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Influence of tempering temperature and time on the α' -Ti-6Al-4V martensite

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Abstract

The decomposition of α' martensite of Ti-6Al-4V by tempering has been studied. The α' martensite transforms during tempering heat treatment, decomposing to α and β phases. Different degrees of α' decomposition, depending on temperature and heating time, have been observed. At low annealing temperatures the decomposition is incomplete, as is shown by the low value of the hardness. At temperatures above M_f the decomposition of α' reaches completion. The microstructures have been observed by means of scanning electron microscopy.

Keywords: Ti-6Al-4V martensite alloy; Decomposition; Temperature dependence; Time dependence

1. Introduction

$\alpha + \beta$ titanium alloys are the most popular of many kinds of titanium alloy, and lots of commercial alloys such as Ti-6Al-4V, Ti-6Al-6V-2Sn and Ti-6Al-2Mo-4Zr-2Sn belong to this group. One of these $\alpha + \beta$ alloys has the greatest commercial importance namely Ti-6Al-4V, making up more than half the sales of titanium alloys. They have the advantage of relatively high tensile strengths and improved formability, although some compromise is found in creep occurring above 400 °C whereas the weldability is reduced by heat treatment in this temperature range [1].

For titanium alloys which have phase diagrams of the β isomorphous type, uniform properties can be obtained by slow cooling from either the β or the $\alpha + \beta$ phase fields, known as the β -annealed or mill-annealed conditions respectively. In the first case, it is usual for the α phase to form as Widmanstätten laths in a β matrix, although β may itself transform to martensite α' when the sample is quenched [1-3].

Titanium martensites transform on heating at elevated temperatures by several reactions the nature of which depends on the crystal structure of the martensite and the chemical composition of the alloy concerned. These reactions may be complex and of various types.

Although there is much information on phase transformations and mechanical properties for these alloys [2-5], only few studies exist on the martensitic transformation and the decomposition of martensite by heat treatment and the influence of this on the mechanical properties. In addition, it is very important to determine these mechanical properties in order to find the optimum condition of heat treatment. In this study, we report on our investigations of the decomposition of α' -martensite of Ti-6Al-4V by tempering and the influence of the temperature and the time of heat treatment on hardness values.

2. Experimental method

The Ti-6Al-4V alloy used in the present work was kindly donated by Industrias Quirúrgicas del Levante S.A. The material came as cylindrical rods of 12 mm diameter, forged at 950 °C and subsequently annealed at 700 °C for 2 h and then cooled in air.

The chemical composition of the alloy is shown in Table 1. The microstructure, as observed using optical metallography, corresponds to that known as 'mill annealed', consisting of equiaxial α grains as well as grains constituted of small α Widmanstätten plates

Table 1
Chemical composition in weight percent

Al	V	Fe	C	O ₂	N	H ₂	Ti
6.1	4.0	0.11	0.021	0.09	0.010	0.003	Balance

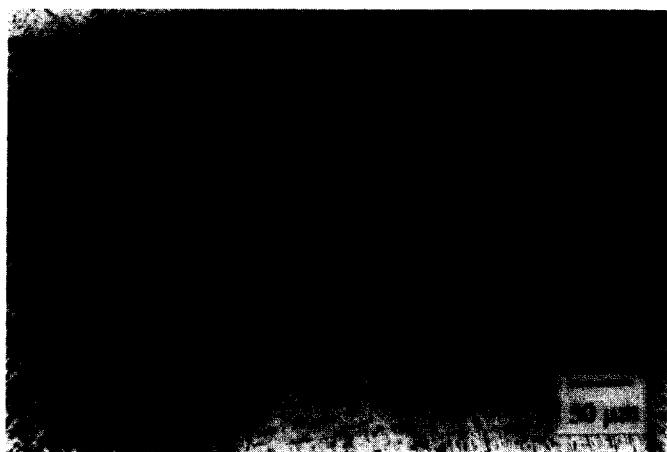


Fig. 1. Microstructure of a non-treated sample.

surrounded by residual β phase, as can be observed in Fig. 1.

The samples were cut into 3 mm long cylinders from a bar 5 mm in diameter. The specimens were held for 30 min in a tubular furnace in argon atmosphere at 1050 °C, which is a temperature just above the $\alpha \rightarrow \beta$ transition temperature for the Ti-6Al-4V alloy, and rapidly quenched in water at room temperature. The resulting microstructure corresponds to acicular α' martensite as can be seen in Fig. 2.

Annealing treatments at temperatures of 400, 600, 700 and 800 °C were applied to these samples for 5, 10, 15, 30, 60 or 120 min.

The microstructures were studied by optical and scanning electron microscopy and the Vickers hardness



Fig. 2. Microstructure of a sample heat treated at 1050 °C for 30 min.

measurements were carried out by applying a load of 1000 gf for 15 s.

3. Results and discussion

Direct quenching in water from 1050 °C resulted in a fully martensitic structure with a Vickers' hardness of 330. This martensite is the hexagonal α' type with acicular morphology that present different orientations.

The α' -martensite transforms during tempering heat treatment, decomposing to equilibrium α and β , whereby the α' structure is transformed into α as a fine precipitate that is nucleated heterogeneously at martensite plate boundaries or at internal structures such as twins.

The tempering of these martensitic specimens produced different degrees of α' decomposition depending on temperature and heating time. Hardness evolution with annealing time is shown in Fig. 3. At each temperature the curve of hardness vs. heating time is of a sigmoidal type, indicating that the precipitation of the α and the β phases from α' occurs by a nucleation and growth process controlled by atom diffusion.

At low annealing temperatures (below 600 °C) the decomposition of α' is incomplete as is shown by the low value of the hardness. Fig. 3 show that at 400 °C the precipitation of α and β stops after 40 min whereby a hardness of 350 HV is reached.

The incomplete nature of the precipitation at this temperature can also be observed in Fig. 4, which shows the microstructure of a specimen annealed at 400 °C for 60 min. At temperature above M_f ($T \approx 800$ °C) the decomposition of α' reaches completion; this fact is reflected in the high saturation value exhibited by the hardness (410 HV). The microstructure obtained at high annealing temperatures is shown

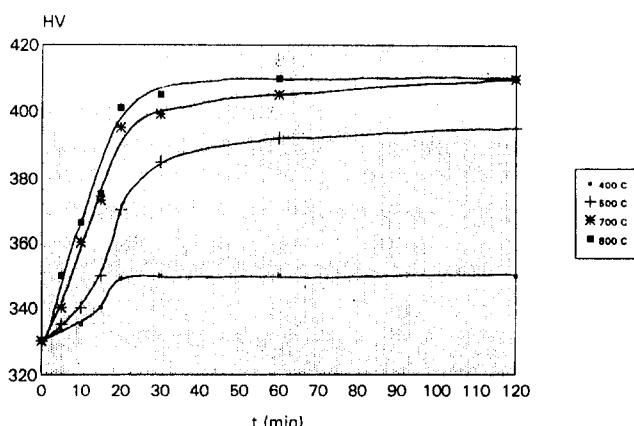


Fig. 3. Plot of hardness evolution with annealing time for different temperatures.



Fig. 4. Microstructure of a sample annealed at 400 °C for 60 min.

in Fig. 5, where α and β phases are now present in a higher proportion.

The hardness data in relation to the temperatures and times of heat treatment can be shown as a topographic chart (Fig. 6), where each curve represents a constant hardness value. This shows clearly that the precipitation process is enhanced by the increase in both time and temperature of heat treatment and reaches a limit for a given temperature–time pair. The relationships between hardness and temperatures and times of heat treatment for the decomposition of α' martensite exhibit an analogy with recrystallization processes. This relation might be the result of the fact that the precipitation is due to nucleation and that the growth process is diffusion controlled, as found in the recrystallization that take place in different metals and alloys.

If this hypotheses is correct, it is possible to obtain the precipitated fraction for the hardness values using the Avrami equation [6]:

$$1 - X = \exp(-\beta t^k) \quad (1)$$



Fig. 5. Microstructure of a sample annealed at 700 °C for 60 min.

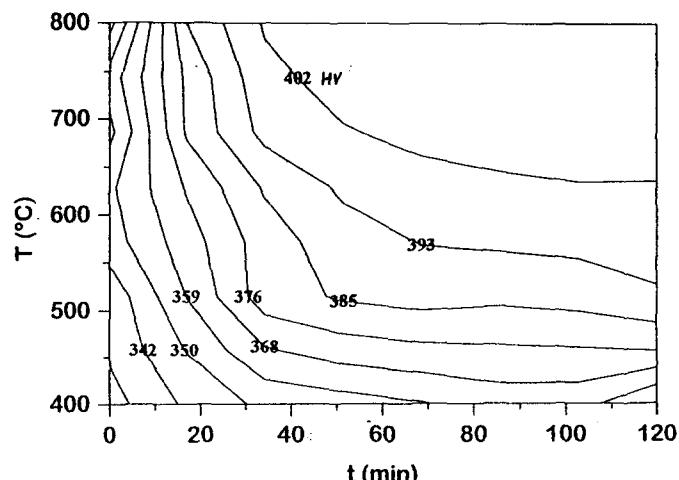


Fig. 6. Plot of hardness data vs. temperature and time.

Table 2
Values for Avrami constants

T (°C)	k	$\ln \beta$	t (min) for $X = 50\%$
400	0.667	0.0192	216
500	1.106	0.0147	32.6
700	1.252	0.0246	25.9
800	1.326	0.0307	10.5

where X is the recrystallized or precipitated fraction, t the tempering time, β a constant and k a constant. It is supposed that the highest hardness value occurs at total precipitation ($X = 1$). Then the values of the constants shown in Table 2 are obtained. Therefore, it can be concluded that the time needed to obtain a 50% precipitation rapidly decreases as the temperature increases, as is predicted from the recrystallization theory.

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