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Isothermal forging of γ-TiAl based alloys①

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Abstract: The true stress—strain curves and processing window of Ti-47Al-2Cr-1Nb were set up through thermal physical simulation. A method for refinement of the as-cast+ HIPped structure was submitted, which included two-step deformation with a short intermediate heat-treatment between double deformations. The break-down operation of the canned ingot was performed by the isothermal forging processing mentioned above. The refining mechanism is characterized as breaking and bending of the as-cast+ HIPped lamellae, dynamic recrystallization, and static globularization. Thus, a uniform and refined billet microstructure is obtained for the final component by forging operation. The deformation of a model disc is accomplished by the subsequent single-step isothermal forging at 1 100-1 150 ℃ using a closed compression die.

Key words: TiAl alloy; isothermal forging; microstructure

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1 INTRODUCTION

Because of their attractive properties, γ-TiAl based alloys are considered for high temperature applications in aerospace and automotive industries. These properties include low density, high specific yield strength, high specific stiffness, good oxidation resistance, and good creep properties up to high temperatures. Research and development on γ-TiAl based alloys have progressed significantly within the last decade. This research has led to a better understanding of the fundamental correlations among alloy composition and microstructure, processing behavior, and mechanical properties[1-3]. Now, a number of engineering alloys (four generations) are emerging which have a good balance of physical and mechanical properties[4]. To promote the application of TiAl alloy, finding the effective processing and production routes has become the focus of researching. The processing for manufacturing TiAl products is very important because the microstructures of TiAl products play a significant role on their mechanical properties[5]. At present, isothermal forging is an extremely effective processing for manufacturing TiAl products with tailored microstructures among all of the TiAl production routes including investment casting, forging, rolling and P/M[6]. In fact, the TiAl compressor blades of aerospace[7] and subscale turbine engine compressor disc and blades[8] have been produced by isothermal forging for ingot break-down and closed-die forging. It is noticeable that the isothermal forging processing is indeed effective especially on developing the required microstructure and properties in the final components. However, so far, these products are not perfect.

At home, the rapid refining and the multi-step thermal mechanical treatment of TiAl have been deeply studied by HUANG[9, 10]. Some works about isothermal forging with an intermediate heat-treatment for TiAl refining were done[11]. In general, the research work on the second processing such as refining billet and manufacturing TiAl forgings especially for those final component with complicated shape is still insufficient. Some technical details during the whole processing from the alloy ingot to the final product need to be clarified. In this paper, the canned TiAl ingot was done by isothermal forging with double deformation. In particular, the experiments including the break-down of TiAl ingot, refining of microstructure and deformation of final component have been conducted systematically so as to investigate the evolution of microstructure and verify the feasibility of the factual processing.

2 EXPERIMENTAL

The TiAl based alloy, with a nominal composition of Ti-47Al-2Cr-1Nb (mole fraction, %) was prepared by crucible induction melting, and it was cast into an ingot with a diameter of 88 mm. The ingot was heated to 1 100 ℃ and held for 8 h for homogenization, and then hot isostatically pressed

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(HIP) at 1 250 ℃, 170 MPa for 4 h to eliminate any residual casting shrinkage or porosity. The initial microstructure of the ingot was characterized as a near lamellar structure with an average grain size of 400 μm. The cylindrical compressive specimens, with a diameter of 8 mm and a height of 12 mm, were machined from the homogenized ingot. The isothermal compressive tests were conducted at 1 100 ℃ with the mica sheet lubricant on the Thermecmaster-Z physical simulation testing equipment. The metallographic samples were mechanically polished and etched with Kroll's reagent(1 mL HF+ 3 mL HNO_3 + 16 mL H_2O), and examined by optical microscope. The TiAl ingot billet of d 88 mm × 122 mm was canned by stainless steel, and was deformed on the 5 000 kN hydraulic pressor.

3 RESULTS AND ANALYSES

3.1 Refining processing and mechanism

In this paper, a simple and effective process of TiAl refining has been studied through thermal physical simulation test. The true stress—strain curves obtained from isothermal compression at 1 150 ℃ is shown in Fig. 1. The curves exhibit an evident flow softening behavior and the stresses are sensitively dependent on the strain rate. At a given deformation amount of 50% (height reduction) in the first step, the limit strain rate without cracking is 0.01 s^{-1} at 1 150 ℃. But the as-cast + HIPped lamellar grains can't be broken completely by 50% deformation.

Then, an effective method which includes two-step deformation and a short intermediate heat-treatment at the deformation temperature for about 30 min between the two deformation was put forward to ensure better refining effect. To avoid the cracking and to control the grain growth, the height reduction during every step should not exceed the limit of the processing window, and the deformation temperature was chosen in the low-temperature region of the ($\alpha+\gamma$) phase field. The previous research results[12, 13] indicated that at the beginning of deformation, the slip and twinning offers conditions necessary for dynamic recrystallization(DRX). When a fine equiaxed grain structure is formed due to DRX, an additional deformation mechanism, grain boundary sliding, is activated, leading to superplastic flow, which in turn promotes microstructural homogeneity. The ductility of alloy was thus improved due to the extensive DRX, and correspondingly, the true stress—strain curves exhibit a flow softening behavior.

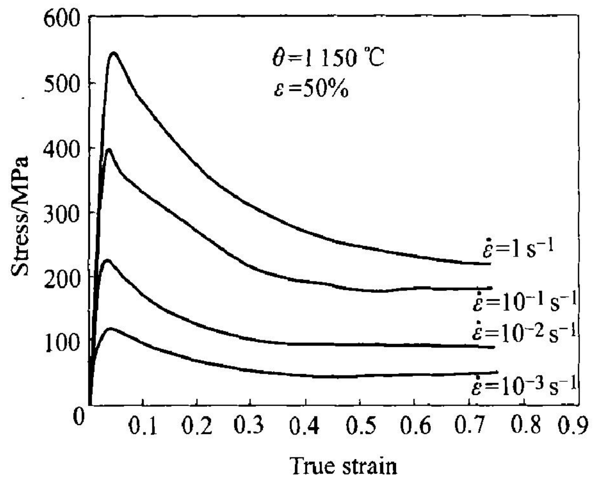

Fig. 1 True stress—strain curves with different strain rates obtained by isothermal compression

After the first deformation, a short heat-treatment was conducted prior to the next deformation step, for a further refinement of the microstructures. During such intermediate heat-treatment period, static globularization of bent lamellae with high distortion energy as well as micro-fine grains caused by DRX took place. Additionally, some lamellae were separated into fine pieces, offering the necessary condition for DRX in the next deformation. Fig. 2 shows the true stress—strain curves of the double step deformation. The peak stress of the second deformation was decreased obviously due to the increase of volume fraction of fine equiaxed grains after the first deformation as well as the static globularization. By above processing, a total deformation amount of 70% (height reduction) was obtained without any crack.

3.2 Primary ingot break-down

The TiAl ingot with the size of d 88 mm × 122 mm was broken down on the 5 000 kN hydraulic pressor by isothermal upsetting processing mentioned above. Stainless steel was used as canning material so that the temperature decreasing during

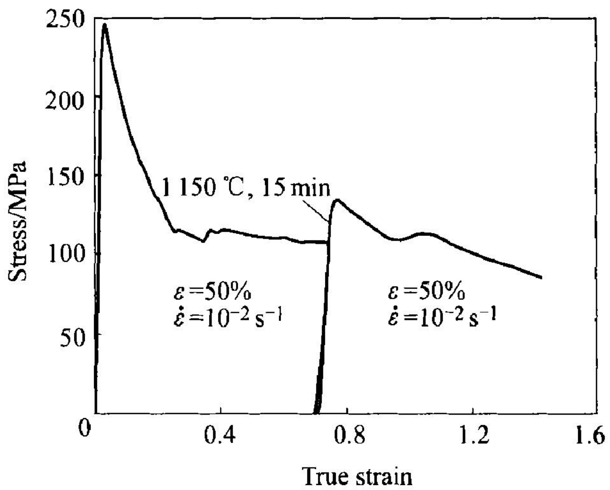

Fig. 2 True stress—strain curves of two-step deformation and a short intermediate heat-treatment

forging can be reduced as possible and a three-dimensional compressive stress condition can be fulfilled. Typical condition for the large sample isothermal forging is: $\theta = 1\ 150 - 1\ 200$ ℃ at strain rate $\dot{\varepsilon} = 0.012 - 0.05\ s^{-1}$, height reduction of 40% in the first step and 50% in the second step, with an intermediate heat-treatment for 30 min in furnace. Finally, the canned billet has been successfully forged with a total height reduction of 70%. The corresponding photograph of the broken-down TiAl billet is shown in Fig. 3. We observed from the cross section of the pancake that the deformation of the can is coincidental with that of ingot, indicating that the can has a good effect on restricting the secondary tensile stress. Fig. 4 provides the microstructure comparison of the initial ingot and the pancake after ingot break-down. The microstructure is primarily comprised of fine equiaxed γ grains with an average size of 20 μm and some broken lamellar pieces. Some bent lamellae still existed in the hard-deformation zone at the both ends of the ingot.

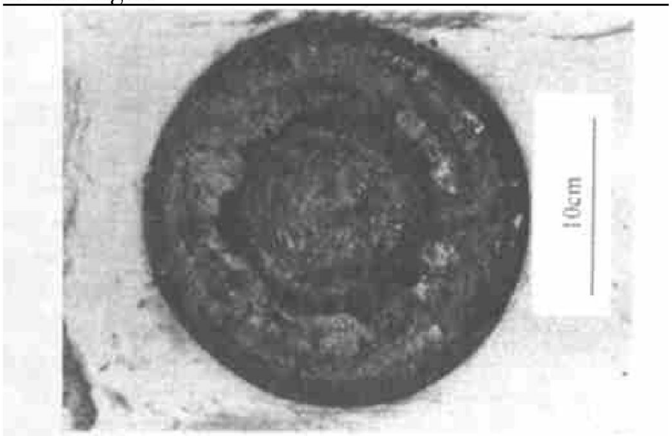

Fig. 3 Photograph of broken-down TiAl billet

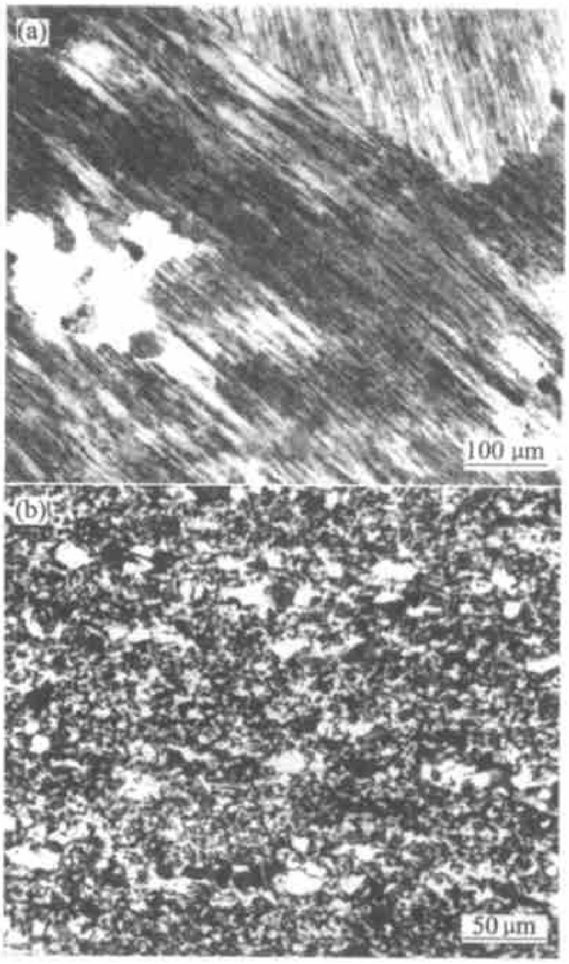

Fig. 4 Microstructures of as-cast+ HIPped(a) and converted(b) γ-TiAl

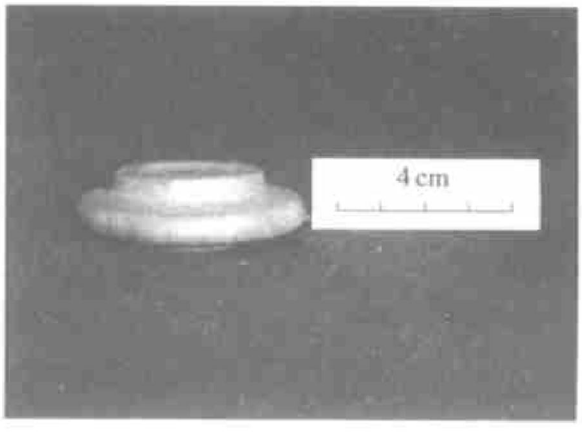

Fig. 5 Isothermal forged TiAl model disc

3.3 Isothermal forging of model disc

The refined microstructures of the broken-down billets meet the requirement of the subsequent isothermal closed-die forging of the model disc. Cylindrical samples of 35 mm in diameter and 27 mm in height was prepared from the pancake using spark-erosion. The closed dies were made by investment casting from a Ni_3Al-based superalloy IC6A.

Forging of complex-shaped components often requires several operations to redistribute material from a standard shape billet stock geometry to the final component geometry. However, due to the current effort, only a single-step forging operation using a closed die is needed for the deformation of the model disc, with the isothermal temperature of $1\ 100 - 1\ 150$ ℃ at the strain rate of $0.12 - 0.05\ s^{-1}$. The billet material shows an excellent die filling characteristic, and the obtained disc component is shown in Fig. 5. The forged disc has very good surface finishes with a high height reduction of 78%. The flow lines at the corners are continuous and smooth. But a crack was observed at the lateral edge of the disc. This crack is thought to be caused by partial deformation of the die cavity at the high deformation temperature which leads to a local metal flowing. Additionally, too high strain rate may be the other reason of the cracking. However, the feasibility of the processing route of disc component with complicated shape, from the two-step refining deformation with an intermediate heat-treatment to the single-step isothermal forging, has already been verified.

Fig. 6(a) shows the photograph of cross-section of the forged disc component at a low magnification. The as-forged component shows a uniform and fine equiaxed grain morphology(Fig. 6(b)), similar to that of the billet stock(Fig. 4(b)), but with a smaller grain size(average size of approximately 10 μm). However, some larger grains were observed in the uppermost part of the pancake, which corresponds to the uncompleted DRX region, concurrently with little strain. If the strain is increased in this region, a better refinement effect can be expected.

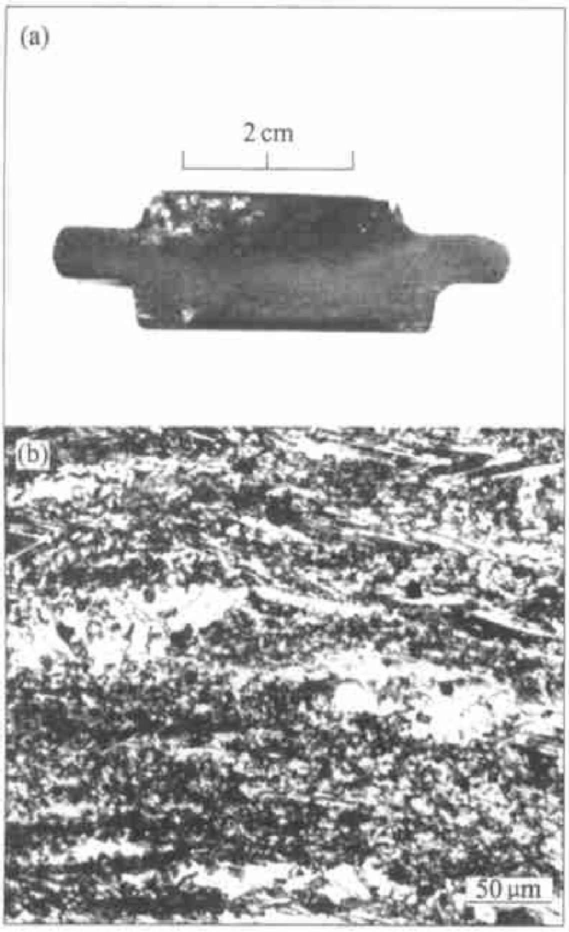

Fig. 6 Macrostructure(a) and microstructure(b) of forged disc

It is generally thought that duplex and lamellar structures are obtainable from the fine equiaxed structures of the as-forged component by post heat-treatment in different phase field, and they will provide superior mechanical properties. The related heat-treatment experiments, together with the study on the further improvement of disc deformation, are still undertaking.

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