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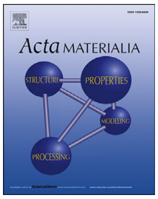

Full length article

Intrinsic impact toughness of relatively high strength alloys

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ABSTRACT

Although the Charpy impact test has been routine for decades to assess the ductile or brittle nature of materials, the impact toughness, which is strongly sample-thickness dependent, is not an intrinsic property. By re-examining the energy absorption during fracturing of relatively high strength alloys, here we find a remarkably good linear relation between the impact energies and the fracture surface areas of samples with different thickness, and the slope essentially renders the intrinsic impact toughness. The new findings, which also provide a scaling law to well predict the thickness effect on the traditional impact toughness, may have broad applications for precisely determining the ductile-to-brittle transition temperature of small-dimensional devices, selecting materials according to their toughness at the thickness in usage, and evaluating the intrinsic toughness of emerging high strength materials with limited achievable size.

1. Introduction

If the designer of *Titanic* had known that the steel used for the hull would lose its toughness and become brittle in icy water, the disaster in 1912 might be avoided [1]. After long-standing efforts, people eventually realize that the toughness, which characterizes the resistance to crack propagation, should be another quite important consideration, besides the strength, in materials selection [2]. Due to the ability to accurately detect the ductile-to-brittle transition (DBT) in steels, the Charpy impact test, which assesses the toughness of materials with the absorbed energy per unit area of fracture surface, has been widely accepted and used since 1940s [3,4]. Now the impact testing remains routine not only for quality control and toughness evaluation of materials, but also for assessing the structural integrity of components [5], though a more intrinsic toughness concept, namely the plane-strain fracture toughness, K_{IC}, has been developed [6]. This is because in comparison with measuring the K_{IC}, the impact testing is fast, inexpensive, and much easy to be conducted in practice.

However, different from other mechanical properties (e.g., strength) that are usually intrinsic constants of materials and independent on the extrinsic sample size (except for at micro-scale or nano-scale [7]), the impact toughness derived from the conventional Charpy testing procedure strongly relies on the sample thickness [8–12]. One example is that the DBT temperature of steels has been found to vary with the dimensions of the impact samples [10,11,13–17], which essentially implies the failure of predicting the mechanical performance of service devices with pre-experiments. Meanwhile, for comparing the toughness values of different materials, it only makes sense if using the same thickness samples. As a result, the 10-mm-thinckness for impact testing samples has been ruled by the ASTM standard [18]. But why is it 10 mm and how does sample thickness affect the impact toughness value?

The restriction on sample dimension brings difficulties in the toughness evaluation for those advanced materials with limited size. For example, while the emerging nanostructured metallic materials, which show extremely high strength and other promising properties, have been extensively developed, they are usually formed in limited size [19–24]. On the other hand, the thickness-dependent impact toughness of materials suggests that the value measured according to the 10-mm rule may not be the exact toughness of structural components with smaller characteristic sizes, implying the invalidation of the measurement.

In this work, we re-examined the definition of impact toughness by analyzing the mechanism of energy absorptions during

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fracturing, and found the intrinsic impact toughness of relatively high strength alloys that is independent on the sample thickness. The intrinsic impact toughness was experimentally confirmed and measured from six groups of engineering alloys, and the relation between the intrinsic impact toughness and the traditional one was analyzed, which further allowed the thickness effect on the impact toughness being well explained.

2. The model

Let us first consider the process of Charpy impact fracturing. The sample usually contains a V-shaped notch, where the crack would initiate from, as shown in Fig. 1(a). During impacting, the side opposite to the notch receives the impact load from a pendulum with specific weight, and the sample fractures in high rate flexure [6]. The impact fracture surface of relatively high strength alloys can be illustrated in Fig. 1(b). The newly formed surface generally has two kinds of regions: cracking region and shear lip region [25]. The cracking region mainly results from the propagation of a fast crack, and usually exhibits flat feature along the cross-section plane of the sample, while the shear lip region, which is close to the sample surfaces, forms an angle of ~45° with respect to the length direction.

Conventionally, the impact fracture toughness, α_K, is defined as,

$$\alpha_K = A_K/S_t, \tag{1}$$

where A_K is the total fracture energy absorbed during impact process, and S_t is the total area of the fracture surface, namely, $S_t = Bh$, with B the sample thickness and h the net height of sample (without including the notch depth).

Although Eq. (1) allows the toughness values being simply obtained, the physical nature of α_K is not so clear. Except for ideally brittle materials, plastic deformation always exists in most metallic materials [26]. This is why shear lip regions usually appear on the fracture surface. Accordingly, the intrinsic impact toughness, which should represent the inherent resistance to crack formation and propagation, must be calculated with the energy only consumed for breaking the area of the cracking region. To achieve this intrinsic toughness, the energy absorptions by cracking and shear lip formation should be separated, respectively.

As shown in Fig. 1(b), the total area of fracture surface (S_t) can be divided into two terms:

$$S_t = S_c + S_s, \tag{2}$$

where S_c and S_s are the area of cracking region and the total projection area of the shear lip regions, respectively. Correspondingly, the total fracture energy can be written as,

$$A_K = U_c + U_s, \tag{3}$$

where U_c and U_s are the energy used for forming the cracking region (i.e., cracking) and the energy consumed by the formation of shear lips, respectively. Thus, the intrinsic impact toughness to resist the cracking, α_c, can be defined as,

$$\alpha_c = U_c/S_c. \tag{4}$$

Substituting Eq. (4) into Eq. (3), we get,

$$A_K = \alpha_c S_c + U_s. \tag{5}$$

Similarly, we can define a nominal shear toughness, α_s, as the energy required to form a unit projection area of shear lip, i.e.,

$$\alpha_s = U_s/S_s. \tag{6}$$

Substituting Eq. (6) into Eq. (5), we have,

$$A_K = \alpha_c S_t + (\alpha_s - \alpha_c) S_s. \tag{7}$$

The formation of shear lip has been found to be strongly related to the plane stress plastic zone at the surface of a plate specimen [27]. As a result, the width of shear lip (W_{SL}) is independent on the sample thickness, and determined by the material properties of the plane strain fracture toughness (K_{IC}) and the yield strength (σ_y) through the expression [27].

$$W_{SL} = C(K_{IC}/\sigma_y)^2, \tag{8}$$

where C is a material-independent constant that may be related to the sample width, fracture rate and testing temperature. According to Eq. (8), for the samples with different thickness but same width and made from the same material, both the projection area (S_s) of

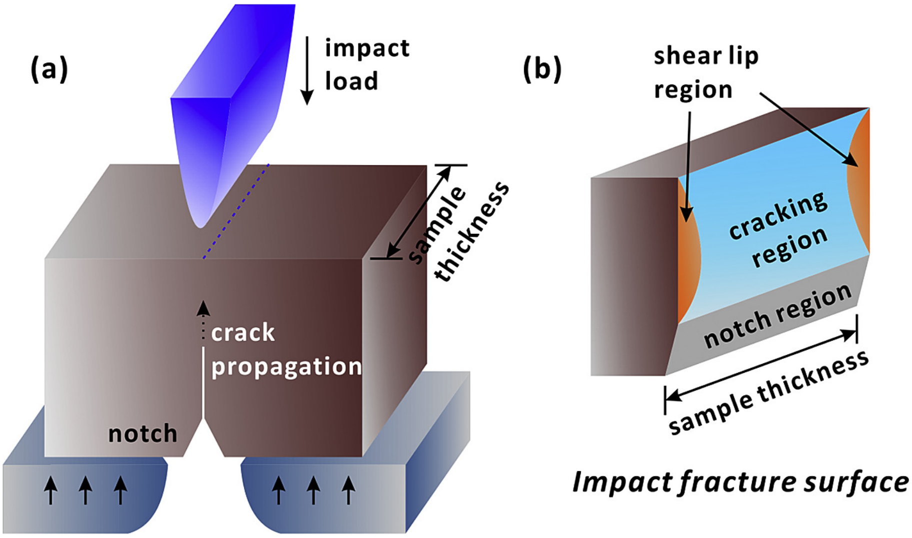

Fig. 1. Illustrations on the impact fracture testing. (a) The fracture process, showing crack propagation along the direction of impact load; (b) the fracture surface, including cracking region and shear lip region.