Influence of Geometrical Variables on Initiation Fracture Toughness (J_{IC}) of Low Carbon High Manganese SA 333 Gr. 6 Steel

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The study of the initiation fracture toughness (J_{IC}) and J – R curve of low carbon SA333 Gr. 6 steel by compact tension (CT) indicates that for thicker specimens, J_{IC} decreases with the increasing ratio of crack depth (a) to specimen width (W), a/W , both for deep and shallow cracks. However, for thinner specimen, J_{IC} decreases with a/W ratio for shallow cracks but for deep cracks, J_{IC} is insensitive to a/W ratio. Initiation fracture toughness increases with decreasing thickness but at relatively lower thicknesses beyond plane strain condition, initiation fracture toughness increases significantly with increasing specimen thickness for different a/W ratio investigated.

KEY WORDS: fracture toughness; J -integral; compact tension; a/W ratio; thickness effect.

1. Introduction

In the analysis of fracture in engineering structures, the fracture criteria, namely, the fracture initiation toughness, J_{IC} and the fracture resistance or J – R curve, have been widely considered as a material property independent of specimen geometry and type of loading.^{1,2)} The crack-tip stress in the J -integral theory of fracture is proportional to J but is independent of geometry as proposed by Rice.¹⁾ Matsoukas *et al.*³⁾ have shown that the hydrostatic stresses are larger for deeper cracks on the basis of slip-line field analysis. A number of finite-element analyses^{4–7)} have also reported that the normalized crack depth a/W has a significant effect on the stress triaxiality ahead of the crack tip. For above circumstances, the relationship between the scaling parameters of J -integral and the near crack-tip stress fields loses the one-to-one correspondence. This loss of uniqueness, often termed as loss of constraint, leads to a variation of fracture toughness with specimen crack depth.

The experimental investigations on the dependence of J_{IC} and J – R curve on the pre-crack length characterized by a/W ratio, have not yielded any unambiguous trend as summarized in **Table 1**. It has been claimed that the tests are carried out following plane strain condition prescribed by ASTM. At lower a/W ratio, for some steels J_{IC} decreases with increasing a/W ratio but for others J_{IC} is insensitive to a/W ratio. A close inspection indicates that higher strength and limited ductility results in insensitivity of J_{IC} to a/W ratio. On the contrary higher ductility and relatively lower strength leads to decreasing J_{IC} with increasing a/W ratio. At higher a/W ratio, J_{IC} may become insensitive for material which has shown at lower a/W ratio decreasing J_{IC} with

increasing a/W . In SA333 Gr.6 steel which has relatively lower strength and very high ductility compared to other steels investigated, it is interesting to observe the unique feature in the intermediate region at a/W between 0.30 and 0.40 where J_{IC} is increasing with increasing a/W ratio, which has not been observed in any material so far. But for J – R curve, most of the studies report no discernible trend. Only Joyce and Link^{11,12)} have reported higher J – R curve with increasing a/W ratio in the ranges of $a/W < 0.4$ or $a/W > 0.75$.

Table 2 summarizes the observed trend of variation of J_{IC} with thickness. ASTM specifies that plane strain condition is ensured if $B \geq 25J_{IC}/\sigma_F$. In the experiment by Mao¹⁶⁾ the thicknesses of 3 and 0.5 mm in CT specimens of A533B-1 steel where the width has been kept constant, does not ensure plane strain condition. Surprisingly, the J_{IC} in CT specimens of thicknesses 25 and 10 mm, satisfying plane strain condition although insensitive to geometrical dimension, are higher than those specimens of lower thickness violating this condition. Ono *et al.*¹⁷⁾ in their study on JLF-1 steel, have used specimen thicknesses under which the stress state has moved from plane strain condition in 25 mm thick specimen towards plane stress situation at 12.5 mm specimen and so J_{IC} may have increased due to change in state of stress. But outside the plane strain domain, J_{IC} decreases with decreasing thickness according to Ono *et al.*¹⁷⁾ which contradicts the observation of Mao.¹⁶⁾ Jitsukawa *et al.*¹⁰⁾ have found that away from plane strain condition, J_Q is insensitive to specimen thickness (for the same width) on three point bend bar specimens of 7075-T6 high strength aluminum alloy and this is at variance with observations of both Ono *et al.*¹⁷⁾ and Mao.¹⁶⁾

Table 1. Behaviour of Fracture Toughness J_{IC} and J - R curve with increasing a/W ratio.

Material and Mech. Properties	Specimen Type	a/W ratio	J_{IC}		J-R Curve Behavior	Investigator
			Behaviour	Measurement		
SA333 Gr. 6 steel $\sigma_0=292$ MPa $\sigma_u=307$ MPa El.=36.2 %	TPB specimen	$a/W = 0.15-0.30$ $a/W = 0.30-0.40$ $a/W > 0.40$	J_{IC} decreases J_{IC} increases J_{IC} decreases	Blunting line without offset	No general trend with a/W	Tarafder <i>et al</i> ⁸⁾
High strength and high toughness alloy steel $\sigma_0=838$ MPa $\sigma_u=967$ MPa El.=20.1%	TPB specimen	$a/W \leq 0.15$ $a/W \geq 0.20$	J_{IC} decreases J_{IC} insensitive to a/W	ASTM Blunting line	No general trend	Li <i>et al</i> ⁹⁾
7075-T6 aluminum alloy $\sigma_0=520$ Mpa $\sigma_u=560$ MPa El.=11 %	TPB specimens	$a/W=0.125-0.5$	J_{IC} insensitive to a/W	ASTM Blunting line	Not reported	Jitsukawa <i>et al</i> ¹⁰⁾
A533B $\sigma_0=400$ MPa $\sigma_u=555$ MPa HY-100 and HY-80 structural steels $\sigma_0=541$ MPa $\sigma_u=603$ MPa El.=32%	CT and TPB	$a/W=0.13-0.83$	J_{IC} insensitive to a/W	ASTM Blunting line	No significant effect on J-R curves in the range $0.55 \leq a/W \leq 0.7$ $a/W < 0.4$ or $a/W > 0.75$ elevated J-R curve	Joyce and Link ^{11, 12)}
Structural steel (C=0.1, Mn = 0.46, Si = 0.3) $\sigma_0=71$ MPa $\sigma_u=104$ MPa El.=19.2 %	TPB specimens	$a/W=0.1-0.5$	J_{IC} decreases	ASTM Blunting line	Not reported	Zhang and Wang ¹³⁾
CSA grade G40.21 350WT plate materials. $\sigma_0=508$ MPa $\sigma_u=631$ MPa El.=44.1%	TPB specimens at -30 °C	$a/W=0.2-0.7$	J_{IC} decreases	ASTM Blunting line	Lower J-R curve	Shen <i>et al</i> ¹⁴⁾
StE 690 steel $\sigma_0=680$ MPa $\sigma_u=770$ MPa El.=24 %	TPB	$a/W=0.1-0.5$	J_{IC} decreases	ASTM Blunting line & SZW method	Not reported	Zheng <i>et al</i> ¹⁵⁾

Table 2. Behaviour of Fracture Toughness J_{IC} with decreasing specimen thickness, B .

Material and Mech. Properties	Specimen Type	Thickness, B	J_{IC}		Investigator
			Behaviour with decreasing B	Measurement	
A533B-1 steel $\sigma_0=495$ MPa $\sigma_u=620$ MPa	CT	$B = 25, 10, 3, 0.5$ mm, corresponding B/W ratio of 0.5, 0.5, 0.3, 0.05	J_{IC} decreases but specimen B/W changed except for $B=25, 10$ mm	Blunting line without offset	Mao ¹⁶⁾
JLF-1 $\sigma_0=450$ MPa $\sigma_u=620$ MPa El.=22.8 %	CT	$B=25, 12.5$ mm corresponding B/W ratio of 0.5, 0.25 $B=12.5, 6.25$ mm, $B/W=0.5$	J_{IC} increases but specimen B/W decreasing J_{IC} decreases for the same specimen B/W	ASTM Blunting line	Ono <i>et al</i> ¹⁷⁾
7075-T aluminum alloy $\sigma_0=520$ MPa $\sigma_u=560$ MPa	TPB specimens	$B = 2.5-15$ mm B/W varies 0.125 to 2	J_{IC} insensitive to thickness but specimen B/W changed	ASTM Blunting line	Jitsukawa <i>et al</i> ¹⁰⁾

In view of an anomalous trend in the behaviour of J_{IC} and J - R , particularly for relatively low strength and high ductility material like SA333 Gr. 6 steel, the present study explores the dependence of fracture toughness on the geometrical parameters of the test specimen. The variations of ini-

tiation fracture toughness in SA333 Gr. 6 steel with changing thickness and pre-crack depth have been investigated along with the impact of these parameters on J - R curves.

2. Experimental Procedure

The chemical analysis of SA333 Gr. 6 steel used in the present investigation has been carried out under simultaneous spark emission spectrometer (Thermo Jarrell Ash TJA181) with a spot size of about 3 mm. The tensile tests have been performed at ambient temperature on tensile specimens, shown schematically in Fig. 1, following specification in ASTM E 8M.¹⁸⁾ The tensile tests were carried out using a crosshead speed of 1 mm/min on a hydraulic universal testing machine. The diameter and gauge length of each specimen was measured prior to and after the test. The yield strength and ultimate tensile strength were estimated from the load–displacement plot. The stress–strain diagrams of all the specimens were further analyzed, in between the yield strength and ultimate tensile strength, following Ramberg–Osgood equation to determine α and n , which represents a dimensionless material constant and strain hardening exponent respectively.

$$\left[(\varepsilon / \varepsilon_0) = (\sigma / \sigma_0) + \alpha (\sigma / \sigma_0)^n \right] \dots\dots\dots (1)$$

where, ε is the observed strain in the material at a given stress of σ at any instant. σ_0 is the reference stress taken as flow stress, $[(\sigma_U + \sigma_Y)/2]$, and, ε_0 is (σ_0/E) .

For fracture toughness testing, the specimens used conforms to ASTM E 1820²⁰⁾ for compact tension (CT) tests shown schematically in Fig. 2, but their thickness (B) is varying from 10 to 25 mm. The tests were carried out on both standard and non-standard samples following ASTM E 1820.²⁰⁾ The nominal specimen width (W) of 62.5 mm for CT was chosen in order to arrive at valid J measurements at large crack extensions. Fracture toughness tests were carried out on servo hydraulic universal testing machine, Instron Model 8800. The fatigue pre-cracking involves dynamic loading through pin clamp in test specimens of different thicknesses to result in crack lengths, a , in the range of a/W between 0.4 and 0.8 with respect to specimen width W . The J_{IC} fracture toughness test was carried out using Fast track J_{IC} program, developed in an environment of LabVIEW programming application from National Instru-

Fig. 1. Schematic diagram of the round tensile specimens. (All dimensions are in mm)

(a)

(b)

Fig. 3. Typical microstructure of base metal in SA 333 Gr. 6 pipes. (a) $\times 100$ and (b) $\times 200$.

ments.

3. Results and Discussion

The chemical composition of low carbon steel, SA333 Gr. 6, is given in Table 3. Typical microstructures of this steel containing ferrite (white) and pearlite (black) in banded morphology are shown in Figs. 3(a) and 3(b) respectively at magnifications of $\times 100$ and $\times 200$.

SA333 Gr. 6 steel under investigation has yield strength of ~ 318 MPa, tensile strength of ~ 446 MPa and percent elongation of 38%. The stress–strain diagram for the base metal has been fitted by Ramberg–Osgood equation and the material parameters α and n are 10.7 and 4.37 respectively.

The equation for offset blunting line with offset distance m , which is used to determine initiation fracture toughness, J_{IC} , may be written as,

$$J = 2M\sigma_f(\Delta a - m) \dots\dots\dots (2)$$

Initiation fracture toughness (J_{SZW}) have been determined by the nonlinear regression of the observed J – R curves to obtain equation of J in term of crack extension (Δa) of the

Fig. 2. Schematic diagram of the compact tension (CT) specimen. (All dimensions are in mm)

Table 3. Chemical analysis of the material.

Chemical composition (Wt. %)				
C	Mn	Si	S	P
0.18	0.90	0.25	0.02	0.02

Fig. 4. Variation of the fracture toughness (J_{IC}) with the pre-crack depth (a/W ratio) in CT specimens of SA333 Gr. 6 steel.

different steels (hot rolled SA333 Gr. 6, annealed SA333 Gr. 6, normalized SA333 Gr. 6 and SAILMA steel) and by putting $\Delta a = (SZW)_t$ measured on the fracture surface of the material. M has been evaluated from Eq. (2) for different offset distances of $m = 0.2$ mm. The equation for M in terms of strain hardening coefficient, n , has been obtained as,

$$M_{0.2} = 1 + 4.53 \times 10^7 (1/n)^{9.59} \dots \dots \dots (3)$$

The initiation fracture toughness, J_{IC} , has been determined by the intersection of offset blunting line given by Eq. (2) using M given by Eq. (3).

The variation of the initiation fracture toughness (J_{IC}) with the pre-crack depth (a/W ratio) for CT specimens of SA333 Gr. 6 steel having thickness of 25 mm, 15 mm and 10 mm are shown in **Figs. 4(a), 4(b) and 4(c)**. The specimen of 25 mm thickness satisfies the plane strain condition of $B = 25J_{IC}/\sigma_y$, both 15 mm and 10 mm thicknesses violate it. These figures show that in a relatively thick specimen with $B = 25$ mm, J_{IC} decreases with increasing a/W ratio over the entire range $0.4 \leq a/W \leq 0.8$ but for thicknesses of $B = 15$ or 10 mm, J_{IC} decreases with increasing a/W ratio till $a/W = 0.6$ but beyond 0.6, there is either no change or a slight increase in J_{IC} . Thus, it appears that under plane strain condition, J_{IC} decreases with a/W ratio both for deep and shallow cracks confirming the observations of Zhang and Wang¹³⁾ and Shen *et al.*¹⁴⁾ But for thinner specimen violating plane strain condition, for shallow cracks J_{IC} decreases with a/W ratio and for deep cracks, J_{IC} is insensitive to a/W ratio, similar to that observed by Li *et al.*⁹⁾ although for different ranges for a/W ratio.

The influence of specimen thickness on the initiation

fracture toughness J_{IC} have been shown in **Figs. 5(a), 5(b) and 5(c)** from the same results of J_{IC} given in Fig. 4, for CT specimens of SA333 Gr. 6 steel. Although it is expected that initiation fracture toughness should decrease with increasing thickness because one is moving towards plane strain conditions but it is observed only in the range of thickness between 15 and 25 mm. But, at relatively lower thicknesses between 10 mm and 15 mm, initiation fracture toughness increases significantly with increasing specimen thickness consistently for different a/W ratio investigated. Possibly this behaviour is dominated by the effect of constraint overcoming the changing state of stress.²¹⁾ The effect of changing B/W may also have a role in determining the state of stress.

Figures 6(a), 6(b) and 6(c) show $J-R$ curves plotted after averaging the coefficients of fitted experimental curves obtained from different CT specimens of as received SA333 Gr. 6 steel having pre-crack depths of around 0.4, 0.6 and 0.8 respectively for thicknesses of 10, 15 and 25 mm. Figure 6(a) shows that at a pre-crack depth of 0.4, $J-R$ curve for 15 mm thick specimen is above that of 25 mm thick specimen possibly due to change in stress state away from plane strain condition. Roos *et al.*²²⁾ have observed that $J-R$ is lower in thicker SENT specimens and the same trend has been confirmed by Mao¹⁶⁾ and Ono *et al.*¹⁷⁾ in CT specimens. But Seok and Kim²³⁾ have not observed any significant effect of thickness on $J-R$ curve of TPB specimens and Jitsukawa *et al.*¹⁰⁾ have confirmed it. In the present study, $J-R$ curve of 10 mm thick specimen is observed to be below that of 25 mm thick specimen and stable crack extension takes place also at a relatively slower rate. But for

Fig. 5. Variation of the fracture toughness (J_{IC}) with the specimen thickness in the CT specimens of SA333 Gr. 6 steel.

Fig. 6. Averaged J - R curve at pre-crack depth of 0.4, 0.6 and 0.8 for different thicknesses of the CT specimens of SA333 Gr. 6 steel.

higher pre-crack depth of $a/W=0.6$ and 0.8 , initially the relative positions of J - R curves appear similar to that observed for $a/W=0.4$ but there is considerable slowing down of crack propagation in 15 and 10 mm thick specimens at higher crack lengths resulting in crossing over of J - R curves as shown in Figs. 6(b) and 6(c) resulting in lowest position for J - R curve of 15 mm thick specimen at higher crack extension. At $a/W=0.8$, there is considerable slowing down of crack in 25 mm thick specimen resulting in J - R curve crossing that of 10 mm specimen at the very beginning. At lower crack extension, J - R curve of 10 mm thick specimen is lowest at $a/W=0.6$ similar to that observed for $a/W=0.4$, but at higher $a/W=0.8$ the J - R curve of 25 mm thick specimen is the lowest till it is crossed by J - R curve for 15 mm specimen. So it appears that when thickness changes from 25 to 15 mm the predominant effect is the change of stress state from plane strain to away from it towards plane stress. But the change in thickness from 15 mm to 10 mm shows a different effect depending on a/W ratio and so, it appears to be constraint effect which is dominating in this thickness range.

4. Conclusions

The present study leads to the following conclusions:

- (1) For thicker specimens conforming to plane strain condition, J_{IC} decreases with a/W ratio both for deep and shallow cracks. However, for thinner specimen violating plane strain condition, for shallow cracks J_{IC} decreases with a/W ratio but for deep cracks, J_{IC} is insensitive to a/W ratio.
- (2) Initiation fracture toughness increases with decreasing thickness if lowering of thickness changes the state of stress away from plane strain condition. But, at relatively lower thicknesses outside plane strain condition, initiation fracture toughness increases significantly with increasing specimen thickness consistently for different a/W ratio investigated.
- (3) When thickness changes from 25 to 15 mm the predominant effect on J - R curve is due to change of stress state from plane strain to away from it, towards plane stress.

But the change in thickness from 15 mm to 10 mm shows a different effect depending on a/W ratio and so, the change of relative position of J - R curve appears to be dominated by constraint effect.

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