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Dynamic fracture toughness of Ti–2.5Cu alloy strengthened with nano-scale particles at room and low temperatures

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Abstract

Instrumented impact tests were carried out on a Ti–2.5 wt.% Cu alloy reinforced by nano-scale particles as a result of solution and two-step aging treatments. The tests were performed at room temperature and at low temperatures (193, 143, and 83 K), using a 300 J capacity impact machine. Although no global plastic yielding was observed, there was evidence for plastic deformation in the front of crack tips. The size of the plastic zones decreases with decreasing testing temperatures, which induces a reduction of the crack initiation and propagation energies at low temperatures. Microstructural examinations show the absence of mechanical twinning in the plastic zones. Plasticity is only occurring via dislocation processes and governs the fracture toughness. The fracture toughness decreases with decreasing temperature from 293 to 83 K. This decrease can be attributed to a reduction in strain hardening properties at low temperatures.

Keywords: Ti–2.5Cu alloys; Dynamic fracture toughness; Instrumented impact test

1. Introduction

The Ti–2.5 wt.% Cu alloy exhibits excellent formability and weldability properties, as well as a good combination of strength and ductility. In the Ti–Cu binary system, the β phase decomposes into an α phase and a Ti_2Cu compound at 798 °C. Consequently, the Ti–2.5Cu alloy can be strengthened by heat treatments. The α phase is strengthened by Ti_2Cu particles when it is subjected to a solution treatment followed by a two-step aging treatment. In technical applications, this alloy has been used up to a temperature of 350 °C. Some investigations were performed on its mechanical properties, for instance on fatigue crack growth in the equiaxed and lamellar microstructure [1], and on tensile and creep strengths in the presence of duplex microstructures [2]. A recent investigation also shows that Ti–2.5Cu exhibits a good combination of tensile strength and ductility at liquid nitrogen temperature [3]. However, few information is available on the dynamic fracture toughness properties. The instrumented impact test of pre-cracked Charpy specimens has been widely used to evaluate the dynamic fracture toughness of materials [4–6]. The aim of the present work is to investigate the dynamic toughness of Ti–2.5Cu at room and low temperatures by instrumented impact testing, on three-point bent specimens. In addition, the temperature dependencies of the load and crack-related energies were analyzed. Microstructural observations of fracture surfaces and plastic zones head of crack tips are also presented.

2. Material and experimental procedure

The starting material was supplied in the form of rods of diameter 20 mm extracted from a hot-rolled Ti–2.5Cu ingot. The chemical composition is, in wt.%: Fe < 0.06%, Si < 0.04%, C ≤ 0.01%, N ≤ 0.01%, H ≤ 0.01%, O ≤ 0.14%, Cu ≈ 2.5%, bal. Ti. The rods were solution-treated at 805 °C for 1 h and aged in two steps, at 400 °C for 24 h and at 475 °C for 8 h. From the resulting microstructure shown in Fig. 1, one can see that particle precipitation occurred in the α grains. These precipitates were identified as Ti_2Cu intermetallic particles by transmission electron microscopy (TEM) analysis [3]. Their length, width and thickness are about 80, 20–30 and 10 nm, respectively.

Specimens for three-point bending tests, of dimensions 10 mm × 10 mm × 55 mm, were obtained by machining. A notch was spark-machined and pre-cracking was performed on

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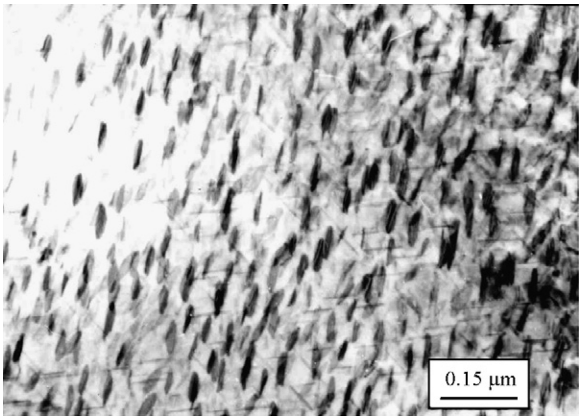

Fig. 1. TEM microstructure of Ti_2Cu intermetallic particles in the Ti–2.5Cu alloy after solution treatment and two-step aging.

an AMSLER5100 fatigue testing machine. The initial ratio of notch length after pre-cracking to specimen width (*a*/*W*) is 0.55. Impact tests were carried out at room and low temperatures (253, 193, 143, and 83 K), using a 300 J capacity impact machine with instrumented systems.

The loading rate was imposed by applying a bending displacement rate of 5 m/s. The variation of load with displacement was computed from the recorded data. After failure, the fracture surfaces were examined by scanning electron microscopy (SEM) in a HITACHI S-2700. The microstructure of the plastic deformation zones beneath the fracture surface was imaged by TEM.

3. Results and discussion

3.1. Variation of load and energy with temperature during impact testing

The elastic load, F_e, the load at specimen yield, F_y, and the maximum load, F_m, were determined from the recorded data. Fig. 2 shows the load–displacement curves at different temperatures and the values of the characteristic loads are given in Table 1 for the different testing temperatures. The load at yield is almost equal to maximum load, which indicates that no plastic flow occurred in the bulk of these specimens in the investigated temperature range. The energies related to crack behavior at different stages of deformation and fracture were also determined from the recorded data. This includes the elastic energy, E_e, the initiation energy, E_i, and the propagation energy of a crack, E_p, as well as the total energy $E_t = E_i + E_p$. These energies are shown in Fig. 3 as a function of temperature. As temperature decreases, the elastic energy is slightly reduced. This can be attributed to the small reduction in elastic load, F_e, recorded with decreasing temperatures (cf. Table 1). The initiation energy can be regarded as the energy at which a crack starts propagating. The crack propagation energy generally includes two contributions, one from the work absorbed to produce plastic deformation and the other from the creation of crack surface energy. For most metals that exhibit plastic deformation, the former is higher than the latter. The plastic deformation work is associated with the size of the deformation zone, R_0, in front of the crack tip. In fracture mechanics, the value of R_0 is given by [7]:

$$R_0 = \frac{1}{2\sqrt{2}\pi}\left(\frac{K_{Id}}{\sigma_s}\right)^2 \quad (1)$$

where K_{Id} is the dynamic fracture toughness and σ_s is the yield strength. Therefore, R_0 can be considered as the maximum size under plane strain. The values of R_0 are 0.67, 0.27 and 0.08 mm at 293, 193 and 83 K, respectively. The size of the plastic zone decreases with decreasing temperature, which means that less energy is consumed for crack propagation. Plastic deformation

Table 1
Characteristic load values determined from impact tests

Load (kN)	T (K)			
	293	193	143	83
Load at yield (F_y)	3.86	2.86	2.94	2.39
Maximum load (F_m)	3.86	2.86	2.94	2.39
Elastic load (F_e)	3.79	2.86	2.94	2.39

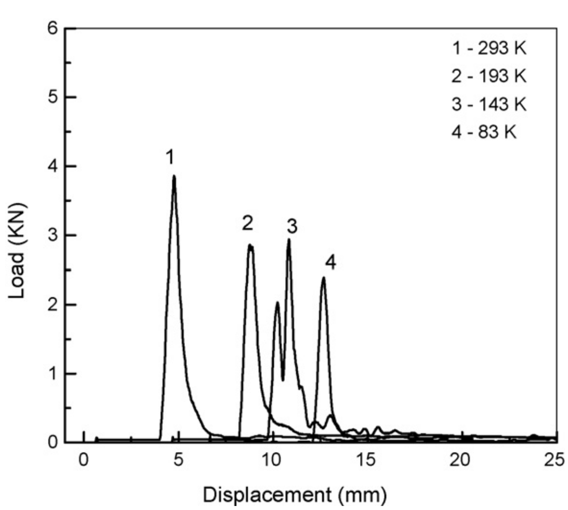

Fig. 2. Load–displacement curves of Ti–2.5Cu at different temperatures.

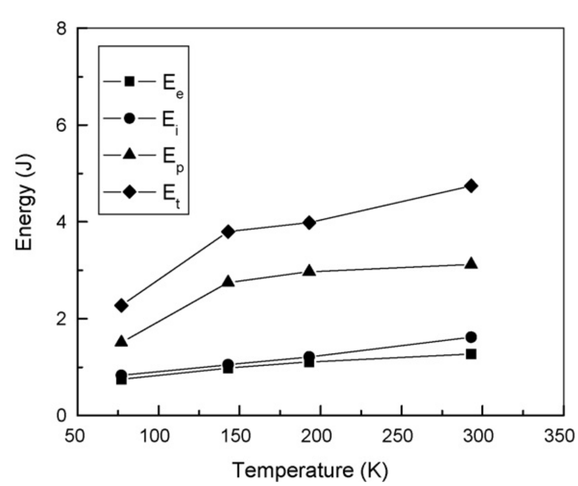

Fig. 3. Crack energies as a function of temperature. E_e is the elastic energy, E_i the initiation energy, E_p the propagation energy and E_t is the total energy.