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HEAT-RESISTANT CAST GAMMA-TiAl ALLOY WITH HIGH NIOBIUM ADDITION FOR PASSENGER VEHICLE TURBOCHARGERS

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Abstract

The development of a heat-resistant cast TiAl alloy for turbine wheels in commercial passenger vehicle turbochargers is reviewed. High concentration of Nb is effective in securing the anti-oxidation resistance and high-temperature strength, both required for this application, and the appropriate Nb concentration is 7 at.%. Furthermore, minute additions of Cr, Si, and Ni also bring about improvements in properties. The anti-oxidation resistance and high-temperature strength of the turbine wheel material made of the developed alloy are far superior to conventional TiAl alloys with low Nb, and the effect of the high Nb concentration is clearly demonstrated. Also, as a result of engine endurance testing, satisfactory durability was confirmed in the actual usage environment.

Introduction

TiAl alloy has substantial high-temperature strength as for a light material. Accordingly, applications under consideration include rotating and reciprocating components, namely turbine blades [1,2] in aerospace engines, as well as exhaust valves [3,4] and turbochargers [5,6] in engines for passenger vehicles.

For turbochargers, application of TiAl alloy for the turbine wheel makes it possible to improve response ability by reducing the inertia for rotation. However, TiAl binary alloys are not usable in this application unless their oxidation resistance and high-temperature strength are greatly improved, because turbochargers operate at much higher temperatures than turbine blades and exhaust valves.

Nb is an essential additive for TiAl alloy, and various TiAl alloys containing Nb have been proposed. In early TiAl alloys, such as GE alloy [7] and XD alloy [8], the amount of added Nb was within 2at.%, but recent proposed alloys have exceeded this level. In particular, the TiAl alloy developed by Tetsui, which have been already used in commercial passenger vehicle turbochargers from 1999 [9,10], is characterized by high concentration of Nb.

This report reviews the development of this commercial TiAl turbine wheel, describing the alloy development, as well as evaluation as a turbine wheels material.

2. Development of Alloy Composition

In the first stage of development the various properties of Ti-Al-Nb ternary alloys in a wide compositional range were evaluated, and the optimal concentration of Nb was determined along with practical considerations such as material cost and specific gravity. Subsequently, the effects of additives on this optimal ternary alloy were assessed, and beneficial elements were clarified, and finally the alloy composition for turbine wheel material was determined.

2.1. Investigation of Ti-Al-Nb Ternary Alloy

Samples prepared by arc-melting were subjected to homogenizing heat treatment at 1100˚C for 100h. Figure 1 indicates the relationship between the composition and specific gravity of the Ti-Al-Nb ternary alloys. The specific gravity rises with the amount of Nb, increasing by 10% with an additive amount of 10at.%. Accordingly, excessive addition of Nb is undesirable, as it acts against lightness, i.e. the main advantage of TiAl alloy.

Figure 2 shows Vickers hardness for each ternary alloys. Hardness was the lowest at 50at.% Al, and rising under and above this level the same as ordinary TiAl alloy. An increase in hardness was observed with higher concentrations of Nb.

Figure 3 presents the lattice parameter for 50Al-0~15Nb γ single phase alloy. Anisotropic behavior is exhibited. The c-axis of the γ phase increases with Nb concentration, but with no change of the a-axis. The ratio of c/a thus increases. From this behavior it can be considered that the increased hardness with Nb concentration is due to the lattice distortion caused by substitution of Nb to Ti.

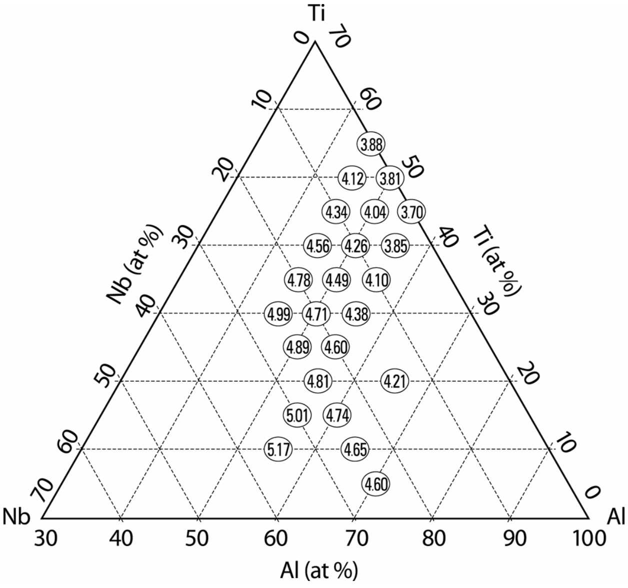

Figure 1. Relationship between the composition and specific gravity of the Ti-Al-Nb ternary alloys.

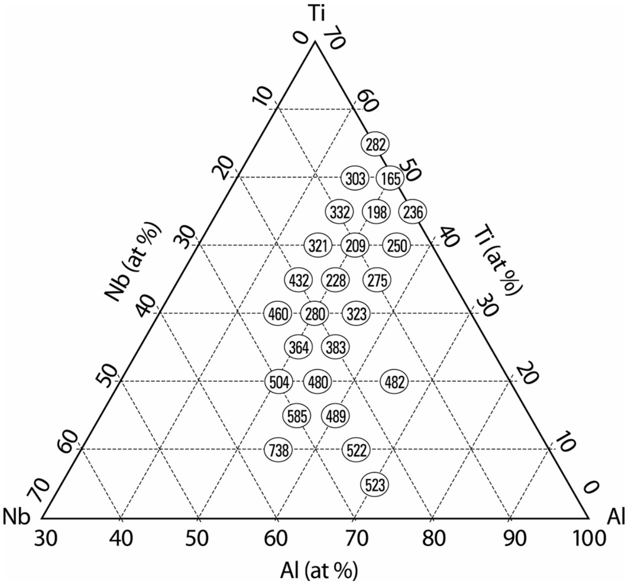

Figure 2. Vickers hardness for the Ti-Al-Nb ternary alloys.

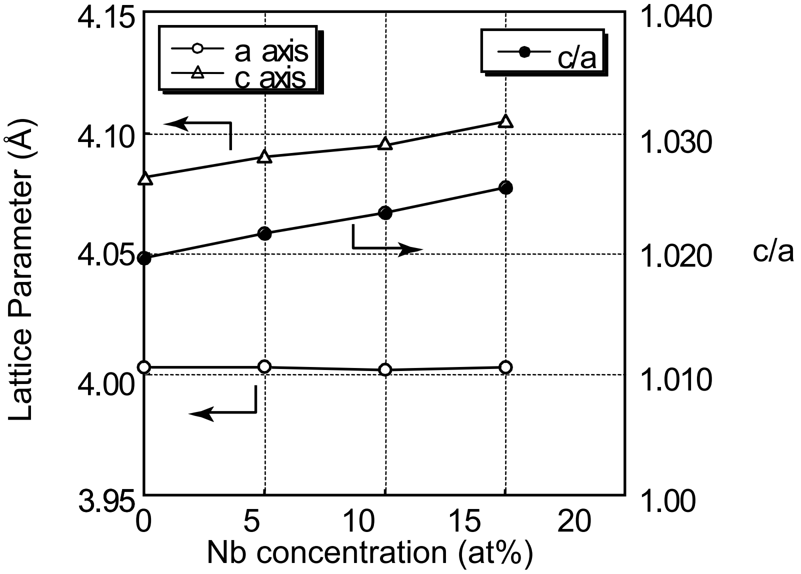

Figure 3. Lattice parameter for 50Al-0~15Nb γ single phase alloy.

Next, the Al concentration was fixed at a practical level of 45at.%, and evaluation was conducted while changing the Nb concentration. Figure 4 shows backscattered electron micrographs of 45Al-xNb arc-melted samples after homogenizing heat treatment at 1100˚C for 100h. The lamellar spacing becomes greater with higher Nb concentration, and the lamellar structure disappears entirely at levels of 12.5Nb and higher. Figure 5 presents the relationship between Vickers hardness and Nb concentration for 45Al alloys. Hardness rises with Nb concentration until the level of 10Nb, confirming the solid solution hardening effect of Nb. On the other hand, strength declines at levels higher than 10Nb. The reason for this is thought to be the disappearance of the lamellar structure as confirmed in Figure 4.

Figure 6 indicates the relationship between weight gain and Nb concentration for 45Al alloys in atmospheric oxidation testing conducted at 900˚C for 400h. The weight gain of 2.5Nb alloy is substantially less than 0Nb alloy, and the improvement in anti-oxidation resistance due to Nb is clearly seen. Anti-oxidation resistance continues to improve with Nb concentration reaching a maximum at 10Nb. However, the degree of the improvement becomes smaller at levels of 5Nb and higher.

The optimal Nb concentration was considered based on the foregoing results. From the perspective of hardness (i.e., strength) and anti-oxidation resistance, the optimal level is 10Nb, but high Nb concentrations result in increased cost and specific gravity. Also, ductility is reduced with greater Nb concentration. Furthermore, there is no significant difference in terms of anti-oxidation resistance between 7.5Nb and 10Nb. Taking these factors into account, the practically optimal Nb concentration is about 7 at.%.

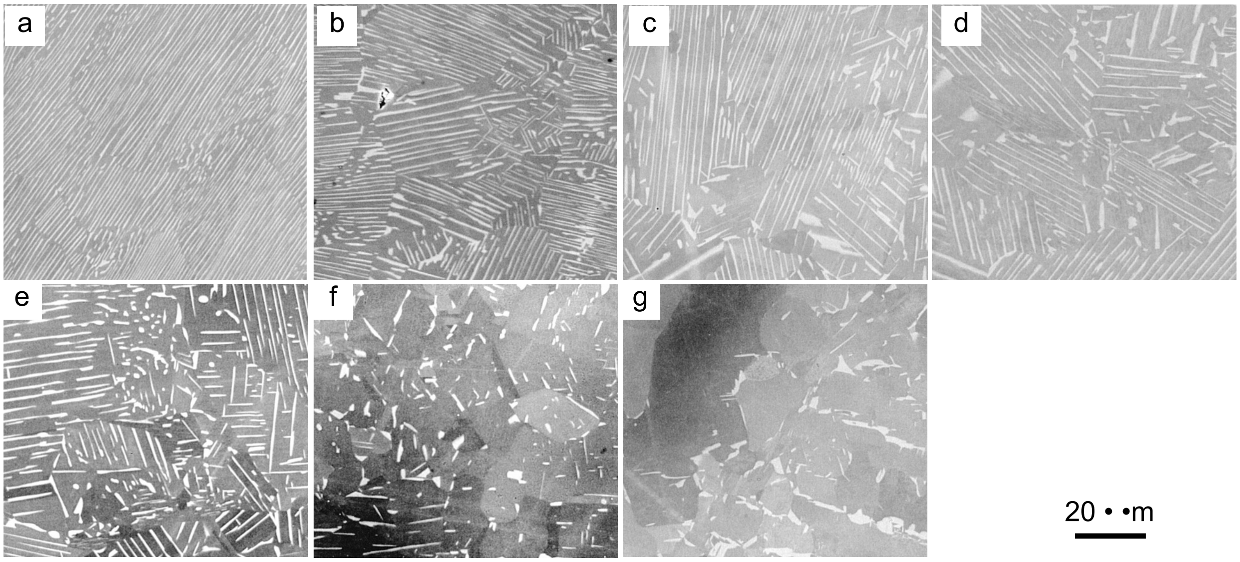

Figure 4. Backscattered electron micrographs of 45Al-xNb arc-melted samples of {(a)0Nb, (b)2.5Nb, (c)5Nb, (d)7.5Nb, (e)10Nb, (f)12.5Nb, (g)15Nb} after homogenizing heat treatment at 1100˚C for 100h.

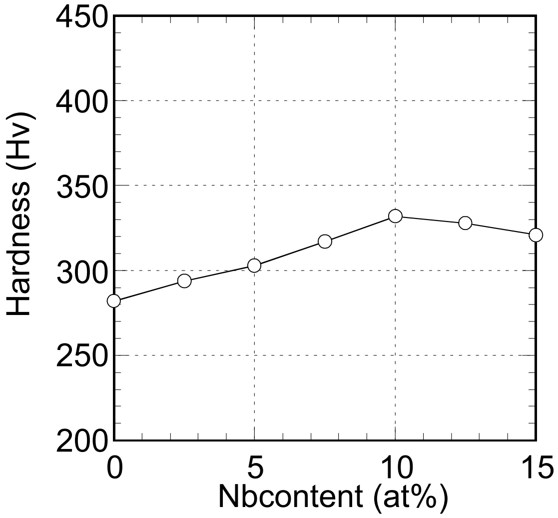

Figure 5. Relationship between Vickers hardness and Nb concentration for 45Al alloys.

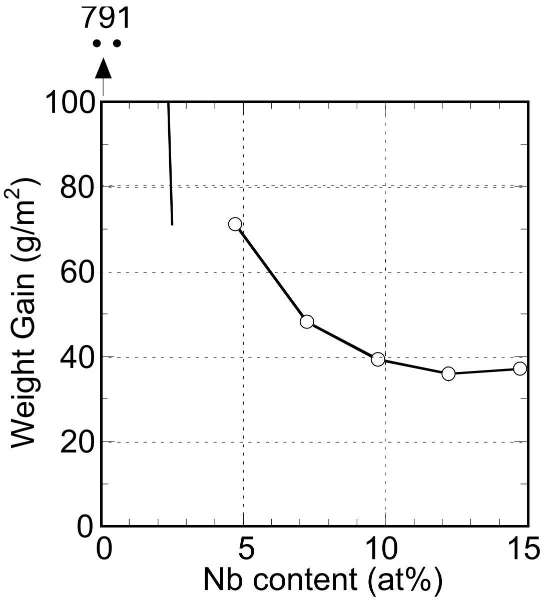

Figure 6. Relationship between weight gain and Nb concentration for 45Al alloys in atmospheric oxidation testing conducted at 900˚C for 400h.

2.2. Improvements due to Additives

Quaternary alloys were prepared by means of arc-melting, with additions of one of 1at.% Cr and Mn, and 0.5at.% Co, Si, and Ni to the 7Nb ternary alloy selected as a result of the consideration described above. HIP treatment was conducted at 1250˚C in order to eliminate the effects of casting defects.

Figure 7 shows the influence of the additive elements on weight gain of 45Al-7Nb alloys in atmospheric oxidation testing at 950˚C for 500h, while Figure 8 presents cross-sectional backscattered electron micrographs of the samples after this oxidation test. The "base" shown in these figures corresponds to 45Al-7Nb without additives. Weight gain for the alloys with 0.5Si and 0.5Ni added was approximately half that of the base, and the oxidation layer was considerably thinner. Furthermore, it can be seen that the oxidation layers of these alloys contain dense Al_2O_3 layer (dark gray-colored layer). This Al_2O_3 layer is thought to serve as an oxygen barrier, thereby improving anti-oxidation resistance of the 0.5Si and 0.5Ni containing alloys. The additions of 1Cr and 0.5Co resulted in a similar weight gain and oxidation layer thickness as for the base, while those became greater for 1Mn containing alloy. That is, Cr and Co had no effect on anti-oxidation resistance, while Mn actually reduced it.

Next, tensile testing was conducted on the alloys with additions of 0.5Si and 0.5Ni (improved anti-oxidation resistance); an alloy with an addition of 1Cr (no change in anti-oxidation resistance, but expected better mechanical properties); and base. Figure 9 indicates tensile strength and elongation for each alloy at room temperature and at 900˚C. Compared to the base, 900˚C strength exhibited improvement for 0.5Si and 0.5Ni containing alloy. In terms of room temperature elongation, the 1Cr containing alloy demonstrated slight improvement, while a reduction was observed for the 0.5Si containing alloy.

A summary of the effects of the additives to 7Nb alloy is as follows. Cr delivered better room temperature ductility, with no effect on anti-oxidation resistance. Mn resulted in reduced anti-oxidation resistance. Co had no effect. Si and Ni delivered improved anti-oxidation resistance and high-temperature strength. However, Si resulted in reduced room temperature ductility.

Given the foregoing considerations, Cr, Si, and Ni were chosen in order to improve the properties of 7Nb alloy. The amounts of all three substances were selected to be low, so as not to form a β phase in the case of Cr and Ni, and not to cause embrittlement in the case of Si. Accordingly, the composition of the turbine wheel material used in the turbochargers of the Lancer Evolution automobile produced by Mitsubishi Motors Corp. was determined to be Ti-46Al-7Nb-0.7Cr-0.1Si-0.2Ni. Since the size of this turbine wheel is large and engenders substantial rotating stress, HIP treatment was conducted after casting so as to be certain of eliminating casting defects.

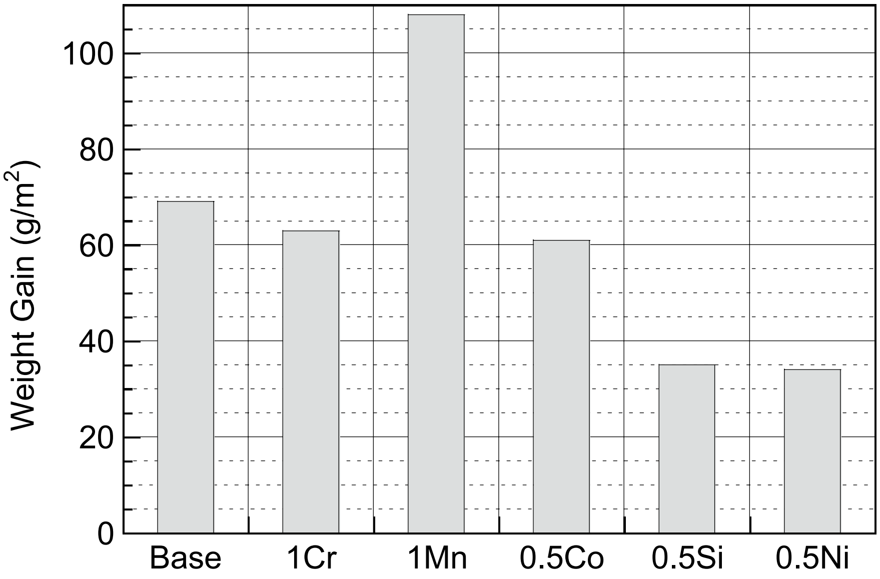

Figure 7. Influence of the additive elements on weight gain of 45Al-7Nb alloys in atmospheric oxidation testing at 950˚C for 500h.

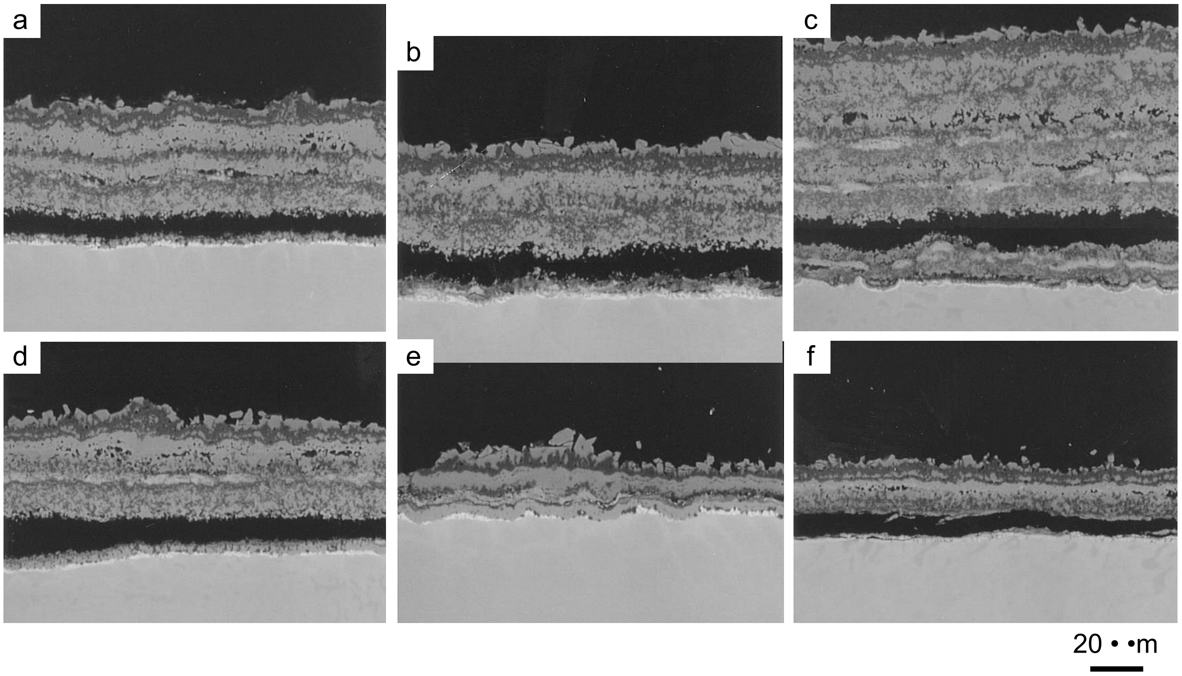

Figure 8. Cross-sectional backscattered electron micrographs of the samples of {(a)Base, (b)1Cr, (c)1Mn, (d)0.5Co, (e)0.5Si, (f)0.5Ni } after atmospheric oxidation testing at 950˚C for 500h.

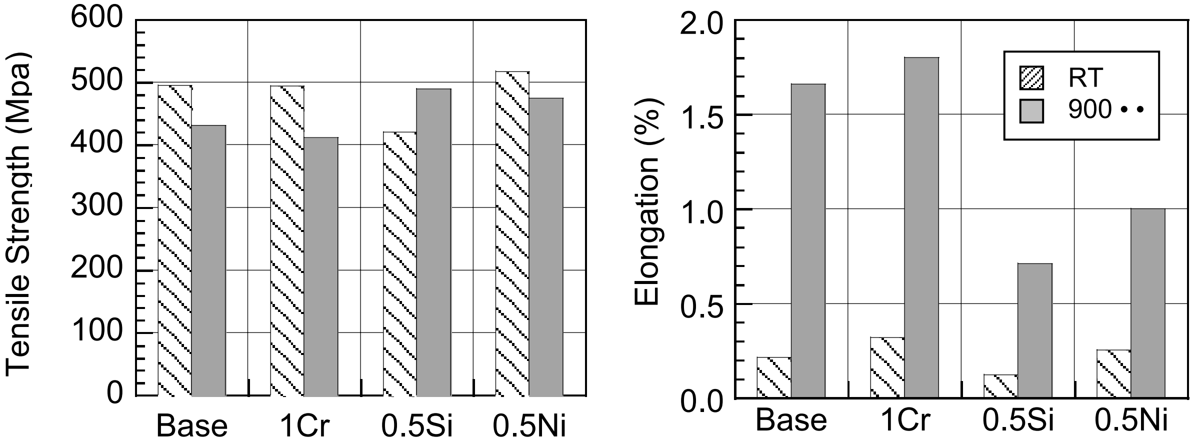

Figure 9. Tensile strength and elongation for each quaternary alloy at room temperature and at 900˚C.

3. Evaluation as a Turbine Wheel Material

3.1. Materials Testing

Figure 10 shows the cross-sectional macrostructure and backscattered electron micrographs of a turbine wheel made of the developed alloy. The microstructure is fully lamellar structure, the same as ordinary TiAl cast alloys. On the other hand, the macrostructure exhibits an equiaxial structure that differs from ordinary TiAl alloy of columnar structure. The reason for this is considered that, due to the effect of high Nb the solidification pass might be changed from conventional alloys.

Figure 11 presents the specific tensile strength from room temperature to 900˚C for the turbine wheel materials, including developed alloy, conventional TiAl alloy (low Nb), and Inconel 713C (currently most commonly used for turbine wheels). There is no particular difference between the conventional TiAl alloy and Inconel 713C, but the developed alloy exhibits greater high-temperature strength.

Figure 12 indicates the results of atmospheric oxidation testing of the same materials at 850˚C for 500h. The developed alloy shows a greater weight gain than for Inconel 713C, but only about 1/4 as much as for the conventional TiAl alloy.

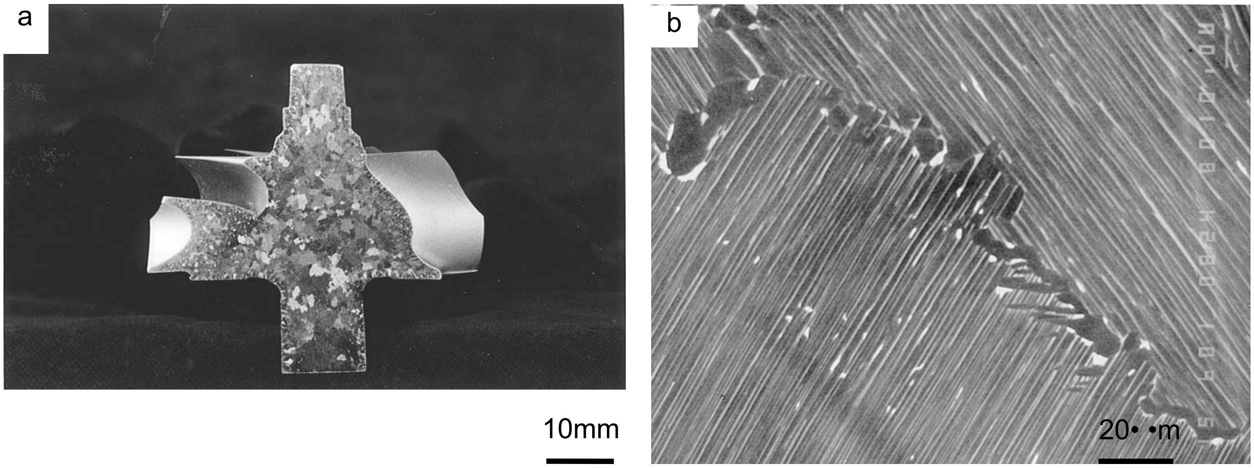

Figure 10. Cross-sectional (a) macrostructure and (b) backscattered electron micrographs of a turbine wheel made of the developed alloy.

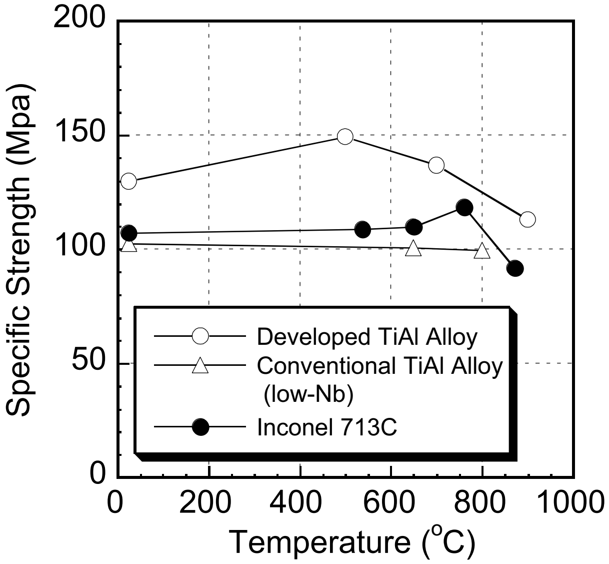

Figure 11. Specific tensile strength from room temperature to 900˚C for each turbine wheel material.

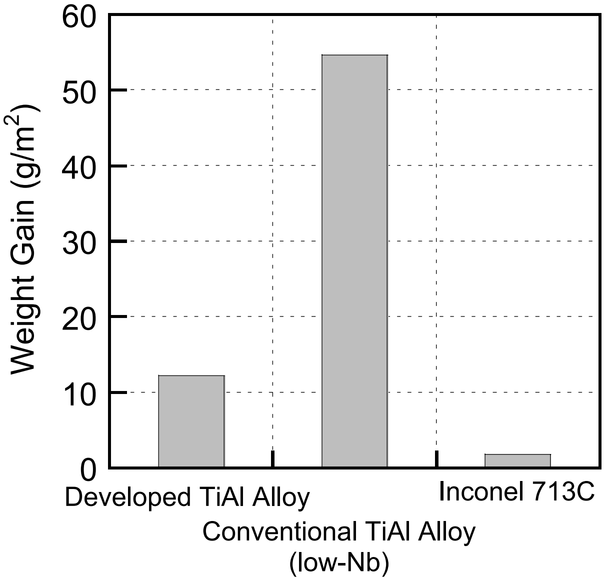

Figure 12. Weight gain for each turbine wheel material during atmospheric oxidation testing at 850˚C for 500h.

3.2. Engine Endurance Testing

Figure 13 presents a comparison of the external appearance of a turbine wheel made of the developed alloy, before and after endurance testing in a gasoline engine. After testing the blades are sound, and there is almost no change. The white scale is not oxidation scale, but rather adhesives came from the engine during testing. The results of the endurance test indicate that there are not particular endurance-related issues in the actual environment of usage.

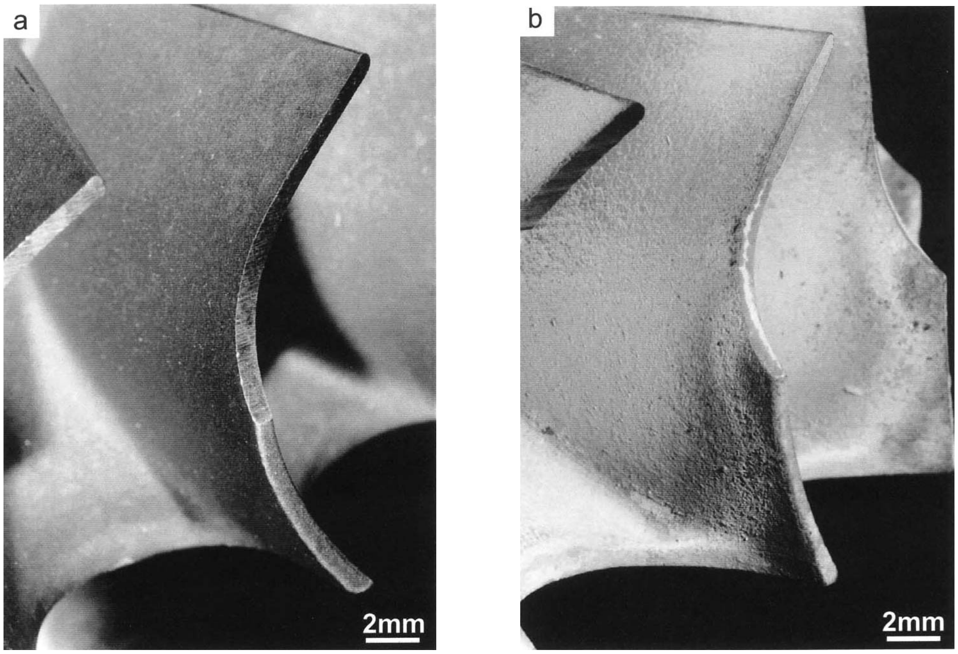

Figure 13. Comparison of the external appearance of a turbine wheel made of the developed alloy, (a) before and (b) after endurance testing in a gasoline engine.

4. Conclusions

This report reviews the development of the heat-resistant cast TiAl alloy for a turbine wheel material in commercial passenger vehicle turbochargers. The major points are summarized as follows:

(1) The inclusion of a high concentration Nb is effective in securing high-temperature strength and anti-oxidation resistance, both of which are essential for this application.
(2) Based on the properties confirmed by material testing, as well as consideration of practical issues, i.e. increased specific gravity and cost, the optimal Nb concentration is 7 at.%.
(3) Cr, Si, and Ni are effective for the improvement of the properties of high Nb TiAl alloy, and the alloy composition of the turbine wheel material, which practically applied is Ti-46Al-7Nb-0.7Cr-0.1Si-0.2Ni.
(4) The high-temperature strength and anti-oxidation resistance of this turbine wheel material are superior to conventional TiAl alloys with low Nb, amply demonstrating the effect of the higher Nb concentration.
(5) As a result of engine endurance testing, no issues in terms of endurance in the actual environment of usage were confirmed for the developed turbine wheel.

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