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Dynamic fracture toughness of TA15ELI alloy studied by instrumented impact test

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Abstract

The dynamic fracture toughness of TA15ELI alloy with two types of microstructures was studied by instrumented impact test. Charpy specimens with both the 0.2 mm U-notch and the $a/W = 0.2$ pre-crack were adopted to compare notch sensitivity in the two microstructures. The result shows that the specimen with Widmanstätten microstructure exhibits a better dynamic fracture toughness and lower notch sensitivity than that with lath-like microstructure. Fracture surfaces in the case of the two microstructures are analyzed to have a ductile and brittle mixed feature under dynamic loading. The fracture surface of lath-like microstructure is composed of dimples and tear ridges, while that of Widmanstätten microstructure is covered with rough block-like facets and dimples and tear ridges. The α phase boundaries and α/β interfaces act as locations for void nucleation and crack arrest and deviation. The decrease in width of α phase lamellae leads to the increase in the amount of boundaries and interfaces, which causes the increase in the consumption of impact energy and results in the improvement in dynamic fracture toughness.

Keywords: titanium alloys; fracture toughness; impact testing; microstructure

1. Introduction

TA15ELI alloy is a kind of damage tolerance titanium alloy, and it is developed from TA15 alloy (Ti-6Al-2Zr-1Mo-1V). The ELI grade TA15 alloy contains a maximum oxygen content of 0.08 wt.%, against 0.1 wt.%-0.2 wt.% in a commercial grade, and therefore has the improved properties of quasi-static fracture toughness and fatigue crack growth. A large variety of microstructures with different α morphologies can be acquired by thermo-mechanical processing, which results in various mechanical properties. It has been tested that TA15ELI thick plate with Widmanstätten microstructure (990°C/1 h/AC + 750°C/8 h/FC) (air cooling, AC; furnace cooling, FC) has a K_{IC} value of ~110 MPa·m$^{1/2}$ [1]. The thick plate with lath-like microstructure obtained by β-processing and duplex annealing in the (α + β) phase field (950°C/1 h/AC + 750°C/8 h/FC) also has a relatively good fracture toughness property, and the K_{IC} value is ~114 MPa·m$^{1/2}$ [2].

Because the importance of fracture toughness in engineering design is widely accepted, standards for evaluating a material's quasi-static fracture toughness have been established and executed for many years. As with other mechanical properties, fracture toughness may be rate dependent [3]. However, there is no widely acceptable or suitable method to evaluate dynamic fracture toughness. The instrumented impact test is a convenient and low-cost method, which is often utilized for evaluating the dynamic fracture toughness of titanium alloys [4-7]. The obtained value of dynamic fracture toughness K_{Id} or J_{Id} indicates crack growth resistance, which is very different from that evaluated as total absorbed energy (E_t, A_{kv} or A_{ku}). The value of K_{Id} or J_{Id} is worthy to be investigated separately if the crack initiation toughness is used alone when considering damage tolerance [4]. The safe use of titanium alloys where dynamic loading and fracture may occur demands an investigation of the dynamic fracture toughness of TA15ELI alloy.

In this paper, TA15ELI alloy with lath-like microstructure and Widmanstätten microstructure was respectively investigated by the method of instrumented Charpy impact test, aiming to evaluate the effects of microstructures on dynamic fracture toughness.

2. Experimental

TA15ELI in this experiment has a composition of 6.3 wt.% Al, 1.7 wt.% Mo, 2.0 wt.% V, 2.0 wt.% Zr, 0.05 wt.% Fe, 0.08 wt.% O, 0.03 wt.% C, 0.03 wt.% N, 0.04 wt.% Si,

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0.012 wt.% H, and with the balance of Ti. The material ingots were multi-forged and rolled into plates of 80 mm in thickness. The beta-transus temperature of the ingots is examined as 970°C. The ingots were subsequently heat treated in (1) 950°C/1 h/AC + 750°C/8 h/AC, or (2) 995°C/1 h/AC, after which lath-like microstructure and Widmanstätten microstructure can be obtained respectively. Specimens for instrumented Charpy impact test were machined in the size of 10 mm × 10 mm × 55 mm, with the $a/W = 0.2$ T-L direction pre-crack (a is the initial crack length; W is the specimen width). For comparison with the effect of pre-cracks, specimens with the 0.2 mm T-L direction U-notch were also adopted. Three specimens were tested in each group.

In instrumented Charpy impact test, the load-time curve can be recorded by computer. According to the load-deflection curve, the total absorbed energy E_t, crack initiation energy E_i, and crack propagation energy E_p can be also analyzed. The fracture of specimens happens after yield for TA15ELI alloy. Thus, the value of J-integral should be calculated according to the value of E_i. The J-integral value to characterize the dynamic fracture property is described as J_d rather than J_{Id} because the specimens do not satisfy the validity criteria of dynamic fracture toughness in plane-strain condition [4].

The microstructure of specimens was examined by an optical microscope Axiovert 200 MAT and a scanning microscope Quanta 400. Specimens were ground, polished, and etched using etchants having the following chemical composition at room temperature: 5% HF + 10% HNO_3 + 85% H_2O.

3. Results and discussion

The optical metallographs of TA15ELI alloy in this experiment are shown in Fig. 1. The lath-like microstructure (Fig. 1(a)) can be obtained by heat treatment at 950°C/1 h/AC + 750°C/8 h/AC. Despite being heated below the beta-transus temperature, the morphology of α phase is significantly different from bi-modal microstructure in the typical two-phase (α + β) titanium alloy but similar to Widmanstätten microstructure. Most of α phase in primary β grains is lath-like; only a small amount of that shows as equiaxed shape. The average size of primary β grains is about 600 μm, in which there exist some α phase colonies in a size of 30-70 μm. The average width of α phase laths in colonies is about 4-10 μm.

The specimen annealed in 995°C/1 h/AC exhibits a typical Widmanstätten microstructure, as shown in Fig 1(b). The average size of primary β grains for Widmanstätten microstructure is similar to the lath-like microstructure mentioned above, about 600 μm. The interlaced α phase lamellae in primary β grains are in a width of 0.5-1.5 μm.

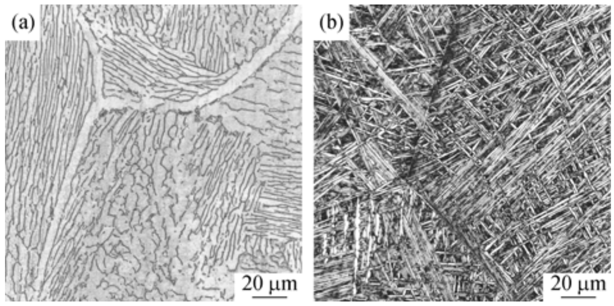

Fig. 1. Metallographs of TA15ELI alloy for instrumented impact testing: (a) lath-like microstructure; (b) Widmanstätten microstructure.

The results of instrumented impact testing for both U-notched and pre-cracked specimens are illustrated in Figs. 2(a) and 2(b). It can be found that there is no direct relationship

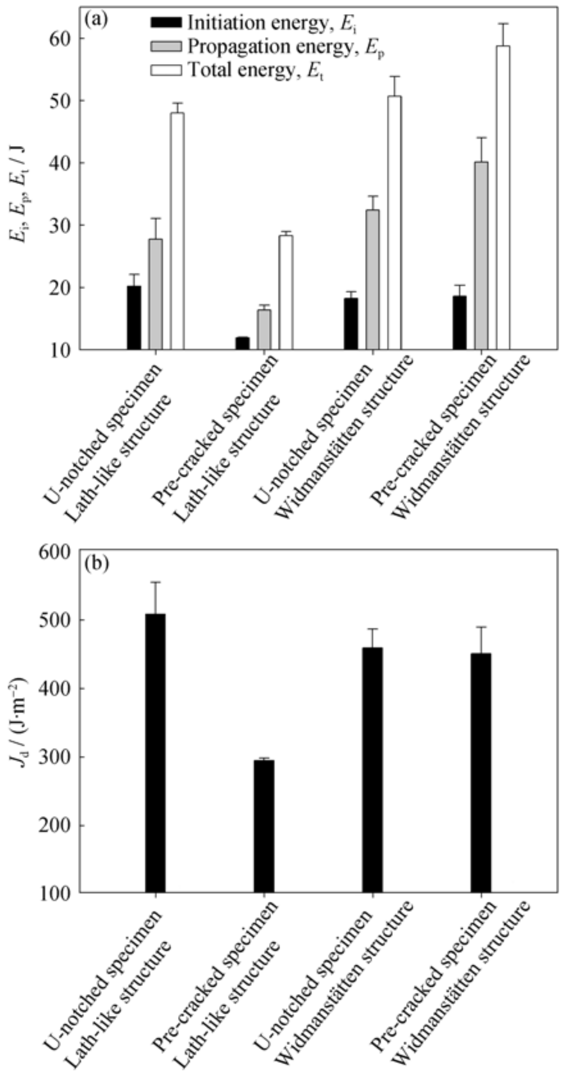

Fig. 2. Results of instrumented impact testing for U-notched and pre-cracked specimens made of TA15ELI alloy: (a) initiation energy, propagation energy, and total energy values; (b) calculated dynamic fracture toughness values of J_d.

between total absorbed energy and dynamic fracture toughness. For the U-notched specimen, the specimen with Widmanstätten microstructure shows a higher value of E_t but a lower ratio of E_i to E_t and a lower value of J_d than that with lath-like microstructure.

The dynamic fracture property exhibits sensitivity to notch-tip radius. To compare with the U-notched specimen, the J_d value decreases for the pre-cracked specimen with both two microstructures. Widmanstätten microstructure is less sensitive to notches. The J_d value decreases from (456 ± 27) kJ/m^2 for the U-notched specimen to (447 ± 39) kJ/m^2 for the pre-cracked specimen (Fig. 2(b)). However, for lath-like microstructure, a significant decrease can be found in J_d values from 505 ± 47 kJ/m^2 for the U-notched specimen to 292 ± 4 kJ/m^2 for the pre-cracked specimen (Fig. 2(b)). In Fig. 2(a), comparing U-notched and pre-cracked specimens with Widmanstätten microstructure, the E_t value of the former is lower than that of the latter because the lengths of U-notches and pre-cracks are difficult to be precisely prepared at the same time. The abnormal results caused by machining accuracy can be avoided in the calculation of J_d.

The research [4] has described the effects of notch-tip radius. The J_d value decreases in proportion to the decrease in notch-tip radius, but the J_d value tends to be a constant when the notch-tip radius is less than a certain value. For TA15ELI alloy, the differences of microstructural parameters between lath-like and Widmanstätten microstructures result in the different sensitivity to notch-tip radius. Thus, the use of U-notched specimens for simplification is inappropriate for evaluating dynamic fracture toughness. Comparing the values obtained by pre-cracked specimens, it is deduced that the material with Widmanstätten microstructure has a better fracture performance under dynamic loading conditions than that with lath-like microstructure, though their static fracture toughness are on the same level.

The macro-fractographs of the specimens in this experiment are shown in Fig. 3. There is no obvious difference between U-notched and pre-cracked specimens for the same microstructures. Large differences can be found in the overall fracture surface between specimens with lath-like microstructure and Widmanstätten microstructure; the former is gray and flat, while the latter is rough. The fracture of the specimen with Widmanstätten microstructure is covered with cleavage facets with metallic lustre showing intergranular features, as well as a number of obvious secondary cracks.

Fig. 4 shows the fractographs of the specimens examined at a higher magnification, which are obtained at the vicinity of the crack initiation area. It is observed that the fracture

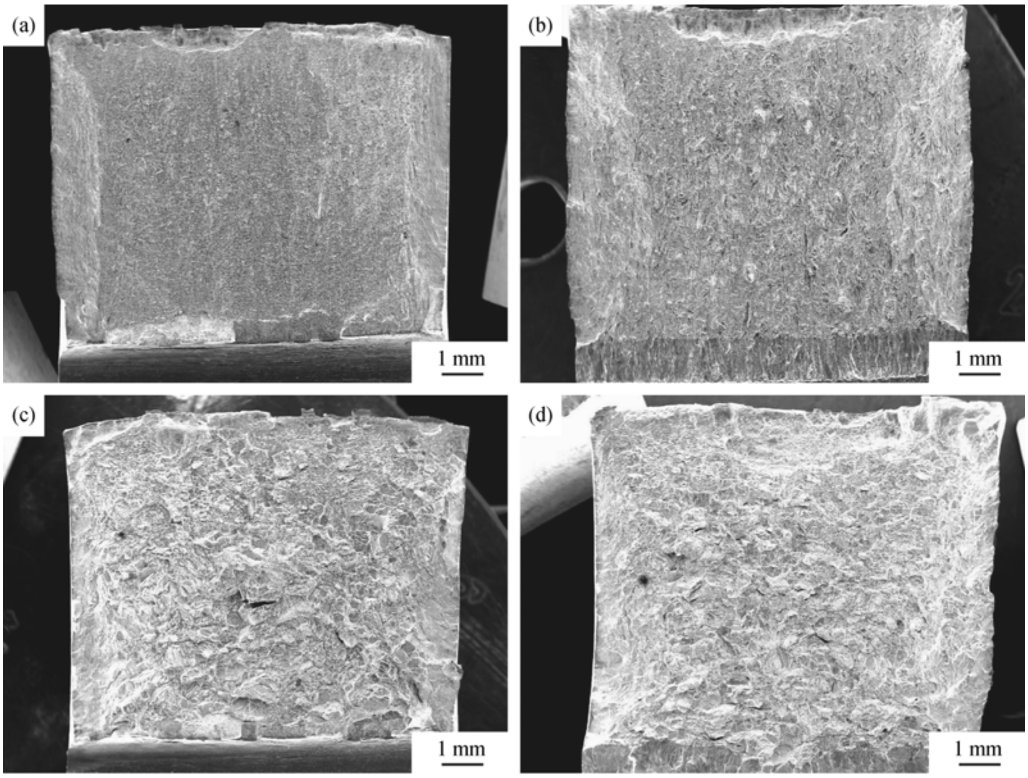

Fig. 3. Macro-fractographs of TA15ELI alloy for instrumented impact test: (a) U-notched specimen, lath-like microstructure; (b) pre-cracked specimen, lath-like microstructure; (c) U-notched specimen, Widmanstätten microstructure; (d) pre-cracked specimen, Widmanstätten microstructure.

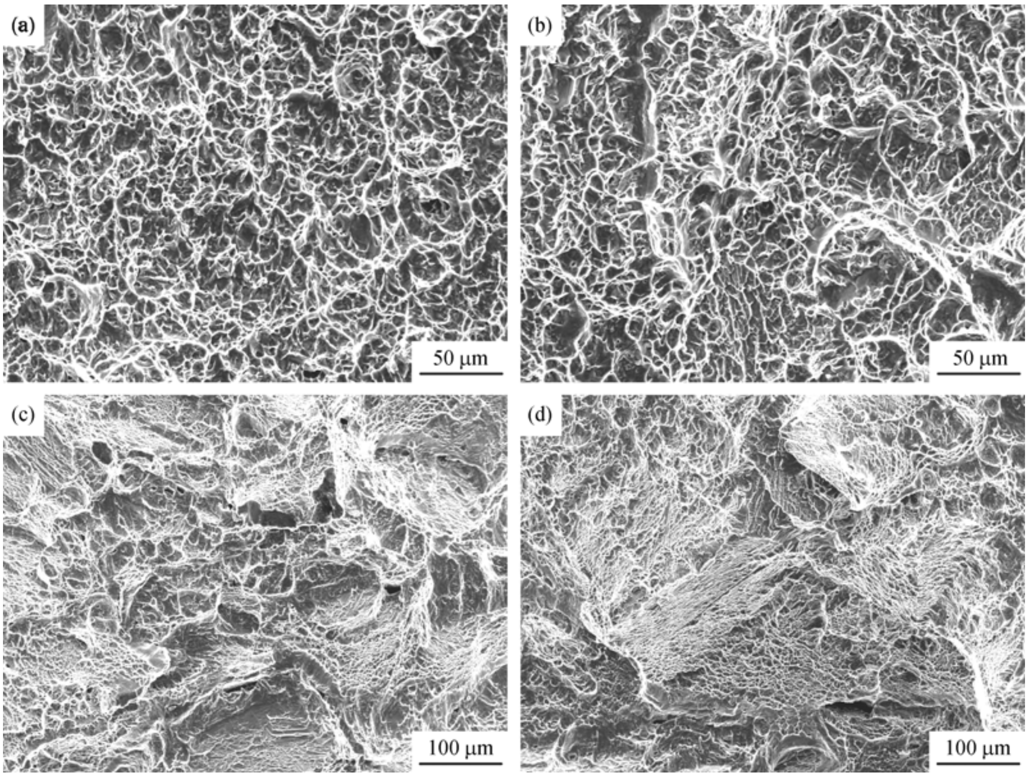

Fig. 4. Fractographs of TA15ELI alloy for instrumented impact test: (a) U-notch specimen, lath-like microstructure; (b) pre-crack specimen, lath-like microstructure; (c) U-notch specimen, Widmanstätten microstructure; (d) pre-crack specimen, Widmanstätten microstructure.

surfaces of both U-notched and pre-cracked specimens with lath-like microstructure are composed of equiaxed dimples (Figs. 4(a) and 4(b)). The average diameter of dimples is 5-13 μm, which is similar to the average width of α phase laths of 4-10 μm. And there also can be found some quasi-cleavage features. A number of tear ridges distribute along the crack propagating direction, which indicates that the specimen with lath-like microstructure has a ductile and brittle mixed fracture surface but mainly ductile in the crack initiation process. The number of tear ridges observed in the fractograph of the pre-cracked specimen is larger than that in the U-notched specimen. The increase in brittle factors corresponds to the decrease in dynamic fracture property tested by the pre-cracked specimen.

The fracture surfaces of specimens with Widmanstätten microstructure, both in U-notch and pre-crack testing, have similar morphology, which are covered with rough block-like facets and dimples and tear ridges (Figs. 4(c) and 4(d)). The similarity results from low notch sensitivity. The size of rough block-like facets is smaller than that of primary grains, but similar to colony size. Though the morphology of the block-like facets is similar to cleavage facets, the edges are covered with very fine dimples. The diameter of dimples in Widmanstätten microstructure is similar to the width of α phase lamellae, much smaller than that in lath-like microstructure. A larger number of secondary micro-cracks can be observed in Widmanstätten microstructure than that in lath-like microstructure. The existence of quasi-cleavage or cleavage-like facets as well as areas with dimples also revealed a mixture mode of ductility and brittleness in crack initiation.

Fig. 5 shows the crack initiation path features of the two structures. It can be observed that the crack initiation path propagates across or along the α laths or lamellae and deflects at α/β interfaces. The amplitude of deflection in Widmanstätten microstructure is much larger.

In the case of both lath-like and Widmanstätten microstructures, a great deal of voids locate in the edges of dimples (Fig. 4), as well as secondary microcracks along the main crack path (Fig. 5). The locations of α/β interfaces, primary β boundaries and colony boundaries are advantageous to the nucleation of voids, which may evolve into microcracks in the initiating process and subsequently become propagation channels [4, 8]. Otherwise, it can be found that main cracks defect and microcracks end at the boundaries and interfaces (Fig. 5). It is indicated that boundaries and interfaces show an effect of deviating and arresting cracks.

Though mixed features of fracture surfaces are observed in the case of the two types of microstructures, there are

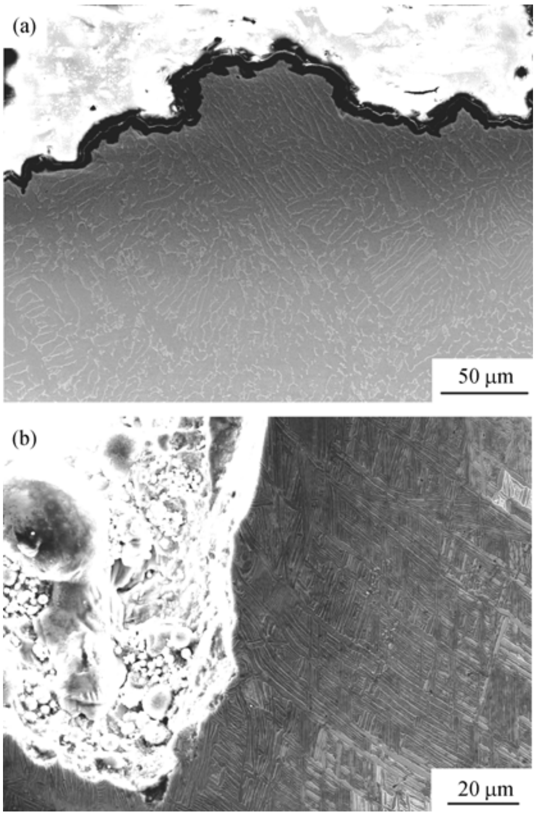

Fig. 5. Crack initiation path features of TA15ELI alloy for instrumented impact test: (a) lath-like microstructure; (b) Widmanstätten microstructure.

large differences in dynamic fracture behavior and morphologies. One of the influencing factors on dynamic properties is deduced to be the width of α phase lamellae. The width of α lamellae in Widmanstätten microstructure is much smaller than that in lath-like microstructure, which results in a bigger amount of boundaries existing in Widmanstätten microstructure. The existence of a bigger amount of locations for void nucleation and crack deviation or arrest corresponds to more consumption of impact energy, which brings in a higher dynamic fracture toughness value and lower notch sensitivity.

On account of various microstructures in TA15ELI alloy and many factors in dynamic fracture test, only the two types of microstructures and the influence of the width of α phase lamellae were discussed in this paper. The effects of other factors on dynamic fracture toughness needs further looking into.

4. Conclusions

(1) TA15ELI alloy with Widmanstätten microstructure has a better dynamic fracture toughness and lower notch sensitivity than that with lath-like microstructure, though they have similar static fracture toughness. The width of α lamellae is deduced to be one of the influencing factors of dynamic fracture toughness.

(2) The fracture behavior of TA15ELI alloy has a ductile and brittle mixed fracture under dynamic loading in the case of both lath-like and Widmanstätten microstructures. The fracture surface of the former is composed of dimples and tear ridges, while that of the latter is covered with rough block-like facets, dimples and tear ridges. The α phase boundaries and α/β interfaces act as locations for void nucleation and crack arrest and deviation.

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