Development of Titanium Hollow Valve and Study of Sodium-potassium Valve

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ABSTRACT

Valve specifications with the largest hollow area possible while still assuring the strength of welded areas were established, achieving a weight reduction of 4.4 g per valve, and applied to races. In addition, a high-quality oxidation resistant process was established for filling titanium valves with sodium-potassium, and technology that cools the high temperature areas of the valve by 100°C or more was developed. These cooling effects enabled expansion of the hollow area, further reducing the weight by 4.8 g per intake valve and 4.6 g per exhaust valve. Engine 2-race event durability tests were completed, but the intake valve experienced a drop in output due to the effects of sodium-potassium heat exchange, and some issues with exhaust valve durability also remained.

1. Introduction

Formula One regulations prohibited the application of intermetallics to engine parts from 2006. Therefore, the titanium-aluminum (TiAl, density 4.05 g/cm^3, Young's modulus 155 GPa) valves had to be changed to titanium alloy valves (in case of intake valve, density 4.65 g/cm^3, Young's modulus 114 GPa).

To reduce the weight and increase the stiffness of titanium alloy (Ti) valves, and increase the engine rotations, it was essential to make the valve head and stem hollow. In addition, filling Ti valves with sodium-potassium was investigated to further reduce the weight by expanding the hollow space.

2. Development Contents

Lightweight, high-stiffness Ti valves were developed by creating a hollow valve structure and establishing a technology for filling it with sodium-potassium.

2.1. Development of Hollow Valve Structure

The valve head was hollowed by drilling out the valve head, lightly fitting and electron beam welding (EBW) a plug, and performing stress-relief heat treatment.

Figure 1 shows a photograph of the valve head section. EBW was performed from the combustion side of the valve head, and melted the periphery of the plug to a sufficient depth. The heat-treated microstructure of the welded area was destroyed and the fatigue strength dropped to 30% of the non-welded area, so the residual thickness of the non-welded area was determined by valve fatigue tests to assure a parts strength equivalent to that of a solid valve head. Figure 2 shows the test results. The residual thickness requirement was set at 1.27 mm or more.

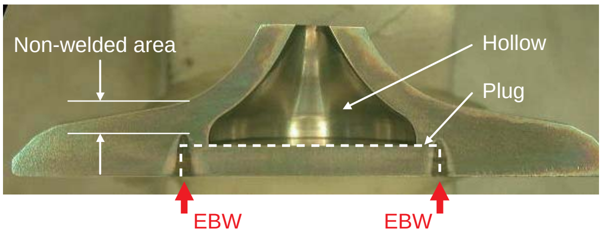

Fig. 1 Section of hollow head of intake valve

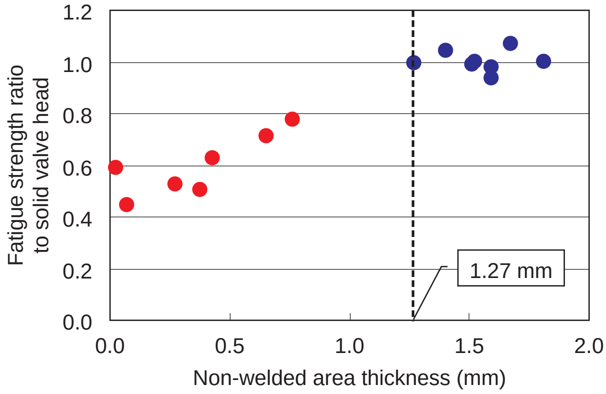

Fig. 2 Fatigue test results for welded valve head

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The valve head was hollowed to the greatest extent that satisfied the residual thickness requirement. Together with hollowing the stem, this achieved a weight reduction of 4.4 g compared to a solid valve.

2.2. Development of Titanium Sodium-potassium Valve

The sodium (Na) and sodium-potassium used as coolants are active, so they readily oxidize in air. In addition, titanium has a lower standard free energy of oxide formation than that of Na and potassium (K)(1), so when the inside of a Ti valve is filled with oxidized sodium-potassium, the inner walls of the valve oxidize and the strength drops. Therefore, a process for filling titanium sodium-potassium valves with non-oxidized sodium-potassium materials is necessary.

Figure 3 shows a photograph of the sodium-potassium exhaust valve section. The valve head and stem have a hollow structure, and the sodium-potassium is sealed by an inner plug and a stem end plug.

Figure 4 shows the sodium-potassium filling facility and filling operation. Before sodium-potassium filling, vacuum gas exchange is performed in the glove box to replace the air inside the hollow area with argon (Ar) to prevent oxygen from entering the hollow area. The oxygen density was set at 10 ppm or less. Na-78wt%K (NaK), which is liquid at room temperature, was selected as the sodium-potassium material, and the chances for contact with oxygen were minimized by filling the inside of the valve directly from the bottle via a filling nozzle. The filling amount was set at 50% of the hollow volume in consideration of fluidity inside the hollow area.

A press machine that fits the inner plug and stem end plug was located inside the glove box, and sealed the valve after NaK filling. Finally, the stem end was laser welded and completely sealed in a normal atmosphere.

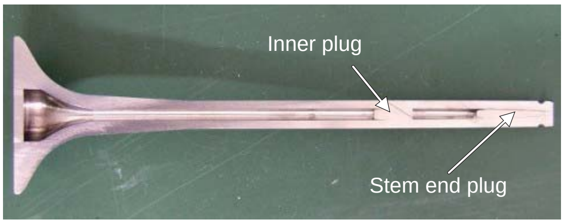

Fig. 3 Section of exhaust NaK valve

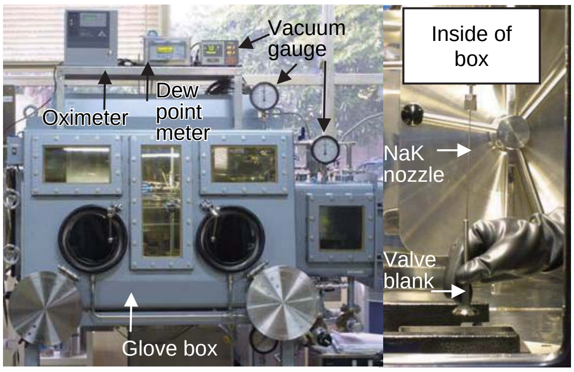

Fig. 4 NaK filling facility and filling operation

Table 1 Comparison of current and NaK valves

	Intake valve			Exhaust valve		
	Current	NaK	Difference	Current	NaK	Difference
Temperature (℃)	718	544	-174	840	737	-103
Fatigue strength (MPa)	227	615	+130%	126	211	+67%
Valve weight (g)	35.1	30.3	-4.8	32.7	28.1	-4.6

3. Engine Test Results

3.1. Temperature Reducing Effects of Sodium-potassium

To confirm the valve head temperature reducing effects, a quenched heat-resistant steel chip was embedded in the center of the valve head, and the valve temperature was estimated from the change in hardness after engine operation. Table 1 shows the results. The intake valve temperature was reduced by 174°C, which increased the material fatigue strength by 130%, enabling per-valve weight reduction of 4.8 g. The exhaust valve temperature was reduced by 103°C, which increased the material fatigue strength by 67%, enabling per-valve weight reduction of 4.6 g.

3.2. Engine Performance and Durability

Motoring head tests confirmed that the sodium-potassium intake valve increased the rotation upper limit by 500 rpm, but the output dropped by 5 kW in the dyno test. As the volumetric efficiency dropped, it is hypothesized that the valve head port side and stem temperatures rose due to the heat exchange of the sodium-potassium, which warmed the intake air and resulted in a drop in the intake air filling ratio.

The sodium-potassium exhaust valves finished a 2-race event as an engine durability test, but hairline cracks were evident in the welded area of the stem end. Since the submission deadline for engine spec homologation that would freeze the specifications was approaching and there was insufficient time to implement crack countermeasures, the exhaust valve was not applied.

4. Conclusion

(1) Valve-head welding technology was established that does not lower the parts strength, and hollowing achieved a weight reduction of 4.4 g compared to a Ti solid valve. The developed hollow valve was applied in races from the first race of 2006.

(2) A high-quality oxidation resistant process was completed for titanium sodium-potassium valves. Cooling effects of 100°C or more in high-temperature areas of the valve were confirmed, enabling weight reduction of 4.8 g per intake valve, and 4.6 g per exhaust valve.

(3) Sodium-potassium filling was confirmed to provide sufficient cooling effects. However, output dropped in some cases, and one factor for this is thought to be a drop in volumetric efficiency in the intake valve.

Reference

(1) Japan Society of Corrosion Engineering: Fusyoku bousyoku handobukku, Maruzen, p. 32 (2000) (in Japanese)

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