

Development of Lightweight Forged Piston Material by Optimizing Size of Needle-type Intermetallic Compound

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ABSTRACT

In order to produce lightweight, high-strength pistons for engines, the manufacturing process has been changed from casting to forging. However, the strength of conventionally forged aluminum alloys tends to be lower in the high-temperature region and the advantages of mass reduction have not been sufficiently achieved. Adding a transition metal to the piston material can enhance thermal stability. The specific gravity of the strengthened materials, however, becomes heavy and the formability is lessened. In order to solve these problems, the authors have developed a new piston material which was designed by dispersing a very fine-scale needle-type intermetallic compound within an Al-Si alloy. Compared to conventionally forged piston materials, this new alloy was 50% stronger at elevated temperatures while maintaining the same specific gravity. The new material has forging capabilities equal to those found in conventional materials, due to the added fine-scale intermetallic compound. As a result, we have achieved the development of a lightweight forged piston, with dramatically enhanced strength in the high-temperature region. Moreover, we can manufacture a lightweight piston without increasing costs while using a high-powered forging machine.

INTRODUCTION

The high maneuverability of super sport motorcycles is attractive to all customers, and there is a strong demand for enhancements in engine performance and reduction in body weight. Lowering the mass of the piston reduces the total weight of the vehicle and decreases the loads on the interlocking piston pin, connecting rod, and crankshaft. Reducing the mass of the piston also enables mass reduction of these other reciprocating parts and this enables downsizing of the entire engine. As the engine is downsized, the frame that supports the engine can be made narrower, further reducing the weight of the vehicle body. In addition, downsizing the engine makes it easier to optimize mass distribution, and this enhances vehicle maneuverability. In short, lowering

the piston mass is an effective way to enhance both vehicle maneuverability and engine characteristics.

In this study the authors focused upon a crystallized form of aluminum alloy intermetallic compound, and a new piston-forging material. The optimum size of the needle-type intermetallic compound was controlled by choosing the composition and amount of the transition metals. As a result, compared with conventional piston forging material, a new piston-forging alloy with the same specific gravity and 50% enhanced fatigue strength was successfully developed without spoiling forgeability. By making use of this new alloy, piston mass can be greatly reduced.

This paper describes the development technique for creating the new alloy and the mechanical properties of the new forged piston.

DEVELOPMENT OBJECTIVE

TARGET MASS FOR THE FORGED PISTON

In order to further emphasize the benefits of lightweight forged piston, it is important to express the enhancement in engine performance with specific figures. In view of past achievements with lightweight reciprocating components, $\geq 5\%$ mass reduction ratios were targeted to attain effective engine performance enhancements.

Figure 1 shows the geometries of both a cast piston and a forged piston and temperatures for each in a water-cooled engine used on super sport motorcycles. The ring groove that holds the piston ring, the pin boss that holds the piston pin in place, and the skirt that facilitates smooth sliding within the cylinder bore are parts that are required for the piston to function. When the specific gravity of the material becomes high, the mass of these essential parts increases and mass reduction cannot be properly achieved with an enhancement in the strength of materials.

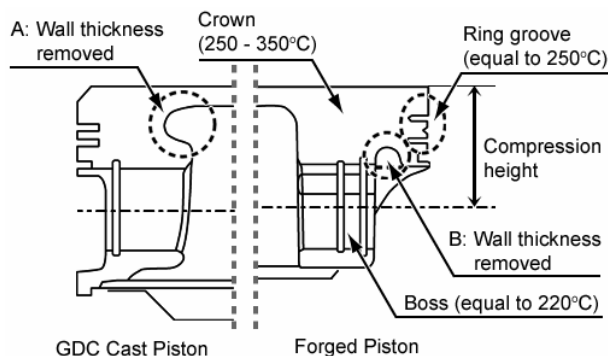


Fig. 1 Schematic illustration and temperature of GDC(Gravily die cast) and forged piston

Figure 2 shows one example of fatigue testing results on test pieces taken from the crowns of a conventional forged piston and from a cast piston. The strengthening mechanism for forged materials requires the addition of a solid solution reinforcement element such as Mg and Cu, and through precipitation hardening, which enhances matrix hardness via heat treatment ^{(1), (2)}. While a crystallization reinforcement type element, such as Fe or Ni, is not required.

Up to 250 °C, a forged piston has higher fatigue strength than a cast piston. However, since the precipitation hardening compound is transformed to coarse grain in the high-temperature range above 250 °C, the forged piston fatigue strength will suddenly fall at temperatures exceeding 300 °C.

When the engine speed is high, load inertia at the bottom of the boss becomes great. Because the temperature around the edges of the boss is below 220 °C, downsizing and mass reduction using forged material is effective.

While some components in a cast piston (Part A in Fig. 1) can be removed to achieve mass reduction, it is impossible to accomplish this in a forged piston. Therefore, with a forged piston, mass is reduced by shortening the compression height (distance from crown face to piston pin) or by removing a part of the boss during forging (Part B in Fig. 1). Because the temperature of the piston crown reaches an operating temperature of 300 °C, the crown wall thickness of a forged piston must be made thicker than that of a cast piston.

One of the most effective measures to achieve a mass reduction of more than 5% is to make the crown wall thinner. Conventionally, to make the crown wall thinner and reduce mass, it is necessary to employ a cooling system like a piston jet and spray oil from the back of the piston to lower the temperature of the crown. It is understood that enhancing the strength of the material to withstand more than 300 °C is an effective way to reduce the mass of the piston.

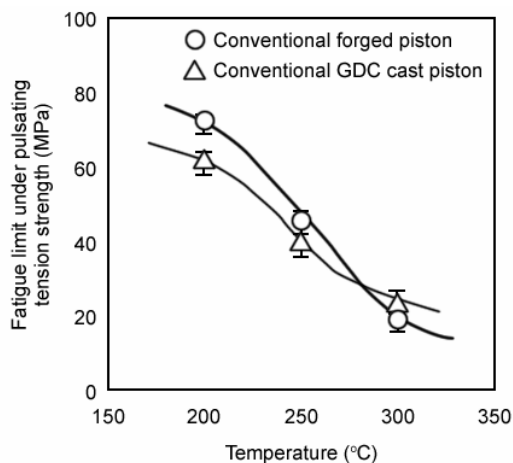


Fig. 2 Pulsating fatigue strength of piston materials tested at various temperatures (Limiting number of fatigue cycle: 1.0×10^7)

TARGET STRENGTH OF THE DEVELOPMENT MATERIAL

Figure 3 shows the effective strength of material that is required in order to achieve a 5% mass reduction, calculated using strength simulation. The most effective means of reducing mass is to make the crown of the piston thinner. To do this, it is imperative to enhance the strength of the materials in the crown, which is exposed to 300 °C during operation.

If the desired strength enhancement is more than or equal to 20% at 300 °C, and 10% at 200 °C, of what can be attained with conventional forged materials, it is understood that equivalent strength of the piston can be achieved even with a 5% piston mass reduction, and this material strength was set as a requirement.

		Conventional Piston	Lightweight Piston
CAE results F.F.= Fatigue factor			
Crown thickness		4.15 mm	3.30 mm
Piston mass		180 g	170 g
Specific strength	200 °C	1.0	1.1
	300 °C	1.1	1.2

Fig.3 Calculated strength of conventional and lightweight pistons

BREAKTHROUGH IN THE DEVELOPMENT OF A NEW PISTON FORGE MATERIAL

FEATURES OF CONVENTIONAL FORGE PISTON MATERIAL

The microstructures of a GDC cast piston (A) and a conventional forged piston (B) are shown in Fig. 4. In the microstructure of the cast piston, the needle type network-shaped intermetallic compound is crystallized on a grain boundary (Fig. 4 (A)). The billet microstructure and forged piston microstructure form spherical particles (Fig.4 (B)). With regard to the forging material, needle type network-shaped crystallization in the intermetallic compound causes failure in material toughness and cracking during the forging process.

Therefore, in many forged piston materials, the addition of a transitional metal is suppressed, such as Mg and Cu, and the methodology to enhance hardness of the matrix employing heat treatment is used. However, reinforcement employing a transitional metal is also an effective method to enhance strength to withstand more than 300 °C.

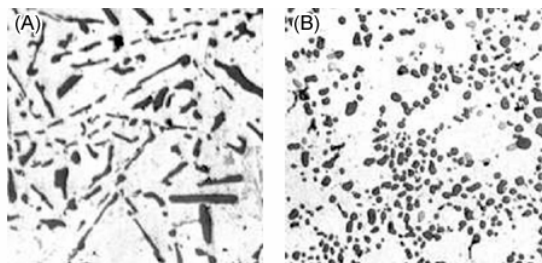


Fig. 4 Microstructures of GDC and forged pistons
(A) GDC cast piston (B) Conventional forged piston

Therefore, the addition of hardening elements like Cu, Fe, Mn, Cr, Ni, and Zr simultaneously or independently to conventionally forged piston material to produce several alloys below the specific gravity of 2.75 Mg/m³, accounts for the largest amount of piston material now being marketed. Figure 5 shows the tensile strength of the forged piston and continuous casting bars before being forged into the piston geometry.

During this examination, a constant strain tensile test was conducted at 300 °C in which a test piece was maintained at 300 °C for 100 hours. Despite the kind of alloy element employed, even if a great amount of hardening element is added to the continuous casting materials, the hardening compound is destroyed by plastic deformation during the forging process and the strength of the forged piston falls to about 80 MPa. In the alloy that produces a network-shaped microstructure, cracking occurs during the forging process. From the above, we see that even if a great amount of hardening material is added to the casting material and strength is enhanced, there is a limitation to the increased strength of the piston after forging, and there is a gain in specific gravity.

Thus, the target tensile strength of the development material before forging at 300 °C was set at 80 MPa.

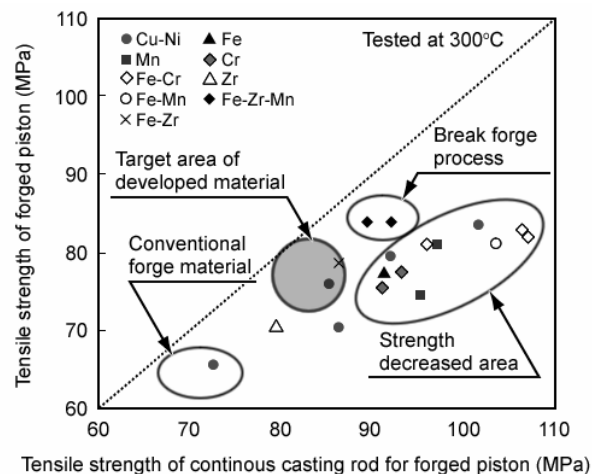


Fig.5 Tensile strength of continuous casting bar and forged piston

STRENGTHENING TECHNIQUE FOR THE DEVELOPED MATERIAL

While developing the lightweight piston material for a super sport motorcycles, an FRM (Fiber Reinforced Metal) strengthening mechanism was chosen as a technique to enhanced high-temperature strength without increasing specific gravity.

With FRM, high temperature strength can be achieved by adding high heat-resistant glass fiber to reinforce the base material. However, a special complex manufacturing process and facilities are required to produce such a composite material.

The new alloy substitutes a crystallizing needle-type intermetallic compound for the reinforced fiber in aluminum. The focus of the new alloy is on improving high-temperature strength while maintaining the same specific gravity found in conventionally forged materials by optimizing the size of the needle-type intermetallic compound, which adds a minimum amount of transition metal element.

PISTON BILLET PRODUCTION TECHNIQUE USING THE DEVELOPED MATERIAL

To obtain a uniformly dispersed microstructure of the needle-type intermetallic compound in the aluminum matrix of the piston billet, a manufacturing method that achieves a stable cooling speed is required. Because the cooling speed is slow during the GDC process, the addition of a small amount of transition metal easily crystallizes a large-sized compound. Thus, it is difficult to obtain a microstructure in which the fine-scale needle-type intermetallic compound is dispersed. The solidification speed of the DC process is very fast and the microstructure of DC is very fine. In order to obtain a very fine-scale needle-type intermetallic compound, large amount of transition metal are added to the alloy.