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THE RELATIONSHIP BETWEEN QUASI-STATIC AND IMPACT TOUGHNESS

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ABSTRACT
The toughness characteristics of structural materials may present critical property for materials selection, as well as for design or integrity assessment. The scope of this paper are terms for evaluation of fracture mechanics parameters, such as fracture toughness, K_c [MPam^{0,5}], or critical J-integral, J_c [kJ/m^2]. This evaluation may be done on the basis of known and easily determined impact toughness, KV [J]. The main difference between these toughness characteristics, i.e. between KV, and K_c and J_c on other side, is in testing conditions. The testing conditions are determined by existence of initial crack, strain rate, and stress-deformation state. Thus the main difference, quasi-static versus impact, and finally the test price follows. The general relationship terms for structural steels, provided in the actual reference technical literature, shall be presented, as well as the "own" terms based on regression analysis of experimentally determined toughness characteristics..
Keywords: relationship, quasi-static toughness, impact toughness

1. BASIS OF TOUGHNESS CHARACTERIZATION

The measure of material toughness is mostly presented as consumed or absorbed energy for deformation and fracture for characteristic type of loading. Therefore the toughness is mostly expressed in units of energy, e.g. Joules [J], as it is a case for the impact toughness, KV. However, there are other approaches, particularly defined in the field of fracture mechanics, where toughness may be presented as "critical stress concentration factor", or the fracture toughness, K_c [MPam^{0,5}]. While the fracture toughness, K_c, present linear-elastic fracture mechanics (LEFM) parameter, mostly used for definition of material's brittle behavior, there are also a number of elasto-plastic fracture mechanics (EPFM) parameters. While considering typical structural materials, e.g. structural steels, they reveal significant plastic deformation before final fracture, and hereby increased toughness. Therefore, for most structural materials it is more appropriate to evaluate EPFM parameters, evaluated from crack-growth resistance curves, and corresponding critical values, as J-integral [kJ/m^2], which is a energetic parameter, or crack tip opening displacement, CTOD [mm], which is a deformation parameter. In addition, the particular problem for determination of structure's material toughness is transferability of specimen's material toughness determined by conventional testing. This is mostly related to a structure's component thickness, and its influence on a material toughness. However, to understand particular toughness characteristic (or parameter), it is of utmost importance to understand a corresponding testing condition. Thus, Table 1, shows a general testing condition for selected toughness characteristics testing.

Table 1. General testing condition for selected toughness characteristics

Toughness characteristic	Label and unit	Testing condition	Specimen type / testing standard	General type of toughness
Absorbed energy by breaking	KV [J]	Charpy pendulum, very-high (impact) strain rate, specimen bending, mostly with complete specimen fracture	Charpy specimen, with initial notch / EN 10045-1	Impact toughness
Fracture toughness	K_c [$MPam^{0,5}$]	Specialized machine, slow load/unload, deformation control, specimen bending, crack growth up to 25% of remaining ligament	CT or SB specimen with initial notch and crack / ASTM E1820, BS 7448	Quasi-static toughness; LEFM parameter
J-integral	J [kJ/m^2]			Quasi-static toughness; EPFM parameter(s)
Crack tip opening displacement	CTOD [mm]			

2. TESTING CONDITION

According to European technical regulations, the Impact toughness test is defined in EN 10045 [1], where V-notched specimen (also, other type of notches are possible), 10x10x55mm in size, is loaded to impact bending by Charpy pendulum. During the test, which takes less than 10ms, an initial crack is developed from the notch tip, and corresponding crack initiation energy is consumed, KV_i [J]. Further during the test, as the specimen is loaded to impact bending, the crack growth occur, all over the remaining ligament of material, and corresponding crack growth energy is consumed, KV_p [J]. Both, KV_i and KV_p may be observed and measured on instrumented Charpy pendulum. Sum of the KV_i and KV_p present total absorbed energy by breaking of specimen, which is the conventional impact toughness characteristic, KV [J] [1].

For the purpose of evaluation and testing of fracture mechanics parameters, the common testing standard is American, ASTM E1820 [2], or British, BS 7448. Testing of fracture mechanics parameters is more complicated and demanding in comparison to impact toughness testing. Briefly, the specimen of carefully selected size and initial notch is pre-loaded on pulsing-fatigue testing machine, where initial fatigue crack is developed. Than, such prepared specimen is mounted on specialized machine for quasi-static bending loading/unloading. In fact, the prepared pre-cracked specimen is continuously loaded and unloaded, with very slow strain rate, approximately 1mm/min, and with control of deformation. During every load/unload sequence, the crack growth occur. In the same time, during the test, the load (force), F [kN], and at least the crack mouth opening displacement, COD [mm], is continuously measured. The loading/unloading sequence last up to maximum COD gauge range, e.g. 5mm, or up to maximum 25% crack growth, Δa [mm], of remaining ligament, b [mm]. After the finished test, the particular demanding calculation procedure of crack tip opening displacement, CTOD [mm], and J-integral, J [kJ/m^2], follows, with final result presented as crack growth resistance curve(s), either as CTOD-Δa, or J-Δa. Finally, on obtained resistance curves, the characteristic "critical" values may be evaluated, as J_{Ic} [kJ/m^2], and $CTOD_{Ic}$ [mm]. The designation "I" in index of values, J_{Ic}, $CTOD_{Ic}$, mean first type of loading (by crack opening, during specimen bending). Finally, for evaluated critical EPFM parameters, J_{Ic} and $CTOD_{Ic}$, the fracture toughness, K_{Ic} [$MPam^{0,5}$] may be calculated [2]. In this way determined LEFM and EPFM parameters, presents material's properties, or critical values which determine material's resistance to crack stable/unstable growth.

From, above described testing condition, the following main differences emerge:

- J_{Ic}, $CTOD_{Ic}$, and K_{Ic} are quasi-static toughness characteristics, or fracture mechanics parameters, while KV is impact toughness characteristic (or parameter);
- It is more complicated to evaluate quasi-static toughness characteristics, in comparison to more simplified impact toughness, while the corresponding testing price is about 10-20 times higher.

Thus, the main question appears: Is there a possibility to define simplified relationship between quasi-static and impact toughness characteristic? Such relationship particularly becomes interesting if it is necessary to evaluate structural integrity, as it defined in novel international procedures, such as the FITNET procedure [3].

3. REALATIONSHIP PRINCIPLES

The general theoretical relationship between fracture mechanics parameters is well known, and it is defined in accordance to strain/stress state, e.g. plane stress or plain strain. This relationship is defined for known material's, modulus of elasticity, E [GPa], yield stress, $R_{p0,2}$ [MPa] and Poisson ratio, ν [-]:

$$\text{plain strain: } K_{Ic} = \sqrt{\frac{E \cdot J_{Ic}}{\left(1-\upsilon^2\right)}} \text{ ; } K_{Ic} = \sqrt{\frac{R_{p0,2} \cdot CTOD_{Ic} \cdot E}{\left(1-\upsilon^2\right)}} \quad \text{...(1)}$$

In this way generally, the lower conservative material's fracture toughness, K_{Ic}, is defined. Obviously, a general variation of fracture toughness depends on material's thickness [3].

According to FITNET procedure, if absorbed energy (impact toughness), KV [J] is known; than the lowest fracture toughness, K_{Ic} [$MPam^{0,5}$] may be estimated, for known specimen thickness, B [mm] in accordance to term (2). In addition, for observed fully ductile fracture, and corresponding impact toughness, KV [J], the lowest fracture toughness may be estimated in accordance to term (3) [3]:

$$K_{Ic} = \left[\left(12\sqrt{KV} - 20\right)\left(\frac{25}{B}\right)^{0,25}\right] + 20 \quad \text{...(2)} \qquad K_{Ic} = 11,9 \cdot KV^{0,545} \quad \text{...(3)}$$

While taking into account variable value of fracture toughness, it is a common way to express relationship between J_{Ic}, $CTOD_{Ic}$ and K_{Ic} in form of term (4) [6]. Also, relationship between fracture toughness, K_{Ic} [$MPam^{0,5}$], as a quasi-static toughness characteristic, and impact toughness, KV [J], is usually provided in form of term (5) [3]:

$$K_{Ic} = a \cdot \sqrt{J_{Ic} \cdot E} \quad ; \quad J_{Ic} = b \cdot \left(CTOD_{Ic} \cdot R_{p0,2}\right) \quad \text{...(4)} \qquad K_{Ic} = m \cdot KV^n \quad \text{...(5)}$$

Values of constants, a, b, in term (4), and, m, n, in term (5), are obtained by appropriate regression analysis of experimental results. Therefore, to define above described relationship it is necessary to perform detailed testing of mechanical properties (at least $R_{p0,2}$), as well as testing of fracture mechanics parameters, J_{Ic}, $CTOD_{Ic}$, K_{Ic}, including impact toughness characteristics, KV. However, obtained relationship may be subject of dependence check to material's thickness and testing temperature. For example of such relationship, the following paragraph will provide typical analysis for two structural materials.

4. EXAMPLE(S) OF RELATIONSHIP FORMULATION

Table 2 provides sample results of toughness characteristics for two structural materials [4,5].

Table 2. Sample results of impact toughness and quasi-static toughness testing

specimen	quenched and tempered structural steels HSQT, $R_{p0,2}$=690-890MPa				heat-resistant structural steel HRSS, $R_{p0,2}$=220-545MPa			
	KV [J]	J_{Ic} [kJ/m^2]	$CTOD_{Ic}$ [mm]	K_{Ic} [$MPam^{0,5}$]	KV [J]	J_{Ic} [kJ/m^2]	$CTOD_{Ic}$ [mm]	K_{Ic} [$MPam^{0,5}$]
1	194	222	0,263	227	120	70	0,181	127
2	160	176	0,141	202	107	50	0,138	107
3	127	122	0,130	168	87	45	0,215	102
4	104	119	0,105	166	70	37	0,061	92

Note:
1) For steel: E=210GPa, ν=0,3;
2) Specimens 1-4 may present various state of material (new, used, as welded, high-temperature property)

The toughness characteristics relationships are obtained after simplified analysis, in accordance to terms (4) and (5), as presented in Figure 1.

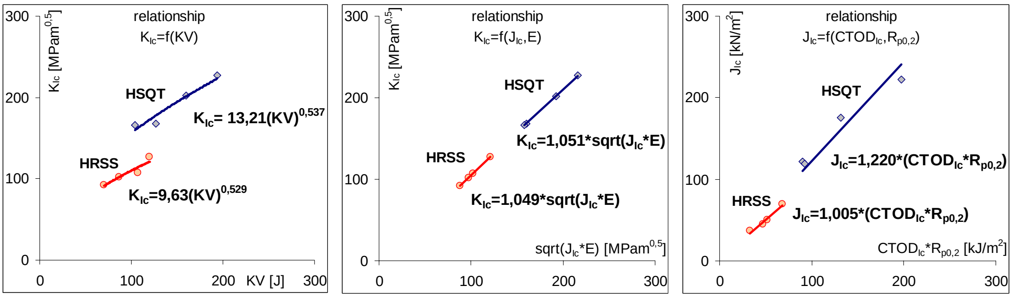

Figure 1. Relationship between impact and quasi-static toughness for two structural materials

6. REMARKS

This paper outlines general principles for testing of impact and quasi-static toughness characteristics. While considering main differences, specimen preparation, initial notch and/or initial crack, type of testing, and finally a testing price, it may be important to establish simplified relationship between different toughness characteristics.

Those relationships particularly become important if modest laboratories are not able to perform quite demanding and expensive testing of quasi-static toughness, or fracture mechanics parameters testing. In addition, novel integrity assessment procedures, as the international FITNET, provide different levels of assessment, defined in accordance availability of material's resistance properties. However, as much as particular material's properties are not available, the final assessment become more conservative. Here particularly, for more reliable and safe assessment, knowing of LEFM and EPFM fracture mechanics parameters may be of utmost importance.

Terms provided in Figure 1, for two structural materials, e.g. high-strength quenched and tempered steel, HSQT, and heat-resistant steel, HRSS, gives relationship between impact toughness, KV [J], fracture toughness, K_{Ic} [$MPam^{0,5}$], critical J-integral, J_{Ic} [kJ/m^2], and critical crack opening displacement, $CTOD_{Ic}$ [mm]. Therefore, if only material's impact toughness, KV, is known, as well as basic mechanical properties, $R_{p0,2}$, E and ν, it is possible to estimate, fracture mechanics parameters, both, LEFM, K_{Ic}, as well as EPFM, J_{Ic} and $CTOD_{Ic}$.

Finally, provided relationship terms are given for few experimentally obtained results of impact and quasi-static toughness characteristics. More precise regression analysis may require testing of different materials thicknesses, and on typical range of service temperatures.

7. REFERENCES

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