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DIRECT MEASUREMENT OF J_{IC} FROM THE LOAD VERSUS LOAD-LINE DISPLACEMENT DATA FOR 20MnMoNi55 STEEL

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ABSTRACT

J_{IC} is the value of fracture toughness for crack initiation and useful input for design. The point is determined from detailed experimental and computational procedures. But the most difficult part of it is to identify the exact point in the *J-R* curve. The different standard procedures show huge variation in estimation of this single representative value. Landes and Pehrson suggest a method to measure J_{IC} based on J_C (the value of *J* at instability) which can be measured from experimental *J-R* curve without ambiguity and in this work this method is applied for 20MnMoNi55 steel. The objective of this study is to examine this method for the material 20MnMoNi55 steel at different test temperature. For this purpose the load and displacement data for a fracture toughness test is used to directly estimate the provisional fracture toughness value and compared with standard test results of fracture toughness.

Keywords: Fracture Toughness, Load Line Displacement, Ductile Fracture.

1. INTRODUCTION

Fracture toughness is a key input variable for assessing critical load of structural component in the given environment. The way material deforms determines the form of the analysis. Fracture toughness test can be conducted for different conditions based on the parameters *K*, *J* or *CTOD*. The value measured from the *J*-integral test is J_{IC} (critical value of *J* at crack initiation) which provides a single point measure of fracture toughness [1]. This point is determined from detailed experimental and computational procedure. From the *J*-integral test a crack growth resistance curve is developed. This curve is the basic representation of the fracture toughness for a material which falls by a ductile fracture mechanism that involves a process of slow, stable crack extension [2]. A single point toughness J_{IC} value can be obtained from this resistance (R) curve through a detail construction procedure. Four different methods ($J_{0.2}$, *ASME*, *JSME*, J_{SZW}) are available to estimate J_{IC} from the *J-R* curve. These methods give much inconsistent results and even the value of J_{IC} obtained depends on the accuracy of the method. J_{IC} values are largely varied from one method to other. Landes and Pehrson [3, 4] suggested a method to get J_{IC} in simpler way with minimum number of calculation. The value of J_C (*J* value at the onset of unstable crack growth) can easily be identified on *J–R* curve. From the experimental results it is observed that the J_{IC} obtained from ASME method is related to the J_C with a thickness dependent constant ratio. In this paper the above method is applied on 20MnMoNi55 low carbon steel to find the J_{IC} at different temperatures using one inch thick compact tension (1T-CT) and 1/2-CT specimens. The relations between J_C and J_{IC} measured by both ASME method and J_{SZW} method are estimated and compared.

2. MATERIAL AND EXPERIMENTAL DETAILS

20MnMoNi55 low carbon steel is used in this work for investigation. The chemical composition of the material is given in Table 1.

Table 1: Chemical composition of 20MnMoNi55 steel

Name of Element	%age Composition (wt.)
C	0.20
Si	0.24
Mn	1.38
P	0.011
S	0.005
Al	0.068
Ni	0.52
Mo	0.30
Cr	0.06
Nb	0.032

Tensile tests are performed on round bar specimen according to ASTM E8 standard. Specimen exhibited ductile fracture are considered for analysis at different temperatures in the range between 22^{0}C and –140^{0}C to evaluate the yield strength, ultimate strength and modulus of elasticity of the material. The tests are conducted in the cryo-chamber attached to a computer controlled Universal Testing Machine with 100 kN grip capacity. The required zero and sub-zero test temperatures are attained by flowing liquid nitrogen from fully automated self pressurized Dewar flask of 120 L capacity. All tensile tests are done under displacement control mode to avoid the strain effect.

The fracture toughness tests in this investigation are performed on standard 1T-CT and 1/2-CT specimens. All the CT specimens are machined according to ASTM E399-90 [5] standard and pre-crack is introduced at room temperature according to ASTM E647 standard in the range of a/W = 0.45 – 0.50. All the pre-cracking experiments are carried out on servo-hydraulic universal testing machine using commercial da/dN (Fatigue crack growth rate per cycle) software at stress ratio of 0.02 using initial frequency of 10 Hz and with a constant ΔK (increment stress intensity factor). Now to determine *J*-integral values, the pre-cracked specimens are tested at different temperature range between 22^0C and -140^0C. The J_{IC} fracture toughness program is used for *J*-integral testing to obtain J–Δa data on universal testing machine according to ASTM E1820 [6]. The required zero and sub-zero test temperature are attained by following liquid nitrogen.

3. RESULTS

3.1 Tensile Test Results

From the tensile test results it has been found that with the decrease of test temperature both yield and ultimate tensile strength increase as expected. The relations between yield and ultimate strength with test temperature are derived using best fit curve and the equations are given below.

$$\text{Yield strength, } \sigma_{ys} = 0.0112T^2 - 0.0432T + 494.01 \quad (1)$$

$$\text{Ultimate strength,} \sigma_{us} = 0.0058T^2\, 0.6817T + 644.81 \quad (2)$$

3.2 *J*-integral Test Results

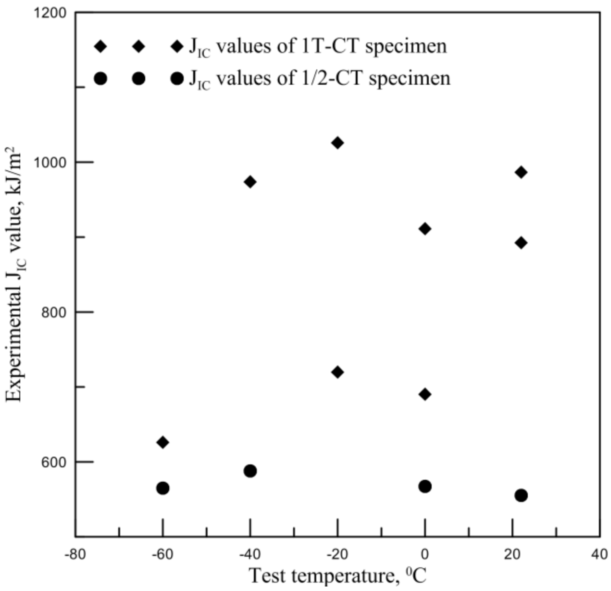

Fig 1. Exp. *J*-integral test results at different temp.

J-integral test is performed according to ASTM E399-90 standard on 1T-CT and 1/2-CT specimens at different temperatures in the range between 22^0C to -140^0C and different a/W ratio. From the experimental results it has been observed that before failure ductile stretch occurs from temperature 22^0C to -60^0C and direct brittle fracture occurs below -60^0C test temperature for this material. All the experimental results using 1T-CT and 1/2-CT at different test temperature for fracture with ductile stretch are shown in Fig 1.

4. STANDARD METHODS

Following two standard methods are used to estimate the J_{IC} as a single point measurement of fracture toughness in this work,

i) ASTM method and
ii) J_{SZW} method

Also the results of these two methods are compared at different temperature.

4.1 ASTM Method

According ASTM E1820 in the *J-R* curve construction the curve is only a series of points. The curve is shown in Fig 2. for 1T-CT specimen at 22^0C, has qualification lines drawn on it. The first is a construction line with a slope of

$$J = 2\sigma_y \Delta a \quad (3)$$

where σ_y is the effective yield strength which is the average of the yield and ultimate strengths, and Δa is the change in crack length.

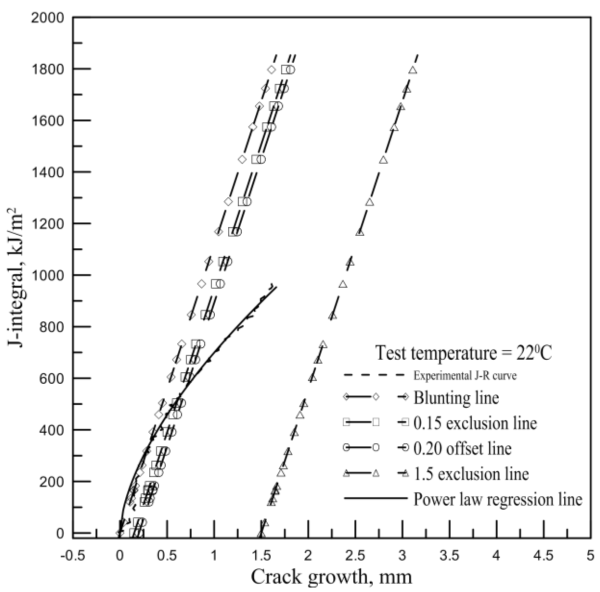

Fig 2. *J-R* curve 22^0C for 1T-CT specimen using ASTM method.

This construction is then offset three times. The first is a minimum exclusion line starting at 0.15 mm crack extension. Only data to the right of this line will be used. The next is the maximum exclusion line which is drawn at 1.5 mm crack extension and only data to the left of this line will be used. These boundaries ensure that the crack growth has not exceeded the measurement limits of the specimen. The third line is the intersection of this line and the *J-R* curve will become J_Q. Since at this stage the *J-R* curve is only a series of points, it will require a regression to get the point of intersection with the offset line. The regression is a power law regression of the form

$$J = C_1(\Delta a)^{C2} \quad (4)$$

where C_1 and C_2 are the constant coefficient and exponent respectively for regressions and not based on measurements. Fig. 2. represent the regression analysis step used in ASTM standard.

From this regression curve and the intersection line the J_Q is calculated for different temperature and specimens. As the above conditions show there are a number of results that could lead to an invalid test result. Some of these may be too restrictive and thus some useful results are needed to eliminate.

4.2 J_{SZW} Method

The stretched zone width (SZW) technique is the most important one recommended in the Japan Society of Mechanical Engineering (JSME) standard. For a very ductile material the value of J_{IC} strongly depends on the choice of the blunting line equation. The SZW can be explained as when the material is subjected to continuously increasing load, the material ahead of crack tip deforms plastically thereby leading to the blunting of the sharp crack. The blunting ahead of the crack tip depends on the ductility of the material. The blunting of the crack tip increases with increasing load or displacement until tearing of the material starts. There is an apparent increase in the crack length due to blunting. This apparent increase in crack length is called stretched zone width. The maximum blunting just prior to initiation of tearing is termed as the critical SZW (SZW_C). The SZW on the fracture surface is measured using the scanning electron microscope (SEM) of 1T-CT specimen tested at 22^0C. The fractured surface is shown in the Fig. 3.

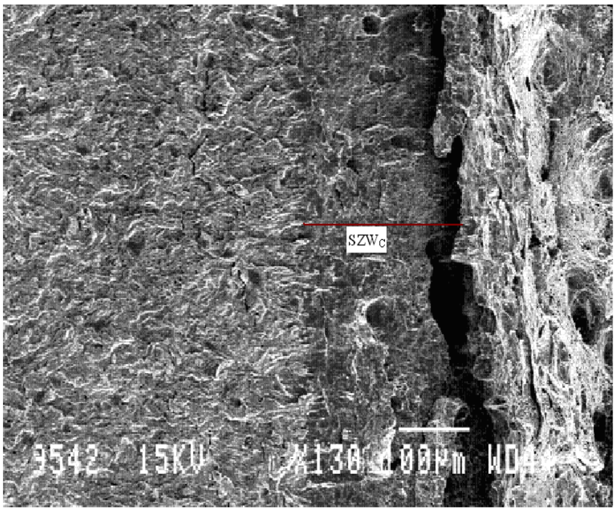

Fig. 3. Fracture surface and Stretch zone for 20MnMoNi55 steel at 22^0C

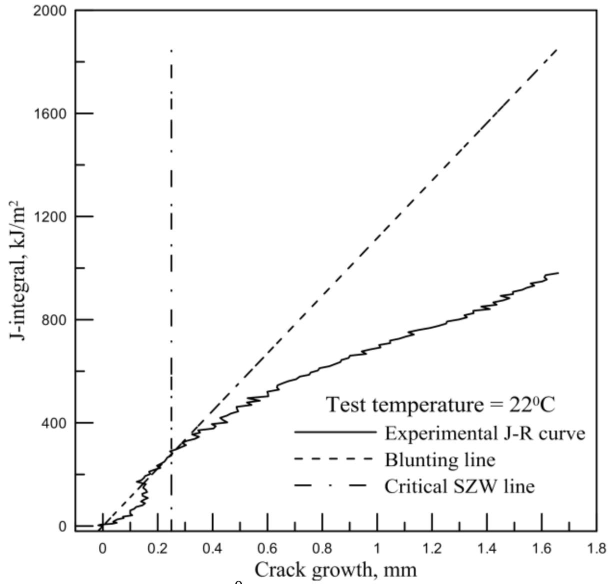

Fig 4. *J-R* curve at 22^0C for 1T-CT specimen using SZW method.

The critical SZW value for the material 20MnMoNi55 steel at 22^0C is 250 micron. This critical SZW value is used to determine the provisional fracture toughness value *(J_Q)* at different temperature. The regression graph at 22^0C according to SZW method is shown in Fig 4.

4.3 Comparison between ASTM and SZW Method

The provisional fracture toughness value at different temperature using 1T-CT specimen measured by ASTM and J_{SZW} method is given in table 2. Also results from these two methods are represented in the table simultaneously.

Table 2: Comparison in J_Q values obtained from ASTM and J_{SZW} method

Test temp., ^{0}C	ASTM Method	J_{SZW} Method	Ratio
22	568	278	2.04
22	520	195	2.74
0	497	261	1.90
0	627	221	2.84
–20	518	262	2.00
–20	508	245	2.07
–60	507	342	1.48

From the table it is observed that the provisional fracture toughness value is depending on the method applied to measure. The value measured from the J_{SZW} method is more conservative than the ASTM method. Hence the results obtained by ASTM method are considered to compare to Landes-Pehrson method.

5. SIMPLIFIED ANALYSIS PROCEDURE

5.1 Landes-Pehrson Method

In ASTM E1820 test method the load displacement data are including a number of unloads that the analysis uses to predict the crack growth. In Landes-Pehrson method unloads are not used. Therefore, a curve of monotonically increasing displacement will produced. At this point energy release is used to find the elastic-plastic toughness:

$$J = (\eta / B\, b_0)*(\int Pdv) \quad (5)$$

where P is load, v is displacement, B is gross thickness, b_0 is uncracked ligament, and η is a coefficient. A direct numerical integration of the above integral equation is shown in the formula,

$$J_{max} = (\eta A_{tot})/(B\, b_0) \quad (6)$$

where A_{tot} is the total area under the load versus displacement curve upto the first occurrence of maximum load. According to Lande-Perhson's suggestion the value of J_{max} will be a good estimation of J_Q only for specimen with W = 50mm. The specimens with other widths required an adjustment factor to get correct estimate of J. The adjustment factor is given by the following equation,

$$J_Q = \sqrt{\frac{50}{W}} J_{max} \quad (7)$$

The load versus displacement curves for 1T-CT specimen at different test temperature for 20MnMoNi55 steel is shown in fig. 5. and the points that are equivalent to the J_Q values and maximum load points are placed on load displacement curves. Similarly for 1/2-CT specimen at different test temperature for same material is shown in fig. 6.

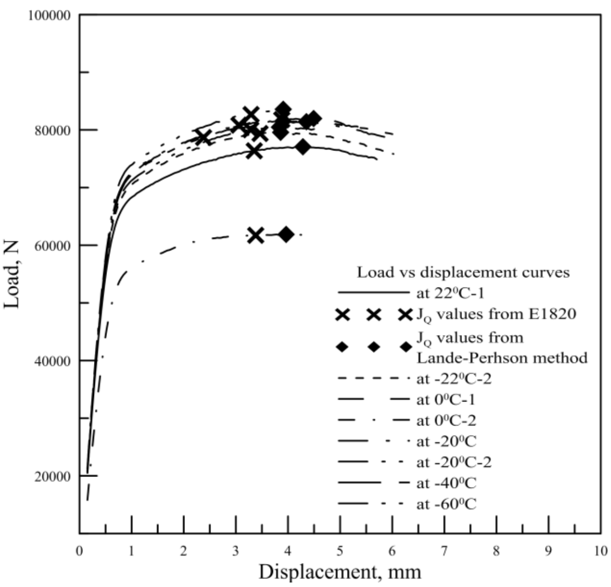

Fig 5. Load vs. displacement curve for 1T-CT specimen at different test temperature.

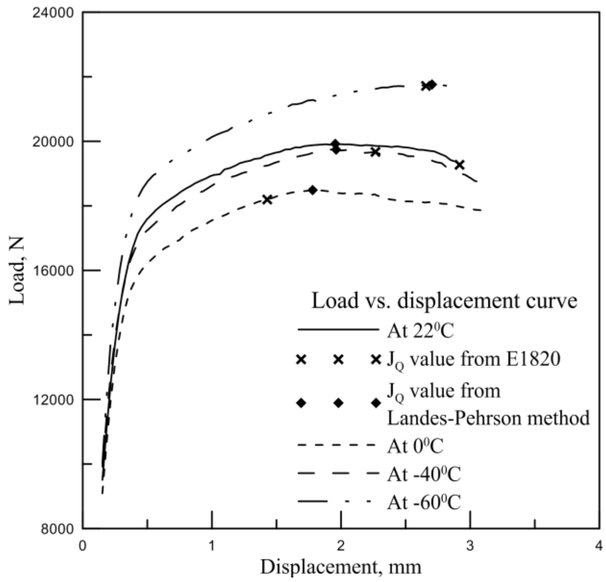

Fig 6. Load vs. displacement curve for 1/2-CT specimen at different test temperature.

5.2 Observations about the J_Q point

Some observations can be made from these plots. The J_Q value fell at approximately the maximum load point on the load versus displacement curve for 1T-CT specimens; therefore this size is taken as unit size. The J_Q for the specimen smaller than the unit size fell after the maximum load point. This is because the smaller specimens have a large plastic component of plastic deformation than the larger specimen. The maximum load point is a convenient point to identify. Since, the specimens other than the unit size have a J_Q value that is not exactly at the maximum load point, therefore an adjustment factor is need to obtain a good estimate of J_Q from the maximum load point. The J_Q value estimated by E1820 and Landes-Pehrson method at different temperature for 1T-CT specimen is listed in table 2 and after size correction the values for 1/2-CT specimen is given in table 3.

Table 2: J_Q values using different method for 1T-CT

Specimen	Temp., ^{0}C	E1820	Landes - Pehrson	Ratio
1T-CT	22	568	634	1.12
1T-CT	22	520	672	1.30
1T-CT	0	497	592	1.20
1T-CT	0	627	731	1.17
1T-CT	-20	518	610	1.18
1T-CT	-20	508	659	1.30
1T-CT	-60	507	610	1.20

Table 3: J_Q values using different method for 1/2-CT

Specimen	Temp., ^{0}C	E1820	Landes - Pehrson	Ratio
1/2-CT	22	555	522	0.94
1/2-CT	0	436	453	1.04
1/2-CT	-40	420	511	1.22
1/2-CT	-60	531	765	1.44

6. CONCLUSION

Lande-Pehrson compared the J_Q values obtained from E1820 method and the value obtained from J values at maximum load. They also provided a size correction scheme for estimating J_Q values at maximum load. In this work the same procedure has been explored for the material 20MnMoNi55 steel. The procedure is tested at low temperature also. From the results it is evident that the ratio of the J_Q values obtained from Lande-Perhson method and E1820 method varies from 1.12 to 1.30 for 1T-CT specimen. For 1/2-CT specimen it is observed that the ratio is increases as the test temperature decreases. For 20MnMoNi55 steel the mean variation in J_Q values obtained by Lande-Perhson method and E1820 method for 1T-CT specimen is 1.21 and for 1/2-CT specimen mean variation in J_Q values is 1.16 after the size correction.

7. REFERENCES

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8. NOMENCLATURE

Symbol	Meaning	Unit
a	Physical half crack size	(mm)
B	Gross thickness	(mm)
b_0	Uncracked ligament	(mm)
J	A path independent integral, J-integral	(KJ/m^2)
J_C	J value at the onset of cleavage fracture	(KJ/m^2)
J_{IC}	Critical J-integral value for mode I loading	(KJ/m^2)
J_Q	Provisional fracture toughness	(KJ/m^2)
P	Load	(N)
W	Specimen width	(mm)
η	Material coefficient	
σ_{ys}	Yield strength	(MPa)
σ_{us}	Ultimate strength	(MPa)

9. MAILING ADDRESS

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