Effect of specimen crack depth and thickness on Initiation Fracture Behaviour of Highly Ductile Low Carbon Steels

*Sandeep Bansal, S. K. Nath, P.K. Ghosh and S. Ray,
Department of Metallurgical and Materials Engg.
Indian Institute of Technology Roorkee, Roorkee-247667, India
* Corresponding Author

Abstract

The effect of crack depth (*a*) to specimen width (*W*) ratio, (*a/W*), and specimen thickness (*B*) on the initiation fracture toughness (J_{IC}) and *J-R* curve of low carbon SA333 Gr.6 steel has been investigated by three point bend test in the context of contradictory trends reported in the literature. The fracture toughness tests have been carried out following ASTM – E1820, making provision for correct offset blunting line based on stretched zone width. The results indicate that J_{IC} increases with increasing *a/W* ratio, but the increase is relatively small and becomes still smaller at lower thickness. The variation of the initiation fracture toughness, J_{IC}, with increasing specimen thickness shows that the J_{IC} is more or less insensitive to increasing thickness, particularly at lower *a/W* ratio of 0.4 and 0.6 but at higher *a/W* ratio 0.8, there is slight increase in J_{IC} as the thickness increases from 15 mm to 25 mm.

Key words: Fracture Toughness, *J*-integral, TPB, *a/W* ratio**,** Thickness effect

* Author for correspondence sand_bansal@yahoo.com

Introduction:

The fracture criteria in terms of the fracture initiation toughness, J_{IC} and the fracture resistance or *J-R* curve, have been widely used for characterization of elastic plastic fracture behavior of engineering materials. 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 [1-8]. It has been claimed that the tests are carried out following plane strain condition prescribed by ASTM [9]. 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 decreasing J_{IC} with increasing *a/W* at lower *a/W* ratio. 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 [4, 5] have reported higher *J-R* curve with increasing *a/W* ratio in the ranges of *a/W*< 0.4 and *a/W*>0.75.

Table-II [3, 9-10] 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 Mao [10], the thicknesses of 3 and 0.5 mm in CT specimens of A533B-1 steel where the width has been kept constant, do 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* [11] 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* [11] which contradicts the observation of Mao [10]. Jitsukawa *et al* [3] 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* [11] and Mao [10].

In view of an anomalous trend in the behaviour of J_{IC} and *J-R* curve, 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 initiation fracture toughness in three point bend specimens of SA333 Gr. 6 steel with changing thickness and pre-crack depth have been investigated in the present study. Since the procedure to determine J_{IC} following ASTM procedure of blunt line of $J = 2M\sigma_f \Delta a$ where $M = 1$ and $\sigma_f = \frac{1}{2}(\sigma_Y + \sigma_U)$, leads to absurdity, the values of M has been determined for low strength high ductility steels using stretched zone width measurements.

Experimental Procedure:

SA333 Gr. 6 steel pipes of 16" diameter and wall thickness of 32 mm, was used in the present investigation. The chemical composition and the mechanical properties with Ramberg-Osgood constant, α and strain hardening exponentat, n at room temperature of this material are given in Table III and IV. Typical microstructures of SA333 Gr. 6 steel containing ferrite (white) and pearlite (black) in banded morphology are shown in Fig. 1 (a) and (b) respectively at magnifications of X100 and X200.

For fracture toughness testing, the specimens used conformed to ASTM E 1820 [12] for three point bend (TPB) tests shown schematically in Fig. 2, but their thickness (B) was varying from 10 to 25 mm. The tests were carried out on both standard and non-standard samples following ASTM E 1820 [12]. The nominal specimen width (W) of 50 mm for TPB 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 Instruments.

The stretched zone width (*SZW*) of the fractured specimens was measured at intervals of 200 μm along the thickness under LEO, 435 VP Scanning Electron Microscope (*SEM* by averaging the local measurements over nine positions as specified in 'Nine-points Method' [13]. Typical appearance of the stretched zone width in SA333 Gr. 6 steel material is shown in Fig. 3 (a) and (b).

Results and Discussion

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

$$J = 2M\sigma_f\left(\Delta a - m\right) \qquad (1)$$

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 different steels (hot rolled SA333 Gr. 6, annealed SA333 Gr. 6, normalized SA333 Gr. 6 and SAILMA steel) and by putting Δa = $(SZW)_t$ measured on the fracture surface of the material. *M* has been evaluated from equation (1) for different offset distances of *m* = 0.2 mm. The equation for *M* in terms of strain hardening coefficient, *n*, has been obtained as,

$$M_{0.2} = 1 + 4.53X10^7 (1/n)^{9.59} \qquad (2)$$

The initiation fracture toughness, J_{IC}, has been determined by the intersection of offset blunting line given by equation (1) using *M* given by equation (2).

The variation of the initiation fracture toughness (J_{IC}) with the pre-crack depth (*a/W* ratio) for TPB specimens of SA333 Gr. 6 steel having thickness of 25 mm, 15 mm and 10 mm are shown in Figs. 4, 5 and 6. The fracture toughness of three point bend specimen of SA333 Gr. 6 steel increases with increasing *a/W* ratio but the extent of increase is relatively small and becomes still smaller at lower thickness. The trend of variation of J_{IC} with increasing *a/W* ratio will depend on the method of the determination of J_{IC} from the *J-R* curve. In the literature there are different types of trends reported for this behavior –starting from decreasing J_{IC} with increasing *a/W* to J_{IC} independent of *a/W*.

In the present study with TPB specimens, J_{IC} has been determined on the basis of mean *SZW* and 0.2 mm offset blunting line based on the slope, determined by matching with the observed mean *SZW* as stated earlier. Stretched zone width has a variation along the thickness of the specimen which originates from in-homogeneity of mechanical properties on microscopic scale and the standard error resulting due to this variation may give rise to an uncertainty in the determination of J_{IC}. The observed increase of J_{IC} in TPB specimens with increasing *a/W* ratio consistently for all the three thicknesses appears to be a genuine trend if initiation fracture toughness is measured on the basis of *SZW*. A strong defence for the measurement of J_{IC} on the basis of *SZW* lies in *SZW* being a directly measurable quantity and its variation along the thickness is a real effect originating from the property of the specimen. Thus, a host of contradictory trend in the variation of J_{IC} could be avoided if J_{IC} is measured on the basis of *SZW* which is directly measurable.

The variation of the initiation fracture toughness, J_{IC}, measured on TPB specimens of SA333 Gr. 6 steel, with increasing specimen thickness have been shown in Figs. 7, 8 and 9 respectively. These figures show that the initiation fracture toughness measured by either 0.2 mm offset blunting line or *SZW* method, is more or less insensitive to increasing thickness particularly at lower *a/W* ratio of 0.4 and 0.6 but at higher *a/W* ratio 0.8, there is a slight increase in initiation fracture toughness as the thickness increases from 15 mm to 25 mm.

Conclusion:

The fracture toughness of three point bend specimen of SA333 Gr. 6 steel increases with increasing *a/W* ratio, but the extent of increase is relatively small and becomes still smaller at lower thickness. The variation of the initiation fracture toughness, J_{IC}, measured on TPB specimens of SA333 Gr. 6 steel, with increasing specimen thickness show that the initiation fracture toughness measured by either 0.2 mm offset blunting line or *SZW* method, is more or less insensitive to increasing thickness.

References

1. Tarafder, S. and Ranganath, V.R, Sivaprasad, S. and Johri, P.: Sadhana, 2003, Vol. 28, pp. 167-186.

2. Li, Q., Zhou, L. and Li, S.: Engineering Fracture Mechanics, 1986, Vol. 23, pp. 925-928.

3. Jitsukawa S., Naito A. and Segawa J.: Journal of Nuclear Materials, 1999, Vol. 271&272, pp. 87-91.

4. Joyce J.A. and Link R.E.: Fracture Mechanics: 26th Vol., ASTM STP-1256, American Society of Testing and Materials, Philadelphia, 1995, pp. 142–177.

5. Joyce J.A. and Link R.E.: Engineering Fracture Mechanics, 1997, Vol. 57, pp. 431-446.

6. Zhang, D.Z. and Wang, H.: Engineering Fracture Mechanics, 1987, Vol. 26, pp. 247-250.

7. Shen, G., Xu, S. and Tyson, W.R.: Defence R & D Canada, Contract Report, DREA CR 2001-091, Defence Research Establishment Atlantic, 2001.

8. Zheng, M., Zhou, G., Zacharopoulos, D.A., and Kuna, M.: Theoretical and Applied Fracture Mechanics, 2000, Vol. 36, pp. 141-145.

9. ASTM E 813, Annual Book of ASTM Standards, 1995, Vol. 03.01.

10. Mao, X.: Engineering Fracture Mechanics, 1991, Vol. 38, pp. 241-254.

11. Ono, H., Kasada, R., and Kimura, A.: Journal of Nuclear Materials, 2004, Vol. 329-333, pp. 1117-1121.

12. ASTM E1820-01, American Society for Testing and Materials, 2001, Philadelphia.

13. ***E***SIS P2-92 [1992], "ESIS procedure for determining the fracture behaviour of materials: ESIS P2-92," *European Structural Integrity Society*, Delft, The Netherlands.

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 σ_0=292 MPa σ_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 *et al* [1]
High strength and high toughness alloy steel σ_0=838 MPa σ_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 *et al* [2]
7075-T6 aluminum alloy σ_0=520 Mpa σ_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 *et al* [3]
A533B σ_0=400 MPa σ_u= 555 MPa HY-100 and HY-80 structural steels σ_0=541 MPa σ_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 [4, 5]
Structural steel (C=0.1, Mn = 0.46, Si = 0.3) σ_0=71 MPa σ_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 [6]
CSA grade G40.21 350WT plate materials. σ_0=508 MPa σ_u= 631 MPa El.=44.1%	TPB specimens at -30 ^{0}C	a/W =0.2-0.7	J_{IC} decreases	ASTM Blunting line	Lower J-R curve	Shen *et al* [7]
StE 690 steel σ_0=680 MPa σ_u=770 MPa El.= 24 %	TPB	a/W =0.1-0.5	J_{Ic} decreases	ASTM Blunting line & SZW method	Not reported	Zheng et al [8]

Table-II: Behaviour of Fracture Toughness J_{IC} with decreasing specimen thickness, *B*

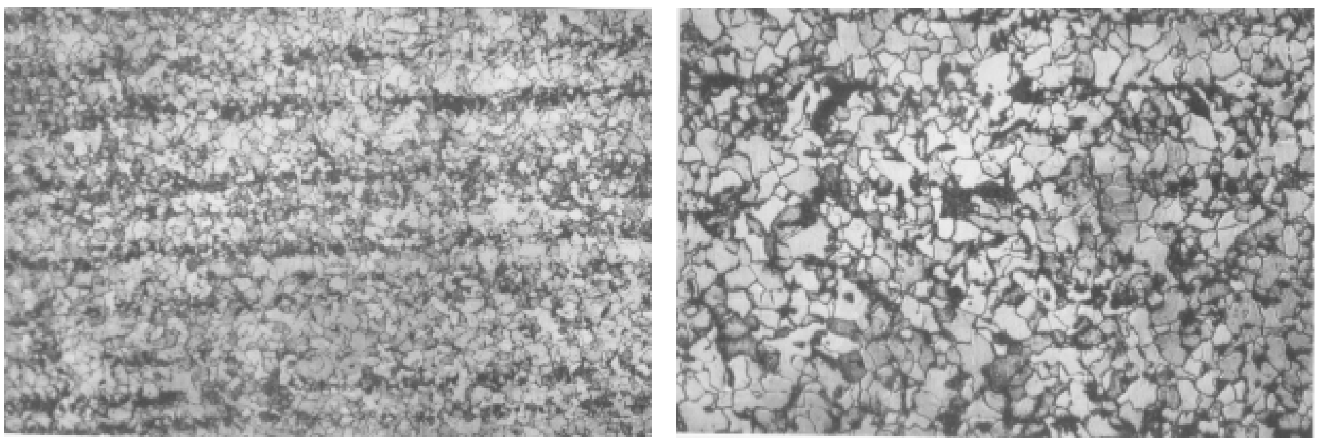
Material and Mech. Properties	**Specimen Type**	**Thickness, *B***	**J_{Ic}**		**Investigator**
			Behaviour with decreasing *B*	**Measurement**	
A533B-1 steel σ_0=495 Mpa σ_u= 620 MPa	CT	*B* = 25, 10, 3, 0.5 mm, corresponding *B/W* ratio of 0.5, 0.5, 0.3, 0.05	J_{IC} decreases but specimen *B/W* changed except for *B*=25, 10 mm	Blunting line without offset	Mao [10]
JLF-1 σ_0=450 Mpa σ_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 *et al* [11]
7075-T aluminum alloy σ_0=520 MPa σ_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 *et al* [3]

Table III The chemical composition of SA333 Gr. 6 steel

Chemical composition (Wt. %)			
C	**Mn**	**Si**	**Al**
0.1680	0.8804	0.1189	0.0489
0.1697	0.8887	0.1208	0.0499

Table IV Mechanical Properties of SA333 Gr. 6

Yield Strength (MPa)	**Tensile Strength (MPa)**	**Elongation (%)**	**n**	**α**
318.47	445.86	38.0	4.37	10.70



(a) (b)

Fig. 1 Typical microstructure of SA333 Gr. 6 pipes. (a) X100 and (b) X200.

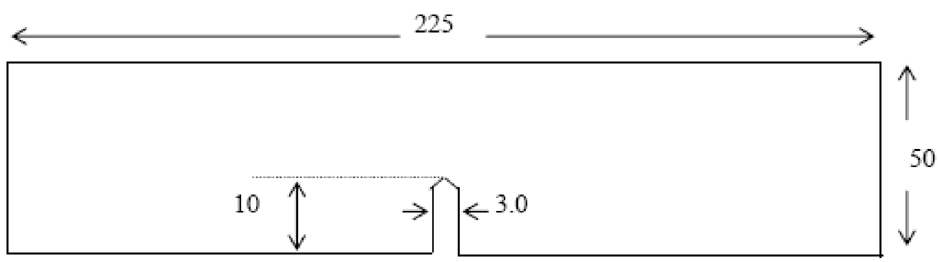


Fig. 2 Schematic diagram of the Three Point Bend (TPB) specimens.

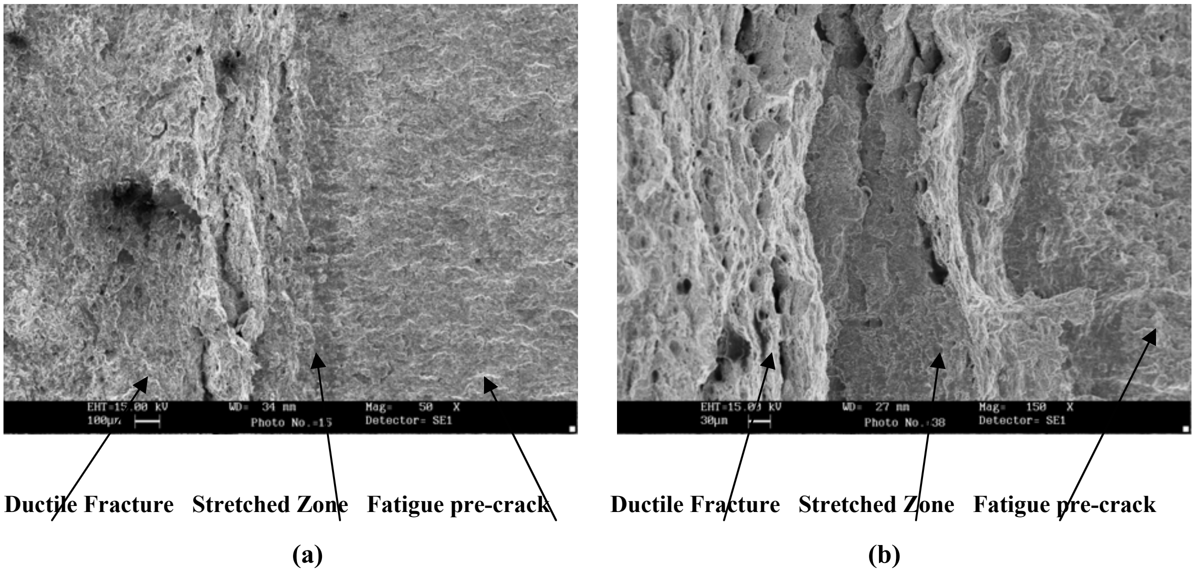


Fig. 3 **Typical appearance of the SZW in SA333 Gr. 6 steel.**

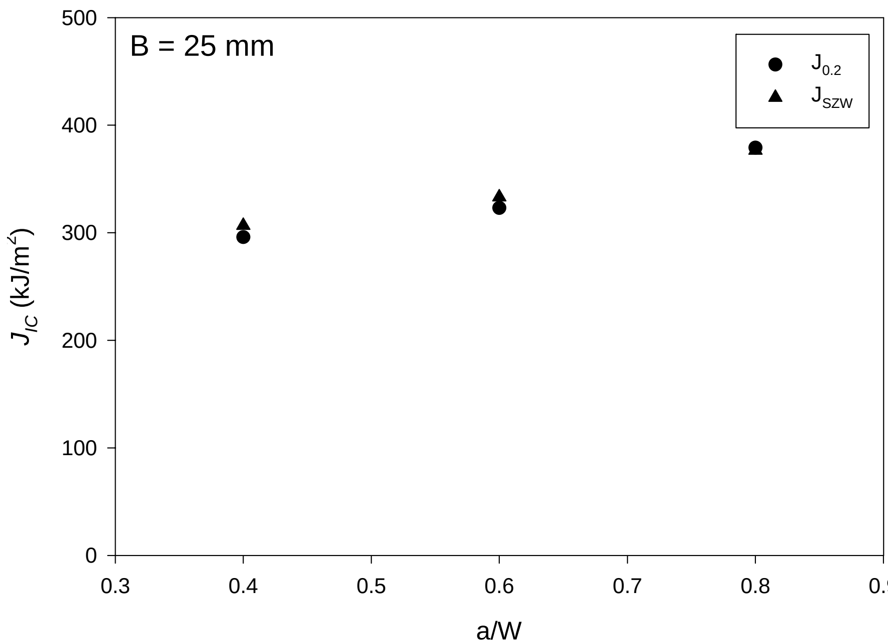


Fig. 4 **The variation of the fracture toughness (J_{IC}) with the pre-crack depth (*a/W* ratio) for 25 mm thickness of the TPB specimens of SA333 Gr. 6 steel.**

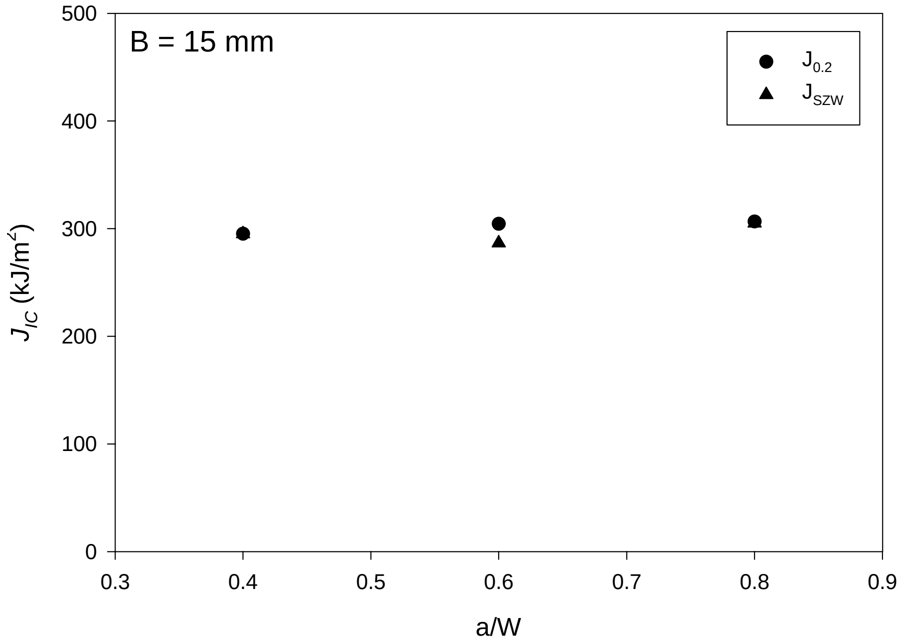


Fig. 5 **The variation of the fracture toughness (J_{IC}) with the pre-crack depth (*a/W* ratio) for 15 mm thickness of the TPB specimens of SA333 Gr. 6 steel.**

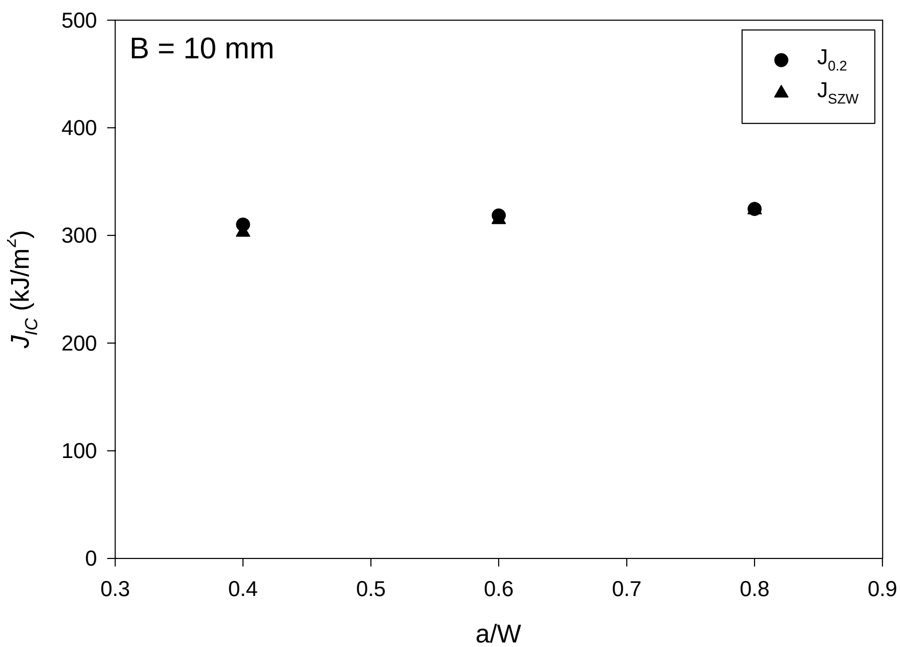


Fig. 6 **The variation of the fracture toughness (J_{IC}) with the pre-crack depth (*a/W* ratio) for 10 mm thickness of the TPB specimens of SA333 Gr. 6 steel.**

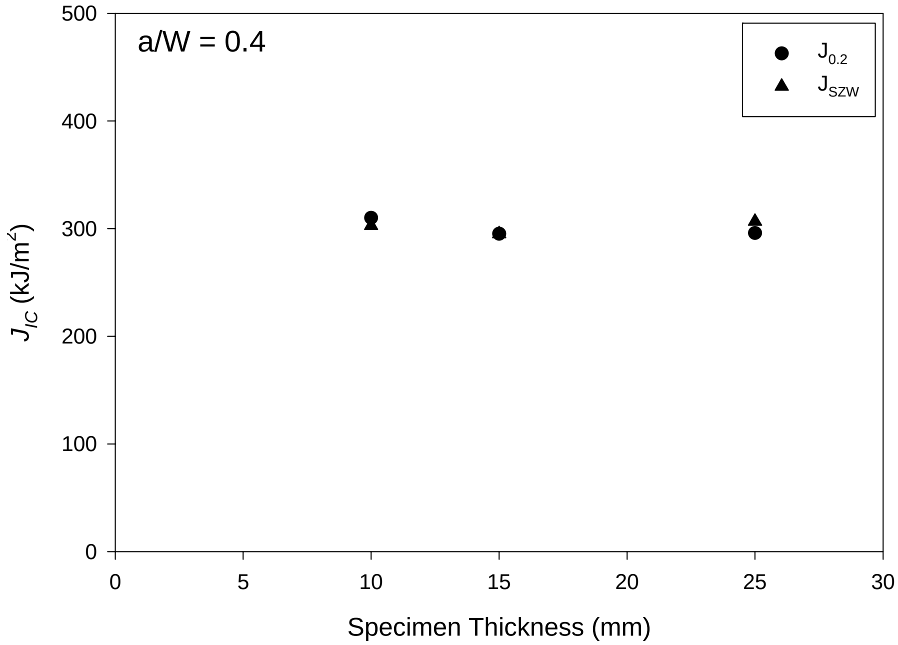


Fig. 7 **The variation of the fracture toughness (J_{IC}) with the specimen thickness at *a/W* ratio of 0.4 in the TPB specimens of SA333 Gr. 6 steel.**

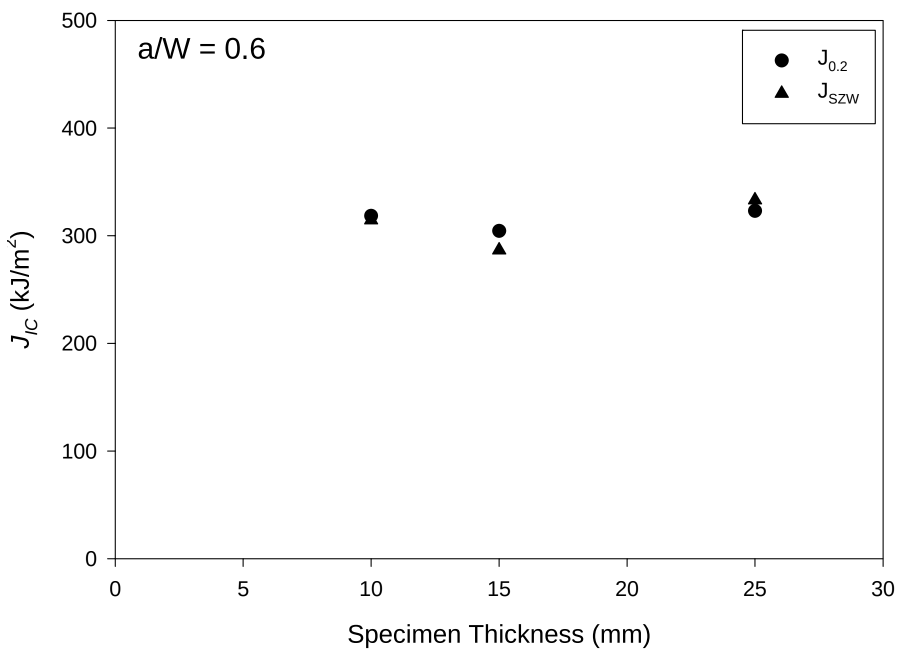


Fig. 8 **The variation of the fracture toughness (J_{IC}) with the specimen thickness at *a/W* ratio of 0.6 in the TPB specimens of SA333 Gr. 6 steel.**

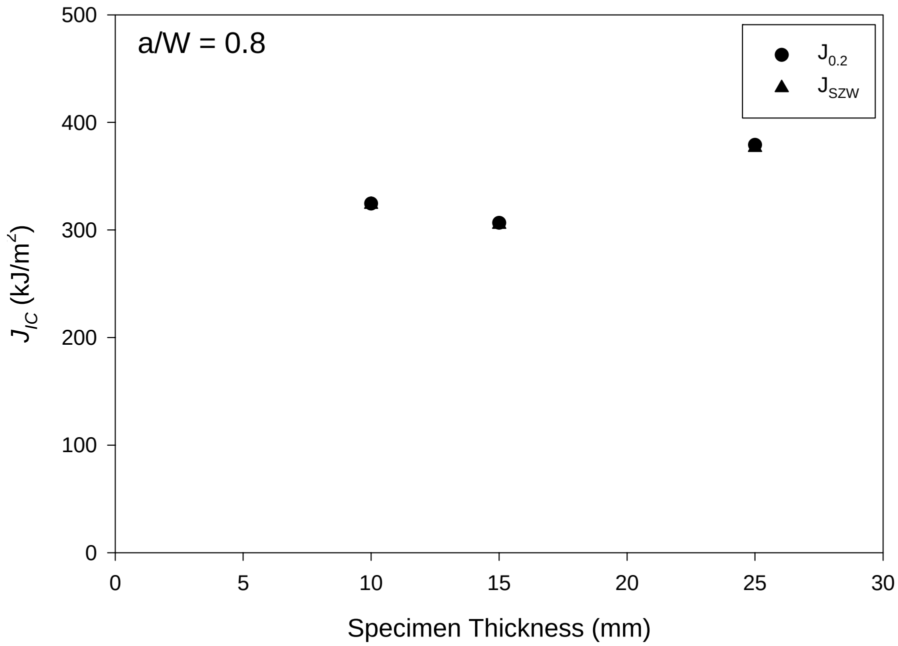


Fig. 9 The variation of the fracture toughness (J_{IC}) with the specimen thickness at *a/W* ratio of 0.8 in the TPB specimens of SA333 Gr. 6 steel.