

Development of Lightweight Forged Piston Material by Controlling Needle-type Intermetallic Compound Size Using Carbon Mold Continuous Casting Method

Hidenori FUJII*

Tomoo OKA*

Masaki YONEYAMA*

Toshiaki DEGUCHI*

Hirotaka MURAKAMI*

ABSTRACT

The addition of transition metals to piston materials is an effective method of increasing their strength at high temperatures. However, the addition of transition metals increases specific gravity and promotes the crystallization of coarse intermetallic compounds, reducing forgeability. To respond to these issues, a new piston material has been developed in which the type and amount of the added transition metals and the size of the crystallized intermetallic compounds has been optimized. In order to control the size of the intermetallic compounds, the material is not produced by conventional metal mold casting, but by a carbon mold continuous casting method that enables a fine and uniform structure to be obtained. The optimization of the elements forming the intermetallic compounds and the quantity of these elements added, in addition to the addition of refining elements, to enable dispersion of needle-type intermetallic compounds throughout the alloy, has resulted in the achievement of levels of specific gravity and forgeability similar to those of a conventional forged piston material, while increasing strength at high temperatures by approximately 50%.

1. Introduction

Heat treatments are applied to forged piston materials such as A4032 in order to exploit the precipitation strengthening mechanism and help to further ensure strength. However, one issue has been the fact that the coarsening of precipitated compounds at around 300 °C results in a decline in strength. To respond to this issue, cooling mechanisms such as oil jets have been employed to reduce the temperature of the crown of the piston, but the higher power of modern engines has placed limits on the degree of cooling achieved using oil jets, and high strength at temperatures of around 300 °C is essential in order to achieve weight savings in the piston crown.

The project discussed in this paper developed an aluminum forged piston material that displayed equivalent specific gravity and forgeability to conventional materials while achieving increased high-temperature strength, by promoting the dispersion of needle-type intermetallic compounds of 3-30 μm in diameter through the aluminum matrix. The new material has helped to enable the achievement of a reduction in piston mass. This paper will discuss the issues associated with conventional forged

piston materials, the control of the microstructure of the developed material and the resulting increase in strength, and the characteristics obtained in the developed material.

2. Method of Development of Forged Piston Material

2.1. Method of Strengthening Developed Material

Table 1 compares the composition, specific gravity, size of intermetallic compounds, and method of piston manufacture for the developed and conventional piston materials. Figure 1 shows schematic diagrams of the microstructures of the conventional (A) and developed (B) piston materials. The precipitation strengthening mechanism^{(1), (2)} has been employed in order to increase high-temperature strength at temperatures of 250 °C and below in the conventional piston material, and the crystallization of intermetallic compounds has been controlled in order to help prevent a decline in material characteristics due to the coarsening of the compounds. In the project discussed here, the strengthening mechanism employed was dispersion strengthening that made direct use of the intermetallic compounds in order to achieve

* Motorcycle R&D Center

Table 1 Chemical composition, specific gravity, size of intermetallic compound and continuous casting mold of conventional forged piston and developed forged piston

	Chemical composition (mass%)								Specific gravity	Size of intermetal. compound (μm)	Continuous casting mold
	Si	Mg	Cu	Ni	Fe	Zr	Ti	Al			
Developed forged piston material	12	1	1	2	0.6	0.1	0.1	Bal.	2.70	Ave. 8 (3 - 30)	Graphite mold
Conventional forged piston material	12	1	1	1	–	–	–	Bal.	2.69	0	Metal mold

increased high-temperature strength at temperatures of around 300 °C. The issues associated with the dispersion strengthening mechanism are controlling the weight and the size of the secondary dispersion layer. The use of a metal matrix composite (MMC)^{(3), (4)} has been considered as a means of responding to these issues. An MMC is formed by adding “whiskers” or other strengthening materials to an alloy matrix. Because of this, it is easy to control the weight and size of the strengthening materials, and high-temperature strength can be increased using this method. However, producing MMC entails complex manufacturing processes and special manufacturing facilities. If alloy design could be used to enable dispersion strengthening, existing manufacturing processes could be employed. The project therefore sought a method by means of which needle-type intermetallic compounds could play the role of the strengthening material, and a fine and uniform dispersion could be achieved in the aluminum matrix in order to help prevent a decline in the material characteristics resulting from coarsening of the compounds. The project attempted to control the cooling rate of the material during manufacture, and to control the size of the intermetallic compounds using an alloy design suited to the cooling rate employed. The goal in using this method was to crystallize intermetallic compounds with the addition of the minimum amount of transition metal, to increase high-temperature strength while achieving an equivalent specific gravity to the conventional material, and to maintain forgeability.

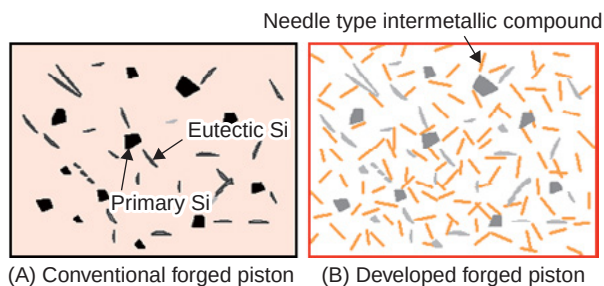


Fig. 1 Schematic illustration of microstructure of conventional forged piston and developed forged piston

2.2. Method of Producing Forging Billet for Developed Material

Control of the cooling rate in the solidification process during manufacture is an important factor in helping to enable control of the dispersion and the size of the needle-type intermetallic compounds in the aluminum alloy matrix. The relationship between the cooling rate of the piston material and the size of the compounds for different manufacturing methods is shown in Fig. 2. Using the standard method of manufacture for pistons, gravity die casting (GDC), it has been necessary to slow the rate of cooling in order to help ensure castability. Because of this, the addition of small amounts of transition metals results in a tendency towards the production of coarse compounds, placing limitations on the ability to actively exploit intermetallic compounds. More recently, the speed of cooling in HPDC has been exploited to enable the addition of large quantities of transition metals in order to produce pistons with higher levels of high-temperature strength^{(5), (6)}. HPDC pistons display high productivity, but the high rate of cooling during casting tends to result in an increase in the amount of transition metals in solid solution in the matrix, and a refinement of the size of the intermetallic compounds. As a result, it is necessary to add a high quantity of transition metals in order to crystallize sufficient intermetallic compounds to achieve the desired increase in high-temperature strength. This increases the

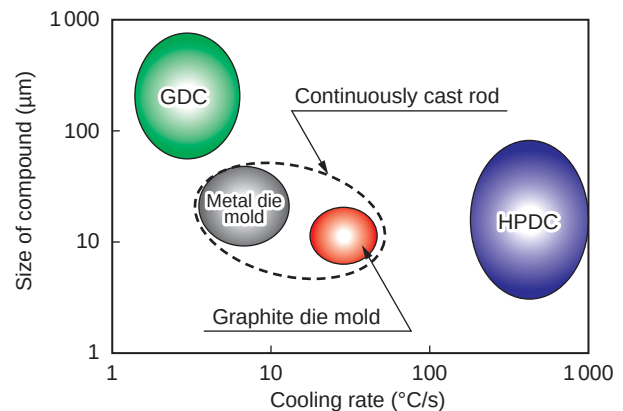


Fig. 2 Relationship between cooling rate of piston material and size of compound

specific gravity of the material, reducing the ability to achieve weight savings in the piston. In both of these casting methods, there are limitations on the ability to control the microstructure because the rate of cooling is determined by castability. By contrast, the use of billets for forging separates the processes of forming the piston and solidifying the material, resulting in a high degree of freedom in the selection of the cooling rate. Using this method, a range of cooling rates intermediate between those of GDC and HPDC can be employed. This cooling rate range has not previously been a subject of research focus. Exploiting this cooling rate range, the effect of coarse intermetallic compounds can be minimized, while also controlling the amount of transition metals in solid solution in the matrix. A carbon mold continuous casting method was employed to produce the billet for the developed material in order to achieve a faster and more stable cooling rate. The billet is produced using a metal mold in the normal continuous casting method. However, when this method is used cooling commences from the surface in direct contact with the mold. Because cooling takes place from the external circumference, the rate of cooling of the center is slow, resulting in a tendency towards coarsening of the microstructure [Fig. 3(A)]. When a carbon mold is used, the cast material can be cooled by means of direct contact with cooling water, enabling the formation of a fine and uniform microstructure⁽⁷⁾. [Fig. 3(B)]

2.3. Forging Process

In contrast to casting, forging presents issues in the formation of near-net shapes. Because of this, when the material has been heated once, a “1 heat 1 press” (1H/1P) formation process is desirable in the forging process. Heating the material multiple times and forging is effective in the case of materials that are challenging to forge, and in the formation of complex shapes. However,

correction in each forming process in order to attempt to prevent forging defects and the necessity of using multiple molds reduces productivity. Forming the product using a 1H/1P process enables the achievement of consistent quality in the forged material, in addition to high productivity. In order to realize 1H/1P formation, the high-temperature elongation of the forging billet should be close to that of a conventional forged material. The project therefore sought an alloy design and a method of control of intermetallic compounds that would help to ensure increased high-temperature strength and high-temperature elongation.

3. Method of Alloy Design for Developed Material

3.1. Design of Base Alloy

The quantities of the main constituents, Si, Mg and Cu, to be added in order to achieve the basic, essential characteristics of an alloy for piston use, were determined in the following ways.

3.1.1. Setting quantities of Si and Mg to be added

In order to attempt to prevent forgeability from declining due to crystallization of primary Si crystals, the ratio of Si to be added was set at 12 mass%, the upper limit of the eutectic point. Mg is effective in increasing creep strength, but the ratio was set at 1.0% in order to attempt to prevent breakage during forging as a result of crystallization of Mg_2Si .

3.1.2. Setting quantity of Cu to be added

The coexistence of Cu and Ni promotes the crystallization of Al-Cu-Ni ternary intermetallic compounds, and this has an effect on high-temperature strength. The effect of the addition of differing quantities of Cu and Ni to the Si 12%-Mg 1% alloy on the high-temperature tensile characteristic at 300 °C was therefore examined. Figure 4 shows the results of varying the quantity of Cu added at a Ni content of 3%, and Fig. 5 shows the results of varying the quantity of Ni added at a Cu content of 1%. Virtually no change was observed with the addition of Cu, while the addition of Ni had a substantial effect. Figure 6 shows a secondary electron image of an alloy with ratios of Ni3% and Cu1%, and Fig. 7 shows a secondary electron image of an alloy with ratios of Ni3% and Cu5%. Needle-type Al-Ni intermetallic compounds crystallize at a Cu ratio of 1%, but at a Cu ratio of 5%, the crystallization of dendritic Y alloys impedes the crystallization of needle-type intermetallic compounds. There is therefore no observable increase in strength at 300 °C with the addition of Cu. Increasing the quantity of Cu added increases the specific gravity of the material, and the ratio of Cu was therefore set at 1%, the minimum content essential to achieving strength up to 250 °C.

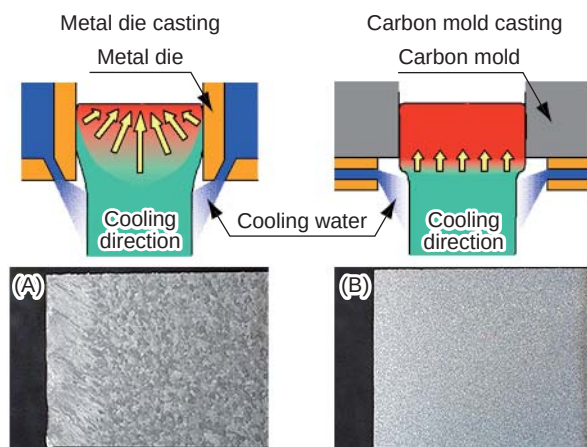


Fig. 3 Schematic illustration of casting method and microstructure of conventional casting material and carbon mold casting material

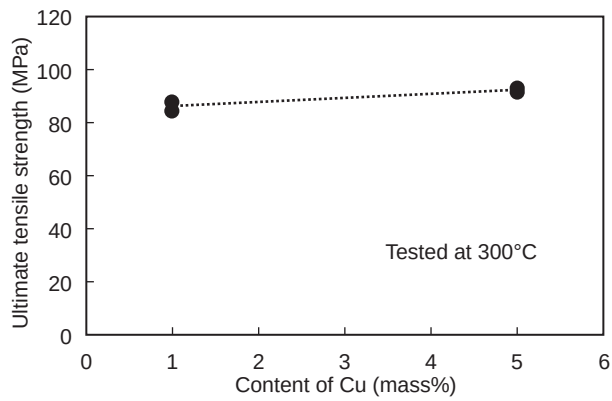


Fig. 4 Effect of Cu addition on tensile strength of Al-Si12-Mg1-Ni3 alloy

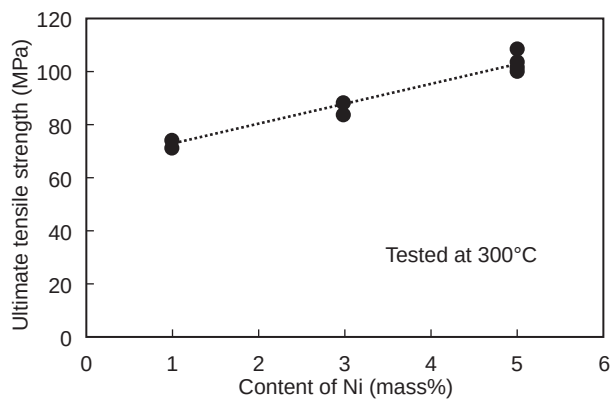


Fig. 5 Effect of Ni addition on tensile strength of Al-Si12-Mg1-Cu1 alloy

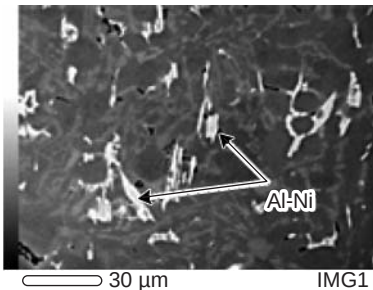


Fig. 6 Microstructure of Al-Si12-Mg1-Cu1-Ni3 alloy

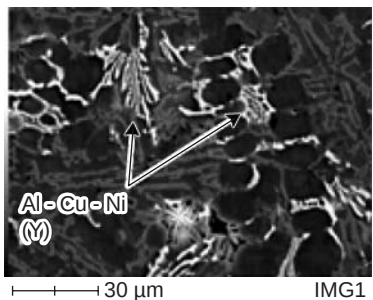


Fig. 7 Microstructure of Al-Si12-Mg1-Cu5-Ni3 alloy

3.2. Selection of Transition Metal

The addition of a transition metal is an effective means of increasing strength at 300 °C and above, but adding transition metals in excessive quantities can result in a decline in forgeability and increased specific gravity. Transition elements were therefore screened from the perspectives of forgeability and specific gravity. Figure 8 shows the results of high-temperature tensile tests conducted on test pieces taken from continuously cast rods (pre-forging) and forged pistons produced from an Al-Si12-Mg1-Cu1 alloy to which different transition metals had been added. The tests were conducted following exposure of the test pieces to a temperature of 300 °C for 100 hr. In the A range, the addition of high quantities of transition metals increased the strength of the continuously cast rod, but strength declined considerably following forging, and the overall strength increase following forging was small in comparison to the increase in specific gravity. This phenomena results from the intermetallic compounds fracturing, brought about by the plastic deformation that occurs during forging. The agglomerated intermetallic compounds that crystallize when the

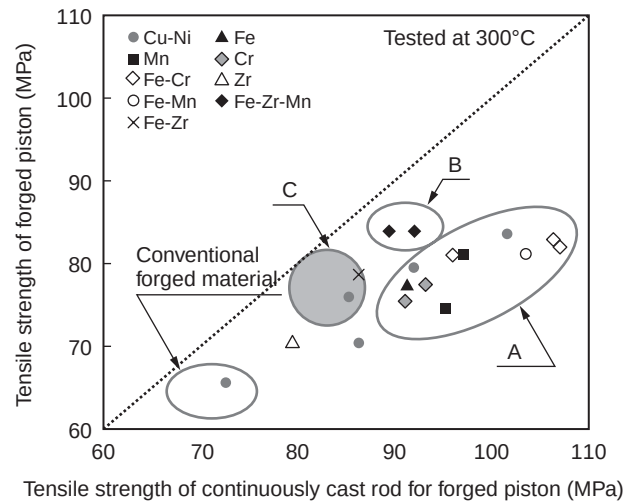


Fig. 8 Tensile strength of continuously cast rod and forged piston

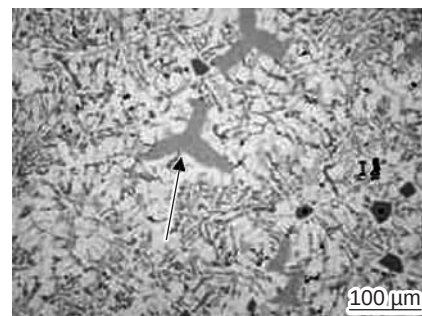


Fig. 9 Shape of intermetallic compound of Mn, Cr added alloy

quantities of Cr and Mn added exceed specific amounts (Fig. 9) also substantially reduce strength following forging. The crystallization of coarse intermetallic compounds was observed in the B range, resulting in the formation of cracks during the forging process. The target range for this project was the C range, which displayed good forgeability, low specific gravity, and high high-temperature strength following forging. Based on the results of the study of transition metals, Ni and Fe were selected for addition. Ni has a low solid solubility limit in aluminum, and is effective in helping to ensure the crystallization of intermetallic compounds. The addition of this element is considered to be effective in increasing high-temperature strength while having a minimal effect on the thermal conductivity of the alloy^{(8), (9)}. In the screening also, the addition of Ni increased strength through the formation of fine, needle-type intermetallic compounds. Fe, by contrast, is recognized as a harmful element that promotes the coarsening of intermetallic compounds, and has conventionally been controlled as an impurity. In the screening, however, Fe was found to not be harmful in the cooling rate range associated with the carbon mold continuous casting method, and its addition was found to be able to increase high-temperature strength through the crystallization of fine, needle-type intermetallic compounds. This project therefore made active use of Fe as an element that was effective in increasing high-temperature strength, and examined the potential for an alloy containing both Ni and Fe.

3.3. Study of Potential for Alloy Containing both Ni and Fe

A study of the potential for an alloy containing both Ni and Fe was conducted based on the relationship between the amounts of each element added, forgeability, and the state of crystallization of intermetallic compounds. Figure 10 shows the results of piston forging tests using Al-Si12-Mg1-Cu1 alloys to which Ni had been added in

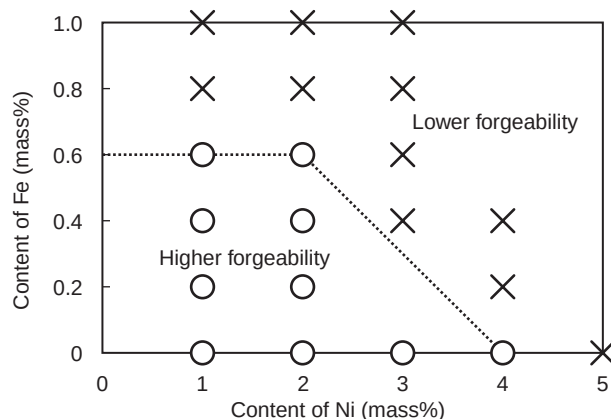


Fig. 10 Effect of Ni and Fe addition on forgeability of Al-Si12-Mg1-Cu1 alloy

isolation and to which Ni and Fe had been added at the same time. Alloys to which Ni was added in isolation displayed no cracking and adequate forgeability up to a ratio of 4%. Forgeability was adequate in the alloys to which Ni and Fe were added simultaneously up to a ratio of Ni 2% and Fe 0.6%. While the acceptable quantity of Fe was low in comparison to Ni, a range was determined in which forgeability was adequate while Ni and Fe were both present in the alloy. Next, a study was conducted from the perspective of the microstructure. The addition of Ni in isolation resulted in the crystallization of needle-type intermetallic compounds at ratios of 2% and higher, and the size of the compounds increased as the ratio of Ni increased. The addition of Ni and Fe together resulted in the crystallization of ternary Al-Fe-Ni needle-type intermetallic compounds. The addition of the elements together promoted increased coarsening of the intermetallic compounds in comparison to the addition of Ni in isolation. However, the crystallization of needle-type intermetallic compounds responded more readily to the amount of Fe added than Ni, and Fe can therefore be regarded as a useful element in enabling specific gravity to be reduced. The effective use of the range of additive amounts in which no coarsening of the intermetallic compounds was observed would therefore enable specific gravity to be reduced. Figures 11 and 12 show the coarse intermetallic compounds in the alloy when Ni is added in isolation in a ratio of 5% (Fig. 11) and when Ni and Fe are added in ratios of 3% and 1% respectively (Fig. 12). The coarse intermetallic compounds produced both by the

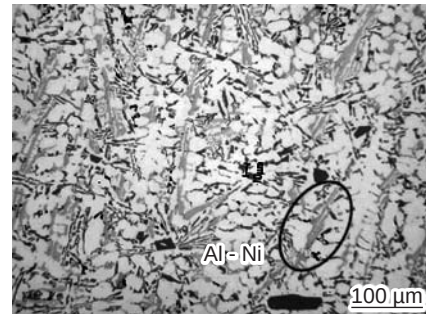


Fig. 11 Microstructure of Al-Si12-Mg1-Cu1-Ni5 alloy

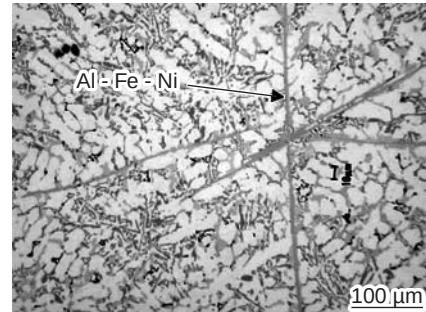


Fig. 12 Microstructure of Al-Si12-Mg1-Cu1-Ni3-Fe1 alloy

Table 2 Chemical composition, specific gravity and average size of intermetallic compound of tested alloy and conventional alloy for forged piston

	No.	Ni	Fe	Mn	Cr	Zr	Ti	Specific gravity	Average size of intermetallic compound (μm)
Tested alloys	1	3	—	—	—	—	—	2.71	20
	2	3	—	1	—	—	—	2.73	25
	3	3	—	—	0.2	—	—	2.71	15
	4	2	0.6	—	—	0.1	0.1	2.70	8
Conventionally forged piston alloy	1	—	—	—	—	—	—	2.69	0

addition of Ni in isolation and of Ni and Fe together would result in cracking during the forging process. Because of the high correlation between the microstructure and forgeability, the refinement of the intermetallic compounds is important to the achievement of good forgeability. A ratio of Ni in isolation of 3% (taking specific gravity into consideration) and a ratio of Ni 2%-Fe 0.6% when Ni and Fe are added together were selected as the highest quantities of transition metals that could be added while retaining the potential to achieve good forgeability, and alloys containing these quantities of the metals were studied comparatively.

4. Size of Needle-type Intermetallic Compounds and Mechanical Properties

4.1. Refining Elements and Size of Needle-type Intermetallic Compounds

Refining elements were added to control the size of the intermetallic compounds in the alloys under study. The addition of Ti+Zr, Mn, Cr and other elements is known to refine the intermetallic compounds in aluminum alloys⁽¹⁰⁾. The relationship between the refining elements and the size of the intermetallic compounds in the alloys was studied in order to clarify the type of high-temperature characteristics that would be obtained as a result of adding these refining elements in order to control the size of the intermetallic compounds. Table 2 shows composition, specific gravity, and average size of needle-type intermetallic compound for the test alloys and a conventional material. Ti+Zr were added to an alloy to which Ni and Fe had previously been added together. Mn and Cr were added to alloys to which Ni had previously been added in isolation. Neither Mn nor Cr was added to alloys to which both Ni and Fe had been added, because this would result in agglomeration of the needle-type intermetallic compounds. In all cases the matrix was an Al-Si12-Mg1-Cu1 alloy. Table 2 indicates that the size of the intermetallic compounds can be controlled by adjusting the quantities of transition elements and refining elements added to the alloy. The study showed that the addition of Ti+Zr to an alloy containing both Ni and Fe

was effective in enabling the formation of fine intermetallic compounds.

4.2. Size of Needle-type Intermetallic Compounds and High-temperature Elongation

The relationship between the average size of the intermetallic compounds and elongation at 300 °C was studied in order to determine the intermetallic compound size at which an equivalent level of forgeability to a conventional forged material was obtained (Fig. 13). Elongation declined as the size of the intermetallic compounds increased. The conventional material displayed an elongation of 35%, while the highest level of elongation among the test alloys was displayed by No. 4 at 23%. The elongation of the conventional material and alloy No. 4 was measured at high temperatures of 300-500 °C in order to study methods of achieving increased elongation as the temperature of the billet was increased during forging (Fig. 14). The results showed that increasing the temperature to which the billet was heated to approximately 50 °C above the conventional forging temperature range of 300-400 °C enabled the achievement of a level of elongation similar to that of the conventional material, indicating that an equivalent level of forgeability

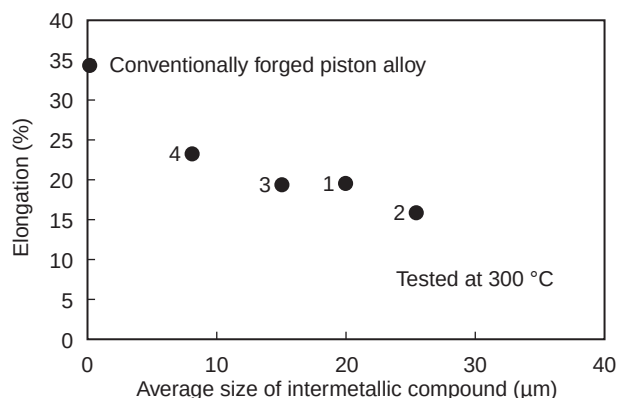


Fig. 13 Relationship between average size of intermetallic compound and elongation

could be achieved with no modification of the conventional forging process. However, at an average intermetallic compound size of 20 mm and larger, there was a substantial decline in elongation, which might necessitate an increase in the number of forging processes or restrict the potential shapes of the pistons. In order to achieve adequate forgeability, it would be necessary to control the average size of the intermetallic compounds to below 20 mm, in addition to controlling the coarsening of the compounds.

4.3. Size of Needle-type Intermetallic Compounds and Fatigue Strength

From the perspective of forgeability, it was desirable to reduce the size of the intermetallic compounds, but this would generate the possibility that sufficient fatigue strength at high temperatures could not be achieved. The relationship between the average size of the intermetallic compounds and fatigue strength at 300 °C was therefore studied. The results are shown in Fig. 15. The test pieces were taken from the crown of a piston following forging

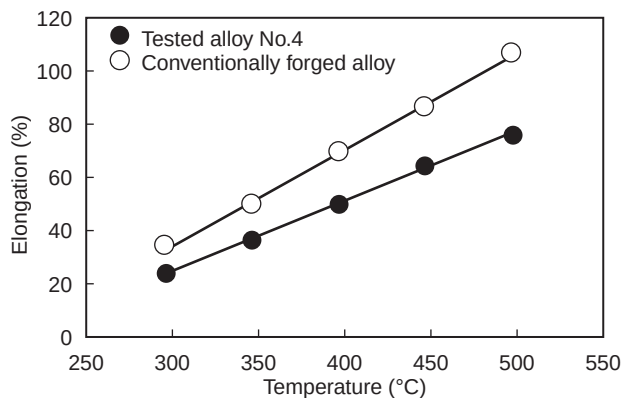


Fig. 14 Elongation of tested alloy No.4 and conventionally forged piston

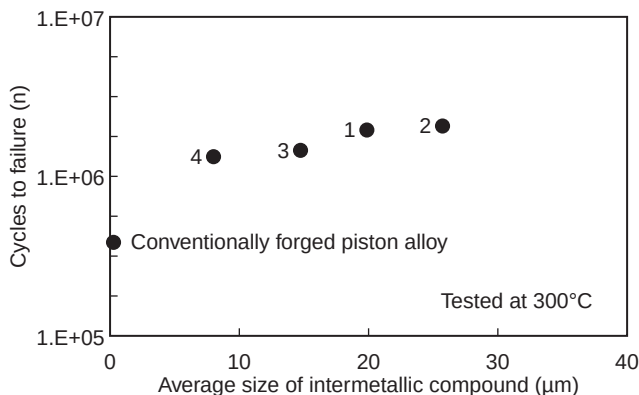


Fig. 15 Relationship between average size of intermetallic compound and cycles to failure

and the application of heat treatments. Fatigue strength was expressed by cycles to failure in a 30 MPa pulsating tension fatigue test. Fatigue strength was increased even in alloy No. 4, which displayed the lowest average intermetallic compound size of 8 mm, and little change in fatigue strength was observed even as the average size of the compounds increased. This indicates that an adequate increase in strength could be achieved at an average intermetallic compound size of 8 mm.

4.4. Needle-type Intermetallic Compounds in Developed Alloy

From the results discussed in sections 4.2. and 4.3., alloy No. 4, containing both Ni and Fe, was selected as the optimum alloy enabling the achievement of both adequate forgeability and high-temperature strength in the piston. The microstructure of the developed material is shown in Fig. 16. A microstructure in which needle-type intermetallic compounds of 3-30 mm are dispersed can be observed. The use of the minimum essential amount of transition metals in this alloy has enabled the achievement of a specific gravity similar to that of a conventional material. The addition of Fe at a ratio of 0.6% has also enabled the use of reclaimed aluminum, contributing to material recycling.

5. Properties of Developed Material

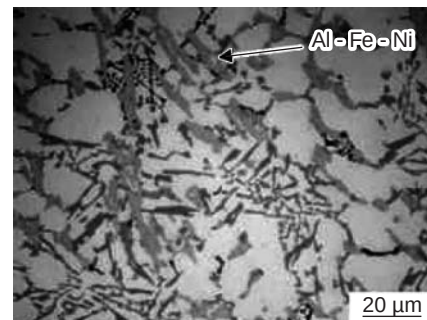


Fig. 16 Microstructure of Al-Si12-Mg1-Cu1-Ni2-Fe0.6-Ti0.1-Zr0.1 alloy

5.1. High-temperature Fatigue Strength

Figure 17 shows the results of fatigue tests between 200 and 300 °C conducted on test pieces from pistons manufactured using the developed material (alloy No. 4), a conventional forged material, and a conventional cast material. The developed material displays higher fatigue strength than the conventional materials from a low temperature of 200 °C to a high temperature of 300 °C. At 300 °C in particular, the fatigue strength of the developed material is approximately 50% higher than that of the conventional forged material.

5.2. Creep Strength

Pistons used in high-temperature environments can become deformed by creep during engine operation, resulting in a decline in engine performance. In achieving weight savings in the pistons, it is therefore necessary to consider creep characteristics in addition to increased fatigue strength. Figure 18 shows the creep strength of a conventional forged piston material and the developed material. Creep strength was evaluated by the time to failure when test pieces from pistons forged using the materials were subjected to a 47.8 MPa stress in a high-temperature environment of 300 °C. The developed material displayed creep strength more than twice as great as that of the conventional forged material.

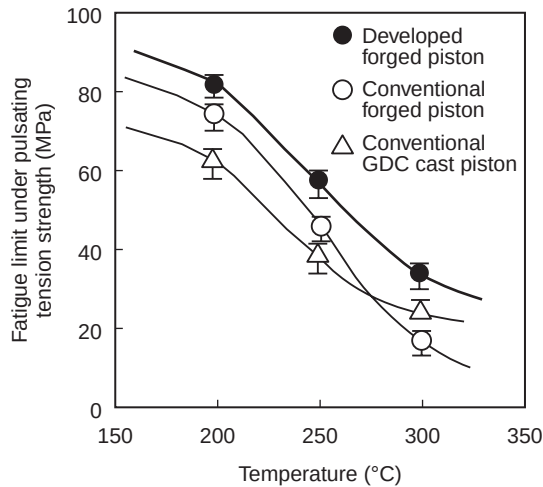


Fig. 17 Pulsating fatigue strength of pistons tested at various temperatures

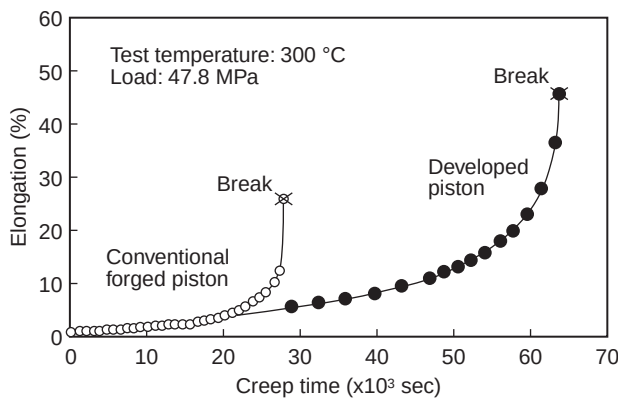


Fig. 18 Creep strength of developed piston and conventionally forged piston

6. Verification in Actual Engine

Based on the results of the tests of the material, its effectiveness in an actual engine was verified. The engine employed was a water-cooled in-line four-cylinder 998 cm³ model. The weight of the pistons was reduced by 5% by reducing the thickness of the crown by 18% against conventional pistons and removing the pin boss ribs. CAE analyses and engine durability tests were then conducted. The shape of the pistons employed in the engine durability tests is illustrated in Fig. 19. The results of the CAE analyses are shown in Fig. 20. The analysis showed that the lighter pistons displayed a similar rate of safety to conventionally-shaped pistons. In addition, the lighter pistons satisfied performance criteria including sliding performance and dimensional stability in engine durability tests under the same loads as the conventional pistons, indicating that they presented no issues in terms of durability.

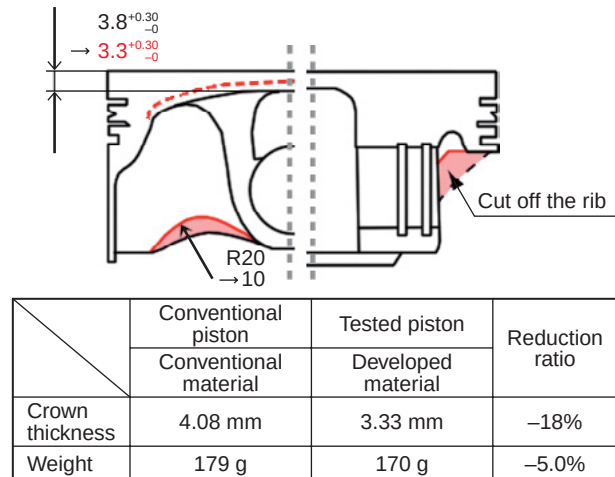


Fig. 19 Schematic diagrams of tested piston and actual crown thickness and piston weight

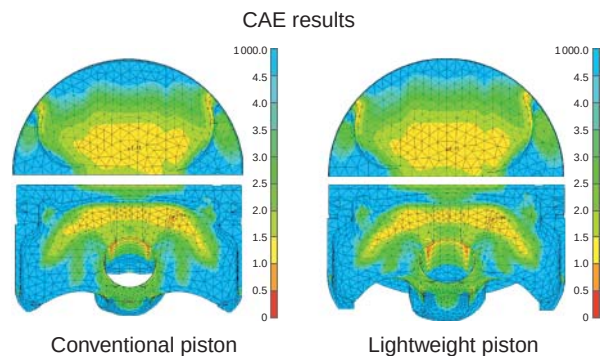


Fig. 20 Fatigue factor of tested piston

7. Conclusion

The project discussed in this paper set out to realize a lightweight piston that could be manufactured using a "1 heat 1 press" (1H/1P) forging process, and developed an Al-Si12-Mg1-Cu1-Ni2-Fe0.6 forged alloy using a carbon mold continuous casting method that enabled the cooling rate to be controlled.

- (1) The exploitation of the refining effect of Zr+Ti to control the size of the needle-type intermetallic compounds to 3-30 mm and the addition of the minimum quantities of Ni and Fe have enabled the achievement of a similar level of specific gravity and forgeability to that of a conventional forged material.
- (2) The developed material displays higher high-temperature strength than conventional forged and cast materials from 200-300 °C, and approximately 50% higher high-temperature strength than a conventional forged material at 300 °C.

The pistons manufactured using the developed material have already begun mass production, beginning with those that are employed in the 2008 CBR1000RR super sports motorcycle.

Acknowledgments

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References

- (1) Belov, N. A., Eskin, D. G., Avxentieva, N. N.: Constituent phase diagrams of the Al-Cu-Fe-Mg-Ni-Si System and their application to the analysis of aluminium piston alloys, *Acta Materialia*, Elsevier Ltd., Vol. 53, Issue 17, p. 4709-4722 (2005)
- (2) Buha, J., Lumley, R. N., Crosky, A. G., Hono, K.: Secondary precipitation in an AL-Mg-Si-Cu alloy, *Acta Materialia*, Elsevier Ltd., Vol. 55, Issue 9, p. 3015-3024 (2007)
- (3) Yamauchi, T., Suzuki, M., Takahashi, M., Takada, I., Toda, M.: Development of Aluminum Borate Whiskers Reinforced Piston by Squeeze Casting - Part2 : Properties of Metal Matrix Composites Reinforced with Granulated Whiskers Preform, *JSAE Annual Congress (Spring) Proceedings 981*, Society of Automotive Engineering of Japan, p. 125-128 (1998)
- (4) Yamashita, M., Kikuchi, T., Kawasaki, M.: Development of High Performance MMC for Diesel Engine Piston, *JSAE Annual Congress (Autumn) Proceedings No. 91-98*, Society of Automotive Engineering of Japan, p. 9-12 (1998)
- (5) Tanihata, A., Sato, N., Katsumata, K., Shiraishi, T., Oda, K., Endo, O.: Development of high-strength piston using die casting process, *Journal of Japan Institute of Light Metals*, Vol. 57, No. 3, p. 131-136 (2007)
- (6) Tanihata, A., Sato, K., Furukawa, K.: Development of High-strength Piston Material with Die Casting, *Honda R&D Technical Review*, Vol. 17, No. 2, p. 122-128
- (7) Akiyama, H., Amaki, Y., Tohma, K.: Development of Peeling-less Casting Billet for Forged Aluminum Suspension Arm, *Honda R&D Technical Review*, Vol. 16, No. 2, p. 31-36
- (8) Polmer, I. J.: *LIGHT ALLOYS Metallurgy of the light metals*, Edward Arnold, p. 126 (1995)
- (9) Catherall, J. A., Smart, R. F.: The Effects of Nickel in Aluminium- Silicon Eutectic Alloys, *Metallurgia*, Vol. 79, No. 476, p. 347 (1969)
- (10) Japan Aluminum Association: *The Handbook of Advanced Aluminum Technology*, Kallos Publishing Co. Ltd., p. 131 (1996)

■ Author ■



Hidenori FUJII



Tomoo OKA



Masaki YONEYAMA



Toshiaki DEGUCHI



Hirotaka MURAKAMI