Further Research on Hardenability of Ti-1023 β Alloy Leading to a New DOE

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1. Abstract

As part of a treatise on the hardenability of Ti-1023, a summary about the nucleation mechanisms of primary and secondary α , the viability of two-step aging, and existence of precipitation-free zones is provided. Assumptions are given on the nucleation mechanism of primary α particles and the effect of higher β stabiliser content on stress-induced martensitic transformation. It is reminded that further research into two-step aging would be beneficial. A proposed design of the experiment deals with the existence of martensite in stressed samples, so that the martensitic transformation is minimized by an increased content of β stabilisers, volume fraction of primary α , and β grain size. Finally, a microstructure with stress-induced ω particles as precursors of secondary α particles may result in a better trade-off of mechanical properties; it is suggested that this be explored.

2. Introduction

Ti-1023 is a β titanium alloy designed to provide better mechanical properties than Ti64 and was patented by Timet in 1974 [1]. This alloy is currently available in three modifications AMS 4984, 4986, 4987 and finds an application in aircraft structural parts such as landing gear, actuators, flap tracks, rotor heads, fittings and fasteners [2] due to material properties such as its excellent combination of strength, ductility, toughness, machinability, weight, superior fatigue properties, corrosion resistance, deep hardenability with reasonable high-temperature strength and creep stability [3][4][5][6][7][8][9]. Due to a wide range of chemical composition, the molybdenum-aluminium equivalent $[\text{Mo-Al}]_{\text{eq}}$ can acquire values app. 5.3-10.4 [10][2], and Ti-1023 is thus positioned predominantly as a near β alloy. The β transus for a varying composition is not known but some reported values are between 788-805°C [11][4][12][13]. A varying composition influencing mainly the β -transus temperature, microstructure and material properties has been causing confusion among researchers since its inception due to possible formation of martensite upon quenching to room temperature, especially when quenching thick sections [4][14][15][16][17][18][19].

Ti-1023 is β forged to increase fracture toughness and finish α - β forged to keep a sufficient level of fracture toughness and to improve ductility [3]. The alloy composition and thermomechanical processing - such as forging history and heat treatments - have an impact on the mechanical properties primarily by a modification of the volume fraction, morphology and distribution of α phase [20].

The resulting microstructure of samples quenched from above or below the β transus and strengthened by α -aging has very good fatigue cycle properties and crack growth resistance [21][6]. Hence the major interest lies in tensile strength, elongation and fracture toughness and their trade-off. Depending on thermomechanical treatment, the ultimate yield strength varies ca. 260-1530MPa, the uniform elongation 0-18% and the fracture toughness 20-70MPa $\sqrt{\text{m}}$ [22][4][7].

Especially for small cylindrical parts, it seems these could be designed in a more efficient and effective process than currently available giving a better trade-off of mechanical properties and reduced cost. A consideration will be given to influence of stress-induced ω phase to clarify whether Ti-1023 finds new applications.

3. Current situation

The following text will summarize the mechanisms of nucleation of primary α_p and secondary α_s phase, two-step aging, precipitation free zones and stress-induced ω phase.

The primary α_p phase exists in samples processed in the α - β field. Tang et al. [23] suggested that with decreasing content of β stabilisers in the titanium alloys the mechanism of formation of α_p lamellae changes from sympathetic nucleation to interface instability. As for Ti-7Mo-3Nb-3Cr-3Al alloy with the $[\text{Mo-Al}]_{\text{eq}}=8.64$, both mechanisms (mixed) were observed.

Hence, it is presumed that Ti-1023 with the $[\text{Mo-Al}]_{\text{eq}}=5.3\text{-}10.4$ can go through sympathetic nucleation at a higher range, mixed at middle and possibly interface instabilities at a lower range. The impact of various mechanisms of formation of α_p lamellae on mechanical properties in general is not clear.

The mechanism of nucleation of the secondary alpha α_s in the absence of pre-existing isothermal omega ω_i phase was documented on many occasions such as in step-quenching from the solution treatment temperature [24], rapid heating [25] or up-quenching [26] or mixed heating [27] to aging temperature and suppression of ω_i formation as a consequence of a higher content of aluminium or oxygen [28]. Terlinde et al. [22] described a secondary alpha α_s of size $3\text{-}8 \times 0.1$ micron that were created in an autocatalytic manner in the case of a high heating rate (not specified) to an aging temperature $>400^\circ\text{C}$ in Ti-1023 alloy not forming martensite upon beta quenching. For the purpose of creation of an isothermal transformation diagram for Ti-1023, Toran and Biederman [14] experimented with step quenching from above the beta transus temperature and confirmed that above 550°C , the acicular secondary alpha α_s formed upon annealing from beta phase. Below 550°C , the acicular martensite formed first. However, neither the composition of this alloy nor any results of mechanical testing were available. Most likely the annealed microstructure of samples formed by step-quenching from above the beta transus and samples previously quenched to room temperature and rapidly heated or up-quenched to the same temperature is very similar despite the fact that the linear defects forming the athermal omega ω_a embryos transform to ω_a in the latter case [29][25][26].

The location of nucleation of secondary alpha α_s particles assisted directly or indirectly by isothermal omega ω_i particles has received a lot of attention recently, especially in the case of samples beta quenched to room temperature. Nucleation of secondary alpha α_s particles has been presumed at the $\beta\text{-}\omega_i$ interfaces for both high and low misfit alloys [30][31][32][33] [34], in ω_i particles [35], near $\beta\text{-}\omega_i$ interface [36] and instead of ω_i particles [27]. During aging, Ti-1023 behaves as an alloy with a high linear misfit. The isothermal omega ω_i particles adopt a cubical shape to minimize the total elastic strain. The lattice misfit increases until exceeding a critical value causing formation of interfacial dislocations where preferentially the secondary alpha α_s nucleates. Hence, secondary alpha α_s particles nucleate at the $\beta\text{-}\omega_i$ interfaces [31][37]. Beta solution treated and water quenched Ti-1023 samples exhibited three different forms of isothermal omega ω_i particles such as nondescript, ellipsoidal and cubical depending on aging temperature and time [4]. Hadjadj et al. [38] experimented with alpha-beta solution treated water quenched Ti-1023 alloy. The atomic probe measurements of the directly aged specimens at a temperature of 300°C showed isothermal omega ω_i zones depleted in all alloying elements and after a longer annealing time also secondary alpha α_s zones with a higher content of aluminium. The authors presumed that secondary alpha α_s precipitated preferentially at the $\beta\text{-}\omega_i$ interface. Three different types of nucleation mechanism of secondary alpha α_s phase during aging were observed such as uniform at temperature $<450^\circ\text{C}$, sympathetic at $>400^\circ\text{C}$ and preferential along $\beta\text{-}\beta$ grain boundaries at $>650^\circ\text{C}$. The achievable strength was the highest in the uniform nucleation scheme [4]. At low heating rates, it was observed that formation of isothermal omega ω_i particles was being replaced by fine secondary alpha α_s at aging temperatures $>400^\circ\text{C}$ in Ti-1023 alloy not forming martensite upon beta quenching [22].

A two-step aging process led to an improved combination of strength and ductility due to pre-existing ω_i particles which directed the distribution and morphology of α_s particles [39][40]. Ellipsoidal isothermal omega ω_i particles formed during a short anneal of a beta solution treated and water quenched Ti-1023 sample at 400°C . The second anneal at 300°C for 45min resulted in cubical shape ω_i particles [4]. A two-step aged Ti-1023 beta quenched sample to room temperature had slightly larger secondary alpha α_s particles and gave very good fracture toughness and strain [7]. However, more sophisticated research into mechanical properties is not available.

Quazi et al. [41] observed precipitate free zones, presumably due to grain boundaries acting as sinks for oxygen in samples aged at increased aging temperature in high-oxygen-enriched Ti-Nb alloys. Mantri et al. [42] and Sakamoto et al. [43] observed an improved ductility in samples forming precipitate free zones. Precipitate free zones are not typical for Ti-1023, however Duerig et al. [4] described a thick layer of grain boundary alpha forming at high aging temperature 680°C after 2000min in an alloy with an oxygen content 0.15 wt pct. Precipitate free zones of a slightly smaller width are apparent from the SEM pictures.

The omega phase has been satisfactorily stress-induced previously by cold rolling or compression at room temperature [44][45] [46][47]. Similar experimental work relating to Ti-1023 has not been located probably due to the stress-induced martensitic transformation typical for this alloy [48][4] and the previously mentioned existence of martensite upon beta quenching. The stress-induced martensitic transformation is however avoidable by both increasing of a volume fraction of primary alpha α_p [4] and increasing the beta grain size [49][50]. Presumably, with a higher beta stabiliser content, the effect of stress-induced martensitic transformation reduces as well. It is further not clear how the structure of the samples changes upon application of various strains and strain rates during an upsetting process at room temperature.

4. Further work with Ti-1023

Barriobero-Vila et al. [19] conducted probably the most sophisticated experimental work with differential scanning calorimetry (DSC) and high-energy X-ray diffraction (HEXRD) describing the phase transformations in beta quenched Ti-1023 when heating from room temperature to 600°C under various heating rates. The $[\text{Mo-Al}]_{\text{eq}}$ was low at 6.36 and orthorhombic martensite α''

was found in a retained β phase matrix upon quenching. Apart from orthorhombic martensite, athermal omega ω_a was also found. Depending on a heating rate the orthorhombic martensite decomposed to beta phase, or also directly to omega phase. The authors suggested a diffusion-controlled mechanism of growth of isothermal omega ω_i from beta at low heating rates and formation of isothermal omega ω_i from orthorhombic martensite at the highest heating rate. An extremely high volume fraction of isothermal omega ω_i about 70-80% of the entire volume was found at temperature ca. 250-400°C for a high heating rate 50°C/min. Considering the fact, secondary alpha α_s likely precipitates preferentially at β - ω_i interface [38], it might be beneficial to explore the effect of heating rate and the volume fraction of isothermal omega ω_i for precipitation of secondary alpha α_s .

5. Design of experiment

The primary objective of this paper was to provide background research to develop a new route to hardening of cylindrical parts of Ti-1023. Two extremes of composition would be used at two levels of $[\text{Mo-Al}]_{\text{eq}}$. The cylindrical workpieces would be heat-treated at four levels, two above and two below beta transus. For both types of material this allows a determination of a suitable beta grain size and a content of primary alpha α_p to avoid either type or martensitic transformation. The cylindrical samples shall be further upset at room temperature at two levels such as 5 and 15% at two levels of strain rate.

6. Summary

The author believes that given experimental work will lead to a more efficient and effective process achieving superior mechanical properties of small cylindrical parts. In addition, several research suggestions have been given that could be clarified as part of planned experimental work.

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