The interrelation between statistical distributions of impact toughness and fracture mechanisms

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Abstract. The purpose of this work is to develop the statistical approach based on the interrelation between statistical characteristics and physical parameters defining the fracture mechanisms. The impact tests of two low carbon steels at different temperatures and detail analysis of cumulative probabilistic curves were carried out. It was shown that cumulative probabilistic curves (KCV – *P*) of impact toughness (KCV) for both steels may be described by the exponential function. It was found that changes in the γ – exponent of this function are connected to those of the relative area of fibrous fracture (*B*) observed on a fracture surfaces of specimens in the interval of ductile–brittle fracture.

Introduction

Numerous works have been devoted to evaluation of the probability of fatigue and impact fracture, in which the Weibull relation involving two or three parameters is often used [1-5]. Using this distribution researchers encounter a problem associated with difficulties in establishment of the interrelation between statistical distribution parameters and fracture mechanisms. For solving this problem, various approaches have been used.

For example, Weibull used two subdistributions corresponding to different levels of the material strength [6]. Other researchers used the weight coefficients [7–8] to evaluate the probability, which allowed them to take into account two different mechanisms of fracture. The author of [9] applied a generalized three–parametric Weibull distribution for describing the variation in the lifetime of bearing steel with the purpose to establish the analytical description associating each of three distribution parameters with the amplitude of stress. This way seems to be rather complicated, and, apparently understanding this, the author of [9] notes the necessity of the development of a scientifically substantiated model of fatigue fracture in a wide range of the number of cycles determining the form of cumulative distributions.

In spite of the numerous works devoted to the fracture probability, the interrelation between the statistical characteristics reflecting the form of probability curves and the fracture mechanisms is studied insufficiently.

The purpose of this work is to develop an approach based on the interrelation between statistical characteristics and physical parameters defining the fracture mechanism.

Experimental procedures

The standard V-notched Charpy specimens of steel 09G2S (0.09 C, 1.68 Mn, 0.91 Si , % wt.) and St.20 (0.2 C, % wt.) at different temperatures were used in the impact tests. During the testing the load-deflection curves (F-Δl), the total impact energy and the impact toughness for both steels were recorded. The fracture surfaces of the impact specimens were examined by Scanning Electron

Microscopy (SEM) and the parameters of microrelief defining the fracture mechanisms were estimated. The standard mechanical properties of steels investigated are given in Table 1.

Table 1. The mechanical properties of steels

Material	**U.T.S. [MPa]**	**Y.S. [MPa]**	**R.A. [%]**	**ε [%]**
09G2S	569	438	70	37
St.20	434	258	42	37

Note: U.T.S. – the ultimate tensile strength, Y.S. – the yield strength, R.A. – the reduction of area, ε – the elongation at fracture.

The statistical analysis of impact toughness (KCV) for both steels was performed using the following exponential equation and coordinates which were reversed to conventional ones

$$\mathrm{KCV} = A\exp\left(\gamma \cdot P\right). \tag{1}$$

Furthermore, the two-parameter form of the Weibull distribution was used

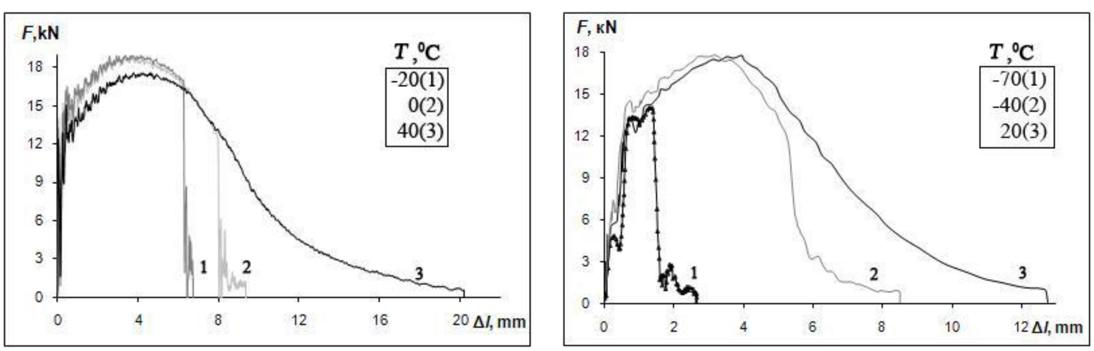
$$W = 1 - \exp\left[-\left(\frac{\mathrm{KCV}}{D}\right)^{\beta}\right]. \tag{2}$$

The W, P are the cumulative probability distributions; γ, A, β, D are the distribution parameters.

Results and discussion

Charpy impact testing

The evolution of load-deflection curves (F–Δl) for both steels are presented in Fig 1.



a b

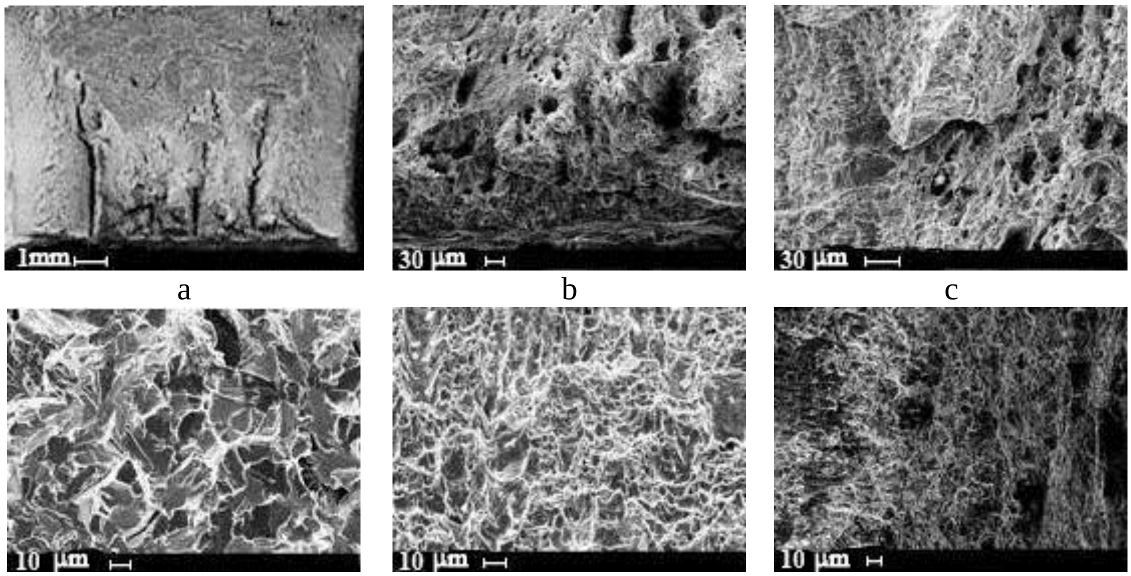
Fig. 1. The evolution of F – Δl curves of (a) St.20 and (b) 09G2S at different temperatures

The results show that decrease in temperature leads to a reduction of impact energy and a change of forms of load-deflection curves. It is well known that these changes are related to the fracture mechanisms.

The SEM fractographic examinations of specimens tested from both steels allowed us to observe the stages of fracture process at different temperatures.

The following zones are observed on the fracture surfaces of specimens in the interval of ductile – brittle transition (Fig. 2): the initial shear zone at the tip of specimen notch (b, c), the ductile rupture zone of stable crack growth; the zone of cleavage fracture (d), the region of final rupture (e) and the shear zones near lateral specimen surfaces (f).

The relative area of fibrous fracture (B) observed on a fracture surfaces of specimens reflecting the changes of fracture mechanisms in the interval of ductile – brittle transition was used to establish the correlation between statistical distributions of impact toughness and fracture mechanisms.



a b c

d e f

Fig. 2. Macro and microrelief of steel 09G2S at T=-40^{0}C

Statistical analysis: the simple exponential distribution

Cumulative probability distributions obtained by using experimental values of the impact toughness (KCV) for steels investigated are shown in Fig. 3. Solid lines (Fig. 3. a, c) correspond to the exponential relations (Eq. 1) with correlations coefficients (r) not less than 0.90 and 0.82 for steel 09G2S and for St.20, respectively. The values of parameters in the mentioned exponential distributions and the ranges of varying impact toughness, in which this interrelation is observed, are noted in Table 2.

It is evident from Table 2 and Fig. 3 (b, d) that the index (γ) in Eq. 1 has complex dependence on temperature for studied steels. As follows from Fig. 3, these changes in the γ – exponent is connected to those in the B – parameters, namely, to changes in the fracture mechanisms. On the graphs in Fig. 3 (b, d) it is possible to separate the three regions reflecting the changes in fracture mechanisms: the region I of brittle fracture; the transition region II and the region III of fibrous fracture. At the critical temperature corresponding to B=-50%, the “peak” of the γ – T curves is observed for both steels.

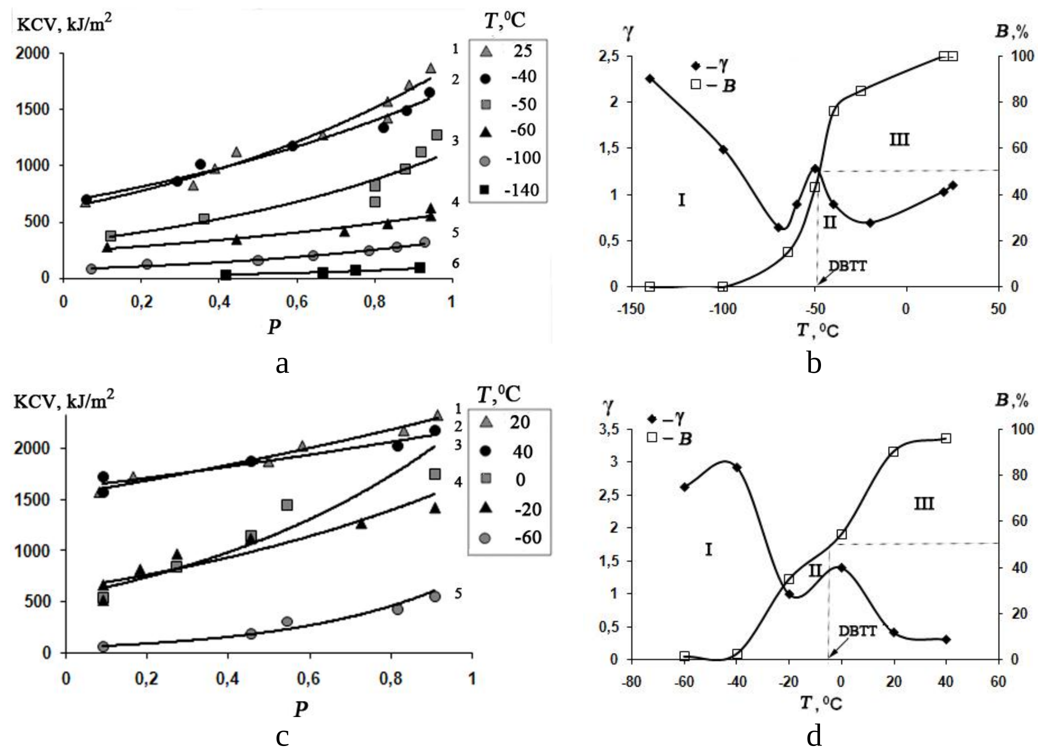


Fig. 3. (a, c) The cumulative probabilistic curves of the Charpy impact toughness (KCV) at different temperatures and (b, d) the temperature dependences of the γ – exponent and the relative area of fibrous fracture (*B*) on a specimen fracture surface for steel 09G2S (a, b) and St.20(c, d). Solid lines in graphs (a, c) correspond to the exponential function (Eq. 1).

Table 2 Correlation coefficients and parameters of exponential distributions (Eq. 1) of the steels

Steel 09G2S						**St.20**					
Curve number on Fig.3,a	***T*** **[^{0}C]**	**Ranges of KCV [kJ/m^2]**	***A***	**γ**	***r***	**Curve number on Fig.3,c**	***T*** **[^{0}C]**	**Ranges of KCV [kJ/m^2]**	***A***	**γ**	***r***
1	25	736-1820	624	1.11	0.97	**1**	20	1592-2260	1555	0.42	0.97
2	-40	692-1674	628	0.90	0.97	**2**	40	1553-2147	1605	0.32	0.92
3	-50	382-1220	314	1.29	0.90	**3**	0	661-1741	561	1.41	0.90
4	-60	245-580	238	0.90	0.94	**4**	-20	504-1436	626	1.01	0.82
5	-100	81-332	78	1.49	0.98	**5**	-60	50-593	56	2.63	0.96
6	-140	32-85	12	2.26	0.98						

Note: *r* is the linear coefficient of the Pearson correlation.

Statistical analysis: the Weibull probability distribution

The cumulative probability distributions obtained by using experimental data on the impact toughness (point distributions) and fitting curves (solid lines) plotted with using the Weibull probability distributions are presented in Fig. 4 (a, c). The simple Weibull distributions without weight coefficients were used to establish the correlation between statistical parameters and fracture mechanisms. The values of parameters in the mentioned distribution and the ranges of varying fracture toughness, in which this interrelation is observed, are presented in Table 3.

It follows from Fig. 4 and Table 3 that the experimental data are well described by the Weibull probabilistic curves.
The temperature dependence of the β – exponent is similar to the $\gamma - T$ dependence (Fig. 3): the regions of the reduction and rising in the mentioned characteristics are observed. For the steel 09G2S, it is possible to separate the three regions reflecting the changes in fracture mechanisms: the region I of brittle fracture; the transition region II and the region III of fibrous fracture.
The $\beta - T$ dependence for the St.20 is smoother and similar to the $B - T$ dependence; the regions of a ductile and brittle fracture may be separated on this graph.
The comparison of Fig.3 and Fig.4 shows that in both cases it is possible to found the correlation between statistical parameters and fracture mechanisms. But the Weibull probability distribution is rather complex than simple exponential one. Moreover in the interval of ductile–brittle fracture the experimental probabilistic curves often deviate from the straight lines (Fig.4. a, curve 4) and using the Weibull distribution becomes inconsistent. Therefore, in this case, the application of the mixed Weibull distributions and reasonable choice of the statistical parameters to establish the interrelation between these parameters and physical properties are required.

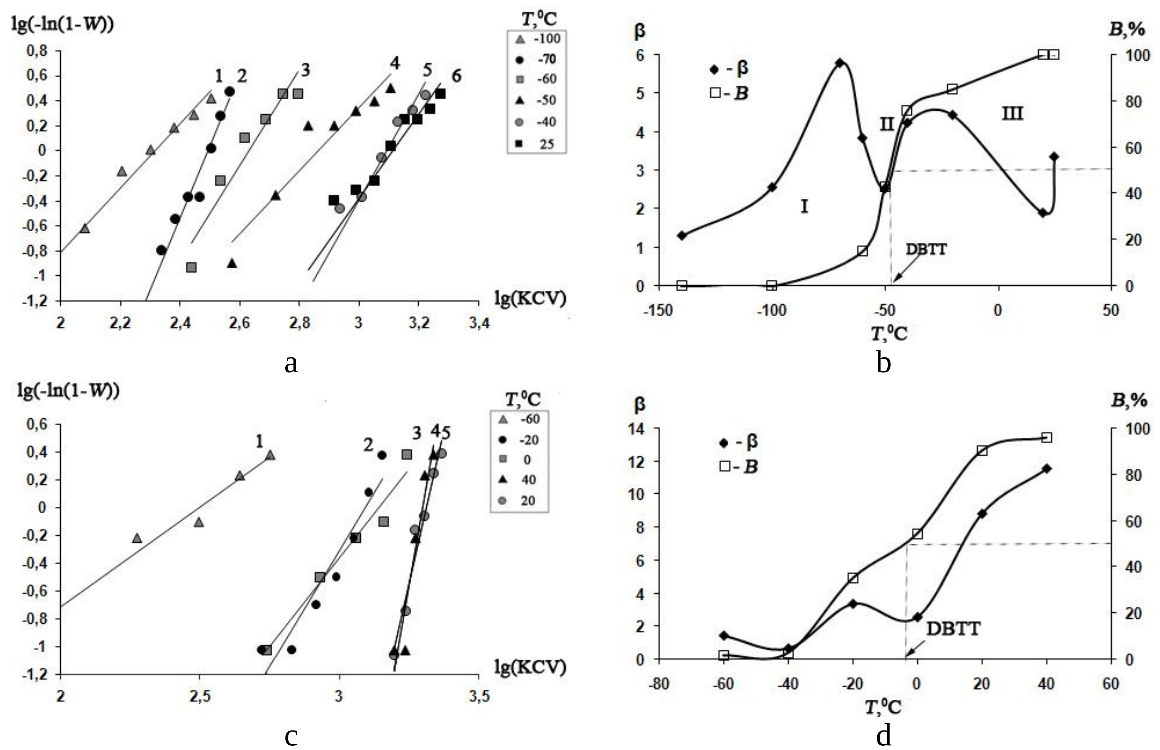


Fig. 4. (a, c) The cumulative probabilistic curves of the Charpy impact toughness (KCV) at different temperatures and (b, d) the temperature dependences of the β – exponent and the relative area of fibrous fracture (B) on a specimen fracture surface for steel 09G2S (a, b) and St. 20(c, d). Solid lines in graphs (a, c) correspond to the Weibull function (Eq.2).

Summary
Thus, the analysis performed allowed us to describe the probabilistic curves obtained under impact loading for two different low carbon steels by simple exponential relations even in the interval of ductile-brittle fracture. The indexes of this distributions characterize the form of probabilistic curves and are associated with the parameters determining the fracture mechanism, namely, the testing temperature and the relative area of fibrous fracture (B).

Therefore, the suggested approach is an alternative to those based on the Weibull relations and requires further investigation of changes of the distribution parameters and their interrelation with fracture mechanisms.

Table 3. Correlation coefficients and parameters of Weibull distributions (Eq. 2) of steels

Steel 09G2S						**St.20**					
Curve number on Fig.4,a	***T*** **[^{0}C]**	**Ranges of KCV [kJ/m^2]**	***D***	**β**	***r***	**Curve number on Fig.4,c**	***T*** **[^{0}C]**	**Ranges of KCV [kJ/m^2]**	***D***	**β**	***r***
1	-100	81-332	207	2.57	0.98	**1**	-60	50-527	311	1.43	0.99
2	-70	181-379	312	5.79	0.98	**2**	-20	504-1436	1238	3.36	0.96
3	-60	245-580	428	3.84	0.96	**3**	0	661-1741	1385	2.55	0.98
4	-50	382-1220	726	2.53	0.96	**4**	40	1553-2147	1989	11.56	0.96
5	-40	692-1674	1232	4.24	0.98	**5**	20	1592-2260	2052	8.83	0.98
6	25	736-1820	1291	3.36	0.96						

Note: *r* is the linear coefficient of the Pearson correlation.

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