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Tailoring of microstructure and mechanical properties of Ti–6Al–4V with local rapid (induction) heat treatment

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ABSTRACT

The evolution of microstructure during local rapid (induction) heat treatment (LRHT) and its effect on the tension and fatigue properties of Ti–6Al–4V with an initial microstructure of fine-grain equiaxed alpha or coarse-grain colony alpha were investigated. LRHT of material with an initial equiaxed condition formed a graded microstructure that varied from a fully transformed one at the surface to a bimodal (equiaxed/transformed) one at the center. After final aging (LRHTA), such a material was characterized by an attractive blend of tension and fatigue properties (UTS = 1285 MPa, elongation = 6.3%, endurance limit 710 MPa). An analysis of the dependence of mechanical properties on the volume fraction of heat-treated material revealed that LRHTA processing to 50% transformed in the critical cross section (from point of view of maximum applied loading) gave a balance of tensile properties similar to those obtained via bulk (100%) rapid heat treatment of Ti–6Al–4V. In contrast, the LRHTA of Ti–6Al–4V with a coarse-grain colony-alpha preform condition required longer heating times to refine the structure and provided only a modest improvement in mechanical properties.

1. Introduction

Titanium and titanium alloys are widely used in the aerospace industry due to their high strength-to-density ratio and excellent fatigue and corrosion resistance [1]. Lutjering and Williams [2] summarized a wide range of data available in the literature and concluded that the mechanical properties of titanium alloys depend strongly on their phase distribution, the microstructure developed during thermomechanical processing, and final heat treatment. Thermomechanical processing of titanium alloys can be used to produce a variety of microstructures depending on temperature and applied deformation [3,4]. The main types of microstructure are (1) coarse-grain with an average β-grain size of several hundred microns and colonies of α + β lamellae, which is formed after slow cooling when deformation or heat treatment takes place at a temperature in the single-phase β-field above the so-called beta-transus temperature T_β (at which the $\alpha + \beta \rightarrow \beta$ transformation takes place) and (2) fine equiaxed (globular) alpha formed after deformation in the two-phase α + β field (i.e., below T_β). The first microstructure is characterized by relatively low tensile ductility, moderate fatigue properties, and good creep and crack-growth resistance. The second microstructure has a better balance of strength and ductility at room temperature and fatigue properties which depend noticeably on the crystallographic texture of the hcp α-phase; however, such properties decrease more rapidly with increasing temperature compared to those of the lamellar microstructure. A third, or bimodal, microstructural condition consisting of primary α-grains and fine lamellar α + β colonies within relatively small β-grains (~10–20 μm in size) often provides an attractive balance of properties.

Previous studies [5,6] showed that the application of rapid heat treatment (RHT) into the single-phase β-field (at rates of the order of tens or even hundreds of degrees per second) can be used to form unique microstructures comprising relatively fine β-grains (≤30–50 μm) with fully transformed intragranular α + β lamellae/laths. This microstructure is characterized by a much better balance of strength, ductility, and fatigue performance compared with other types of microstructures. RHT performed using direct-resistant electric heating can be applied only to semi-finished objects having a constant cross-section along their length. For components having a complex shape, induction, salt bath, or others methods may be used to conduct through- or local- rapid heating. For example, in [7] rapid induction heating (with its ability to generate temperature gradients) was used to form *graded* microstructures. Induction heating was also applied to titanium alloys in latter investigations [8,9] for local heating, but the comparatively long exposure times at high temperatures resulted in relatively coarse β-grains and hence poor ductility.

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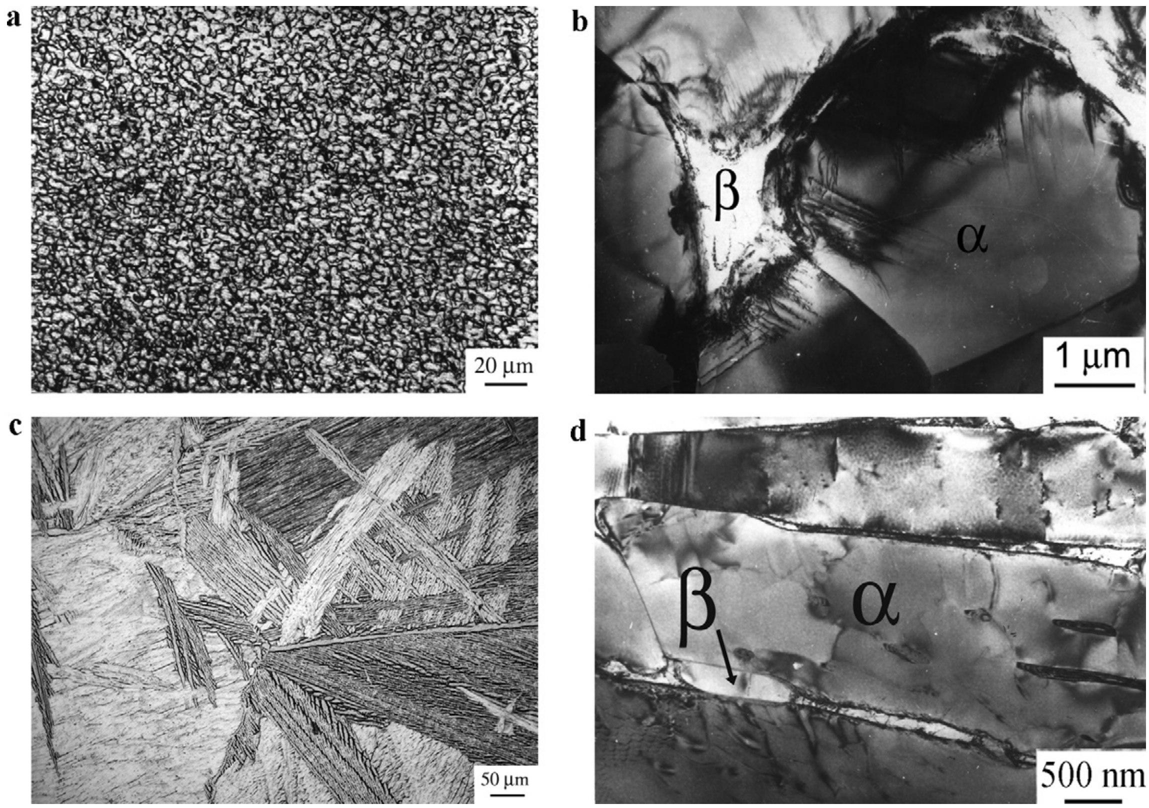

Fig. 1. Microstructure of Ti–6Al–4V program material with different preform microstructures (a and b) equiaxed-alpha (developed by annealing 800 °C/1 h) and (c and d) colony-alpha (developed by beta annealing 1100 °C/1 h and furnace cooling). (a and c) LM, (b and d) TEM.

Many applications would benefit by varying the properties in different sections of the same part, depending on the specific temperature, applied stress, etc. experienced in service, as has been demonstrated for turbine engine parts [10]. For a compressor blade, for instance, wear resistance and fretting behavior may be important for the dovetail, while fatigue performance, creep behavior, erosion resistance, and impact toughness are critical in other locations. To achieve optimum performance, therefore, microstructure (and phase composition) should be tailored on a local scale to improve upon the uniform, but only moderate, properties obtained by bulk treatments.

It has been shown [3,11] that local/selective heat treatment can be accomplished using a number of conventional high-energy-density methods such as those based on electromagnetic induction, electron-beam, infrared, and laser heating. Each of these techniques has been widely applied to produce primarily one-dimensional graded microstructures in relatively simple parts. For example, the authors of Ref. [7] established that induction heat treatment of round bars of Ti–6Al–4V can be used to obtain a graded microstructure comprising a transformed-beta surface layer and an equiaxed-alpha microstructure in the core. Furthermore, each method is characterized by various parameters such as heating/cooling rate and heat distribution, which affect the temporal and spatial distribution of temperature and consequently the final microstructure/phase composition and location-specific service properties.

In a previous effort [12], we determined that local rapid heat treatment (LRHT) could be used to improve the tension and fatigue properties of commercial-purity titanium (CP-Ti) through the formation of a well-developed dislocation substructure and some quantity of martensite-like laths. Unfortunately, similar process-design data for *alloys* of titanium do not exist in the literature. The objective of the present work, therefore, was to delineate the microstructural transformations and mechanical properties that pertain to LRHT of the workhorse of the titanium industry, i.e., Ti–6Al–4V, used widely for more than 50 years in such diverse industries as jet propulsion, power generation, food processing, and medicine.

2. Materials and experimental procedures

Phase-transformation behavior during LRHT was investigated using Ti–6Al–4V as the program material. Its measured composition (in weight percent) was 6.20 aluminum, 4.08 vanadium, 0.17 oxygen, 0.03 nitrogen, 0.008 hydrogen, 0.052 carbon, 0.21 iron, 0.08 silicon, balance titanium. The alloy was received as 12 mm diameter hot-rolled bar produced by VSMPO-AVISMA (Russia). The as-received condition comprised a well-worked, fine, equiaxed-alpha microstructure. To eliminate any traces of residual hot work (such as nonuniform phases or microstructure) and to ensure a fully stable microstructure, the material was annealed for 1 h at 800 °C (Fig. 1a and b).

The formation of a coarse β-grain, colony-alpha microstructure tends to reduce first-tier mechanical properties such as strength and ductility [2]. The application of LRTH to refine the colony lamellae may result in a possible improvement of mechanical properties. Hence, an alternate, beta-annealed preform microstructure was also utilized for the present investigation. It was developed by a 1-h beta heat treatment at 1100 °C followed by slow (furnace) cooling. By this means, a coarse, fully transformed beta-grain structure (average β grain size of ∼600 μm, Fig. 1c) consisting of colonies of alpha- and beta-phase lamellae was produced (Fig. 1d).

Cylindrical specimens having a diameter of 8 mm and a length of 70 mm were machined from heat treated bars in the two different preform conditions. The 8 mm diameter specimens were