DETERMINATION OF FRACTURE TOUGHNESS OF METALLIC MATERIALS USING ROUND BAR SPECIMEN

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Abstract

Fracture toughness (K_{IC}) is the one of the most important parameters for evaluating the fracture resistance of the machine elements or structural parts subjected to cyclic loading. These cyclic stresses can cause damage or premature failure. For these reasons, prior knowledge of the fracture toughness is critical. Some institutions have proposed the standards for determination of fracture toughness values. But these procedures of the standards are difficult to manufacture the specimens and cost a high price in terms of instrumentation. The objective of this work is determining fracture toughness with alternative methods which uses round bar specimens with and without fatigue precracking. In this way, fracture toughness can be evaluated rapid and inexpensive test methods. Two different approaches are investigated for S355 and Domex 700MC in experimentally. The values can be comparable with the values reported in the literature which are obtained by standard test specimens.

Keywords: Fracture toughness, notched round bar, circumferentially cracked round bar

1. INTRODUCTION

In recent years, using of high strength steels has grown in railway industry. Increasing axle load capacity and reduction of fuel consumption is possible with remove unnecessary material. Most common procedure for lowering the weight of vehicle is replacing low strength materials by high strength steel [1]. It is important to know prior knowledge of fracture toughness value when new material is introduced. Fracture toughness is one of the most important mechanical properties for fracture mechanics. The determination of fracture toughness is based on the stress intensity factor (K_{IC}) at the crack tip. Subscript “I” symbolize the fracture toughness test is performed in tensile mode and “C” symbolize the critical value of stress intensity factor. When K reaches critical value, the crack propagation becomes unstable and result failure of components [2].

Generally, K_{IC} is determined by different methods such as using compact - tension specimen or single edge notched bend or three-point loaded bend specimens. Material testing institutions have proposed some fracture toughness measurement techniques. For example, a standard test method for linear elastic plane-strain fracture toughness (K_{IC}) of metallic materials is given by American Society for Testing and Materials (ASTM) designation E399-12e3 [3]. This standard is discussed to be one of the accurate ways to specify K_{IC} of low ductility, high strength materials [4]. However, these methods are inconvenient and the specimen preparation is complex and time consuming. One of the disadvantages is fatigue pre-cracking. If the precrack is not proper, results of the test do not reflect the reality. Alternative testing methods have always been seeking researchers. In the literature, there are two different approaches to determining fracture toughness of metallic materials. The first one uses a notched round bar that is allowed to rotate under fatigue load in an R.R. Moore fatigue testing machine, then a precracked specimen is loaded in a tensile machine and pulled till failure. After that, crack lengths are measured with optical measuring devices and fracture toughness calculated using the proposed equations [5-7]. The second approach uses a notched round bar that is directly loaded in a universal tension testing machine, and fracture toughness is calculated using suitable equations [8]. In this study, Domex 700MC which has started to use in railway application was chosen to determine fracture toughness with using round bar specimen method. The steel grade of S355 was tested as comparative steel commonly used in also railway applications.

2. EXPERIMENTAL PROCEDURE

S355 steels are structural steels that are used extensively in general engineering applications. They are particularly useful because they offer a unique combination of good welding properties with guaranteed strengths. Domex 700MC, a thermo-mechanically hot rolled cold forming steel, characterized bya low carbon content and small additions of microalloying elements, was also tested in this study. The chemical composition of the steels used for the tests is shown in **Table 1**. No heat treatment was applied for both kind of steels.

Table 1 Chemical composition of tested steels [wt. %]

	C	Mn	Si	P	S	V	Al	Ti	B
DOMEX 700MC	0.13	1.23	0.21	0.02	0.024	0.05	0.026	0.01	0.0005
S355	0.06	1.82	0.27	0.012	0.003	-	-	-	-

The round bar specimens were machined. Smooth surface quality was obtained on the specimen and as well as at the notch. The dimensions of the specimens were: for S355 steel, gauge length 220 mm (L_0), diameter of notched section 10 mm (d), diameter of unnotched section 12 mm (D) and for Domex 700MC steel gauge length 220 mm (L_0), diameter of notched section 7 mm (d), diameter of unnotched section 9 mm (D), V-notch angle is (α) 60° for both steel as shown in **Figure 1**.

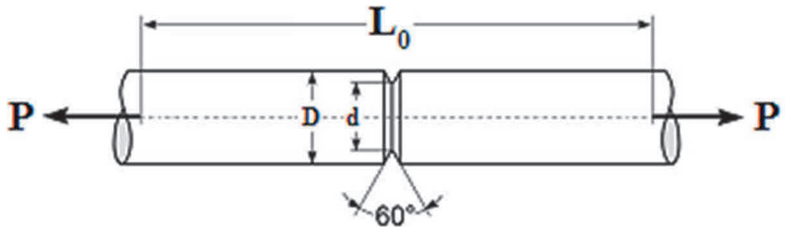

Figure 1 Dimensions of round bar specimen

For the pre-cracking procedure, the samples were subjected to cyclic tensile - compressive loads of equal amplitude were applied with the stress ratio R equal to minus one (R = -1). Pre-cracking was done at a suitable bending load (M) using a four-point R.R. Moore rotating beam fatigue testing machine. The limit load selected was such that the maximum stress intensity factor (K_{max}) should not exceed 60 % of the minimum expected fracture toughness K_{IC} of the test material. For calculation of the fracture toughness value, crack lengths of the fractured surface were measured. The effective diameter (d_{eff}) was calculated by the sum of the machined notch depth (a_m) and the length of the fatigue pre-crack (a_f) as in Equation1

$$d_{eff} = D - 2(a_m - a_f) \quad (1)$$

Equation1 is used for calculation of the fracture toughness in equation (2) where P_f is the fracture load,

$$K_{IC} = \frac{P_f}{D^{3/2}}\left[1.72\frac{D}{d_{eff}} - 1.27\right] \quad (2)$$

The second approach uses a notched round bar without fatigue test that is directly loaded in a tensile test machine. The term of notched tensile strength (σ_{NTS}) for calculation of fracture toughness is calculated by equation (3) where P_f is the fracture load. Notched tensile strength (σ_{NTS}) is calculated according to equation (3) and fracture toughness is calculated using equation (4),

$$\sigma_{NTS} = \frac{4P_f}{\pi d^2} \quad (3)$$

$$K_{IC} = 0.454\sigma_{NTS}D^{0.5} \quad (4)$$

Some researchers [2] suggest using equation (5), which is same as equation (2), but in this formula the notched section diameter is used instead of (d_{eff}) for calculation of the fracture toughness.

$$K_{IC}=\frac{P_f}{D^{3/2}}\left[1.72\frac{D}{d}-1.27\right] \tag{5}$$

During the experiments, for mode-I loading condition, the round bar specimen was loaded in tension on 800 kN electro-hydraulic test stand was used. Crosshead displacement rate is 0.5 mm / min until failure. The displacement was measured using extensometer. Minimum of three specimens of the material were tested for fracture toughness at room temperature. The maximum loads for all specimens were recorded and dimensions were measured. Test stand and a round bar specimen mounted in the fixture are shown in **Figure 2**.

Figure 2 Electro-hydraulic test stand and mounted bar specimen

3. RESULTS

After the tensile experiment fracture toughness was calculated using fracture load and measured diameter values according to equations (2), (4) and (5). The representative force (kN) vs. displacement (mm) graphs are documented in **Figure 3**.

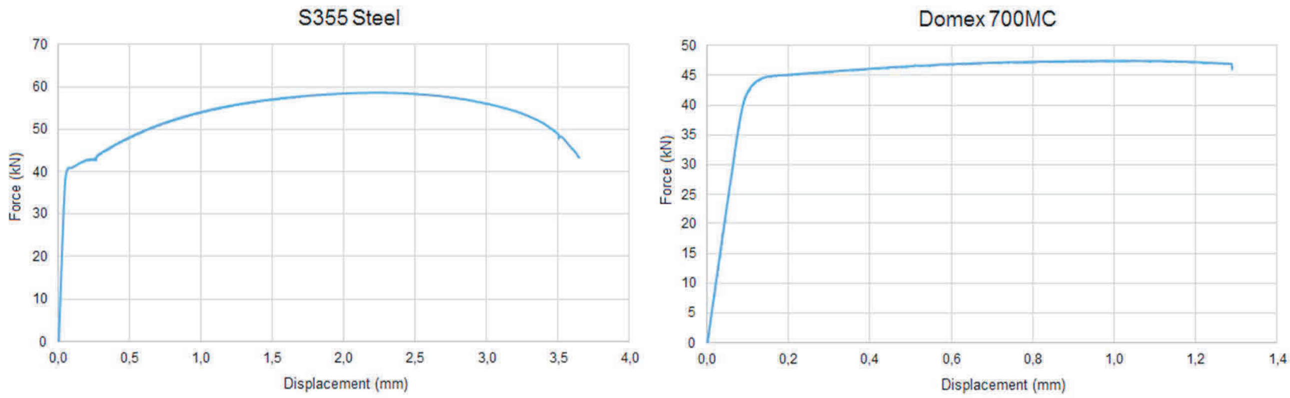

Figure 3 Force - displacement graph for S355 (on the left) and Domex 700MC (on the right)

It can be deducted from **Figure 3**, S355 steel exhibits ductile force - displacement graph. For Domex 700MC steel shows bi-linear characteristics. The mean value of notch tensile strength (σ_{NTS}) for S355 steel is 809.56 MPa, for Domex 700MC is 1319.5 MPa. Domex 700MC notch tensile strength is approximately by 38.56 % higher than in case of S355 steel.

The fracture toughness values calculated using equation (2) for S355 from the data of the tensile test on the circumferentially cracked round bar (CCRB) specimens and also the dimensions of the fractured surface, fracture load, notched and unnotched dimension, are tabulated in **Table 2**.

Table 2 Summary of Fracture Toughness Values and Dimensions for CCRB S355

Sample No	P_f (N)	D (mm)	a_m (mm)	a_f (mm)	d_{eff} (mm)	d_{eff}/D	K_{IC} (MPa.m$^{1/2}$)
S-1	46603	11.9	0.99	0.67	8.58	0.72	40.4
S-2	47644	11.8	0.98	0.5	8.84	0.74	38.13
S-3	51433	11.72	0.99	0.188	9.36	0.79	35.78

The fracture toughness (K_{IC}) of pre-cracked S355 steel varies from 35.78 MPa / m$^{1/2}$ to 40.4 MPa / m$^{1/2}$ according to equation (2). The average fracture toughness experimentally obtained is 38.1 MPa / m$^{1/2}$. In **Figure 4**, fracture surface of pre-cracked sample is shown and fatigue signs can be seen in this figure. According to the second approach, which uses notched bar specimens without fatigue pre-cracking, the calculated fracture toughness is tabulated in **Table 3** and the average value of (K_{IC}) was 39.6 MPa / m$^{1/2}$ for equation (4). Fracture toughness was also calculated using equation (5) and in this approach the average value was 37.94 MPa / m$^{1/2}$.

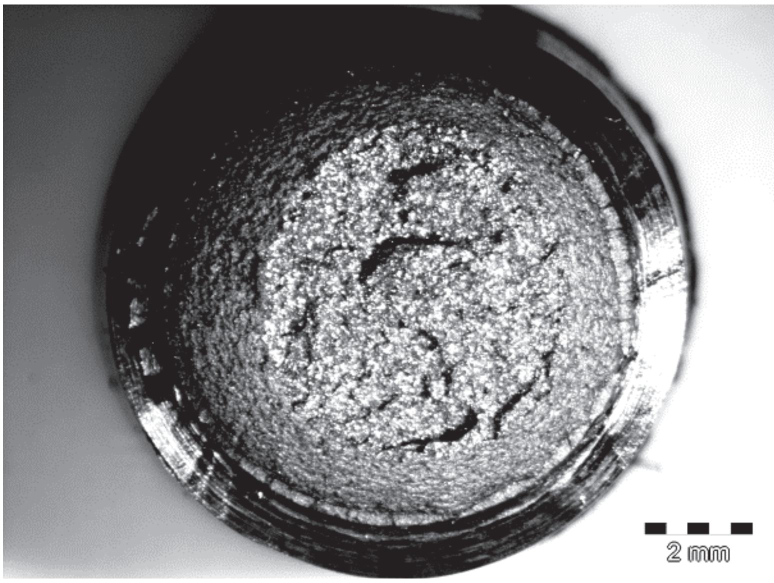

Figure 4 Pre-cracked fracture surface of S355 steel after tensile test

Fracture toughness of Domex 700MC steel is calculated by only using second approach which use without fatigue pre-cracking procedure. The fracture toughness (K_{IC}) of Domex 700MC steel is tabulated in **Table 4**. The mean of fracture toughness (K_{IC}) values of Domex 700MC are 56.3 MPa / m$^{1/2}$ and 55.56 MPa / m$^{1/2}$ according to equation (4) and (5) respectively.

Table 3 Fracture toughness values and dimensions for S355 steel

Sample No	P_f (N)	D (mm)	d (mm)	σ_{NTS} (MPa)	K_{IC} (MPa$\sqrt{m}$) Equation 4	K_{IC} (MPa$\sqrt{m}$) Equation 5
S-1	58190	11.58	9.58	807.3	39.4	37.78
S-2	59880	11.68	9.68	813.7	39.9	38.20
S-3	58710	11.62	9.62	807.7	39.5	37.85

Table 4 Fracture toughness values and dimensions for Domex 700MC steel

Sample No	P_f (N)	D (mm)	d (mm)	σ_{NTS} (MPa)	K_{IC} (MPa$\sqrt{m}$) Equation 4	K_{IC} (MPa$\sqrt{m}$) Equation 5
S-4	47440	8.7	6.7	1345.6	57.0	56.32
S-5	47240	8.82	6.82	1293.2	55.1	54.43
S-6	50500	8.98	6.98	1319.7	56.8	55.95

The fracture surfaces of unprecracked S355 and Domex 700MC samples are shown in **Figure 5** in loading direction and perpendicular to the loading direction (side view of the samples). The surface of S355 steel has moderate amount of necking and it is almost cup and cone fracture characteristics. In central region has an irreguler and fibrous apperance, which signifies plastic deformation. In outer side of the fracture surface can be seen 45° shear lips. This angle represents the direction of maximum shear stress that causes shear lip in final stage. Domex 700MC exhibits untypical fracture surface. In side view of the samples, extremely high and sharp macro grooves are existed. This situation can be explained by hot rolled cold forming process.

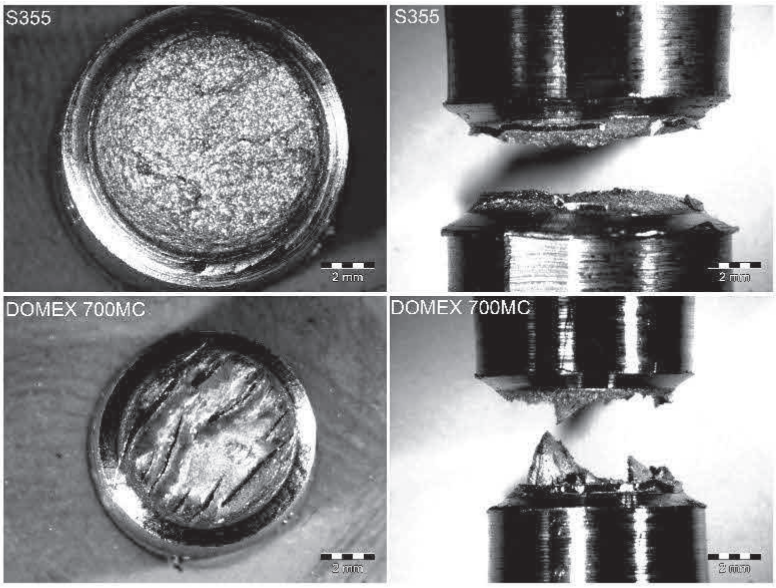

Figure 5 Unprecracked fracture surfaces of S355 and Domex 700MC

Based on the testing of S355 steel, the precracked vs. the unprecracked samples gives acceptable reutls and the difference between two different calculated fracture toughness are very close to each other. For equation (4), because the fracture toughness were calculated by using the fracture loads of the notched specimens, an increase in fracture toughness with the increase in notch tensile strength is evident. In the literature, the fracture toughness of structural steels (including low, medium and high carbon steels) varies from 12 MPa / $m^{1/2}$ to 92 MPa / $m^{1/2}$ [9]. These values are calculated using standard test methods while some of them heat treated steels, which means that higher fracture toughness values can be obtained.

4. CONCLUSIONS

In this research, a method which uses a circumferentially cracked round bar (CCRB) specimen and another approach which uses a circumferentially notched bar specimen without fatigue precracked can be used to determine the fracture toughness values of metallic materials. The difference between two suggested methods is remarkable and it is investigated from fracture mechanics aspect. Two different equations which uses without fatigue precracking procedure were validated. All testing approaches can be used for tested steel types. This method exhibits an accurate, fast and reliable procedure for fracture toughness measurement. In comparison to S355, the fracture toughness value of Domex 700MC is subtantially higher and its application is prospective way to icrease the safety against sudden cracks propagation. The obtained values are found to be in good agreement with the literature but in future experiments standardized test methods should be performed on samples of S355 and Domex 700MC, the methods could be compared and the suggested equations should also be investigated.

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