EFFECTS OF CONSTRAINT AND GRAIN SIZE ON DUCTILITY AND TOUGHNESS IN TI ALLOYS

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ABSTRACT

The effects of stress triaxiality on the process of micro-void coalescence type of fracture and ductility of α/β titanium alloys with equiaxed α phase were investigated. Materials tested were 3 types of titanium alloys (Ti-6Al-4V, Ti-4.5Al-3V-2Fe-2Mo, and Ti-10V-2Fe-3Al alloy) and two or three different heat treatments were conducted for these three alloys in order to obtain different grain size. It was shown that the most of micro-voids in α/β titanium alloys were nucleated at α/β interface, and the micro-structural parameter defined as the average distance between α/β interfaces was closely related to the dimple size on the fracture surface. The refinement of microstructure leads to the reduction of ductility and fracture toughness, though near-β titanium alloys with ultra-fine particle of α ($< 1\ \mu$m) have exceptionally a different tendency from other α/β titanium alloys.

Fracture toughness testing was performed and J_{IC} values were evaluated. Correlation between the toughness and the ductility under the high triaxial stress state was investigated to clarify the dominant factors constructing the fracture toughness.

KEYWORDS

Micro-void coalescence type of fracture, Micro-void nucleation, Stress triaxiality,
Dimple size, Fracture toughness, Local fracture criterion approach, Constraint effect,
α/β Ti alloys

INTRODUCTION

Titanium alloys with $\alpha+\beta$ phase are attractive materials for commercial application because of well balanced mechanical properties, in strength, ductility and fracture toughness. It is shown the fracture of α / β Ti alloys generally take micro-void coalescence type of ductile fracture [1] . Several studies by Niinomi and Kobayashi [2-4] and Teruo Kishi [5] have shown that the mechanical properties of α / β Ti alloys is quite sensitive to the variation of microstructure. In case of structural steels, micro-voids are nucleated at non-metallic inclusions and grown up to coalescence with the help of stress triaxiality and plastic strain [6] , and ductility is not sensitive to a little variation of microstructure but is influenced by the volume fraction of inclusions and strength of the materials. In the present work, tensile test and fracture toughness tests were performed for several types of α / β Ti alloys with different grain size. The effects of grain size and stess triaxiality on the ductility were investigated focusing the mechanisms of micro-void coalescence type of fracture. Then, the effect of grain size on the fracture toughness was investigated in relation to the ductility.

EXPERIMENTAL PROCEDURE

Materials tested were three types of titanium alloys of which chemical compositions were different (Ti-6Al-4V, Ti-4.5Al-3V-2Fe-2Mo, and Ti-10V-2Fe-3Al). Mill annealing and solution treatment with aging were performed to each materials to obtain different grain sizes with almost the similar equaxed microstructure. Hereafter, the materials are designated as 64-An, 64-STA, Fine-An, Fine-STA1, Fine-STA2, 10-2-3-STA1, !0-2-3-STA2, 10-2-3-STA3 (An=mill anneal., STA=solution treatment with aging) .Tensile tests were performed on smooth and 1mm radius notched round bar specimens with a diameter of 3.5mm. The equivalent strain at minimum cross section was taken as a measure of ductility and the stress triaxiality, $\sigma_m / \bar{\sigma}$, where σ_m = average value of the three principal stress, and $\bar{\sigma}$ =equivalent stress, was evaluated from Bridgman's formula [7]. The fracture toughness tests were performed on a half inch CT-specimens with 5 or 10mm thickness. The fracture toughness tests were carried out at the room temperature and the toughness and the resistance curve of crack growth were evaluated in terms of J integral and converted to K_C values as K_C(J) in accordance with the JSME S001.

MICROSTRUCTURES

Figure 1 shows the microstructures of the materials observed by scannning electron microscope. All microstructures consist of the primary α phase which morphology is equiaxed and β matrix phase. For some of

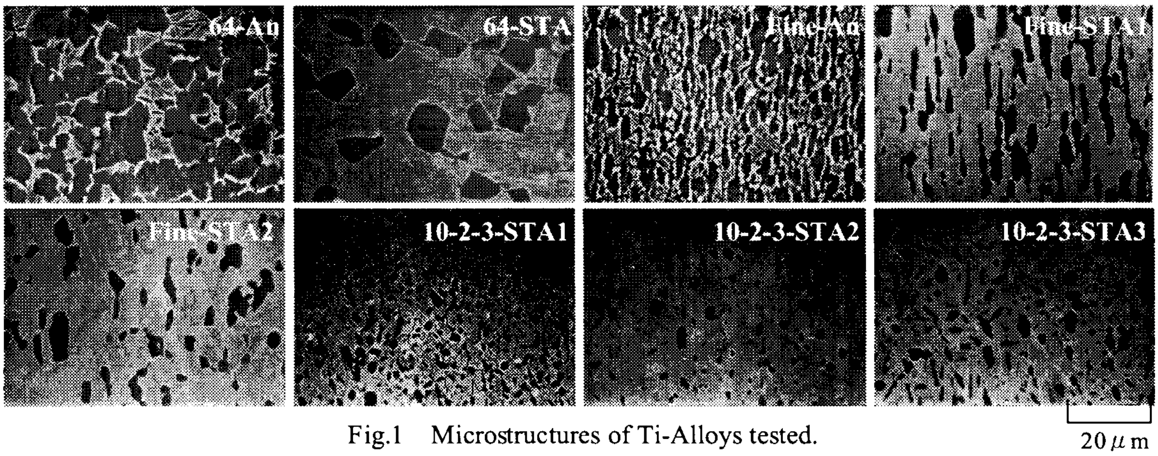

Fig.1 Microstructures of Ti-Alloys tested.

materials that are called STA materials, the high temperature solution treatment was followed by a low temprature aging treatment, that leads to the precipitation of fine secondary α phase in the β matrix.

RESULTS ON TENSILE TESTS

Figure 2 shows the failure elongation in smooth specimens in relation to the yield strength of materials, σ ys. Increase of the yield strength causes significant reduction of the ductility irrespective of the microstructure. Figure 3 shows examples of fractographs on the center part of smooth specimens. The fracture surfaces are occupied with equiaxed dimples, while the sizes of dimples are different in each material. The dimple sizes in Ti alloys are generally small in comparison with that of structural steels. In the case of Ti alloys, the most of void nucleation sites are the interface between primary α phase and β matrix as is shown in Figure 4. More than 80% of micro-voids in every materials are nucleated at α / β interface as is reported by K.H.Schwalbe [8] . The average distance between α / β interfaces is taken as a microstructural parameter, D. Figure 5 shows relations between D and the dimple sizes in the smooth specimens and the CT specimens. The dimple sizes are related to the distance of α / β interfaces especially in the CT specimens. It implies that the void nucleation sites in the α / β Ti alloys are closely related to the microstructure. The difference in dimple sizes

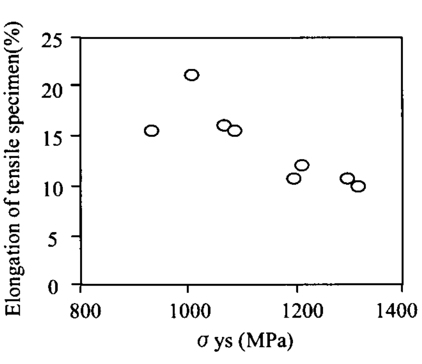

Fig.2 Relations between σ ys and elongation for materials tested.

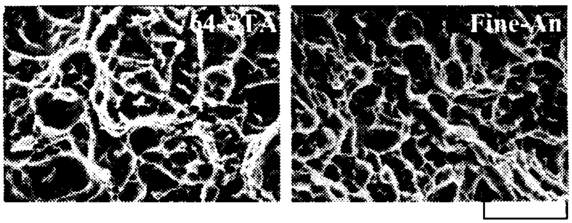

Fig.3 Fractgraphs s of 64-STA and Fine-An in smooth specimens.

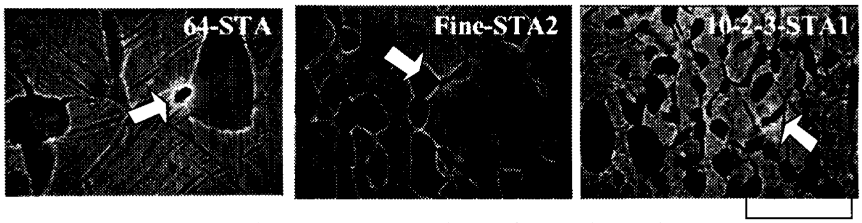

Fig.4 Micrographs of longitudinal sections of smooth specimens.

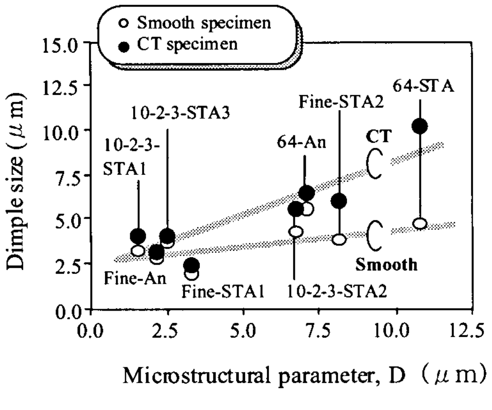

Fig.5 The relationship between Microstructural parameter and dimple size.

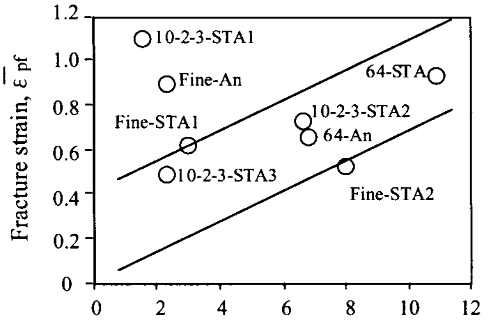

Fig.6 The relationship between microstructural parameter and fracture strain.

for the smooth specimen and the CT specimens are attributed to the difference of the stress triaxiality as is discussed later.

Figure 6 shows relation between fracture strain in the smooth specimen and the parameter, D. It should be noticed that the materials with fine microstructure show smaller ductility except for 10-2-3 STA1 and Fine-An. Exceptional results on both two materials in spite of their fine structure might be caused by the difference in void nucleation strain. As far as 10-2-3-STA1 is concerned, the particle size of α phase is smaller than 1 μm. The ductility must be governed with the void nucleation strain and void growth strain up to the coalescence. The critical stage of void coalescence is strongly depending on the number of voids or volume fraction of voids. An increase of the void nucleation sites generally leads to the reduction of ductility but not always the case.

Figure 7 shows the effect of stress triaxiality on the fracture strain obtained in the round bar specimens. Significant reduction of the fracture strain with the increase of the triaxiality is observed for every material. However, the reduction due to the high triaxiality is different in each material. The Fine-STA1,2 and 10-2-3-STA2,3 show small dependency. It arises from the difference in the void growth strain because void growth is strongly depending on the stress traxiality as is shown in Rice and Tracey Model [9] . Figure 8 shows the void nucleation strain and fracture strain for each material. The void growth strain in higher strength materials is relatively small and it results small dependency of the triaxiality on the ductility. In the Fine-An and 10-2-3-STA1, void growth strain are large, while the dimple sizes are small. This results indicate that the void nucleation strain is relatively large and the number of void nucleation from α phase is relatively small in the materials with ultra-fine microstructure, and result high ductility as shown in Figure 6.

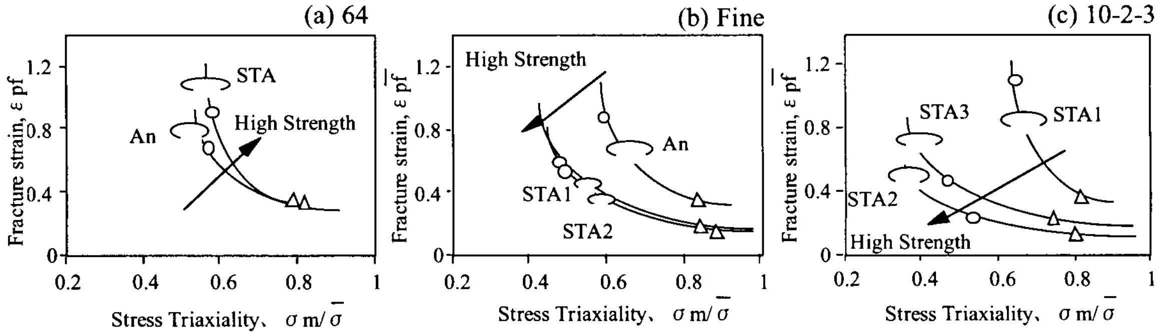

Fig.7 Effects of stress triaxiality on fracture strain.

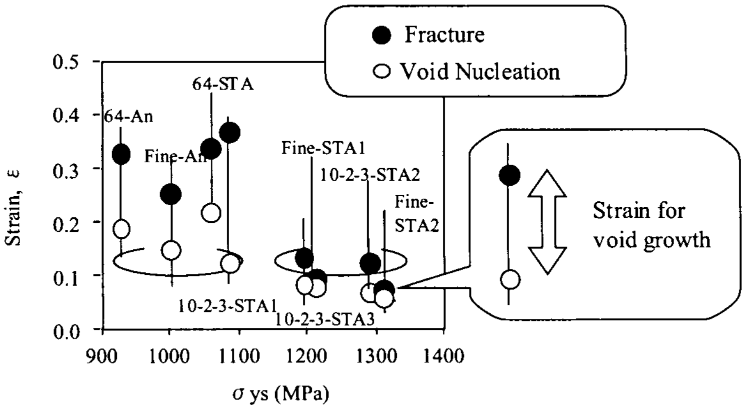

Fig.8 Void nucleation strain and fracture strain.

RESULTS ON FRACTURE TOUGHNESS TESTS

The fracture initiation toughness, $K_{IC}(J_{IC})$ are shown in Figure 9 in relation to the yield strength and the failure elongation of the materials, respectively. Correlation to the yield strength seems to be better though a few materials involving 10-2-3-STA1 doesn't fit in correlation. A description of the ductile fracture toughness in terms of mechanical properties is proposed by several authors. Ritchie and Thompson [10] have proposed

$$J_i = D_j \lambda \sigma_{ys} \bar{\varepsilon}_{pi} \tag{1}$$

, where λ is a material constant denoted as 'Characteristic distance' as is shown in Figure 10 , D_j is a material constant related to the strain hardening or so on, and $\bar{\varepsilon}_{pi}$ is the critical plastic strain under the high stress triaxiality. Taking the fracture strain in the notched specimens as the critical strain, $\bar{\varepsilon}_{pi}$ and the micro-structure parameter, D as the characteristic distance, λ , the fracture toughness in terms of J_{IC} is shown as a function of $\lambda \sigma_{ys} \bar{\varepsilon}_{pi}$ in Figure 11. Linear proportional relation is observed here again except for 10-2-3-STA1 and Fine-An. Exceptional two materials have fine microstructure and low strength.

The average sizes of dimples on the fracture surface at the crack tip are shown in Figure 5 in comparison with the results on the smooth specimens. The average sizes of dimples in the CT-specimens also show linear relationship with the microstructure parameter, D, though those are larger than that of the smooth specimens. It arises from the constraint effect, that is, the effect of the stress triaxiality. The high strength materials show a tendency of little difference in the size of dimples. It is noticed as a reflection of the results in Figure 8, since the void growth strongly depends on the stress triaxiality.

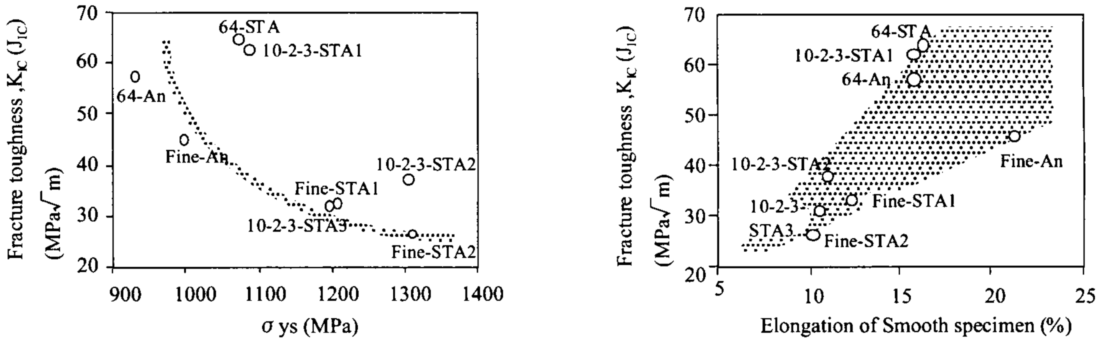

Fig.9 Relationship between fracutre toughness and mechanical properties of materials

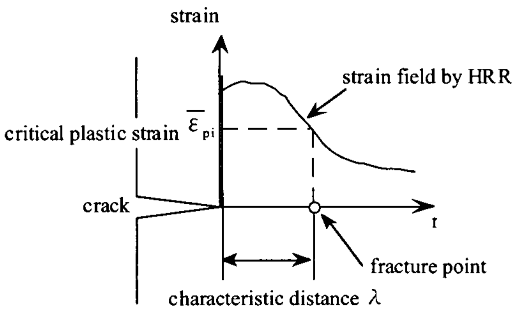

Fig.10 Characteristic Distance Model

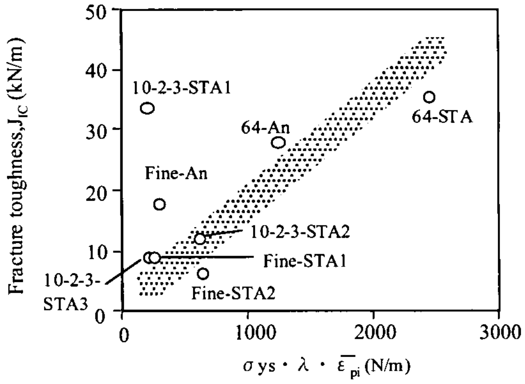

Fig.11 Fracture toughness and the toughness parameter according to Characteristic Distance Model

CONCLUSIONS

The effects of microstructure and constraint on the ductility and the fracture toughness of α/β Ti alloys with equiaxed α particles were investigated. The main conclusions are as follows; 1) The most of micro-voids nucleate from α/β interface and the dimple size on the fracture surface is related to the distance between α/β interfaces. 2) Refined microstructure leads to the increment of the nucleation sites of voids and high strength, then results low ductility. However, materials with extremely fine α particles show different behavior from other materials and high ductility. 3) The local fracture criterion approach, such as the characteristic distance model, can be applied to describe the toughness in terms of the strength and ductility of materials. A few exceptional materials are the same with the materials which show different tendency in the relation of the ductility and dimple sizes. 4) Conclusively, it is noticed that the improvement of ductility and toughness of the α/β Ti alloys can be achieved by the extreme refinement of α phase and decrease of the strength. Half done of refinement may cause reduction of the ductility and the toughness.

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