Development of Titanium Aluminide Valve

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ABSTRACT

Titanium aluminide intermetallic compound has a high specific stiffness close to 40 GPa/g·cm^3, the maximum allowed under the regulations. The material also has high temperature strength and its use in the cylinder head valves of Formula One engines has contributed to achieving higher engine speed. Vacuum annealing has been developed to try to enhance fracture toughness, and a technique has been established to prevent products with micro-cracks from being shipped if they occur during processing, by optimizing eddy current inspection technology to overcome quality issues.

1. Introduction

Titanium aluminide (below, TiAl) has a Young's modulus of 155 GPa, density of 4.05 g/cm^3 and great strength under high temperatures. Substituting with this material in cylinder head valves (below, valves) that use titanium has enabled the achievement of higher engine speed by giving them more stiffness at lighter weight. However, the fact that this material is an intermetallic compound means that valve breakage often occurs because of the low fracture toughness and the quality of production (Fig. 1), increasing the need for high fracture toughness and enhanced quality.

Valve blank is produced through a process of twice extruding with the use of vacuum arc remelting (VAR) material[1]. This blank is produced by only one company in Europe[2], and negotiations and development that include quality assurance and process sharing up to the completion of the valve have progressed in tandem with the material's application in racing engines with the aim of achieving higher engine speed.

Fig. 1 Broken valve

Table 1 Chemical composition of TiAl (atomic%)

	Al	Cr	Nb	Ta	B	Ti
2002	46.5	2.5	1.0	0.5	0.1	Bal
2003-2005	42.0	2.5	1.0	0.5	0.1	Bal

2. Development Technology

2.1. Annealing for high fracture toughness

Since 2003, materials regulations have prohibited material with specific stiffness of greater than 40 GPa, so Honda engineers have switched to a composition with less Al, as shown in Table 1. Because of electrode dripping during VAR, valves initially have a segregation structure as shown in Fig. 2, and in 2003 valves were sorted by quality based on observation of the structure of all valves. Subsequently, melting rods for VAR were shortened and a quality sorting technique was established that used samples showing structural limits.

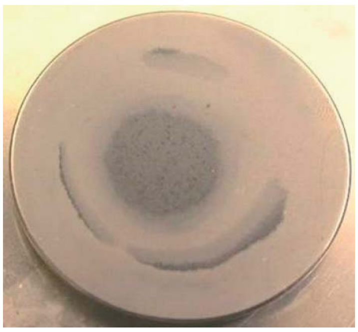

Fig. 2 Segregation structure of valve

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On the other hand, X-ray diffraction phase analysis of the material determined that the structure consisted of $\alpha 2$-phase (Ti_3Al) / γ-phase (TiAl) / β-phase (bcc-Ti). Because the β-phase is a metal phase, it contributes to fracture toughness, but the amount is very small and the valve material is made with a heated extrusion production method, so it is considered to be a semi-stable phase. Moreover, the amount of β-phase did not stabilize because of segregation and variance in extrusion conditions when producing the material.

Annealing was used to stabilize the amount of β-phase and enhance material elongation. Vacuum annealing was performed with a soaking heat treatment at 1000°C, in which the three phases of $\alpha 2 + \gamma + \beta$ exist, and subsequently the amount of β-phase was raised to more than 20 atomic% by forced cooling with argon gas. Mechanical characteristics evaluation results are shown in Fig. 3. This elongation of more than 2% at room temperatures and rotating bending fatigue strength of more than 800 MPa at room temperatures, and ensures both high strength and high fracture toughness in the valve.

2.2. Micro-crack Scanning Non-destructive Quality Assurance Technology

During the TiAl extrusion process, the material is covered with a stainless sheath. For this reason, during machining both the highly malleable sheath and the TiAl with low fracture toughness have to be planed, and there is a possibility of cracks resulting from the vibration of machining. In addition, there is residual stress in the material during the extrusion process, so it was also conceivable that cracks could occur during finishing. If there are cracks open to the surface, they can be detected by a dye penetration test such as fluorescence dye penetration, but in some cases there are cracks with compression stress that are not open to the surface, and these can slip through without being detected by dye penetration testing. As can be experienced with Co-Ni bolts, there are also cases where high-strength materials manufactured by extrusion processing experience cracks with compression stress in the grinding process.

The technology of eddy current scanning, which detects changes in eddy current where cracks exist, was optimized, and non-destructive quality assurance was conducted. Eddy current scanning is done twice: after blank machining with the sheath and TiAl removed; and after complete machining. This enhanced detection precision. The blank machining status, from which there is a certain amount of material yet to be removed, allowed detection of relatively large cracks and was effective. For eddy current scanning on valves that have completed machining, a new sensor probe was developed, positioning was done by robot arm, the gap between sensor and valve was optimized, and noise was prevented by optimizing the signal processing filter. This made it possible to detect micro-cracks 100 μm deep in actual valves, as well as detecting micro-cracks 10 μm deep in test pieces.

Figure 4 shows the appearance of eddy current scanning.

2.3. Effects

In 2002, techniques to make inlet valves lighter helped cut 6.0 g from the weight of earlier titanium valves while raising engine speed by 600 rpm, and in 2003, valves became 2.4 g lighter and engine speed 240 rpm faster.

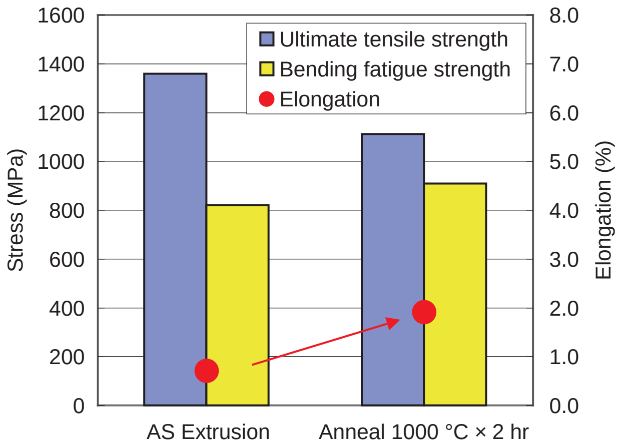

Fig. 3 Mechanical properties of TiAl

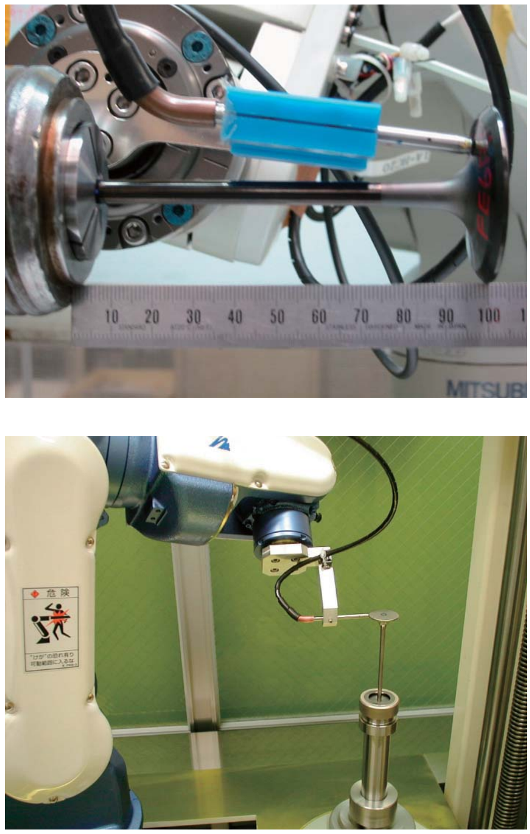

Fig. 4 Method of eddy current inspection

3. Conclusion

Using vacuum annealing heat treatment and eddy current scanning, Honda developed lightweight TiAl valves with long-distance reliability. This technology was applied to inlet and exhaust valves to help create engines able to produce higher engine speed.

References

(1) Publication of unexamined patent application, 2000-24748 (2000), Japan
(2) http://www.mwracing.eu/

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