The Effect of Microstructure on Estimation of the Fracture Toughness (K_{IC}) Rotor Steel Using Charpy Absorbed Energy (CVN)

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ABSTRACT

The proportional relationships between the Charpy absorbed energy (CVN) and the K_{IC} values have been established for a wide variety of steels. Several formulae have been proposed that predict K_{IC} from CVN. The purpose of this study is to investigate, by means of compact testing fracture toughness specimens, the effective role of microstructure for estimation of the fracture toughness (K_{IC}) of rotor steel using Charpy absorbed energy (CVN). To achieve this objective, a number of rotor steel samples were heat treated by step quenching procedure, and the fracture toughness and impact energy were measured. It was found that the calculated fracture toughness values, which were derived using a developed CVN-K_{IC} relationship, disagreed with the experimental results.

1. Introduction

The methods for determining K_{IC} are divided into direct and indirect routes. The direct methods ultimately result in the numerical value of K_{IC}, while the indirect ones are estimating and based on direct methods. The most current and applicable experiment by which K_{IC} can be directly calculated is the outcome of a decade of research which has been presented as ASTM E 399 standard [1]. One of the shortcomings of this method is the inevitability of plane-strain in experiment samples, the cost and the statistical scattering of the values obtained from the test. In methods such as J-integral, Crack Tip Opening Displacement (CTOD) and Begly-Logsson method, the value of K_{IC} is indirectly determined [2, 3]. Another indirect method for estimating the value of K_{IC} is using the information obtained from Charpy V Notch (CVN) impact test. The data obtained from this experiment present a certain behavior of the material which cannot be observed by stretch or hardness experiments.

Since 1970 a great deal of researches and studies have been accomplished in order to estimate the value of K_{IC} from CVN values [4, 20].

In pressure vessels, power plants, nuclear reactors and compressors, determining K_{IC} from CVN values is an economical, rapid and convenient method for evaluating the structural continuity and estimating the life extension of the constructions.

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From among the most important methods presented with respect to determination of KIC from CVN values which have challenged metallurgical issues besides considering fracture mechanics and have resulted in presenting formulae, Barsom-Rolfe, Begley-Logsdon and Sailors-Cortens methods can be mentioned [3, 19].

Table 1 shows the most important equations for determining K_{IC} from CVN values. Although there are numerous methods as well as extracted formulae which can relate K_{IC} to CVN, however, there is no general and unique equation in this regard. Only the formulae called -Roos-Kussmaul (equation 1) may be exceptional [20].

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 1.23\left(\frac{CVN}{\sigma_y} - 0.0061\right) \quad (1)$$

Where $MPa(m)^{1/2}$, MPa and J are fracture toughnss unit, yield stress, and impact energy, respectively. This equation is used for measuring fracture toughness from the values of impact energy in pressure vessels steels.

In the present study the effect of microstructure on fracture behavior in impact and fracture toughness tests, an affect which has been overlooked in all equations presented by other researchers [3, 19-33]. For this prurpose, estimation of K_{IC} based on the data obtained from CVN values was investigated for Ferrite-Bainite-Martensite microstructures with different percentages of Ferrite in rotor steel. The principal aim of this research is the study of microstructure variations on the calculated K_{IC} values and comparing it with measured values.

2. Materials and methodology

In this study a chromium–molybdenum steel plate. Chemical composition of this material is shown in Table 2.

Three different microstructures of Ferrite-Bainite-Martensite were developed in the samples via step quenching procedure. To do this, the samples were first heated up to 850 ºC and austenitised for 1 hour at this temperature, followed by quenching in salt bath at 650 ºC. To produce Ferrite phase the samples were isothermally cooled at this temperature for 4, 8 and 12 minutes. The specimens were again quenched from 650 ºC at 550 ºC (the upper Bainite transformation range) and isothermally kept at this temperature for 4 minutes to generate Bainite phase. Finally, in order to obtain the Martensite phase specimens were quenched in oil. For metallography the samples were etched in 4% nital solution and Ferrite weight fraction in triple-phase microstructures was obtained by using image analysis softwares by the ratio of Ferrite area to total area. Also, in order to facilitate the distinguishing of the phases another solution was used for tint etching. To produce this solution Pikral 4% and Sodium Metabite Sulphite (1.5gr Sodium Metabite Sulphite+100CC distilled water) were separately prepared and the compound of these two solutions was used for etching. For hardness testing, Vickers microhardness test was used. I this method, a 10gr weight was used for hardness testing. For impact test, according to DIN 50125 standard, a pendulum device with the hammer speed 3.3 m/s was used. In fracture toughness testing, standard C(T) samples with Chevron notch was used (Fig. 1). Loading frequency was 20Hz and in sinusoidal wave. Meanwhile, in fatigue crack formation process $\frac{P_{Min}}{P_{Max}}$ was chosen as 0.1.

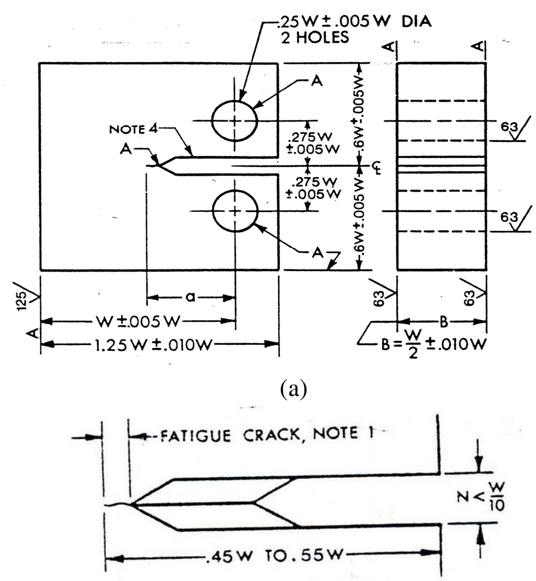
By testing 13mm-thick C(T) specimens K_{IC} values were measured according to ASTM E399 standard. The otaied values were verified by comapison with the standrard.

Table1. Relationships between the Charpy absorbed energy (CVN) and the K_{IC} values

Reference	Range	Formulae	Equation Title
26	3<CVN<82 J	$\frac{K_{IC}^2}{E} = 0.22(CVN)^{3/2}$	Barsom-Rolfe
27	7<CVN<68 J	$K_{IC} = 14.6(CVN)^{1/2}$	Sailors-Cortens
[88]	6<CVN<55 J	$K_{IC} = 18.2(CVN)^{1/2}$	Thorby-Fergusn
[88]	Lower shelf	$K_{IC} = 20(CVN)^{1/2}$	Marandet-Sanz
28	Lower shelf	$K_{IC-LS} = 0.093\sigma_{0.2}(F16)$	Begley-Logsdon
29	Lower shelf	$K_{IC} = \frac{6600}{60} - (T - FATT)$	Jones
30	760<σ_{ys}<1700 MPa	$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 0.64\left(\frac{CVN}{\sigma_y} - 0.01\right)$	Rolfe-Novak
31-32	UHS aircraft steel	$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 1.37\left(\frac{CVN}{\sigma_y}\right) - 0.045$	Ault
33	Pressure vessel steels	$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 1.23\left(\frac{CVN}{\sigma_y} - 0.0061\right)$	Kussmaul - Roos

Table2. Chemical composition of experimental steel (wt.%)

C	Cr	Mo	Mn	Si	P	S
0.35	1.1	0.235	0.52	0.36	0.014	0.006



(a)

(b)

Fig.1. a) Compact specimen C(T) in accordance with ASTM E399 b) Chevron starter notch and fatigue crack [4]

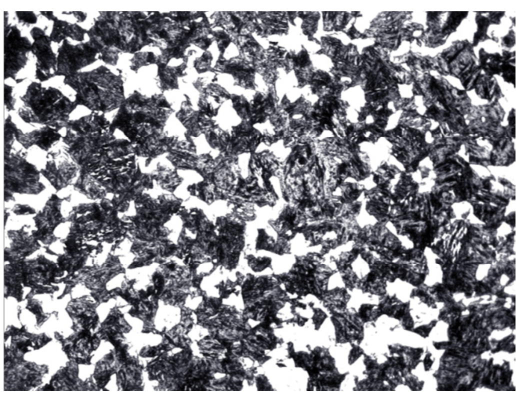
Table3. The heat treatment cycles and microstructures

Microstructure	Heat Treatment Cycle	Index
Martensite-Bainite-Ferrite 24%	$850\,^{o}C, 1hr \rightarrow 650\,^{o}C, 4\min \rightarrow 430\,^{o}C, 4\min \rightarrow w.q$	FBM-1
Martensite-Bainite-Ferrite 33.4%	$850\,^{o}C, 1hr \rightarrow 650\,^{o}C, 8\min \rightarrow 430\,^{o}C, 4\min \rightarrow w.q$	FBM-2
Martensite-Bainite-Ferrite 40.6%	$850\,^{o}C, 1hr \rightarrow 650\,^{o}C, 12\min \rightarrow 430\,^{o}C, 4\min \rightarrow w.q$	FBM-3

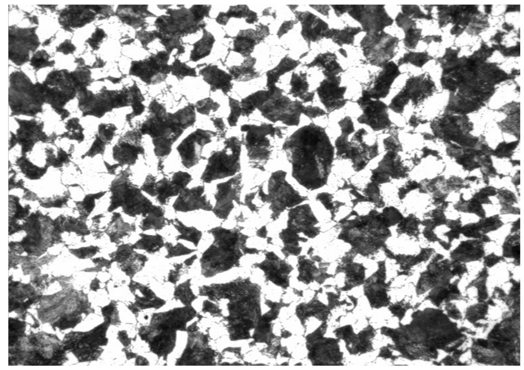
3. Results and Discussion

The microstructure of steel specimens which were heat treated in step quenching manner was triple-phase Ferrite-Bainite-Martensite microstructure. The results of metallographical studies by optical microscopy are given in Table 3.

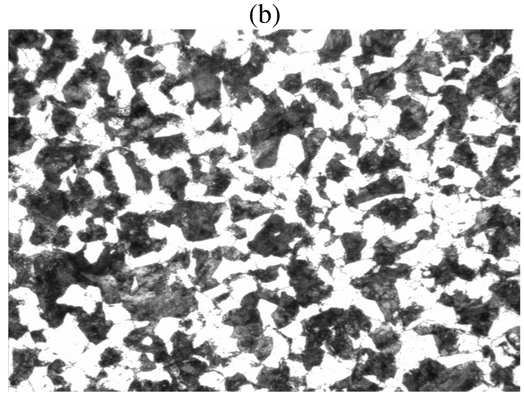
Micrographs of triple-phase microstructure obtained from step quenching are shown in Fig 2. For all specimens the microstructure included Ferrite, Bainite and Martensite phases. In this graph only two phases in white and black are observed. To make sure of the generation of triple-phase microstructure by step quenching procedure, chromic metallography was also performed on steel specimens. In color metallography the three phases of Ferrite, Bainite and Martensite were observed in azure blue, light brown and white, respectively (Fig 3). To identify the color of each single phase, hardness testing was performed.



(a)



(b)



(c)

Fig. 2. Micrograph of Ferrite-Bainite-Martensite microstructure a) FBM-1f_v (α) = %24, b) FBM-2 f_v (α) = %33.4, c) FBM-3 f_v (α) = %40.6

According to table 4, in hardness testing the hardness of ferrite, bainite and martensite phases was determined as 220, 280 and 457 Vickers, respectively. Comparison of the obtained values with the results found by others confirms the results of color metallography regarding accurate distinction of the phases. In the studies by other researchers the values of 200, 300 and 400 Vickers were obtained for hardness of ferrite, bainite and martensite phases, respectively [34-36]. In color metallography the etching solution was prepared by equal ratio of two solutions. In some cases this solution may

Generate only a single color. If all the phases are observed in azure blue color, the addition of a small amount of Pikral solution will solve this problem.

Table 4. Micro-hardness of individual phase in triple phase microstructure

Phase	Ferrite	Bainite	Martensite
Hardness (HV)	220	280	457

If only brown color is observed in triple phase microstructure, it is necessary to increase the amount of metabite sodium sulphate solution. The reason for the appearance of different phases in colors could be due to the chemical composition of steel. The elements in the phases are the only cause for the coloring of the phases by etching solution.

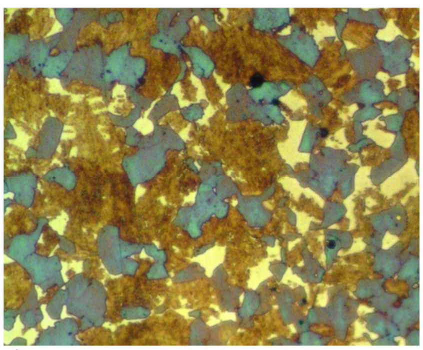


Fig. 3. Optical micrograph of the Ferrite-Bainite-Martensite microstructure after tint etching. Ferrite, bainite and martensite were observed in azure blue, brown and white colors, respectively.

The results from impact test, fracture toughness and the values of fracture toughness obtained from Roos- Kussmaul equation (equation 1) are shown in Table 5. By comparing the calculated and measured values confirms dramatic numerical diiference between measured fracture toughness values and the calculated ones. Comparison of measured fracture toughness and calculated fracture toughness for FBM-1 samples with FBM-2 and FBM-3 samples reveals that variations of measured fracture toughnessfor these samples are small and negligible, whereas variations of calculated fracture toughness values are dramatically high, so that a 100% difference between calculated fracture toughness values for samples FBm-1 and FBM-3. In like manner, using the other formulae in Table 1 would show dramatic differences between measured and calculated fracture toughness values.

Table 5. Impact energy, calculated and measured fracture toughness values.

FBM-3	FBM-2	FBM-1	sample
76±5	39±2	15±1	Absorbed energy(J)
64.14±5	62.55 ±7	56.155±3	Fracture toughness ($MPa\sqrt{m}$)
186	152	91	Calculated fracture toughness) ($MPa\sqrt{m}$

The difference between calculated and measured values has caused the variety of the relations so that no single, specified relation can be presented for calculating fracture toughness. The reported relations are valid under specific conditions. Yield strength, impact energy and shelf temperature are some of the issues which validate offered relations only in the specified range. However, this is not sufficient in its own turn since variations of calculated and measured fracture toughness values in this research reveals the important point that microstructure variations can be one of the effective parameters on validity and accuracy of these relations. It is assumed that although in many cases the value of fracture toughness cannot be estimated by calculating methods, but these relations can be effective and useful in signifying and investigating the manner of fracture toughness variations with respect to impact energy. However, the results obtained from our study do not confirm this matter and the offered relations are probably not useful in investigating the way fracture toughness varies with impact energy. Therefore, it is ultimately concluded that in addition to yield strength, impact energy and shelf temperature as the parameters which affect the estimation of fracture toughness from impact energy it is necessary to specify the role of microstructure in this regard, too. In other words, in applying the relations for estimating fracture toughness of steel it is necessary to pay attention to microstructure as an effective parameter.

4. Conclusions

In the present study the effect of microstructure variations on calculated K_{IC} and comparing it with measured values was investigated. It was concluded that the effect of microstructure on calculated fracture toughness values was more than on measured values. Therefore, it is necessary to consider microstructure as an effective parameter in applying relations for estimating steel fracture toughness. In presenting all the relations related to determining fracture toughness by low-cost and simple methods, fracture mechanics is often used for scrutinizing fracture and relevant issues, but what is important is the way microstructure variations and metallurgical parameters are effective, an issue which demands attempts beyond fracture mechanics.

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