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Fracture behavior of reactor steel 20MnMoNi 55 in the transition temperature region

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Abstract

The fracture represents the final phase of crack propagation, and the causes of their occurrence or partial crack propagation in the real constructions made of ferritic steels can be different. Along with cracks, influences such as stress concentration and low temperature contribute to fracture being “faster” and have an impact on the fracture mechanics parameters, as well as on the fact that fracture is more likely to occur due to cleavage. The parameters discussed in this study are J_c and r_c (parameter, i.e. distance between fatigue crack tip and cleavage initiation site) by testing of C(T)50 specimen in the transition temperature region. Grooved C(T) specimens were made of reactor steel 20MnMoNi 55 with two thickness values, since an additional goal of this study was to present the influence of thickness of tested specimens. Along with it, other parameters that have influence on the understanding of transition temperature region and fracture in this region of ferritic steel are presented.

Keywords: J-integral, transition temperature region, ferritic steel, cleavage fracture, thickness dependance

1. Introduction

Structures such as pressure vessel equipment are mostly made of ferritic steels and used in service in the transition temperature region, when brittle fracture is possible and more likely to occur [1, 2]. During brittle fracture, an unstable

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crack growth can cause material fracture and structure failure. Therefore, from the aspect of structural integrity, there was a need to develop a methodology with the aim of determining the fracture toughness of ferritic material in this sensitive temperature area for them. One of the basic requirements during designing of any engineering construction is to estimate the time in service without any damage which may causes losing structure functionality. The failure of some construction can occur in different ways. However, the most complex and dangerous ways are caused by brittle fracture, especially cleavage one, which is often unpredictable, caused by aforementioned unstable crack growth [3]. Fracture toughness of ferritic steels in transition temperature region, as well as appropriate characterization of it, have been described for many years. Explanations and understanding of this phenomena were searched by applying the disciplines such as fracture mechanics [4-6], with the application of other disciplines, such as numerical methods [7], or most used statistics [8-11], which is mostly used for material behavior prediction, especially prediction of fracture.

In this study, the effects that contribute and have an influence on cleavage fracture toughness of ferritic steel 20MnMoNi 55 are considered and discussed. Along with cracks influences, as a stress concentrator, low temperature contributes to the fracture of the steel in question to be “faster” and have an impact on the fracture mechanics parameters values. This aforementioned were performed by analyzing the obtained parameters of J_c, r_c and z_c, to be more accurate – their scatter, by testing of C(T)50 specimens in the transition temperature region at -60 and -90°C. Grooved C(T) specimens were made of ferritic steel 20MnMoNi 55 with two thickness values, since the additional goal of this study was to investigate the influence of specimen thickness. Some results of previous study by Djordjevic et al. [11, 12] were added in this study which will be presented in further text. Along with previous said, influence of displacement rates during testing are discussed as well. It should be emphasized that this study relies on Heerens work [4, 13].

Nomenclature

J_c	J-integral at the moment of cleavage fracture
r_c	distance between fatigue crack tip and cleavage initiation site
z_c	distance of r_c from medium line of specimen thickness

2. Ductile to brittle Fracture Transition

The structure of the ferritic materials defines the nature of their fracture, as well as load levels and exploitation conditions that the construction is subjected to [14, 15]. Most of the structural materials, such as material with ferritic crystal structure, have affinity toward brittle fracture. The conditions, such as low temperatures or sudden high load, represent the most common reasons for brittle fracture of engineering structure. The same material that has different applications in terms of exploitation conditions can behave either as ductile or brittle, depending on the conditions that is exposed.

Studies over time have confirmed that in the case of ferritic steels, the change in temperature results in the change in mechanical properties, wherein the toughness decreases as well as the fracture mechanics parameters. In general, brittle-to-ductile fracture mechanism change depends on material properties which shows its dependence on general sensitivity to temperature changes, in this case steel 20MnMoNi 55 which is observed by Heerens [4, 16], and other researchers as well [9]. Previously mentioned temperature dependence of fracture mechanism could be illustrated on Fig. 1, which shows how temperature affects the absorbed energy value during Charpy testing. Brittle and ductile regions are clearly distinguished, with transition temperature in the middle, and low energy corresponds to the brittle fracture. But beside temperature, other influences can have influences on the fracture mechanism as well.

Conditions under particularly ferritic steels change their fracture mechanism, from ductile to brittle, depend on [14]:

- shape and dimensions of the structural element in exploitation or in the tested specimen
- load and displacement rate of the workpiece or tested specimen
- work or test temperatures.

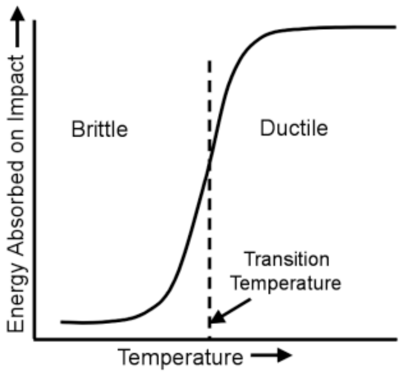


Fig. 1 Temperature dependence of fracture mechanism

As it is well known, plane stress and strain state contribute to plastic or brittle fracture, respectively. Under plane stress state, fracture is ductile, whereas under plane strain conditions, it is brittle. One of the ways of achieving plane strain state in specimens is to increase specimen thickness [17], i.e. fracture of specimen with larger thickness is more likely to be brittle. However, thickness is not the only factor that has an influence on brittle fracture – so does specimen width, hence the statement from previous sentence could be related to size effect of the structure [18, 19].

Change of displacement rate during testing in certain cases can affect the change of material mechanical properties, or the selection of the relevant fracture mechanics parameter. Depending on the displacement rate, metals can be divided into those not sensitive to it (to be more accurate, not noticeably sensitive), and those whose mechanical properties change with this change.

By adding the temperature influence as a plus factor to these previous mentioned conditions, problem becomes more complex and demanding. Choosing of relevant fracture toughness parameters according to fracture behaviour is the first step after experimental testing that will provide initial ground on how to do adequate interpretation of obtained results (table 1). The interpretation of the relevant parameter values in the manner of scatter, which is main the problem in transition region studies of ferritic steels, represents next step and very difficult and demanding task.

Table 1. Fracture toughness parameters according to fracture behaviour.

	Fracture behaviour	
Deformation behaviour	brittle	ductile
Linear-elastic	K_{Ic}	K_{Ic}, *K-R* curve
Elastic-plastic	J_c, $CTOD_c$	J_{Ic}, *J-R* curve, $CTOD_m$

3. Experimental testing

1.1. Steel 20MnMoNi 55

Ferritic steel 20MnMoNi 55 is a material used for low-temperature service, and its chemical composition and yield strength and modulus of elasticity at various temperature are given in tables 2 and 3, respectively. This steel is used for production of pressure vessels equipment and power plant reactors, generally applied in extreme exploitation conditions. Grooved C(T) specimens meant for cleavage tensile testing are cut out of a plate.

Table 2. Chemical composition of 20MnMoNi 55 in mass percent.

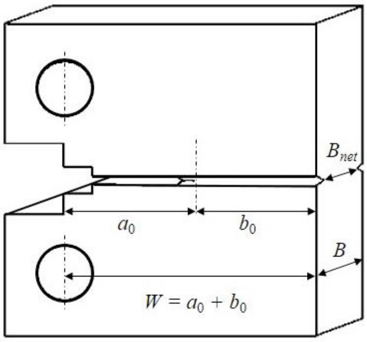
element	C	Si	Mn	Cr	V	Cu	Al	Ni	Mo	Co	As	Sb	Ti
%	0,19	0,2	1,29	0,12	0,02	0,11	0,015	0,8	0,53	0,014	0,030	0,03	0,05

Table 3. Mechanical properties of tested steel at room temperature

T [°C]	$R_{0,2}$ [N/mm^2]
-90°C	550
-85°C	545
-70°C	520
-60°C	500
-55 °C	495

1.2. Plan and method of testing

The testing of C(T)50 specimens made of steel 20MnMoNi 55 were carried out at two temperatures: -60 and -90 ℃. A total of 11 specimens with width B_{net} = 16 mm, and 2 mm side grooves on both sides, were tested on -60℃. These sets of specimens were tested with displacement rates 0.5 and 0.02 mm/min, which is denoted for each specimen. 16 specimens with width B_{net} = 20 mm, and 2.5 mm side grooves on both sides, were tested on the -90℃, while displacement rate during testing was 0.5 mm/min. Side-grooves on C(T) specimens increase the level of constraint and it provides a more uniform stress state along the crack front and inhibits shear lip development [15, 20]. Geometry of the grooved C(T) specimen was presented on Fig. 2. Cooling at a set temperature during testing was performed in a liquid nitrogen chamber, while temperature regulation was achieved by valves regulator. Both tests involved cleavage fracture according to standard ASTM E1820 [21], which includes certain procedure and summary.



B – specimen thickness
B_{net} – net specimen thickness
W – specimen width
a_0 – initial crack length
b_0 – initial ligament of the specimen

Fig. 2 Geometry of the grooved C(T) specimen

1.3. Results of the testing

Tables 4 shows the values of J_c, as well as parameters r_c and z_c for specimens thickness B_{net} =16 mm tested at -60 ℃. Displacement rates during testing were given for each specimen. J_c values are shown in ascending order, which affects r_c values as well. In table 5, the values of J_c parameter as well as parameters r_c and z_c for specimens tested at -90℃ are shown. From the table 5, smaller values of J_c and parameters r_c can be observed in comparison to specimens tested at -60°C.

In order to get a broad picture on other effects, the results from previous testing given in [12] were presented in table 6, i.e. results of C(T)50 specimens testing at -60 °C with larger thickness B_{net} = 20 mm. In the table 6 are shown J_c values only. Displacement rates during testing was 0.5 mm/min.

Table 4. Values of Jc , r_c and z_c of tested C(T)50 specimens at -60°C

J_c N/mm	B_{net} mm	r_c mm	z_c mm	Displ.rate v (mm/min)
178.2	16.0	0.60	4.91	0.500
211.8	16.0	0.62	2.53	0.020
241.2	16.0	0.63	2.63	0.020
286.9	16.0	0.53	2.89	0.020
340.3	16.0	0.75	0.25	0.500
409.0	16.0	1.35	3.28	0.020
424.1	16.0	1.35	0.1	0.020
447.5	16.0	1.11	0	0.500
483.4	16.0	1.17	2.68	0.020
582.3	16.0	1.44	0.51	0.020
660.8	16.0	2.1	/	0.500

Table 5. Values of J_c , r_c of tested C(T)50 specimens at -90°C

J_c N/mm	B_{net} mm	r_c mm	Displ.rate v (mm/min)
49.4	20.0	/	0.500
49.7	20.0	0.15	0.500
50.6	20.0	0.13	0.500
63.8	20.0	0.19	0.500
82.3	20.0	0.71	0.500
84.4	20.0	0.31	0.500
85.2	20.0	0.69	0.500
121.2	20.0	1.00	0.500
121.3	20.0	0.35	0.500
129.2	20.0	0.42	0.500
135.2	20.0	0.36	0.500
153.9	20.0	/	0.500
176	20.0	0.36	0.500
179.2	20.0	0.23	0.500
233.6	20.0	0.47	0.500
270.2	20.0	0.69	0.500

Table 6. Values of J_c of tested C(T)50 specimens (B_{net} = 20 mm) at -60°C

J_c N/mm	B_{net} mm	Displ.rate v (mm/min)
60	20.0	0.500
120	20.0	0.500
124	20.0	0.500
168	20.0	0.500
195	20.0	0.500
215	20.0	0.500
286	20.0	0.500
304	20.0	0.500
340.3	20.0	0.500
434	20.0	0.500
448	20.0	0.500
518	20.0	0.500
560	20.0	0.500
630	20.0	0.500

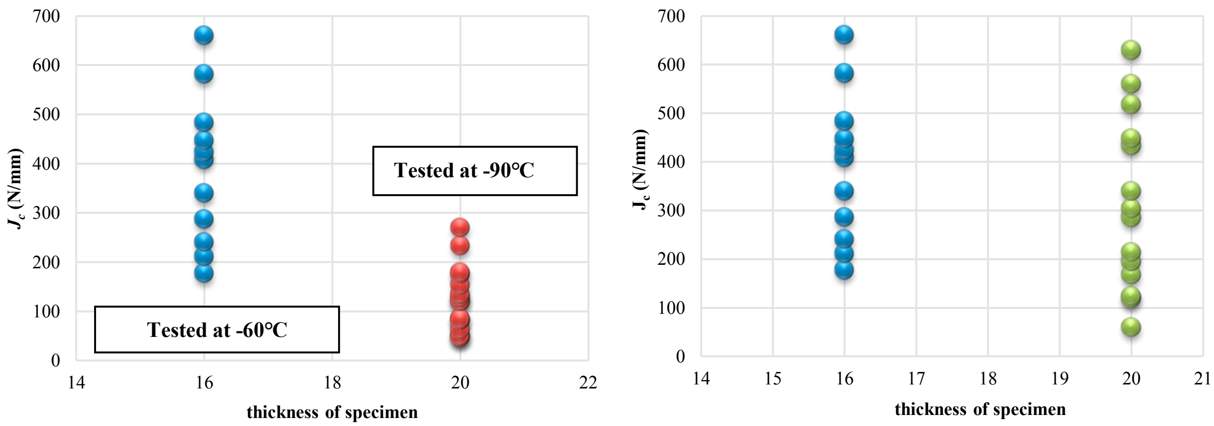
1.4. Discussion

Based on the obtained results, i.e. obtained J_c parameter, scatter can be observed to be greater with higher temperature, as can be seen on the Fig. 3a. As well with temperature influence, it can be observed obvious influence of the specimen thickness on the J_c values as well, from the diagram in Fig. 3b, which shows the results from previous testing along with new ones at -60°C. Both series of testing are marked with specimen thickness. From diagram in

Fig. 3, it can be seen that values of J_c are bit a lower on B_{net}= 20 mm specimens in comparison to one with B_{net}=16 mm. Larger thickness provides more concervative data, but there is still a severe scatter of results.

Influence of the temperature on r_c-J_c dependance can be observed in Fig. 4a. The values or blue and red dots represent different values of r_c-J_c. The blue dots have higher values than red ones and can be observed in a somewhat linear form of distribution. As for the red dots (results of testing at -90°C) no visible distribution can be observed, but scatter of r_c are seems to be larger in comparison to blue ones. Besides that, influence of thickness is also present and has to be examined.

In Fig. 4b, dependence of r_c and z_c can be observed for the C(T)50 specimens tested at -60°C. Idea here was to show influence of displacement rates on the cleavage initiation sites, which r_c and z_c parameters represent. Scatter is obvious along with scatter of J_c parameter. From this small number of results, it can be concluded that greater displacement rate during testing provide cleavage initiation more to be on the middle of the specimen, but yet more results need to confirm this statement.



a) b)

Fig 3 (a) Influence of the temperature on J_c scatter; (b) Influence of the specimen thickness on J_c scatter (testing at -60°C)

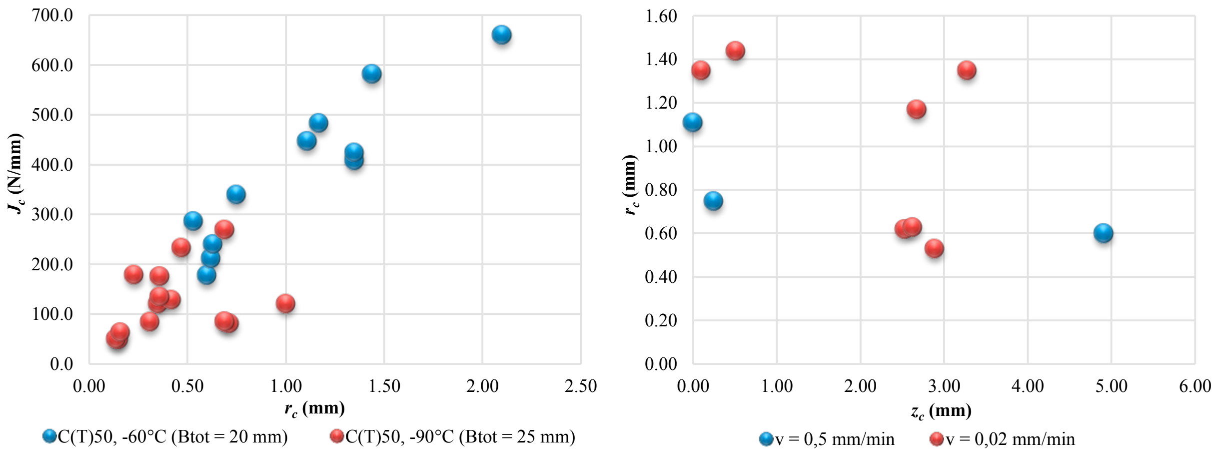


Fig. 4 (a) J_c-r_c dependence on temperature (testing at -60℃ and -90℃); (b) r_c-z_c dependence on displacement rates (testing at -60℃)

4. Conclusion

Like numerous studies in this field, this one represents a statistical interpretation of the obtained results. From the obtained results and discussed parameters, few observation could be emphasized:

- Scatter of the J_c parameters is larger with increasing temperature, which can be seen from direct of comparison (as it is expected)
- Scatter of the J_c parameters is larger with specimen thickness increasing, but it was not seen from the result of testing of C(T) specimens with B_{net} 16 and 20 mm. The only thing that could be said is that thicker specimen gave conservative results, and yet upper values of J_c scatter are also large.
- Scatter of r_c parameter as well as its value are greater with increasing the temperature
- Uniform linear distribution of r_c can be observed at -60°C.
- Effect of displacement rates on cleavage fracture require more testing and results. Initial conclusion is that dependence exists, i.e., cleavage fracture and initiation sites are dependent from displacement rates.

The effect of test specimen thickness of steel in question represents a specific challenge and leaves room for future analyses that will represent a continuation of this study. One thing needs to be taken into account when considering everything that was previously mentioned: scatter of wanted results in transition temperature region makes result interpretation much harder.

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