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Notch-texture strengthening mechanism in commercially pure titanium thin sheets

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ABSTRACT

Simultaneous effects of notch and texture on strengthening mechanisms of rolled thin sheets of commercially pure titanium were investigated. The presence of notch led to the restriction of deformation systems and different fracture behaviors compared to un-notched specimens. The loss of material's ability to accommodate plastic deformation at the notch tip with increase in rolling reductions changed the notch strengthening phenomenon to the notch weakening one. At medium levels of deformation, due to the simultaneous development of a triaxial stress state and strong basal texture at the notch tip, a new strengthening mechanism which is called "notch-texture strengthening mechanism" led to a significant enhancement of tear strength. However, the lack of stress triaxiality in un-notched tensile specimens and a strong basal texture component in other notched specimens reduced the impact of strengthening. It was found that the restriction of deformation systems due to the *c*-axis compression condition at the notch tip was responsible for this strengthening mechanism.

1. Introduction

Commercially pure (CP) titanium presents many advantages, especially in biomedical applications, owing to its low density–strength ratio, high biocompatibility and corrosion resistance [1]. Thin sheet devices as internal and external bone fixators are one of the major applications of titanium and its alloys. Unfortunately in this field of application the use of CP-titanium in comparison to Ti–6Al–4V alloy due to its relatively low strength properties has been limited [2]. Consequently, the allocation of more attentions to modify metallurgical variables and improve the strength properties of this material is an interesting research area.

Microstructural refining and texture strengthening, as potential strengthening mechanisms, have widely been used to improve strength properties of CP-titanium. Although many studies have been done on the effects of microstructural refinement on strengthening mechanisms [3–5], the idea of strengthening metals through the control of textures is relatively modern. As revealed by the experimental investigations, a principal factor in the texture strengthening mechanism is the simultaneous existence of a specific crystal orientation and loading direction [6]. In fact, useful strengthening is obtained when the orientation of the crystal structure makes slip and hence yield more difficult under some envisaged applied stress systems. In this field, it is reported that the titanium alloys with strong basal texture can, under biaxial stress condition, exhibit substantial increase in tensile strength [7]. Barnett [8] showed that when deformation occurs in AZ31 alloy, in the case of *c*-axis compression, the prismatic $\langle a \rangle$ slip system will become difficult in this orientation and the deformation is mainly contributed by the pyramidal $\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$ slip system, thus resulting in a high flow stress and strain hardening rate. In addition, author's previous study [9] revealed that when in CP-titanium deformation occurs in the case of *c*-axis tension, the restriction of deformation systems can strongly improve strength properties.

Implant designs may contain intended or unintended stress concentrators such as fillets, grooves, cracks, notches, bends or holes due to the manufacturing process, service applications or damages developed during service. When a ductile material such as CP-titanium is deformed in the presence of a stress concentrator, a phenomenon known as "notch strengthening" may occur [10–12]. Due to this phenomenon, it is possible for the axial yield stress of the notched sample to be greater than that of the un-notched one. On the other hand, the occurrence of a "notch weakening" effect when the ductility of the un-notched-bar is less than 5% or 6% has been reported [13]. Although the notch weakening effect is frequently considered in the design of engineering components, less attention has been paid to the notch strengthening phenomenon as a mechanism for the load bearing capacity improvement of engineering components. Therefore, it is of interest to analyze the behavior of CP-titanium as a biomaterial in the presence of design-related stress-risers.

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In our previous work [14] the effects of rolling reduction on mechanical properties anisotropy and fracture behaviors of CP-titanium was studied. In the present study, the simultaneous effects of crystallographic texture as a metallurgical variable and notch as a geometrical variable on the strengthening of rolled CP-titanium thin sheets are investigated and a new strengthening mechanism, which is called "notch-texture strengthening mechanism", is introduced for the first time.

2. Experimental procedure

The material used in this work was CP-titanium grade2 in the form of a hot-rolled and annealed plate with the thickness of 2 mm. The chemical composition of the alloy is (in wt.%): 99.375 Ti, 0.015 H, 0.030 C, 0.030 N, 0.250 O, and 0.300 Fe. To investigate the effects of notch and texture on strengthening mechanisms in CP-titanium, un-notched and notched specimens with various rolling reductions of 0%, 25%, 50%, 75% and 85%, according to ASTM:E8 and ASTM:B871 standards were used, respectively. Based on ASTM:B871 test method, the tear strength of the material was calculated by the summation of maximum nominal direct and bending stress components that the specimen is capable of sustaining. To calculate the tear stress the following equation was used:

$$\textit{Tear strength} = \frac{P}{A} + \frac{MC}{I} = \frac{P}{bt} + \frac{3P}{bt} = \frac{4P}{bt} \tag{1}$$

where P is the maximum force which can be extracted from the load–displacement curves, A is the specimen's cross section, b is the specimen's width (distance between notch root and back edge of the specimen), t is the specimen's thickness, M is the bending moment, C is the distance from neutral axis to the outermost fiber, and I is the moment of inertia. Loading axes in the mechanical tests were parallel to the rolling direction and the thickness of the specimens was equal to that of the cold rolled samples. Fig. 1 shows the geometry of the test specimens. Mechanical tests were performed at room temperature under displacement control using an Instron servo-hydraulic testing machine at the strain rate of $10^{-3}\ s^{-1}$ for tensile specimens and the crosshead speed of 1 mm min^{-1} for Kahn specimens. The R-values were obtained from the strain measurements of the deformed grids on the tensile specimens at 4% tensile strain. Texture measurements were performed in the back-reflected mode by X-ray diffraction (XRD) and the Cu Kα radiation. Pole figures were constructed from the X-ray diffraction data. Fracture surfaces were studied using a scanning electron microscope (SEM).

3. Results and discussion

The effects of rolling reduction on mechanical properties of the un-notched tensile and notched specimens are shown in Fig. 2. In un-notched tensile specimens, the increase in rolling reduction led to the increase and decrease in the material's strength and ductility, respectively. However, in notched specimens, the tear strength increased with increase in the rolling reduction up to 50% and decreased with further reductions. In addition, with the exception of the specimen with 85% reduction, notched specimens have greater strength properties compared to the un-notched tensile ones. Owing to the same microstructure and texture of the un-notched and notched specimens, different trends of mechanical properties could be related to the different specimen geometries and their effects on the stress distribution and the restriction of deformation systems.

During the rolling process, the density of dislocations, grain boundaries and twins and in general the density of obstacles in front of plastic deformation, due to the occurrence of microstructural refinement and mechanical fibering, gradually enhances. Fig. 3 represents the microstructural evolution during the rolling process. The microstructure of the as-received material (Fig. 3a) consists of the recrystallized α grains and the dispersed β phase. The average grain size of α phase was 27.3 μm. With increase in rolling reductions to medium levels a heterogeneous microstructure (Fig. 3b and c) consisting of elongated grains, due to the activation of slip systems in some grains, and deformation twins developed. Finally, at high levels of deformation, grains were completely elongated along the rolling direction (Fig. 3d and e). Clearly, without considering the role of texture and notch, the increase and decrease in the material's strength and ductility respectively, due to the increase in rolling reductions, can be predicted. The (0002) pole-figure measurements for CP-titanium cold rolled to reductions of (a) 0%, (b) 50% and (c) 85% are shown in Fig. 4. The as-received material revealed a combination of basal and split-basal texture components. The split distribution of basal texture refers to the rotation of basal planes from the normal direction (ND) towards the transverse direction (TD). The degree of rotation was about ±25–35. In the condition that the loading direction was parallel to the rolling direction, deformation must be accommodated by the operation of easier $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ prismatic slip

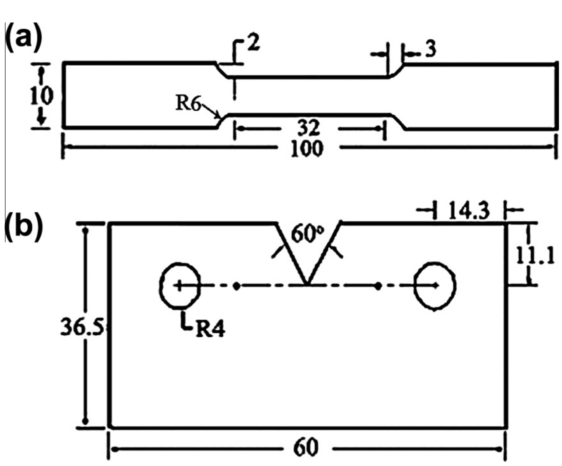

Fig. 1. The geometry of the test specimens (scale in mm): (a) un-notched tensile and (b) notched tear specimen. The thicknesses of the specimens were 0.3, 0.5, 1, 1.5 and 2 mm.

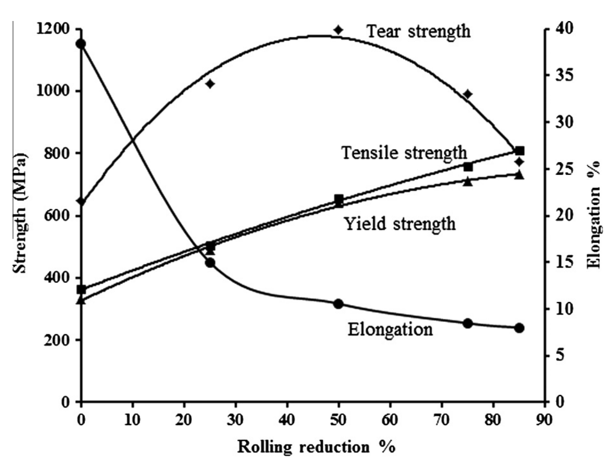

Fig. 2. Effects of rolling reductions on mechanical properties of un-notched tensile and notched specimens.