Defect Tolerance of Steel Weldments

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AND

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INTRODUCTION

Welding has come to stay as an important fabrication technique since the past six decades, after its economy and productivity have been established. In the early days of fabrication by welding, statements like 'Welding promotes brittle failure' were often made (1) to focus the attention towards the influence of weld defects. It is recorded in numerous documents of the international Institute of Welding that brittle as well as fatigue failures originated from weld defects, which acted as fracture initiation sites. Over the years, detailed investigations (2) were carried out to understand the fracture behaviour of welded joints, particularly as to the significance of weld defects.

Failure Mechanisms :

The significance of weld defects is better understood if we analyse the various failure mechanisms (3) involved. There are, in general, five failure mechanisms, viz., ductile, brittle, fatigue, creep and stress corrosion failures. Each has characteristic crack initiation and propagation phenomena.

Ductile Fracture :

In which the fracture initiates perhaps from a weld defect, whereby both initiation and propagation occur with appreciable plastic deformation. The plastic deformation can be highly localised or can occur as a global phenomenon. The crack growth is essentially by slow and stable mechanism. Plastic collapse can be a design feature for such a failure.

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Brittle Fracture :

In which the fracture occurs by negligible plastic deformation. It must be recognised that brittle fracture can occur in an otherwise ductile material, if favourable conditions exist. Hence design against brittle failure has to be done taking due account of the presence of weld defects (increase in stress concentration), service temperatures (in relation to transition temperature) and loading rates (dynamic or impact).

Fatigue Failure :

Fatigue failure occurs essentially by relatively slow crack growth mechanism, when a crack originates from a defect site and grows as a time-dependent mechanism.

Creep Failure :

Creep failure occurs by the combined influence of stress, temperature and time. The initiation of failure can be from such insignificant dimensions as grain boundary. It is essentially a time-dependent failure mechanism, where higher temperatures have led to the material damage.

Stress Corrosion Failure :

Stress corrosion failure occurs by the combined action of stress and corrosive media, over a length of time. Failure occurs earlier than would normally occur either by stress or by corrosion alone. Weld defects, particularly in higher strength materials, are significant with respect to this failure mechanism.

Design Concepts :

It should be noted that all the five failure mechanisms reported earlier are primarily based on the stress acting on the member. Over the years, the design concepts that were evolved for resistance against failure, can be conveniently grouped into three generations of existence [4], as follows :

$$Pr\ (\text{FAILURE})\ \text{IF}\ Pr\ [y \geq x]$$

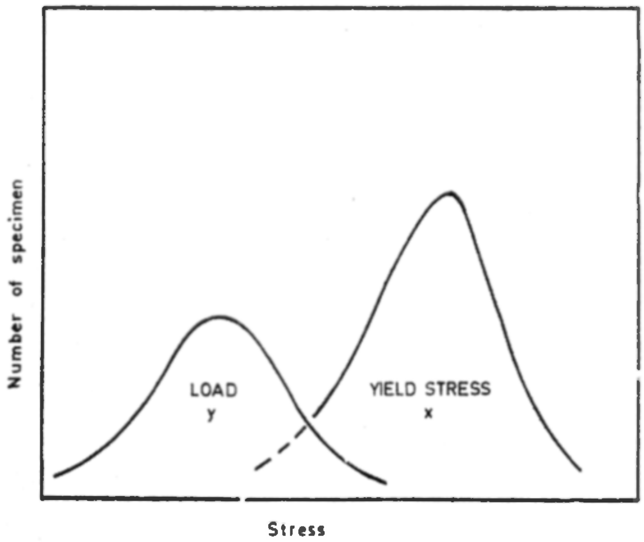


Fig. 1 Probability of Failure

The first generation design concept :

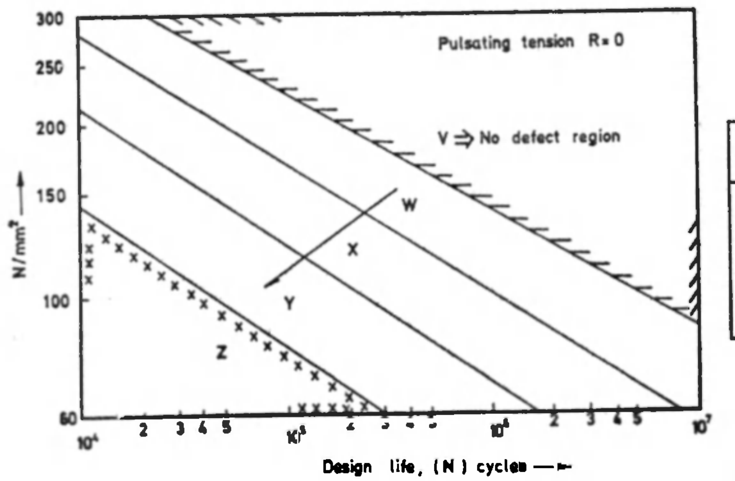
The first generation design concept consists of assuming that the material is homogeneous and isotropic. The design stress is based on the nominal yield or ultimate strength of the material. Failure occurs when the applied stress exceeds the fracture stress of the material, (Fig. 1) due to situations not anticipated in the original design. The probability of failure is not directly connected to the possibility of existence of defects.

The second generation design concept :

Makes allowances for the existence of defects or discontinuities in a material. The design is based essentially on the information obtained from two types of tests viz.,

(i) Tests on notched specimens, like notched-tensile or notch toughness tests (charpy impact tests). In these tests, the notch is made to represent the discontinuity or a defect that may exist in a structure. The important result of these tests is that even though the strength may apparently be increased because of the presence of a notch, the exhaustion of ductility at the notch tip leads to possible brittle failure. The charpy impact toughness data is still being widely used for qualitative evaluation of materials for design against brittle failures.

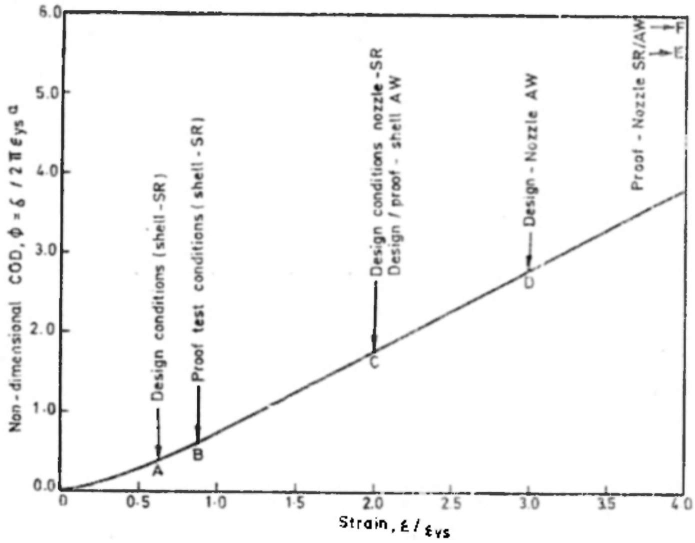
(ii) Tests with specimens containing actual weld defects : Though these type of tests have greater utility because of the reliability of data so obtained, the reproducibility of test specimens with known defects makes the technique less popular. While reasonable amount of data [5] is obtained with specimens containing porosity (Fig. 2), no consistent data



Quality	% Porosity	Slag incl	
		Rate	Low H₂ Weld
V	0	0	0
W	3	1.5	5
X	8	10	25
Y	20	No max	
Z	20	No max	

Ref : I.W.D.C = 583·80

Fig. 2 Fatigue design with porosity



$$a_{max} = k . \frac{\delta_c}{\varepsilon_{ys}}$$

ε_{ys}	ϕ	k
0.65	0.32	0.50
0.90	0.64	0.25
2.00	1.75	0.09
3.00	2.75	0.06
6.00	5.75	0.30
7.00	6.75	0.024

REF: BURDEKIN & DAWES 1971

Fig. 3 Design Using COD Value

is available for slag inclusions. The main difficulty of this technique is that it requires large number of test specimens to determine the influence of a wide variety of defects.

The third generation design concept

The third generation design concept considers the effect of the most severe defect on the worst type of failure. It is assumed that the situation so described will be the worst situation, one can envisage. This concept is known as Fracture Mechanics and is described subsequently. A quantitative data (Fig. 3) is here obtained for design purposes (6).

Fracture Mechanics :

Fracture Mechanics describes precisely the mechanics of fracture of materials, under the presence of a sharp crack in a linear elastic field or in an elastic plastic stress situation. Fig. (4) describes the valid ranges of fracture toughness analyses.

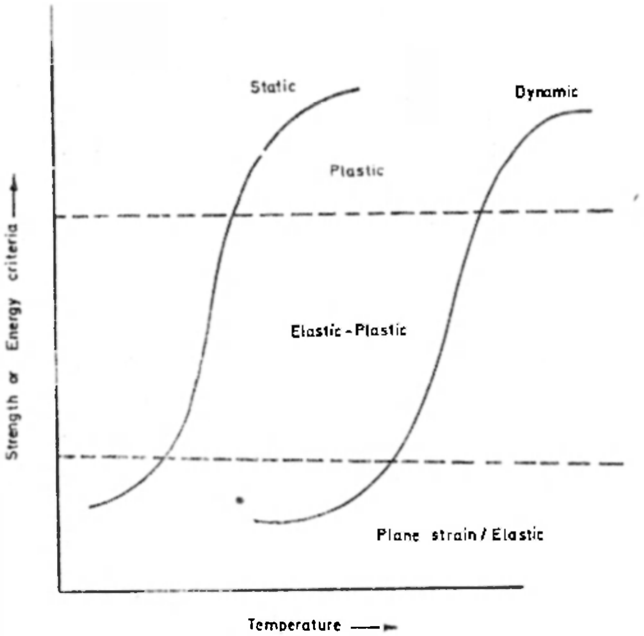


Fig. 4 Fracture Toughness Analysis

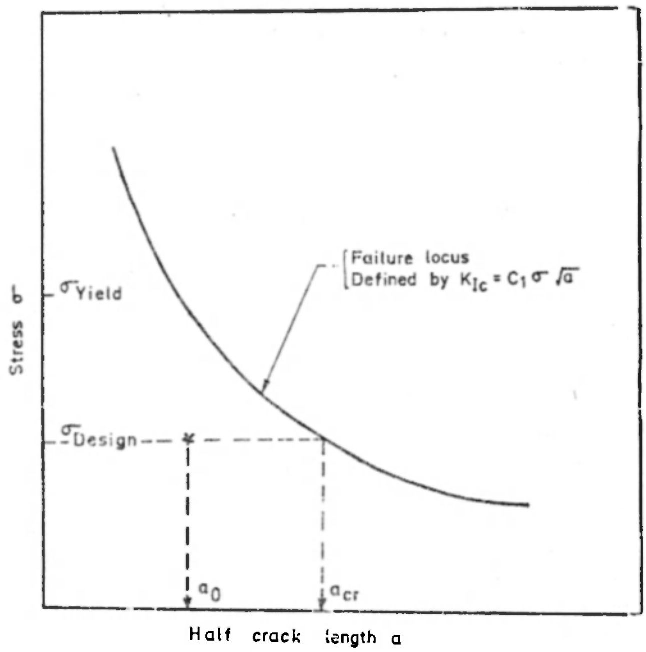


Fig. 5 Concept of CEFM

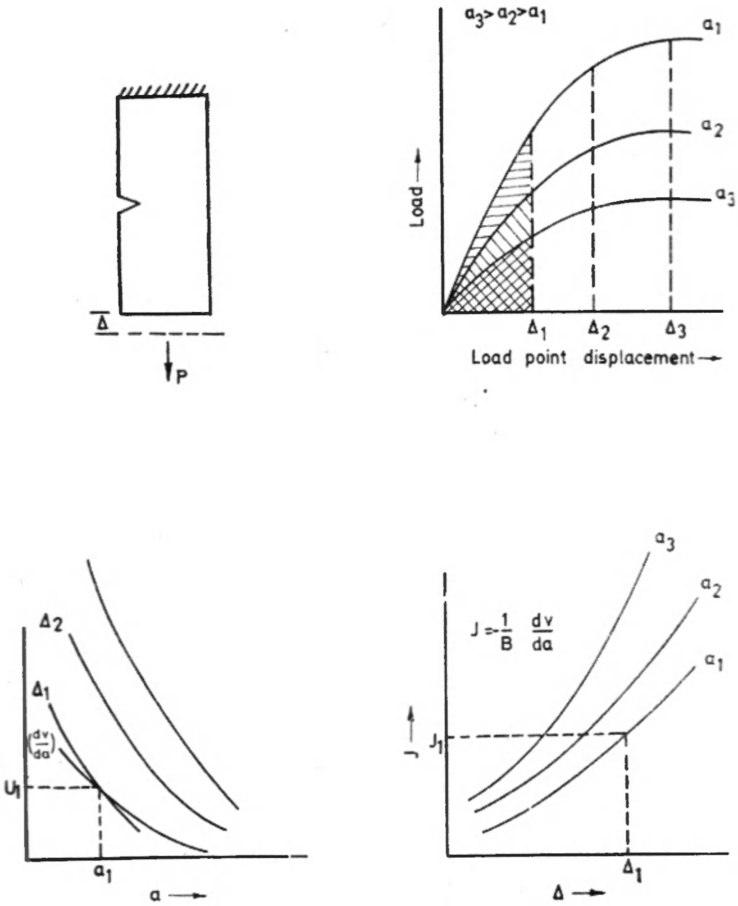


Fig. 6 J-Integral Concept

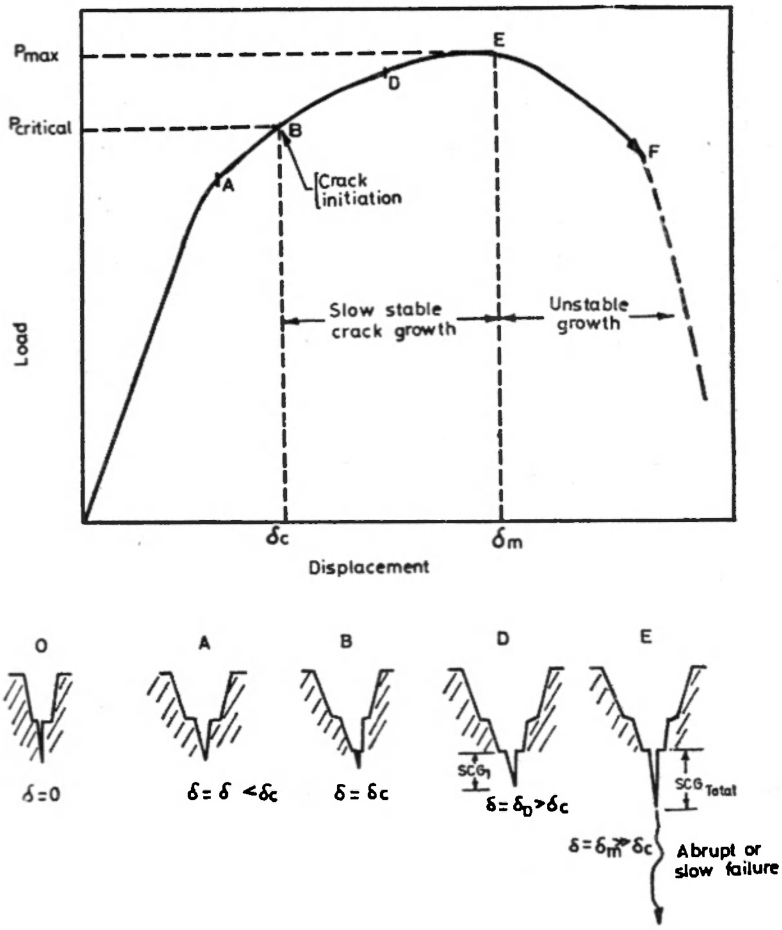


Fig. 7 COD Concept

Linear Elastic Continuum :

The concept of K_{Ic} of linear elastic fracture mechanics (LEFM) concerns a sharp crack in the field of linear elastic continuum. The stress field ahead of the crack tip is described by a stress intensity factor K_I and is related to the applied stress and crack length as

$$K_{1c} = \sigma f(a) \qquad ...(1)$$

The criterion for fracture is when the factor K attains a critical value K_{1c}, known as the fracture toughness of material. The defect tolerance concept says that the structure will fail either if the applied stress reaches a critical stress for a given crack length or when the crack reaches a critical crack length for a given applied stress. Fig. (5). Then the critical crack length is given by the equation

$$a_c = \frac{1}{\pi}\left(\frac{K_{1c}}{\sigma}\right)^2 \qquad ...(2)$$

Elastic-Plastic Fracture Mechanics :

In the elastic-plastic stress situation, there are two types of concepts viz.

(a) J-integral and

(b) Crack opening displacement.

J-integal method :

The J-integral method of fracture toughness tests is essentially an energy criterion. It describes difference in potential energy of two identically loaded bodies having neighbouring crack sizes ; Fig. (6). In other words, it describes the energy required to be spent in causing an incremental crack length in an elastic-plastic situation. It is possible to relate the J_{1c} value to K_{1c} values by the equation such as

$$J_{1c} = K_{1c}^2 (1-\nu^2)/E \qquad ...(3)$$

Here again the defect tolerance is based on the critical crack length calculated from the K_I value so obtained.

In the crack opening displacement testing, the relative movement of the crack surfaces at the crack tip is measured and is taken as the criterion for material failure (Fig. 7). The appropriate interrelationship with K_I concept is given as

$$K_{Ic} = (E\sigma y \delta_c)^{1/2} \quad ...(4)$$

Where σy is the yield stress and δ is the cirtical COD. The fracture mechanics equations connecting the COD value and the applied stress is given as :

$$\delta = \frac{8\ \sigma_y a}{E} \log_e \sec\left(\frac{\pi\sigma}{2\sigma_y}\right) \text{ where } \sigma < \sigma_y \quad ...(5)$$

δ is the COD at the crack tip
a is the half crack length and
σ is the applied stress

Since above the yield stress limit theoretical analysis is violated, it has been shown that the relationship between COD and overall applied strain is linear. In order to obtain a unified approach to defect tolerance calculations a design curve is proposed purely based on experimental data. A recent version of the defect tolerance equation[8] is of the form

$$\bar{a}_{max} = \frac{\delta_c E\sigma_y}{2\pi\sigma_I 2} \text{ if } \sigma_I \leqslant 0.5\sigma_y \quad ...(6)$$

$$\bar{a}_{max} = \frac{\delta_c E}{2\pi(\sigma_1 - 0.25\sigma_y)} \text{ if } 0.5\sigma_y < \sigma_1 < \sigma_y \quad ...(7)$$

where σ_I is the effective pseudo-elastic stress

$\sigma_I = (\sigma \text{ x SCF}) + \sigma_R)$

where σ_R = Residual stress and

SCF = Stress concentration factor.

The above equation provides a means of calculating the defect size that can be tolerated in a weld joint, if the relevant fracture toughness data is obtained by actual tests.

Fatigue Fracture Mechanics :

The fatigue failure of a component can be thought of as comprising three distinct stages viz., crack initiation, crack propagation and final consequential failure. The principles of fracture mechanics (Fig. 8) can be applied to describe the conditions leading to the crack growth. As the crack extends due to cyclic loading, the crack tip stress intensity factor increases due to the increase in crack length as given by the equation [9]

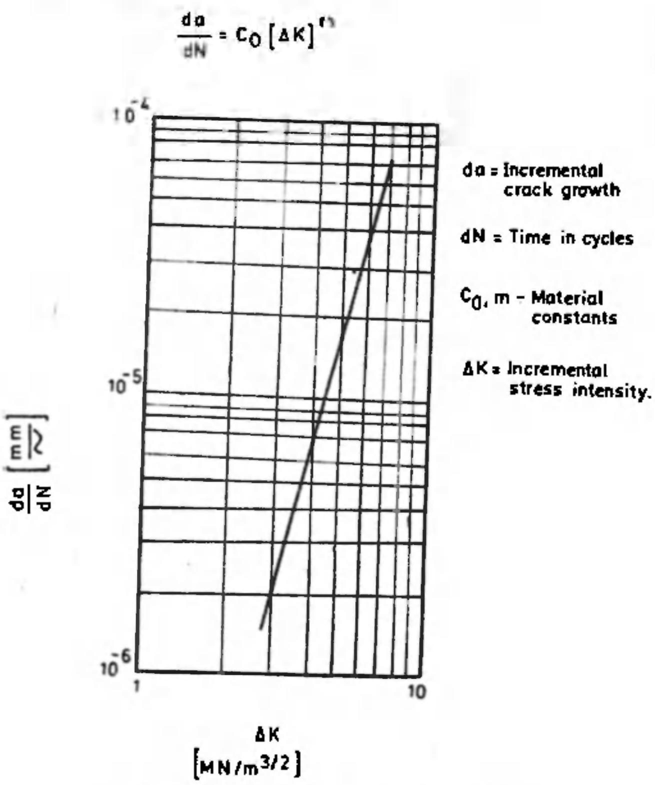


Fig. 8 Fatigue Fracture Mechanics

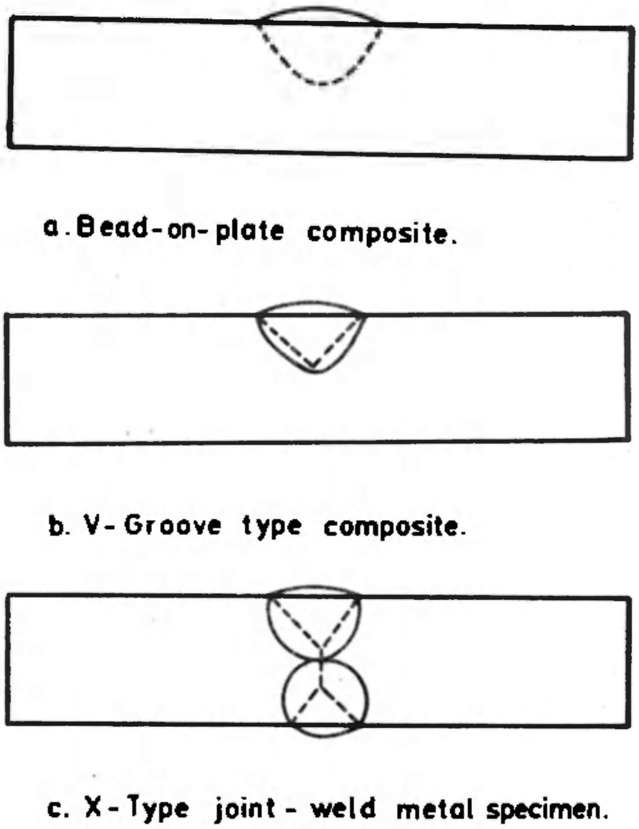


Fig. 9 Joint Designs Used

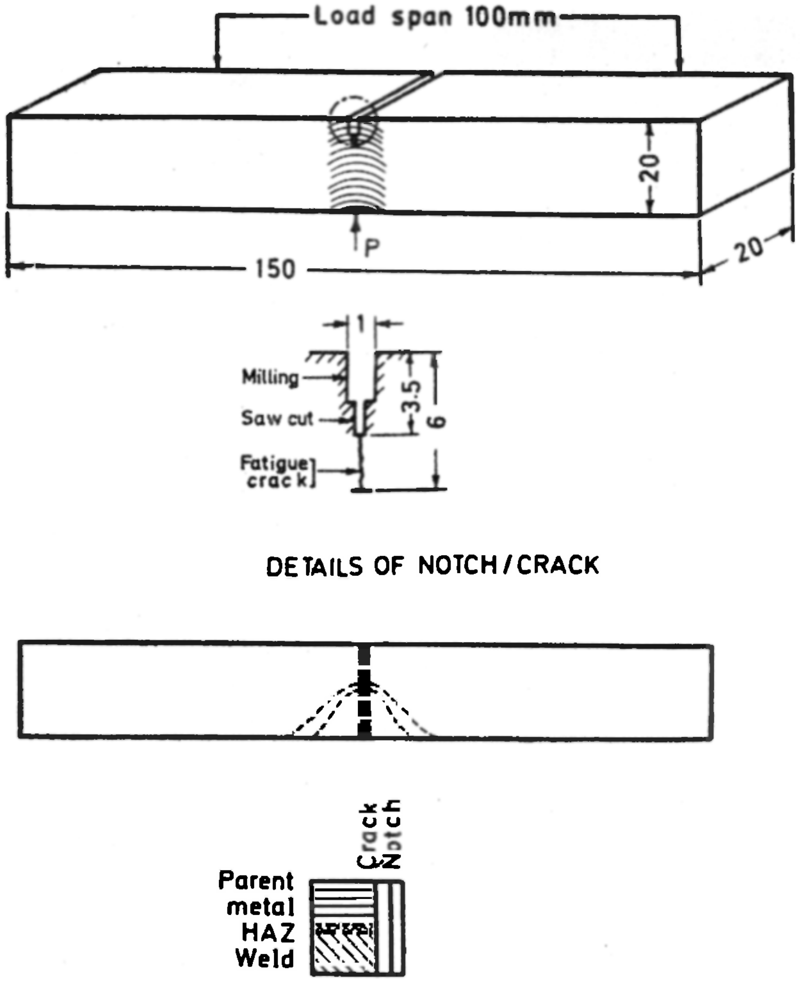


Fig. 10 Weld-Composite test specimens

$$\frac{da}{dN} = Co\,(\triangle k)^{n} \qquad ...(8)$$

Where da/dN is the fatigue crack growth, and Co and n are characteristics of material and $\triangle$ k is the increase in stress intensity factor for an incremental crack growth $\triangle$a. By employing this equation, one may decide the expected increase in crack length in service life of the component and thereby define the defect tolerance of the component.

Experimental Procedure :

For these investigations, an Indian Standard Structural Steel (IS : 2062) was made use of. The tests conducted were based on the principles of fracture mechanics. Since an evaluation of the weld joint has to take care of all the different regions of the weldment, tests were conducted on the parent metal and the weld metal, as well as on weldment taken as a composite body. Tests were conducted both at room temperature and at a lower temperature of —40°C. The details of the experiments are as follows :

Welding :

A bead on plate test as well as with V-preparation were carried out. Weld-metal test specimens were taken from a X-type of specimen, (Fig. 9) submerged arc welding with a filler (S2) and (UM 80) flux combination at an optimum heat input of 40 KJ/cm (30V/750A/40 cm/min) was made use of.

Test Specimens :

Full plate thickness (20 mm) test specimens were prepared from the welded plates. Apart from the test specimens from parent metal and weld metal, weld-composite specimen (10) were also tested. In these specimens, (Fig. 10) the notch and the crack traverse all the regions of the weldment.

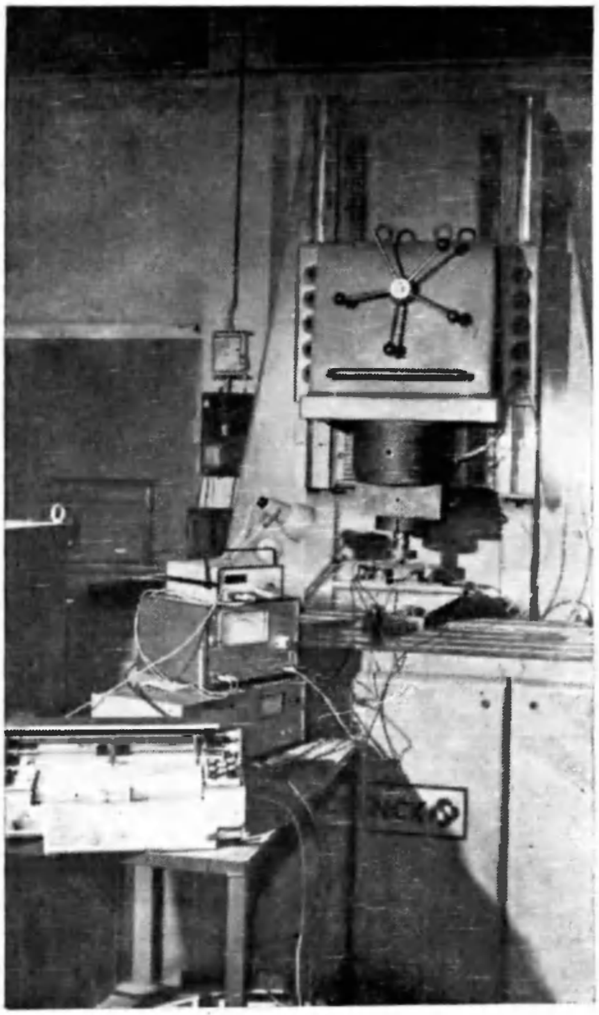


Fig. 11 Pulsator for Fatigue Pre-cracking

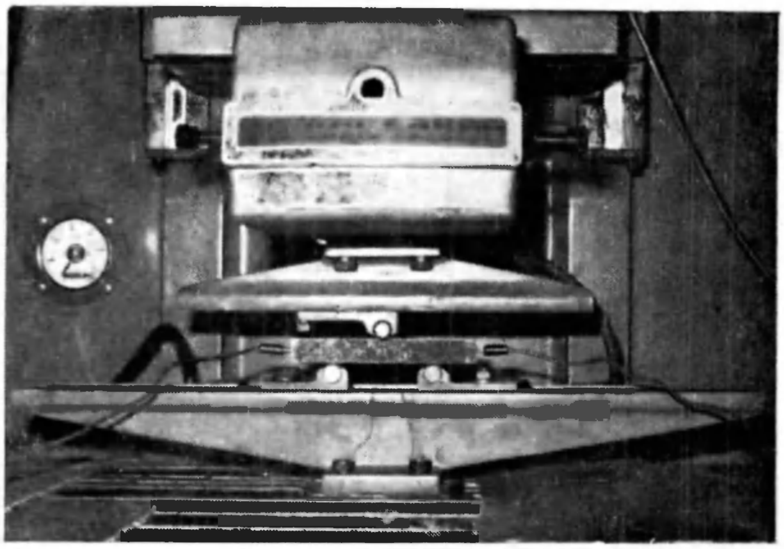


Fig. 12 Electrical Potential Method

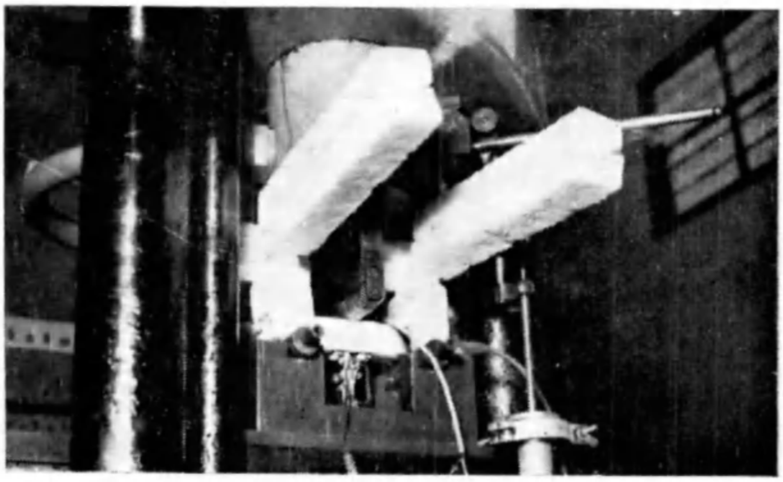


Fig. 13 J-Integral Test Set up

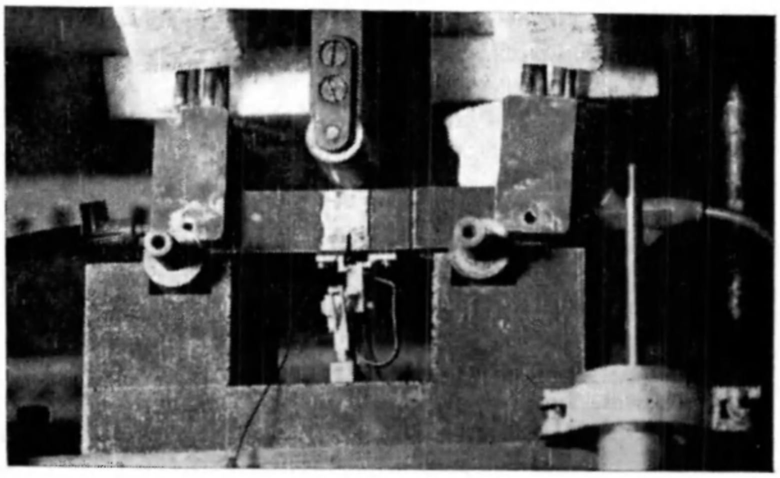


Fig. 14 COD Test Set up

Fatigue Pre-cracking :

Since fracture toughness testing requires specimens of known crack length, fatigue precracking was employed to introduce cracks in the test specimens. A 20 Tonne pulsater (Fig. 11) at a frequency of 3000 cpm was used. An electrical potential [11] method (Fig. 12) was made use of to determine and monitor the crack lengths during fatigue pre-cracking. The record of crack length with time was used to plot the fatigue crack growth rate.

J-Integral Tests :

(Fig. 13) The J-integral test requires that the energy for onset of crack extension be found for specimens containing neighbouring crack sizes. Fatigue pre-cracking technique was used to develop different crack lengths in these test specimens. The energy for the critical event is arrived at by using a planimeter on the

TABLE-1

TYPICAL FATIGUE PRECRACKING DATA

Load range : 440 Kg_{fmin} to 1760 Kg_{fmax}
Frequency : 1500 cpm

Material	Fatigue cycle	Crack length (Total) mm	a/w	Fatigue stress intensity Range K_{fmin} - K_{fmax} ($kN/mm^{3/2}$)	ΔK	Crack growth rate mm/cycle (average)
Parent metal	94000	6.18	0.31	0.31-1.24	0.93	
	90000	8.54	0.43	0.42-1.68	1.26	4.1×10^{-5}
	71000	6.90	0.35	0.30-1.20	0.90	
Weld metal	300000	7.82	0.39	0.38-1.19	0.81	1.8×10^{-5}
	146000	8.34	0.42	0.41-2.05	1.64	9.2×10^{-5}
	185000	9.68	0.48	0.49-2.45	1.96	7.7×10^{-5}
Composite B	319000	8.37	0.42	0.1-1.33	1.23	
	314000	9.02	0.45	0.1-1.45	1.35	2.7×10^{-5}
	160000	8.22	0.41	0.4-1.60	1.20	
Composite V	239000	7.00	0.35	0.1-1.10	1.00	2.3×10^{-5}
	137000	7.42	0.37	0.1-1.16	1.06	2.0×10^{-5}
	104000	8.64	0.43	0.42-1.69	1.27	5.9×10^{-5}

load—load point displacement curve obtained by static loading conditions.

COD Tests :

(Fig. 14) : COD tests were performed ([12]) as per the British standard DD 19 : 1972, now revised as BS 5762 : 1979 by using a clip gauge instrumentation at the crack mouth and converting the values to crack tip displacement. The critical COD is defined as the COD value at which the onset of crack extension occurs, which is again identified by the electrical potential method.

Results and Discussions :

The fatigue pre-cracking data for the parent metal, the weld metal and the weld-composite specimens is given in Table (1). It may be noted that different crack lengths were generated in the specimens to provide suitable test specimens for J-integral testing. Selected specimens were also subjected to COD testing. The a/w ratio was maintained between 0.30 and 0.50.

For a stress intensity range of 0.90 to 1.26 $kNmm^{3/2}$, the fatigue crack growth rate is of the order of 4.1×10^{-5} mm per cycle in the parent metal. The crack growth rate in the weld metal and weld composite specimens are slightly lowered for lower stress intensities, whereas the rates are much higher at higher stress intensity ranges. The observation of the fractured specimen later indicated that fatigue crack profile is uniform (within ±5%) in all these specimens.

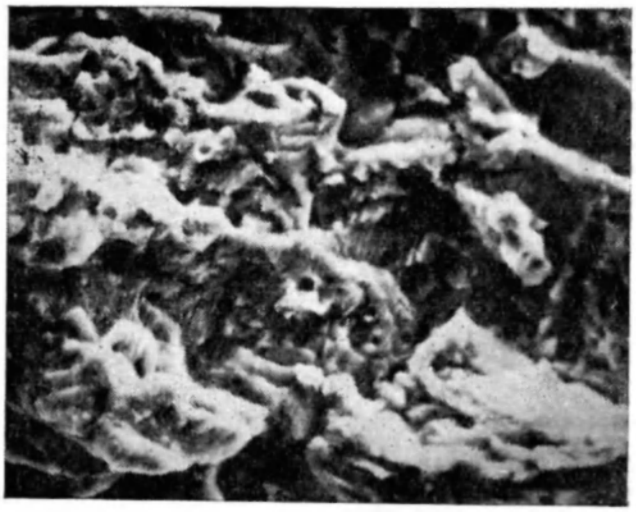


Fig. 15 Fatigue Crack

TABLE-2

J-VALUES

Material	+25°C		−40°C	
	J_c Kgf/mm	K_{Jc} KN/mm^{3}/^{2}	Jc Kgf/mm	K_{Jc} KN/mm^{3}/^{2}
Parent metal	6.94	3.95	1.15	1.61
	6.96	3.96	2.88	2.55
	7.32	9.06	2.88	2.55
Weld metal	6.67	3.87	4.54	3.20
	6.67	3.87	4.54	3.20
	7.11	4.11	6.33	3.77
Composite B (HAZ)	8.41	4.35	10.54	4.65
	8.45	4.36	10.99	4.87
	9.19	4.55	9.60	4.97
Composite V (HAZ)	10.67	4.90	9.42	4.60
	11.37	5.06	9.98	4.74
	11.43	5.07	12.14	5.23

Generally it is expected that during the Stage II crack growth, the rate of crack growth is independent of factors like material composition, microstructure and tensile strength. Perhaps the crack growth rate in this investigation is influenced by the presence of residual stresses, since as-welded specimens without stress relieving were made use of. This observation is similar to the trend noted by Kapadia et al ([13]).

J-Integral Test Results

The results of the J-integral tests conducted at room temperature (+25°C) as well as at low temperature of —40°C are given in Table (2). The critical J_c values are taken as the energy difference between the two specimens containing neighbouring crack sizes, when the crack starts to extend from the already provided fatigue crack. The energy value depends both on the load taken and the displacement observed. Since the load for crack initiation was found to increase, there is significant increase in J_c values for parent metal, weld metal and weld-composite specimens. With decrease in temperature, generally the J_c values also decreased. By using the conversion formula, the J_c values are transformed to equivalent K_c values, denoted as KJ_c values in Table (2). It may be noted that parent metal displays significantly lower values, at —40°C, even though matching weld metal was used. The values for weld-composite specimens, consisting of parent metal, HAZ and weld metal, were significantly higher, again indicating that the IS : 2062 steel possesses the least fracture toughness in the as received condition.

COD Test Results

The results of the COD tests on different regions of the weld joint are given in Table (3). It may be noted

TABLE—3
COD VALUES

Material	kT+25°C	—40°C
Parent metal	0.29	0.05
	0.31	0.11
	0.35	0.14
Weld metal	0.21	0.14
	0.21	0.14
	0.25	0.15
Composite-B (HAZ)	0.24	0.12
	0.29	0.16
	0.26	0.17
Composite-V (HAZ)	0.31	0.09
	0.32	0.11
	0.36	0.12

that all the regions possess COD values in the range of 0.2 to 0.35 mm at room temperature. But these values are significantly lowered at —40°C. If we take 0.1 mm as the COD value for brittle transition, the parent metal and the composite-V specimen exhibit a tendency towards brittle failure at —40°C ; under static loading conditions (14). When the variation in J_c values and COD values with variation in temperature is compared, it is observed that COD values show more sensitive response.

Defect Tolerance

As stated elsewhere, the tolerable defect sizes can be calculated from the J-integral values as well as the COD values. Assuming a nominal stress of 180 N/mm², the tolerable defect sizes calculated from Tables (2) and (3) are given in Table (4). For this low yield strength

TABLE—4

DEFECT SIZE mm

Material	COD data		J-integral data	
	+25°C	—40°C	+25°C	—40°C
Parent metal	83	37	122	57
Weld metal	51	34	117	81
Weld Joint (composite-B)	63	40	150	186
Weld joint (composite-V)	83	26	201	176

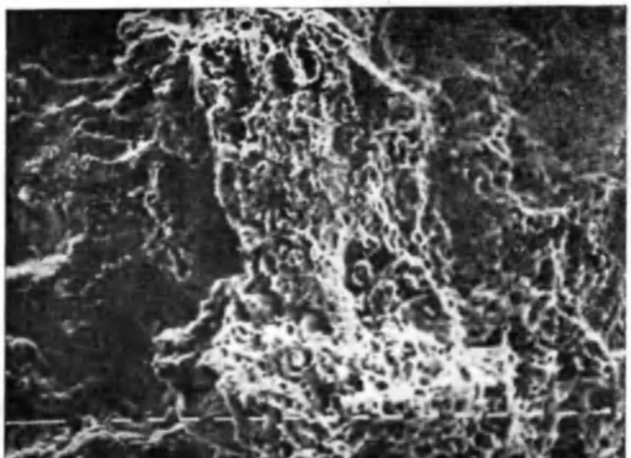


Fig. 16 Ductile Fracture Surface (SEM Photo)

Fig. 17 Mixed Fracture (SEM Photo)

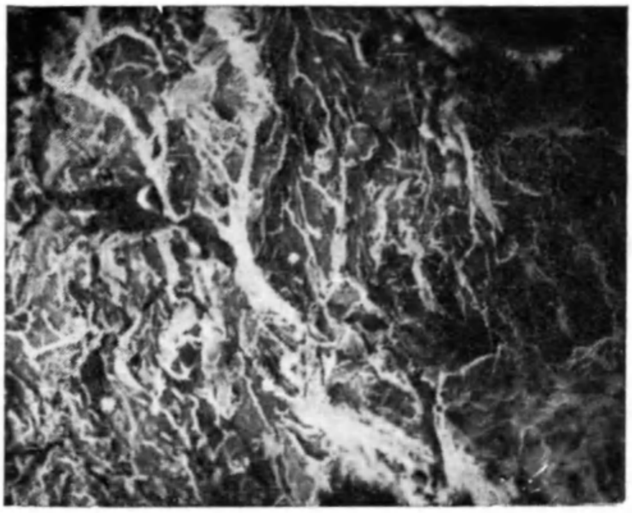


Fig. 18 Cleavage Failure (SEM Photo)

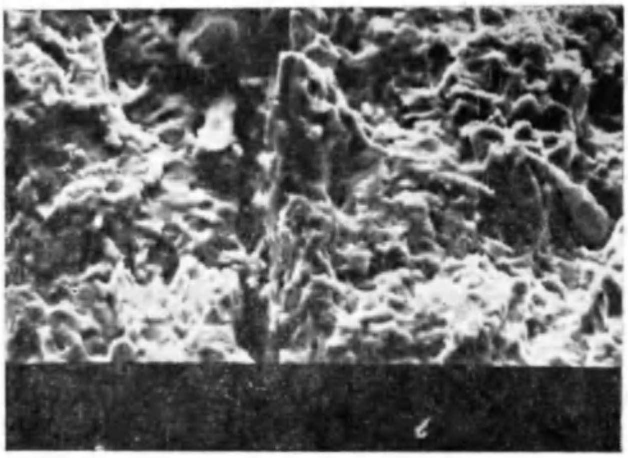


Fig. 19 (Voids in Haz Weld Composite Specimen) (SEM Photo)

steel, the tolerable defect sizes are of the order of 50 to 80 mm at room temperature and go down to a low value of 26 mm at —40°C. Generally the defect sizes calculated from the COD values are more conservative and perhaps more realistic than the J-integral calculations.

Fracture Mechanism

The fracture mechanisms in parent metal and weld metal are clear, showing ductile fracture at room temperature (Fig. 16), mixed or cleavage failure at lower temperatures (Fig. 17 and 18). But the analysis of the results of weld-composite specimens are better understood by the observation of voids in the HAZ. (Fig. 19). It has been proved elsewhere ([15]) that the weld-composite specimens represent the behaviour of the HAZ in a weldment. Hence the fracture toughness results of weld-composite specimens represent the toughness of HAZ as it is the controlling factor for fracture initiation.

Conclusions

The following conclusions can be drawn from this investigation :

(1) The fatigue crack growht rate in parent metal specimens is of the order of 4.1×10^{-5} mm per cycle, for a stress intensity range of 0.90 to 1.26 $kN/mm^{3}/^{2}$.

(2) The fatigue crack growth is different in weld metal and weld composite specimens, perhaps influenced by the presence of residual stresses.

(3) The parent metal shows significantly lower J_c values than the weld metal or weld-composite specimens.

(4) The COD values are again lower for the parent metal than other regions, at —40°C.

(5) The COD values are more sensitive than the J-integral values, for the low strength steel investigated.

(6) The defect sizes calculated from COD values are more conservative estimates.

(7) The scanning electron fractography indicates that the behaviour of the weld-composite specimen reflects the behaviour of the heat affected zone.

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