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Fracture toughness estimation by means of indentation test

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1. Introduction

The latest works [1, 2] prove the possibility of materials fracture properties estimation by means of indentation test. For this purpose a concept of an indentation energy to fracture (IEF) was suggested. The IEF model assumes fracture conditions to occur if the stress produced by the ball indentation exceeds the material's critical cleavage fracture stress (σ_f). The analysis of results show that the stress triaxialities present at a crack tip in a fracture toughness specimen and at the center of the contact surface under the indenter are similar [1, 2]. For this reason, the material at the center of the contact surface under the indenter experiences a degree of constraint similar to that experienced by the material at the crack tip. The deformation energy at the center of the impression is hence comparable to that at the front of a crack tip. Therefore, it has been postulated [1, 2] that the indentation energy per unit contact area up to critical fracture stress is related to the fracture energy of the material in transition region.

Previously [3], our application of the IEF concept for the estimation of impact strength, *KCV*, of low alloyed pipeline and pressure vessel steels was presented. It is well-known that most steels display almost similar behavior in impact strength and fracture toughness tests. For this reason in the present paper the correlation between IEF and K_{Ic} was examined.

2. Testing procedures and results

Chemical composition and mechanical properties of investigated steels are listed in Tables 1, 2. This data was obtained at the Institute for Strength Problems of the Ukrainian National Academy of Sciences [4]. Then the broken specimen parts were offered to the authors of the present paper.

All ball indentation tests were carried out at the Volgograd State Technical University (Russia).

The loadings of a spherical (D=5 mm) indenter in the load range from 147 to 11875 N within absolute temperature range 77 - 293 K were performed. For this purpose the standard Brinell (TŠ-2) and Rockwell (TK-2) hardness testers were used. After that the relationships $P=f(d^2)$, $P=f(h_{rec})$ and $HM=f(h_{rec})$ were obtained. Here P is the load value, d and h_{rec} – impression diameter and its recovered depth, respectively; HM - the Meyer's hardness determined as

$$HM=P/(\pi d^2/4) \quad (1)$$

The IEF values were calculated as

$$U_f = \int_0^{h_f} HM(h_{rec})dh_{rec} \quad (2)$$

Here h_f is critical recovered impression depth ($h_{rec}=h_f$) which corresponds to the condition $HM=\sigma_f$. The detailed description for U_f calculation was considered in our previous paper [3]. Our investigations of the dependencies $HM=f(P)$ at different temperatures for all steels have demonstrated that the Meyer's hardness, HM, under the load 147 N at the temperature 77 K is approximately equal to fracture stress, S_k at 77 K. For this reason the Meyer's hardness, HM, under the load 147 N at the temperature 77 K was taken for the material's critical cleavage fracture stress: $HM_f=\sigma_f$.

At first critical load P_f corresponding to $HM_f=\sigma_f$ was found from the $HM=f(P)$ experimental relationship. Then h_f value was determined from linear relationship $P=f(h_{rec})$. At last U_f values were found from Eq. (3). The results of these calculations were compared to K_{Ic} values in all investigated temperature range 77 - 293 K.

Data obtained for K_{Ic} and U_f is presented in Fig. 1. It reveals the linear relationship between K_{Ic} and U_f (Fig. 1). The dependencies $K_{Ic}=f(U_f)$ for steels 17G1S-U, 06G2NAB, 10G2FB-U, 10HGNMAYu, 10G2FB, 17GS, respectively, can be described by Eqs. (3)-(7).

Table 1

Chemical composition of investigated steels [4]

	10G2FB	17GS	17G1S-U	V St. 3 kp	06G2NAB
C	0.10	0.15	0.16	0.17	0.08
Mn	1.60	1.31	1.39	0.59	1.50
Si	0.33	0.51	0.51	0.22	0.25
S	0.004	0.016	0.018	0.025	0.01
P	0.020	0.017	0.015	0.016	0.02
Cr	—	—	0.02	—	—
Al	—	—	0.042	—	0.03
Ti	0.021	—	0.064	—	—
As	—	0.004	0.010	0.002	—
V	0.097	—	—	—	—
Nb	0.025	—	—	—	0.15
Ni	—	—	—	—	0.70

Table 2

Mechanical properties of investigated steels

Test temperature T, K	Yield stress $R_{p0.2}$, MPa	Ultimate stress R_m, MPa	Fracture stress S_k, MPa	Elongation A %	Reduction in area Z_k, %	K_{Ic}, MPa√m	K_{Jc}, MPa√m
10G2FB							
293	460	630	1140	24	59	40	240
243	500	665	1180	24	59	52	230
213	560	690	1460	25	59	66	180
77	960	1020	1530	21	40	40	—
Vst. 3kp							
293	280	420	1860	33	55	40	170
243	370	510	1920	33	53	40	134
213	400	540	1770	33	51	44	—
77	850	910	1500	18	22	28	—
17GS							
293	397	555	891	27	52	40	136
243	449	626	1063	28	53	44	126
213	452	630	984	28	50	52	106
77	830	898	1240	18	31	28	—
17G1S-U							
293	340	470	2170	30	58	46	164
243	435	590	2591	29	56	50	186
213	500	630	2474	30	54	54	164
77	815	915	2077	26	40	36	—
06G2NAB							
293	359	562	1128	33	66	50	130
213	383	665	1191	29	61	54	170
77	758	948	1618	26.6	51	38	—

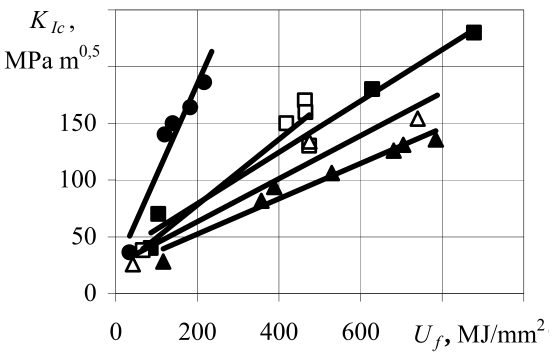

Fig. 1 Relationship between IEF value, U_f, and fracture toughness, K_{Ic}: ● – 17G1S-U, □ – 06G2NAB, ○ – 10G2FB-U, Δ – 10HGNMAYu, ▲ – 17GS

$$K_{Ic} = 0.808 \cdot U_f + 23.003 \quad (3)$$

$$K_{Ic} = 0.2888 \cdot U_f + 20.493 \quad (4)$$

$$K_{Ic} = 0.2264 \cdot U_f + 33.957 \quad (5)$$

$$K_{Ic} = 0.1898 \cdot U_f + 25.141 \quad (6)$$

$$K_{Ic} = 0.1556 \cdot U_f + 21.299 \quad (7)$$

The angular coefficient in Eqs. (3)-(7) depends on the value of fracture stress S_k, at the temperature 77 K and can be calculated as

$$\varphi = 0.0008 \cdot S_k - 0.9936 \quad (8)$$

At last the relationship between S_k and Misses stresses σ_i in the center of ball impression at the temperature of 77 K was investigated. It is known that the indentation does not induce any cracking in the tested materials. The stresses at the center of contact surface of the test specimen under the indenter are compressive, whereas the stresses in front of a crack tip in a fracture specimen are tensile. Nevertheless, the results of computer analysis show that the stress triaxilities present at crack tip in fracture toughness specimen and at the center of contact surface under the indenter are similar [1, 2]. Therefore, the material at the center of contact surface under the indenter experiences a degree of constraint similar to that experienced by the material at the crack tip. The deformation energy at the center of the impression is hence comparable to that at the front of the crack tip.

If the material in plastically deformed volume under the impression follows the power-law hardening curve $\sigma_i = f(\varepsilon_i)$, it is possible to compare the deformation energy consumed for the formation of a plastic zone under the ball impression to that at a small scale yielding zone ahead of the crack tip.

3. Analysis

According to Tabor [5], the ball indentation strain can be determined as d/D, where d and D are referred to the impression and ball diameter, respectively. The maximal value of this strain equals d/D=1. This strain approximately corresponds to uniform strain ε = 0.2 for low strength steels in tensile test. For the purposes of further analysis it is important to know stresses and strains in the deformed volume of metal under the impression. For this reason the relationship between Misses stresses, σ_i, and strains, ε_i, along the indentation axis and mechanical properties in tension was investigated.

Let's place the coordinate origin at the center of the indenter. Assume that Misses equivalent normal stress σ_i (stress intensity) in the plastic zone under the ball impression along the indentation axis Z, is a function of an Misses strain ε_i, and the graph of this function coincides with the tensile test diagram.

The σ_i values along the indentation axis were calculated as [6]

$$\sigma_i = \frac{1.5Ap_0\varepsilon_i}{3\varepsilon_i + exp\left[-1.5\varepsilon_{i0} + C\left(z-R\right)\right]} \tag{9}$$

where p_0 is normal pressure in the center of contact; R is indenter radius; ε_i is equivalent elastic-plastic strain, calculated as

$$\varepsilon_i = k\,h\,exp(-k(z-R)) \tag{10}$$

where k depends on material's elastic properties; h is recovered impression depth.

The ε_{i0} value in the center of impression is determined from Eq. (10) where $z=R$.

Normal pressure in the center of contact, p_0, was found as

$$p_0 = \left(1+0.5\frac{a}{D}\right)HM \tag{11}$$

where a is impression radius.

Constants A and C, respectively, are calculated as

$$A = \frac{h_s^3}{ln\frac{h_s+R}{R}\sqrt{\left(h_s^2+a^2\right)^3}} \tag{12}$$

$$C = \frac{1}{h_s}\left[-1.5\varepsilon_{i0} + ln3\varepsilon_y\left(\frac{Ap_0}{2\sigma_T}-1\right)\right] \tag{13}$$

where h_s is plastic zone length, ε_{i0} is Misses strain in the center of impression, ε_y is strain corresponding to the yield stress σ_y.

$$h_s = \sqrt{\frac{P}{2\sigma_y} - 1.6a^2} \tag{14}$$

We have found that at the temperature of 77 K Misses stress σ_i in the center of impression is a linear function of fracture stress S_k, at the same temperature (Fig. 2). Such correlation is not observed at room temperature. This can be explained by the fact that the material's critical cleavage fracture stress (σ_f) is reached at a low temperature, when yield stress σ_y, ultimate strength R_m, and fracture stress S_k, converge. For many steels this situation corresponds to the temperature T=77 K. For this reason very often it is assumed that material's critical cleavage fracture stress σ_f, equals the S_k value at T=77 K.

The correlation between S_k and σ_i at the impression center for the temperature 77 K may be described by the next empirical equation

$$S_k = 3.4814\sigma_i - 2103.7,\ \text{MPa} \tag{15}$$

For the experimental estimation of K_{Ic} values, angular coefficient φ, in the Eqs. (3)-(7) was calculated from formula (8), where fracture stress values S_k, were found from Eq. (15).

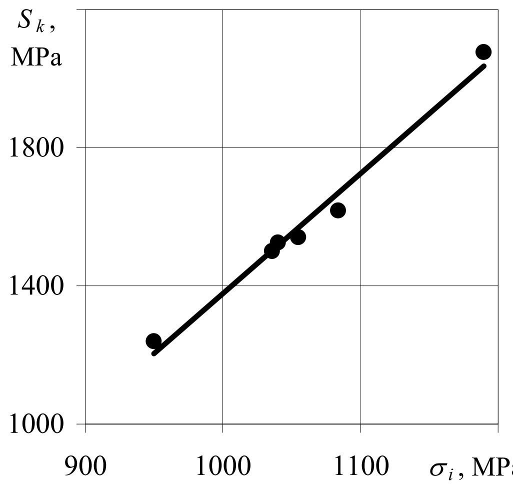

Fig. 2 Relationship between fracture stress, S_k and equivalent stress σ_i, in the center of impression at the temperature 77 K

As can be seen, in Eqs. (3)-(7) free terms have the scatter from 20.493 to 33.957. For the purpose of the formula unification a unified free term value – 25 was taken. Further calculations have shown that this simplification does not result in significant errors for K_{Ic} estimation.

4. Conclusions

According to the results presented in this paper, the procedure of the fracture toughness estimation can be described as follows. At first, ball indentation tests are carried out. Then the critical load P_f corresponding to $HM_f=\sigma_f$ is found from the $HM=f(P)$ experimental relationship. Then h_f value is determined from linear relationship $P=f(h_{rec})$. U_f values are calculated from Eq. (5), S_k values – from Eq. (15), and φ values – from Eq. (8). At last, K_{Ic} values can be calculated from the unified equation for all investigated steels

$$K_{Ic} = \varphi \cdot U_f + 25 \tag{16}$$

The error of indirect K_{Ic} estimation at room temperature does not exceed 20%. At the same time, it equals 40% at 77 K. It is accounted for by small K_{Ic} values at low temperatures.

The presented results allow to suggest the express method for fracture toughness investigation through the results of indentation test.

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ATSPARUMO ĮTRŪKIUI ĮVERTINIMAS KONTAKTINIO DEFORMAVIMO METODU

R e z i u m ė

Straipsnyje pateikiami vamzdinio plieno mėginių bandymo, atlikto įspaudžiant į juos 5 mm skersmens sferinį indentorių, rezultatai. Indendorius buvo apkraunamas apkrova, kintančia intervale nuo 147 iki 11875 N, absoliučiųjų temperatūrų intervale 77-293 K. Apskaičiuotos indentoriui įspausti reikalingos energijos U_f vertės, esant sąlygai $HM = \sigma_f$, kur HM ir σ_f – atitinkamai kietumas pagal Mejerį ir kritinis trūkio įtempis. Energija U_f atitinka įspaudimo kritinę energiją IEF. Nustatyta linijinė priklausomybė tarp tirtų plieno mėginių atsparumo trūkiui K_{Ic} ir U_f verčių visame temperatūrų intervale. Atliekant tempimo bandymus 77 K temperatūroje kampinis koeficientas φ priklausomybėje $K_{Ic}(U_f)$, yra atsparumo trūkiui S_k funkcija. Kuriant nesuardomąjį bandinio tyrimo metodą, įspaudo centre buvo nagrinėtas ryšys tarp tikrojo atsparumo trūkiui S_k 77 K temperatūroje ir Mizeso įtempio σ_i. Nustatyta, kad priklausomybė $S_k(\sigma_i)$ atitinka linijinį dėsnį. Tai įgalina visų tyrinėtu rūšių plieno priklausomybę $K_{Ic}(U_f)$ aprašyti viena apibendrinta lygtimi ir pasiūlyti greitą metodą atsparumui trūkiui nustatyti.

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FRACTURE TOUGHNESS ESTIMATION BY MEANS OF INDENTATION TEST

S u m m a r y

This paper presents the results of ball indentation tests carried out on specimens of pipeline steels. The loadings of a spherical (D=5 mm) indenter in the range from 147 to 11875 N within absolute temperature range 77-293 K were applied. Then the indentation energy U_f, corresponding to condition $HM = \sigma_f$, where HM and σ_f are the Meyer's hardness and the material's critical cleavage fracture stress, was calculated. This energy U_f, is known as IEF (indentation energy to fracture). The comparison of fracture toughness K_{Ic}, and U_f values reveals linear relationships $K_{Ic}(U_f)$ for all steels in all the investigated temperature range. Angle coefficient φ, in these relationships depends on fracture stress in tension S_k, for every steel. For the purposes of non-destructive S_k estimation, the relationship between S_k and Misses stress σ_i, in the center of impression at the temperature 77 K was established. At last K_{Ic} values can be calculated from the single unified equation for all investigated steels. Thus, the method of indirect fracture toughness K_{Ic}, estimation for pipeline and pressure vessel steels, based on the IEF (Indentation Energy to Fracture) model, is developed and discussed.

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ОЦЕНКА ТРЕЩИНОСТОЙКОСТИ МЕТОДОМ КОНТАКТНОГО ДЕФОРМИРОВАНИЯ

Р е з ю м е

В статье представлены результаты испытаний образцов трубных сталей методом вдавливания сферического индентора диаметром 5 мм. Испытания проводились в интервале нагрузок на индентор от 147 до 11875 Н, в диапазоне абсолютных температур 77-293 К. Затем рассчитывали энергию, затраченную на вдавливание индентора U_f, отвечающую условию $HM = \sigma_f$, где HM и σ_f – соответственно твердость по Мейеру и критическое напряжение скола. Установлена линейная зависимость между величиной U_f и трещиностойкостью K_{Ic} у рассмотренных сталей во всем интервале температур. Установлено, что угловой коэффициент φ в зависимостях $K_{Ic}(U_f)$ является функцией истинного сопротивления разрыву S_k при температуре 77 К в испытаниях на растяжение. Для разработки неразрушающего метода оценки величины была исследована зависимость между истинным сопротивлением разрыву S_k и эквивалентным напряжением σ_i в центре отпечатка при температуре 77 К. Получено, что зависимость $S_k(\sigma_i)$ следует линейному закону. Это позволяет описать зависимость $K_{Ic}(U_f)$ одним обобщенной уравнением для всех исследованных сталей и предложить оперативный метод оценки трещиностойкости исследованных сталей путём контактного деформирования.

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