Materials Science & Engineering A 617 (2014) 97–109

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

On the elasto-viscoplastic behavior of the Ti5553 alloy

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ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form
19 August 2014
Accepted 19 August 2014
Available online 1 September 2014

Keywords:
Ti5553 alloy
Ti–6Al–4V alloy
Norton–Hoff model
Viscoplasticity
Anisotropy
FE simulations

ABSTRACT

The elastoviscoplastic behavior of the Ti5553 alloy is characterized and compared to the classical Ti–6Al–4V alloy. The true stress–strain curves are determined based on tensile tests performed under different strain rates at room temperature and at 150 °C, from which the elastic constants and the parameters of a Norton–Hoff viscoplastic model are identified. The strength of the Ti5553 alloy is 20–40% higher than the strength of the Ti–6Al–4V alloy. The Ti5553 alloy constitutes thus a promising candidate for advanced structural applications. In view of modeling structural applications of forming operations, the elastic and plastic initial anisotropy of the two alloys is investigated by combining compression on cylinders with elliptical sections, uniaxial tensile tests in different material directions, plane strain and shear tests. The initial anisotropy of the different alloys is very weak which justifies the modeling of the mechanical behavior with an isotropic yield surface. The identified elastoviscoplastic model is validated by comparing experimental results with FE predictions both on cylindrical notched specimens subjected to tensile tests and on flat specimens subjected to plane strain conditions.

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1. Introduction

Titanium alloys are heavily used in aeronautic applications owing to a low density, good corrosion behavior, and excellent mechanical properties. The well-known Ti–6Al–4V is the most commonly selected Ti alloy in aerospace components. It accounts for more than 50% of the Ti production. However, the need to increase, for weight reduction reasons, the strength of Ti–6Al–4V components combined with the inherent limited strain hardening capacity has created an impetus for the development of new alloys. Over the past few years, Ti5553 has been identified as a promising candidate to advantageously replace Ti–6Al–4V in some components [1,2], but the mechanical data available for supporting such a choice are still scarce. Near β Ti5553 alloy (Ti–5Al–5V–5Mo–3Cr) [3] is a variation of the Russian alloy VT22 [4] and an alternative to the alloy Ti-10-2-3 [5].

The aim of the present work is to investigate the elastoviscoplastic mechanical response of the alloy Ti5553 under two heat treatment conditions (leading to two different microstructures named hereafter Ti5553-1 and Ti5553-3) involving a comparison with the Ti–6Al–4V alloy. The first objective of this paper is to identify the elastic constants and the Norton–Hoff viscoplastic parameters [6] based on uniaxial tensile tests carried out under four different strain rates ($5\times10^{-5}\,s^{-1}$, $2\times10^{-4}\,s^{-1}$, $4\times10^{-3}\,s^{-1}$, $10^{-2}\,s^{-1}$) and at two temperatures (room temperature and 150 °C). The second objective is to analyze the elastic and plastic anisotropy in view of modeling structural applications of forming operations. The anisotropy is investigated on the basis of compression tests, uniaxial tensile tests in different directions, plane strain tests and shear tests.

The outline of the work is the following:

- In Section 2, the chemical composition and heat treatment of the different microstructures are presented.
- In Section 3, the different mechanical parameters (elasticity, viscoplasticity) are identified after the presentation of the experimental procedure and results.
- In Section 4, the elastic and plastic anisotropy of the two alloys is analyzed.
- In Section 5, the identified elastoviscoplastic model is validated by comparing experimental results on notched and one plane strain specimens with FE predictions.
- In Section 6 the overall conclusions are highlighted.

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http://dx.doi.org/10.1016/j.msea.2014.08.055
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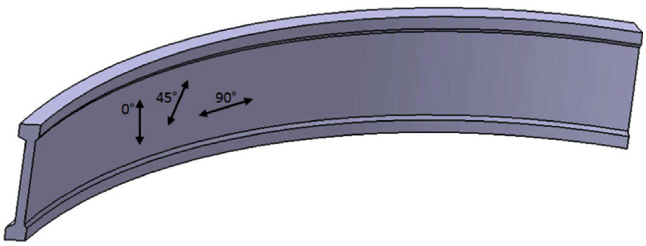

Fig. 1. Forged part made of alloy Ti–6Al–4V (with extraction directions).

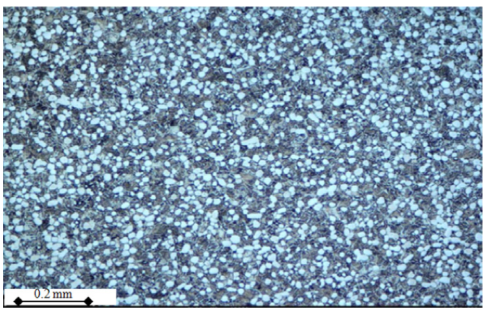

Fig. 2. Microstructure of alloy Ti–6Al–4V.

Table 1
Chemical composition of alloy Ti–6Al–4V, in weight per cent (wt%).

	C	Si	Mn	Mo	Al	V	Fe	Cu
Bottom	0.014	< 0.01	< 0.01	< 0.01	6.50	4.12	0.16	0.02
Top	0.012	< 0.01	< 0.01	< 0.01	6.46	4.05	0.15	0.03
	B	**Zr**	**Y**	**O**	**N**	**Sn**	**Cr**	**Ni**
Bottom	< 0.001	< 0.01	< 0.001	0.16	0.008	< 0.01	< 0.1	0.01
Top	< 0.001	< 0.001	< 0.001	0.18	0.006	< 0.01	0.1	0.01

Table 2
Chemical composition of the Ti5553 alloy (values are in wt%).

	Mo	Zr	Fe	V	Si	Al
Bottom	4.82	< 0.005	0.3	4.93	< 0.03	5.26
Top	4.87	< 0.005	0.3	4.94	< 0.03	5.33
	C	**O**	**N**	**Cr**	**Y**	**H**
Bottom	0.009	0.14	0.005	3.04	< 0.001	0.006
Top	0.007	0.14	0.004	3.05	< 0.001	0.004

2. Materials

As for any metallic alloys, the mechanical properties of Ti alloys are very sensitive to the initial microstructure, thermo-mechanical loading history, and chemical composition [7–10]. From a microstructural point of view, the Ti–6Al–4V and Ti5553 alloys are significantly different in terms of volume fraction and morphology of the primary α phase and of the transformed β phase. A detailed comparison between the microstructures of the two alloys can be found in [2].

2.1. *Alloy Ti–6Al–4V*

2.1.1. *As received Ti–6Al–4V*

The Ti–6Al–4V specimens are directly machined from a forged part provided by the company Techspace Aero (Fig. 1).

The Ti–6Al–4V alloy of this work is made of equiaxed primary α grains and secondary α lamellae dispersed in a β matrix (Fig. 2). The volume fraction of the α phase is between 80% and 90%. The transus temperature is about 995 °C [2,7]. After forging in several steps in the α+β domain, the final heat treatment consists in an annealing performed at 750 °C (1 h) followed by air cooling.

2.1.2. *Chemical composition*

The chemical composition from the top and bottom regions of the initial ingot (used to machine the forged component of Fig. 1) is reported in Table 1.

The molybdenum equivalent in terms of chemical composition is defined as follows [11]:

$$wt\%Mo.Eq. = 1.0\,(wt\%Mo) + 0.66\,(wt\%V) + 0.33\,(wt\%N) + 3\,(wt\%Fe) + 3\,(wt\%Cr). \quad (1)$$

Using the above table and formula, the Mo equivalent was estimated as equal to 3.48.

2.2. *Ti5553 alloy*

The Ti5553 alloy involves a large amount of β stabilizer elements such as Mo, V, Fe and Cr (see chemical composition in Table 2). The transus temperature is about 860 °C [4]. The Ti5553 alloy involves a high sensitivity to minute variations of the heat and thermomechanical treatment. This sensitivity has a significant impact on the microstructure as demonstrated hereafter.

The material of the present study has been provided by the company Techspace Aero in the form of forged pancakes (Fig. 3). The forging of the pancakes was performed at 815 °C using a 2500 tons forging press. The final thickness of the pancakes is equal to 47 mm. Based on the chemical composition (Table 2) and Eq. (1), the Mo equivalent was estimated as equal to 18.18.

The chemical composition from the top and bottom regions of the ingot is reported in Table 2.

The final heat treatment used to generate the two microstructures of Ti5553 alloy is defined by the following heat cycles (see Fig. 4):

- Ti5553-1: heated from room temperature up to 830 °C+hold at 830 °C during 2 h+air cooling+ageing at 610° C during 8 h+air cooling.
- Ti5553-3: heated from room temperature up to 830 °C+hold at 830 °C during 2 h+air cooling+ageing at 670° C during 8 h+air cooling.

The resulting microstructures are made of equiaxed primary α grains and secondary α needles embedded in a β matrix. These two microstructures are thus bi-modal; the primary α phase has a nodular morphology and the secondary α is lamellar. The volume fraction of the α phase is about 20%.

The first aging at 830 °C (Fig. 4) is responsible for the nucleation of the nodules of α. This aging is the same for both microstructures, explaining why there is no difference between the morphology and the size of the nodular α phase. The only difference between the two microstructures is related to the aging temperature. This temperature was responsible for the formation of the secondary α phase, which contains needles like particle shape or very small plates. The microstructure of Ti5553-1 shown in Fig. 5(a), is slightly finer compared to the Ti5553-3 microstructure shown in Fig. 5(b), due to a lower aging temperature (610 °C). Note that the presence of the secondary α phase is an important source of hardening in the alloy.

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