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Weibull probability distribution for reactor steel 20MnMoNi55 cleavage fracture in transition temperature

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Abstract

This paper presents the results and methods used for determining of fracture toughness of reactor steel, denoted as 20MnMoNi55, typically used for structures working at low temperatures, in transition temperature area. In addition, the effect of test specimen geometry and temperature on fracture toughness was investigated in order to predict the fracture behavior and probability of failure. Failure probabilities (i.e. cleavage fracture) in the function of J_c for large test specimens, CT100 and CT200 were determined based on the results obtained by testing of small CT50 specimens, for the purpose of direct savings and decreased costs of specimen testing. Failure probability, represented using Weibull distribution of experimental data, will provide a clear insight into material behavior at different temperatures. Other factors affecting the obtained test results will also be discussed.

Keywords: 20MnMiNi55 steel; Failure probability; Weibull distribution; *J*-integral; prediction

1. Introduction

It is well-known that material toughness changes with temperature, which means that, depending on the test temperature, the same material may exhibit both, plastic or brittle failure [1, 2]. Temperature interval during which the failure nature changes is known as the ductile to brittle transition temperature interval or vice-versa [1-3]. Taking into account that this temperature is significant not only when manufacturing and selecting materials, but also when

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monitoring material behavior during exploitation. Ferritic steels and alloys used for low temperature applications must fulfill a number of requirements regarding their mechanical properties, including strength, toughness, plasticity, physical properties (e.g. thermal expansion coefficient, corrosion resistance, etc.). Toughness of steels and alloys used at low temperature is typically defined for a specific transition temperature.

Considerable scatter of results obtained for the J-integral or the stress intensity factor *K* in transition temperature area makes the proper interpretation of these results rather challenging. Numerous studies are based on statistical processing of experimentally obtained values resulting from cleavage fracture. Stienstra el al [4] did statistical inferences on cleavage fracture toughness data and they used the "least square" method. McCabe et al [5] did that something similar with characterization of K_{Jc} in the lower-bound fracture toughness curve. Anderson et al [6] their research suggested a model to predict the magnitude of scatter of data in transition region, while Wallin [7] examined different existing models for cleavage fracture initiation in ductile-to-brittle transition region, and so did Landes [8]. The main goal of this research was to predict, understand and describe the behavior of ferritic steels in low temperature exploitation.

In this paper, the behavior, i.e. fracture of larger CT100 and CT200 specimens are predicted based on statistical data obtained by using Weibull distribution for experimental results of CT50 specimens with two different thickness values at a test temperature of -60°C. Weibull distribution was used due to significant scatter of results for J_c obtained by experiments. Statistically obtained fracture probability was directly compared to obtained J_c values in the case of large CT specimen failure. The parameter that was directly compared, obtained by tests and statistical probability under cleavage fracture conditions, was J_c, due to difficulties in determining K_c for this micro-alloyed steel according to appropriate standard [9]. Forces applied during the tests were defined under controlled displacement (displacement rate). Tested CT specimens were made of reactor steel 20MnMoNi55, typically used at low temperatures applications. The goal of this study is to directly compare experimentally obtained results with a statistically obtained probability curve, showing values of J_c at fracture, and to use these results in order to predict material behavior, i.e. to predict the cleavage fracture of some real construction based on tests of smaller CT specimens, without the need to perform testing on the bigger ones.

2. Test methodology

Tests performed as a part of this study aimed to predict the behavior of larger CT specimens, namely the most probable J_c value at cleavage fracture, which would then be compared with experimental results, at a temperature of -60°C. For this purpose, CT50 specimens were tested first, followed by larger CT100 and CT200 specimens, in order to compare the results with predictions made using Weibull distribution. Fracture cleavage tests were performed in accordance with [10].

All specimens were made of ferritic reactor steel 20MnMoNi55, whose chemical composition and mechanical properties are given in tables 1 and 2, respectively. This steel is used in manufacturing of pressure vessels and power plant reactors, and is generally meant to work in extreme conditions. The specimens were cut out of a plate.

Table 1. Chemical composition of 20MnMoNi55 in mass percent [11].

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 2. Mechanical properties of steel tested at room temperature.

σ_Y - Yield strength [MPa]	σ_u - Tensile strength [MPa]	Elongation [%]
450	610	/

In order to describe the obtained result which had shown considerable scatter, the "Weakest link model" [8, 12] was used. It is one of the two suggested procedures for statistical explaining of the effect of test specimen thickness on obtained results.

Failure probability of CT50 specimens as a function of J_c was represented using a two-parameter Weibull distribution (Eq.1-3). *P*(*J*) represents the probability that *J* for cleavage will occur at some value. Fitting was performed based on experimentally obtained failure probabilities for CT50 specimens at test temperatures, which were displayed using a logarithmic coordinate system. The parameters of fitted Weibull distributions are then calculated analytically via "least square" method, i.e. using regression analysis in form given in [4, 13]. Scale parameter of Weibull distribution is expressed as J value when $P(J)$ is 0.632 [14]. Both parameters were calculated and derived from experiments.

$$P\left(J_c\right) = 1 - e^{-\left(\frac{J}{\theta}\right)^{\beta}} \tag{1}$$

$$P_i = \frac{i}{N+1} \tag{2}$$

$$J_{B_2} = J_{B_1}\left(\frac{B_1}{B_2}\right)^{\frac{1}{\beta}} \tag{3}$$

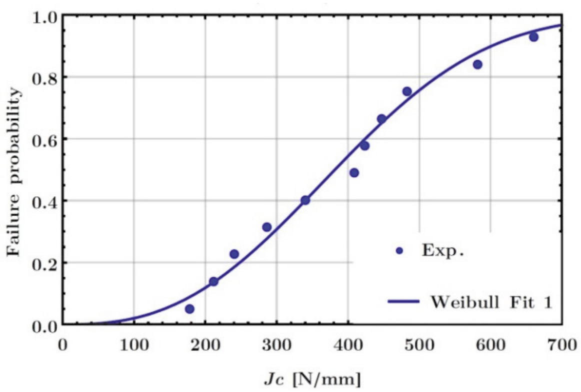
Table 3. J_c values for CT50 specimens tested at -60°C.

Specimen no.	**J_c [N/mm]**	**B [mm]**	**B_{net} [mm]**	**Displ.rate v [mm/min]**
EP1	60.0	25.0		0.500
EP2	120.0	25.0		0.500
EP 3	124.0	25.0		0.500
EP4	168.0	25.0		0.500
EP5	178.2	20.0	15.827	0.500
EP6	195.0	25.0		0.500
EP7	211.8	20.0	15.754	0.020
EP8	215.0	25.0		0.500
EP9	241.2	20.0	15.822	0.020
EP10	286.0	25.0		0.500
EP11	286.9	20.0	15.820	0.020
EP12	304.0	25.0		0.500
EP13	340.3	25.0		0.500
EP14	340.3	20.0	15.704	0.500
EP15	409.0	20.0	15.829	0.020
EP16	424.1	20.0	15.800	0.020
EP17	434.0	25.0		0.020
EP18	447.5	20.0	15.737	0.500
EP19	448.0	25.0		0.500
EP20	483.4	20.0	15.813	0.020
EP21	518.0	25.0		0.500
EP22	560.0	25.0		0.500
EP23	582.3	20.0	15.714	0.020
EP24	630.0	25.0		0.500
EP25	660.8	20.0	15.829	0.004 &0.50

3. Experimental results

Notched CT50 specimens with two different thickness values were tested in accordance with relevant standards, and were made with side grooves equal to 20% of specimen thickness. Testing and determining of J_c was performed in accordance with [10]. A total of fourteen CT50 specimens with following dimensions were tested: width, B = 25 mm (B_{net} = 20 mm, side grooves on both sides were 2.5 mm). The second type of tested CT50 specimens had a width of B = 20 mm, wherein B_{net} was 16 mm, and side grooves were 2 mm deep. A total of eleven such specimens were tested. Thus, a total of 25 specimens with two different thickness values were considered. Tests were performed on a commercial test machine, with a capacity of 20 tons. Displacements rates during testing of CT50 during testing were 0.5 and 0.02 mm/min. Cooling was performed in a chamber filled with liquid nitrogen, whereas temperature regulation was achieved by ventilation. Tests were performed at -60°C. Table 3 shows the values of J_c in N/mm, along with other relevant parameters.

Failure probability of specimens for both thickness values as a function of J_c is shown using a two-parameter Weibull distribution (Fig. 1). On the left side of this figure (1a), the Weibull distribution for B_{net} = 16 mm is shown, whereas on the right side, the results for B_{net} = 20 mm can be seen. Points represent J_c values for tested specimens, and the fitting was performed using analytical methods. Two seemingly identical curves can be used to show the failure probability of tested specimens.



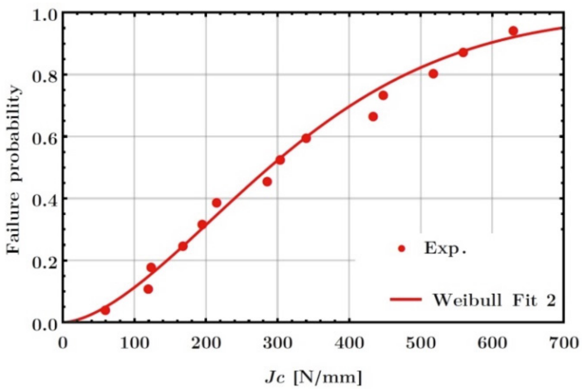


Fig. 1. Experimental results of tested CT50 specimens at -60°C with B_{net} on left) 16 mm and Weibull distribution of specimen cleavage fracture (failure probability) in the function of J_c; right) 20 mm and its failure probability.

Fig. 2 shows a direct comparison of Weibull distribution diagrams for failure probability of both types of CT50 specimens. Here it can be seen that specimen thickness affects the distribution, at least in the part where J_c ranges from 0 to 500 N/mm, and in this region, failure probability is higher for thicker specimens, with B_{net} of 20 mm, compared to the 16 mm ones, under same loading conditions. However, this does not apply to higher J_c values.

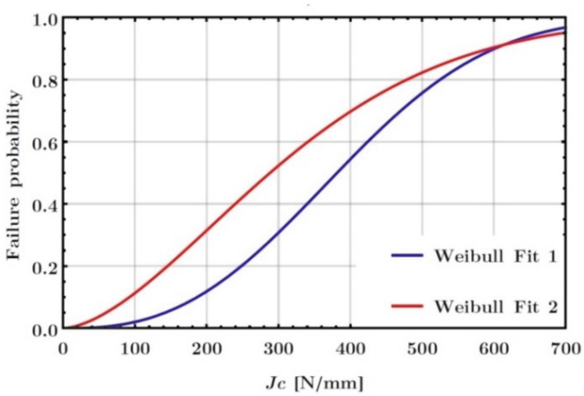


Fig. 2. Direct comparison of Weibull distributions of cleavage fracture of both CT50 specimen thicknesses (at -60°C)

By unifying the results of CT50 specimen test with repeated Weibull distribution fitting, a new failure probability curve was obtained, and is shown in Fig. 3. In this way, the effect of thickness was neglected within the group of same CT50 specimens for the purpose of predicting cleavage fracture probability as a function of J_c for larger, CT100 and CT200 specimens at test temperature of -60°C. Side groove depths were taken into account. Repeated analytical calculation provided the failure probability curves, also shown in Fig. 3. Parameters for all three Weibull probabilities were re-calculated based on the CT50 Weibull Fit 3 curve.

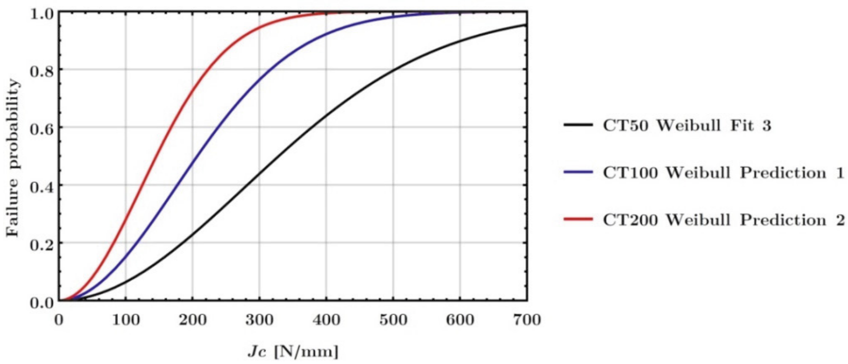


Fig. 3. Weibull fit curve 3 based on the result obtain from aforementioned tested CT50 (black); CT100 Weibull prediction (blue), CT200 Weibull prediction (red) in the function of J_c at -60°C.

In order to verify the obtained prediction curves and to gain better insight into the results, a total of 12 CT100 and 2 CT200 specimens were tested at the same temperature (-60°C) in accordance with standard [10]. Tests were performed in the same manner as with the CT50 specimens, in a nitrogen-cooled chamber, in controled condition by appropiriate displacement rate for CT100 specimens and CT200 specimens. Obtained results of testing are shown in the table 4. Direct comparison of J_c values obtained by testing of CT100 and CT200 specimens and prediction of their failure in terms of J_c obtained by Weibull distribution can be seen in Fig. 4. It can be seen in this diagram that the Weibull curve shows good agreement with the experimental results.

Table 4. J_c values of tested CT100 I CT200 specimens at -60°C

Specimen no.	**J_c [N/mm]**	**B_{net} [mm]**	**Displ.rate v [mm/min]**
CT100 EP1	57.5	40	0.500
CT100 EP2	93.5	40	0.500
CT100 EP3	152	40	0.500
CT100 EP4	159.1	40	0.500
CT100 EP5	203.7	40	0.500
CT100 EP6	213.4	40	0.500
CT100 EP7	229.8	40	0.500
CT100 EP8	276.3	40	0.500
CT100 EP9	324.5	40	0.500
CT100 EP10	335.6	40	0.500
CT100 EP11	336.3	40	0.500
CT100 EP12	368.2	40	0.500
CT200 EP1	120.8	80	1.000
CT200 EP2	171	80	1.000

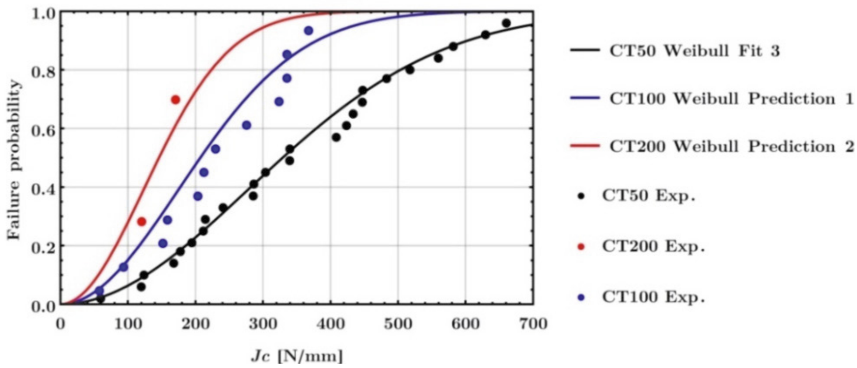


Fig. 4. Weibull curves from Fig. 3 and obtained experimental results for CT100 and CT200 at -60°C.

4. Discussion and conclusion

Cleavage failure probability diagrams obtained for larger CT specimens, represented by Weibull distribution as a function of J_c can be used to show the effect of test specimen thickness and dimensions on its expected values during fracture. Based on the experimental results and the probability diagrams obtained in this research by using statistical methods of data manipulation, it is possible to obtain relatively accurate prediction of steel 20MnMoNi55 behavior at low temperature. Similar to other studies, the work presented here attempted to interpret considerable scatter of obtained J_c values. The effect of specimen thickness and their behavior was explained in terms of this data scatter and Weibull distribution for cleavage failure probability, for both smaller and larger specimens.

Probability for which the suggested distribution laws can be accepted or rejected can be determined using some of the available goodness-of-fit test methods, wherein the output is the obtained probability value (pValue), which can provide a realistic image about the interpretation method itself, and is still open for additional discussion.

Analysis of temperature opens up even more possibilities. Additional experiments performed at both lower and higher temperatures would, along with the existing results for the temperature used in this experiment, provide a more comprehensive insight into material behavior in such sensitive low temperature areas. Decrease in temperature would increase the share of ductile cleavage in CT specimens, with reduced scatter. Anyhow, the use of statistical methods would certainly provide a clearer image, at least regarding the scatter of experimentally obtained results.

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