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Short communication

A novel method for grain refinement and microstructure modification in TiAl alloy by ultrasonic vibration

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ABSTRACT

In this paper, the ultrasonic vibration treatment was applied to the TiAl alloy melt during the solidification aiming at modifying the coarse microstructure and improving the mechanical properties. Effects of ultrasonic vibration on the microstructure and mechanical properties of TiAl are elaborately studied. The results show that the grain size was refined from 545 μm to 96 μm, the yield strength was improved from 419 MPa to 854 MPa, and the coarse dendrite structure was modified into fine non-dendrite grains after ultrasonic vibration. Given the high melt viscosity and narrow liquid–solid temperature range, the predominant refinement mechanism of ultrasonic vibration for TiAl is the cavitation-enhanced nucleation due to the nucleus activation and/or heightened supercooling.

1. Introduction

It is well known that the fine-grain solidification technology has been widely studied, which have certified the fine-grain microstructure could significantly improve the mechanical properties as well as eliminate casting defects [1–3]. For the last two decades, the ultrasonic vibration treatment has attracted extensive attentions for its efficient grain refinement effects, which provides a novel method for grain refinement during solidification [4–7]. For now, the ultrasonic treatment has been widely applied in some nonferrous materials, such as Al, Mg and Cu, where the ultrasonic vibration can effectively refine the grains as well as modify the microstructure [8–10]. Unfortunately, the application of ultrasonic vibration is always restricted in high temperature alloys due to the erosion and the reactivity of the radiator at high temperature [11], especially for the highly reactive alloys, such as TiAl alloys.

Major attentions have been concentrated on the TiAl alloys for their excellent mechanical properties, which is the most potential substitute candidate for nickel-based superalloy among the temperature range of 600–1000 °C in the automobile and aerospace industries [12,13]. However, the as-cast ingots of TiAl alloys always show the coarse dendrite structure with large grain size and serious composition segregation, which leads to the poor ductility at room temperature, low fracture toughness, high fatigue crack growth rate and hinder back the manufacture process and application [14–16].

In this paper, the ultrasonic vibration treatment was introduced into TiAl alloy melt during solidification and the effects of ultrasonic vibration on the microstructure and mechanical properties were studied.

2. Material and methods

In this study, the raw as-cast TiAl ingot with the normal composition of Ti–44Al–6Nb–1.0Cr–2.0V was conducted and round bars cutting from the as-cast ingot with the size of Ø19 mm × 50 mm (about 60 g) were remelted in the Al_2O_3 ceramic mold. In order to prevent contamination, the mold was coated with Y_2O_3. The round bars were put in the ceramic mold and directly melted by high-frequency induction heating; when cutting the heating power, the ultrasonic vibration was immediately introduced to the liquid TiAl alloy melt; the melt was cooled in the vacuum and continuous cooling solidified. The ultrasonic vibration was sustained for 0, 25 s, 50 s, 75 s, 100 s respectively with the ultrasonic power of 1200 W and vibration frequency of 20 kHz.

After the standard metallographic preparation, the macro/microstructure of remelted samples with and without ultrasonic vibration was investigated through the Olympus-GX-71 optical microscope (OM) and Quanta 200FEG scanning electron microscopy in back-scattered electron mode (SEM-BSE) with the accelerated voltage 20 kV. The grain size (here refer to the lamellar colony)

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was measured by the line-intercept method from at least five SEM micrographs. The Vickers microhardness tests were conducted by metallographic microhardness tester under load of 10 N for 20 s. The compression specimens with the size of Ø4 mm × 6 mm were prepared and the compression tests were carried out on the 5569 Instron testing machine at the room temperature in air at the constant train rate of 10^{-4} s^{-1}. The test apparatus and procedure were consistent with the ASTM E9-2009. At least three separate compression tests were conducted for each specimen, and the mean yield-strength values were reported.

3. Results and discussion

The representative metallographic microstructures of TiAl alloy with and without ultrasonic vibration are shown in Fig. 1. It can be seen that the raw as-cast TiAl alloy shows the conventional full lamellar microstructure with the coarse lamellar colony of approximately 1500 μm. As known, the microstructure of TiAl alloys is mainly depended on the alloy composition and cooling condition. In this study the alloy composition is constant, so the microstructure is relied on the cooling condition. Due to the different cooling condition comparison with the raw as-cast alloy, the TiAl alloy presents developed dendrites structure after remelted under static condition. Additional, the primary dendrite arm is up to 1 mm, which indicates that the dendrite is in the range of a few millimeters.

Under the ultrasonic vibration, as displayed in Fig. 1(c)–(f), the samples obviously exhibit the uniform fine non-dendrite macrostructure with the grain size in the range of 80–120 μm. It can be concluded that the ultrasonic vibration can remarkably refine the grain as well as modifiy the structure morphology from the developed coarse dendrites to the non-dendrite nearly spherical grains.

The microstructure of TiAl with and without ultrasonic vibration is illustrated in Fig. 2. Due to the low diffusion capabilities of the heavy alloyed elements (Nb, Cr, and V) [17], it is inevitable to form segregation and precipitates and there is some block γ grains and β/B2 precipitated phase in the raw as-cast TiAl alloy, which decorated in the grains or on the grain boundaries, as shown in Fig. 2(a). After remelting without ultrasonic vibration (see Fig. 2 (b)), the block γ grains and β/B2 precipitated phase are disappeared, but there is still some white network segregation distributed within the large grains. By contrast, after the ultrasonic vibration treatment, the microstructure exhibits fine rosette grains and the white network segregation also disappears.

The grain size (DL) with and without the ultrasonic vibration was measured by a line-intercept method, as displayed in Fig. 3. In absence of ultrasonic vibration, the grain size is refer to the primary dendrite arm space, while the lamellar conoly in presence of ultrasonic vibration. In Fig. 3, it can be seen that the grain is well significantly refined by ultrasonic vibration and the grain size decreases gradually from 545 μm to 96 μm after the ultrasonic vibration treatment.

The vickers microhardness (HVm) and the 0.2% offset compressive yield strength ($\sigma_{0.2\%}$) of TiAl under different ultrasonic vibration time are shown in Fig. 4. Both the microhardness and yield strength increase with the increasing of ultrasonic vibration time and exhibit the similar growth trend. The microhardness is increased to 485 HV from 430 HV as-cast when the ultrasonic vibration time is 100 s. Unlike the microhardness, the yield strength is sharply improved by ultrasonic vibration, which is increased from 419 MPa without ultrasonic vibration up to 854 MPa after ultrasonic vibration for 100 s.

As microhardness is measured as the resistance to tiny permanent damage and the yield strength is tested with 0.2% plastic deformation, it demonstrates the yield strength can be correlated with the microhardness [18]. Fig. 5 shows the dependence of the compression yield strength on the microhardness and the variation of yield strength along with the grain size. As shown in Fig. 5, the yield strength increases linearly with the microhardness, which demonstrates that the yield strength can be estimated by testing the microhardeness without destroying the sample and this result is consistent with other researchers [19,20].

In Fig. 5, the “original fitting line” shows the fitting curve for yield strength and grain size according to the Hall–Petch equation, which reflects a bad degree of fitting. For further optimizing fitting curve by removing the remelting sample without ultrasonic vibration, the “modified fitting line” shows a good fitting curve in accordance with the Hall–Petch equation [21]. In the “modified

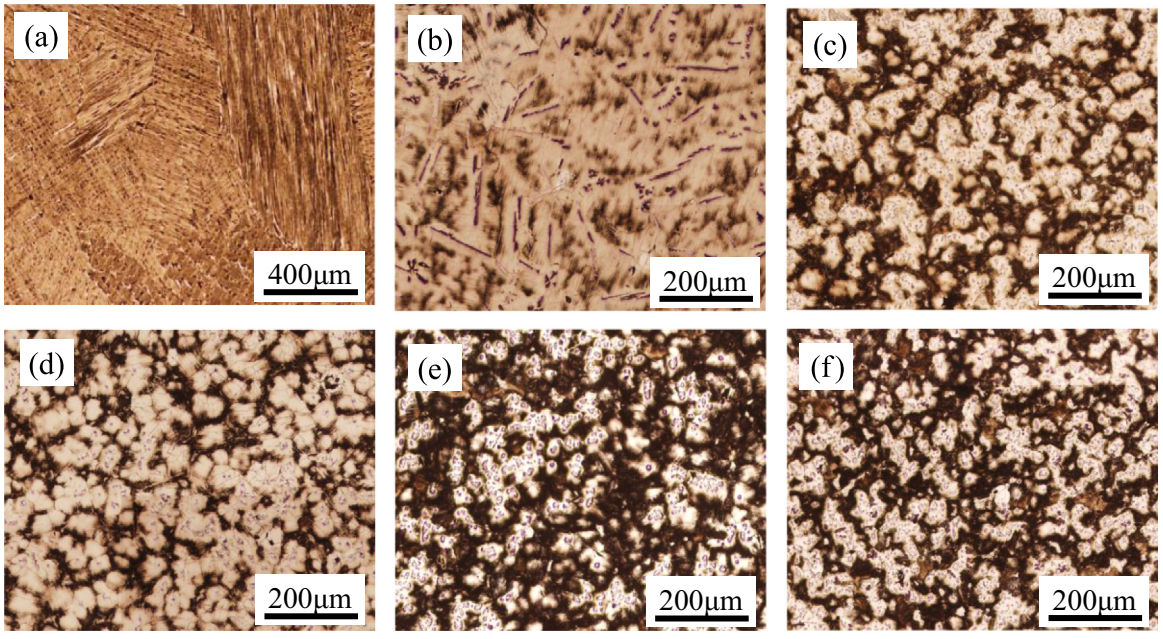

Fig. 1. Metallographic microstructures of the samples of TiAl alloy: (a) raw as-cast, (b) remelted under static state, (c)–(f) remelted with ultrasonic vibration for 25 s, 50 s, 75 s and 100 s, respectively.