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Strengthening a high-strength TiAl alloy by hot-forging

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Abstract

As part of efforts to expand the range of applications for TiAl alloy, strengthening was pursued through hot-forging. Using Ti–42Al–10V (at.%), the hot workability of which was improved by introduction of the β phase, formability testing and material property evaluation were carried out. Blade formation was found to be possible by means of closed-die forging. A fine lamellar structure characterized by an average grain size of 9 μm and average lamellar spacing of 40 nm composed about 70% of the area fraction in the microstructure; tensile strength was improved as a result of this fine lamellar structure, and strength of over 1200 MPa was maintained up to 700 °C. Charpy absorbed energy at room temperature using a 2 mmV-notch specimen was 5 J/cm^2, which is satisfactory for a TiAl alloy. This alloy is a potential substitute for conventional forged alloys used at temperatures up to 700 °C.

Keywords: A. Titanium aluminides, based on TiAl; B. Phase diagram; C. Extrusion; D. Microstructure

1. Introduction

Lightweight heat-resistant alloys based on the intermetallic compound TiAl have long been positioned as next-generation structural materials and investigated extensively. However, commercial application has only been realized recently in the form of turbochargers for passenger vehicles [1–4]. Because lighter weight turbines have directly enabled improved performance, i.e., better response ability, this application takes direct advantage of the lightweight nature of TiAl alloy. Furthermore, the material properties required for this application had only to be about the same as for the alloy being replaced.

However, utilization of a TiAl alloy in other areas has stagnated. Reasons for this include the essential issues of reliability and high cost, in addition to the fact that the material properties of a TiAl alloy are not greatly superior to those of comparable conventional alloys. That is, when the lightweight nature of a TiAl alloy cannot be directly exploited as in the case of turbochargers, it should be assumed that the properties must substantially exceed those of the conventional alloy to be substituted for.

Strength is one of the primary properties of a TiAl alloy that requires improvement; strength in the high-temperature region is generally about the same as for superalloys, even when compared in terms of specific strength. Furthermore, it is inferior to heat-resistant titanium alloy and Super α_2 alloy at medium and low temperatures. Accordingly, no particular necessity for the utilization of a TiAl alloy can be seen as a substitute for these alloys.

It is known that the reduction of grain size and lamellar spacing of the lamellar structure is effective in improving the strength of a TiAl alloy [5–12]. Air cooling from the high-temperature α region is sufficient to reduce lamellar spacing, while plastic deformation at high-temperature reduces the grain size. In other words, hot-forging as normally carried out for ordinary metallic materials should serve to obtain higher strength TiAl alloy. Research has already been conducted from this perspective, and Liu et al. [5–8] have reported a high strength TiAl alloy having a fully lamellar structure prepared by hot-extrusion of a small bar.

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Nevertheless, no examples of practical applications for this fully lamellar TiAl have been reported. This is because the flow stress of this material is high, and deformability is low in high-speed deformation; it is therefore presumed that it would be difficult to produce industrially required large and complex parts from this alloy by means of hot-forging, due to limited equipment capability, material cracking, etc. Thus, for the practical application of hot-forged TiAl alloys, reduction of high-temperature flow stress and improvement of deformability is essential.

In the case of TiAl alloys, the most effective way to accomplish this is the introduction of a β phase [13], and, if the phases during hot-forging were changed from an α single phase to α + β dual phases, high-temperature deformability would definitely increase. Also, given that the α phase changes to a lamellar structure during the cooling process, optimization of the ratio between the α and β phases at high-temperature through control of the alloy composition would serve to deliver a microstructure wherein a lamellar structure would predominate.

Based on these points, Ti–42Al–10V (at.%—also hereafter) was selected as being likely to provide the above-noted effects. Formability tests were initially conducted by means of hot-extrusion and closed-die forging and shape impartation and cracking status were assessed after these tests. The properties of the hot-forged Ti–42Al–10V were then evaluated, the microstructure was observed, and various mechanical tests were performed. From these results, the possibility of manufacturing high-strength TiAl parts on an industrial scale by means of hot-forging was considered.

2. Materials and experimental procedures

2.1. Materials

Ingots of Ti–42Al–10V were produced by means of plasma skull casting by Daido Steel Co., Ltd. Ingot size was about 100 mm in diameter and 250 mm in length, with specific a gravity of 4.06. Fig. 1 shows the external appearance of an ingot, while Table 1 indicates the chemical composition. Fig. 2 presents the phase diagram of this alloy by Kobayashi et al. [14]. It appears quite different from ordinary TiAl alloy, exhibiting a wide α + β phase field in the high temperature region and a B2 + γ phase field in the medium and low temperature regions. The main point of the manufacturing process requires heating of the ingot in the α + β phase field and then hot-forging during rapid cooling.

Fig. 1. External appearance of a Ti–42Al–10V ingot.

2.2. Experimental procedures

2.2.1. Formability tests

Two types of formability test were performed, namely hot-extrusion and closed-die forging. Fig. 3 shows schematic illustrations of the samples before and after the hot-extrusion test. Following machining to a diameter of 95 mm and a length of 109 mm, the ingot was vacuum-sealed in a 5 mm thick low alloy steel case with a ceramic sheet in order to prevent reaction between the TiAl alloy and the steel. Given that the post-extrusion diameter was 50 mm, the reduction in area was 1/5.3. After heating to 1260 °C, the sample was set into a die

Table 1
Chemical composition of a Ti–42Al–10V ingot

At.%			Wt. ppm		
Ti	Al	V	C	O	N
Bal.	41.9	10.1	120	900	90

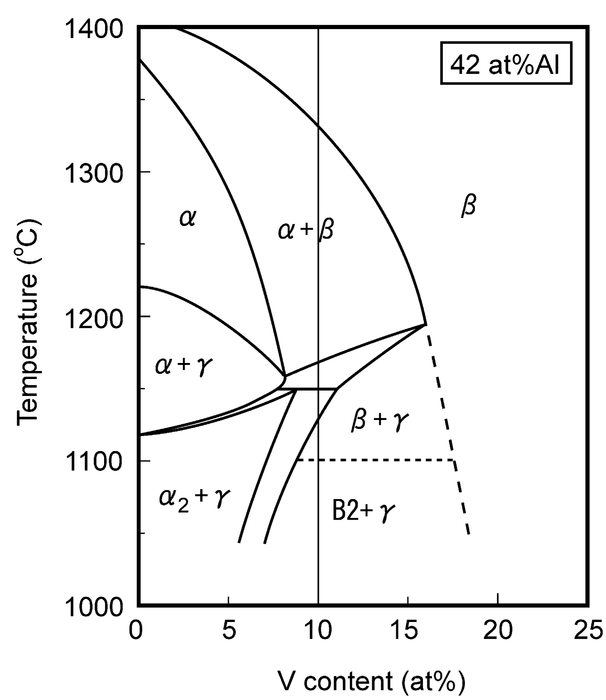


Fig. 2. Vertical section in Ti–Al–V ternary system at 42Al.

at room temperature, and extruded in a single pass using a hydraulic press. The time required for this step was within 1 s.

In the closed-die forging test, the objective shape was a turbine blade. Fig. 4 shows schematic illustrations of the samples before and after the closed-die forging test. In the latter illustration, the dotted lines indicate extra material outside the blade section. Bar samples having diameters of 20 and 48 mm were prepared by means of machining from the ingot, and then vacuum-sealed in a 3 mm thick steel tube with a ceramic sheet. The thickness of the profile portion in the targeted blade was about 1–5 mm. After being heated to 1260 °C, the sample was set in a forging die that had been heated to about 200 °C, and then forged in a single blow using a hydraulic press. The time required was within 1 s.

2.2.2. Property evaluation methods

The external view and cross-sectional macrostructure were observed following the formability tests. The microstructure was also observed using optical, back-scattered electron, and transmission electron microscopes, while the quantitative lamellar microstructural data such as area fraction, average grain size, and average lamellar spacing were determined by means of image processing.

Next, mechanical tests were conducted using the hot-extruded material. The tensile test was performed at room temperature, 500, and 700 °C, using a round bar test piece having a diameter of 4 mm at the gauge. The Charpy impact test using a 2 mmV-notch test piece was performed at room temperature. In addition, the creep rupture test was performed under two conditions, 700 °C

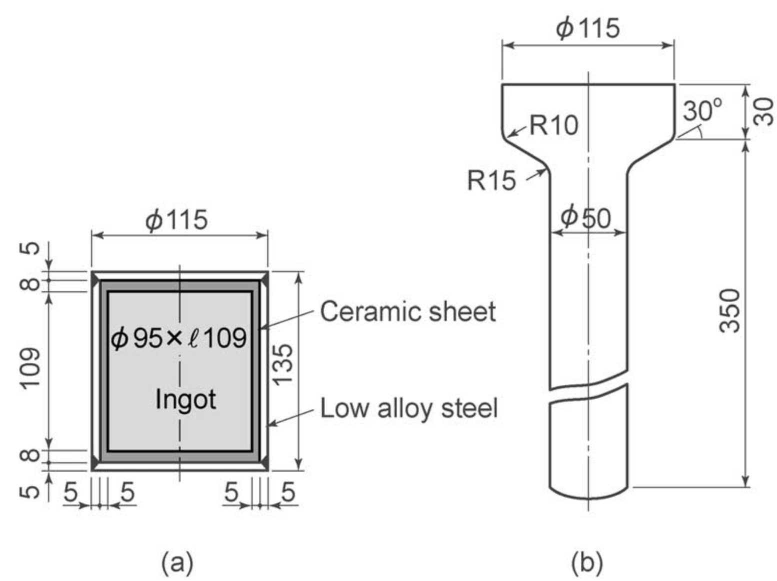


Fig. 3. Schematic illustrations of hot-extrusion test samples, (a) before the test, (b) afterwards.

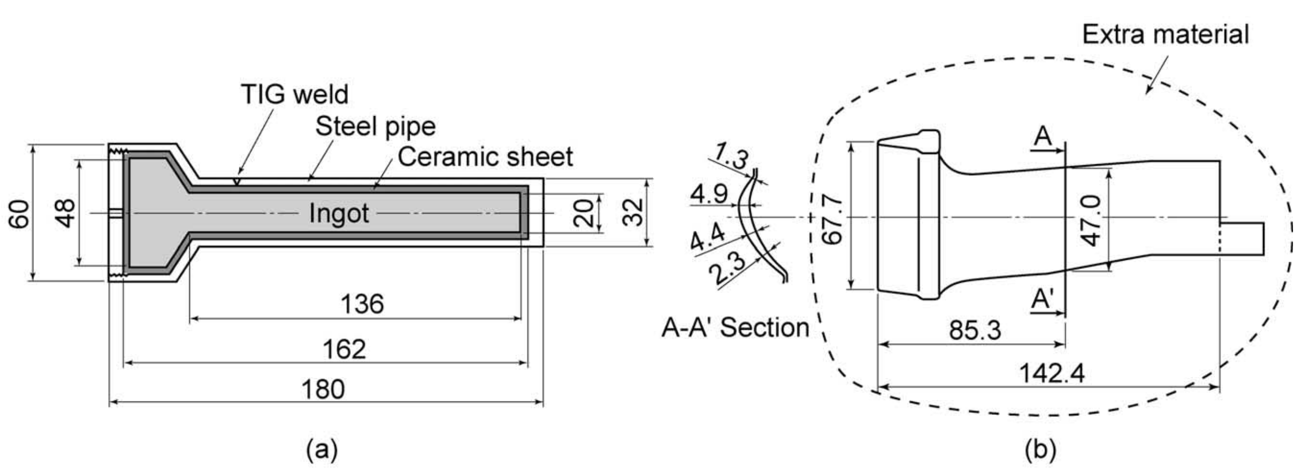
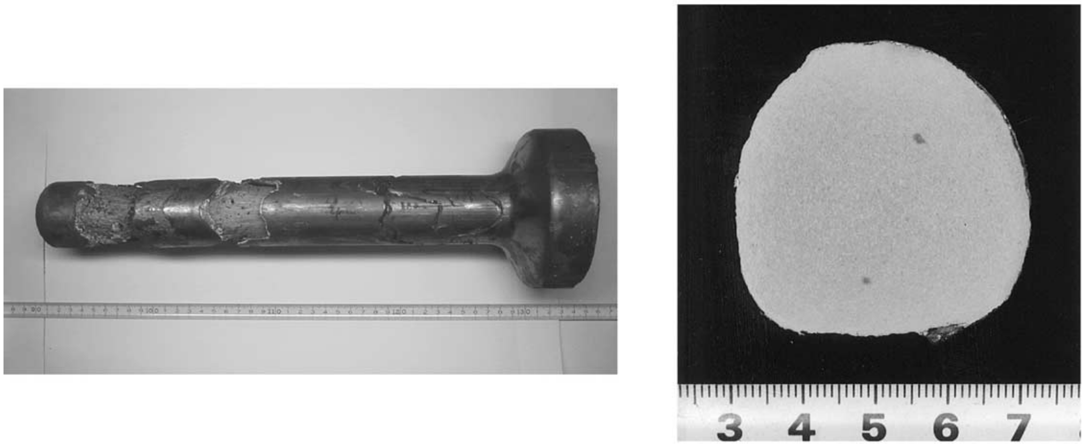


Fig. 4. Schematic illustrations of closed-die forging test samples, (a) before the test, (b) afterwards.



(a) (b)

Fig. 5. Hot extruded Ti–42Al–10V, (a) external appearance, (b) cross-sectional macrostructure.

× 363 MPa and 750 °C × 264 MPa, also using a round bar test piece having a diameter of 4 mm at the gauge.

3. Results and discussion

3.1. Formability tests

3.1.1. Hot-extrusion

The external appearance of the hot-extruded Ti–42Al–10V is shown in Fig. 5, together with the cross-sectional macrostructure after removal of the steel sheath. Although the sheath was torn, the material inside was sound. The cross section was thinner than anticipated, and since only the sheath was torn, it would appear that the Ti–42Al–10V exhibited greater deformability than the low alloy steel sheath in this test.

3.1.2. Closed-die forging

The external appearance of the closed-die forged blade with the extra material is presented in Fig. 6. The position of the crack is in the extra material and at the weld in the sheath material. Fig. 7 shows the cross-sectional macrostructure at the profile and root in the blade section, with the sheath still on. Note that there is no internal cracking. Plastic flow is also satisfactory, and there is no portion with insufficient filling. In particular, the material is filled out even at the thin tip of the profile.

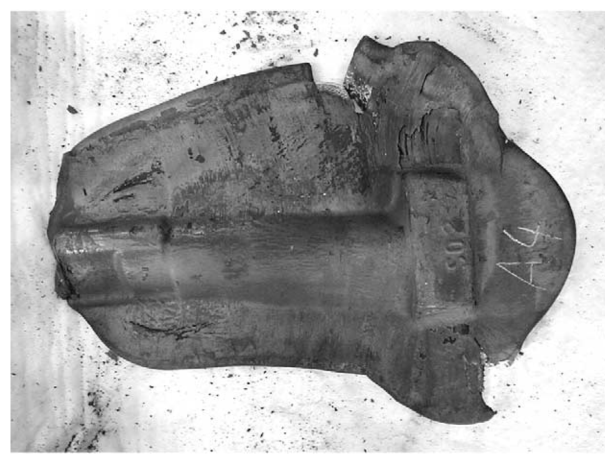


Fig. 6. External appearance of closed-die forged Ti–42Al–10V.

3.2. Material properties

3.2.1. Microstructure

Fig. 8 presents optical and back-scattered electron micrographs of the hot-extruded Ti–42Al–10V, as well as a TEM image of the lamellar structure. The microstructure of the closed-die forged blade was also the same. As can be seen from the optical micrograph, the microstructure is extremely fine and uniform. The white phase in the back-scattered electron micrograph is the β phase (ordered to a B2 phase), while the black phase is the γ phase. The gray area is the lamellar structure, but, because the lamellar spacing is so narrow, the layered structure can hardly be discerned in this photograph. The TEM image confirms the extremely fine lamellar structure, in which the α_2 phase is more predominant than the γ phase. This is considered to be due to suppression of γ phase precipitation from the α phase during cooling as a result of the high cooling speed.

Table 2 presents the quantitative lamellar microstructural data, i.e., the area fraction, the lamellar grain size, and the lamellar spacing. The grain size and spacing are smaller than those for ordinary TiAl alloys.

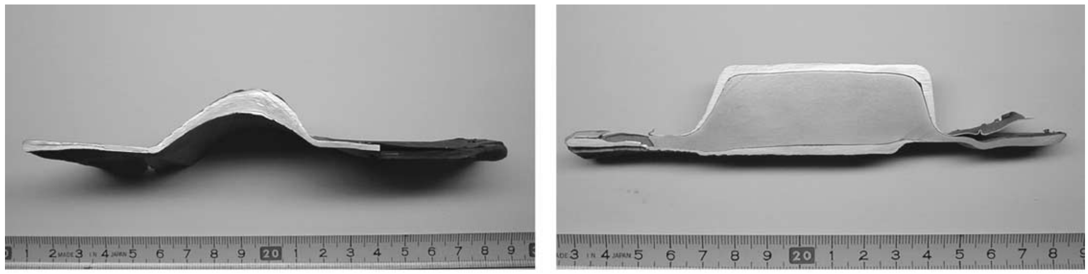


Fig. 7. Cross-sectional macrostructure of closed-die forged Ti–42Al–10V, (a) profile section, (b) blade root section.

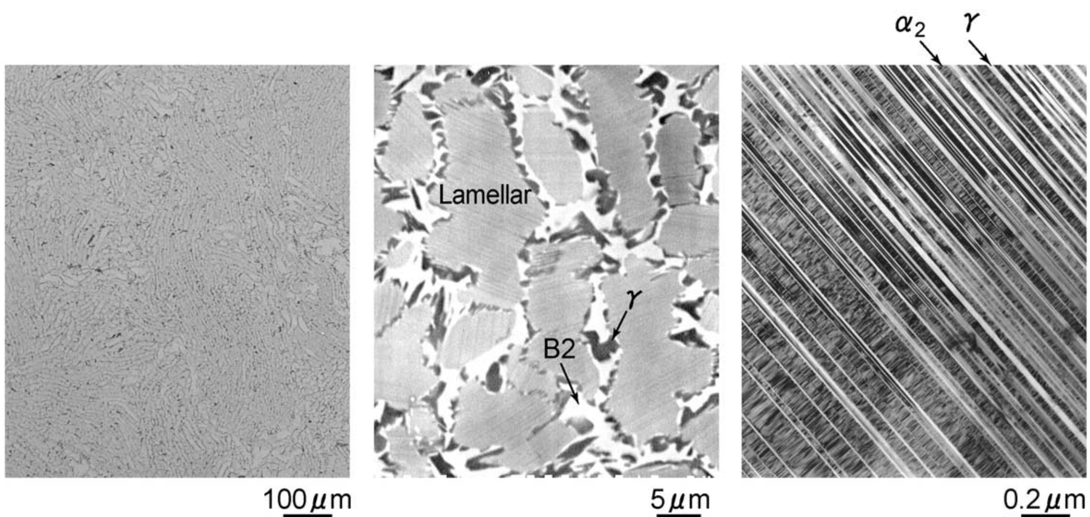


Fig. 8. Microstructure of hot-extruded Ti–42Al–10V, (a) optical micrograph, (b) back scattering electron image, (c) TEM image.

Table 2
Quantitative lamellar microstructural data on hot-extruded Ti–42Al–10V

Fraction (%)	Grain size (μm)	Interlamellar spacing (nm)
71.6	9.0	40

This is likely to be the result of the larger plastic strain applied during extrusion, as well as the high cooling speed. Another factor is considered to be the smaller grain size of the α phase during high-temperature holding before forging due to the presence of the β phase, as compared to normal α single phase alloy. The lamellar area fraction of this alloy is about 70%, which is obviously less than for fully lamellar alloy, but nevertheless accounts for the greater part. This suggests that these lamellar microstructural characteristics do govern the properties of this alloy.

Table 3
Tensile properties of hot-extruded Ti–42Al–10V

Temperature (°C)	Yield strength (MPa)	Fracture strength (MPa)	Elongation (%)
25	1265	1334	0.35
500	1049	1385	1.2
700	655	1236	2.1

3.2.2. Mechanical properties

Table 3 presents the tensile properties of the hot-extruded Ti–42Al–10V. Tensile strength at room temperature is extremely high at 1334 MPa, which is thought to be due to the very fine grain size and lamellar spacing. Analysis by Dimiduk et al. [9] performed on TiAl alloys having fully lamellar structure indicates that room temperature, 0.2% yield strength and grain size

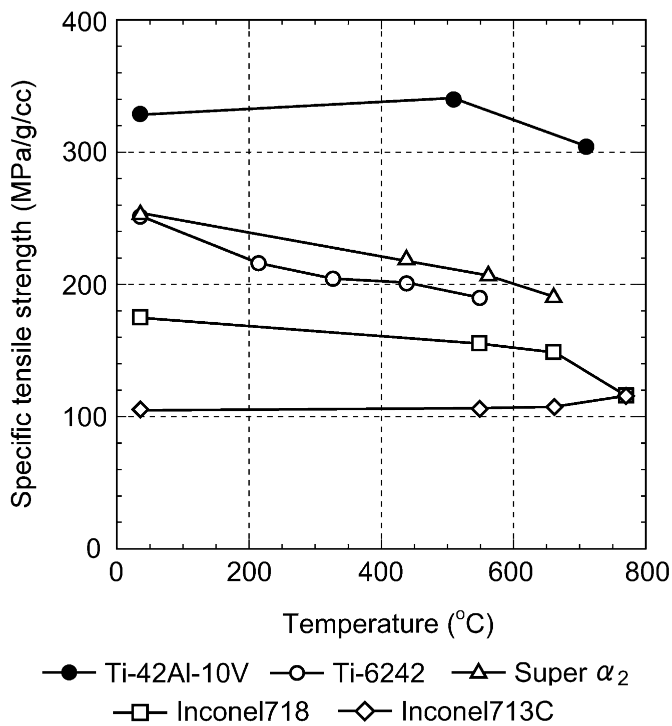


Fig. 9. Comparison of the specific tensile strength between the hot-extruded Ti–42Al–10V and other conventional heat-resistant alloys.

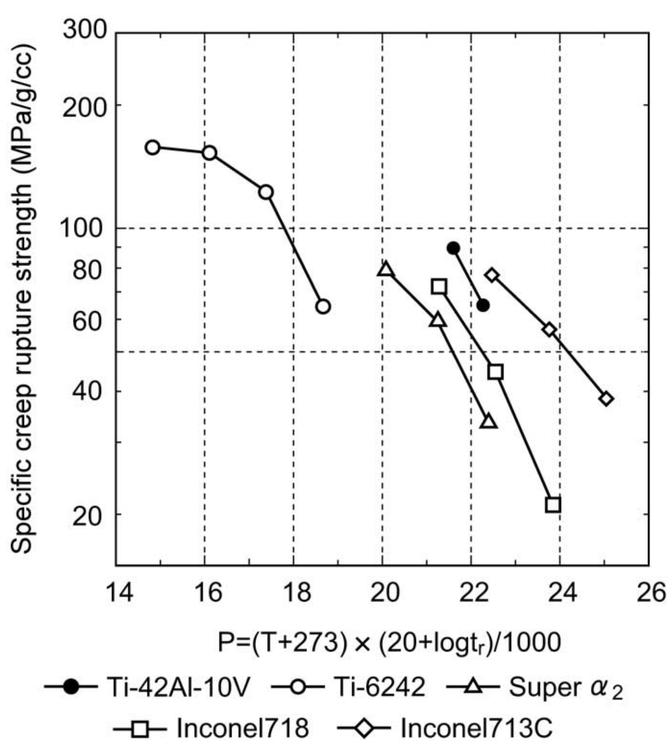


Fig. 10. Comparison of the specific creep rupture strength between the hot-extruded Ti–42Al–10V and other conventional alloys, with a Larson–Miller parameter of $C=20$.

Table 4
2 mmV-notch Charpy impact test results for hot-extruded Ti–42Al–10V

Temperature (°C)	Absorbed energy (J/cm^2)
25	5

can be related using the Hall–Petch formula of $\sigma_y = 581 + 2.7 \times d^{-1/2}$. Using a lamellar grain size of 9 μm for this alloy, σ_y would be 1481 MPa. The actually measured strength was 1265 MPa, somewhat lower than the presumed value, but this is considered to be an appropriate level in view of the fact that the lamellar area fraction of this alloy is about 70%. That is, the high strength of the hot-extruded Ti–42Al–10V is seen to result from the fine-grained lamellar structure.

Strength at 500 °C is about the same as at room temperature; even at 700 °C, tensile strength is high at 1236 MPa. Fig. 9 shows the comparison of the specific tensile strength between the hot-extruded Ti–42Al–10V and other conventional heat-resistant alloys [15–17]. In the range of RT–700 °C, the hot-extruded Ti–42Al–10V exhibits the highest strength.

Table 4 presents the results of the Charpy impact test. The absorption energy is 5 J/cm^2, which is satisfactory for a TiAl alloy. This is considered to be due to the high strength of this alloy. The Charpy absorption energy is generally given as the sum of the resistance of the material to crack initiation and its resistance to crack propagation [18], and the former depends mainly on strength. For normal ductile metallic materials, the latter energy is greater, meaning that substantial absorption energy is obtained even for low-strength materials. However, as the latter energy is extremely small for TiAl alloys, the absorption energy is almost completely accounted for by the former [19]. Thus, in the case of TiAl alloys, strengthening serves as a means of raising the Charpy absorption energy, and, this is definitely the case with this alloy. While it is of course desirable in practical terms to increase the resistance to crack propagation, this must be considered nearly impossible for TiAl alloys with all phases composed of intermetallic phases.

Fig. 10 presents the comparison of the creep rupture strength in terms of specific strength between the hot-extruded Ti–42Al–10V and other conventional alloys [15,17,20], with a Larson–Miller parameter of $C = 20$. The creep strength of this alloy is seen to be greater than for heat-resistant titanium alloy (Ti-6242), Super α_2 alloy, or forged Ni-based superalloy (Inconel←718). However, it remains inferior to cast Ni-based superalloy (Inconel←713C). The reasons why the creep rupture strength of this alloy is not as substantial as would be expected from its high tensile strength are thought to be the fine grained microstructure and the existence of a β phase. Accordingly, the hot-forged Ti–42Al–10V alloy described above can be positioned as a substitute for conventional forged alloys, and it may be useful in applications requiring both lightweight and high-strength properties at temperatures up to 700 °C.

4. Conclusion

As part of efforts to expand the range of applications for TiAl alloy, strengthening was pursued through hot-forging. Using Ti–42Al–10V (at.%), the hot workability of which was improved by the introduction of a β phase, formability testing and material property evaluation were carried out. The results obtained are summarized below.

(1) It was confirmed that a high-degree of working without cracking is possible by one-pass hot-extrusion and closed-die forging. In particular, in the latter case thin profile portions of a turbine blade were adequately filled out.

(2) A fine lamellar structure characterized by an average grain size of 9 μm and average lamellar spacing of 40 nm composed about 70% of the area fraction in hot-extruded Ti–42Al–10V.

(3) The effect of finer grains increased the tensile strength such that it was maintained at over 1200 MPa until 700 °C, i.e., much stronger than conventional heat-resistant alloys.

(4) Room temperature 2 mmV-notch Charpy absorption energy was 5 J/cm^2, which is satisfactory for a TiAl alloy. The high tensile strength of this alloy is thought to be the cause.

(5) The specific creep rupture strength was superior to heat-resistant titanium alloy, Super α_2 alloy, or forged Ni-based superalloy, but inferior to cast Ni-based superalloy due to the effect of the fine grains and the β phase.

(6) This alloy is a potential substitute for conventional forged alloys used at temperatures up to 700 °C.

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