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A new multi-element beta titanium alloy with a high yield strength exhibiting transformation and twinning induced plasticity effects

S. Sadeghpour [a,b,*], S.M. Abbasi [a], M. Morakabati [a], A. Kisko [b], L.P. Karjalainen [b], D.A. Porter [b]

[a] Metallic Materials Research Center, Malek Ashtar University of Technology, Tehran, Iran
[b] Centre for Advanced Steels Research, University of Oulu, 90014 Oulu, Finland

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ABSTRACT

A new multi-element β titanium alloy Ti-3Al-5Mo-7V-3Cr (Ti-3573) was designed using the d-electron method based on a commercial alloy. An excellent yield strength of 750 MPa, and a high strain hardening rate (SHR) of 1800 MPa as well as 19% uniform elongation are some of the formidable mechanical characteristics exhibited by the designed alloy. Microstructural evaluation suggested that simultaneous transformation and twinning induced plasticity is responsible for the enhanced tensile properties. The results show that with precisely controlled alloying, it is possible to increase the yield strength with solid solutioning and still keep the SHR and ductility high enough.

Beta Ti alloys are an important category of Ti alloys due to their widespread applications in aerospace, automotive and medical industries [1]. Several deformation mechanisms such as dislocation slip, mechanical twinning and stress-induced martensite (SIM) formation may occur during the deformation of these alloys resulting in a wide range of mechanical properties [2–4]. It has been shown that when mechanical twinning is the dominant deformation mechanism, the β Ti alloys typically exhibit a high strain hardening rate (SHR) and consequently a large uniform elongation [5,6]. In contrast, the alloys deformed by the dislocation slip mechanism, thanks to the solid solution effect, generally display a high yield strength (YS) but a low SHR and a very low ductility [6]. Activation of different deformation mechanisms is strongly dependent on the stability of the β phase so that with increasing the β phase stability, the main deformation mechanism changes from SIM transformation to twinning and then to dislocation slip [2,7]. Therefore, controlling the β phase stability and thereby tailoring the deformation mechanisms has a key role in optimizing the mechanical properties of β Ti alloys.

During the last decade, many efforts have been devoted to design new β Ti alloys using theoretical approaches [8,9], and particularly with an emphasis on the d-electron alloy design method [10,11]. It has been shown that a combination of mechanical twinning (TWIP effect) and SIM transformation (TRIP effect) can improve the strain hardening capability and subsequently the uniform elongation of β Ti alloys [12]. Nonetheless, the introduced TRIP/TWIP β Ti alloys are confined to simple binary [11] or very recently ternary alloys [12] that usually show a low YS. On the other hand, most of the high-YS β Ti alloys contain several alloying elements which increase the stability of the β phase and, as a result, the deformation mechanism is changed to slip. This change in deformation mechanism produces some drawbacks such as low strain hardening and low ductility which limits the application of the alloys.

In the present study, a new multi-element β Ti alloy was designed using the d-electron method that has an enhanced solid solution hardening (a high YS) and simultaneously exhibits TRIP and TWIP effects resulting in an enhanced strength-ductility combination. It has been shown in earlier studies [11,13] that an M_d = room temperature (RT) curve can be drawn on the $\overline{Bo}$-$\overline{Md}$ diagram, showing the position of alloys with the ability to exhibit the TWIP and TRIP effects simultaneously (Fig. 1a). M_d is the minimum temperature above which β is stable and does not transform to martensite by deformation. Therefore, the region around the M_d = RT curve is supposed to be a desired location for TRIP/TWIP β Ti alloys. In this regard, starting with the composition of a commercial Ti-5553 alloy, i.e. Ti-5Al-5Mo-5 V-3Cr (all contents are in wt%), a linear combination of alloying vectors V_{Al}, V_{Mo}, V_V and V_{Cr} was selected in such way that the final composition lies at a position close to the M_d = RT curve on the stability diagram (Fig. 1a). Finally, the alloy Ti-3Al-5Mo-7V-3Cr (coded here Ti-3573) with the electronic parameters $\overline{Md} = 2.356$ and $\overline{Bo} = 2.778$ was chosen as a composition suitable to show a TRIP/TWIP effect. Tensile properties were determined and microstructural evolution was examined on deformed samples of the alloy to validate the prediction made by the d-electron method.

* Corresponding author at: Metallic Materials Research Center, Malek Ashtar University of Technology, Tehran, Iran.
E-mail address: sinsad64@yahoo.com (S. Sadeghpour).

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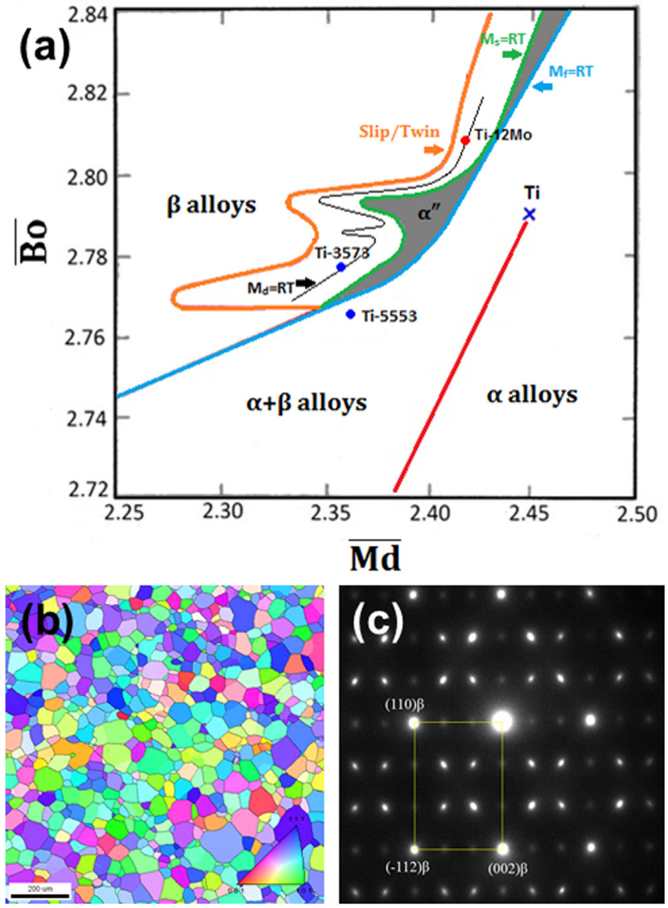

Fig. 1. The designed Ti-3573 alloy. (a) The d-electron alloy design map showing the position of Ti-3573, along with Ti-5553 and Ti-12Mo, (b) EBSD inverse pole figure map of the alloy annealed at 900 °C for 5 min after 70% cold rolling and (c) SAED pattern along $[110]_\beta$ zone axis corresponding to (b).

Ingots of the designed Ti-3573 alloy along with the base Ti-5553 alloy were melted twice using vacuum arc melting. After homogenizing for 4 h at 1100 °C, the ingots were forged at this temperature and then rolled to 20 mm thick plates at 750 °C. Samples from the plates were solution-treated at 1000 °C for 30 min followed by water quenching. The solution-treated samples of both alloys exhibited equiaxed β grains with a grain size (GS) of about 250 μm. The solution treated samples were cold-rolled at room temperature to reduce the thickness by 70% and then annealed at 900 °C for 5 min and quenched in water. The tensile test specimens were cut parallel to the rolling direction. Uniaxial tensile tests were conducted at RT using an Instron 8502 machine on sub-sized specimens with the gage dimensions of 15 × 6 × 1 mm at an initial strain rate of $0.7 \times 10^{-3}\ s^{-1}$.

Microstructural examinations were performed on a JEOL JEM-2200FS transmission electron microscope (TEM) operated at 200 kV and a field emission gun Zeiss Sigma scanning electron microscope equipped with an electron backscatter diffraction (EBSD) device. Specimens for TEM were first ground to a thickness of 100 μm and then prepared using twin-jet electropolishing at −15 °C in an electrolyte consisting by volume of 6% perchloric acid, 35% butanol and 59% water. Samples for EBSD scans were first mechanically polished down to 1 μm and then chemically polished with a solution of H_2O_2 and OP-S (oxide polishing suspension from Struers, a colloidal silica suspension with a pH of 9.8 and a grain size of 0.04 μm). The EBSD scans were performed with a step size of 0.05 μm.

EBSD images of the cold-rolled and annealed microstructures shown in Fig. 1b displays equiaxed single phase grains with an average GS of 64 μm. Only β grains are visible with no evidence of other phases. However, a [011] zone axis selected area electron diffraction (SAED) pattern of the alloy reveals additional spots which represent the athermal ω phase (Fig. 1c). It has been reported that the presence of the ω phase may also be contributing to the formation of mechanical twins [14].

Fig. 2a shows the true stress-strain curve of the designed alloy in comparison to Ti-5553. As seen, Ti-3573 exhibits a very high YS of 750 MPa which is much higher than those of the binary or ternary TRIP/TWIP Ti alloys, developed earlier [11–13,15]. For example, a YS of 480 MPa and 504 MPa has been reported for Ti-12Mo (GS ≈ 50 μm) and Ti-15Mo (GS ≈ 80 μm) binary alloys, respectively [11,15]. The yield strength of the present alloy is also much higher than that of its commercial counterpart (GS ≈ 250 μm), as shown in Fig. 2a. This improvement in the YS can be attributed to solid solution and grain boundary strengthening (GS = 64 μm) in the designed alloy. Regarding the solid solution effect of different alloying elements, iron, manganese and chromium prove to be the strongest strengtheners, then come aluminum, molybdenum and vanadium [16]. In the case of multi-element alloys, the hardening effect would, probably, be the sum of hardening effects of all elements. Based on the average data used in practical work with titanium alloys [16] a rough estimate of solid solution strengthening action of alloying elements in single β phase Ti alloys can be made as follows:

$$\Delta\sigma = 1.5n[\mathrm{Fe}+\mathrm{Mn}] + 1.3n[Cr] + n[\mathrm{Al}+\mathrm{Mo}] + 0.7n[\mathrm{V}+\mathrm{W}] + 0.5n[Sn] + 0.4n[Zr] + 0.3n[Nb] \quad (1)$$

where [M] is the amount of each element in weight percent (wt%) and n is a constant between 40 and 50 MPa. According to Eq. (1) the YS of Ti-3573 is expected to be 750–840 MPa. This value was calculated to be 540–600 and 600–750 MPa for Ti-12Mo and Ti-15Mo, respectively which is consistent with experimental results. In addition to high YS, Ti-3573 shows an excellent uniform elongation close to the strain of 20% which is attained at a high level of tensile stress (1100 MPa).

As seen in Fig. 2b, the strain hardening rate (SHR) of the alloy is very high (~1800 MPa) in comparison to that of most of Ti alloys, and even to some alloys possessing the twinning deformation mechanism [15]. To the best knowledge of authors, such a combination of high YS, significant SHR over a wide strain range and excellent elongation in a single phase β alloy has been reported limitedly in the literature [11,13,15]. The high elongation of the present alloy is supposed to be related to its special strain hardening behavior. As seen in Fig. 2b, the strain hardening behavior of this alloy is quite different from the conventional Kocks-Mecking [17] strain hardening behavior and exhibits three stages: I, II and III. These stages correspond to the deformation mechanisms discussed in the following. After the transition from the elastic to plastic region, the SHR continuously decreases in the stage I down to the level of ~1800 MPa. This stage is related to the beginning of plastic deformation and the activity of dislocations. In stage II, the SHR stays at a constant level of 1800 MPa until high true strain levels (15%). Typically, in other TRIP/TWIP β Ti alloys, the SHR decreases abruptly after reaching a peak value [11–13]. The plateau region (stage II) in the SHR of Ti-3573 can be attributed to the high incidence of twinning. Kalidindi [18] showed that mechanical twinning increases the SHR and can lead to a peak or plateau region in the SHR vs. true stress (or strain) curve. In Cr-Mn austenitic stainless steels, the SHR also shows a plateau region continuing up to high strain levels, when mechanical twinning occurs and the TRIP effect is not strong [19]. In stage III in Fig. 2b, necking takes place and SHR is gradually decreasing over strains up to failure. It is reasonable to suppose that at this stage, the volume fraction of twins reaches its maximum and dislocation-twin and dislocation–dislocation interactions become frequent and more significant [15].

To understand the origin of the enhanced tensile properties, EBSD and TEM investigations were carried out on deformed samples. Fig. 3 shows the EBSD maps of deformed samples after 10% tensile true strain.