

Development of High-strength Piston Material with Die Casting

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ABSTRACT

The pistons are an essential element in the achievement of greater engine efficiency. A method of increasing the strength of the material employed in pistons to respond to increased thermal and mechanical loads and reducing weight has been developed to contribute to the quest for enhancements in power and fuel economy.

This method is used in the die cast production process, which has a rapid rate of cooling. The limit for addition of Ni to the aluminum alloy employed has been increased to 5.5 mass%. At the same time, less than 0.4 mass% of Fe is added and the Mn/Fe ratio is controlled to less than 0.6 in order to limit the coarsening of the crystals. This technique has increased the high-temperature fatigue strength of the material by more than 1.5 times against the material conventionally employed. In addition, the uses of die vacuum and additional pressure have enabled quality exceeding that of conventional GDC pistons.

Optimization of the piston shape to match the characteristics of the new material has resulted in decreasing engine friction by 4.4% and increasing fuel efficiency by 2.2% in engine bench testing.

1. Introduction

In response to increasing demand for more environmentally responsible automobiles, Honda has worked to develop engines with greater fuel efficiency and lower emissions, such as the i-Series of next-generation power plants⁽¹⁾⁻⁽⁴⁾. The demand is growing for pistons that are lighter and capable of withstanding greater thermal and mechanical load, which in turn requires piston materials with better high-temperature strength.

A method of adding Cu, Ni, Fe, Mn, or some other elements that enhance heat resistance, to the AC8A aluminum alloy base has been used to increase the high-temperature strength of piston material. However, in the case of Gravity Die Casting (GDC), the

method used for the majority of pistons, there are limits to the amount of such elements that can be added to the materials due to the low cooling rate of casting, which causes intermetallic phases to form large crystals. To speed cooling, some manufacturers use a powder forging process for two-cycle engine pistons, which are examples of increasing strength by greater quantities of additive elements⁽⁵⁾. However, this method has yet to be adopted for automobile pistons because of several issues related to reliability and cost, such as oxide films formed by the powders, impurities, strength anisotropy (which results from metal flow during forging), and the complexity of fabrication procedures such as quality control.

On the other hand, automobile manufacturers in Europe and Japan^{(6),(7)} are increasingly using die casting for chassis components

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and other aluminum parts; some are even using vacuum die casting for subframes to enable welding. Consequently, die casting technology and the quality of die cast components have advanced considerably in recent years. Since die casting's cooling rate is higher than that of GDC, greater amounts of additive elements can be added due to the rapid cooling effect. Nevertheless, the application of die casting to pistons is limited to general-purpose engines, in which case the technique is used to increase productivity⁽⁹⁾; there are no reports of applications in which the goal was greater piston strength.

Recently, a high-strength piston material with die casting that offers enhanced high-temperature strength without significant cost increases has been developed and, moreover, is now used in the mass-production of automotive pistons. This paper discusses microstructure control used for the new material, its enhanced strength, the high-quality pistons made with the material, and the benefits of using the pistons in engines.

2. Development Goals and Strategy for Achieving Goals

2.1. Development Goals

The primary functions of a piston are to form part of the combustion chamber and to transmit the pressure and heat of combustion. The important material properties are therefore high-temperature strength, abrasion resistance, fracture toughness, Young's modulus, thermal conductivity, and the coefficient of thermal expansion. The goal in developing the new material was to achieve a fatigue strength of at least 1.5 times greater than that of Honda's high-strength material made by GDC in the high-temperature range of 523 K and above (which is the operating environment for the piston materials). Another goal was to achieve casting quality comparable to or better than that of GDC pistons in order to assure the durability that is required of pistons.

2.2. Strategy for Achieving Goals

The piston material exhibits a complex microstructure comprising an aluminum matrix phase with elements such as Cu or Mg in solid solution (the α phase), Si particles and intermetallic phases consisting of crystallized intermetallic products of Ni, Fe, Mn, among others. High-temperature environments of 523 K or greater cause considerable softening of the α phase, from which cracking tends to originate due to stress loading. Increasing high-temperature strength therefore necessitates protecting the α phase by increasing the quantity and micro-dispersion of the crystallized material. Figure 1 shows a schematic of the target microstructure sought for this material.

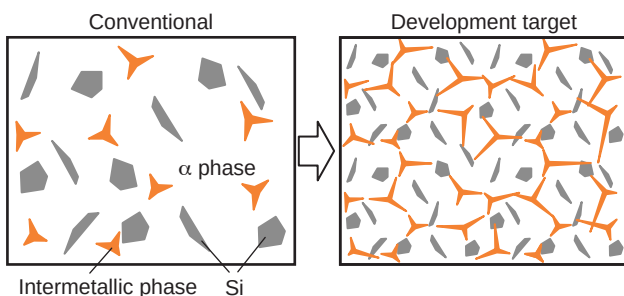


Fig. 1 Schematic microstructures of conventional material and developmental target

Nickel was thought to be a candidate additive material (i.e., to add in greater quantities) because of its large solubility⁽⁹⁾ during quench, low diffusion coefficient in aluminum⁽¹⁰⁾ (an indicator of heat resistance), and low electrical resistivity (an indicator of thermal conductivity)⁽¹¹⁾. The increase in strength and microstructure resulting from greater amounts of Ni for GDC and other techniques are shown in Figs. 2 and 3, respectively. As the figures show, greater amounts of Ni in the case of GDC result in larger crystals and only a slight increase in strength, whereas with die casting, the greater micro-dispersion of the crystals increases strength significantly. It was therefore decided that the strategy would be to increase the quantity of Ni and use die casting in order to increase the high-temperature strength of the piston material. From this strategy, the detailed specifications were determined.

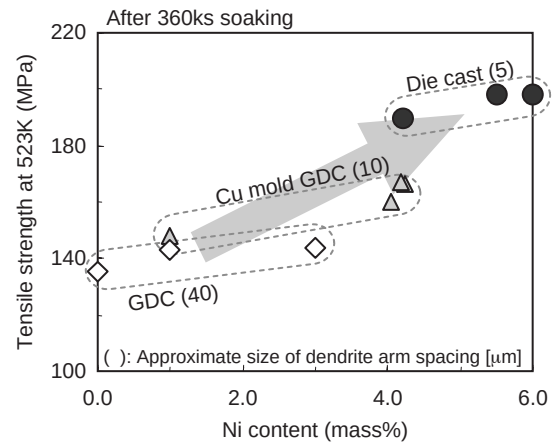


Fig. 2 Effect of Ni on tensile strength in various manufacturing processes

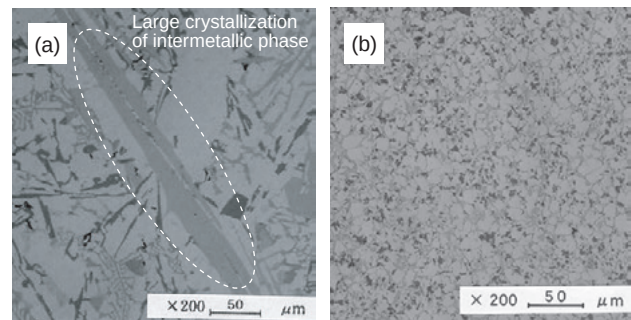


Fig. 3 Microstructures of (a)GDC-Ni 4mass% added and (b)Die cast-Ni 6mass% added

3. Method of Experimentation

Because die casting requires considerable time for determining the casting plan, die fabrication, and determining casting conditions, the following procedure was followed to determine the detailed specifications.

- (1) A wedge-shaped specimen is fabricated by GDC to determine the correlation between microstructure at the time of quenching and Ni amount added. This determines the basic components.
- (2) A simplified piston-shaped specimen (simplified piston) is die cast to determine material properties.
- (3) An actual piston is die cast to determine quality.

3.1. Determining the Basic Components of the Wedge-shaped Specimen

Alloy samples consisting of Al-12%Si-4%Cu-1%Mg as the base alloy and Ni ranging between 4.5% and 6.0% (all mass%) were prepared for determining the maximum amount of Ni that can be added during quenching. Fe, which is believed to have good affinity with Ni crystals, was ranged between 0.2–0.5 mass% to determine the element's effect on crystallization. In addition, since Mn is known to modify the shape of Al-(SiFe) plate crystals⁽¹²⁾, samples were prepared with an Mn/Fe ratio of 0.2 to 1.0 to investigate this effect.

The wedge-shaped specimens were fabricated with a molten-metal temperature of 993 K and a die temperature of 343 K. The microstructure was observed with a metal microscope at the thickness which corresponds to the cooling rate of an actual die-cast piston. Vickers hardness testing was also performed to determine the microstructure's effect on strength. Figure 4 shows a schematic diagram of the wedge-shaped specimen.

3.2. Determining the Material Properties of the Simplified Piston

Table 1 lists the composition of the experimental alloy and a conventional alloy used for comparison. A simplified piston made of the experimental alloy was fabricated with a 350-ton die cast machine at a molten metal temperature of 973 K, a casting pressure of 80 MPa, and a gate speed of 80 m/s. After T5 heat treatment, a 10-mm-thick sample was taken from the crown of the simplified piston. The conventional alloy was cast into a JIS4 boat shape with a molten metal temperature of 1 023 K and a die temperature of

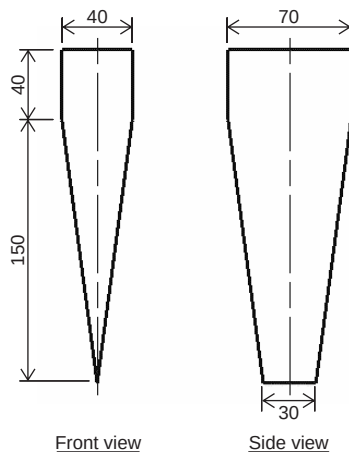


Fig. 4 Schematic diagram of wedge specimen

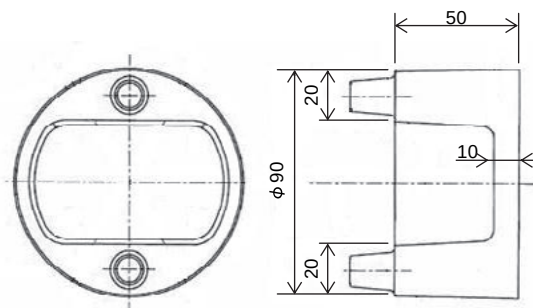


Fig. 5 Schematic diagram of temporary piston

Table 1 Chemical composition of experimental alloy for die cast and conventional alloy for GDC

	(mass%)					
	Si	Cu	Ni	Mg	Fe	Mn
Experimental alloy	12.4	3.9	5.4	1.0	0.4	0.2
Conventional alloy	12.6	4.8	1.0	1.0	0.1	–

Table 2 Test methods and temperature conditions

	Method	Temperature (K)					Soaking time
		R.T.	473	523	548	573	
Tensile strength	JIS Z2241		○	○		○	360ks
Fatigue strength	Push-Pull servo pulser		○	○		○	
Abrasiveness	Abrasion tester			○	○	○	360ks
Young's modulus	JIS Z2280	○					
Thermal conductivity	JIS R1611			○			
Thermal expansion	TMA			○			
Notch fatigue strength	Push-Pull servo pulser			○			

593 K. After T7 heat treatment, a sample was taken from the bottom at the 10-mm point. Measurements were taken at multiple temperatures, and averages were calculated for tensile strength, fatigue strength, hammer abrasiveness, Young's modulus, thermal conductivity, coefficient of thermal expansion, and notch fatigue strength. The simplified piston shape is shown in Fig. 5, the test methods and temperature conditions in Table 2.

3.3. Determining Quality of the Actual Piston

Taking the die cast method into account, thickness at various points on the actual piston was altered based on the piston for a 1.3-L engine; the resultant shape is shown in Fig. 6. The experimental alloy had the composition listed in Table 1 and was formed into the piston using a 250-ton die cast machine with a molten metal temperature of 1 003 K, a casting pressure of 95 MPa, and a gate speed of 80 m/s. To assure high quality, a vacuum to the die cavity and additional pressure were applied.

Liquid penetrant inspection and porosity rate were measured as indicators of internal quality. Porosity rate χ (%), indicator for the space ratio inside the piston, was calculated from theoretical density ρ_r (g/cm³) and actual density ρ_a (g/cm³) using Equation (1):

$$\chi = \frac{(\rho_r - \rho_a)}{\rho_r} \times 100 \quad (1)$$

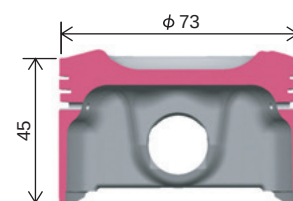


Fig. 6 Schematic diagram of piston

Instead of theoretical density, which is difficult to calculate, this study used the density of a specimen sample obtained by the Ransley method, which is considered to have a low probability of resulting in blowholes.

4. Results and Analysis

4.1. Microstructure

4.1.1. The effect on microstructure by the quantity of added Ni and Fe

Figure 7 shows the correlation between amount of added Ni and Fe and the occurrence of large (>100 μm) crystals in the microstructure. At 4.5 mass% Ni, the desired microstructure, with no large crystals, is observed up to 0.5 mass% Fe. When the amount of Ni increases, the relative amount of Fe that forms large-crystals decreases. At 6.0 mass% Ni, some large crystallization is seen even at 0.2 mass% Fe.

The reason that Fe effects large crystallization is believed to be that Fe is substituted in the Al-Ni crystals, altering the Al-Ni to Al-(NiFe) crystals, thereby promoting large crystallization. A binary phase diagram for Al-Ni indicates that its eutectic point is roughly 5.7 mass%. In view of the danger of primary crystal formation and crystallization due to Fe substitution, Ni and Fe content should not exceed 5.5 mass% and 0.4 mass%, respectively.

4.1.2. The effect on microstructure by the quantity of added Mn

The microstructure and hardness of specimens with varying Mn/Fe ratios were examined in anticipation that the effectiveness of Mn in modifying the shape of Al-(SiFe) plate crystals, as stated in Section 3.1, would manifest itself in Al-(NiFe) crystals. Figure 8 shows the results. Contrary to expectations, a higher Mn/Fe ratio resulted in larger crystals and lower Vickers hardness.

To determine Mn distribution, the component elements of the large crystals were analyzed with an Electro-probe X-ray microanalyzer. Figure 9 shows the results. It was revealed Mn substitution is seen in Al-(SiFe), Al-Fe, and Al-(NiFe) crystals,

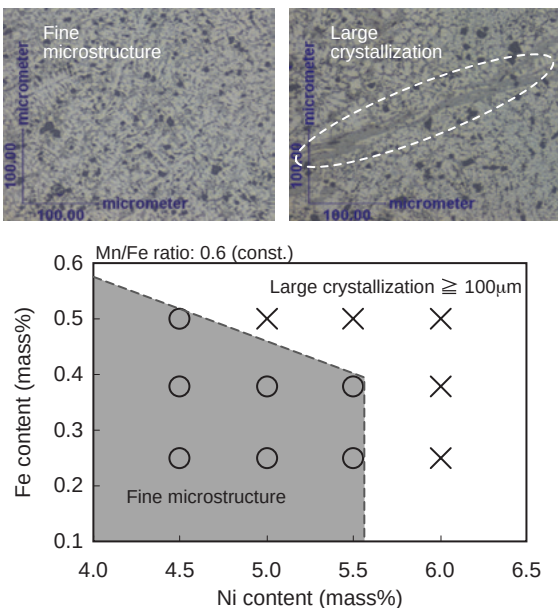


Fig. 7 Effect of Ni and Fe content on microstructure

Table 3 Chemical composition of developed alloy

	Si	Cu	Ni	Mg	Fe	Mn
Developed alloy	13	4	5	0.8	0.4	≤ 0.2

and some Al-(SiFe) integrated with Al-Fe lumps due to the Mn substitution, but it was found that Mn substitution caused Al-(NiFe) to form large plate crystals.

The preceding suggests that the decrease in hardness due to the addition of Mn in a high-Ni alloy containing Fe is because Mn promotes the formation of large Al-(NiFe) plate crystals, reducing the amount of micro-dispersed crystals. Although the mechanism by which Mn affects the various crystals is a subject for further research, the results of this study suggest that the Mn/Fe ratio should not exceed 0.6.

4.2. Basic Composition Determined in This Research

In view of the results detailed in Section 4.1, the following composition was decided for the new alloy: 5.0 mass% Ni, 0.4 mass% Fe, and 0.2 mass% or less Mn. Table 3 shows chemical composition.

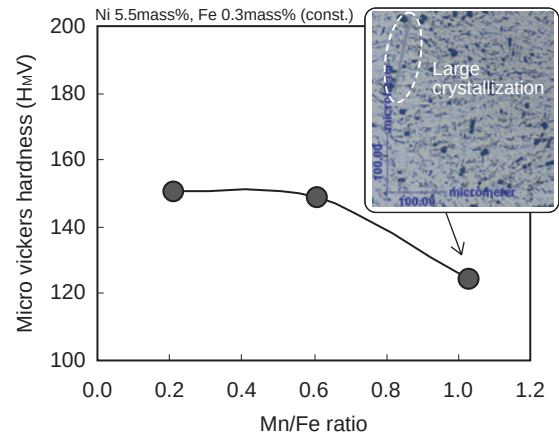


Fig. 8 Effect of various Mn/Fe ratios on microstructure and hardness

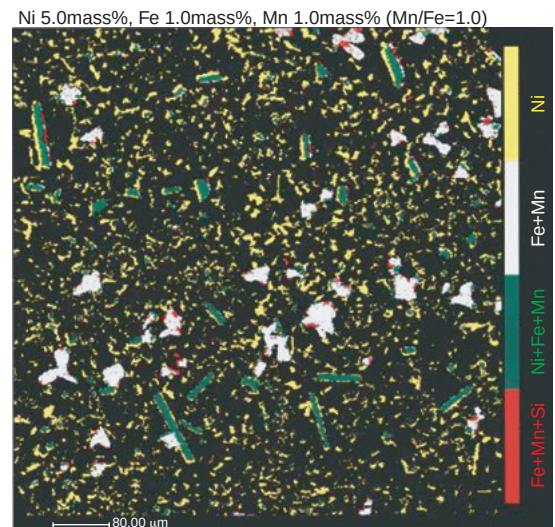


Fig. 9 Photograph of EPMA element mapping

4.3. Material Properties

4.3.1. High-temperature strength

Figure 10 shows testing results for tensile strength and fatigue strength. The new material achieved the goal for fatigue strength by exhibiting 1.5 and 1.8 times the fatigue strength of the conventional material at 523 K and 573 K, respectively.

4.3.2. Ring groove abrasiveness

Figure 11 shows the results of hammer abrasion testing. The new material exhibited one-sixth of the abrasion of the conventional material at 523 K. This is possibly because the lower surface area of the aluminum substrate, due to the addition of Ni, delays the onset of microwelding and lessens the softening of the material at high temperatures. Figure 12 compares the microwelding onset time and softening of the new material and of the conventional material.

4.3.3. Fracture toughness and physical properties

Figure 13 gives the test results for notch fatigue strength, Young's modulus, coefficient of thermal expansion, and thermal conductivity. Although the new material's notch fatigue strength increased by a factor of only 1.2 over the conventional material, which is less than the increase exhibited by the unnotched test piece, it did demonstrate sufficient fracture toughness. Young's modulus and the coefficient of thermal expansion were 16% higher and 6% lower, respectively. Nickel has been known to greatly enhance these properties^{(13), (14)} and apparently performed the same function in this material. Although thermal conductivity was 11% lower compared to the conventional material, Computer Aided Engineering (CAE) predictions of temperature increase indicate that this would entail an increase of only 5 K over the conventional material. This, in addition to the absence of any observed decrease in knocking properties in an actual engine, suggests that the material possesses the properties required for pistons.

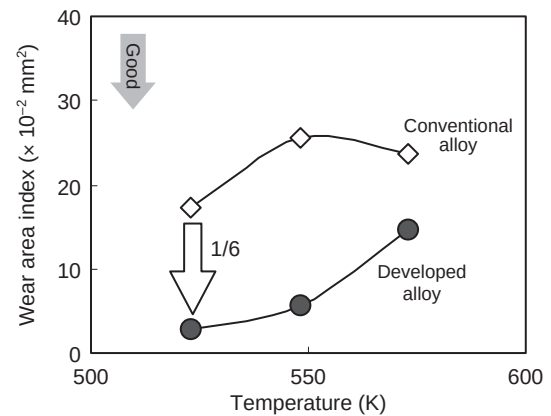


Fig. 11 Abrasiveness

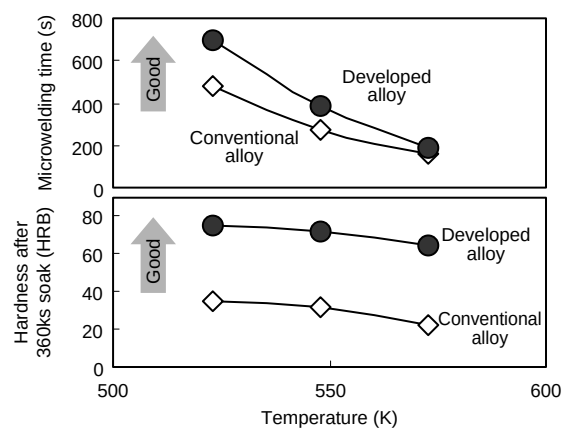


Fig. 12 Comparison of microwelding time and hardness

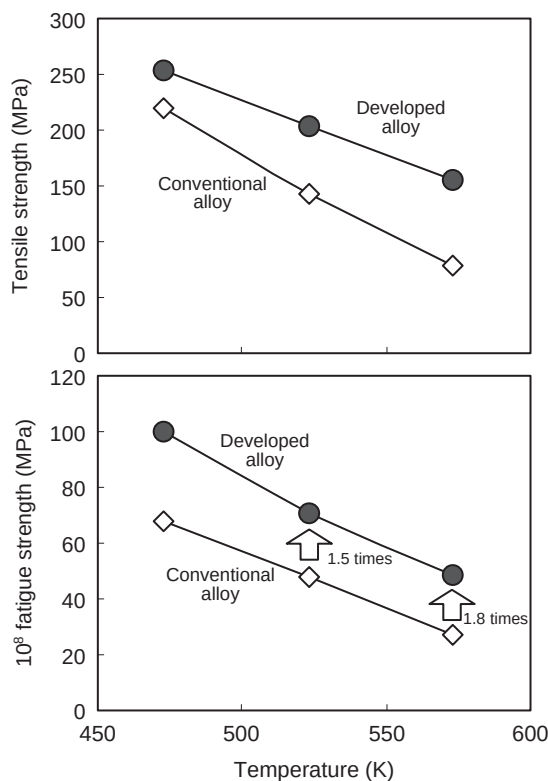


Fig. 10 Tensile and fatigue strength

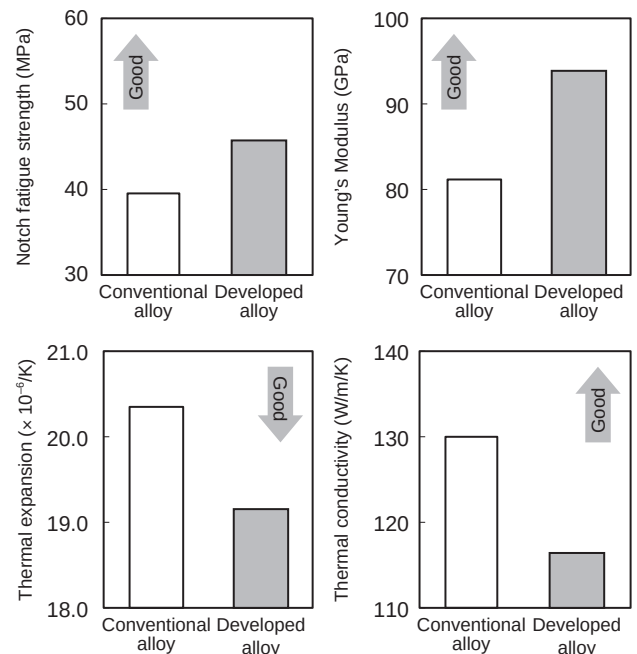


Fig. 13 Notch fatigue strength and physical properties

4.4. Casting Quality

Figure 14 shows the increase in quality made possible by the use of vacuum and additional pressure. With die casting, internal blowholes caused by the infusion of air are often an issue, but the application of vacuum and additional pressure have made it possible to achieve porosity rates lower than those of GDC pistons. Additional pressure has a greater porosity-lowering effect than vacuum, indicating the importance to compensate solidification shrinkage in die casting.

With regard to the sludge, oxide film, and scattered chill structure that occur during melting or injection of the molten metal, high quality was achieved by optimizing the casting plan, molten metal treatment, the type of plunger sleeve material, the amounts of mold release agent and sleeve lubricant, among others.

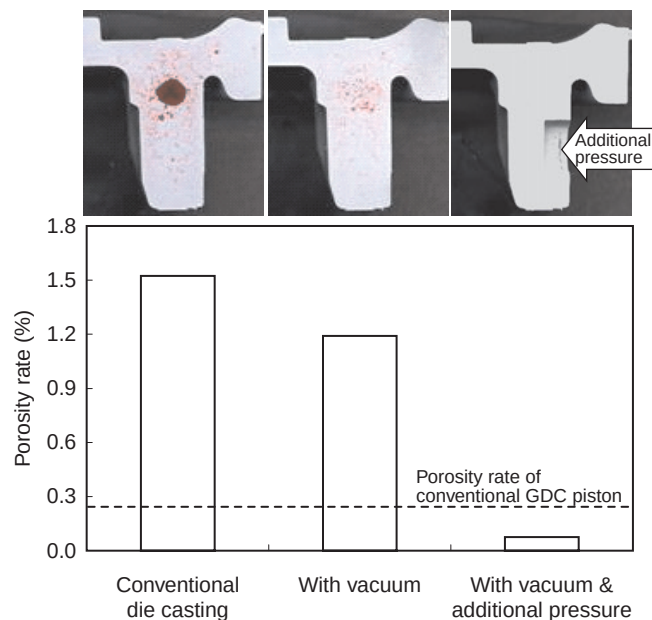


Fig. 14 Effect of vacuum and additional pressure on casting quality

5. Effectiveness in Actual Piston Application

5.1. Basic Piston Specifications

Table 4 lists the basic specifications of the piston made with the new material. The engine selected was one designed for optimum fuel efficiency. Using CAE, the shape of each part of the piston was optimized for minimum friction without sacrificing durability. An example of surface pressure distribution on the piston skirt, optimized with three-dimensional piston dynamics calculations, is shown in Fig. 15.

5.2. Application Effectiveness

Friction and fuel-efficiency measurements of the piston described in Section 5.1 are given in Fig. 16. In engine bench testing, friction was 4.4% lower and fuel efficiency was 2.2% higher.

Table 4 Specifications of developed piston

	Conventional piston	Developed piston
Diameter (mm)	73	73
Compression height (mm)	26.2	26.2
Crown thickness (mm)	5.2	4.5
Land height [top/2nd/3rd] (mm)	5.55/3.0/2.5	5.55/3.0/2.5
Skirt width x height (mm)	34 x 29.5	38 x 29.5
Skirt thickness [skirt/side wall] (mm)	2.0/3.5	2.5/3.45
Piston weight (g)	207	205
Piston shape		
Specific power of applied engine (kW/L)	47.1	52.3
Top ring material/Outer surface treatment	Carbon steel/Hard chromium plating	Carbon steel/Ion plating

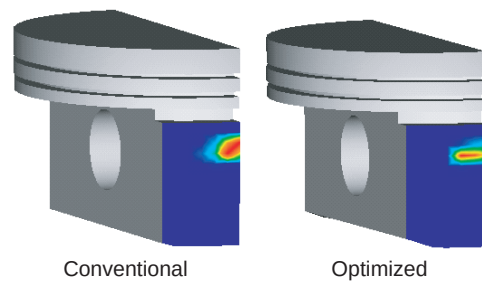


Fig. 15 Three-dimensional piston dynamics calculation

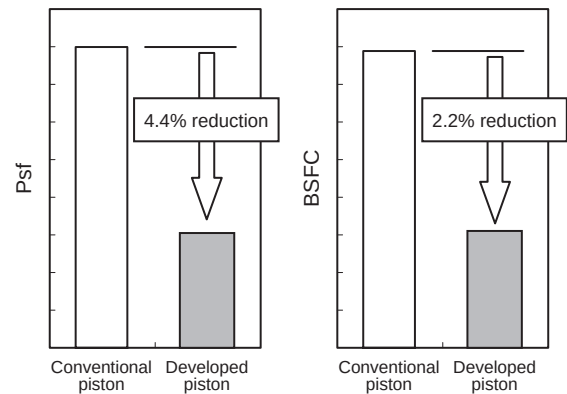


Fig. 16 Effect of developed piston on brake specific fuel consumption (BSFC) and friction loss (Psf)

6. Conclusion

The technology for a new, high-strength piston material was developed by using die casting to raise the limit of Ni that can be added to aluminum alloys. The conclusions obtained in this development are as follows.

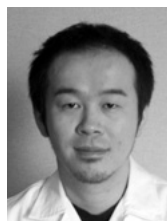
- (1) Using the die casting method allowed the amount of Ni added to be increased to 5.5 mass%, raising the fatigue strength of the new material at temperatures of 523 K or higher by a factor of 1.5 over a conventional material made by GDC.

- (2) The amounts of Fe and Mn added must be controlled to prevent large crystallization: Fe added must be kept within 0.4 mass%, and the Mn/Fe ratio to within 0.6.
- (3) Application of vacuum to the die cavity and using additional pressure enabled quality exceeding that of conventional GDC pistons.
- (4) Pistons made with the new material decreased engine friction by 4.4% and increased fuel efficiency by 2.2% in engine bench testing.

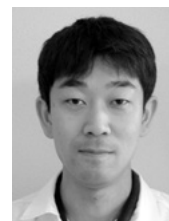
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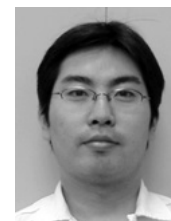
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