Materials Science & Engineering A 731 (2018) 239–248

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

# Microstructural evolution and its effect on the mechanical behavior of Ti-5Al-5Mo-5V-3Cr alloy during aging

Baozhen Jiang[a,b,*], Satoshi Emura[a], Koichi Tsuchiya[a,b,*]

[a] Research Center for Structural Materials, National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan
[b] Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan

ARTICLE INFO

*Keywords:*
Ti-5553 alloy
High-pressure torsion
α phase precipitates
Mechanical properties
Strengthening mechanism

ABSTRACT

Development of different microstructures with α phase precipitates by a series of aging of Ti-5Al-5Mo-5V-3Cr (mass%, Ti-5553) alloy and their influences on the mechanical behavior were studied. Coarse acicular α phase formed in the solution treated (ST) samples, while ultrafine equiaxed α phase formed in the high-pressure torsion deformed (HPTed) samples. The strengthening by the precipitation of α phase could be explained by the Hall-Petch relationship between the yield strength and the α-to-α interphase spacing. The Hall-Petch coefficient of the HPTed samples was larger than that of the ST samples, because the equiaxed α phase was harder than the acicular α phase. The ductility of the HPTed samples was enhanced by the homogeneous distribution of equiaxed α phase.

## 1. Introduction

Ti alloys have been used in many industrial fields thanks to their attractive combination of mechanical properties. Among them, metastable β-Ti alloys exhibit unique combination of high strength-to-density ratio, excellent hardenability and good corrosion resistance [1–4]. Ti-5Al-5Mo-5V-3Cr (mass%, Ti-5553) alloy is a recently developed metastable β-Ti alloy with promising mechanical properties for aerospace structural applications [1,5–7]. Ti-5553 alloy exhibits a higher strength and a better high-cycle fatigue property over Ti-6Al-4V (Ti-64) alloy which is the most widely used Ti alloy in aerospace industry [8]. The wider processing window and the better deep-hardenability of Ti-5553 alloy make it an ideal candidate for the thick forging applications in the landing gear components to replace Ti-10V-2Fe-3Al (Ti-1023) alloy [5–7]. Ti-5553 alloy can be heat treated in a section size up to 152 mm accompanied with only a slight drop in properties at the thicker section size by air cooling, whereas Ti-1023 alloy requires a water quenching and the section size is limited to 76 mm. This is mostly due to the more sluggish precipitation of α phase in Ti-5553 alloy because of the addition of Mo and Cr.

There have been several studies on Ti-5553 alloy, showing that the microstructure can vary substantially as a function of thermo-mechanical processing and heat treatment and the mechanical properties of Ti-5553 alloy are critically dependent on its microstructure [9–14]. Quantitative microstructural analysis were carried out to clarify the influence of microstructure, especially the α phase precipitates, on the flow behavior [9], the fracture toughness [11] and the tensile properties [12–14] of Ti-5553 alloy. The volume fraction and size of α phase precipitates were considered as important microstructural features that could affect the mechanical properties. From the viewpoint of precipitation/dispersion hardening mechanism, the influence of α phase precipitates on the mechanical properties is mostly due to the creation of a large number of α/β interfaces which act as effective dislocation barriers.

Recently, it has been shown that severe plastic deformation, such as high-pressure torsion (HPT) and equal channel angular processing (ECAP), can bring about a change in the morphology of α phase from acicular to equiaxed [14–19]. Zafari *et al.* [17] investigated the mechanism for the change in the morphology of α phase in HPT deformed Ti-5553 alloy by examining the α precipitation at the very early aging stages. The present authors carried out a series of aging on HPT deformed Ti-5553 alloy to investigate the formation and growth process of equiaxed α phase [19]. Ultrafine equiaxed α phase distributed homogeneously in Ti-5553 alloy subjected to HPT deformation of 10 revolutions. However, in all the cases mentioned above, the influence of the precipitation of equiaxed α phase on the mechanical properties was not included. Further investigations are required to develop a deeper fundamental understanding of the strengthening mechanism by the precipitation of equiaxed α phase. The present study shows the results of a systematic study done on the HPT deformed Ti-5553 alloy. The evolution of microstructure and mechanical properties as a function of aging is presented. As a comparison and to establish the microstructure-

* Corresponding authors at: Research Center for Structural Materials, National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan.
*E-mail addresses:* JIANG.Baozhen@nims.go.jp (B. Jiang), TSUCHIYA.Koichi@nims.go.jp (K. Tsuchiya).

https://doi.org/10.1016/j.msea.2018.06.064
Received 7 March 2018; Received in revised form 14 June 2018; Accepted 15 June 2018
Available online 18 June 2018
0921-5093/ 

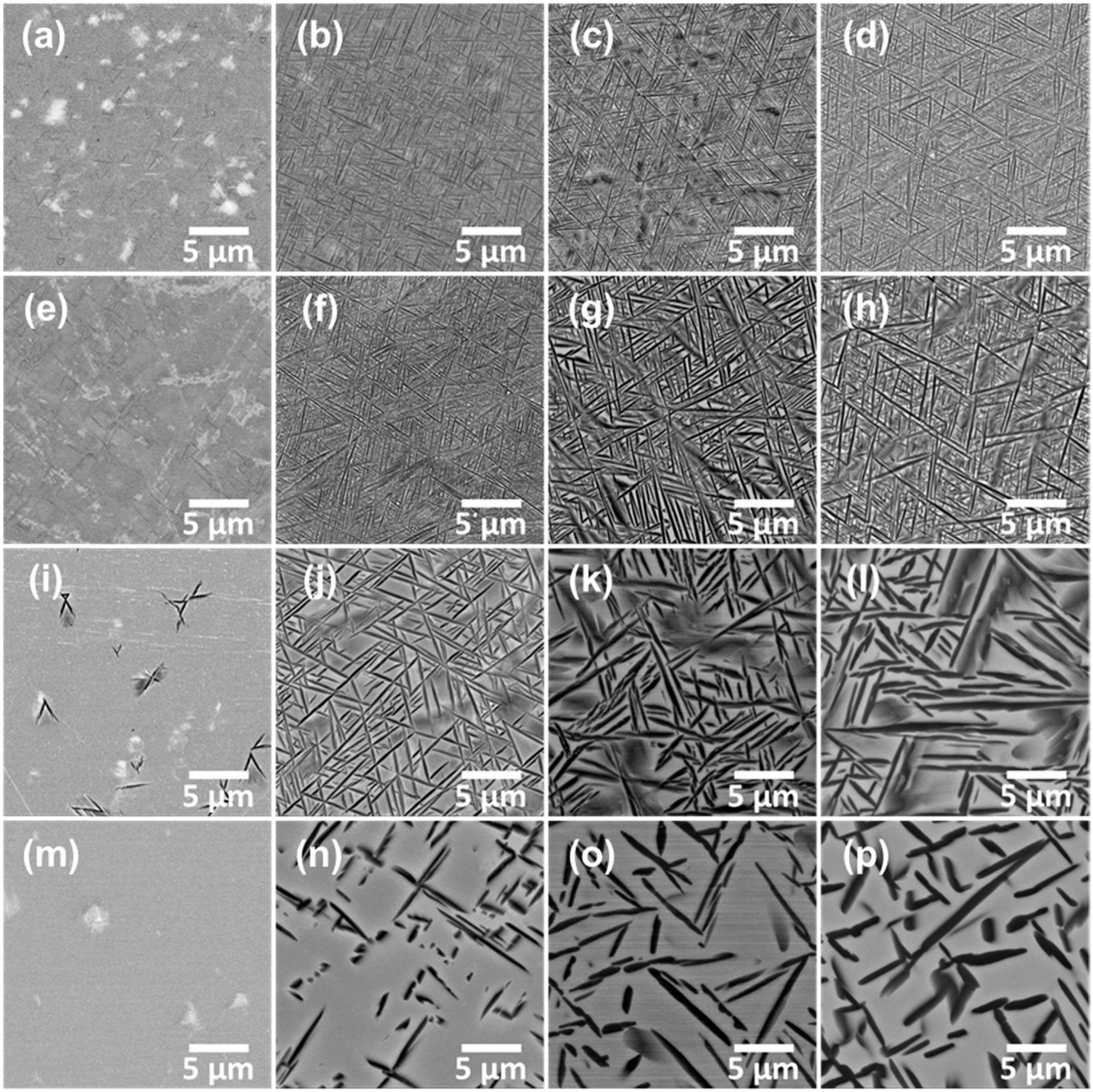


**Fig. 1.** BSE micrographs of the ST samples after aging at 823 K for (a) 0.3 ks, (b) 1.2 ks, (c) 14.4 ks and (d) 360 ks; aging at 873 K for (e) 0.3 ks, (f) 1.2 ks, (g) 14.4 ks and (h) 360 ks; aging at 923 K for (i) 0.3 ks, (j) 1.2 ks, (k) 14.4 ks and (l) 360 ks; and aging at 1023 K for (m) 0.3 ks, (n) 1.2 ks, (o) 14.4 ks and (p) 360 ks.

mechanical properties correlation, the evolution of microstructure and mechanical properties as a function of aging in the Ti-5553 alloy without HPT deformation is also presented. The influences of the equiaxed α phase and the acicular α phase on the mechanical behavior will be discussed in detail.

## 2. Experimental

An ingot of Ti-5553 alloy was prepared by cold crucible levitation melting (CCLM) with a weight of around 1.2 kg. The analyzed chemical composition is Ti-5.04Al-5.14Mo-4.91V-3.04Cr (mass%). After hot forging and rolling at 1473 K, a bar of the alloy was cold swaged to a diameter of 10 mm. Disk samples with a thickness of 0.9 mm were sliced from the bar and were solution treated above the β transus temperature (1129 K) at 1273 K for 3.6 ks. After grinding the surface to a thickness of 0.85 mm, deformation by high-pressure torsion (HPT) was applied on the disk samples at room temperature under a pressure of 5 GPa and a rotation speed of 0.2 rpm for 10 revolutions. Hereafter, the solution treated samples are referred as ST samples and the HPT deformed samples are referred as HPTed samples. The microstructures of Ti-5553 alloy after ST and HPT deformation have been reported by the present authors [19]. A series of aging were done on the ST samples and HPTed samples. The aging temperatures were 823 K, 873 K, 923 K and 1023 K, and the aging time ranged from 0.3 ks to 360 ks. The