DETERMINATION OF METAL FRACTURE TOUGHNESS BY METHOD OF THERMAL IMPULSE

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ABSTRACT

The results of determination of metal fracture toughness by method of thermal impulse (due to heat quantity being evolved because of plastic deformation in zone of yielding) are given in this paper. It is shown that the values of stress intensity factor under plane deformation and plane-intensified condition stated by methods of mechanical fracture and by method of thermal impulse are in linear connections and differ within the errors of thermal impulse measurement.

KEYWORDS

Work of plastic deformation, heat, thermal impulse, method of thermal impulse.

THEORY

It is known that the work of plastic deformation in terms of physical state characterizes the metal resistance to fracture rather fully. However, the use of this characteristics for the analysis of fracture toughness is not provided by existing methods of fracture mechanics but the known methods of determination of plastic work by results of instumental measurements of deformation in fracture zone can be used only under the developed yielding. Therefore, the analysis of fracture toughness with the help of thermal impulse according to the quantity of heat being evolved in zone of yielding (Wells, 1953) is of interest. It is shown (Taylor and Quenney, 1934) that the work of plastic deformation in metals changes into heat by more than 90%, but the rest part of it is fixed as a potential energy of a crystalline lattice. Under a fracture the layer of plastically deformed metal appears on the surface of crack. Heat accumulated in this layer is being diffused through the metal into the sides from crack, i.e. the thermal impulse occurs corresponding to the work of plastic deformation in zone of yielding. If a crack is considered to be as an instantaneous plane source of heat, the maximum value of temperature T_m at a distance of X from the surface of fracture in a condition of adiabatic character of heat diffusion will be:

$$T_m = q/c\rho(2\pi e)^{1/2}X, \qquad (1)$$

where q is a specific capacity of source; c, ρ are the heat capacity and metal density; e is the base of natural manganese. From expression (1) by heat quantity one can determine the work of plastic deformation γ_p under the formation of unit surface of crack which is called as a specific work of crack running (α_r), i.e. we obtain:

$$\alpha_{rti} = c\rho(2\pi e)^{1/2}T_m X\ ,^{*)} \qquad (2)$$

According to the conception of Orowan-Irwin at a quasibrittle fracture of metals the intensity of emitted tensile energy G corresponds to the work of plastic deformation γ_p in zone of yielding, i.e. we have:

$$G = \gamma_p \qquad (3)$$

From this, with the account of those, mentioned above, it follows that now all taken characteristics of fracture toughness can be determined by thermal impulse method due to work of crack running α_{rti} with the use of certain correlations in fracture mechanics. In this investigation the method of thermal impulse was used for determination of force characteristics of fracture toughness as stress intensity factor K according to expression:

$$K_{ti} = (\varphi E'\alpha_{rti})^{1/2}\ , \qquad (4)$$

where E'=E in a plane-strained condition, $E' = E/(1-\nu^2)$ at a plane deformation; φ is the coefficient of units correlation.

EXPERIMENTS

Measurement of Thermal Impulse. For measuring the thermal impulse it is advised to use the thermocouple (Wells, 1953). However, at a brittle fracture when the temperature values T_m are especially small, the thermocouple appears to be not available. Therefore, the specialized system has been developed: temperature transducer and measuring amplifier of direct current. Unlike the thermocouple, the used transducer has a higher sensitivity, the low level of noise and a high-stable temperature characteristic. The developed system allows to change the small values of temperature (up to 10 K) with an error being not more than 5% at a quick action of 0.1 s and sensitivity up to 10^{-3}K/mm on a scale of oscillograph H117/1. For measurement, one thermosensitive element of transducer is placed at a distance of X from expected line of fracture but the other is arranged in a point of constant temperature out of a loading object. The signal from transducer is sent to an amplifier and then to a high-frequency galvanometer of oscillograph H117/1.

Steels and Specimens. The chemical composition and mechanical properties of investigated steels and also the mark, the thickness of section and number of specimens for tests are given in Table 1.

Table 1. Steels and specimens.

Steel	Specimen		Propeties, H/mm^2		Composition, %				
	Mark (number)	Thickness, mm	σ_y	σ_u	C	Mn	Si	S	P
M 76	A1(15)	18.0	530	941	0.76	0.86	0.21	0.030	0.025
M 76	A2(9)	12.0	530	941	0.76	0.86	0.21	0.030	0.025
17GS	B (10)	9.0	363	510	0.15	1.31	0.51	0.016	0.017
17G1S	C (10)	10.0	402	549	0.16	1.39	0.51	0.015	0.018
09G2S	D (15)	11.0	343	490	0.12	1.30	0.50	0.016	0.017
18Gps	E (15)	11.0	235	372	0.18	1.50	0.65	0.015	0.017

The rectangular specimens A1 with a margin and the cylindrical specimens A2 with an annular crack were made of steel with an average strength and were tested for tension according to GOST 25.506-85. The specimens B, C, D, E of 150 x 75 mm in size with V-shapped marginal notch were made of different steels of low strength and were tested at a loading according to the scheme of bend with a tension. The test was being made at a normal temperature with a velocity of loading as 0.25 mm/s.

EXPERIMENTAL RESULTS AND DISCUSSION

It is stated that fracture of specimens A1 and A2 is characterized by P-V I type diagram. With account of it, the design values of stresses intensity factor as K_Q were determined according to GOST 25.506-85.

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*) Index "ti" here and further shows that the mean value is obtained by method of thermal impulse.

Measurement of thermal impulse on specimens A1, A2 was carried out at a distance of 5 mm from a notch axis. From oscillogram, Fig.1, it is seen that under linearly increasing load P to P_a the temperature in a point of measurement decreases from initial size T1 to T2. The origin of yielding in a weakened section is accompanied by non-linear growth of force and velocity decrease of temperature change on area 2 - 3. In time of fracture at a force P_c the elastic unloading of specimen takes place and the temperature jump increases from size T3 to T4,being equal to T1.Then,during propagation of heat evolved as a result of plastic deformation in yielding zone,the temperature increases to size of T_m. The maximum size of temperature T_m is defined due to the distance size $T4-T_m$. The average sizes of T_m constituted 0.347 and 0.153°K, but the average values of α_{rti} obtained by expression (2) constituted 1.52 and 0.67 J/cm^2 respectively for specimens A1 and A2. The obtained values of α_{rti} were applied for determination of design values of stresses intensity coefficient K_{ti} by expression (4) at E'=E, i.e. there is the commonest case of fracture under plane-stress condition.

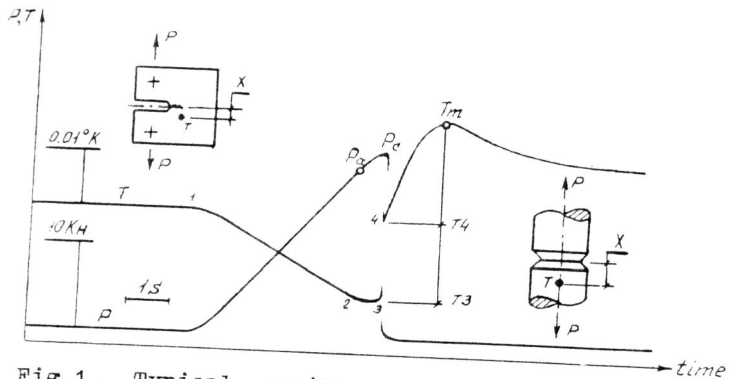

Fig.1. Typical oscillogram of force P and temperature T for specimens A1 and A2.

The design values of K_Q and K_{ti} are presented in Fig. 2 and their average values obtained with trusting probability of 0.95 at a quadratic mean decline Y1 and a relative error Y2 are given in Table 2. It is seen that a difference between average values of K_Q and K_{ti} is not high than 8% for specimens A1 and 3% for specimens A2. The analysis showed that there was a linear connection with coefficient of correlation of 0.956 between K_Q and K_{ti}, i.e. 91% of distribution is explained by correlation of K_Q to K_{ti}. The connection between K_Q and K_{ti} with probability of 0.95 can be presented by equation of regression mode:

$$K_Q = 0.75\ K_{ti} + 9.93 \qquad (5)$$

Table 2. Average values of K_Q and K_{ti}.

Specimen	K_Q,MPa$\sqrt{m}$	Y1	Y2,%	K_{ti},MPa$\sqrt{m}$	Y1	Y2,%
A1	52.0±1.6	9.705	2.8	56.0±1.5	9.083	2.5
A2	36.0±1.3	6.110	3.7	37.0±1.7	2.350	4.5

The results of points estimations showed that the values K_Q, obtained according to GOST 25.506-85 and by expression (4) were in coincidence with each other having an error not more than 13%.It was shown above that the determination of K_{ti} was based on principles of fracture mechanics.From this it follows that the known conditions of correction determination of fracture toughness force characteristics according to GOST 25.506-85 can be used and also for checking the correction determination of K_{ti}. The results of checking showed that the obtained values of K_Q and K_{ti} for the investigated steel at a test of specimens A1 were the critical conditional stress intensity factor of K^*_c and K^*_{cti} according to GOST 25.506-85 but at a test of specimen A2 the values of critical factor of K_{Ic} and K_{Icti} were obtained.With account of checking results, the average value of K_{Icti} by expression (4) at $E'=E/(1-\nu^2)$ and $\nu=0.25$ will be equal to 39.5 MPa$\sqrt{m}$ and the difference between K_{Ic} and K_{Icti} will constitute 9.7%.

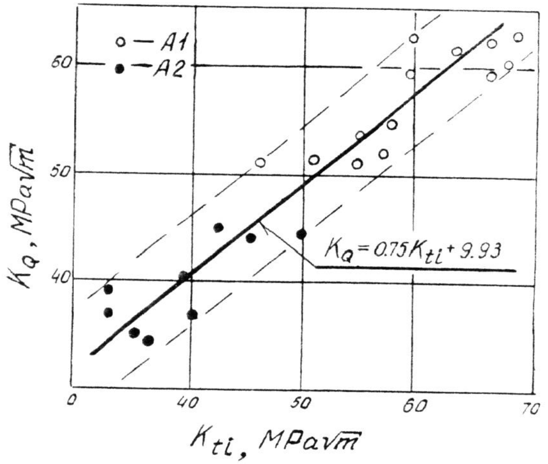

Fig.2. Correlation field and straigt line regression of K_Q to K_{ti} for specimens A1, A2.

Measurements of thermal impulse on specimens B, C, D, E, were being made at X=14 mm simultaneously in three sections, Fig. 3,

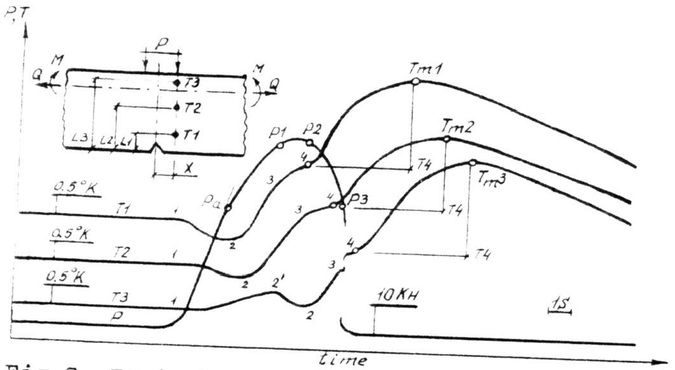

Fig.3. Typical oscillogram of force P and temperatures T1-T3 for specimens B - E.

placed at a distance of 10,30,50 mm from a noticed edge for one group of specimens and 20,40,60 mm for the other. From oscillogam it is seen that in time of development of elastic elongations under linearly increasing force P the temperature in expanded part of specimen decreases (area 1-2 on curves T1, T2), but in compressed part as a result of elastic shortenings the temperature increases (area 1-2'on a curve T3). Yield development in a notch is accompanied by non-linear growth of loading force and by temperature increase in the first section T1 from notch and then in the section T2 (area 2-3 on curves T1, T2). In this case the velocity of temperature increase becomes gradually high, then decreases (area 3-4 on curves T1, T2) and again increases (area 4-T_m on curves T1, T2). By means of filming it is stated that there is the coincidence in a time of section fracture moment T1 under a force P1 and section T2 at P2 with the beginning of area 3-4 on curves T1 and T2 respectively. Schönert and Weichert (1969) also observed the decrease and further temperature increase of specimens before fracture and explain the temperature decrease by acceleration of elastic deformations and tensions, but the further increase by plastic flow in the top of crack. From mentioned above it follows that the appearance of area 3-4 on curves T1 and T2 is connected with the fracture of discussed sections, but the temperature increase in area 4-T_m is caused by heat liberation as a result of plastic deformation in the top of crack crossing the appropriate section. With account of this, the maximum value of temperature T_m was being defined according to segment size $T4-T_{m1}$ for section T1 and a segment $T4-T_{m2}$ for section T2. In time of fracture of the expanded part of specimen the tensions in compressed part decrease and this in its turn causes the lowering of temperature in section T3 (area 2'-2 on curve T3).

A further change of temperature in section T3 occurs so as in section T1 and T2. And with this the area 3-4 appears under the load P3 and the temperature value T_m is defined by size of segment $T4-T_{m3}$. It is stated that the average values of T_m range at 1.7...4.8°K but less than the values obtained near the notch and larger in the farest sections.The values of α_{rti}, obtained by expression (2) near by the notch at a distance of 10 and 20 mm are the constants and constituting 40,48 and 55 J/cm^2 for specimens B, C, D but on specimens E they increase from 67 to 82 J/cm^2. In a middle part by height at a distance from 30 to 50 mm for specimens B, C and from 30 to 40 mm for specimens D, E the constant values of α_{rti} being equal to 56, 67, 81 and 89 J/cm^2 respectively are also obtained. In the farest sections at a distance of 60 mm the values of α_{rti} sharply increases to 67-82 J/cm^2 for specimens B, C and to 107 - 127 J/cm^2 for specimens D, E.

According to values of α_{rti}, using the expression (4) at E'=E, the values K_{cti} have been defined in different sections by height of specimens. For the comparison in the same sections the values of k_c have been determinated by known expression of fracture mechanics:

$$K_c = (6M_c/BW^2)\,L^{1/2}Y, \qquad (6)$$

where B, W are the thickness and height of specimens. The length of crack L was taken as being equal to a distance from notched edge up to the discussed section T1,T2 or T3.The values of bending moment M_c were being defined by force P1,P2 or P3 for appropriate section. For determining M_c and values of correction function Y the expressions recommended for the conditions L/W>0.3 (Ostsemin and et al.,1983,1984) have been used. In a result of comparison it is

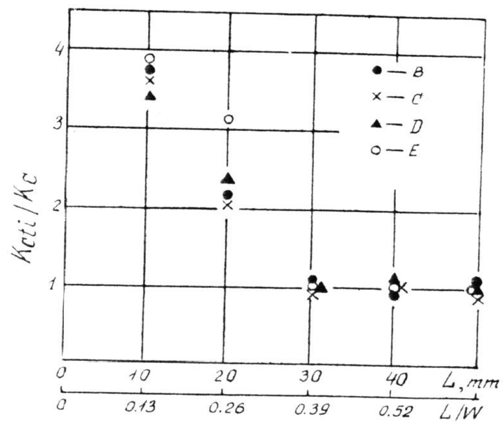

Fig.4. Changes of K_{cti}/K_c depending on L and L/W.

stated that at L/W>0.3 the relations of K_{cti}/K_c are near a one, Fig.4, and range between 1.12...0.89, 0.99...0.77, 1.11...1.06 and 1.15...1.09 for specimens B, C, D and E respectively.

CONCLUSION

Therefore, in time of thermal impulse application there is an opportunity to estimate fracture toughness according to the work of plastic deformation at a different level of yield in the fracture zone. With this the values of force fracture toughness characteristics obtained for steels being investigated by methods of fracture mechanics and by method of thermal impulse are satisfactorily in accordance with each other.

According to data by author of this paper the method of thermal impulse can be used for estimating the fracture toughness of metals on specimens and construction elements of different sizes, shapes and thickness under normal and lower temperatures, static and dynamic loading, that underlines the reliability and perspective of advised approach to the analysis of fracture toughness.

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