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Regular Article

A low-cost and high-strength Ti-Al-Fe-based cast titanium alloy for structural applications

Zhi Liang [a], Jiashi Miao [a], Tyson Brown [c], Anil K. Sachdev [c], James C. Williams [a,d], Alan A. Luo [a,b,*]

[a] Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA
[b] Department of Integrated Systems Engineering, The Ohio State University, Columbus, OH 43210, USA
[c] General Motors Global R&D, Warren, MI 40892, USA
[d] University of North Texas (part-time), Denton, TX 76203, USA

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ABSTRACT

A cost-effective α-β titanium casting alloy, Ti-6Al-5Fe-0.05B-0.05C,[1] has been designed using Calculation of Phase Diagrams (CALPHAD) method and the workhorse alloy Ti-6Al-4 V as a baseline. The substitution of iron for vanadium significantly reduces the raw material cost and improves the castability compared to the Ti-6Al-4 V alloy. The very fine α phase in the microstructure of the new alloy, likely due to Fe partitioning, provides exceptionally high strength (1023 MPa yield strength and 1136 MPa ultimate tensile strength) and reasonable ductility (3.71% elongation) for structural applications.

Titanium alloys have proved to be important lightweight structural materials since 1960's, due to their excellent intermediate temperature mechanical properties, corrosion resistance and weldability [1]. Their good property-to-weight ratios make them ideal for many high-end and weight-sensitive applications, such as aeronautics engines [2]. However, the application of titanium alloys is still limited due to the high costs in raw materials and manufacturing. Currently, Ti-6Al-4 V (Ti-6-4) alloy accounts for about 50% of titanium products including castings [3], but Ti-6-4 was designed for wrought applications. Therefore, its performances in other manufacturing processes are not optimal. Compared with wrought processing, other net-shape and near-net-shape manufacturing techniques such as casting and powder metallurgy are more cost-effective in producing complex geometry components. There is, thus, a need in designing new lower-cost titanium alloys for structural applications, which is the subject of this paper.

Net-shape or near-net-shape processes such as casting are attractive for titanium alloys due to both the high metal costs and the cost of machining for making components from wrought titanium products [4]. Compared with commonly used wrought components, titanium castings can potentially provide similar mechanical properties at significantly lower costs. For example, for Ti-6-4, the monotonic loading strength for cast and wrought β-annealed products are approximately the same. However, individual properties such as toughness, crack growth resistance and creep strength of wrought titanium alloys can be tailored by thermomechanical processing, but at additional cost. Thus, titanium castings are used in structural applications that are limited by static properties such as strength or toughness [5,6]. Furthermore, casting microstructure can be heat-treated to improve strength or ductility. In this paper, a new cast titanium alloy was designed for structural applications, to address two challenges in current cast titanium alloys, i.e., castability and raw material costs.

In this design, Ti-6Al-4 V was selected as the baseline alloy since this alloy is presently the workhorse in the industry with well-documented properties and microstructure characterization. It is also the main alloy that is used in castings today. In order to reduce the cost of this alloy, iron (Fe), the strongest β stabilizer, was selected as a cost-effective replacement for vanadium (V). The additions of boron (B) and carbon (C) were also selected, the former for grain refinement and the latter for strengthening. The addition of Fe to the Ti-Al system can potentially improve the alloy castability by decreasing liquidus temperature and enlarging liquidus-solidus gap as shown in Fig. 1. There have been relatively few investigations of the alloying effects of Fe in titanium alloys in recent years, i.e., since the availability of improved characterization tools. In 1980–90s, a few α-β titanium alloys were developed for hot working processes such as Ti-5Al-2.5Fe [7], TIMETAL 62S [8] and Ti-5.5Al-1Fe [9]. Ti-Al-Fe alloy system has attracted interests as a potential replacement of Ti-Al-V for some time. Fuji and Takahashi [9] conducted

* Corresponding author at: Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA.
E-mail address: luo.445@osu.edu (A.A. Luo).

[1] All compositions in wt% except otherwise stated.

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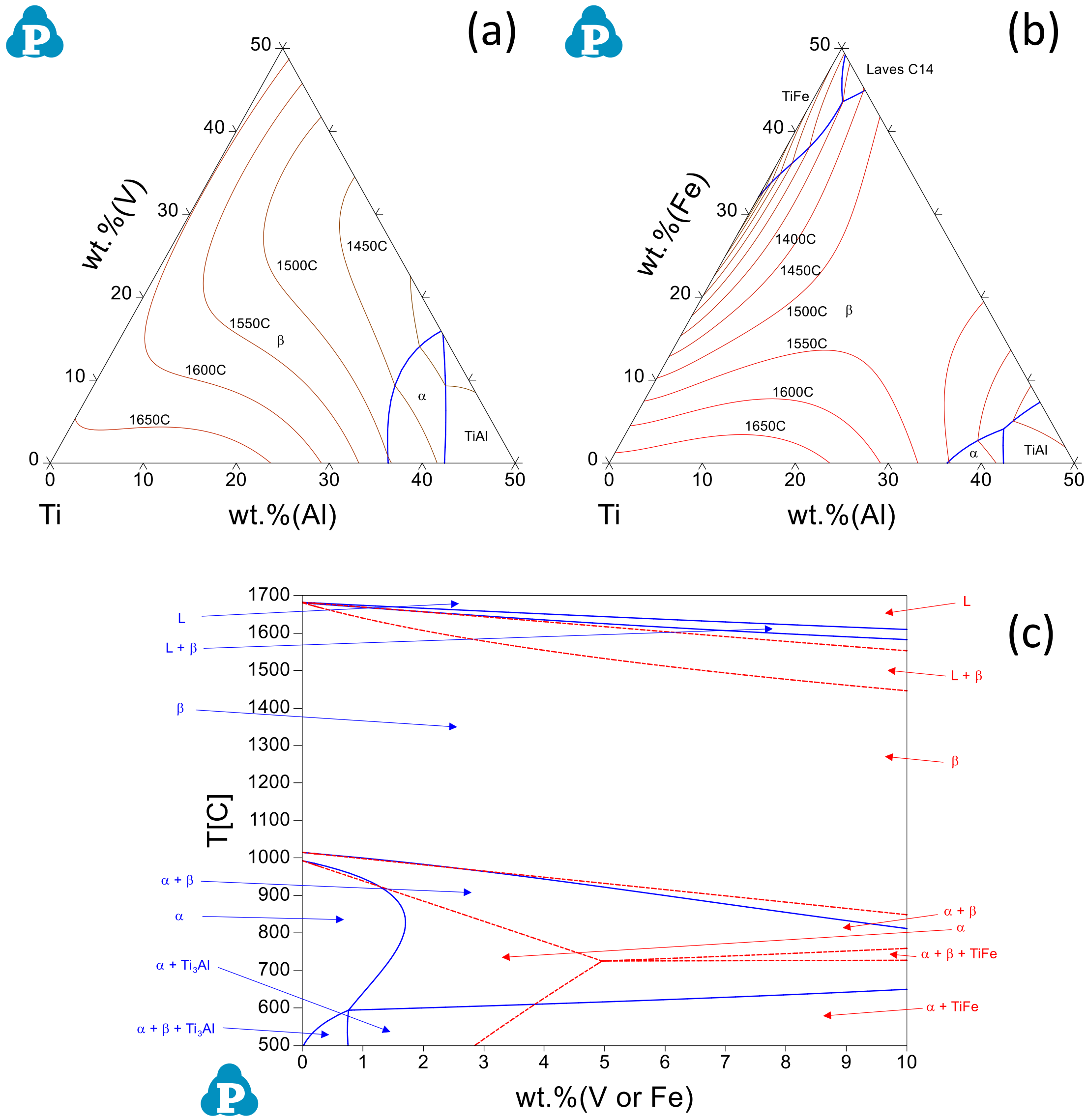

Fig. 1. Calculated liquidus projections of (a) Ti-Al-V and (b) Ti-Al-Fe ternary systems; and (c) comparison of calculated isopleths of Ti-6Al-xV (blue) and Ti-6Al-xFe (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

an experimental investigation of Ti-Al-Fe alloy system including multiple thermo-mechanical treatments and mechanical property assessments of a few Ti-Al-Fe compositions. However, the lack of systematic investigations, such as comprehensive alloying behavior, heat treatment schedules, and castability analysis, has impeded further development and applications of this alloy system. In this paper, a combinatory experimental and CALculation of PHase Diagram (CALPHAD) modeling approach was used to guide the alloy design in Ti-Al-Fe system.

The Al content in the new Ti-Al-Fe alloy design was kept at the same level (6%) as the Ti-6-4 baseline. This provides solid solution strengthening of the α-phase and to retain an important (α + β) heat treatment window while avoiding the formation of the α_2-phase (Ti_3Al) which causes loss of ductility due to intense strain localization around the particles. The Fe content in this alloy composition was determined by the equilibrium threshold in CALPHAD simulation as shown in Fig. 1(c). In this isopleth, since TiFe intermetallic phase is not desired in the alloy due to its brittle nature, the phase region (β + TiFe + α) can be avoided by limiting Fe content. However, the Fe content also affects the temperature gap of (α + β) region with the maximum gap at about 5%, which is preferred for better control of aging temperatures. Based on these two factors, the Fe content of 5% was chosen for this alloy at the left limit of (β + TiFe + α) phase region while retaining the maximum (α + β) gap.

As for B and C additions, both have been reported to provide grain refinement effects in titanium alloys [10–13]. The significant grain refinement effect of B addition on the solidification microstructure of Ti-6Al-4V alloy has been reported by Roy et al. [10], and also in several aerospace titanium alloys by Tamirisadandala et al. [11]. The combined B and C additions on a few metastable β alloys have been studied by Banoth et al. [12] and Sarkar et al. [13], which suggested that both α and β grain sizes can be refined by C and B addition respectively. Since grain refinement proves to be beneficial to mechanical properties [14, 15], B and C additions are also applied in this alloy design.

The experimental alloy with nominal composition Ti-6Al-5Fe-0.05B-0.05C (designated as T65–0.05BC, wt%) was prepared in an induction skull melter under high purity Ar atmosphere (ISM, PVT Inc., an InductoTherm Group company) using high purity titanium (99.99%, Kamis Inc.), aluminum (99.9%, Alfa Aesar), iron (99.9%, Alfa Aesar), TiB_2 (99.5%, Alfa Aesar), and carbon slug (99.5%, Alfa Aesar). Each specimen was flipped and re-melted three times to ensure homogeneity. The oxygen content was 0.061% and tested by Luvak Inc. according to