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ISSN 0543-5846
METABK 48(4) 253-256 (2009)
UDC – UDK 669.15-194.5:620.163.4:539.551 = 111

TESTING SAMPLES SIZE EFFECT ON NOTCH TOUGHNESS OF STRUCTURAL STEELS

Received – Prispjelo: 2008-02-08
Accepted – Prihvaćeno: 2009-02-20
Original Scientific Paper – Izvorni znanstveni rad

In the paper notch toughness assessment of full scale testing samples (FS) form the upper bound toughness of sub-sized (SS) samples of structural carbon-manganese steels. The relations proposed by Schindler (2000) are in good agreement with experimental data. Empirical proportionality constant $q^* = 0{,}54$ between notch toughness of full scale and sub-sized samples of studied structural steels agrees well with theoretically estimated constant $q^* = 0{,}50$–$0{,}54$. More precise knowledge of the size effect of testing samples on temperature dependence of notch toughness requires an analysis of scatter in experimental data.

Key words: structural carbon steel, notch toughness, upper bound, sample size, sub-sized sample

Utjecaj veličine uzorka na žilavost konstrukcijskih čelika. U radu je data metoda utvrđivanja žilavosti za normirane (NU) i male uzorke (MU) probom savijanja za C – Mn čelike u temperaturnom dijapazonu gornje granice žilavosti. Za sve ispitivane čelike potvrđene su jednadžbe po Schindleru (2000) i u dobroj su korelaciji sa eksperimantalnim vrijednostima. Empirički utvrđena konstanta pravca g* = 0,54 između žilavosti normiranih i malih uzoraka suglasna je s teorijski izračunatom vrijednosti te konstante, koja se mijenja u rasponu g* =0,50 – 0,54. Precizniji podaci utjecaja veličine ispitivanih uzoraka na toplinsku ovisnost žilavosti zavisna je od analiza rasipanja eksperimentalnih podataka.

Ključne riječi: konstrukcijski uglični čelik, žilavost, gornja granica, veličina uzorka, mali uzorak

INTRODUCTION

The increasing need in the mechanical testing of sub-sized samples motivated the present study focused on the effect of the size of samples. Sometimes, attempts are made, due to economic reasons, to replace testing of the fracture toughness by a cheaper testing of notch toughness. Several empirical relations, pertaining to relations between fracture toughness and energy consumption in impact testing, as well as different methods of loading, have been suggested in works of Barsom and Rolfe [1], Barsom [2] and Marendet and Sanz [3]. An in-depth analysis is needed, not only from the point of view of specific methods of testing samples of different sizes, but, also, for the development of solid criteria for evaluating the fracture characteristics, particularly in view of risks involved in applying results of testing of small samples to a real structures.

THE INFLUENCE OF TESTING SAMPLES ON THE NOTCH TOUGHNESS

The energy consumed in the impact dynamic loading of notched samples is often a sufficient measure of the resistance of material to fracture. Determining a connection between the impact energy KV in tests of notch toughness and fracture toughness K_C is, however, quite complicated, especially in regard to different states of strain in material surrounding the notch and in a sharp fatigue crack, as well as from the point of view of different rates of deformation in the dynamic and quasi static loading. Several authors – Barsom and Rolfe [1], Barsom [2] and Marendet and Sanz [3] suggested empirical relations, where applicability under general conditions is unclear.

An interesting suggestion for evaluating fracture toughness in terms of impact energy KV was made by Schindler [4]. Analytical relations for fracture characteristics under substantial plastic deformation based on comparison of the fracture energy of notched samples with the one of fatigue cracks in the three-point geometry (Figure 1) and the impact energy KV from the impact test in bending. From the dependence of force F on the displacement s of notched samples with sharp fatigue cracks tested on an instrumented impact pendulum, it is possible to state energy W_m achieving maximal force F_m and the entire fracture energy W_t. The common dependence of J – integral on the growth of crack length Δa can be expressed as Anderson [5],

$$J = C \cdot \Delta a^{p} \quad \Delta a < \Delta a_m \tag{1}$$

where parameter C given by

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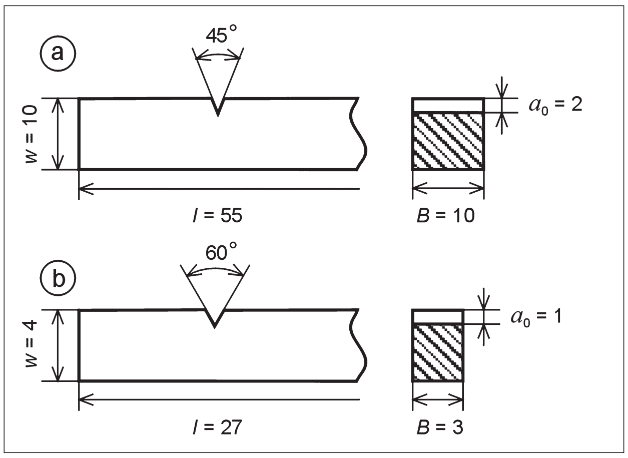

Figure 1. Geometry and dimensions of testing specimen for Charpy notch toughness test a) standard size (FS), b) sub-size sample (SS) (dimensions in mm).

$$C = \left(\frac{2}{p}\right)^p \cdot \frac{\eta \cdot (a_0)}{B_0 \cdot (w - a_0)^{p+1}} \cdot W_t^p W_m^{1-p} \quad (2)$$

is dependent, in addition to the geometry of the testing sample a_0, B_0, w (Figure 1), on parameters p and $\eta(a_0)$. These parameters have been suggested by Anderson [5] as

$$p = \frac{3}{4} \cdot \left(1 + \frac{W_m}{W_t}\right)^{-1} \quad (3)$$

$$\eta(a) = 13{,}81 \cdot (a / w) - 25{,}12 \cdot (a / w)^2; \quad 0 < a / w < 0{,}275 \quad (4)$$

where a is the crack length.

For strengthening material controlled by stress-strain behavior in the form $\sigma = A\varepsilon^n$, the growth of the crack at maximal force Δa_m, is given by Schindler [4] as follows:

$$\Delta a_m = \frac{n \cdot p \cdot (w - a_0)}{2} \quad (5)$$

where A is a constant, and n is the strain hardening coefficient. Since $W_m = nW_t$, and the strain hardening coefficient n is approximately equal to ductility A_f introduced by Kraft [5],

$$J = \left(\frac{2}{p}\right)^p \cdot \frac{\eta \cdot (a_0)}{B_0 \cdot (w - a_0)^{p+1}} \cdot W_t A_f^{1-p} \Delta a^p \quad (6)$$

$$p = \frac{3}{4} \cdot (1 + A_f)^{-1} \quad (7)$$

When $W_t = KV$ a comparison of equations (6) for two different geometries of testing samples of indexes 1 and 2 leads to the following relation:

$$KV_2 = \frac{\eta \cdot (a_{01})}{\eta \cdot (a_{02})} \cdot \frac{B_{02} \cdot (w_2 - a_{02})^{p+1}}{B_{01} \cdot (w_1 - a_{01})^{p+1}} \cdot KV_1. \quad (8)$$

From the knowledge of the results of the standard tests of notch toughness of KV_1 it is possible to use eq. (8) to find impact energy KV_2 in other geometries of testing samples with notches. Verifying the validity of this result for structural steels, an appropriate technical explanation in the replacement of classical testing of notched samples on sub-size samples can be obtained.

EXPERIMENTS AND RESULTS

For the study of influence of the size of testing samples on the temperature dependence of notched toughness, seamless pipes were used, made of carbon-manganese steel S355J2H manufactured according to EN 10210 and steel Gr6 according to ASTM A333, gas seamless pipes from carbon-manganese steel X52 and X60 manufactured according to norm API 5L and low-alloyed steel F22, F3VCb and A533 used in the production of pressure systems and equipment in nuclear energetic and chemical industries.

Steel F3VCb was studied in its basic state and also in the state of the step cooling from a temperature of 595 °C. A similar method of heat treatment was applied to low-alloyed F22 steel and for carbon-manganese A533 steel. All observed steels displayed a typical ferrite-pearlitic microstructure. Overall, eight basic structural types of structural steel were subjected to tensile testing basic strength and plastic properties, the yield point in tension $R_{p0,2}$, the ultimate tensile stress R_m, ductility A_5 and a reduction in area Z at normal temperature for these steels and their structural states are given in Table 1.

Table 1. **Basic strength and plastic properties of tested steels**

Material	Product	Orientation testing sample	R_{eH}, $R_{p0,2}$ / MPa	R_m / MPa	A_5 / %	Z / %
S355 J2H	pipe	tang.	326	490	33,6	76
Gr 6	pipe	tang.	286	449	34	64
X60	pipe	tang.	529	732	22,9	62
X52	pipe	tang.	393	538	33	72
F22	plate	long.	434	586	25,3	74
F3VCb (TZ)	plate	long.	498	620	20	76
F3VCb	plate	long.	509	618	21,6	77
A533	plate	trans.	522	652	23,4	74

(TZ) – Heat treatment - step cooling from a temperature of 595 °C

The temperature dependence of impact energy KV (J) and notch toughness KCV (J/cm^2) were tested on all eight types of steel in standardized Charpy samples with a V notch (Figure 1a) (marked as FS) and in non-standard samples (Figure 1b) (marked as SS). The experimental results on temperature dependence of the notch toughness for FS and SS samples by the least square method was fitted to a curve in the form

$$KCV(T) = kc_1 + kc_2 \cdot \tanh\left(\frac{\vartheta + \vartheta_1}{\vartheta_0}\right) \quad (9)$$

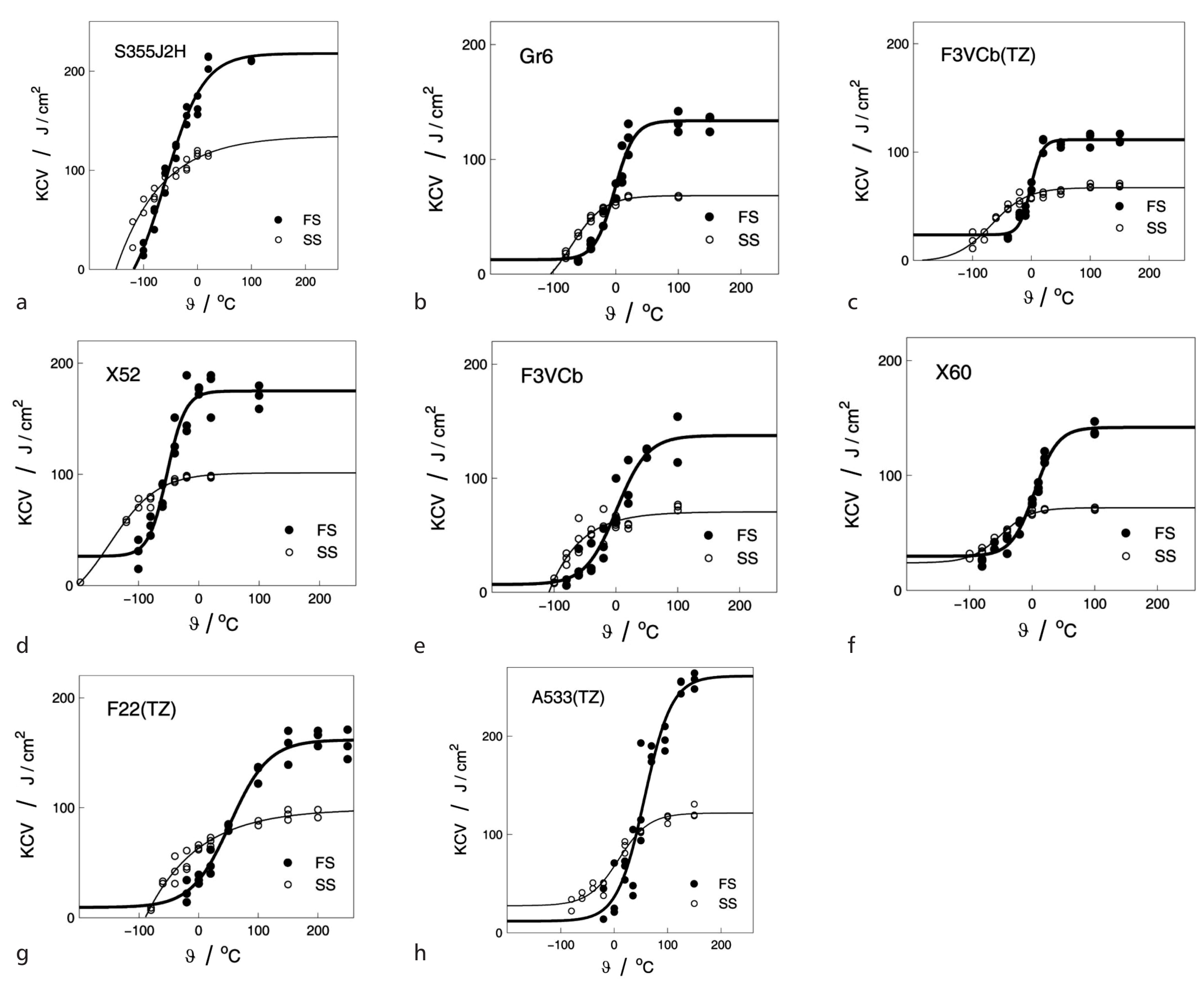

Figure 2. The temperature dependences assessed at standardized of notch toughness (FS) and sub-sized (SS) testing samples of studied structural steels.

where ϑ (°C) is the testing temperature, kc_1 (J/cm^2) and kc_2 (J/cm^2) are constants, with sum kc_1+kc_2 determining the upper limit of the notch toughness and ϑ_0 and ϑ_1 are constants in (°C), that determine the inflexion point of eq. (9) function. In graphs, the experimentally determined temperature dependence of notch toughness is given in Figure 2 for both types of testing samples.

The dependence of the upper bound notch toughness of sub-size SS samples on the upper bound notch toughness of standard FS samples determined from the results is given in Figure 3. The discovered relationship between upper bounds in notch toughness of sub-sized and full scale samples has the linear shape,

$$KCV_{\mathrm{uSS}} = q^* \cdot KCV_{\mathrm{uFS}} \qquad (10)$$

where q^* = 0,5438 is a numerical factor.

Comparing the numerical factor $1/q^*$ = 1,84 with the experimentally found ratio $KCV_{\mathrm{uFS}} / KCV_{\mathrm{uSS}}$ produces a good agreement. The ratio of $KCV_{\mathrm{uFS}} / KCV_{\mathrm{uSS}}$ is also compared with computed ratio $f_{\mathrm{FS}}^{\mathrm{SS}} KV_{\mathrm{uFS}} / KV_{\mathrm{uSS}}$ employing eq. (8), where $f_{\mathrm{FS}}^{\mathrm{SS}} = A_{SS} / A_{FS}$ = 0,1125, and A_{SS} = 9 mm^2 is the cross section area of the sub-size sample and A_{FS} = 80 mm^2 is the area of the cross section of the standard testing sample under the notch. For minimal $f_{\mathrm{FS}}^{\mathrm{SS}} KV_{\mathrm{uFS}} / KV_{\mathrm{uSS}}$=1,85 and maximal value of this quotient, $f_{\mathrm{FS}}^{\mathrm{SS}} KV_{\mathrm{uFS}} / KV_{\mathrm{uSS}}$=0,1,98 then for constant q^* = 0,54 and q^* = 0,50 from eq. (10) is the key of the predicted dependence KCV_{uSS} on KCV_{uFS} shown graphically in Figure 3.

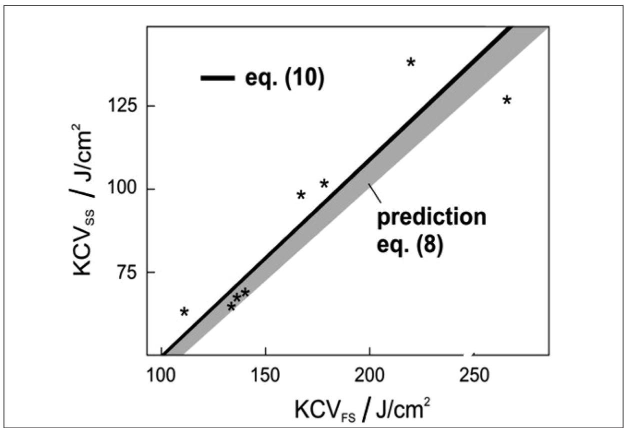

Figure 3. The relationship between upper bound notch toughness sub-sized specimen KCV_{uSS} and standardized specimens KCV_{uFS}.

Eq. (10), then recalculated as KCV_{uFS} on the notch toughness of sub-size samples KCV_{uSS} was valid for a maximal agreement, when $q^* = 0,5438$ in the entire studied temperature interval. The results are graphically shown in Figure 2. For all studied steels, it is shown that the recalculation of notch toughness of large samples for the sub-size samples using eq. (10) is very accurate in regions of the upper bound notch toughness. For sub-size samples the transition region shifts to a lower temperature. Both pieces of information are important for applications of testing results.

CONCLUSIONS

From Schindler's analysis of the relation between J-integral and the impact energy KV in the upper bound, we suggest a relation between notch toughness of large and sub-size specimens. We verified this relation experimentally on eight structural states of the selected steels with a ferrite-pearlitic structure. The proportionality constant between the notch toughness of large and sub-size samples determined from the experimental value of the upper bound $q^* = 0,54$ is in good agreement with the scatter interval corresponding to the stress-strain characteristics of studied steels, $q^* = 0,50 – 0,54$.

This work was made possible by financial support of GA ČR, Grant Agency Czech Republic 101/07/1569.

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Note: The responsible for the English language is B. Strnadel, Czech Rrepublic.