EVALUATION OF DYNAMIC FRACTURE TOUGHNESS IN A Cr-Mo-V CAST STEEL WELD JOINT

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ABSTRACT

A weld joint in CrMoV steel casting, used in steam turbine casings, has been evaluated for dynamic fracture toughness, K_{Id}, for the first time employing the precracked Charpy V-notch impact specimens. In the present studies the weld joint is considered as a composite structure such that the precrack front envelopes all the zones simultaneously. Base metal, weld metal, HAZ and the weld joint have been characterized for K_{Id} at room temperature as well as uppershelf temperature. Of all the zones investigated the composite weld joint is found to possess lowest toughness.

KEYWORDS

Dynamic fracture toughness, Instrumented Charpy testing, brittle fracture, weld joint, bainite, fractography.

INTRODUCTION

Low alloy ferritic steels of CrMoV type find significant applications in power plant equipments. Of these, the 1Cr-1Mo-0.25V cast steel is of interest for its extensive use in the steam turbine casings. It is an usual practice to remove the defects in these massive castings by suitable welding techniques. Fracture mechanics principles are now applied in taking decision whether a defect is to be removed prior to the component is put into service or it is allowed to remain (Wessel, Wilson and Clark, 1975). The weld joint toughness is, therefore, critical to the structural integrity assessment and may be determined by testing precracked Charpy impact specimens on an instrumented impact testing machine with the advantage of small size specimens.

There have been many attempts recently to evaluate the weldment integrity through dynamic fracture toughness (Logsdon, 1977, 1981, 1982; Logsdon and Begley, 1977; Hahn and Kanninen, 1981). In all these studies reported to date, the approach to toughness evaluation in weld joints has been to characterize weld metal and heat affected zone (HAZ) individually. More commonly HAZ is found to be the weakest zone (Logsdon, 1981). However, the fracture behaviour of HAZ may be affected by the constraints arising from the dissimilar structures in the base metal and the weld metal lying on its either side. Recognizing this, Scribner (1979) has attempted to determine brittle fracture tendency of the three weld zones simultaneously through a burst test which is applicable only to the tubular products.

In the present investigation, dynamic fracture toughness of a weld joint considered as a composite structure has been determined for the first time. In this configuration the precrack front in a Charpy V-notch specimen meets all the weld zones simultaneously. In addition, the individual zones of the weldment have been characterized for K_{Id} at 23°C and 95°C.

MATERIAL AND EXPERIMENTAL PROCEDURE

Quenched and tempered keel-blocks of 1Cr-1Mo-0.25V steel castings, with chemical composition as given in Table 1, have been utilized in the present investigation.

TABLE 1 Chemical Composition of Weld Keel-Block Investigated (Weight %)

Element	C	S	P	Si	Mn	Cr	Mo	V	Al
Base material	0.16	0.013	0.014	0.35	0.75	1.05	0.90	0.23	<0.01
Weld material	0.06	0.011	0.017	0.25	0.63	2.40	1.00	--	<0.01

Upper bainitic microstructure (Fig.1a) has been observed for this material with two different grain sizes corresponding to ASTM No.1 and 6 (Figs.1b and 1c). The keel-blocks were welded with E9015-B3L type electrodes by manual metal-arc welding technique followed by subsequent post-weld stress relieving treatment at 680°C for 6 hrs. The chemical analysis of the weld metal is also given in Table 1. The microstructure of weld joint has revealed columunar and equiaxed grains for the weld metal, Fig.1d and 1e, and coarse and fine grains of martensite in the HAZ, as shown in Fig.1f. The room temperature tensile and impact properties of the base, weld, HAZ and the weld joint are given Table 2. Special precautions were taken in HAZ and weld joint impact sample preparation to see that the precrack front and the fracture plane were within the zone of interest throughout. The weld joint samples were taken in two orientations: (i) the crack initiation to take place in one region followed by propagation through HAZ to the third zone, designated as cross-weld orientation, and (ii) the precrack front enveloping all the three zones simultaneously, designated as composite orientation (Fig.2). The fracture surface of tested specimens were examined in scanning electron microscope.

TABLE 2 Mechanical Test Results of Cast Steel Weldment Investigated

Weld zone	0.2% proof strength (MPa)	Ultimate Tensile strength (MPa)	Total elongation (%) (Gauge length= $5.65\sqrt{S_o}$)	Reduction in area (%)	Charpy V-notch impact energy (J)
Base	598.2	732.5	18.8	58.8	68.0 Fine grains 30.0 Coarse grains
Weld	563.1	637.1	20.6	52.9	52.8
HAZ	-	-	-	-	37.7
Weld joint	539.4	671.7	13.4	49.5	20.0

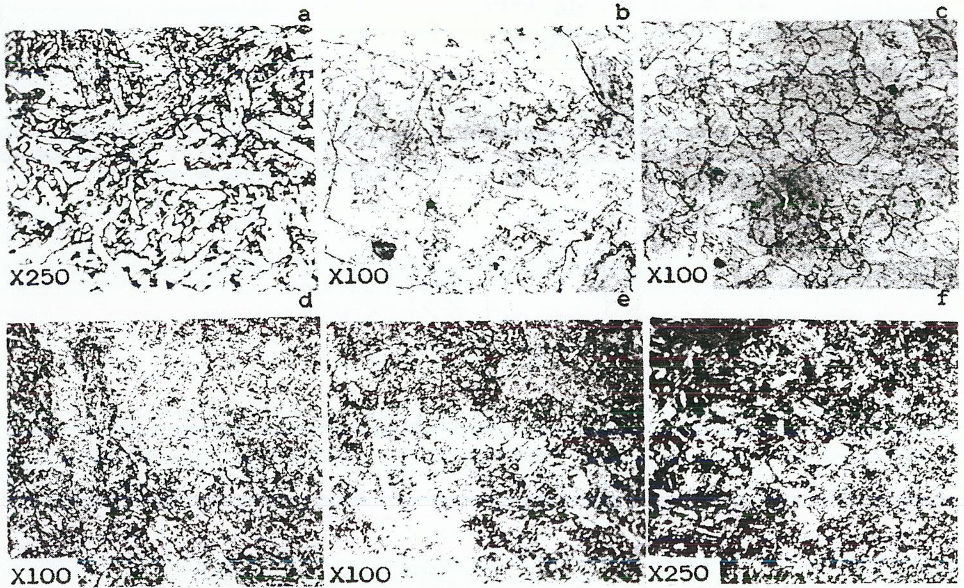

Fig.1 Microstructures for: a) base, b) base - coarse grains, c) base - fine grains, d) weld - columunar grains, e)weld equiaxed grains,f) HAZ

RESULTS AND DISCUSSION

Dynamic fracture toughness, K_{Id}, has been obtained directly at low temperatures employing LEFM principles whereas uppershelf dynamic fracture toughness has been evaluated through J-integral technique. The appropriate parameter has been selected on the basis of oscillograph profiles obtained on the instrumented impact test equipment and the corresponding fractographic features. A linear load-time trace with an abrupt drop at maximum alongwith a cleavage mode of fractographic feature represents situations where LEFM principles could be applied. A load-time trace with a deviation from linearity alongwith either a fully ductile or mixed mode fractographic feature indicates that general yielding has set in prior to initiation of fracture and that LEFM principles could not be applied in such situations. Expressions employed in this study for the estimation of dynamic fracture toughness parameters are given below:

<u>LEFM Principle</u> (Koppenaal, 1974; Rice, 1968)

$$K_{Id} = \frac{6YM}{BW^2}(a)^{0.5} \tag{1}$$

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

<u>J-Integral Method</u> (Iyer and Milcot, 1974; Begley and Landes,1972)

$$J_{Id} = -\frac{1}{B}\frac{d}{da}(Ep) \tag{3}$$

and $$K_{Id} = (J_{Id}E)^{0.5} \tag{4}$$

where Y=f(a/w); M=applied bending moment; a=total crack-length; B=specimen thickness; w=specimen width; Ep=energy corresponding to maximum load; E=Young's modulus; v=Poisson's ratio

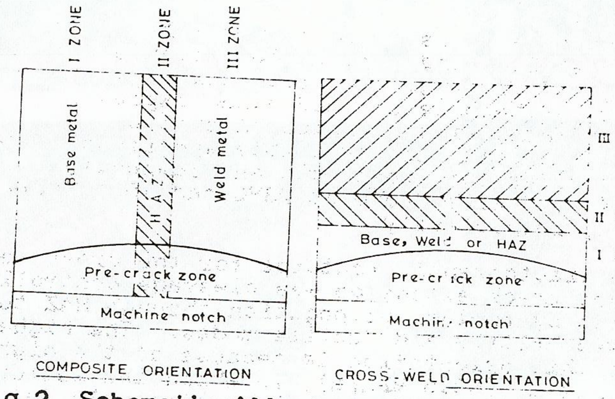

Fig.2 Schematic illustration of two weldjoint orientations investigated

<u>Dynamic Fracture Toughness of Base, Weld, HAZ and Weld joint at 23°C and 95°C</u>

The oscilloscope profiles obtained at 23°C and 95°C test temperatures for base, weld, HAZ, and weld joint specimens are shown in Fig.3. The respective SEM fractographs are shown in Fig.4.

For tests at 23°C and 95°C the J-integral techniques were employed to base and weld metals. The respective oscilloscope profiles and fractographic features are shown in Figs.3a to 3d and Figs.4a to 4d, which corroborate the selection of J-integral route.

The variation in Ep versus crack-length 'a' at 23°C and 95°C temperatures are indicated in Figs.5a,b and 6a,b for base and weld metals, respectively. The J_{Id} values determined from thes plots for the base and weld metals are 0.047 and 0.024 MJ/m^2 at 23°C and 0.134 and 0.424 MJ/m^2 at 95°C, respectively. The respective K_{Id} values for base and weld metals are 93.5 and 63.5 $MPa\sqrt{m}$ at 23°C and 158 and 270 $MPa\sqrt{m}$ at 95°C, respectively. A large scatter was, however, observed in Ep values for tests at 23°C in base metal. Two possible slopes in Fig.5a are interpreted to give K_{Id} values of 93.5 and 167 $MPa\sqrt{m}$. The localised variations in grain size observed in Figs.1b and c, could be th reason for such a difference in K_{Id}. The grain size dependence of fracture toughness is well known (Chowdhury and Brook, 1976; Nakazawa and Krauss, 1978). Canonico and Crouse (1979) have also reported similar grain size dependence of dynamic fracture toughness. At the uppershelf temperature of 95°C when the material behaves in a ductile manner, no such influence of grain size on K_{Id} has been noticed.

The oscillographs and fractographs for the HAZ specimens tested at 23°C and 95°C are shown in Figs.3e and f, and 4e and f, respectively. As the fractures are observed to be fully cleavage controlled at both temperatures, the K_{Id} parameter has been evaluated using expression (1) and found to be 46.8 and 85.7 $MPa\sqrt{m}$ at 23°C and 95°C respectively.

The oscillographs and fractographs for weld joint precracked sp cimens tested at 23°C and 95°C in two orientations are given in Figs.3g,h,i,j and Figs.4g,h,i,j respectively. In both cases th K_{Id} parameter has been determined using expression (1) for test at both temperatures since J-integral evaluation at 95°C could not be carried out with the available specimens. The weld join K_{Id} values obtained for cross weld and composite orientations are 70.6 $MPa\sqrt{m}$ and 42.7 $MPa\sqrt{m}$ at 23°C and 75.1 $MPa\sqrt{m}$ and 71.9 $MPa\sqrt{m}$ at 95°C, respectively.

At 23°C, the fractographic features for the cross weld orientation show that crack extension was cleavage controlled in weld metal followed by further propagation through HAZ to the base metal in mixed brittle and ductile modes. The higher K_{Id} value obtained for this orientation is because of the higher toughnes of the weld metal, (63.5 $MPa\sqrt{m}$), in which initiation of crack extension has occurred. For the composite weld joint orientation the fractographic features along the precrack front have revealed cleavage in HAZ, cleavage and intergranular in weld and primarily a brittle mode in the base metal. The HAZ did not show any stretching at the crack tip. The fractographic feature therefore indicate that crack extension first occurred in HAZ, followed by weld metal and at last in the base metal. At 95°C, the fractographic features for the cross weld orientation have shown that crack extension has taken place in the base metal followed by further propagation with intergranular and ductile mode features through HAZ and weld metal regions. The obtained K_{Id} value of 75.1 MPa$\sqrt{m}$ may be due to the toughness of HAZ metal at 95°C (85.7 MPa$\sqrt{m}$). On the other hand, for the composite weld joint orientation tested at 95°C the fractographic features along the precrack front have revealed intergranular mode in base, cleavage in HAZ and ductile tearing in weld metal. These features thus denote that the crack extension first occurred in HAZ and base metal followed by weld metal. The experimentally obtained K_{Id} values for all weld zones are given in Table 3.

TABLE 3 K_{Id} Test Results for 1Cr-1Mo-0.25V Cast Steel Weldment Studied

Temperature	Base, MPa$\sqrt{m}$	Weld, MPa$\sqrt{m}$	HAZ, MPa$\sqrt{m}$	Weld joint: Cross weld orientation, MPa$\sqrt{m}$	Weld joint: Composite orientation, MPa$\sqrt{m}$
23°C	93.5	63.5	46.8	70.6	42.7
95°C	158.0	270.0	85.7	75.1	71.9

The crack propagation at both temperatures in the composite weld joint orientation is thus controlled by brittle fracture. The constraints imposed by different zones on one another prevented, stress relaxation to occur, resulting in dominance of brittle fracture.

CONCLUSIONS

1. Dynamic fracture toughness, K_{Id} on CrMoV cast steel weldment is determined based on the load-time oscilloscope profiles obtained and the corresponding fracture morphology using either LEFM principles or J-integral technique.

2. The dynamic fracture toughness of a weld joint considered as a composite structure has been found to be the lowest as compared to the individual zones. Constraints due to dissimilar structures lying on either side of the HAZ may have affected the fracture behaviour of HAZ which normally is the least tough zone.

3. The orientation of the weld joint with respect to the precrack front has a significant influence on the dynamic fracture toughness value. The composite weld joint configuration found to result in lower K_{Id} value than cross-weld configuration. This is explicable based on the fracture mechanisms operating during crack extension in the HAZ as it has a controlling effect on the toughness.

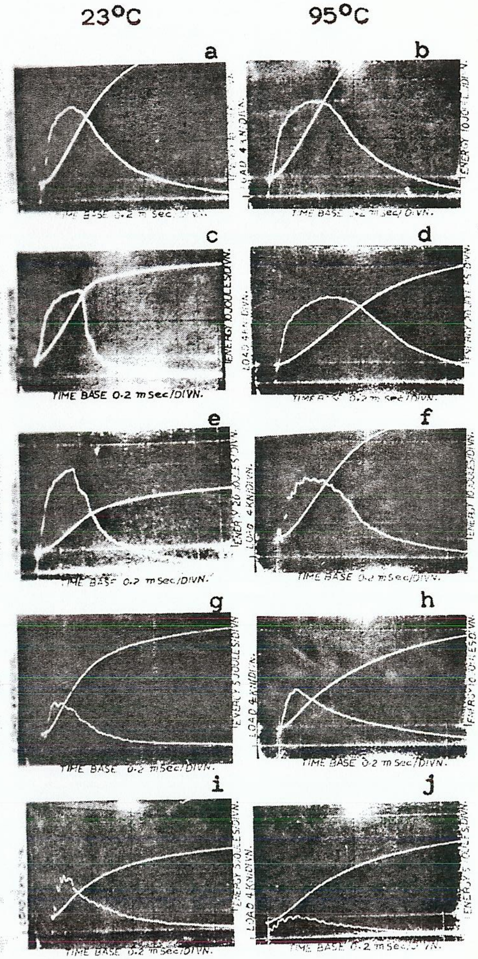

Fig.3. Oscilloscope profiles at 23°C, 95°C respectively for a,b) base, c,d) weld, e,f) HAZ, g,h) cross weld joint, i,j) composite weld joint.

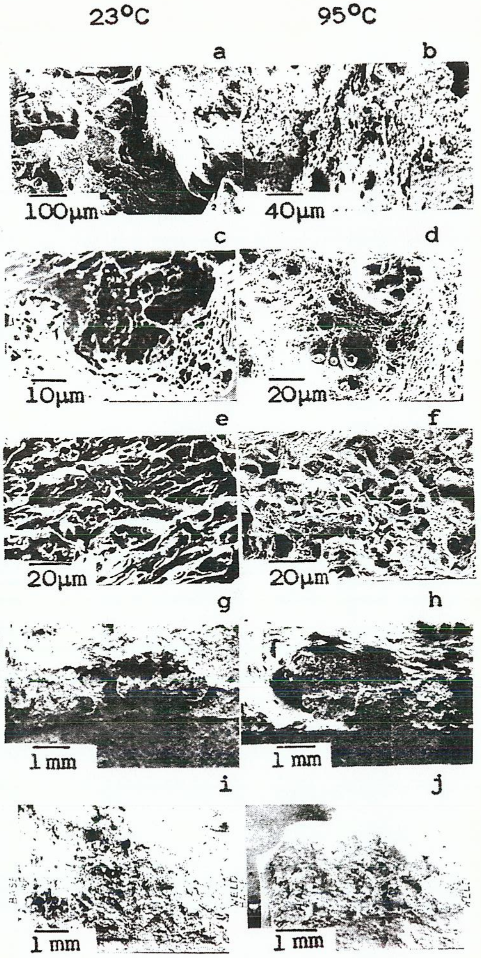

Fig.4. Fractographic features at 23°C, 95°C respectively for a,b) base, c,d) weld, e,f) HAZ, g,h) cross weld joint, i,j) composite weld joint.

4. A difference in K_{Id} value observed in base metal at room temperature has been attributed to the microstructural variations; fine grain structure yielding a higher value as compared to a coarse grain structure.

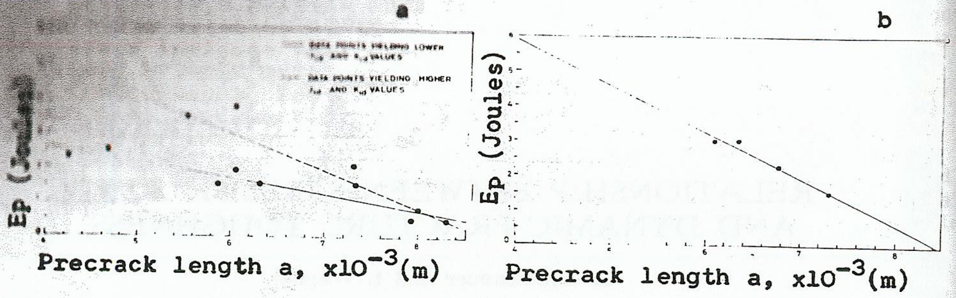

Fig.5. Variation of Ep versus crack length for base material samples tested at a) 23°C, b) 95°C.

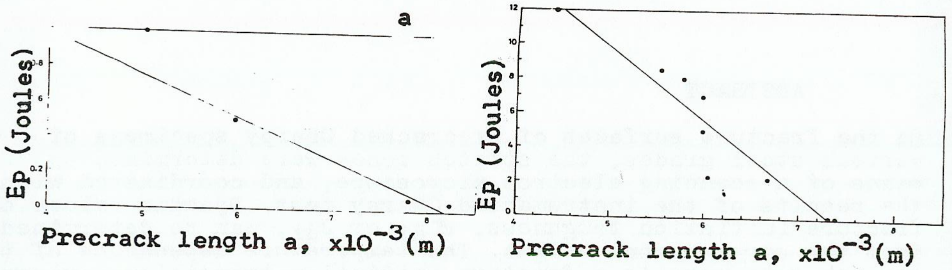

Fig.6. Variation of E_p versus crack length for weld material samples tested at a) 23°C, b) 95°C.

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