Development of Lightweight Titanium-aluminide Piston Pin

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ABSTRACT

An intermetallic titanium aluminide material displaying increased fracture toughness and fatigue strength, and a process enabling the formation of the material into components, have been developed. Exploiting the material's low specific gravity and high modulus of elasticity, it was employed to manufacture a piston pin, enabling the achievement of a 17% reduction in weight and a 28% increase in rigidity against a conventional nitriding steel piston pin. The developed piston pin has contributed to increased speed, power and long-distance reliability in V10 engines, which have been required to complete two race distances since 2005.

1. Introduction

In addition to possessing high specific stiffness at the upper limit of Formula One material regulations and excellent high-temperature strength, titanium aluminide (TiAl) also displays excellent fatigue strength at ambient (or room) temperatures. For these reasons, manufacturers have been attempting to extend the use of the material to the main reciprocating components, which are the subject of a constant quest for weight savings. However, there have been concerns over the low fracture toughness and the quality of the European materials employed in engine valves(1), and other significant issues have arisen, including insufficient resources for development due to oligopolistic supply.

The aim of the project discussed in this paper was to develop an original high-quality TiAl material by balancing fracture toughness with strength, and to contribute to the achievement of increased engine speed by reducing reciprocating mass through the application of the material in piston pins.

2. Developed Technology

2.1. Material Design

In order to increase the strength and fracture toughness of TiAl, the first important step is to use an extrusion process to refine the coarse lamellar microstructure produced by ingot casting. The piston pin material must be produced at a diameter of 19 mm, and therefore necessarily possesses an insufficient extrusion ratio. For this reason, refinement of the microstructure during working was promoted by adopting a chemical composition design in which an intermetallic γ phase (TiAl), α phase (hcp-Ti), and β phase (bcc-Ti) coexist at 1150 °C, the final hot working temperature.

In addition, the exploitation of the metastable β phase in the final microstructure, which promotes strength and fracture toughness, is a factor in the achievement of increased ductility. Therefore, the chemical composition was designed to produce large quantities of the β phase material in a stable state at the annealing temperature of 1000 °C. Figure 1 shows the results of a comparison of microstructures and phase volume fractions using Thermo Calc(2).

2.2. Forming Process

A process of cold crucible induction melting and continuous casting, in which the molten developed material is solidified while being subjected to electromagnetic mixing, is used to obtain a uniform ingot microstructure.

TiAl possesses a high level of resistance to heat deformation. Stainless steel sheets are generally used for canning to control the decline in the work temperature and the material undergoes hot plastic working between 1200 °C and 1350 °C(1), (3). For the developed material, on the other hand, a dedicated antioxidant was selected.

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The use of this antioxidant in combination with a die glass lubricant reduces the material's deformation resistance, enabling hard working at an extrusion ratio of 58 at a lower temperature than specified above, between 1150 °C and 1200 °C. Refinement of the microstructure during the formation process is promoted in this range.

Finally, the material is subjected to annealing at 1000 °C for 2 hours, followed by forced cooling (Ar gas cooling) in order to obtain a β phase between 20% and 35%. By this means, stable elongation of 2% or more at ambient temperatures has been balanced with fatigue strength of 800 MPa or more (rotating bend) at ambient temperatures. Figure 2 shows the microstructure of the material (phase volume fraction) and its effect on the material's mechanical properties under each of the conditions used in the formation process.

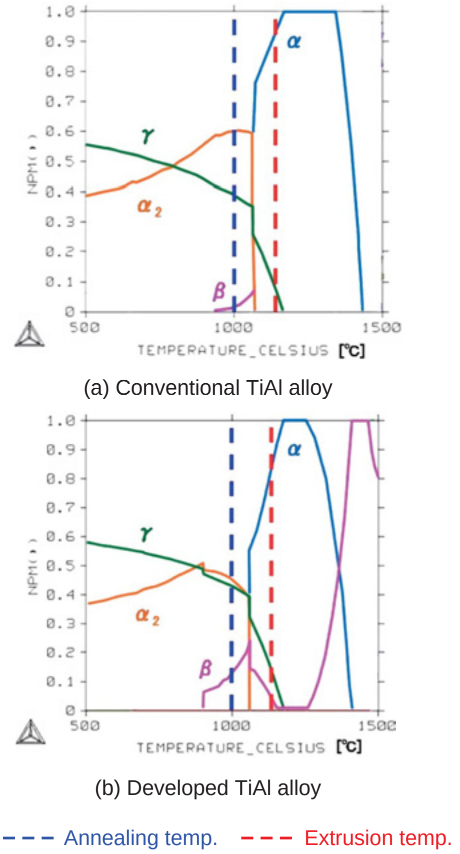


Fig. 1 Comparison of phase ratio (Thermo-Calc)

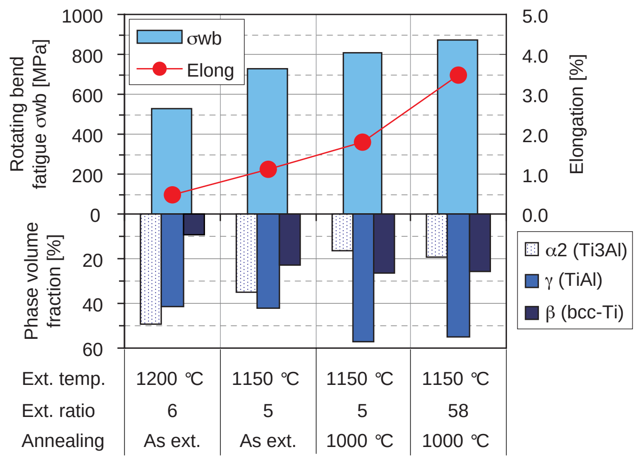


Fig. 2 Effect of phase structure on mechanical properties

3. Component Specifications

CAE and stress measurements were conducted to determine the piston pin design in view of the strength of the piston pin itself and the effect to the piston, and the component design was changed from the conventional tube type used with nitriding steel to a solid type. The solid design increased rigidity in the collapsing direction by 28% and reduced stress on the piston pin boss, which had previously represented a reliability issue, by 6%, while the application of the new material enabled the achievement of a 17% weight saving. Figure 3 shows comparison results of deformation in CAE analysis.

In addition, given the decline in hardness of the base material with the use of TiAl, a high-hardness diamond-like carbon (DLC) coating with a 7 μm Cr_2N film formed by PVD sputtering as a backup layer was employed as the surface treatment, enabling adhesion strength and scratch resistance to be increased.

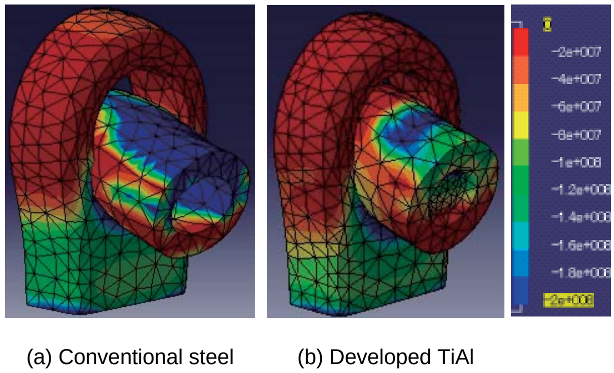
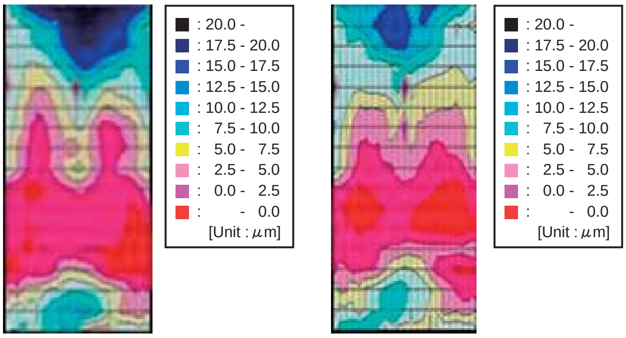


Fig. 3 Piston pin deformation (Catia V5 CAE)

4. Performance Results

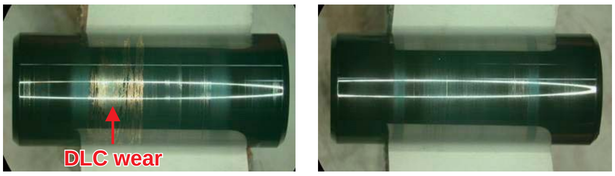
The solid TiAl piston pin was evaluated in high-load durability mode in an engine. As an effect of the achieved weight savings, the level of conrod bearing wear was equivalent to that associated with a conventional nitriding steel piston pin, even though the engine speed had been increased by 200 rpm.

In addition, the high rigidity of the developed material reduced the level of piston pin DLC wear and piston boss cracks, which had previously represented a concern in terms of reliability over long distances. Figure 4 compares the film thickness of the remaining overlay layer on the surface of conrod bearings produced using the developed and conventional materials following the endurance test. Figure 5 shows a comparison of the condition of the piston pin DLC for the developed TiAl and conventional steel following the endurance test.



(a) Conventional steel (18800 rpm/1503 km) (b) Developed TiAl (19000 rpm/1485 km)

Fig. 4 Overlay thickness of connecting rod bearing after endurance test



(a) Conventional steel (18800 rpm/1503 km) (b) Developed TiAl (19000 rpm/1485 km)

Fig. 5 DLC condition of piston pin after endurance test

5. Conclusion

Control of microstructure by means of chemical composition design and management of the formation process has enabled the development of a TiAl material that balances high fatigue strength with excellent fracture toughness (displaying an elongation of 2% or more). The use of this material to manufacture a piston pin has resulted in the achievement of a 17% reduction in weight, and has contributed to a 200 rpm increase in engine speed, and, by means of a reduction in the level of deformation of the pin, to reduced DLC wear and increased reliability in the piston pin boss section.

Acknowledgments

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