FRACTURE TOUGHNESS OF STRUCTURAL MATERIALS AND THEIR WELDED JOINTS

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ABSTRACT

This paper offers structures of small-size cylindrical samples with a ring crack in order to determine a fracture toughness characteristic (K_{1C}) of structural materials and their welded joints with the average and low strength.

They include a solid cylindrical sample with a ring crack, a sample with shrunk-on thread rings on an outer surface of the base, a sample with a ring groove for weld-on of the material investigated and a ring crack within this weld-on. Relationships are calculated in order to determine the K_{1C} characteristic of the material for these structures and are presented here too.

KEYWORDS

Cylinder, sample, groove, crack, joint, weld-on, fracture toughness, diameter, cut, machine, recess, thread, ring, steel, welding, argon.

INTRODUCTION

When studying half-brittle materials in order to determine the K_C or K_{1C} characteristics according to the British (Draft for Development.3:1971) and American standards (E.399-74), corrections have been made pertaining to the crack length with account of the top size of a plastic zone:

$$ry=1/2\pi(K_C/\sigma_{0.2})^2, \quad ry=1/6\pi(K_{1C}/\sigma_{0.2})^2 \qquad (1)$$

According to these corrections the width of the sample during an eccentric tension test is equal

$$B \geq 2.5(K_C/\sigma_{0.2})^2, \quad B \geq 2.5(K_{1C}/\sigma_{0.2})^2 \qquad (2)$$

for flat-strained and flat-deformed states respectively.

Proceeding from the condition of the pre-destruction zone onconformity (Panasyuk, 1991; GOST 25.206-85) the dimensions of the cylindrical sample with the ring crack are

$$D \geq 2.3(K_{1C}/\sigma_{0.2})^2, \quad d \geq 1.6(K_{1C}/\sigma_{0.2})^2, \quad L=10D \qquad (3)$$

where D is the outer diameter, d is the diameter of the sample with the ring crack, L is the length of the sample, $\sigma_{0.2}$ is the material yield limit.

However, in various authors' opinion the above mentioned correlations need to be corrected because the factual values of K_{1C} and K_C are influenced by the sample size, the amount and configuration of the plastic zone before the crack, deformation rate, temperature, medium, defects scale, material strength etc. When investigating half-brittle materials in order to determine factual K_{1C} one needs large-size samples and a powerful testing equipment due to the great consumption of the material to manufacture them and difficulties of the test methods.

We shall make an attempt to define the most important fracture toughness characteristic K_{1C} of the material for the cheaper cylindrical samples with the ring crack.

DETERMINATION OF K_{1C} CHARACTERISTIC OF MATERIALS

Calculating K_{1C} of the Material for the Small-Size Cylindrical Samples. Having analysed numerous experimental results (Kogut, 1986) for the small-size cylindrical samples (D=8...10 mm) with the ring cracks we found that during investigation of brittle materials the factual characteristic K_{1C} of the material had been obtained for the sample with small diameters and visa versa, less brittle materials required samples of a larger diameter. We have also discovered that during the destruction of brittle and viscous materials, correlation $\sigma^*/\sigma_{0.2}$, where σ^* is the amount of the ultimate tensile stress during extension of a small-size cylindrical sample with a crack, and $\sigma_{0.2}$ is the yield limit of the given material, varies differently.

When $\sigma^*/\sigma_{0.2} \leq 1$ the value of the outer diameter is calculated by formula (3) and $K_C=K_{1C}$. Taking this into consideration and accounting for a large number of experimental data regarding K_C for small-size samples of various types of materials a simpler empiric dependence is suggested:

$$K_{1C}=K_C \cdot \sigma^*/\sigma_{0.2} \, . \qquad (4)$$

When $\sigma^*/\sigma_{0.2}=n$ (where n is the material strengthening coefficient) formular (4) may be generalized as follows:

$$K_{1C}=K_C \cdot n \, . \qquad (5)$$

As it appeared, n may essencially change, depending on the properties of the material under investigation and the sample diameter, i.e. $N=f(\sigma_B, \sigma^*, D)$. In the experiments carried out n=0.9 ... 2.5. Then $K_C \cdot n=\text{const}$ independently from the diameter of the tested sample with the crack, i.e. maximum K_C pertains to minimum K_{1C} and visa versa. When $K_C=K_{1C}$, $n \leq 1$.

Formulas (4) and (5) have been proved true with 40 grades of the materials under investigation (low-carbon, low-alloy, multi-alloy steels and high-durable titanium and aluminium alloys), which have different structural states (σ_B=380...2250 MPa) corresponding to the values of K_{1C}, which were determined when taking into account correction of the size of the plastic zone $ry=\Delta l+l$ in reference to the crack length, after measuring micro-hardness in its top and taking K_{1C} data for the large-size samples (Kogut, 1980).

Thus, during K_{1C} test a sample should have such a diameter that it do not permit crossing its netto-section by a plastic deformation zone starting from the top of a ring crack (D≥10 mm).

Calculating K_{1C} of the Material in the Cylindrical Samples with Thread Rings. When defining K_{1C} fracture toughness of viscous materials valuable information can be provided by test methods of the cylindrical samples with thread rings. The structure of such a sample (Fig.1) comprizes a base 1, a ring cut 2, a ring crack 3, a thread surface 4 and two thread rings 5. Fatigue fracture has been formed by a circular bend according to the methods described in (Kogut, 1986).

Due to the fact that the material for rings is harder than material for the base, and the very thread joint is strained, plastic yield of a viscous material is retarded during the extension and consequently the possibility of brittle destruction arizes. The investigation results obtained after testing tne samples if the suggested structure (D=16 mm, dk=12mm, d=11mm and L=150mm) with shrunk-on thread rings made of high-carbon steel Cт8 after hardening in oil (thread M16x2, D_o=80mm, 2L=64mm) were (K_{1C}=58,9 MPa$\sqrt{m}$) for normalized steel 20X, (K_{1C}=68.2 MPa$\sqrt{m}$) for normalized steel 40X and

(K_{1C}=62.3 MPa$\sqrt{m}$) for steel Ст3 of the initial state. These results are well agreable with K_{1C} tests carried out with the large-size samples of the same steels.

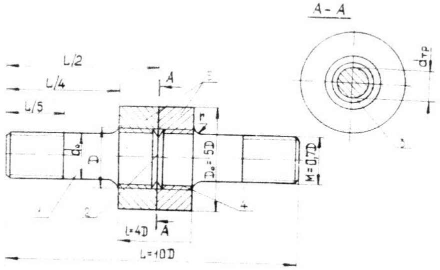

Fig.1. Structure of a cylindrical sample with shrunk-on thread rings.

Calculating K_{1C} of the Materials for the Cylindrical Samples with a Ring Groove for Weld-on. We also suggest methods of calculating K_{1C} of viscous materials for the samll-size cylindrical samples with a ring groove for the weld-on of the material under investigation (Kogut et al., 1991). As it has been earlier found the flat-deformed state occurs in the top of the crack during the extension of the cylindrical sample and plastic zone, which appears to have two isoclinic lines directed at the angle of 72° to the crack plane (Fig2).

Their length equals to

$$l^* = 0.184(K_{1C}/\sigma_{0.2})^2 \qquad (6)$$

In this case the condition of the pre-destruction zone inconformity is being preserved. Then, the diameters of the samples will be

$$d \geq 1.6(K_{1C}/\sigma_{0.2})^2, \quad D \geq 2.3(K_{1C}/\sigma_{0.2})^2.$$

And under the conditions

$$x_o \leq 0.035d \quad \text{or} \quad x_o \leq 0.015(D-d) \qquad (7)$$

$$x_o = l^* \cdot \cos 72^\circ, \qquad (8)$$

where x_o is the length of the plastic zone, l^* is the crack length. Having taken that the groove height is 2c=3mm and assuming that relative size of the crack λ =d/d=0.7 by formulas (7) and (8), the outer diameter of the cylindrical sample can be calculated proceeding from the condition

$$c \leq x_o \cdot \mathrm{tg}\ 72^\circ \qquad (9)$$

or

$$c \leq \mathrm{tg}\ 72^\circ \cdot 0.035 \cdot 0.7D \qquad (10)$$

From the above we have $\quad D \geq 20.78$ mm $\quad$ (11)

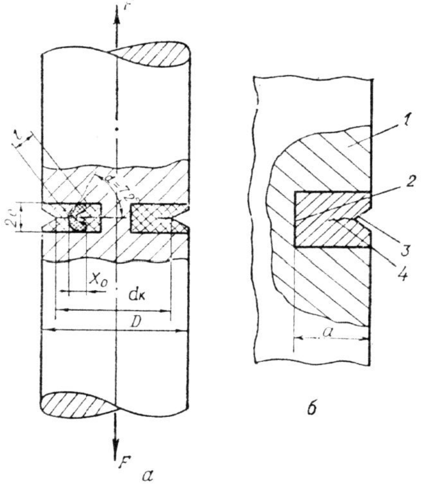

Fig.2. Loading diagram of the sample with a ring crack and configuration of the plastic zone in the crack top of the weld-on (a) and its structural elements (b).
1-base, 2-ring groove, 3-cut, 4-crack.

As we see: if a cylindrical sample is made of the material for which the inconformity conditions are preserved at D=21mm and at the groove height 2c=3mm for the weld-on, K_{1C} being determined is a factual characteristic of the material under investigation.

For the material which does not meet the pre-destruction zone inconformity conditions the base (diameter) of a sample should be increased or the size of the plastic zone before the crack should be limited in the following way.

A ring groove with the depth $a=0.2D$ and the height $2c=3$mm is recessed in the cylindrical sample made of the material that meets the inconformity conditions (Fig.2 (a),(b)). It is then welded on by the investigated viscous material and turned and grinded to the diameter D. Alongside the middle of the weld-on height a ring cut $dk/D=0.8$ is done and a ring fatigue crack is formed with $d/D=0.7$. K_{1C} is calculated by

$$K_{1C}=\frac{F^{*}}{D\sqrt{D}}\cdot Y \quad ; \qquad (12)$$

$$Y=\frac{0.7976\sqrt{1-\lambda}}{\lambda\sqrt{\lambda}\cdot\sqrt{1-0.8012\lambda}}, \qquad (13)$$

where Y is the function which depends upon relative size of the crack ring $\lambda=d/D$.

The sample structure suggested has been tested on the base made of high-carbon steel У 7 with D=22mm diameter with a ring groove of 2c=3mm height and 2a=18mm depth, which was welded on by the argon-arc welding using the following materials: Cт 3 for the first batch, 20X for the second batch and 40X fo the third one. Final sample dimensions after grinding and formation of the ring cut ($\rho \leq 1$mm) and the initial ring crack (Kogut,1986) were D=21mm, dk=18mm, d=16mm. The obtained values of K_{1C} for the weld-on materials are $K_{1C}=62.1$ MPa$\sqrt{m}$ for 20X, $K_{1C}=65.7$ MPa$\sqrt{m}$ for 40X and $K_{1C}=63.3$ MPa$\sqrt{m}$ for Cт 3. They totally agree with K_{1C} values for the same steels for the large-size samples (Zazulyak, 1981; Kogut et al., 1991).

Hence, the plastic zone in the top of the ring crack of the weld-on material when axis loading,is stopped due to the confrontation with a facing groove surface of a sample with much harder base. This causes favourable conditions for brittle destruction of the viscous material under investigation. This is confirmed by the fact of brittle reliefs which appear at the fractured surface,proving that the obtained values of K_{1C} are true.

CONCLUSIONS.

1. Testing small-size cylindrical samples enabled to discover theoretical evidence of the determination of factual value of K_{1C} through K_C and n - the material strengthening coefficient, i.e. $K_{1C} = K_C \cdot n$. This is approved experimentally with 40 materials of various strength.

2. Application of shrunk-on thread rings of an increased strenghth and hardness at the outer surface of the base hinders plastic deformation of a viscous material. This causes favourable conditions for flat deformation and determination of factual K_{1C} values for the small-size cylindrical samples.

3. Application of the cylindrifal sample with a ring groove for the weld-on of a viscous material in the casing of a harder one implements the inconformity conditions of the pre-destruction zone when defining fracture toughness K_{1C} of a welded joint for a small-size cylindrical sample as well as for a large-size one.

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