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THE EFFECT OF TEMPERATURE AND LOADING RATE ON THE CRACK INITIATION AND PROPAGATION ENERGY IN CARBON STEEL CHARPY SPECIMENS

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The Charpy impact tests were carried out at different temperatures and loading rates. The temperature dependences of crack initiation and propagation in carbon steels 45 and St. 3 under impact testing were determined from the obtained force variation plots. The effect of the impact velocity in the range from 1 to 4.4 m/s on the fracture toughness temperature dependence is estimated.

Keywords: carbon steels, Charpy specimen, instrumented impact testing machine, fracture toughness, crack initiation and propagation energy, ductile-brittle transition temperature.

Introduction. One of the main characteristics of materials in the assessment of the strength and reliability of structures and constructions is the ductile-brittle transition temperature (DBTT). In order to determine it, various testing methods are used, of which the Charpy impact testing is the most simple and widespread. Usually, as a result of such testing, the temperature dependences of fracture toughness are determined, and by their processing, there are determined the ductile-brittle transition temperatures [1–3]. In so doing, it should be taken into account that the fracture toughness is an integrated characteristic that includes the specimen deformation energy, crack initiation and propagation energy.

The use of instrumented impact testing machines makes it possible to record force versus time plots during testing and thus to get much more information on the material behavior [1, 4–7]. The use of modern high-speed digital recording systems increases considerably the capabilities of processing of the obtained data. These data permit analyzing various approaches to determination of the ductile-brittle transition temperature and the energy spent at different stages of deformation and fracture of Charpy specimens under impact testing [2].

The goal of the present work was to study the behavior of carbon steels, such as St. 3 and 45, at different temperatures and loading rates using an instrumented vertical impact testing machine.

Testing Procedure and Processing of the Results. Impact testing of steels was carried out using an instrumented vertical impact testing machine equipped with a multichannel system for high-speed recording of forces and strains (the sampling frequency is 20 MHz) and a system for cooling and heating specimens in the temperature range $T =$ from -150 to 400°C [8]. Standard Charpy specimens of steels St. 3 and 45 of $55 \times 10 \times 10$ mm in size served as objects of the study [9, 10]. The impact velocity v_0 was varied from 1.0 to 4.4 m/s, the temperature from -135 to 315°C.

It is known that the mode of specimen fracture changes depending on the test temperature and strain rate. From the obtained $P(t)$ plots having a sufficiently high resolution in both of the coordinates (Fig. 1), it is possible to determine the energy spent for fracture of the specimen and also to separate it into the energy before the moment of the crack initiation (crack nucleation) and the energy of the ductile and/or brittle crack propagation [5].

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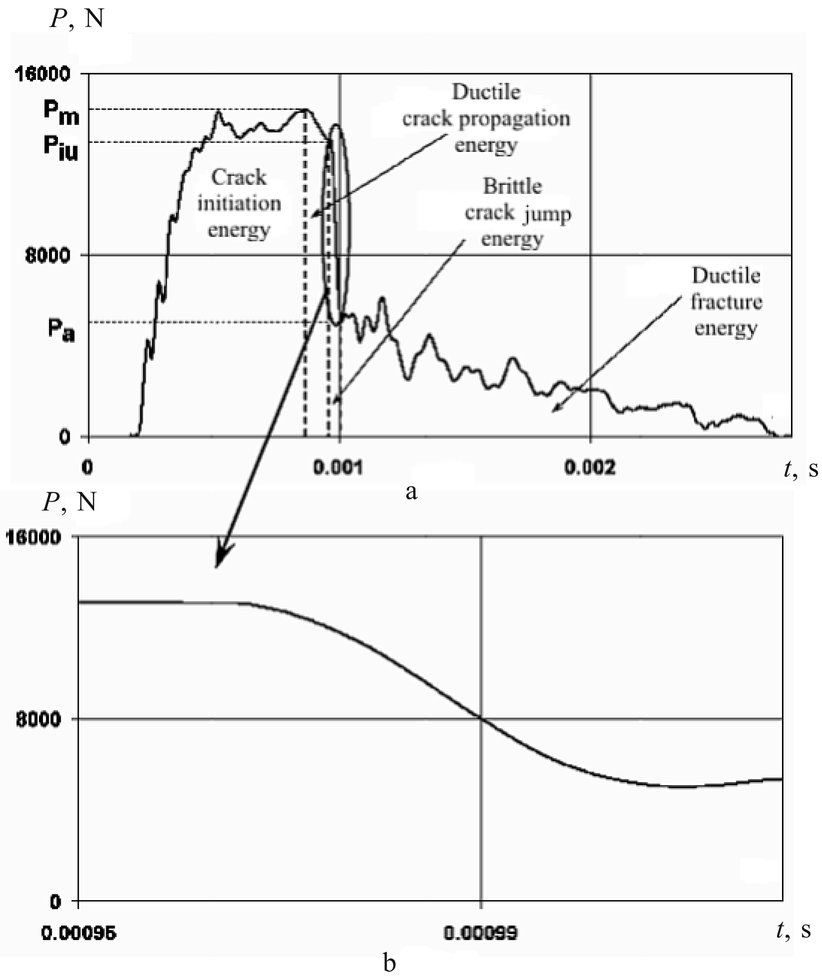


Fig. 1. A typical $P(t)$ plot for steel 45 in the ductile-brittle transition region at $v_0 = 2$ m/s, $T = 20$°C (a) and the signal variation during the brittle crack jump using a time scale magnification (b).

The value of the energy components can be determined in two ways. The first implies a transformation of the load P versus time t into a load P vs displacement s relationship. For this purpose, from the known striker (loading device) mass m, initial impact velocity v_0, and the $P(t)$ relationship, the variation in the striker velocity, $v(t)$, during loading of the Charpy specimen is found using the successive double integration from the equation:

$$v(t) = v_0 - \frac{1}{m}\int_{t_0}^{t} P(t)dt.$$

Next, the striker displacement s versus time t dependence is found from the following equation:

$$s(t) = \int_{t_0}^{t} v(t)dt.$$

From the obtained dependences, it is possible to plot the calculated $P(s)$ curve and determine the components of the energy spent for fracture. However, this way seems to be rather time-consuming due to the double integration involved.

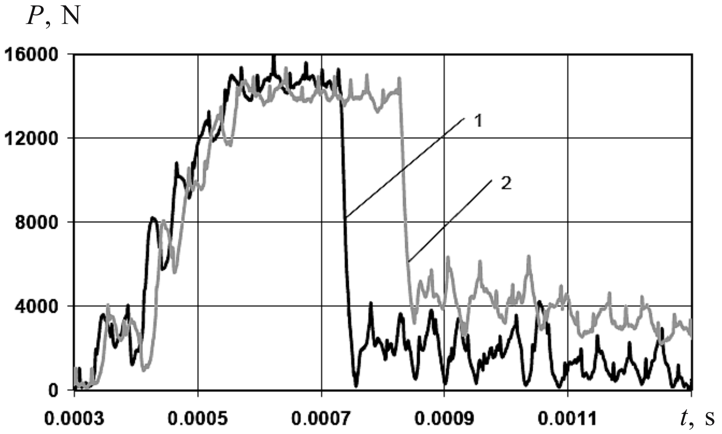
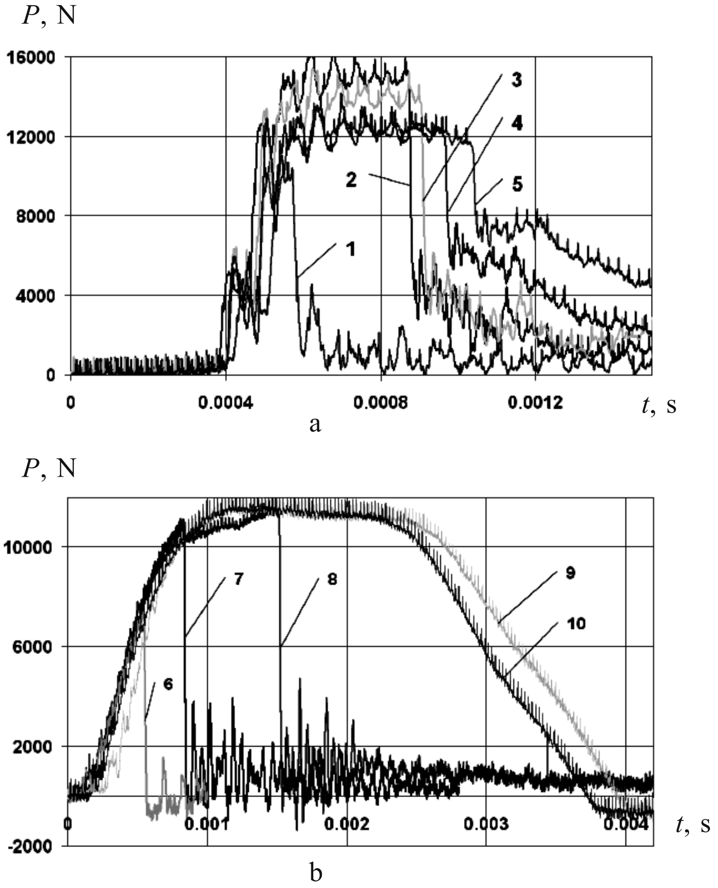


Fig. 2. $P(t)$ plots for steel 45 at the loading rate of 2 m/s: (*1*) $T = 10°\text{C}$; (*2*) $T = 20°\text{C}$.



a

b

Fig. 3. $P(t)$ plots for steel St. 3 at the loading rate of 4.4 (a) and 1 m/s (b): (*1*) $T = -5°\text{C}$; (*2*) $T = 20°\text{C}$; (*3*) $T = 30°\text{C}$; (*4*) $T = 40°\text{C}$; (*5*) $T = 50°$; (*6*) $T = -20°\text{C}$; (*7*) $T = 0°\text{C}$; (*8*) $T = 10°\text{C}$; (*9*) $T = 20°\text{C}$; (*10*) $T = 55°\text{C}$.

According to the second way proposed in [11], the deformation and fracture energy of Charpy specimens is determined by the formula

$$A(t_1,\, t_2) = \frac{1}{m}\left[q(t_1) - \frac{1}{2}\Delta q(t_1,\, t_2)\right]\Delta q(t_1,\, t_2),$$

where $q(t) = mv(t)$, m is the striker mass, and v is the striker velocity.

TABLE 1. Values of the Total Deformation and Fracture Energy and Its Components as a Function of the Loading Rate and Testing Temperature for Steel 45

Specimen No.	v_0, m/s	T, °C	E_t, J	E_i, J	E_b, J	E_d, J
203	2.0	–135	1.38	1.25	0.12	–
206	2.0	–90	1.90	1.75	0.16	–
205	2.0	–50	2.75	2.62	0.13	–
212	2.0	–20	5.59	5.36	0.22	–
204	2.0	0	9.80	7.11	0.29	2.40
215	2.0	10	15.92	9.72	0.36	5.85
231	2.0	10	10.26	6.33	0.40	3.54
207	2.0	20	23.15	9.84	0.41	12.89
232	2.0	20	17.26	6.64	0.40	10.22
233	2.0	40	20.75	7.28	0.38	13.08
223	2.0	44	23.19	8.86	0.38	13.94
224	2.0	100	28.32	9.98	–	18.34
230	2.0	155	25.26	9.15	–	16.11
211	4.4	–50	3.15	2.41	0.73	–
214	4.4	–20	4.34	3.33	0.61	0.39
209	4.4	0	6.86	5.77	0.82	0.26
217	4.4	10	11.56	5.90	1.08	4.57
222	4.4	20	15.61	7.98	0.86	6.77
234	4.4	20	14.29	6.94	0.91	6.44
225	4.4	43	24.32	7.55	0.90	15.87
235	4.4	50	31.91	9.58	0.76	21.57
226	4.4	100	33.54	10.14	–	23.40
236	4.4	150	31.46	9.62	–	21.84

Note. E_t is the total deformation and fracture energy, E_i is the crack initiation energy, E_b is the brittle fracture energy, and E_d is the ductile fracture energy.

Thus, to calculate the work at the time interval from t_1 to t_2, it is required to determine the momentum stored by the beginning of the time interval t_1 and the variation of Δq at this interval. It was precisely in this manner that the calculations of the deformation and fracture energy values of specimens have been made.

Analysis of the Testing Results. Typical force versus time plots are presented in Figs. 2 and 3. During testing of steels 45 and St. 3 at temperatures below 50°C, a brittle crack jump was observed. It is seen that the value of the force P_a, at which the brittle crack arrest is observed with a consequent ductile final fracture of the specimen, decreases monotonically to zero as the testing temperature decreases. The brittle fracture zone that is observed on the specimen fracture surface increases monotonically as well.

Based on the analysis of the force plots, we can propose the following simple procedure for determining the upper and lower temperature boundary of the ductile-brittle transition zone (DBTZ) in carbon steels. The disappearance of a sharp decrease (jump) of the force ($P_{iu} - P_a = 0$) with increasing test temperature on the $P(t)$ plot is indicative of the upper boundary of the DBTZ, whereas a decrease in the force to zero ($P_a = 0$) with decreasing temperature is indicative of the lower boundary of the zone.

A high sensitivity of the digital signal recording system enables stretching the scale of the signal in time in the region of the brittle crack propagation (Fig. 1b). The estimates made show that the duration of the brittle jump is $t = 15$–35 μs. This makes it possible to estimate the mean velocity of the brittle crack propagation v_{cr} (the crack length can be determined from the fracture surface of the failed specimen). For steel 45, v_{cr} varies in the range from 150 to 400 m/s, a similar picture is observed for steel St. 3. It is seen from Fig. 1b that the decrease in the load during the brittle crack propagation occurs rather smoothly, without sharp jumps. It is also possible to estimate the velocity of brittle fracture propagation – the velocity of such crack is from 1 to 20 m/s. These magnitudes of velocities agree with the estimate obtained from the testing results for a shipbuilding steel [12].

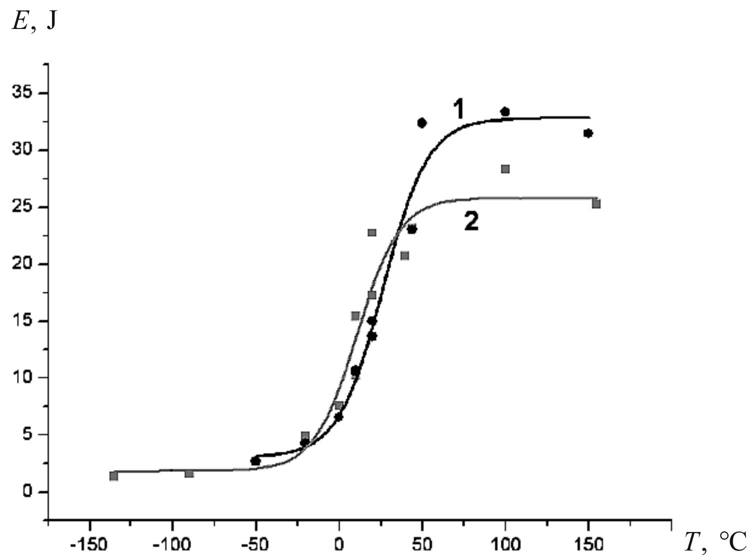


Fig. 4. Temperature dependences of the total deformation and fracture energy at different rates of deformation of Charpy specimens from steel 45: (*1*) $v_0 = 4.4$ m/s; (2) $v_0 = 2$ m/s.

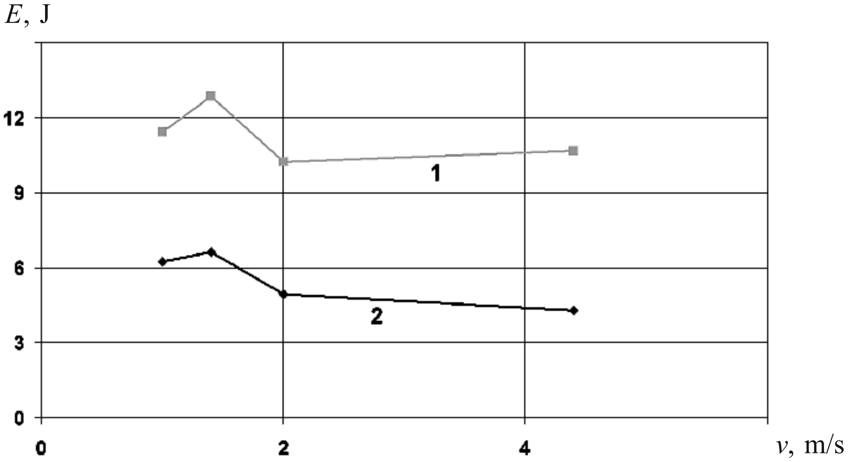


Fig. 5. Variation in the total fracture energy of steel 45 with the loading rate at $T = 10$°C (*1*) and −20°C (*2*).

Figure 4 illustrates the temperature dependences of the total energy of deformation and fracture at different strain rates for Charpy specimens of steel 45. The Table 1 presents the values of the energy components. It is seen that the energy versus temperature dependence in the DBTZ is weakly sensitive to the impact velocity and the DBTZ is within the temperature range from −20 to 50°C.

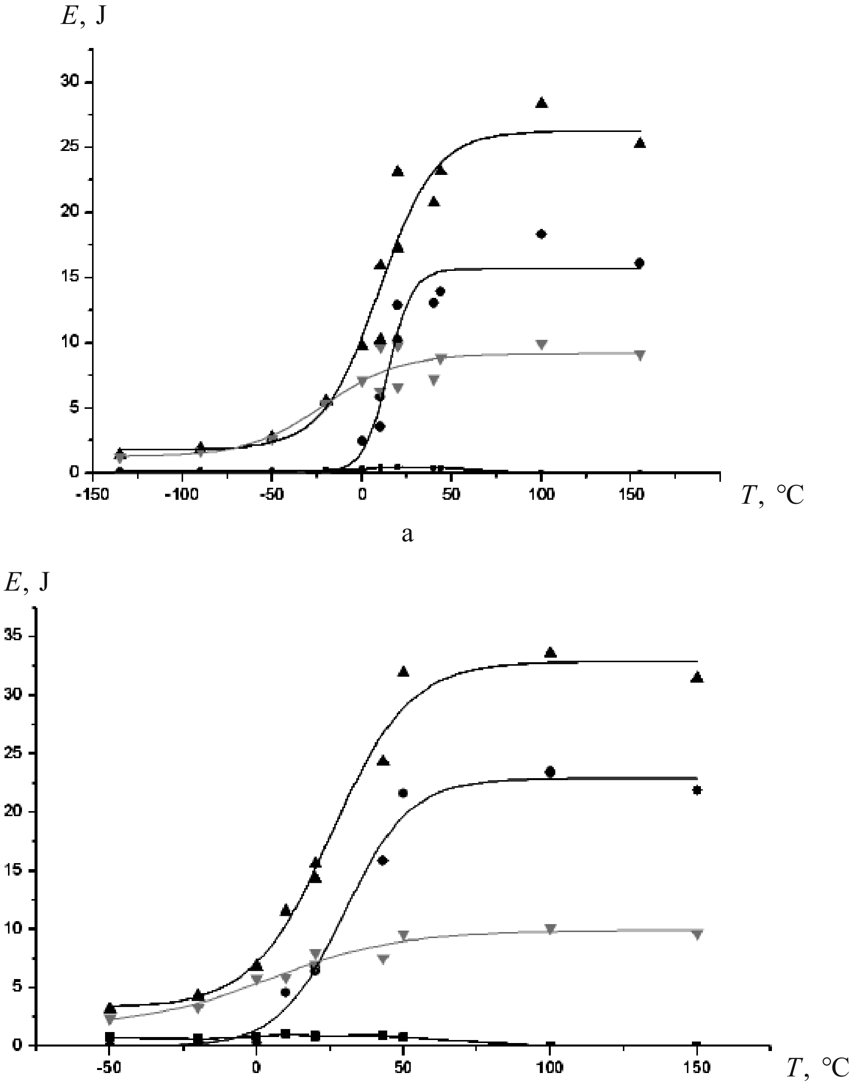
The tests were also carried out at lower loading rates: $v_0 = 1$ and 1.4 m/s. According to Fig. 5, the total fracture energy depends only slightly on the striker velocity in the range from 1 to 4.4 m/s.

The similar temperature dependences of the total fracture energy were obtained for steel St. 3 for which the DBTT is in the range from 0 to 50°C.

Figure 6 illustrates the testing temperature dependences of all the components of the deformation and fracture energy of steel 45 Charpy specimens for the loading rates $v_0 = 2$ and 4.4 m/s. It is seen that the most part of the energy is spent for ductile fracture, whereas the energy spent for brittle fracture is small.

The similar temperature dependences of the fracture energy components were obtained for steel St. 3.

Conclusions. The Charpy impact tests performed using an instrumented vertical impact testing machine have enabled us to obtain the temperature dependences of the crack initiation and propagation energy in carbon steels at the loading rates over the range from 1 to 4.4 m/s.



a

b

Fig. 6. Temperature dependences of the crack initiation energy E_i (▼), ductile fracture energy E_d (●), brittle fracture energy E_b (■), and total energy of deformation and fracture E_t (▲) at $v_0 = 2$ m/s (a) and $v_0 = 4.4$ m/s (b) for steel 45.

The procedure for determining the lower and upper temperature boundary of the DBTZ in steels has been proposed.

It has been demonstrated that in ductile fracture, the crack propagation velocity in Charpy specimens of carbon steels is about 1 to 20 m/s, whereas in brittle fracture, it is 100 to 400 m/s.

REFERENCES

1. N. A. Makhutov, E. M. Morozov, and Yu. G. Matvienko, “The history and development of impact testing in Russia,” in: Proc. *Charpy Centenary Conference* (Poitiers, France, 2–5 Oct., 2001), Poitiers (2001), pp. 557–566.
2. *Proceedings of the Charpy Centenary Conference* (Poitiers, France, 2–5 Oct., 2001), Vol. 1 and 2, Poitiers (2001).

3. A. Ya. Krasovskii, Yu. A. Kashtalyan, and V. N. Krasiko, *Investigation of the Fracture Toughness of Pressure Vessel Steels under Static and Dynamic Loading Taking into Account the Size Effect of the Specimens under Testing* [in Russian], Preprint, Academy of Sciences of Ukraine, Institute of Problems of Strength, Kiev (1982).
4. B. Tanguy, R. Piques, and A. Pineau, "Experimental analysis of Charpy V-notch specimens," in: Proc. *Charpy Centenary Conference* (Poitiers, France, 2–5 Oct., 2001), Poitiers (2001), pp. 425–432.
5. C. Gallo, J. A. Alvarez, F. Guttierrez-Solana, and J. A. Polanco, "Predicting crack arrest behavior of structural steels using small-scale material characterization tests," in: Proc. *Charpy Centenary Conference* (Poitiers, France, 2–5 Oct., 2001), Poitiers (2001), pp. 661–668.
6. O. Ya. Znachkovskii and I. V. Novikov, "Recording strain diagrams in low-temperature impact bending tests," *Strength Mater.*, **4**, No. 12, 1472–1474 (1972).
7. V. A. Strizhalo, O. Ya. Znachkovskii, and L. S. Novogrudskii, "Propagation of cracks in structural alloys at a temperature of 4.2 K," *Strength Mater.*, **29**, No. 6, 586–589 (1997).
8. E. A. Kodryakov, V. N. Zhmaka, V. V. Kharcheko, et al., "System of strain and load measurement in dynamic testing of materials," *Strength Mater.*, **37**, No. 3, 331–335 (2005).
9. *ISO 14556. Steel Charpy V-Notch Pendulum Impact Test – Instrumented Test Method*, Introduced 05.01.2005.
10. *Standard GOST 9454-78. Metals. Method for Impact Bending Testing at Lowered, Room, and Elevated Temperatures* [in Russian], Introduced 01.01.79.
11. O. A. Bakshi, I. O. Pinchuk, A. G. Kukin, et al., "Measuring device for determining the material brittleness criteria using the method of strain gauging the specimen fracture process by impact bending," in: *Equipment for Studying the Physical Properties of Materials* [in Russian], Naukova Dumka, Kiev (1974), pp. 200–206.
12. Z. Domazet, J. Raic, and J. Papic, "Introduction of instrumented testing in shipyards," in: Proc. *Charpy Centenary Conference* (Poitiers, France, 2–5 Oct., 2001), Poitiers (2001), pp. 683–689.