

## Evaluation of the Fracture Parameters for SA - 516 Grade 70 Material

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**Abstract:** Pressure vessels are used in variety of industries like petroleum refining, oil and gas, chemical, power, fertilizers etc. In this paper the rupture phenomenon occurring in the ductile failure has been studied using the Fracture Mechanics approach. The material selected for this study is the low carbon steel (SA-516 Grade 70) widely used for making pressure vessels. Compact Tension (C(T)) specimens of 9.6 mm thickness made of the carbon steel SA-516 Grade 70 are investigated for the fracture toughness. Stress Intensity factor ( $K$ ), Energy release rate ( $G$ ) and  $J$ -Integral are some of the parameters for the fracture study, which are determined in this work for the chosen material. The aim of the work is to study and predict the fracture strengths of the selected material.

**Keywords:** Ductile failure, Fracture toughness,  $J$ -Integral, Energy Release Rate, Stress Intensity Factor

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### Nomenclatures:

#### Latin characters

$a$  = Crack length (mm)  
 $B$  = Thickness of specimen (mm)  
 $E$  = Modulus of elasticity ( $\text{N/mm}^2$ )  
 $G$  = Energy release rate ( $\text{kJ/m}^2$ )  
 $J$  =  $J$ -Integral ( $\text{N/mm}$ )  
 $J_{el}$  = elastic component of  $J$  ( $\text{N/mm}$ )  
 $J_{pl}$  = plastic component of  $J$  ( $\text{N/mm}$ )  
 $K$  = Stress intensity factor ( $\text{MPa}\sqrt{\text{m}}$ )  
 $P$  = Applied load (N)  
 $W$  = Width of specimen (mm)

#### Greek characters

$\Delta$  = displacement (mm)  
 $\sigma_y$  = Yield stress ( $\text{N/mm}^2$ )  
 $\mu$  = Poisson's ratio  
 $\Gamma$  = separation energy

### I. Introduction

A pressure vessel is defined as a container with a pressure differential between inside and outside. Pressure vessels are the basic equipment for any fluid processing system. The liquid and gaseous chemicals are reacted or stored in pressurized chambers (Pressure Vessel) for a chemical reaction or as an aide to the chemical reaction. This pressure may be obtained from an external source or by the application of heat from a direct or indirect source, or any combination thereof. Usually the pressure vessels contain fluids at a very high pressure which may be hundreds of times more than atmospheric pressure. In this conditions pressure vessels may be vulnerable to failures like corrosive, erosive fracture or fatigue failure due to improper pressure and heat distributions. Because a minor flaw in design of a pressure vessel or improper selection of welding method and inaccuracy may cause loss of billions as well as loss of lives. It should be borne in mind that the rupture of a pressure vessel has a potential to cause extensive physical injury and property damage.

The aim of the paper is to study and predict the fracture strengths of the vessel plates. The material selected for this study is carbon steel SA-516 Grade 70, which is the widely used material for the manufacturing of pressure vessels. In the Fracture Mechanics approach, there is an intrinsic assumption that the component is having a crack or a flaw in the body which will grow under loading condition. The Fracture may be viewed as the rupture separation of the structural component into two or more pieces caused by propagation of the crack. Stress Intensity factor ( $K$ ), Energy release rate ( $G$ ) and  $J$ -Integral are some of the essential parameters for the fracture study. [1]

Formation of cracks can be divided into three categories as shown in Fig. 1. Where mode-1 shows opening mode with the displacement is normal to crack surface. Mode-2 is a sliding mode with displacement is in the plane of plate. Here separation is asymmetric and the relative displacement is normal to the crack front. Mode-3 causes sliding motion as well, but displacement is parallel to front crack causing tearing effect.  $K$  and  $G$  for mode 1 will be denoted as  $K_1$  and  $G_1$  respectively. When the load is at peak and the crack begins to propagate, at that time the values of  $K_1$  and  $G_1$  will be denoted as the critical values, i.e.  $K_{1c}$  and  $G_{1c}$ . According to linear elastic fracture mechanics (LEFM), only elastic analysis is done to determine stress and displacement fields close to the crack tip with characterizing parameters like Stress Intensity Factor ( $K$ ) and the energy release rate ( $G$ ). LEFM is applicable only as long as nonlinear material deformation is restrained to a small region surrounding the crack tip. Elastic plastic fracture mechanics applies to the materials that exhibit plastic deformation i.e. non-linear behavior beyond yield point. The crack tip opening displacement (CTOD) and the  $J$  contour integral, both parameters illustrate crack tip conditions in elastic-plastic.

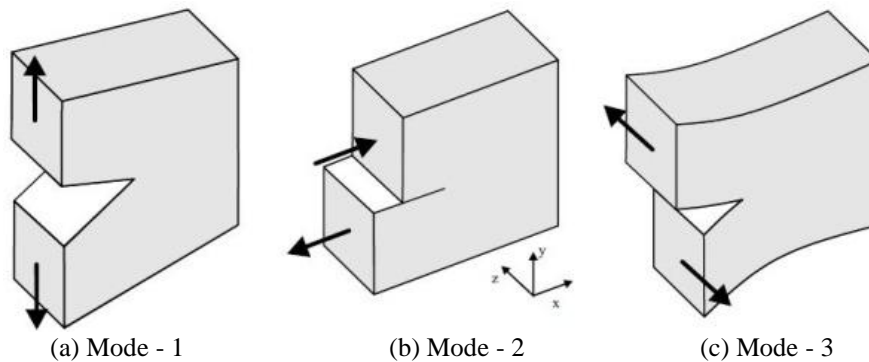


Figure 1: Three modes of fracture

The  $K$  factor was proposed in 1957 by Irwin to explain the intensity of elastic crack-tip fields, and represents the linear elastic fracture mechanics. The  $J$ -integral was anticipated in 1968 by Rice to describe the intensity of elastic-plastic crack-tip fields, and designates the elastic-plastic fracture mechanics. The CTOD concept was anticipated in 1963 by Wells to provide as an engineering fracture parameter, and can be equally used as  $K$  or  $J$  in practical relevance. Various experimental techniques have been developed for measuring these parameters to depict fracture toughness of materials. The comprehensive explanation of these fracture mechanics factors and their applications can be found in the textbooks of fracture mechanics, such as Anderson [2], Kumar [1] and others. Standard terminology relating to fracture toughness testing and assessment has been defined in E1823 by the American Society for Testing and Materials (ASTM). All terminology and perception affecting to fracture tests used in this work are dependable with those defined by ASTM E1823 [3].

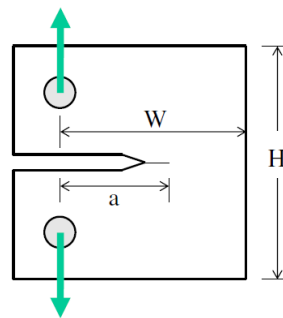
The crack moves quite easily, in the components made of brittle materials. In the brittle failure, the material is influenced to a very shallow depth for the concerned crack growth and the remaining material remains unaffected. On the other hand, in a ductile fracture, there is a great quantity of plastic deformation to a considerable depth. Ductile fracture growth occurs because of large plastic deformation and formation of microvoids in the vicinity of the crack tip. The plastic deformation and coalescences of voids absorbs a big amount of energy and so, a crack doesn't grow easily in ductile materials [1]. For brittle fracture, an annular region of linear elastic deformation surrounds and governs the crack tip and the commencement toughness governs the material fracture resistance with only slender further resistance to crack extension beyond crack initiation. Often the energy necessary to enlarge the crack beyond initiation is little in comparison with the energy accumulated in the test machine, the specimen fails drastically, and no measurement of the fracture resistance beyond initiation is achievable. Therefore the toughness is mostly calculated as a point value and distinguished by the stress intensity factor  $K$  or the energy release rate  $G$  at crack initiation. The earliest fracture toughness test standard ASTM E399 [4] was developed to find out the point value of plane strain fracture toughness at or close to the beginning of crack initiation,  $K_{Ic}$ .

For ductile fracture, the plastic deformation dominates at the crack tip and the material resistance against fracture increases as the crack develops, and as a result the toughness is often described in a resistance curve format by the  $J$ -integral or CTOD. The  $J$ -integral is a nonlinear elastic extent rather than being a true plastic quantity and this needs care in its application to elastic-plastic fracture toughness measurement and application. Extensive experimental and computational effort has been devoted to represent the applicability of the  $J$ -integral as a valuable measure of fracture toughness for applications using elastic-plastic metallic materials. A  $J$ - $R$  (or  $\delta$ - $R$ ) curve is a plot of resistance to steady crack extension, deliberated in terms of  $J$  (or  $\delta$ ), plotted versus ductile crack propagation, generally taken as  $\Delta a_p$ , the measured physical crack extension, while in

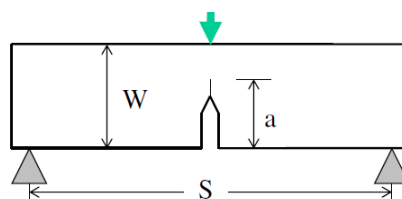
numerous cases only estimates of this crack extension are accessible. ASTM E1820 was developed for determining the elastic-plastic initiation toughness  $J_{Ic}$  and  $J$ -R curves or the consequent  $\delta_{Ic}$  and  $\delta$ -R curves in plane strain situations.

Chand and Garg [5] predicted the crack growth rates by the developed crack propagation law. They compared the investigational data of various materials including aluminum alloys and steels, and attained relationship between them. Mahanty and Maity [6] explained the experimental results on mode I and mixed mode steady crack expansion under static loading condition for aluminum alloy D16AT. They used compact tension type fracture specimens for the experiment. Wang et al. [7] have studied the dependence of the crack growth constraint on the local stress triaxiality and local effective plastic strain close to crack tip of ductile materials. Their experiments and analysis for various steels show that the crack tip opening displacement (CTOD) at initiation and the critical local effective strain reduces with increase in stress triaxiality.

James and Newman Jr. [8] compared the experimental crack-front shapes recorded at different stages of crack growth during fracture tests conducted on 2024-T351 aluminum alloy. In their examination, crack-front profiles were determined by fracturing the specimen to a predetermined amount of crack growth. Chen et al. [9] investigated the interrelation between the cohesive strength,  $T_{max}$ , and the separation energy,  $\Gamma$  and the crack tip triaxiality For 10 mm thick compact tension specimens made of pressure vessel steel 20MnMoNi55. Samer Mahmoud and Kevin Lease [10] performed fracture tests on specimens made of 2024-T351 aluminum alloy with various thicknesses. They described that the crack tip opening angle (CTOA) exhibits an initially high value followed by a transition to a steady value after a small amount of crack propagation, among this transition diminishing appreciably with increasing specimen thickness and the critical CTOA was shown to lessen with increasing specimen thickness. The quasi-static tearing analysis were carried out by J. Q. Wang and J. Shuai [11] to investigate the crack propagation process and fracture mechanism in X70 and X80 pipeline steels. The crack tip opening angle (CTOA) was deliberated by a single specimen method using modified double-cantilever beam (MDCB) specimen. Experimental outcomes illustrated that critical CTOA values increase with increasing specimen thickness, which indicated an opposite trend in contrast with the earlier studies.



**Figure 2(a):** Compact tension (C(T)) type fracture specimen



**Figure 2(b):** single edge-notched bend specimen (SE(B)) in three-point bending.

Fig. 2(a) and Fig. 2(b) are showing the C(T) and SE(B) specimens containing a through-thickness tensile crack, i.e., mode-I crack. In this figure,  $W$  is the specimen width,  $B$  is the specimen thickness,  $H$  is the height of C(T) specimen,  $a$  is the crack length,  $S$  is the span of SE(B) specimen. In most cases,  $W = 2B$ ,  $H = 1.2W$ ,  $S = 4W$  and  $a/W \approx 0.5$ . Compact Tension (C(T)) specimens of 9.6 mm thickness made of the carbon steel SA-516 Grade 70 are investigated for the fracture toughness.

In this work particular attention is paid to the practice of fracture toughness test method developed by ASTM for measuring the fracture mechanics parameters of the stress intensity factor  $K$  (or the energy release rate  $G$ ) and the  $J$ -integral. Six types of conventional fracture test specimens are permitted in ASTM fracture test standards. These include compact tension (C(T)) specimen, single edge-notched bend (SE(B)) specimen in three-point bending, middle-cracked tension (M(T)) panel, disk-shaped compact tension (DC(T)) specimen, arc-shaped tension (A(T)) specimen and arc-shaped bend (A(B)) specimen. Compact tension (C(T)) specimens have been employed for the experimentation in this work.

## II. Experimental Work

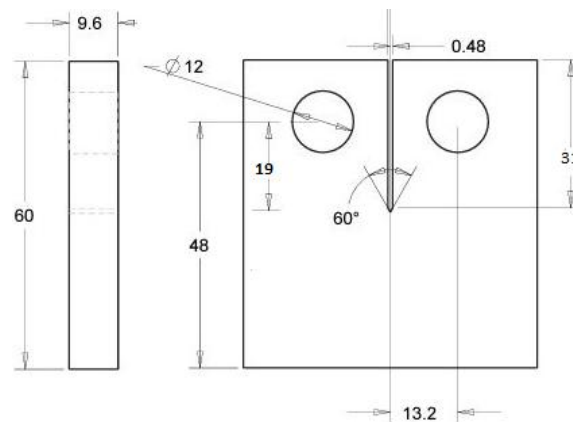
### 2.1 Specimen Preparation

Specimens were made from low carbon steel SA-516 Grade 70 material, which is commonly referred to as pressure vessel steel [12]. It is mostly used for the construction of pressure vessels. The chemical composition of the material is described in Table 1, which data are given by manufacturer. Tensile tests were done to obtain its mechanical properties. For the tensile testing, ‘ASTM E8 - Standard Test Methods for Tension Testing of Metallic Materials’ [13] was followed. Tensile test specimens were prepared with gauge length of 50 mm and reduced section width of 12.5 mm, with 6 mm thickness.

**Table 1:** Chemical composition of SA-516 Grade 70

Alloying elements (in weight per cent)	
Carbon	0.19
Manganese	1.1
Silicon	0.22
Sulfur	0.002
Phosphorous	0.009
Chromium	0.03
Nickel	0.23
Copper	0.02
Aluminum	0.035
Iron	Remaining content

For the fracture testing, the standard ‘ASTM E1820 – Standard Test Method for Measurement of Fracture Toughness’ [14] has been followed. We have chosen C(T) fracture specimen for fracture testing. The most significant feature in C(T) specimen is the ratio of crack length to the width of specimen i.e.  $a/W$  ratio. For the fracture testing, Pin loaded C(T) specimen made of SA-516 Gr. 70 are as shown in Fig. 3 and 4. In this case,  $a/W = 19/48 = 0.4$ .



**Figure 3:** Compact tension (C(T)) specimen dimensions (in mm)



**Figure 4:** Compact Tension (C(T)) specimen made of SA-516 (before testing)

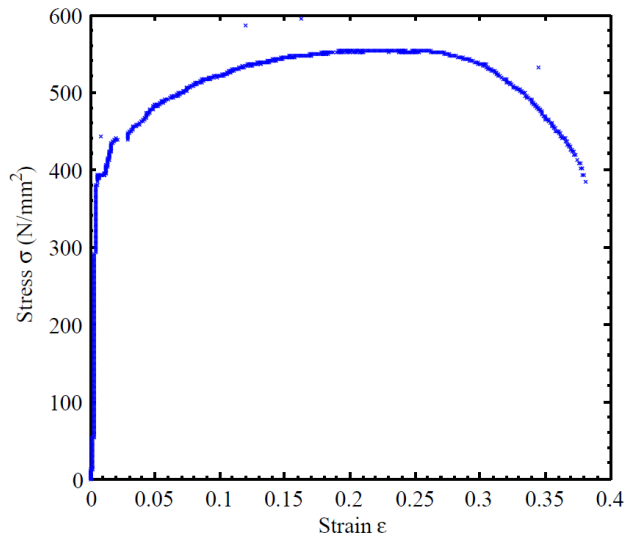
### 2.2 Tensile and Fracture Experiment Test Procedure:

For the Tensile testing of flat type dog-bone shaped specimen and fracture testing of the pin loaded C(T) specimen, the Universal Testing Machine with attached computer has been used. The tests were carried out

at 'Bhumi civil testing and research center', at Ring Road, Surat. The UTM model number is TFUC - 600kN and is made of Techno-fine Instruments Pvt. Limited. The machine is having capacity of 600,000 N load with least count of 10 N load and 0.01 mm of piston movement for accurate measurements.

**Table 2 :** Mean Mechanical Properties of SA-516 Grade 70 (at room temperature)

Modulus of elasticity E (GPa)	$2.1 \times 10^5 \text{ N/mm}^2$
Yield Strength $\sigma_y$ (MPa)	441.36 $\text{N/mm}^2$
Ultimate Strength $\sigma_u$ (MPa)	593.76 $\text{N/mm}^2$
Percentage Elongation	38.44 %
Percentage reduction in area	63.08 %



**Figure 5:** Engineering stress-strain curve.

Table 2 shows the results obtained after the tensile testing of the material. While, Fig. 5 shows the engineering stress-strain curve obtained while tensile testing of SA-516 Gr. 70 material. Total 3 numbers of tensile specimen with identical dimensions were tested. The results and the plot is considered for the average value of ultimate stress values obtained out of all three specimens. The procedure of fracture testing is similar like tensile testing. Total 3 numbers of fracture specimens were tested. The C(T) specimen contains the holes for attaining pin loading mode-1 condition. Pertaining to that, the fixtures made of the same materials were designed which contained the circular pins of 9 mm diameter. The specimen fixed in the fixtures as shown in Fig. 6, were attached to the jaws of UTM as shown in Fig. 7 and the tests were carried out with constant displacement rate.



**Figure 6:** C(T) specimen with pin and fixtures



**Figure 7:** C(T) specimen loaded on UTM for fracture testing

Fig. 8 (a) shows the commencement of crack propagation. This phenomenon occurs after the load value ( $P$ ) reaches to its maximum value. Figure 8 (b) and (c) are showing further crack propagation and the full rupture of the specimen, respectively.



Figure 8(a): crack propagation commenced



Figure 8(b): crack propagation advances



Figure 8(c): crack propagation reaches to full rupture

It is clearly visible that there is substantial amount of plastic deformation is occurred while crack propagation. It is observed that before initiation of crack propagation, plastic deformation is occurring around crack tip vicinity. After achieving considerable amount of plastic deformation, the crack begins to grow. This plastic deformation takes place only in the case of ductile material, which intends to resist the crack propagation.

### III. Results And Discussions

#### 3.1 Load-Displacement measurements:

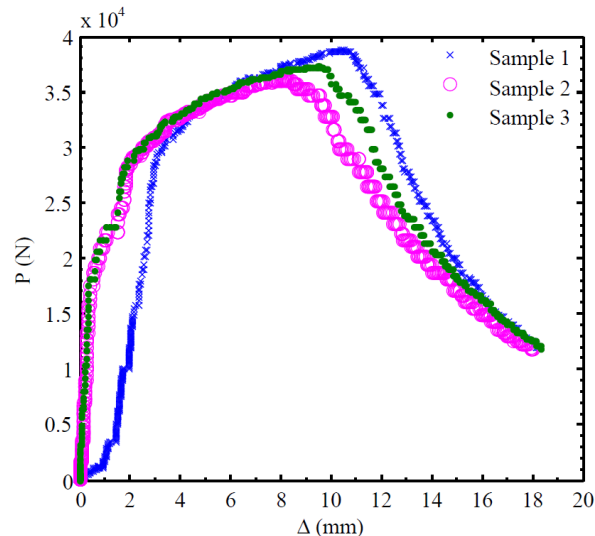


Figure 9:  $P-\Delta$  curves during fracture testing

After carrying out the fracture tests, Load-Displacement curves ( $P-\Delta$  curves) were obtained for all three the specimens, as shown in Fig. 9. The load value  $P$  increases with the load line displacement  $\Delta$  until the crack initiation takes place. As the crack initiates and crack propagation begins, the load value starts falling till the full rupture of specimen. It is visibly detectable that the curves are self similar and they pursue nearly identical pathway for the crack propagation.

#### 3.2 Calculations:

##### 3.2.1 Stress Intensity Factor $K$ :

For the C(T) specimen, the SIF (for the mode-1 loading) can be found by the equation given below:

$$K_{Ic} = \frac{P}{B\sqrt{W}} f(\alpha) \quad (1)$$

where,  $\alpha = a/W$  for  $0 < \alpha < 0.6$  and  $B =$  Plate thickness,

$$f(\alpha) = \frac{(2+\alpha)(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)}{(1-\alpha)^{3/2}} \quad (2)$$

During the fracture testing the peak load value ( $P$ ) obtained for sample- 1, 2 and 3 were 38712 N, 36120 N and 37320 N respectively. Also,  $\alpha = 0.4$ ,  $B = 0.0096$  m and  $W = 0.048$  m.

So, calculated  $K_{Ic}$  value for SA-516 Gr. 70 sample-1 is 133.97 MPa $\sqrt{m}$ . Likewise,  $K_{Ic}$  value for sample- 2 and 3 are, 125.00 MPa $\sqrt{m}$  and 129.15 MPa $\sqrt{m}$  respectively. Thus, one can predict the average  $K_{Ic}$  value for SA-516 Gr. 70 is 129.37 MPa $\sqrt{m}$ .

### 3.2.2 Energy Release Rate G:

The critical energy release rate required to initiate crack propagation and create new surface, can be found by the following equation:

$$G_{Ic} = K_{Ic}^2 / E^* \quad (3)$$

Where,  $E^* = E$  (young's modulus) for plain stress condition and  $E^* = E/(1 - \mu^2)$  for plain strain condition. Here,  $E = 2.1 \times 10^5$  N/mm<sup>2</sup> and  $\mu = 0.3$

So, calculated  $G_{Ic}$  value for sample-1 is 77.77 kJ/m<sup>2</sup> or 77.77 N/mm considering plain strain condition. Likewise,  $G_{Ic}$  value for sample-2 and 3 are 67.71 kJ/m<sup>2</sup> and 72.28 kJ/m<sup>2</sup> respectively. Thus, one can predict the average  $G_{Ic}$  value for SA-516 Gr. 70 is 72.59 kJ/m<sup>2</sup>.

### 3.2.3 J-Integral:

$J$ -integral is also a parameter to characterize a crack. In fact  $G$  is a special case of  $J$ -integral; that is  $G$  is usually applied only to linearly elastic material whereas  $J$ -Integral is not only applicable to linear and nonlinear elastic materials but is found very useful to characterize materials exhibiting elastic-plastic behavior near the crack tip.

$$J = J_{el} + J_{pl} \quad (4)$$

where,

$J_{el}$  = elastic component of  $J$ , and

$J_{pl}$  = plastic component of  $J$

The elastic component of  $J$  is same as the elastic energy release rate  $G_{Ic}$  (i.e.  $J_{el} = G_{Ic}$ ) and the simplified equation of  $J_{pl}$  for engineering application is:

$$J_{pl} = \alpha \sigma_0 \epsilon_0 b g_1 h_1 \left( \frac{P}{P_0} \right)^{n+1} \quad (5)$$

where,  $\alpha = a/W$ ,  $\sigma_0$  is chosen to be same as  $\sigma_y$ ,  $\epsilon_0$  is strain at yield point,  $P$  is the applied load per unit thickness of plate at yield point,  $P_0$  is the limit or collapsed load of the plate based on  $\sigma_y$ ,  $b$  is the un-cracked ligament length,  $g_1$  and  $h_1$  are geometric factors which depend on  $a/W$  and  $n$  (strain hardening exponent).

For the C(T) specimen,

$$g_1 = 1,$$

$$P_0 = 1.455\beta b \sigma_y \quad (\text{for plain strain}),$$

$$\beta = [(2a/b)^2 + 4 a/b + 2]^{1/2} - 2 a/b - 1, \quad (6)$$

$$h_1 = 2.15 \text{ for } a/W = 0.4, n = 1 \text{ and for plain strain condition. (Kumar, 2011)}$$

Also,  $\alpha = 0.4$ ,  $b = 0.048$  m,  $\sigma_0 = 441.36$  N/mm<sup>2</sup> and  $\epsilon_0 = 0.0082$ .

Calculated  $J$ -integral value for sample-1 is 216.26 N/mm. Likewise, for sample-2 and 3 are 206.20 N/mm and 210.77 N/mm respectively. Thus, one can predict the average  $J$  - integral value for SA-516 Gr. 70 is 211.08 N/mm.

## IV. Conclusions

Fracture tests for 9.6 mm thick compact tension specimens made of SA 516 Gr. 70 material were carried out. The essential conclusions established during the study are mentioned below:

- i. According to the LEFM approach, Stress Intensity factor ( $K_{Ic}$ ) is one of the crack characterizing parameter. The stress will be infinity at the tip of the crack (i.e. when crack tip radius  $r = 0$ ). In this work, the  $K_{Ic}$  value found for SA-516 Gr. 70 material is 129.37 MPa $\sqrt{m}$ .
- ii. As the material tested here is a ductile and tough material, just  $K_{Ic}$  is not the sole parameter enough to denote the fracture toughness of the same material. Energy release rate  $G$  is also an important parameter.

The critical energy release rate ( $G_{Ic}$ ) for the crack propagation, calculated for SA-516 Gr. 70 material is 72.59 kJ/m<sup>2</sup>.

- iii.  $J$ -integral is an essential parameter to characterize a crack for elastic-plastic material.  $J$ -integral is not only applicable to linear and nonlinear elastic materials but is found very useful to characterize materials exhibiting elastic-plastic behavior near the crack tip. The  $J$ -integral found for SA-516 Gr. 70 material is 211.08 N/mm.

These experimentally obtained fracture parameters are denoting the material's fracture properties. By knowing these values, one can predict the maximum load the object or part made of this material can withstand with existing crack. These values of  $K_{Ic}$ ,  $G_{Ic}$  and  $J$ -integral can be useful for the Finite Element analysis of the objects made of SA-516 Gr. 70 materials and predict the sustainable load as well as the crack propagation.

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