

Microstructure and Mechanical Properties of Ti-5Al-2.5Fe Alloy Produced by Powder Forging

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Abstract. Blended elemental powder metallurgy is a cost effective approach to produce near net shape titanium alloy parts; however, the residual pores remaining in sintered parts are detrimental to the mechanical properties. In this study, elemental powders (Ti, Al and Fe) were used to produce the Ti-5Al-2Fe alloy by a powder forging process, involving cold compaction, vacuum sintering, forging and heat treatment. The residual pores of the sintered parts were removed completely by forging at the temperature of 1250°C. The effect of solution and aging and mill annealing heat treatments on the mechanical properties of the forged Ti-5Al-2Fe parts were studied. It is found that the ductility of the forged Ti-5Al-2Fe parts is improved significantly by both solution and aging treatment and mill annealing, without decreasing their ultimate tensile strength, which sits around 1000 MPa. The enhancement of the mechanical behaviour is justified via understanding the evolution of the residual porosity and of the microstructural features of the materials.

Introduction

Titanium and titanium alloys have been drawn more attention on manufacturing a variety of components in aerospace [1], automobile [2], marine [3], chemical [3] and biomedical [4] industries. Especially they are highly demanded to manufacture prosthesis and implants for the medical and dental fields [5, 6], due to their low Young's modulus, good corrosion resistance and excellent biocompatibility. As the titanium alloy workhorse, Ti-6Al-4V (wt%) has been widely used to produce various prosthesis as an implant material [6]. Recently, V-free titanium alloys such as Ti-6Al-7Nb (wt%) [7-9] and Ti-5Al-2.5Fe (wt%) [10, 11] have been developed to replace Ti-6Al-4V alloy in the medical application, to avoid the toxicity caused by element V. Among these, the addition of Fe is regarded as an effective way to reduce the cost of titanium alloys by replacing expensive alloying elements (e.g. V, Nb, Mo and Zr) [2, 12]. Similarly, powder metallurgy is gaining momentum as effective near net shape methods to produce titanium-based components because they are considered low cost manufacturing process [13, 14]. In powder metallurgy, the blended elemental approach is a cost effective to produce titanium and its alloy components using elemental powders [15, 16]. The aim of this work is to study the feasibility of using the blended elemental powder metallurgy route to produce titanium alloys parts, specifically considering the $\alpha+\beta$ Ti-5Al-2.5Fe alloy, by means of the conventional powder forging process seeking to synthesize fully dense Ti-5Al-2.5Fe components. Solution plus aging and mill annealing heat treatments are also investigated aiming to understand their effect on the microstructural features and mechanical properties of the as-forged Ti-5Al-2.5Fe parts.

Experimental Procedure

Hydride-dehydride (HDH) Ti powder, pure atomized Al powder and Carbonyl Fe powder were used to synthesize the Ti-5Al-2.5Fe alloy in this study. The powders, whose characteristics are listed in Table 1, were mixed for 24 hours using a two-roll mill.

Table 1. Characteristics of the powders used in this studied.

Powder	Particle size	Particle shape	Purity
Ti	<75 μm	irregular	>99.5%
Fe	5-9 μm	irregular	>99.0%
Al	45-75 μm	spherical	>99.7%

After blending, the powder mixtures were uniaxially pressed into a cylindrical compact at 400 MPa at room temperature. Then, the compacts were sintered under vacuum at the temperature and soaking time of 1250°C and 2 hours. Subsequently, the sintered parts were forged into a disc at the temperature of 1250°C in air. For the solution and aging treated, the as-forged material was solution treated at the temperature of 950°C for 2 hours, quenched in water, and finally aged at the temperature of 550°C for 8 hours. On the other hand, another as-forged material was mill annealed by the combination of 750°C as temperature and 10 hours of treatment time.

X-ray diffraction (XRD) using Cu K_{α} radiation source at a scanning rate of 2°/min was carried out to determine the phase constituents of forged Ti-5Al-2.5Fe alloy. The metallographic sample were ground, polished and etched by Kroll's reagent (2 ml HF, 6 ml HNO₃ and 92 ml distilled water) to reveal their microstructure which was examined via optical microscopy (Olympus BX60) and scanning electrical microscopy (SEM, Hitachi S4700). Flat dog-bone specimens with a cross section of 2x2 mm² for tensile test were prepared from each manufacturing process including vacuum sintering, forging, solution and aging treatment and mill annealing treatment. The tensile test was done at room temperature at a strain rate of $1 \times 10^{-4} \text{s}^{-1}$. During the testing, the strain was recorded by an extensometer. The fracture surface of the tensile specimens was also examined using SEM.

Results and Discussion

Figure 1a) shows that the microstructure of vacuum sintered Ti-5Al-2.5Fe alloy is a fully lamellar structure consisting of coarse α lamellae and fine β lath between the α lamellae. It can be noticed that a homogeneous microstructure has been synthesized by vacuum sintering at 1250°C for 2 hours. However, a large amount of pores are still present in the sintered part and they are detrimental for the mechanical properties, as pores will act as crack initiation sites once the materials is loaded.

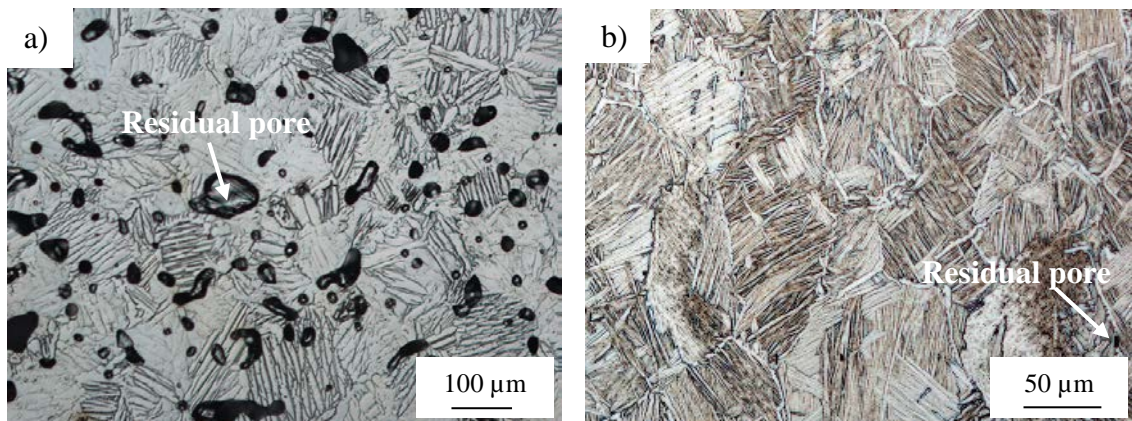


Figure 1. Optical micrographs of (a) the vacuum sintered and (b) the as-forged Ti-5Al-2.5Fe alloy.

To remove the residual porosity, forging was performed to collapse the pores by plastic deformation. Pores are actually nearly completely removed after forging with the exception of a small amount of elongated pores still present (Figure 1b). The microstructure of as-forged part is also a fully lamellar structure; however, the width of α lamellae in the as-forged part is much finer than those found in the vacuum sintered part and this is attributed to the faster cooling rate of the former process. Specifically, forged parts are naturally cooled in air while sintered parts are furnace cooled. The XRD pattern in Figure 2 shows that the as-forged Ti-5Al-2.5Fe alloy has α phase and a small amount of transformed β phase, which is in agreement with the results of the microstructural analysis.

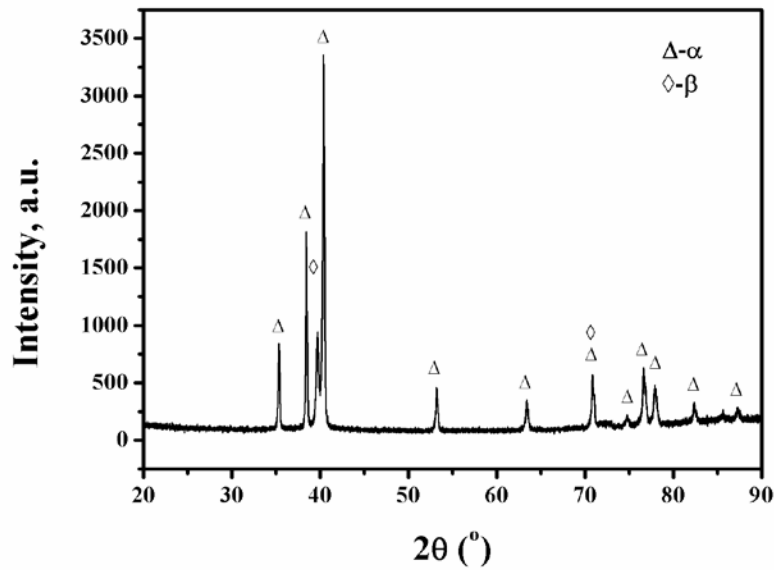


Figure 2. XRD pattern of the as-forged Ti-5Al-2.5Fe alloy.

Subjected to solution and aging treatment, the microstructure of the forged alloy transformed into a coarse fully lamellar structure with a smaller α length/width aspect ratio of 11 as per image analysis (Figure 3a). Moreover, the shape of residual porosity turned into rounded pores, which is consistent with the pore rounding during the sintering process. Performing a mill annealing at the temperature of 750°C for 10 hours keeps the microstructure of the forged part as a fine fully lamellar structure with the absence of severe microstructure coarsening (Figure 3b). Furthermore, the shape of residual pores becomes spherical after mill annealing.

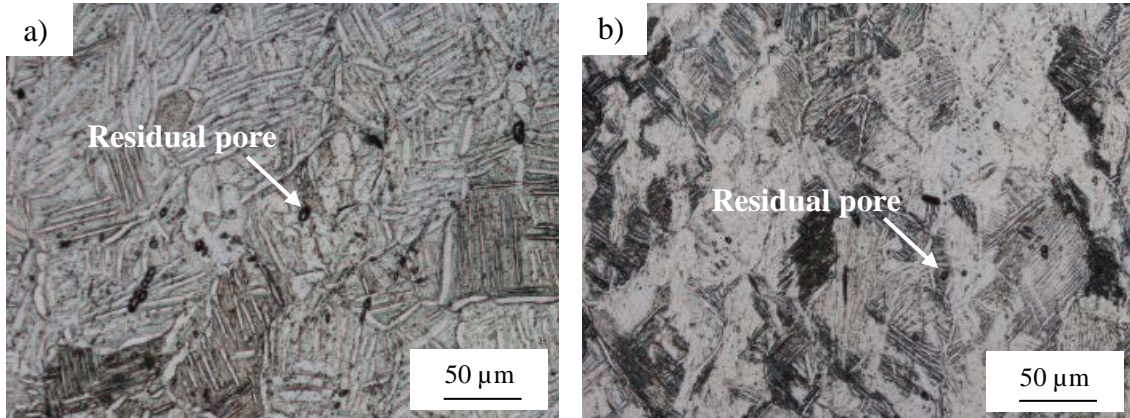


Figure 3. Optical micrographs of (a) the solution plus aging treated and (b) the mill annealed Ti-5Al-2.5Fe alloy.

Typical tensile engineering stress-strain curves of the sintered, forged and heat treated Ti-5Al-2.5Fe alloy are shown in Figure 4. The vacuum sintered part has a yield strength (YS) of 710 MPa, a fracture strength of 812 MPa and an elongation to fracture of 0.7%. Its low elongation to fracture is caused by the large amount of residual pores left by the sintering, which makes the material to fracture in a fairly brittle way. After forging, YS, ultimate tensile strength (UTS) and elongation to fracture of the as-forged part are increased to 947 MPa, 1020 MPa and 4.2%, respectively, as a result of the removal of residual pores by forging. However, the residual elongated pores still has still a critical effect on the elongation to fracture of the as-forged alloy due to the stress concentration at the sharp edge of elongated pores. Heat treatment can help in smoothing the sharp edge of residual pores left by forging via pore rounding.

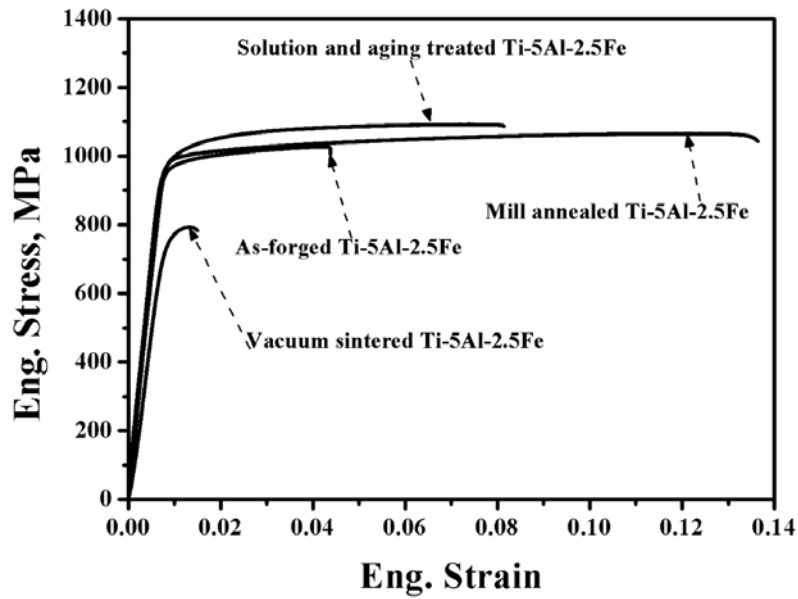


Figure 4. Engineering stress-strain curves of sintered, forged and heat treated Ti-5Al-2.5Fe alloy.

Consequently, after the solution and aging treatment the elongation to fracture of heat treated part was improved to be 6.6% meanwhile the yield strength and UTS were significantly increased to be 997 MPa and 1096 MPa, respectively. The increase of the tensile strength is attributed to the reduction of $\alpha+\beta$ colony size, which is the main parameter to determine the strength of two phase titanium alloy [17]. Via the mill annealing treatment the elongation to fracture is increased to 11.0% while achieving YS and UTS of 996 MPa and 1068 MPa, respectively. The improvement of the mechanical properties of the forged materials is the consequence of the switch of the morphology of the residual pores. Additionally, the change of phase fraction after heat treatments could also affect the mechanical properties of the forged materials, further study is needed to clarify this aspect. Although there are a few residual pores present in the forged Ti-5Al-2.5Fe part which are not removed by the subsequent heat treatment, the mechanical properties of forged and heat treated Ti-5Al-2.5Fe alloys are comparable to those of cast Ti-5Al-2.5Fe [18] and wrought Ti-6Al-4V (Table 2) [19]. Therefore, the low cost Ti-5Al-2.5Fe parts produced by powder forging in this study could be a good alternative to replace the Ti-6Al-4V alloy in different engineering applications.

Table 2. Tensile properties of powder forged Ti-5Al-2.5Fe, cast Ti-5Al-2.5Fe and wrought Ti-6Al-4V alloy.

Material	YS (MPa)	UTS (Mpa)	Elongation to fracture	Ref.
Forged Ti-5Al-2.5Fe	947±13	1020±7	4.2%±0.7	This study
Solution and aged Ti-5Al-2.5Fe	997±12	1096±7	6.6%±1.0	This study
Mill annealed Ti-5Al-2.5Fe	996±5	1068±3	11%±1.6	This study
Casted Ti-5Al-2.5Fe	820	900	6	[18]
Annealed wrought Ti-6Al-4V	875	965	13%	[19]
Solution and aged Ti-6Al-4V	1151	1103	13%	[19]
Mill annealed Ti-6Al-4V	945	1069	10%	[19]

Figure 5 shows the fracture morphologies of the vacuum sintered, as-forged and heat treated Ti-5Al-2.5Fe alloy. The vacuum sintered Ti-5Al-2.5Fe part has a dimples fracture pattern with a large amount of residual pores in the fracture surface. The forged Ti-5Al-2.5Fe part has both dimples and cleavage fracture pattern with a few residual pores in the fracture surface. In the case of the solution and aging treated, the material has a fracture surface showing both dimples and cleavage feature, which is consistent with its better ductility and higher strength with respect to the forged part. The

fracture surface of the mill annealed alloy consists of a large amount of dimples (Figure 5d), which is in agreement with its higher ductility compared to the other processing conditions. As a result, the heat treatment in this study enables the fracture mode of the forged part to transform from brittle (i.e. cleavage) to ductile (i.e. dimples).

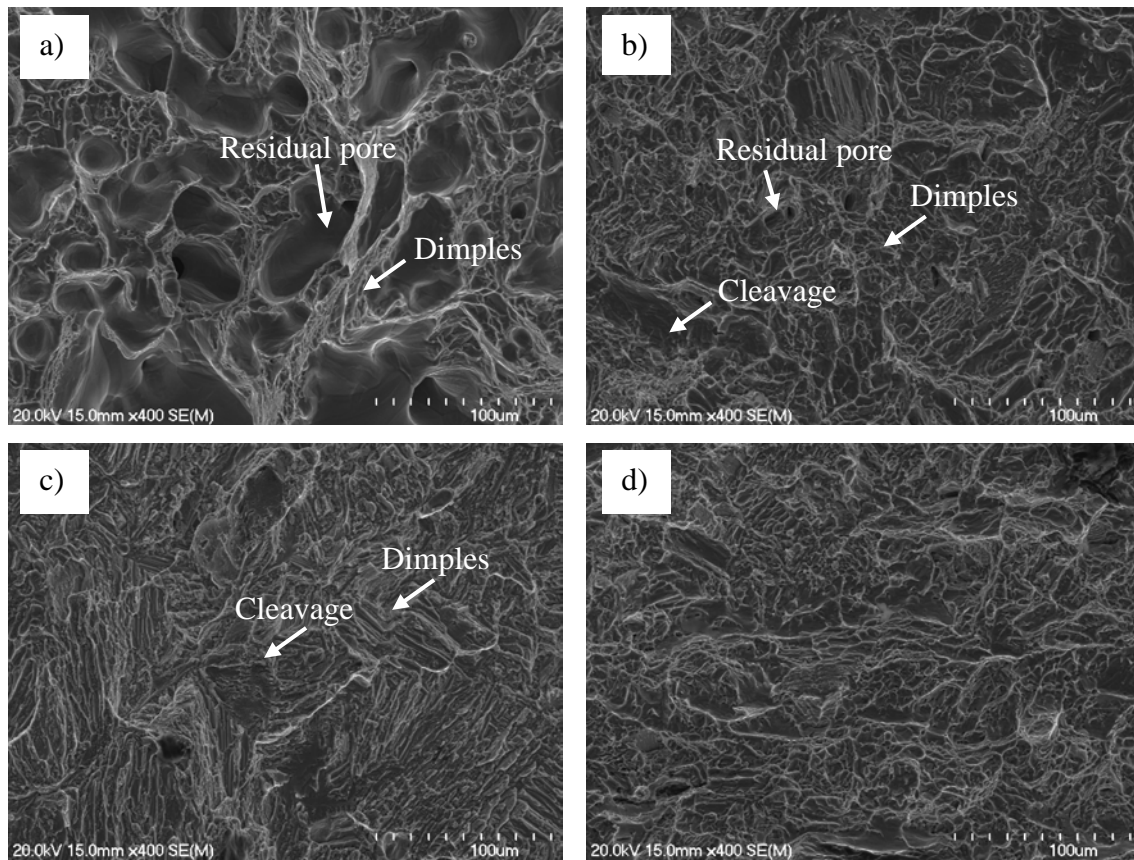


Figure 5. Fracture morphology of the Ti-5Al-2.5Fe alloy: a) vacuum sintered, b) forged, c) solution and aged, and d) mill annealed.

Conclusions

Conventional powder forging including vacuum sintering and forging was used to produce fully dense Ti-5Al-2.5Fe parts. A large amount of residual pores were removed by the forging process, except a small amount of elongated residual pores. Due to the stress concentration of elongated residual pores, they are detrimental to the ductility of forged Ti-5Al-2.5Fe parts. The elongation to fracture of the forged Ti-5Al-2.5Fe alloy is improved by subsequent heat treatments including solution and aging treatment and mill annealing, which convert the forged Ti-5Al-2.5Fe alloys a low cost good alternative to Ti-6Al-4V. Solution and aging treatment increase the tensile strength of forged Ti-5Al-2.5Fe parts significantly and can be used to tailor the properties of the alloy.

Acknowledgments

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