MICROSTRUCTURES OF THE HOT-DEFORMED Ti-Al-Nb-W-B ALLOYS

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ABSTRACT

A large ingot produced through the magnetic-flotation-melting method with the composition of Ti-45Al-7Nb-0.15B-0.4W, in atomic percent, tends to have a larger grain size (~ 110 μm) and a larger amount of the β-phase in the alloy compared with the small drop-casted specimens, which have a fine grain size of ~ 50 μm, after the HIPping and homogenization treatment.[1] In order to reduce the amount of the β-phase, heat treatments have been conducted. Additional deformation techniques, such as hot forging, have been chosen to refine the grain size of the alloy. The microstructual evolution of the TiAl-based alloy after hot forging and related heat treatments has been investigated. Mechanical properties of the alloy after the deformation and heat treatments have been studied. A duplex structure, obtained after hot-deformation and heat-treatments, has a refined grain size and enhanced room-temperature ductility and yield strength.

Keywords: TiAl alloys; heat treatment; hot forging

INTRODUCTION

The TiAl-based intermetallics have great application potentials in the aviation and automobile industry for their excellent high-temperature properties, such as the good oxidation resistance and high strength. Thus, the TiAl-based intermetallics have attracted the interests of many materials researchers and have been in the front field of materials-science studies for all times.[2-5] But the TiAl alloys have encountered many difficulties for large-scaled applications in the industry because of their low toughness, and especially their low ductility at ambient temperature. The TiAl-based alloy can be manufactured by the casting or powder metallurgy. The powder-metallurgy technique has been extensively studied, and some achievements have been applied in the industry.[6-10] Since the melting point of the TiAl alloy is high, and its chemical activity is very strong at elevated temperatures, the alloy is very easy to be oxidized. Thus, the TiAl-alloy powder with less oxygen is very difficult to produce. Hence, the use of the powder-metallurgy technique in the TiAl alloy is limited. The procedure of casting is relatively simple, and its cost is relatively low, so that it has been widely used in producing the TiAl alloy. But the grain size of the alloy produced by this technique is quite large, which severely impacts the mechanical properties of the alloy. The refinement of the grain size in this TiAl-based alloy is necessary in order to improve the mechanical properties. One of the refining methods is to add elements into the TiAl alloy.[11-13] Cyclic heat treatment can also refine the grain size of the alloy.[14-17] Another effective way to refine the grain size is through mechanical processing. Based on a reasonable choice of the alloy system, a grain size of 60 μm, in the as-cast condition, has been obtained through the magnetic-floatation-melting method in the present work. Since the TiAl alloy is very brittle at room temperature, it is very difficult to be cold worked for the grain refinement. One effective way to refine the grain size of the TiAl-based alloy is through hot working.[18-22] Since the TiAl alloy remains quite brittle at elevated temperatures, it needs to be coated while hot deformation takes place. With the coating, the alloy can be iso-pressed during the hot deformation at elevated temperatures, this step counteracts with the tensile strength induced during forging, which improves the efficiency of hot working.[23] The relationship among the hot working, microstructures, and mechanical properties of the TiAl-based alloy can be studied, and the TiAl-based alloy with an enhanced mechanical property can be obtained.

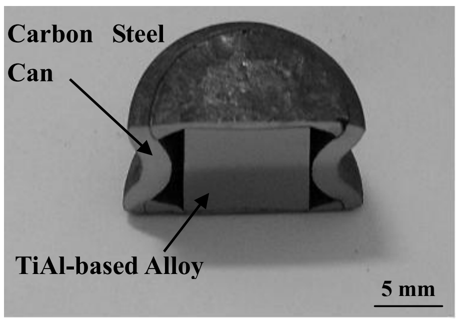
EXPERIMENTAL PROCEDURES

The Ti-45Al-7Nb-0.15B-0.4W (at.%, atomic percent) ingot of 15kg was produced by the magnetic-floatation-melting method, using a German magnetic floatation cold crucible furnace. High-purity Nb, W, and B powders, Ti particles (99.6% purity), and Al pieces (99.99% purity), were uniformly placed in the copper crucible for magnetic floatation melting. The large ingot sample is levitated and melted in the middle of the magnetic field created by the induction coils. Small samples, 10 mm in diameter (d) and 10 mm in length (l), were spark-eroded from the large ingot for hot-simulation experiments. The small samples were canned in the carbon steel, and then hot-pressed on the Gleeble1500 hot simulator for the hot-simulation experiments. The hot-compression temperatures range from 1,050^{0}C to 1,230^{0}C, with a deformation of 50%, at a strain rate of 0.02 s^{-1}. The optimal hot-deformation temperature of the TiAl alloy is between 1,180^{0}C - 1,200^{0}C. Hot deformation had been conducted to the TiAl-based alloy after the hot-simulation experiments. The TiAl alloy had been hot deformed twice, first at 1,180^{0}C, with a deformation of 60%, and a strain rate of 0.02 s^{-1}; and, then, at 1,180^{0}C, with a deformation of 50%, and a strain rate of 0.02 s^{-1}. After the first hot-deformation procedure, the samples had been heat treated at 1,220^{0}C. A second hot-deformation process had been conduced on the TiAl-based following the heat treatment. After the second deformation procedure of the TiAl-based alloys, heat treatments had been performed on the alloys in order to obtain different kinds of microstructures. For more detailed structure and composition analyses, the JSM-5600LV scanning-electron microscopy (SEM) was used, with an acceleration voltage of 20 KV.

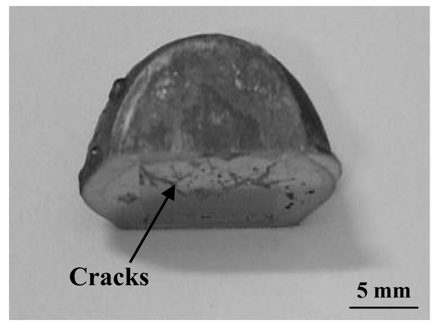
EXPERIMENTAL RESULTS

1. Hot simulation of the TiAl-based alloys.

The TiAl-based alloy samples were canned in the carbon steel for hot-simulation experiments. As shown in Fig. 1(a), at a compression temperature of $1{,}050^0$C, the TiAl-based alloy showed no deformation while the can had deformed. At a temperature of $1{,}100^0$C, the TiAl-based alloy started to deform. As the temperature became higher, at $1{,}180^0$C, the alloy deformed at a relatively larger strain without any cracks initiated at its cross section. While the hot-compression temperature reached $1{,}230^0$C, as indicated in Fig. 1(b), the can had deformed severely, and cracks had been initiated in the cross section of the TiAl-based alloy.



(a) $1{,}050^0$C



(b) $1{,}230^0$C

Fig. 1 Canned Ti-45Al-7Nb-0.15B-0.4W alloy after the hot compression at (a) $1{,}050^0$C and (b) $1{,}230^0$C

2. Microstructures of the alloy after the first forging and heat treatment.

The microstructure of the as-cast Ti-45Al-7Nb-0.15B-0.4W alloy, after the hot-isostatic pressing (HIPping) at $1{,}250^0$C / 4 h / 150 MPa and homogenization treated at $1{,}250^0$C / 16 h, is composed of a near-fully lamellar structure. A significant amount of the β phase, mainly distributing along the lamellar grain boundaries, can be observed in the alloy, as shown in Fig. 2. The average grain size of the alloy is 110 μm. After the first forging process at $1{,}180^0$C, with a deformation of 60%, at a strain rate of 0.02 s^{-1}, the grains in the alloy have been deformed. The β phase remains in the alloy after this deformation, Fig. 3. A heat treatment has been conducted on the hot-deformed alloy at $1{,}220^0$C / 4h / air cool. The un-deformed grains, surrounded by recrystallized small grains, can rotate and deform easily in the second deformation process.

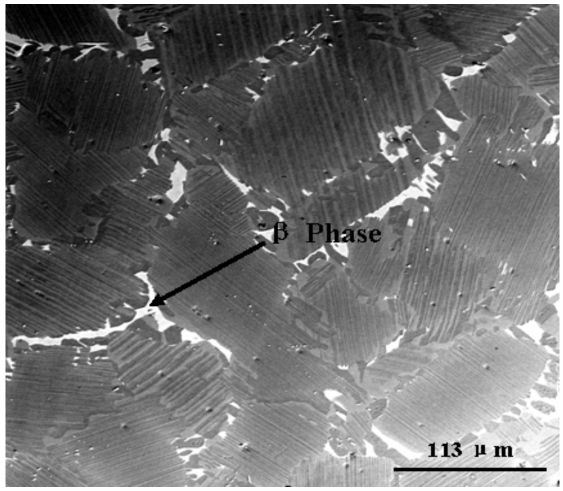


Fig. 2 Microstructure of the Ti-45Al-7Nb-0.15B-0.4W alloy after the HIPping and homogenization treatment

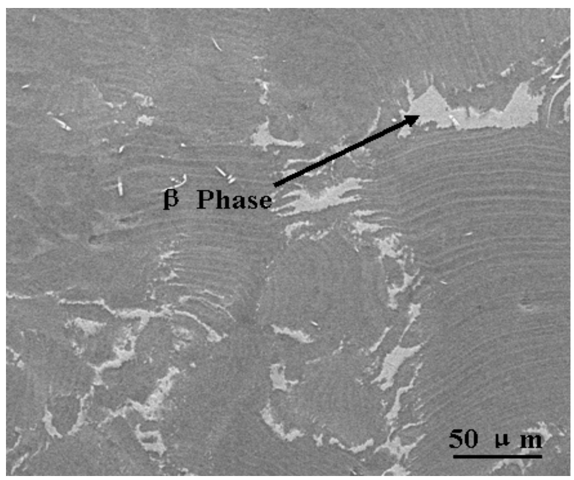


Fig. 3 Microstructure of the as-forged Ti-45Al-7Nb-0.15B-0.4W alloy

3. Microstructures of the alloy after second-forging and heat treatments.

After the heat treatment, a second hot-deformation process at a temperature of 1,180^{0}C, with a deformation of 50%, and at a strain rate of 0.02 s^{-1}, has been conducted on the alloy. Compared to the first deformation process, the grains in the alloy have been thoroughly deformed after the second deformation process, the remaining β phase can still be observed in the alloy, Fig. 4. Different heat treatments have been performed to the hot-deformed alloy. As shown in Fig. 5, after heat treating the alloy at 1,260^{0}C / 5h / furnace cool (FC), a duplex structure can be obtained. The microstructure of the alloy is composed of the lamellar structure and the primary γ phase. No β phase has been observed after this heat treatment. The average grain size of the alloy is approximately 20 μm. After heat-treating the hot-deformed alloy at 1,250^{0}C, 5h + 1,295^{0}C, 10 min., FC, a fully-lamellar structure with an average grain size of 100 μm can be obtained. No β phase has been observed in the alloy after this heat treatment.

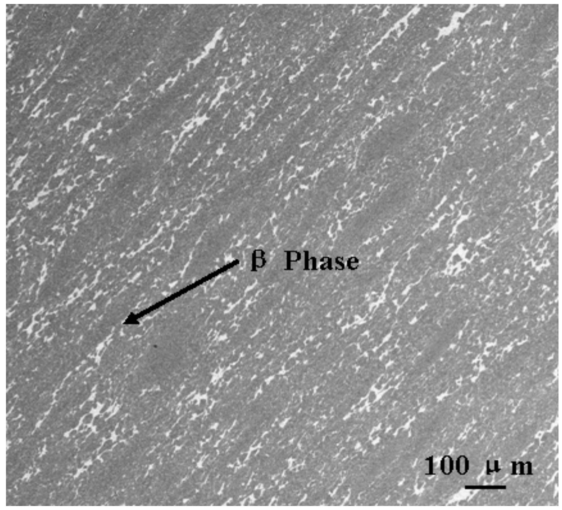


Fig. 4 Microstructure of the as-forged-II Ti-45Al-7Nb-0.15B-0.4W alloy

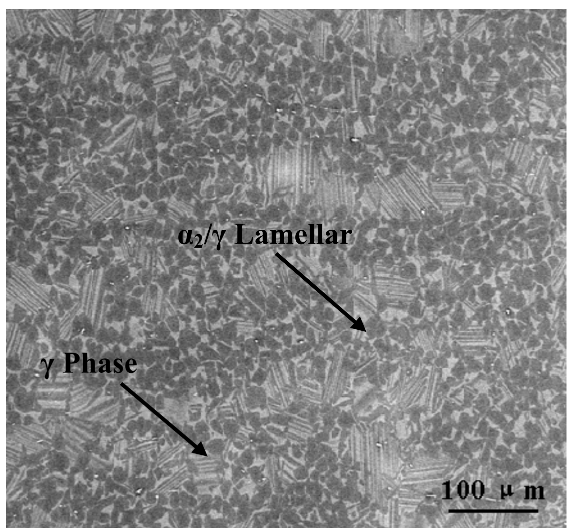


Fig. 5 Microstructure of the deformed Ti-45Al-7Nb-0.15B-0.4W alloy heat treated at 1,260^{0}C / 5h / furnace cool (FC)

4. Tensile properties of the hot-forged TiAl-based alloys.

For the as-cast TiAl-based alloy, the ductility is nearly 0, and the yield strength is also low. Tensile tests have been conducted on the hot-deformed alloy, heat treated at 1,260^{0}C / 5h / furnace cool (FC), with the duplex structure. The ductility of the alloy can reach 2.0%, and the yield strength of the alloy is 710 MPa. For the hot-deformed alloy, heat treated at 1,250^{0}C / 5h + 1,295^{0}C / 10 min. / FC, with the fully-lamellar structure, the ductility of the alloy is 1.4%, and the yield strength of the alloy is 530 MPa.

DISCUSSIONS

1. Microstructure of the as-cast large TiAl-based alloy.

The large as-cast Ti-45Al-7Nb-0.15B-0.4W alloy, produced through the magnetic-flotation-melting method, is composed of an equiaxed structure with an average grain size of 60 μm. After the HIPping and homogenization treatment, the average grain size grows to 110 μm. The microstructure of the alloy is composed of a near-fully lamellar structure and residual β phase. Compared with the same composition produced through drop casting, with a much smaller ingot size, the average grain size of the alloy is approximately 50 μm, after the HIPping and homogenization treatment. The microstructure of the small drop-cast alloy is a duplex structure, composed of a lamellar structure and the primary γ phase. No β phase was found under this condition. The difference in the microstructural features of the alloys is mainly due to the size of the ingot, which greatly affects the cooling rate of the TiAl-based alloy. When the small ingot produced through arc-melting is cooled down rapidly, the as-cast microstructure of the sample is composed of a non-equilibrium structure, and there is no microsegregation in the alloy. Thus, after the HIPping and homogenization treatment at a temperature of 1,250^{0}C in the α + γ phase range, the microstructure of the alloy reaches an equilibrium condition, and there is no β phase observed in the alloy. For the large ingot produced through the magnetic-flotation-melting method, the cooling rate is suppressed due to the large ingot size, 110 mm in diameter (d) and 300 mm in length (l). Hence, the high-temperature remaining β phase can be observed in the as-cast condition. After the HIPping and homogenization treatment at 1,250^{0}C, the kinetic energy for the atomic diffusion is not sufficient to reach an equilibrium condition. Therefore, the β phase remains in the alloy. In order to reduce the amount of the β phase, and refine the grain size of the large ingot, hot deformation has been conducted.

2. Effects of hot simulation on the TiAl-based alloy.

Below the temperature of 1,050^{0}C, the force resistance for deformation is large in the TiAl-based alloy, the canned TiAl-based alloy cannot be hot deformed, Fig. 1(a). At a temperature of 1,100^{0}C, the force resistance for the deformation of the TiAl-based alloy starts to decrease, the canned alloy can be hotly deformed at a temperature equal to or higher than 1,100^{0}C. At the temperatures of 1,100^{0}C, and 1,180^{0}C, the TiAl-based alloy had deformed without any cracks initiated at its cross section, the deformation amounts of the canned TiAl alloy along the compressing direction are 30% and 50%, respectively. Thus, the TiAl-based alloy can be hot-compressed by the minimum force to obtain enough deformation in this temperature range. While hot-compressed at 1,230^{0}C, cracks had been initiated in the cross section of the TiAl-based alloy. The can had been largely deformed, and its strength decreased, resulting in losing its protection for the TiAl-based alloy, as shown in Fig. 1(b). This trend shows that when using the carbon steel as canning materials for the TiAl alloy, the hot-deformation temperature should not exceed 1,230^{0}C. Since cracks could initiate and propagate easily in the alloy, which could lead to the failure in the hot deformation of the TiAl alloys. An optimal temperature range has been chosen according to which the capsule was strong enough to support the hot deformation of the samples without any cracking initiating in the specimens in this temperature range. Therefore, for the carbon-steel-canned

TiAl-based alloy, the temperature range for hot deformation is $1,180^0C$ – $1,200^0C$, and the optimal temperature is $1,180^0C$.

3. Effects of hot-forging and heat-treating on the large TiAl-based alloy.

The Ti-45Al-7Nb-0.15B-0.4W alloy produced through the magnetic-flotation-melting method was first hot deformed with a deformation of 60% at $1,180^0C$. After this deformation process, the grains in the alloy have been deformed, and the β phase still remained in the deformed alloy. Heat treatments have been conducted on the hot-deformed alloy in order to benefit the rotation of the un-deformed grains in the second deformation process. Small grains recrystallized in the alloy after heat treating at $1,220^0C$ / 4 h / air cool. The average grain size did not grow larger under this heat treatment. As the annealing time exceeds 4 hours at $1,220^0C$, the grain size tends to grow larger in the alloy. The recrystallization of small grains in the alloy after the heat treatment causes the un-deformed grains in the alloy to rotate and deform easily in the second deformation process.

The second hot deformation at $1,180^0C$, with a deformation of 50%, was conducted. The alloy has been severely deformed. The β phase still remains in the deformed alloy. In order to reduce the amount of the β phase, different heat treatments have been conducted. When heat treating the TiAl-based alloy above the eutectoid temperature (T_e, approximately $1,175^0C$), and under the α-phase transus temperature, T_α ($1,290 \pm 5^0C$), a duplex structure can be obtained. Above T_e, as the heating temperature increases, the volume fraction of the γ phase tends to decrease as the amount of the α phase increases. The grain size also generally increases as the heat-treating temperature increases in this range. After the hot-deformation process, the amount of the β phase can be reduced as the heat-treating temperature is hold still at a certain temperature range, such as $1,260^0C$, 6h, FC. Since through the hot deformation, the kinetic energy has been stored in the deformed grains, the microsegregation in the alloy can be eliminated due to the fast atomic diffusion, when heat treating the alloy in the α + γ, two-phase temperature range. Thus, when heat treating the deformed alloy at $1,260^0C$ / 5h / FC, a duplex structure with a fine grain size of ~ 20 μm, with no β phase, can be obtained, Fig. 5. If the heat-treating temperature is increased to $1,270^0C$, the grain size tends to grow larger, the amount of the γ phase decreases, and the microstructure tends to turn into a fully-lamellar structure. As the heat-treating temperature increases to T_α, a fully-lamellar structure can be obtained. In order to control the grain growth, the heat-treating time cannot exceed 5 hours. A fast cool is required so as to restrain the growth of the primary γ phase, and to obtain a fully-lamellar structure. Hence, when heat treating the hot-forged alloy at $1,250^0C$ / 5 h + $1,295^0C$ / 10 min., FC, a fully-lamellar structure with a grain size of 100 μm, with no β phase, can be obtained.

4. Effects of hot-forging on mechanical properties of the TiAl-based alloys.

The tensile elongation of the TiAl-based alloys at room temperature is strongly dependent on the colony size, showing an increased ductility with decreasing the colony size. The strength at room and elevated temperatures is sensitive to the interlamellar spacing, exhibiting an increased strength with decreasing the interlamellar spacing.[24-25] For TiAl-based alloys, the fully-lamellar (FL) structure, composed of α_2/γ lamellae, has a low tensile ductility at room temperature but higher fracture strength than the other microstructures. On the other hand, the duplex (DP) structure, composed of the lamellar colony and primary γ phase, tends to have a good room-temperature tensile ductility but low fracture strength.[24] The as-cast large ingot specimen after the HIPping and homogenization treatment, with a near fully-lamellar structure and an average grain size of 110 μm, exhibits both low yield strengths and room-temperature tensile ductilities. After the hot-forging process, a duplex structure with a fine grain size of ~ 20 μm can be obtained. The ductility of the alloy with the duplex structure has been increased to 2.0%, and the yield strength of the alloy has been increased to 710 MPa. With other additional heat treatment at $1{,}250^0$C / 5h + $1{,}295^0$C / 10 min. / FC after the hot deformation, a fully-lamellar structure with an average grain size of ~ 100 μm can be obtained. The ductility of the alloy is 1.4%, and the yield strength is 530 MPa. As in comparison to other hot-forged and heat-treated TiAl-based alloys in previous reported work, Ti-48Al-2Cr-2Nb-1B and Ti-44Al-8Nb-1B,[27] with grain sizes varying from 70 ~ 110 μm, the highest yield strength was 670 MPa, and the best ductility was 1.9%, the Ti-45Al-7Nb-0.15B-0.4W alloy with a duplex structure, obtained after the hot deformation and consequent heat treatments, tends to have a smaller grain size and exhibits better tensile ductility and yield strength.

CONCLUSIONS

1. A large sample produced through the magnetic-flotation-melting method with the composition of Ti-45Al-7Nb-0.15B-0.4W has an equiaxed structure with an average grain size of 60 μm in the as-cast condition. After the HIPping and homogenization treatment at $1{,}250^0$C, the average grain size of the alloy increases to 110 μm. The microstructure is composed of a near-fully lamellar structure, with a significant amount of the β phase dispersed along the grain boundaries.
2. Hot forging and subsequent heat treatments are effective ways to refine the grain size and reduce the amount of the β phase in the alloy. The optimal hot-deformation temperature for the Ti-45Al-7Nb-0.15B-0.4W alloy is between $1{,}180^0$C – $1{,}200^0$C.
3. A duplex structure with a fine grain size of ~ 20 μm, and no β phase, can be obtained after hot-forging and heat-treating the alloy at $1{,}260^0$C / 5h / FC. A fully-lamellar structure with a grain size of 100 μm, with no β phase, can be obtained after hot-forging and heat-treating the alloy at $1{,}250^0$C, 5h + $1{,}295^0$C, 10 min., FC.
4. Both the tensile ductility and the yield strength of the alloy can be increased in the TiAl-based alloy with a duplex structure, after the hot forging and heat treatment.

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