rupture. On the other hand, the voids of the 55-degree specimen (Fig. 4.b) were small and relatively uniform. The small dimples are associated with low-energy dissipation and low J_{totC} and T_{tot}. Shear-stress components distorted the shape of the voids and produced the voids elongated in the shear direction (see Fig. 4.b). A comprehensive analysis of the fracture-surface morphology and its dependency on Φ is currently underway.

5. Discussion

It has been found recently that adding mode III component to mode I loading could increase, decrease, and have no effect on the J_{totC}, depending on the toughness of the materials. For brittle materials, such as glass [18], and 0.29C-0.83Cu steel [6,10-12] and 1.25C bainitic steels [6,10-12], where fracture was controlled by tensile stress and the local crack-opening displacements, additing mode III components had no or little effect on the J_{iC} (mode I J component at crack initiation), but tended to increase J_{totC}. For tough steels, such as HPRS, which failed primarily by microvoid coalescence, additional shear stress produced incompatibility stresses at the particle interfaces in the trajectory of the crack, causing decohesion or particle fracture. This process led to void formation that limits the mode I plastic flow field (shear damage). For those materials with intermediate toughnesses, such as AISI 1090 steel, introducing a mode III component decreased J_{iC} moderately, and had little effect on the J_{totC}.

F-82H steel is a very tough steel and very sensitive to incompatibility stresses at particles caused by the mode III component. The sensitivity to shear damage was manifested in Fig. 5 by plotting normalized J_{iC}/J_{IC} vs J_{iiiC}/J_{IIIC}. One can see that adding mode III loading greatly reduced J_{iC}s. The least-square curve fit showed that J_{iC}/J_{IC} was related by an equation of $(J_{iC}/J_{IC})^m + (J_{iiiC}/J_{IIIC})^m = 1$ with $m = 0.56$, as shown also in Fig. 5. The value of m is an index to the sensitivity of a material to shear damage. The greater the value m, the less sensitive the material is to shear damage. Accordingly, m would be greater than 1 for brittle materials, such as ceramics, glasses, 0.29C-0.83Cu steel, and 1.25 C bainitic steel; m would be approximately equal to unity for intermediate-toughness steel, such as AISI 1090 steel and less than unity for tough materials, such as HPRS and F-82H steel. Furthermore, a curve fit to the data from Ref. 7 for HPRS yielded $m = 0.74$, which was greater than 0.56 for F-82H steel and indicated that F-82H steel was more sensitive to shear damage. However, F-82H steel had a higher toughness, and the minimum mixed-mode toughness (J integral) was still more than 200 kJ/m^2, higher than J_{IC} of some tough and intermediately tough steels, such as HPRS (J_{IC}: 186 kJ/m^2, J_{min}: 100 kJ/m^2) [7] and AISI 1090 steel (J_{IC}: 73 kJ/m^2, J_{min}: 73 kJ/m^2) [9].

The significance of the present investigation shows once again that for tough materials, mode I loading may not be the worst stress condition for a pre-existing crack to initiate and propagate, and it might be necessary to measure the mixed mode K or J values for a tough material and use it as a design criterion. In a complex engineering component, it is expected that cracks will exist at a variety of angles relative to the principal stresses. Therefore, the results of this study indicate that J_{min} is probably the safest value to be used in design. Further research is in progress to evaluate the dependence of J_{min} on temperature, hydrogen and radiation.

6. Summary

F-82H steel is a very tough steel. Both J_{IC} and J_{IIIC} are about 500 kJ/m^2, and T_I is about (360 kJ/m^2)/mm. Mixed mode I/III loading dramatically lowers both the J_{MC} and T_M. The lowest J_{MC} and T_M are about 240 kJ/m^2 and (110 kJ/m^2)/mm, respectively and occur at a crack angle between 40 to 50 degrees, where the ratio of σ_i/σ_{iii} is 0.84 to 1.2. The fracture surface roughness is also reduced by mode III components. The fracture surface of a mode I specimen consisted of both large and small voids, but those of 30 to 55 degree specimens consisted of only small voids, which corresponded with low J_{MC} and T_M. While the upper shelf toughness of F-82H depends on the loading mode, the J_{min} remains higher than most tough materials.

Acknowledgements

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Fig. captions

Fig. 1. The geometry of the modified compact tension specimen.

Fig. 2. The dependence of the critical total J integrals of F-82H on the crack inclination angles. The dash-dot lines represent a ±20% error band from the best fitted line (dash line). The solid circle represents J_{IIIC}, which was determined with multiple-specimen technique (five specimens). The J_{totC} vs Φ equation was generated by a least-squares curve fit.

Fig. 3. The dependence of the total tearing muduli on the crack inclination angles .

Fig. 4. SEM fractographs showing the effect of crack angles on the morphology of the fracture surfaces of F-82H. The photos were taken at the areas immediately close to pre-existing cracks. The arrows indicate the shear directions. a. a 10 degree specimen; b. a 55 degree specimen.

Fig. 5. The effect of the J_{iiiC} (mode III component) on the J_{iC} (mode I component), which represents the sensitivity of F-82H to the shear damage.

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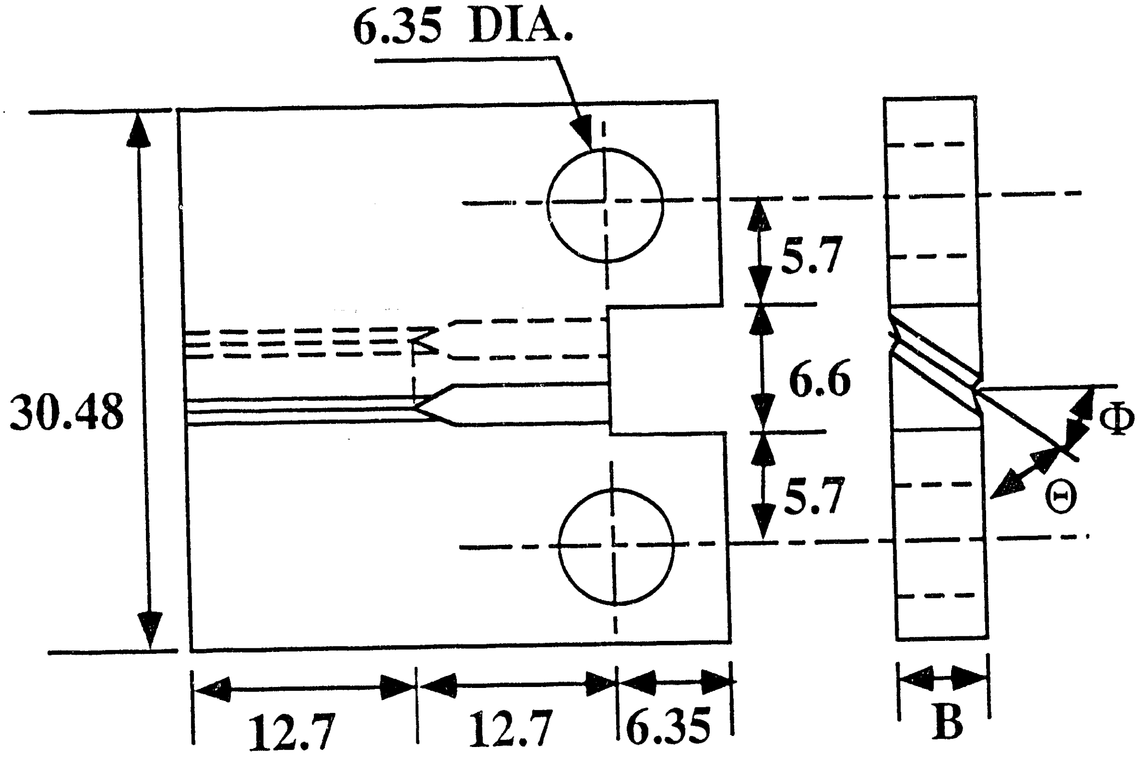
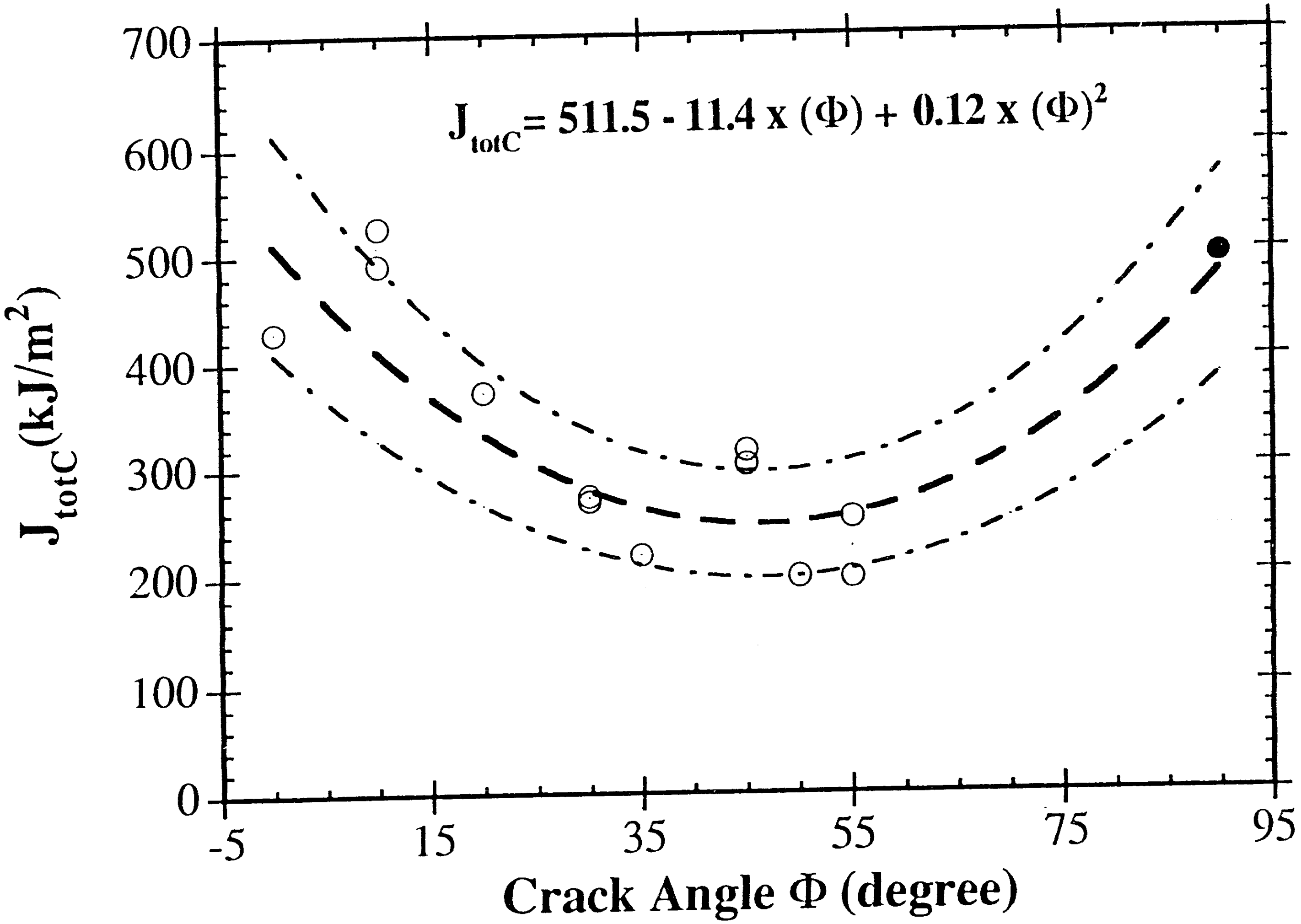


Fig. 1



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J_{totC}(kJ/m^2)
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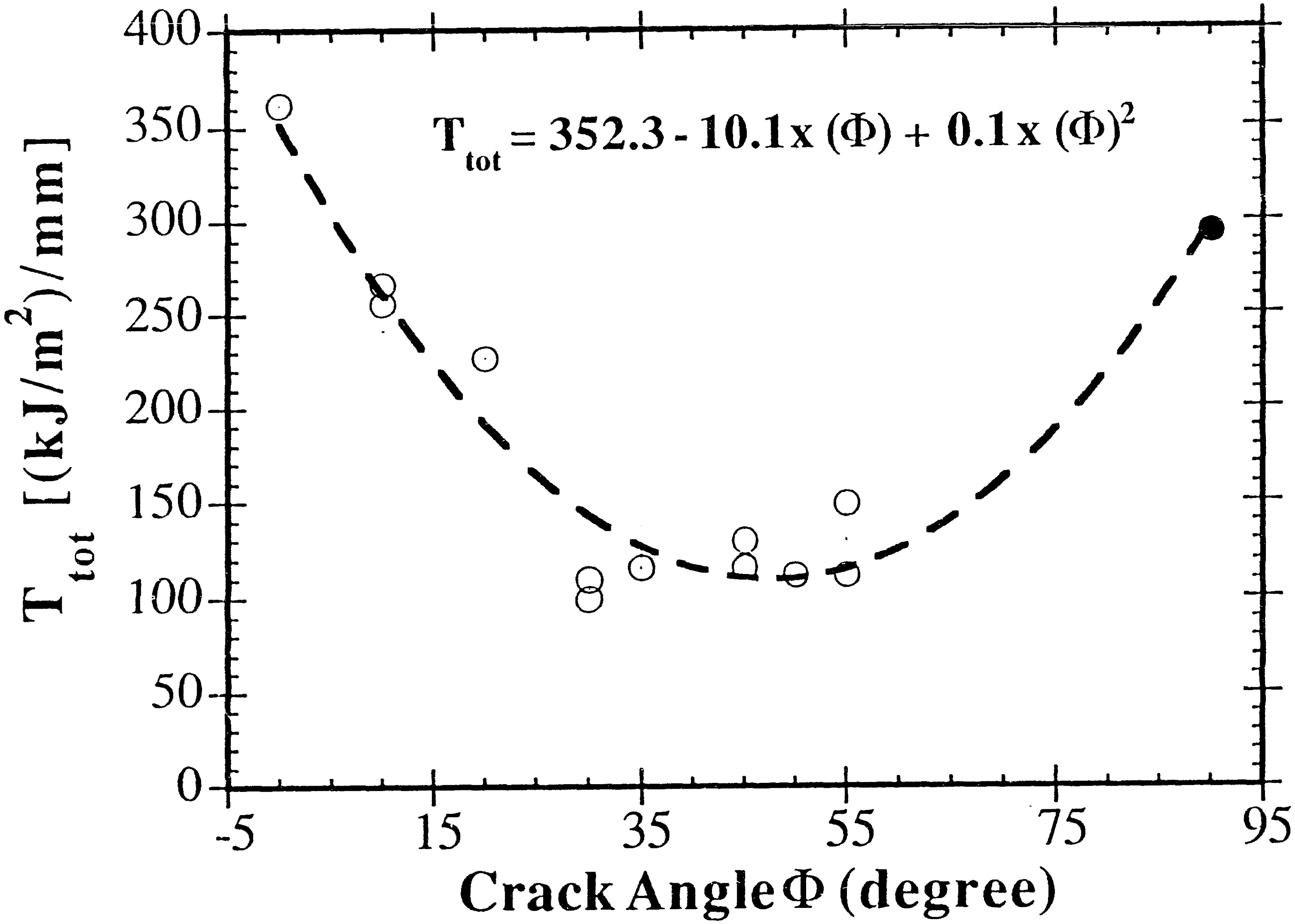
Crack Angle Φ (degree)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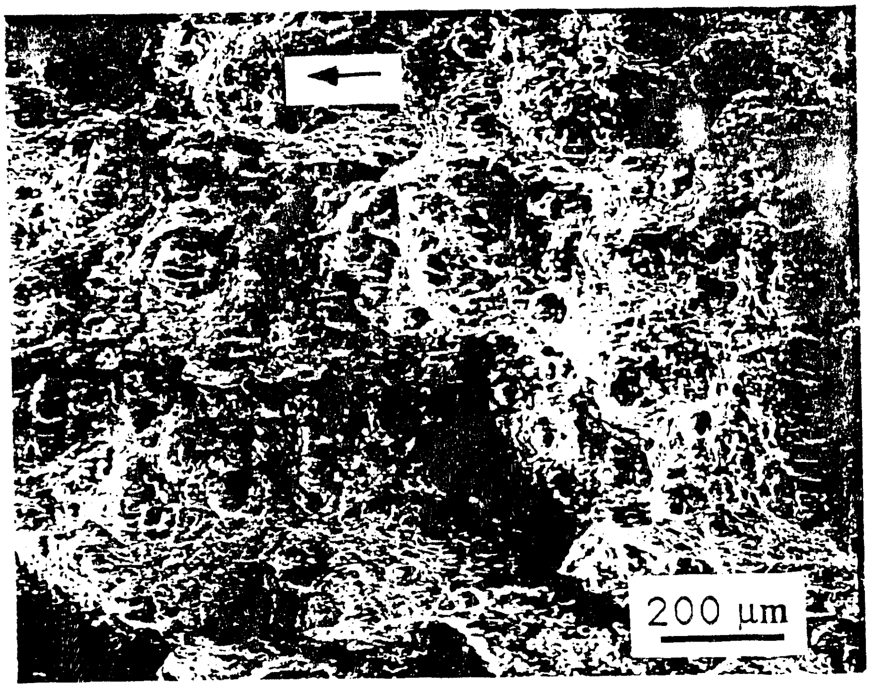
Crack Angle Φ (degree)



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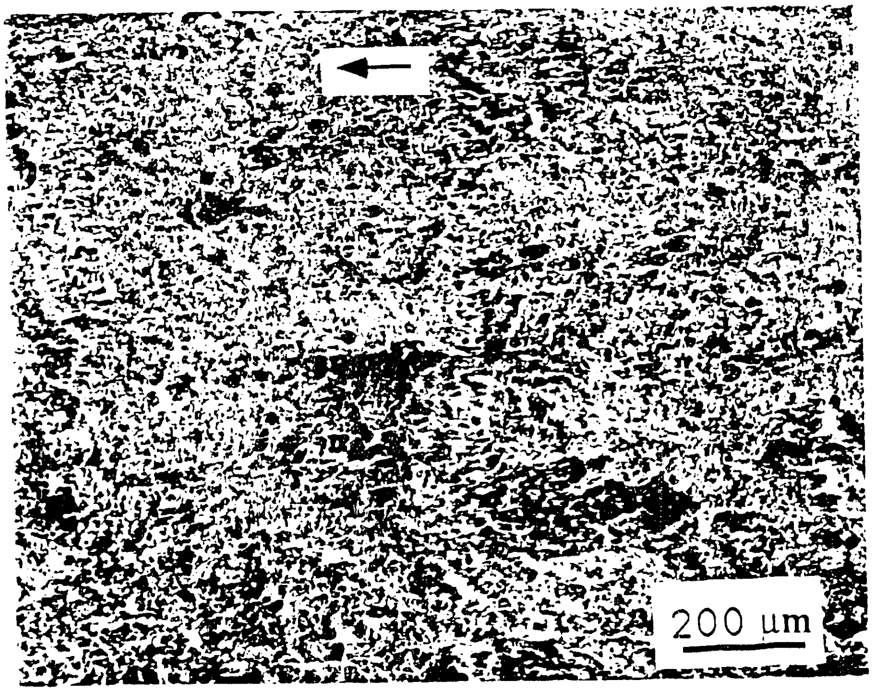

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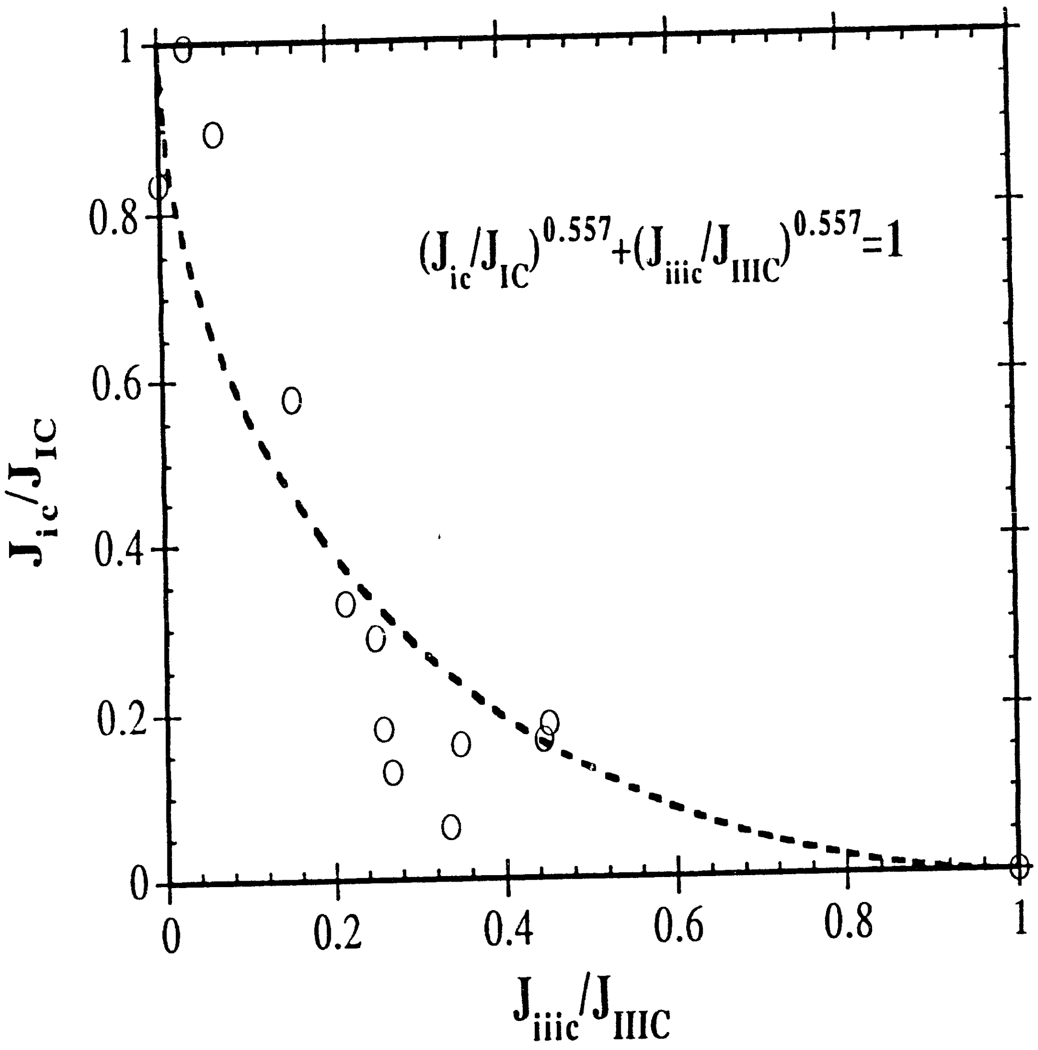
Fig.4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