Development of a TiAl Turbocharger for Passenger Vehicles

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Reducing the weight of the turbine wheel is the most effective way to improve turbocharger response in passenger vehicles. No light-weight materials have the required heat-resistance and formability, however. We developed a high-performance alloy based on a light-weight TiAl intermetallic compound together with the required manufacturing technology. Its feasibility in turbochargers has been confirmed by engine tests, leading to practical application. MHI has produced high-response turbochargers using this new material, and they have been used in Mitsubishi Motors Inc. Lancer Evolution VI *automobiles since January 1999.*

1. Introduction

A turbocharger is a device in which heat energy from engine exhaust gas turns a turbine along with a compressor on the same axis, such that inflow air is pressurized by the compressor and supplied to the engine, thereby improving the engine's combustion efficiency. **Fig. 1** illustrates the structure of a typical turbocharger[1]. In order to comply with near-future environmental regulations pertaining to exhaust emissions from passenger vehicles, as well as to improve vehicle drivability, improved response has been put forth as a priority for turbochargers in recent years.

The simplest way to improve response is to make rotating parts lighter in weight, and this approach is most effective with respect to turbine wheels that make use of Ni-based superalloys (Inconel 713 C) having a specific gravity of approximately 8. However, as turbines are subject to long-term exposure to high temperature exhaust gases of at least 850℃, heat resistance is an essential prerequisite for turbine wheel materials, such that conventional light-weight metallic materials (Al or Ti-based alloys) cannot be used. Although ceramic materials, which are light-weight and heat-resistant, are being used for turbine wheels, applications are still limited due to the fact that costs remain high and the shape cannot be sufficiently optimized.

In the project reported here, a new TiAl alloy was developed together with various manufacturing technologies for turbocharger production, and the performance and endurance of the newly developed TiAl turbocharger were confirmed through numerous engine tests. Accordingly, commercial application of TiAl was achieved in a passenger vehicle turbocharger for the first time in history.

2. TiAl properties and prior development status

TiAl is an alloy based on an intermetallic compound in which Ti and Al are combined one to one. As both of the compositional elements are light-weight, the specific gravity of the resulting alloy is approximately 4. Also, as the bonding force between the atoms is strong, there is an additional advantage in that high temperature strength is substantially greater than either Al or Ti-based alloys. On the other hand, it is inferior to normal metallic materials in terms of toughness, although superior to ceramics, and can thus be considered as possessing properties in between those of metals and ceramics.

While ceramics are also endowed with light-weight and heat-resistant properties, TiAl has the advantage of fabricability using the same precision casting methods as for metallic materials. Thus, TiAl does not suffer from the cost and formability problems of ceramics, and can be positioned as a substitute material for metals in terms of making turbines lighter in weight.

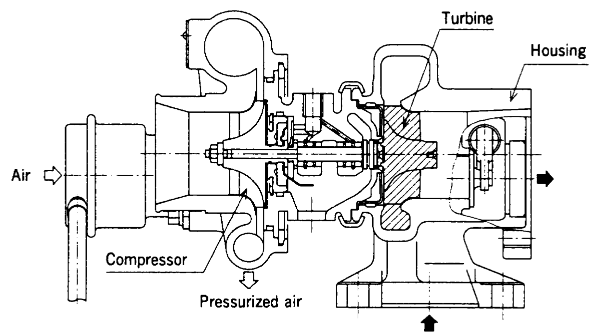

Fig. 1 Structure of turbocharger for passenger vehicles

Given the excellent properties of TiAl noted above, it has also attracted attention with respect to potential aerospace applications, and corresponding development efforts have been actively undertaken for more than a decade in the US, Europe, and Japan. A major target of this research in the US has been turbine blades for next-generation jet engines[2][3], with projects pursued by NASA and by various jet engine manufacturers, while the focus in Japan has been on passenger vehicle components such as turbochargers[4][5][6] and engine exhaust valves[7][8]. In Europe, research has been seen in both of these areas.

Several international conferences are held annually on TiAl, and over 100 papers are typically published each year. But despite this dynamic level of research activity, there have thus far been no examples of actual products in market. Reasons for this are that a) reliability for jet engine blades has yet to be sufficiently established, and b) design methods specialized to TiAl are still being developed. With respect to turbochargers, conventional TiAl alloy does not possess sufficient anti-oxidation or high temperature strength properties at temperatures of 850℃ and above, and available manufacturing technologies for casting, joining, machining, etc are insufficient for mass production.

3. Development of new high-performance TiAl alloy

The newly developed TiAl alloy includes a comparatively high-concentration Nb and various other trace elements.

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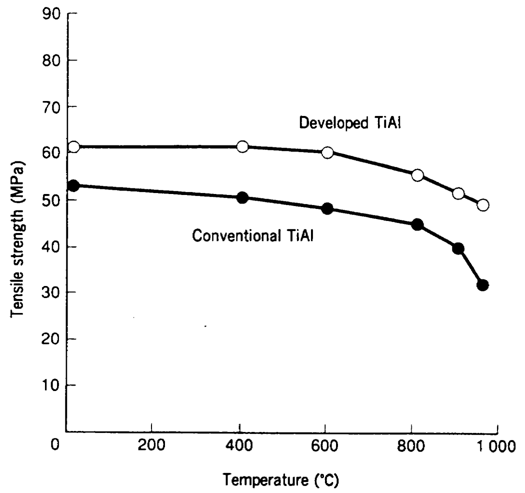

Fig. 2 Comparison of tensile strength of newly-developed TiAl and conventional TiAl

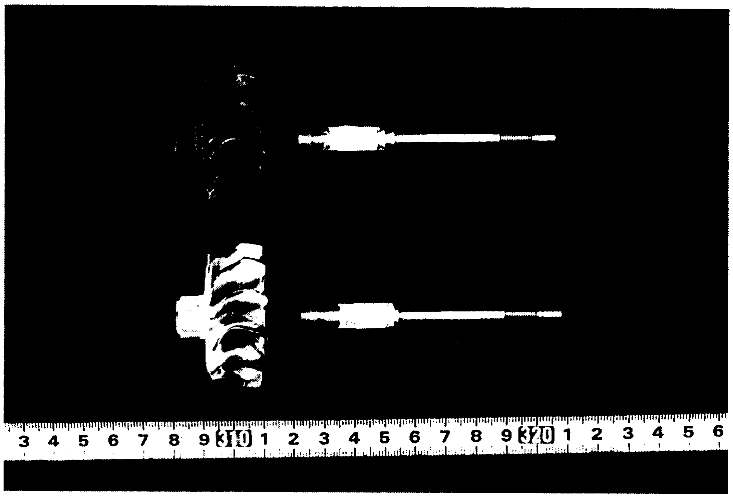

Fig. 3 External appearance of newly-developed TiAl turbine and conventional TiAl turbine after 900℃ engine endurance testing

Fig. 2 shows a comparison of tensile strength of conventional and new TiAl alloy, and the latter can be seen to be substantially stronger. **Fig. 3** presents a comparison of anti-oxidation properties as seen in the external appearance after engine endurance testing at 900℃. Conventional TiAl alloy demonstrates obvious oxidation, while the new TiAl alloy is hardly oxidized at all.

4. Development of manufacturing processes

4.1 Turbine wheel casting technology

The lost wax precision casting method was applied for TiAl turbine wheel casting, similar to the method for Ni-based superalloy turbine wheels.

4.2 Joining technology

The difference between a TiAl turbocharger and a conventional one is the material used for the turbine wheel. Accordingly, the most important technology in manufacturing of TiAl turbochargers is the joining of the turbine wheel to the steel shaft. Because the linear expansion coefficient differs greatly between TiAl and steel, the quality of the joint would deteriorate under the thermal cycle conditions characterized for turbochargers operation, if the joint were made directly. To address this issue, an insert material having a liner expansion coefficient close to that of TiAl was used. The joint between the TiAl turbine wheel and the insert material is accomplished by brazing, and that between the insert material and the steel shaft is performed using conventional EBW (electron beam welding).

The brazing is the more difficult of the two joining processes, and there were previously no methods that could secure sufficient reliability on a mass production scale. In response, investigations were made concerning the design of the joined portion, the brazing filler, and brazing conditions, and this led to the development of highly reliable brazing technology featuring almost no defects and satisfactory strength throughout the range from room temperature to high temperature. **Fig. 4** shows a TiAl turbine joined to a shaft.

4.3 Mass production

For mass production of TiAl turbochargers, a batch-type vacuum brazing method was adopted for joining the TiAl

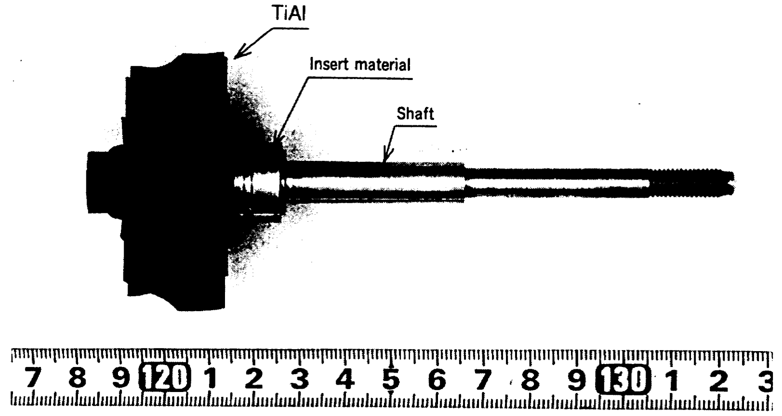

Fig. 4 External appearance of TiAl turbine

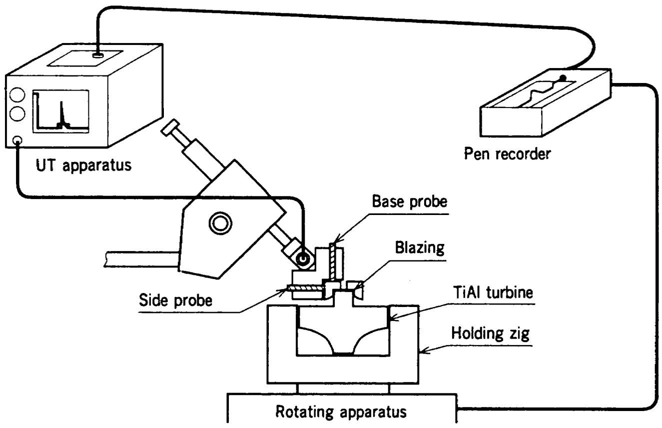

Fig. 5 Developed ultrasonic inspection system

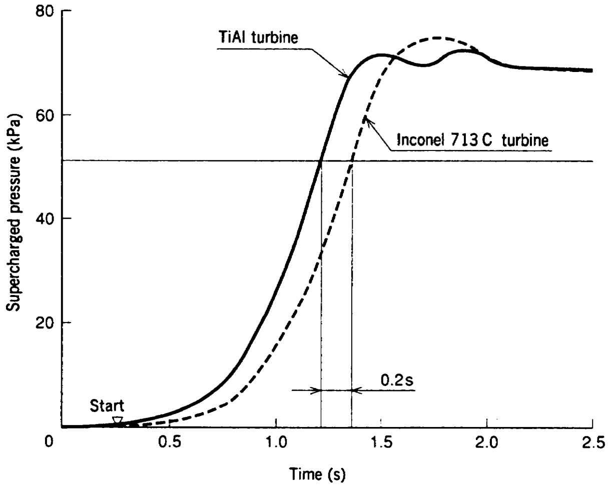

Fig. 6 Comparison of response ability of TiAl turbine and Inconel 713 C turbine

turbine wheels and the insert materials. Also, the ultrasonic inspection system illustrated in **Fig. 5** was developed in order to ensure the quality of the brazed portion. Following brazing and inspection, TiAl turbines are placed on the existing turbocharger production line, and undergo the same manufacturing processes to completion.

5. Application test

5.1 Turbocharger performance test

The performance and endurance of the newly developed TiAl turbocharger are indicated below. **Fig. 6** shows a comparison of response ability, (i.e., the original objective of this development project) for the TiAl turbocharger and for an ordinary Inconel 713 C turbocharger. The time to the requisite supercharged pressure is substantially reduced, and the effectiveness of the weight reduction of turbine wheel through the use of TiAl is clearly recognized.

5.2 Hot spin test

Fig. 7 presents the results of hot spin testing at a TIT (turbine inlet temperature) of 1 000°C. The materials used for comparison were Inconel 713 C (most widely used for turbochargers) and Mar-M 247 (special material used in racing car turbochargers). A major increase in burst tip speed was observed for the TiAl turbocharger, reflecting the excellent

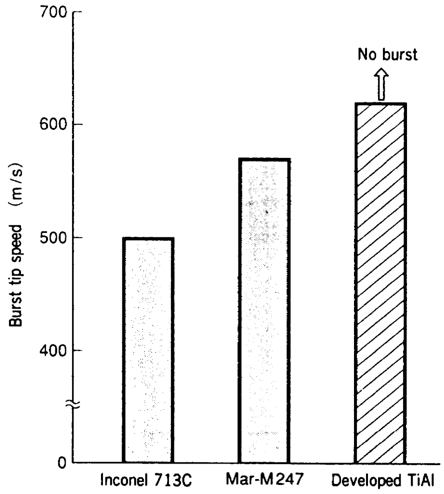

Fig. 7 Comparison of burst tip speed of newly-developed TiAl turbine and conventional metal turbines

high temperature specific strength of the new TiAl alloy. This results indicates that the new TiAl alloy should permit further enlargement of turbine diameter and/or greater efficiency (e.g. higher applied stress) in aerodynamic design, that have not been allowed by conventional metal turbines. Thus, design changes should enable higher output and efficiency during cruising operations for TiAl turbochargers, providing further advantages in addition to high response ability during acceleration.

5.3 Engine endurance tests

Engine endurance testing of the TiAl turbocharger was conducted in a gasoline engine for passenger vehicles. Endurance testing modes consisted of continuous, acceleration/deceleration, and thermal cycle operations, all of which far exceeded normal driving conditions. **Fig. 8** shows the external appearance of a TiAl turbine after gasoline engine endurance testing. It is seen to be sound, with no problems related to shape change, blade chipping, breakage, etc.

6. Practical application

The high-response TiAl turbocharger that was developed in the context of this project has been used in Lancer Evolution VI automobiles made by Mitsubishi Motors Corp., and marketed since January 1999. This turbocharger has also been adopted at World Rally Championship competitions, and contributed to victory in 1999 due to its excellent response ability.

7. Concluding remarks

TiAl, a new generation light-weight and heat-resistant alloy, which can be fabricated using the same processes as for conventional metallic materials, can be positioned as a material that fills the gap between heat-resistant metals and ceramics. Although MHI has successfully adopted TiAl for use in turbochargers, the first such accomplishment in the world, this marks only the initial stage of practical application. The properties possessed by TiAl are extremely attractive for rotating components in general, and future cost reductions are desired in order to realize other practical applications.

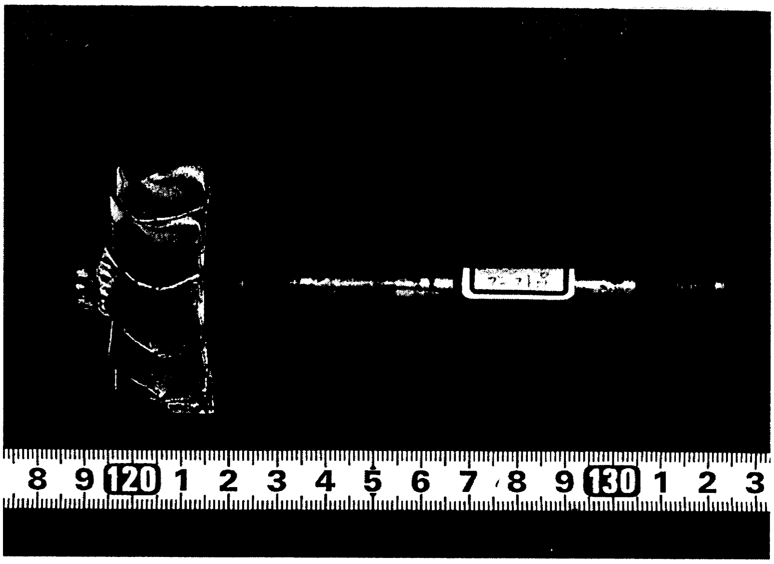

Fig. 8 **External appearance of TiAl turbine after gasoline engine endurance testing**

References

(1) Matsudaira, N. et al., Development of the TD-H Series Turbocharger, Mitsubishi Heavy Industries, Ltd. Technical Review Vol.24 No2 (1987) p.1

(2) Matsuda, K., Application of Intermetallic Compounds for Aircraft Engines, Shinsozai, No.12 (1996) p.6 (Japanese)

(3) Bartolotta, P. et al., The Use of Cast Ti-48Al-2Cr-2Nb in Jet Engines, JOM Vol.49 May (1997) p.48

(4) Nishiyama, Y. et al., Development of titanium aluminide turbocharger rotors, High Temperature Aluminides and Intermetallics, TMS (1990) p.557

(5) Tetsui, T. et al., Endurance and the Effects of Composition and Microstructure of TiAl Used in Turbochargers, Intermetallics Vol.7 (1999) p.689

(6) Tetsui, T., Gamma Ti Aluminides for Non-aerospace Applications, Current Opinion in Solid State and Material Science Vol.4 (1999) p.243

(7) Noda, T. et al., Development of a High Performance TiAl Exhaust Valve, Denki Seiko, Vol.67 No.2 (1996) p.109 (Japanese)

(8) Keller, M. M. et al., The Development of Low-cost TiAl Automotive Valves, JOM Vol.49 May (1997) p.42