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A method for impact strength estimation

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1. Introduction

Obviously that all properties of the material, defined by different mechanical tests, represent its concrete nature. The existence of relationships between different mechanical characteristic is fully explicable. The method for the estimation of mechanical properties in tension by means of hardness measurement is well known. This method makes it possible to get information on metal properties of an object directly, under conditions of its operation, without preparing specimens and their testing. The significant achievements in this field belong to D. Tabor [1], P.O. Pashkov [2], S.S. Vasauskas [3], M.P. Markovetz, [4], M.S. Drozd [5]. At the same time, the methods for fracture toughness and impact strength determination through the results of indentation test today are still under development. At present many investigators are occupied with the development of nondestructive methods for impact strength and fracture toughness determination. The latest works [6 - 8] prove the possibility of these properties estimation by means of automated ball indentation test (ABI). The use of the indentation technique for fracture properties estimation is not apparent because indentation does not induce any cracking in the material. Furthermore, the stresses at the center of the 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. It is assumed [6, 7], that although compressive loading does not promote fracture, it does introduce triaxiality in the material through the indentation process. Elasticity theory and preliminary computer analysis 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 [6, 7]. Therefore, 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 that the indentation energy per unit contact area upto a critical fracture stress is related to the fracture energy of a material in the transition region. This parameter is referred to as Indentation Energy to Fracture (IEF), and it represents the fracture energy as determined from ABI-measured stress-strain curves up to either the critical fracture stress or strain, depending upon the controlling micromechanism causing fracture, which in turn depends on the test temperature. The concept of a critical fracture stress is applied to the transition region and the concept of a critical fracture strain is applied to the upper shelf region. 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 . Hence if the value of stress at the point of contact is known as a function of indentation depth, the depth at which the stress exceeded σ_f could be calculated. If the energy deposited in the material by the indenter could be determined as a function of the depth, then the energy deposited upto assumed fracture stress could be predicted. This energy is termed the Indentation Energy to Fracture [6, 7].

Originally, this model was developed for the automated ball indentation test (ABI) [6, 8].

A possible approach to the problem of indirect impact strength estimation for pipeline and pressure vessel steels, based on the IEF model, is presented below.

2. Testing procedures

For experiments several low-alloyed pipeline and pressure vessel steels were used. Their mechanical properties within temperature range 77-293 K are presented in Table. The Charpy impact strength test and tension testing of steels were carried out by Krasowsky and Krasiko [9]. After testing, the specimens were offered to the authors of the present paper. All traditional, nonautomated ball indentation tests were carried out in 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 $F=f(d^2)$, $F=f(h_{rec})$ and $HM=f(h_{rec})$ were obtained. Here F is the load value, d and h_{rec} – impression diameter and its recovered depth, respectively; HM - the Meyer's hardness determined as

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

3. Analysis

The recovered impression depth, h_{rec}, was calculated as [10]

$$h_{rec} = \frac{D-\sqrt{D^2-d^2}}{2} - \frac{0.628\ F}{10000\ d} \quad (2)$$

The first and the second terms in formula (2) are geometrical (nonrecovered) impression depth for absolutely rigid spherical indenter under the load and elastic recovery of the impression depth, respectively. Elastic recovery of impression diameters d, was not taken into account because of very small difference between d values under the load and after unloading.

In the model discussed here, an assumption was made that the constraint of plastic flow of the material under the indenter is close to that in the crack tip, and fracture conditions occur when stress σ_z in the center of impression exceeds critical cleavage fracture stress σ_f. This assumption is in agreement with the maximum stress theory, Table

Mechanical properties of investigated steels

Test temperature T, K	Yield stress $\sigma_{0.2}$, MPa	Ultimate stress σ_u, MPa	Fracture stress S_k, MPa	Elongation δ, %	Reduction of area ψ_k, %	KCV, J/cm^2
10G2FB						
293	460	630	1140	24	59	142
243	500	665	1180	24	59	123
213	560	690	1460	25	59	73
77	960	1020	1530	21	40	10
Vst. 3kp						
293	280	420	1860	33	55	70
243	370	510	1920	33	53	27
213	400	540	1770	33	51	17
77	850	910	1500	18	22	10
17GS						
293	397	555	891	27	52	66
243	449	626	1063	28	53	45
213	452	630	984	28	50	31
77	830	898	1240	18	31	10
17G1S-U						
293	340	470	2170	30	58	65
243	435	590	2591	29	56	62
213	500	630	2474	30	54	51
77	815	915	2077	26	40	10
06G2NAB						
293	359	562	1128	33	66	132
213	383	665	1191	29	61	124
77	758	948	1618	26.6	51	16

which is correct for brittle fracture (for instance at low temperatures). The exact value of σ_f is not known. Often the least value of fracture stress S_k at 77 K is taken for the critical stress of a brittle fracture, but this is not quite correct because for many steels the values of fracture stress S_k, ultimate strength σ_u, and yield stress σ_y at the temperature of 77 K do not coincide. Real values of σ_f can be significantly higher.

The σ_z value in the center of impression under the load equals the specific pressure value p_0, on the contact surface in this point and can be calculated as 1-1.2 HM [11]. Our investigations of the dependencies $HM=f(F)$ at different temperatures for all steels presented in the table have shown that Meyer's hardness HM, under the load of 147 N at the temperature of 77 K is approximately equal to fracture stress S_k at 77 K. For this reason Meyer's hardness HM, under the load of 147 N at the temperature of 77 K was taken for critical cleavage fracture stress: $HM_f = \sigma_f$. If σ_f value as a function of an impression depth is known, the calculation of critical recovered depth value h_f, is possible.

After that the relationships between HM and h_{rec} for different temperatures within investigated temperature range were established. In preliminary analysis the dependencies $HM=f(h_{rec})$ were approximated by straight lines (Fig. 1).

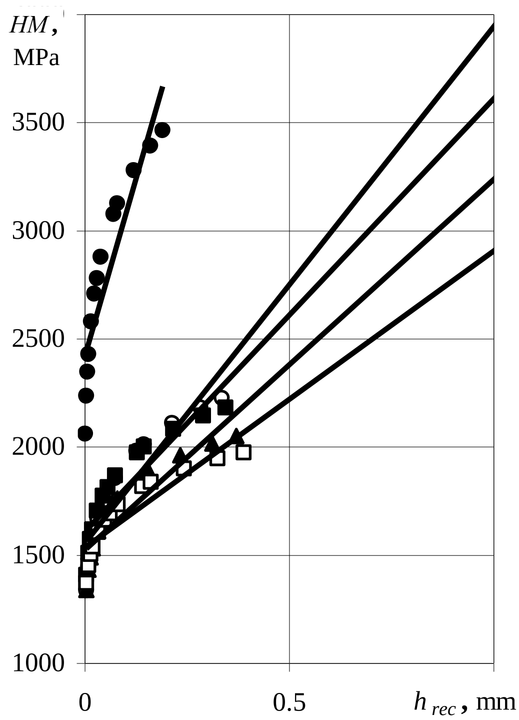

Fig. 1 Relationship between HM and h_{rec} for steel 06G2NAB: ● – 77 K, ○ – 193 K, ■ – 230 K, ▲ – 260 K, □ – 293 K

Taking into account the assumption that critical cleavage fracture stress σ_f, does not depend on temperature, critical recovered impression depths ($h_{rec}=h_f$) at any temperature were found from Fig. 1 as abscissa of the intersection point of horizontal line $y=\sigma_f$ and straight lines $HM(h_{rec})$. Then for this point the indentation energy U_f, was calculated as

$$U_f = \int_0^{h_f} HM\left(h_{rec}\right) dh_{rec} \quad (3)$$

here the HM value was found from formula (1) where h_{rec} is calculated from Eq. (2).

The value of load F_f, in formula (1), which corresponds to h_f, was found from linear relationships $F = \gamma\, h_{rec}$, where γ is an angle coefficient. This relationship for steel 06G2NAB is presented in Fig. 2. As can be seen, the linear relationship between load F and recovered impression depth h_{rec} is observed for all investigated steels at every testing temperature.

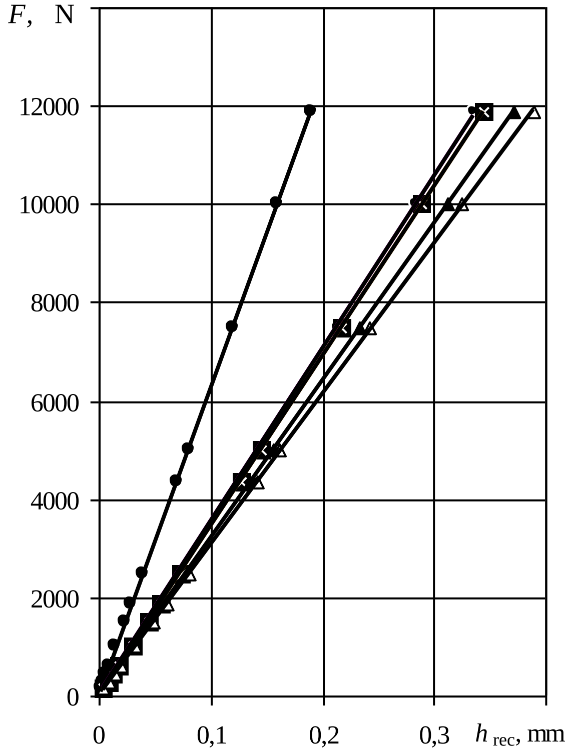

Fig. 2 Relationship between load F and recovered impression depth h_{rec}, for steel 06G2NAB: ● – 77 K, ○ – 193 K, ■ – 230 K, ▲ – 260 K, □ – 293 K

From Eqs. (3) and (4) we get [6]

$$U_f = \int_0^{h_f} \frac{\gamma\, h_{rec}}{\pi\left(Dh_{rec} - h_{rec}^2\right)} dh = \frac{\gamma}{\pi}\, ln\left[\frac{D}{\left(D - h_f\right)}\right] \qquad (4)$$

Critical indentation energy U_f is necessary for the formation of an impression corresponding to $HM_f = \sigma_f$.

After that the values of U_f and impact strength KCV, at different temperatures within temperature range 77 - 293 K were compared. As can be seen from Fig. 3, in all cases there is a linear relationship between U_f and KCV for all steels investigated.

These relationships for steels 17G1S-U, 06G2NAB, 10G2FB-U, 10HGNMAYu, 10G2FB, 17GS, respectively, in the temperature range 77 - 293 K are represented by the following equations

$$KCV = 0.341 \cdot U_f - 127.44 \qquad (5)$$

$$KCV = 0.118 \cdot U_f - 85.039 \qquad (6)$$

$$KCV = 0.204 \cdot U_f - 61.942 \qquad (7)$$

$$KCV = 0.126 \cdot U_f - 14.834 \qquad (8)$$

$$KCV = 0.035 \cdot U_f - 13.593 \qquad (9)$$

$$KCV = 0.105\ U_f - 22.62 \qquad (10)$$

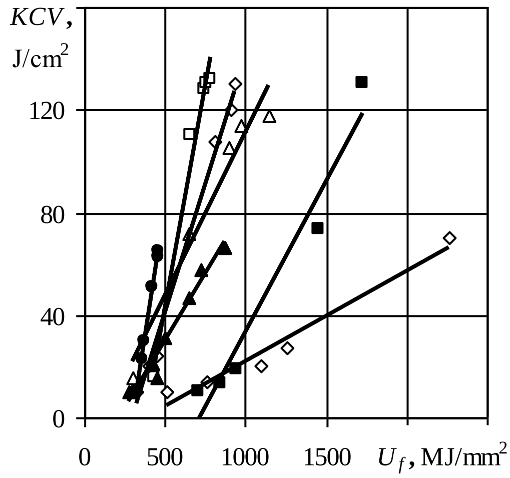

Fig. 3 Relationship between critical indentation energy U_f and impact strength, KCV: □ – 06G2NAB, ■ – 10G2FB, ○ – 10G2FB-U, Δ – 10HGNMAYu, ◊ – Vst3kp, ▲ – 17GS, ● – 17G1S-U

To increase calculations accuracy, the renewed method for U_f calculation was suggested. At first the critical load F_f corresponding to $HM_f = \sigma_f$ was found from the $HM = f(F)$ experimental relationship. Then h_f value was determined from linear relationship $F = f(h_{rec})$, Fig. 2. Finally U_f values were found from Eq. (3). Results of these calculations are presented in Fig. 4.

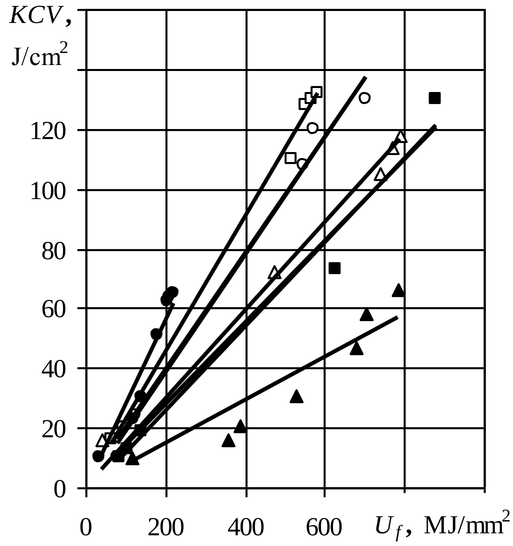

Fig. 4 Relationship between critical indentation energy U_f and impact strength, KCV: ● – 17G1S-U, □ – 06G2NAB, ○ – 10G2FB-U, Δ – 0HGNMAYu, ■ – 10G2FB, ▲ – 17GS

It is evident that in investigated temperature range the relationships between KCV and U_f can be described by unified equation: $KCV = \varphi\ U_f$.

Our further experiments have shown that for all steels angular coefficients φ depend on fracture stress $S_{k,77}$ at 77 K (Fig. 5). It was mentioned above that fracture stress $S_{k,77}$ at a temperature of 77 K can be taken for critical cleavage fracture stress σ_f. It is well known that this stress is a constant of material and almost does not depend on testing temperature.

The relationship $\varphi(S_{k,77})$ can be described as follows

$$\varphi = 0.0002\, S_{k,77} - 0.2143 \quad (11)$$

And finally it results in the following equation

$$KCV = (0.0002\, S_{k,77} - 0.2143)\, U_f \quad (12)$$

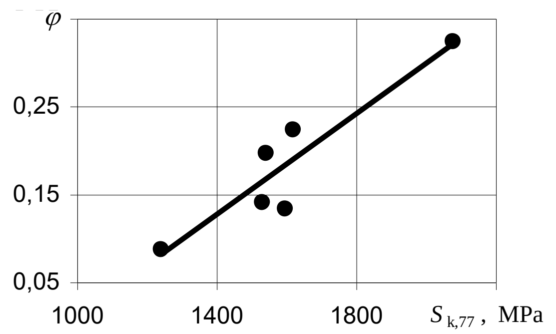

Fig. 5 Relationship between angular coefficient φ and fracture stress $S_{k,77}$ at the temperature of 77 K

Respective relationships for every steel investigated (17G1S-U, 06G2NAB, 10G2FB-U, 10HGNMAYu, 10G2FB, 17GS) are presented below. They are valid in the temperature range of 77-293 K.

$$KCV = 0.2798 \cdot U_f \quad (13)$$

$$KCV = 0.2252 \cdot U_f \quad (14)$$

$$KCV = 0.1950 \cdot U_f \quad (15)$$

$$KCV = 0.1476 \cdot U_f \quad (16)$$

$$KCV = 0.1369 \cdot U_f \quad (17)$$

$$KCV = 0.0727 \cdot U_f \quad (18)$$

The analysis described above shows the possibility of indirect impact strength evaluation by means of indentation and tensile test.

4. Conclusions

1. The results of mechanical properties investigations of pressure vessels and pipeline steels, such as tensile properties, Meyer's hardness and impact strength are presented and discussed.

2. The solution of the problem of indirect impact strength, KCV estimation for pipeline and pressure vessel steels, based on the IEF (Indentation Energy to Fracture) model, is presented.

3. The relationship between critical indentation energy value U_f , according to condition $\sigma_z = \sigma_f$, and impact strength *KCV*, appears to be linear and can be described by unified linear equation: $KCV = \varphi\, U_f$.

4. For all steels φ values depend on fracture stress S_k at 77 K. Thus, final relationship between *KCV* and U_f can be described as $KCV = (0.0002\, S_{k,\,77} - 0.2143)\, U_f$. It is valid in all the temperature range investigated of 77-293 K.

5. The present paper shows the possibility of impact strength *KCV*, estimation through the results of indentation and tensile tests.

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APIE VIENĄ SMŪGINIO TĄSUMO ĮVERTINIMO METODĄ

R e z i u m ė

Pateikiami vamzdinių plienų mechaninių bandymų, atliktų temperatūrų intervale 77-293 K, rezultatai. Nustatyta kietumo pagal Mejerį, bandomosios apkrovos ir sferinio indentoriaus įspaudos gylio tarpusavio priklausomybė. Išanalizuotas modelis smūginiam tąsumui nustatyti pagal sferinio indentoriaus įspaudą. Modelis pagrįstas žinoma įspaudimo kritinės energijos koncepcija IEF. Išanalizavus pateikiamą modelį daroma prielaida, kad suardymo sąlygos atsiranda tada, kai įtempis σ_z įspaudos viduryje viršija kritinį trapiojo medžiagos suardymo įtempį σ_f. Apskaičiuotos indentoriui įspausti reikalingos energijos U_f reikšmės, esant sąlygai $\sigma_z = \sigma_f$. Pereinamųjų temperatūrų intervale nustatytos tirtų plienų linijinės šios energijos ir smūginio tąsumo *KCV* tarpusavio priklausomybės: $KCV = \varphi\ U_f$. Kampinio koeficiento φ reikšmės šioje lygtyje priklauso nuo tikrosios atsparumo nutraukimui S_k dydžio reikšmės, esant temperatūrai 77 K. Parodyta galimybė smūginį tąsumą *KCV* netiesiogiai įvertinti pagal įspaudimo ir tempimo bandymų rezultatus.

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A METHOD FOR IMPACT STRENGTH ESTIMATION

S u m m a r y

The results of mechanical properties investigations of pressure vessel and pipeline steels, such as tensile properties, Meyer's hardness, *HM*, and impact strength are presented and discussed. The correlation between *HM*, load and recovered impression depth was investigated. The solution of the problem of indirect impact strength, *KCV* estimation for pipeline and pressure vessel steels, based on the IEF (Indentation Energy to Fracture) model, is presented. According to this model, fracture conditions occur when the stress σ_z in the center of ball impression exceeds critical stress of brittle fracture σ_f . The relationship between critical indentation energy value U_f , according to condition $\sigma_z = \sigma_f$, and impact strength *KCV* can be described by unified linear equation: $KCV = \varphi\ U_f$. It was found that for all steels φ values depend on fracture stress S_k at the temperature 77 K. The present paper shows the possibility of impact strength *KCV* estimation in the transition temperature range through the results of indentation and tensile tests.

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ОБ ОДНОМ МЕТОДЕ ОЦЕНКИ УДАРНОЙ ВЯЗКОСТИ

Р е з ю м е

Приведены результаты механических испытаний ряда трубных сталей в интервале температур 77-293 K. Установлены зависимости между твердостью по Мейеру, испытательной нагрузкой и глубиной восстановленного отпечатка сферического индентора. Рассмотрена модель для оценки ударной вязкости по результатам внедрения сферического индентора, основанная на известной концепции критической энергии вдавливания (IEF). В рамках указанной модели предполагается, что условия разрушения возникают тогда, когда напряжение σ_z в центре отпечатка превысит критическое напряжение хрупкого разрушения материала σ_f. Рассчитаны значения энергии вдавливания индентора U_f, соответствующие условию $\sigma_z = \sigma_f$. Установлены линейные зависимости вида $KCV = \varphi\ U_f$. между этой энергией и ударной вязкостью *KCV* исследованных сталей в интервале переходных температур. Значения углового коэффициента φ в этом уравнении зависят от величины истинного сопротивления разрыву S_k при температуре 77 K. Показана возможность косвенной оценки ударной вязкости *KCV* по результатам испытаний на вдавливание и растяжение.

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