Fracture Toughness of Indian Structural Steel IS 2062

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Introduction

The present decade has seen an important development in the field of welding viz., the application of the principles of fracture mechanics for analysing the fracture behaviour of welded joints. This is a direct result of the long-standing efforts made in characterising the influence of the weld defects like cracks, on the fracture behaviour of weldments. Probably the most important consequence of the development of various test procedures of fracture mechanics is the possibility of applying these quantitative principles to structural steels, with reasonably small specimens. In this respect, first attempt has been made to determine the fracture toughness parameters of one of the most widely used fusion-weldable quality structural steel, IS 2062. It is hoped that these parameters will help the designers and fabricators in welding industry to arrive at a fail-safe design and understand the consequences of defects that may be present in these joints.

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Fracture Mechanics

The objective of fracture mechanics is to predict the behaviour of defects detected in large engineering structures from an analysis of the results obtained from laboratory scale test specimens. From these tests, fracture toughness of the material is defined with the help of a fracture behaviour characterising parameter, which is, as per the principles of fracture mechanics, assumed to be the same in both the test specimen and the structure. The most important fracture mechanics test procedures are K_{Ic} test, based on the principles of linear elastic fracture mechanics and COD test based on the principles of elastic-plastic fracture mechanics. The J-integral test, as can be seen in Fig. (1), bridges the gap between the two tests mentioned above. Table (1) gives a comparison of various fracture mechanics tests[1].

The present investigation reports the results of the COD and J-integral tests carried out on IS 2062 steel and its weldment.

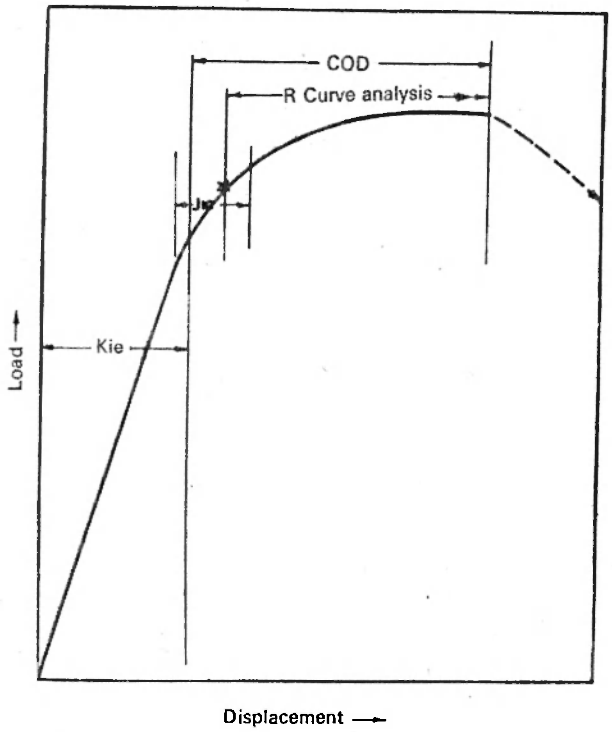


Fig. 1 : Valid ranges of fracture mechanics concepts

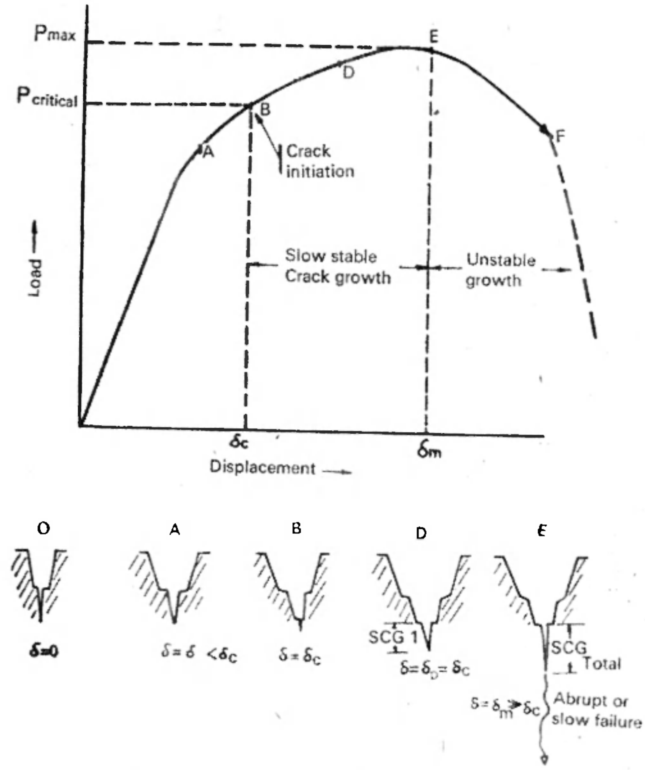


Fig. 2 : Crack opening displacement—principle

Experimental Investigation

Plates : The material used in this investigation is the fusion weldable quality structural steel, governed by the Indian standard IS 2062. The 20 mm thick plates used had a nominal composition of 0.18C, with 0.05 Phosphorus and 0.05 Sulphur.

Welding : To demonstrate the effect of highest heat input, submerged arc welding with backing pass of 500 A, 40 cm/min (Q_b=23 KJ/cm) and a sealing pass of 750 A, 40 cm/min (Q_s=39 KJ/cm) were made use of, for a double V-grooved butt joint, with acid flux (UM 80) and a filler wire (SAI) combination.

Specimen preparation : Three point specimens of single edge notched bend type (SENB) of dimension 150×20×20 mm was used for both COD and J-integral testing.

Fatigue pre-cracking : The fracture mechanics tests requires the presence of a crack of known length in the test specimen. This crack should be of natural sharpness and hence fatigue cracking of the test specimen was resorted to. A 2 ton high speed pulsator, with fluctuating bend loading was used to pre-crack the specimens. The fatigue crack lengths and rate of fatigue crack growth were recorded by electrical potential test set up. [2,3,4]

COD—test : (Fig 2) The COD testing was conducted by the use of clip gauge instrumentation. The test was conducted both at room temperature as well as at—40°C. The low temperature test was made with in-situ cooling as described in an earlier paper.[5]

J-integral : (Fig 3) J-integral test method requires specimens of differing crack lengths for calculating the potential energy difference of specimens with neighbouring crack sizes. Hence specimens of different crack lengths were produced by the controlled fatigue pre cracking set up. (Table 2). Further, the load-point displacement was measured by a LVDT set up.

Charpy impact test : The standard charpy V notch impact test was done to get the transition temperature behaviour of the steel as well as the weldment.

Results and Discussions

Table (3) gives the results of fracture toughness tests viz COD and J-integral tests conducted at room temperature as well as at —40°C. The J-integral method allows the conversion of J_c values to K_c values. It may be noted that both COD and J values are critical values, which means that the values are taken at the critical load at which the onset of crack extension from the original length was observed.

Table 1 : Comparison of Fracture Mechanics Tests

Type of Test	Standards/codes	Characteristics	Application
K_{Ic}	ASTM-E-399-74 BS DD 3-1972 IS Draft-1978	Linear elastic behaviour Plane strain stress intensity factor quantitative crack length applied stress relationship	High strength materials Large thicknesses Low temperature
K_c	ASTM-E-399-74	Invalid data from K_{Ic} test Plane stress Stress intensity factor/Approx. crack length—applied stress relationship	Medium-to-high strength materials Medium thickness Normal temperatures
J-integral	No standard-ASTM-STP-560-74 gives recommended procedures	Elastic-plastic behaviour Invalid data of K_{Ic} test Plane strain/plane stress Energy parameter Quantitative relationship between J_{Ic} and K_{Ic}	High strength material Extension to medium thickness and normal temperatures
COD	BS : DD 19-197	Elastic-plastic behaviour plain strain/plane stress Deformation parameter Wider range of applicability Quantitative relationship between applied sttess, COD and yield stress.	Low to medium strength steels wide temperature range
Charpy V-votch impact (CVN)	ASTM-E-23	Elastic-plastic behaviour Near-plane strain to plane stress behaviour Qualitative data of energy absorption	Low-medium-high strength steels complete temperature range

Table 2 : Fatigue precracking data

Sl. No.		Load F min	Load F max	Total no. of cycles	Frequency cycles/mm	Crack length mm
	1	770	—1430	6.7×10^4	3400	6.18
	2	770	—1430	9.1×10^4	3400	8.90
Base metal	3	770	—1430	7.1×10^4	3300	7.08
	4	770	—1430	9.0×10^4	3400	8.54
	5	770	—1430	11.7×10^4	3400	8.56
	1	770	—1365	3.55×10^5	3500	7.06
	2	770	—1430	5.12×10^5	3400	8.36
	3	770	—1385	3.10×10^5	3400	8.52
	4	770	—1430	7.10×10^5	3500	9.42
	5	770	—1430	5.5×10^5	3500	9.10

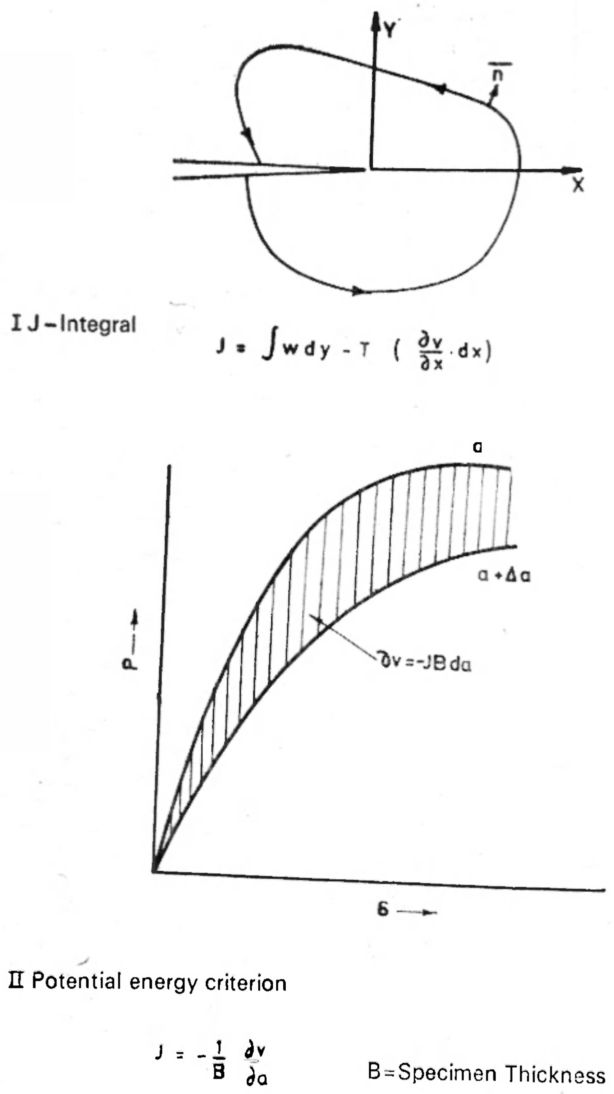


Fig. 3 : J-integral method—principle

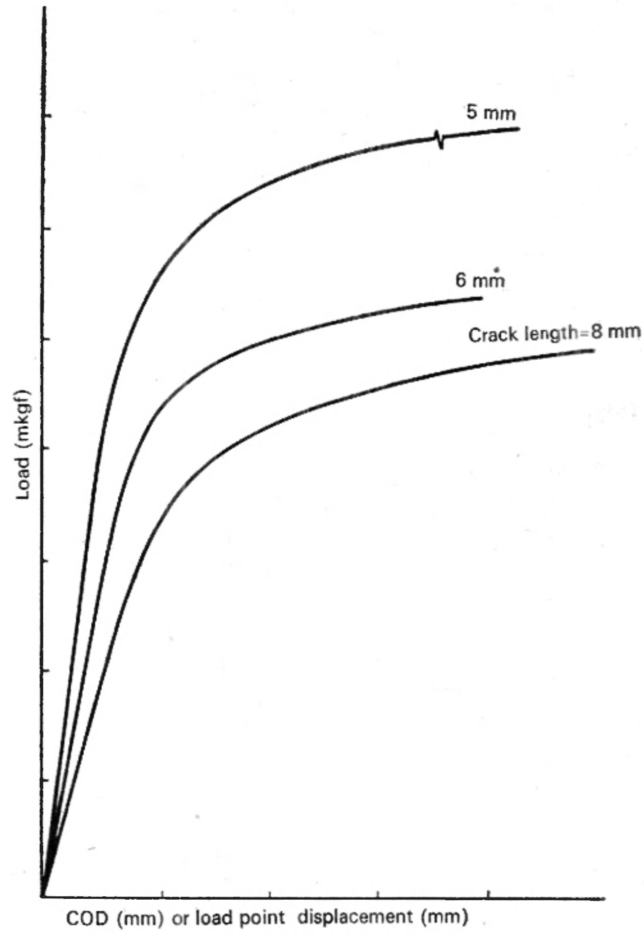


Fig. 4 : Typical autographic load displacement curves

The optical macrograph (Fig 6a) shows the uniform fatigue crack obtained in the fatigue pre cracking stage. It also shows that there is negligible subcritical crack growth in the specimen. The electron fractograph Fig 6(b) shows clearly the fatigue striations in the specimen. Fig 7(a) shows the stretch zone observed immediately under the original crack tip, before cleavage fracture sets in—fig 7 (b)—at—40°C.

Conclusions :

The following points can be deduced from the experimental results :

1. As per the charpy impact test data, the ductile to brittle transition temperature for this batch of steel lies around 0°C—Fig (5).

2. Even through the as-welded submerged arc weld metal shows higher shelf energy, its transition also lies around the same temperature range. In this investigation, only as-welded material is tested as it is significant for the many structural applications.

3. If 0.1 mm is taken as the COD criterion for brittle behaviour, the transition occurs at —40°C for this steel, under static loading conditions. This is significant as this class of steel is mostly used for structures loaded statically.

4. Even at this temperature of—40°C, the structure can allow a crack length of upto 50 mm without giving rise to catastrophic brittle failure. This value of critical crack length has been arrived at, by taking the K_{Ic} values from the experiments and assuming a design stress of 14.20 kgf/mm^2 which is allowed as per IS : 816—1956.

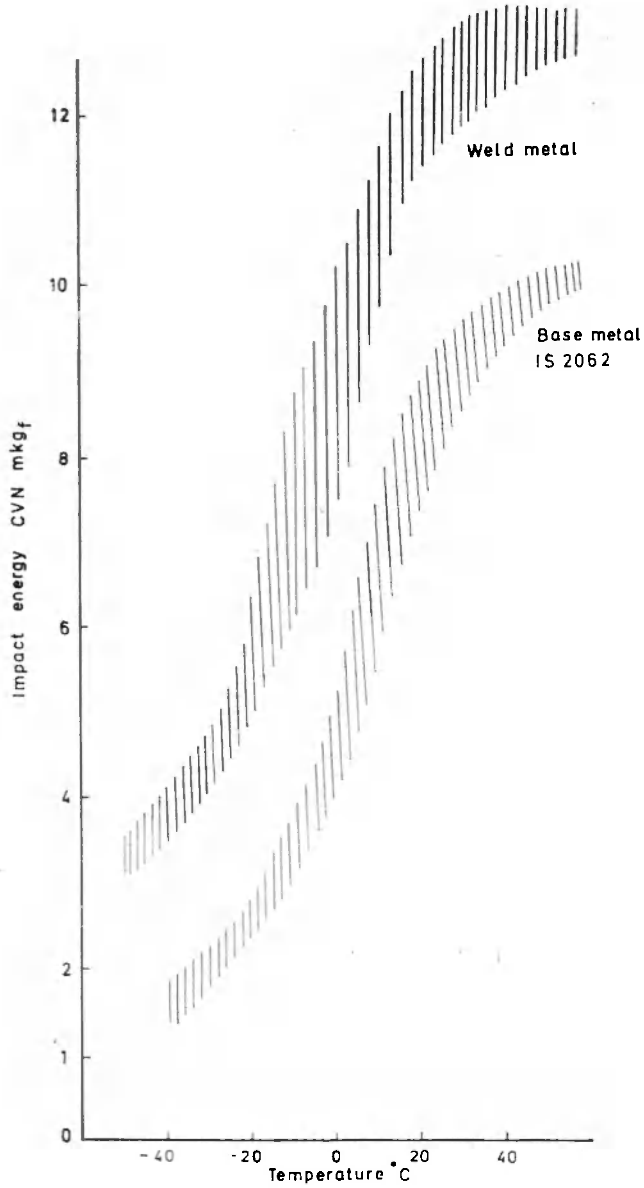
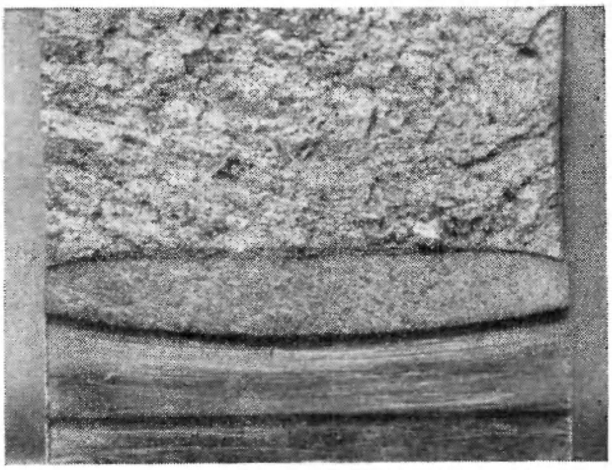
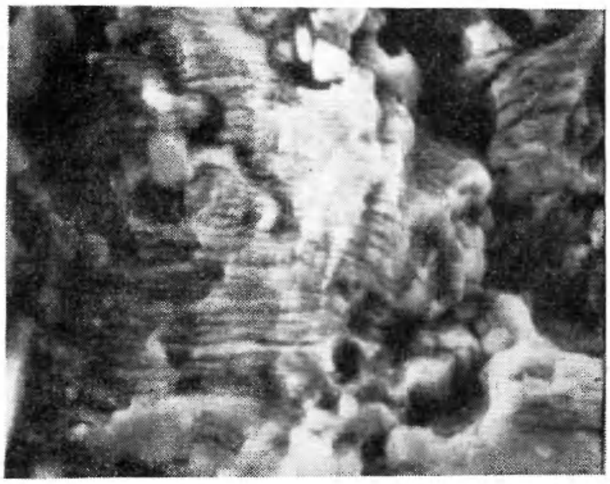


Fig. 5 : Notch toughness of IS 2062 steel



(*a*) *optical macrograph* $\times 3$



(*b*) *Electron fractograph* $\times 1250$

Fig. 6 : Fatigue crack for fracture testing

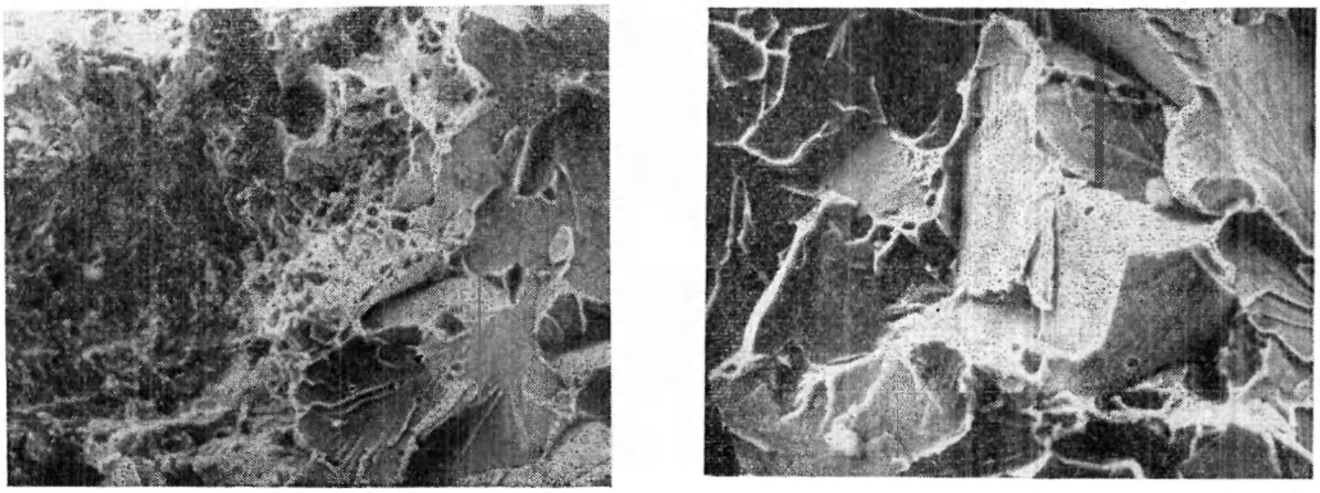
5. Under normal ambient temperature of +25°C encountered in most parts of India, the steel can safely withstand failure, even when defects like incomplete penetration or fusion are present in the structure, upto a length of 50 mm. This is particularly significant for submerged arc welded girders and beams, where interpenetration is at present sometimes mandatory.

6. The fracture behaviour of the as-welded submerged arc weld metal is similar to the base metal at—40°C, even though it can tolerate cracks of the order of 100 mm at room temperature, without causing brittle failure.

7. An analysis of fatigue cracking data reveals that, with a nominal applied stress of 15 kgf/mm², the crack growth rate is of the order of 3×10^{-5} mm/cycle, for the IS 2062 steel and 0.5×10^{-5} mm/cycle for the as-welded material, at room temperature. Hence care must be exercised in selecting this steel for fatigue loading application. It is suggested that the fatigue load should be lowered much below the statically recommended value of 15 kgf/mm² and also to avoid weld defects like incomplete fusion which provide easier fatigue crack initiation, which subsequently may grow at a fast rate of 3×10^{-5} mm/cycle.

Table 3 : Fracture Toughness Measurements

Zone of Testing	Temp °C	Crack length mm	COD mm	J_c Kgf/mm	K_c kN/mm$^{3/2}$
Base metal	RT				
	(+25°C)	6.90	0.31	7.32	4.06
		8.54	0.29	6.96	3.96
		8.90	0.35	6.94	3.95
	—40°C	6.18	0.14	2.88	2.55
		7.08	0.13	2.80	2.50
		8.56	0.05	1.15	1.61
Weld metal	RT				
	(+25°C)	7.82	0.25	8.02	4.25
		9.14	0.21	7.11	4.00
		9.38	0.21	6.61	3.87
	—40°C	7.62	0.15	4.54	3.20
		8.25	0.14	6.33	3.70
		8.52	0.07	2.14	2.17



(a) Stretch zone/cleavage fracture ×650 *(b) Cleavage fracture*

Fig. 7 : Fracture surfaces

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