

Development of an Alloy for High Pressure Die Cast Pistons

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ABSTRACT

High pressure die casting material was developed for the use of pistons in various mass-produced, small, general-purpose engines. This new material enables a significant reduction in casting tact time, allows a continuous line through the casting and machining processes, which is impossible to achieve by the permanent mold gravity die casting method (GDC), and contributes to production cost reduction. This material provides a material hardness of HRB65, which is equivalent to the material used in conventional methods, due to the high speed filling of the molten metal into the dies and the quick solidification of it. The material also accomplishes the high temperature durability requirements after undergoing a short T5 process. For the stabilization of the material properties in mass production, various alloy prototypes were produced and evaluated on strength, residual stress, seizure, microstructure, and actual engine durability in order to determine the optimal alloy composition.

1. Introduction

Small, general-purpose engines are now used in many different applications. In Japan, 6 to 7 million units are produced annually, and accompanying this growth, the manufacturers are exhaustively studying and implementing measures for reducing product costs. Honda released GC engines⁽¹⁾ and Mini 4-Stroke engine series⁽²⁾ in 1997 and we have continued to supply high-performance, low-priced engines. In respect to specific engine components, we have developed a single cam resin gear, an integrated cylinder head and block, and a FCD crankshaft among other components in an effort to reduce costs while maintaining function.

The use of aluminum alloy for piston materials is already common practice for reducing the weight. The production of general-purpose engine pistons at Honda is primarily done by permanent mold gravity die-casting (GDC). Recently, however, the small-displacement engines (22-50 cc) manufactured by Honda and other firms⁽²⁾ have begun to use pistons made by high-pressure die-casting (DC). Cost reductions from the shape of general-purpose engine pistons can already be said to have about reached their limit. On the other hand, when considering cost reductions from the manufacturing process used by Honda for multi-type, large-volume production (4 million units/year), the greatest opportunity lies within the use of a continuous production line that incorporates casting, heat treatment, machining and other operations of the process.

The most critical technical issue to be solved for realizing a continuous production line involving casting, heat treatment and machining is the time required for the heat treatment process; this process takes much longer than other processes, thereby inhibiting the application of efficient, continuous production throughout the processes. The current requirements for heat treatment time are:

- 5 to 6 hours for the T7 heat treatment of GDC pistons, and
- 4 to 5 hours for the T5 heat treatment of DC pistons.

There is no possibility of realizing a continuous production line unless this time is shortened to about 30 minutes at most.

This paper describes the course of development of the piston material that combines the advantage of short process time inherent to the DC production method with rapid solidification. The results of this material's evaluation are also presented.

2. Objectives

The major objective of changing the casting process from the conventional GDC method to the DC method was to create a continuous production line for the manufacturing process by synchronizing the casting and heat treatment processes with the machining process as this would result in a considerable improvement in production efficiency. A further objective of applying the DC method was to achieve the following by taking advantage of the rapid solidification and material characteristics inherent to this method:

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and material characteristics inherent to this method:

- Omission of the solution heat treatment
- Significant reduction in the casting tact time
- Minimization of the amount of machining by improving the dimensional accuracy of the as-cast product

The development of a material suitable for the new rapid heat treatment had the following aims:

- Providing mechanical characteristics such as high-temperature tensile strength and fatigue strength
- Providing physical characteristics such as high dimensional stability and thermal conductivity

3. Experimental method

3.1 Test Materials

The GDC casting material, AC8H, with 0.8wt.% of iron added to protect the mold was used for the tests to identify differences in the casting methods. This alloy was named DC8H, and its chemical composition along with that of AC8H are shown in Table 1. Alloys DC8Z/#1-#10 were used to examine the alloy composition. These were prepared for use in testing in the form of alloys exclusively for DC casting by adding various amounts of Si, Cu and Mg to the HD2 base metal, HDS. Table 2 shows the target compositions of the alloys examined, together with the melting point (mp) measured just before casting. Melting point was measured with a recorder specially designed for (AE Meter), which allowed the measurement of liquidus temperature through solidus temperature of each Al alloy sample as shown in Fig. 1-a, and the cartridge shell cup for AE meter shown in Fig. 1-b.

Each test material for a piston with a diameter of 68 mm was melted in a graphite crucible and cast from molten metal maintained at a temperature of 700°C with a 350-ton cold chamber die-casting machine. Various test pieces were then

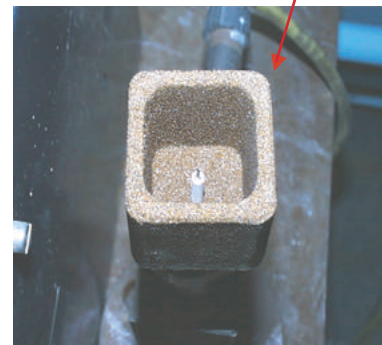
cut from each cast piston. The shapes of the test pieces used in the tensile strength test and fatigue strength test are shown in Figs. 2-a and 2-b, respectively.

3.2 Mechanical and physical properties

The tensile strength test was conducted with an Instron universal testing machine at a strain rate of 0.3%/min up to 0.2% proof strength, and at a cross-head rate of 3 mm/min after reaching 0.2% proof strength. The test temperatures



a. Recorder and Cartridge



b. Cartridge shell cup for aluminum alloy

Fig. 1 Recording thermometer for molten metal

Table 1 Chemical compositions

Composition	Cu %	Si %	Mg %	Zn %	Fe %	Mn %	Ni %	mp °C
AC8H	3.0	11.2	0.9	0.08	0.35	0.09	0.03	569
DC8H	3.0	11.3	0.9	0.07	0.82	0.08	0.03	569

Table 2 Chemical compositions for alloy designing

Composition	Cu %	Si %	Mg %	Zn %	Fe %	Mn %	Ni %	mp °C
AC8H	2.5 ~ 3.5	10.5 ~ 11.5	0.8 ~ 1.4	< 0.10	< 0.40	< 0.10	< 0.05	569
DC8Z/#1	5.0	14.0	2.0	< 2.5	< 1.1	< 0.5	< 0.5	550
DC8Z/#2	4.0	14.0	2.0	< 2.5	< 1.1	< 0.5	< 0.5	549
DC8Z/#3	3.3	14.0	2.0	< 2.5	< 1.1	< 0.5	< 0.5	552
DC8Z/#4	3.3	14.0	1.5	< 2.5	< 1.1	< 0.5	< 0.5	553
DC8Z/#5	3.3	13.0	1.5	< 2.5	< 1.1	< 0.5	< 0.5	555
DC8Z/#6	3.3	11.5	1.5	< 2.5	< 1.1	< 0.5	< 0.5	549
DC8Z/#7	3.3	13.0	1.0	< 2.5	< 1.1	< 0.5	< 0.5	553
DC8Z/#8	3.3	13.0	2.0	< 2.5	< 1.1	< 0.5	< 0.5	547
DC8Z/#9	3.3	14.0	1.2	< 2.5	< 1.1	< 0.5	< 0.5	558
DC8Z/#10	3.5	13.0	1.4	< 2.5	< 1.1	< 0.5	< 0.5	554

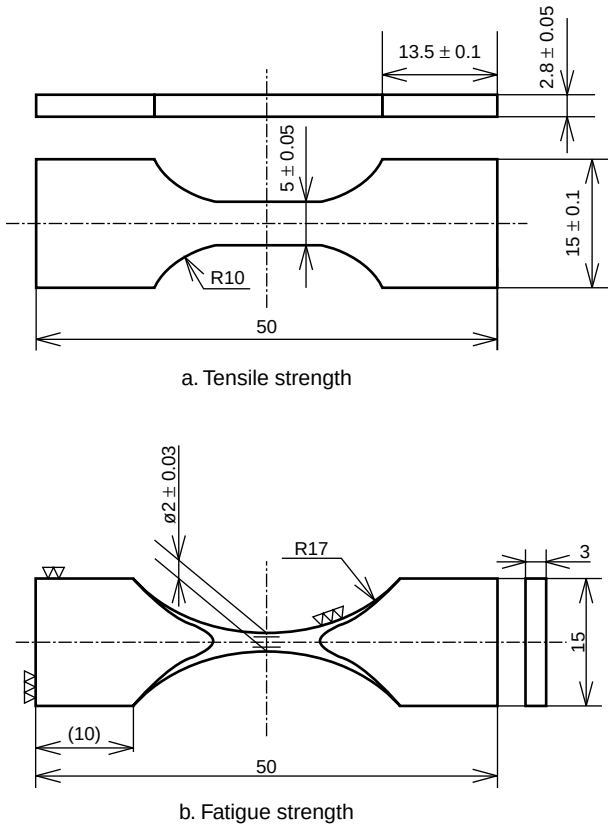


Fig. 2 Tensile and fatigue strength test piece under high temperature

were 200°C and 300°C, and the tensile strength test was performed after soaking the test piece at each temperature for 15 minutes. The fatigue strength test was conducted with an electro-hydraulic servo type fatigue strength tester with a capacity of ± 1 tf. Test conditions applied were a sine waveform for the applied load, a stress ratio of -1, a test frequency of 5 Hz to 17 Hz, and 1.00×10^7 test cycles. Testing was conducted under these conditions with test piece temperatures of 200°C and 300°C.

The hardness test and measurement were based on the Rockwell hardness testing method (JIS Z2245). The thermal expansion coefficient was measured over a range of 20-400°C by the TMA method, thermal conductivity was measured according to the laser flash method, and density was measured according to the Archimedes method.

4. Results

4.1 Effects of the different casting methods and heat treatments on the dimensional stability of the piston

In order to assess the necessity of heat treatment due to the change from the GDC method to the DC method, the effects of the thermal load on the dimensions and residual stress of the AC8H-T7 (GDC) and DC8H-F (DC) piston materials are shown in Table 1. In addition, the effects of changes in heat treatment conditions on the dimensional stability and residual stress of the DC8H material were also investigated.

4.1.1 Dimensional stability and internal residual stress of the DC material without any heat treatment

The change in piston diameter, which is used as an indicator of dimensional stability, was determined from the dimensional difference before and after evenly heating in an oven to a temperature that simulated the thermal load during actual engine operation. A machined piston to which no heat treatment had been applied was measured, before being placed in the uniform heating oven at 230°C for 10 hours. The piston was then removed from the oven and allowed to cool down to room temperature, after which the dimensions were measured again.

The residual stress was measured after drilling a hole of 30 mm in diameter in the center of the piston crown to reduce its rigidity and attaching strain gauges at the locations shown in Fig. 3. After leaving the strain gauges attached to the piston for at least 10 hours, they were connected to a data logger and zero-balanced. The piston was cut at the centerline between the strain gauges (section x-x in Fig. 3) to release the residual stress. The strain was measured after cutting, and then converted to the internal residual stress. Two mass-produced AC8H-T7 and two prototype DC8H pistons were tested to evaluate the dimensional changes and internal residual stress, and strict precautions were taken to avoid measurement error, such as loading the pistons into the heating oven simultaneously.

The change in diameter in the thrust direction (major diameter) and the piston pin direction (minor diameter) before and after thermal load tests for each of the AC8H-T7 and DC8H-F pistons are shown in Figs. 4-a and 4-b. The results of measuring the internal residual stress are shown in Fig. 5. Compared to the AC8H-T7 piston, which increased in diameter only about 20 μm , the DC8H-F piston increase by nearly three times that amount (about 60 μm). In addition, since the measured stress values during parting were positive, the residual stress was determined to be in the centripetal direction thus compressing the piston. In comparative terms, the DC8H-F piston exhibited values for the residual stress about one to six times greater than those for the AC8H-T7 piston.

On the basis of these experimental results, DC pistons without heat treatment were found to be difficult to achieve dimensional stability and internal residual stress equivalent to those of GDC pistons.

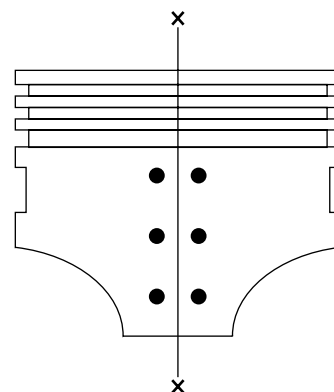


Fig. 3 Measurement points for residual stress

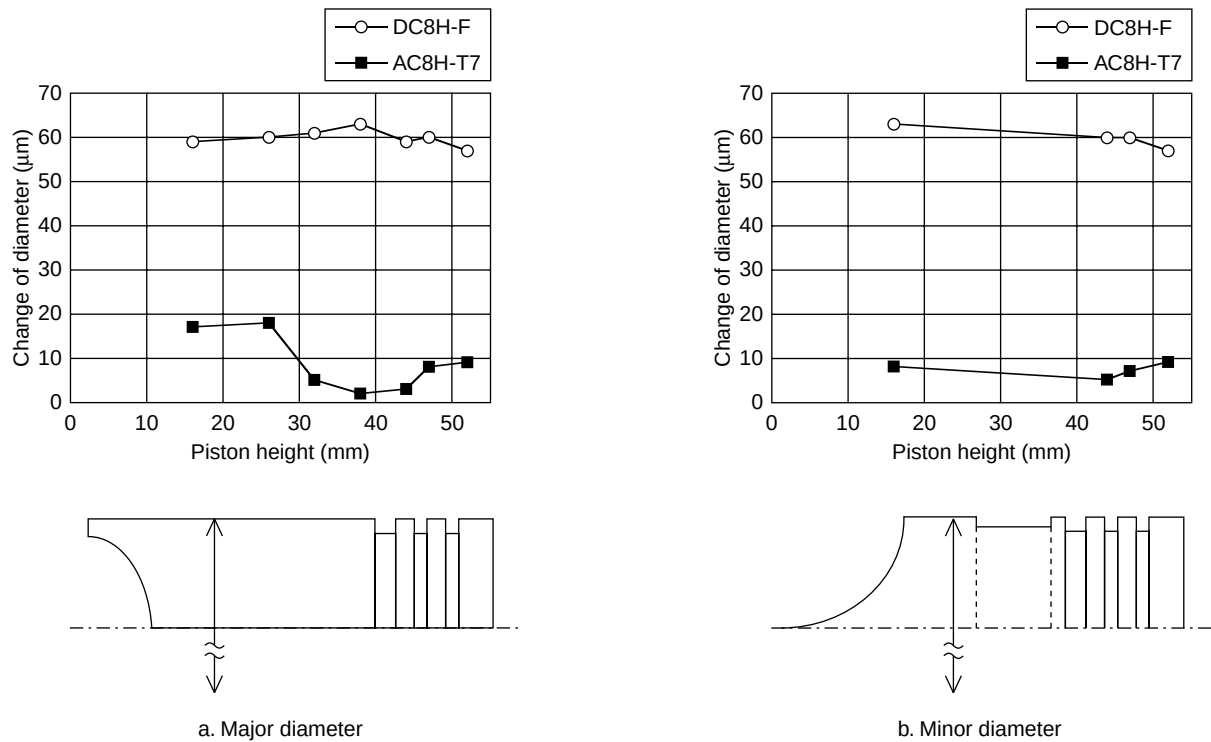
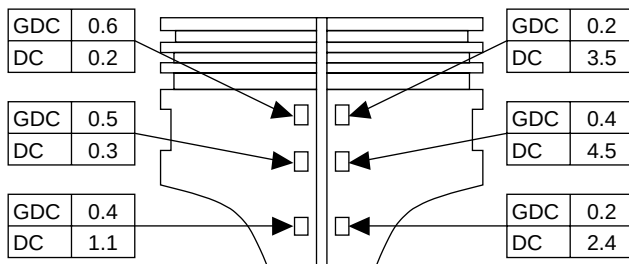


Fig. 4 Changes in major and minor diameters at each piston height after heating (230°C-10h)

Fig. 5 Residual stress after heating (kgf/cm²)

4.1.2 Heat treatment conditions and dimensional stability of the DC8H material and piston

The measured changes in diameter and internal residual stress of the pistons made of the DC8H material and heat treated at temperatures of 190°C, 225°C, 250°C and 275°C for 10, 20 and 30 minutes are shown in Figs. 6-a and 6-b. The thermal load test conditions were as that described in section 4.1.1; that is, the parts were heated for 10 hours at 230°C in a uniform heating oven. It was determined that as the temperature of heat treatment increased, the time needed for the internal stress to be released decreased. The heat treatment conditions required to obtain a change in diameter and internal residual stress equivalent to those of the AC8H-T7 piston described in the previous section were heating at a temperature of at least 225°C for 10 minutes or more. The

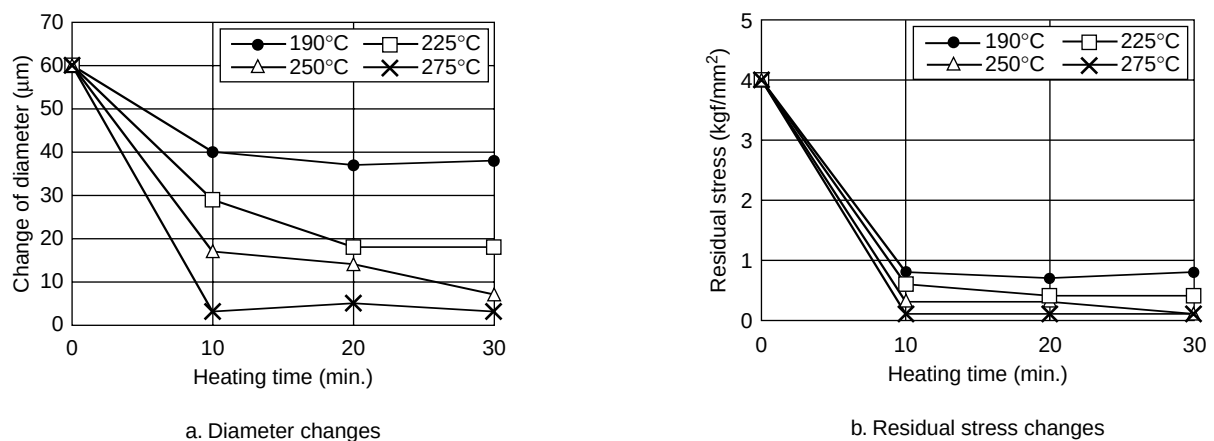


Fig. 6 Influence of heat treatment condition, temperature and time, on major diameter and residual stress

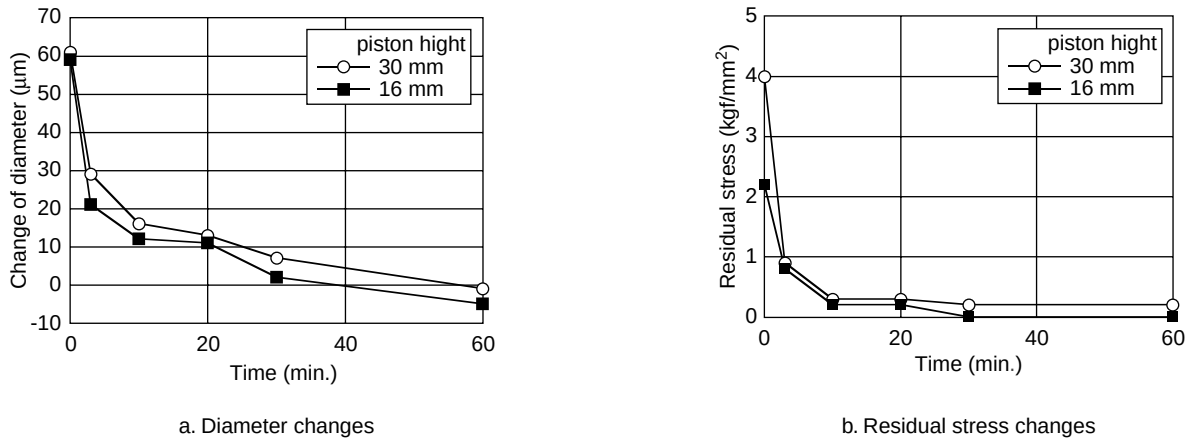


Fig. 7 Influence of heat treatment time on diameter and residual stress changes at 250°C

from an increased heat treatment duration at 250°C are shown in Figs. 7-a and 7-b. The graphs show that piston diameter and internal residual stress changes comparable to those of the AC8H-T7 piston could be achieved with a heat treatment duration of about 2 minutes.

Since the AC8H piston is subjected to the T7 heat treatment, the internal residual stress during casting is considered to be negligible. Thus, the cause of the internal residual stress and dimensional changes that occurred is presumed to be strain resulting from machining. In addition, the cause of the large dimensional change exhibited by the DC8H piston is believed to be the release of both the internal residual stress resulting from being subjected to high-pressure solidification during casting and the strain resulting from machining.

4.2 DC piston alloy composition

The results of an investigation of the dimensional stability associated with the DC method have been described in the previous section. In this section, experimental results are presented of the basic characteristics required of materials in consideration of the control range for the alloy composition when using DC cast alloy materials DC8Z/#1-#10 shown in Table 2. The casting (molten metal) temperature was the regular setting standard of 130-150°C above the melting point, based on the measured melting points of these alloys, and casting was carried out at 700°C.

4.2.1 Material hardness after casting

The molten metal temperature from the start of casting up to 100 shots, and the temperature of the piston crown immediately after removing it from the mold (referred to as the work temperature) are shown in Fig. 8 for each alloy. The molten metal temperature could be reliably controlled to $700 \pm 10^\circ\text{C}$ throughout the complete casting test, while the work temperature could be reliably controlled to $380 \pm 20^\circ\text{C}$, after increasing during the first 20 casting shots while the mold warmed up.

The work temperature and hardness (HRB) of the as-cast black skin during the first 10 casting shots for the 10 types of alloy are shown in Fig. 9. The hardness of the as-cast black skin material was measured after cooling with

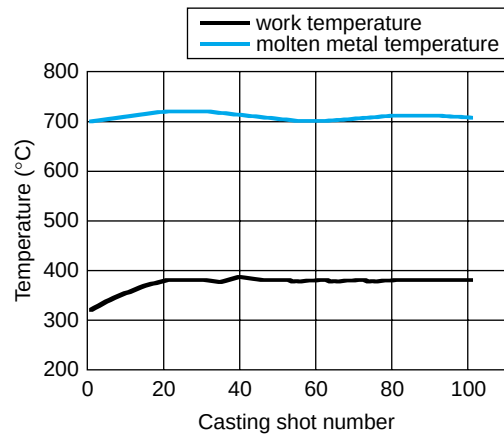


Fig. 8 Changes of molten metal and piston-top temperature after casting with the increase of casting shot number

water following the DC process. The first shot, having a low work temperature, was the hardest. As the work temperature subsequently stabilized, the hardness of the as-cast black skin material also became stabilized. Alloy #6 exhibited considerable variations in initial hardness, while alloy #9 exhibited a decrease in initial hardness as the work temperature increased, thus indicating that these alloys would not be suitable for practical use. An evaluation of the relationship between the added amounts of Mg, Si and Cu and the initial material hardness for the 10 types of alloy showed that the target hardness of HRB 65 or higher could be achieved with minimum contents of 1.4% Mg, 13% Si and 3.3% Cu.

4.2.2 Heat degradation characteristics

The effects of temperature and soaking time on the hardness of test pieces DC8Z/#5-T5 and AC8H-T7 after their heat treatment (250°C, 30 minutes, T5) are shown in Figs. 10-a and 10-b. In this experiment, the test pieces were reheated after the heat treatment and then allowed to cool to room temperature, before the hardness was measured.

The decrease in hardness at each soak temperature

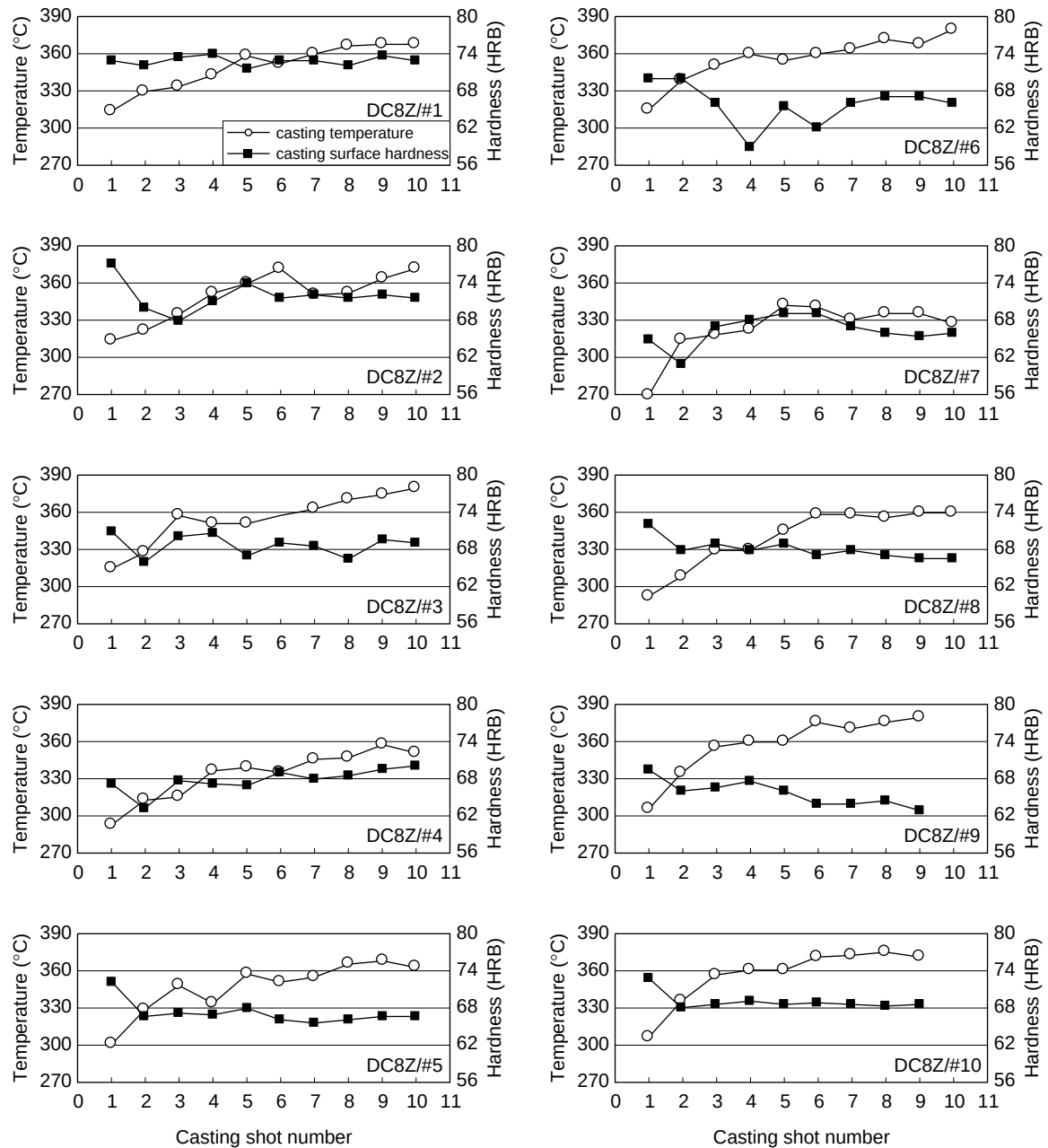


Fig. 9 Stability of alloy depending on composition of base material

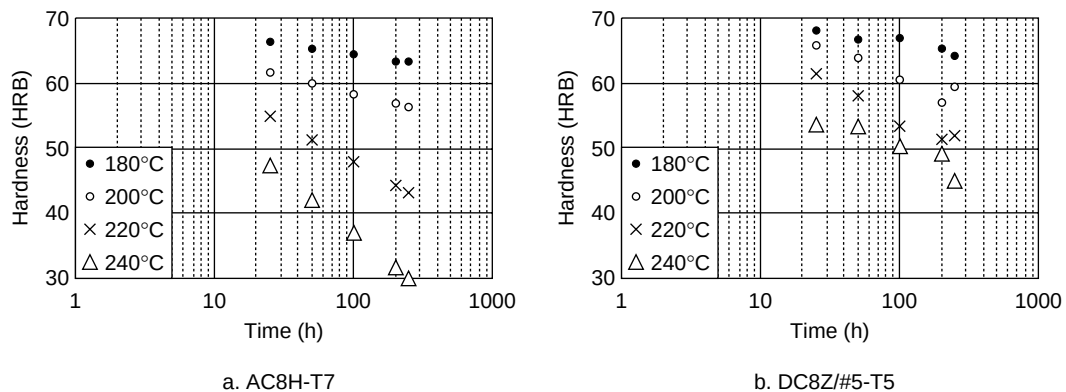


Fig. 10 Changes of hardness with after heating at various temperatures

The decrease in hardness at each soak temperature exhibited by the DC8Z/#5-T5 material was smaller compared to the AC8H-T7 material. The results reflect the study of Fukai *et al.* with AC8A and B materials.⁽³⁾ The difference in softening is thought to be due to the following: 1) the increasing fineness of the crystal grain size due to the rapid solidification characteristics of the DC process; and 2) the fine undissolved intermetallic compounds resulted from not performing a solution treatment were maintained in an evenly dispersed state, and these compounds act to resist movement of the dislocation line. Thereby the decrease in hardness after heating was reduced.

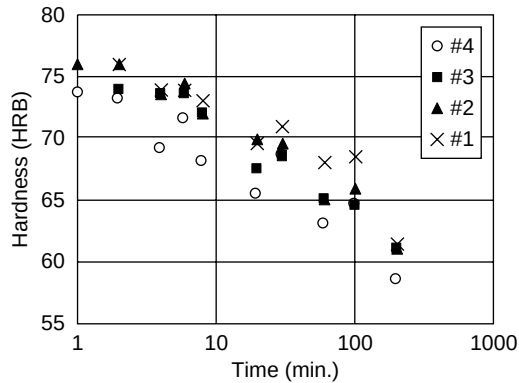
4.2.3 Selection of the optimum alloy composition and heat treatment conditions

Since the change in piston diameter was stabilized by heat treating at 225°C for at least 10 minutes as described in section 4.1.2, the change in hardness due to age hardening of each alloy when using the temporary T5 heat treatment conditions of 250°C for 30 minutes was evaluated as shown in Figs. 11-a and 11-b. If the target initial hardness is set to be a minimum of 65 (HRB), the average value for the GDC piston (AC8H-T7), alloys #7 and #10 are not suitable. In addition, since the test piece for alloy #1 occasionally exhibited brittle failure during machining, it was also excluded for the poor machinability.

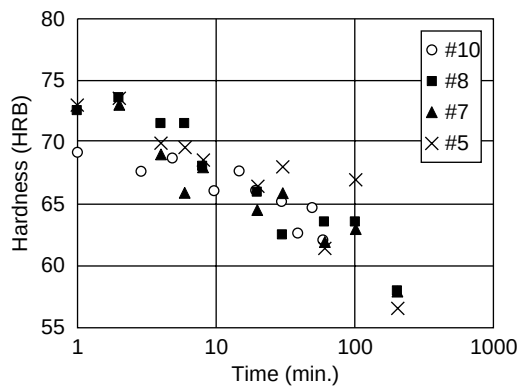
After evaluating the 10 types of alloy (DC8Z) according to various criteria, DC8Z/#2, #3, #4, #5 and #8 were determined to have desirable mechanical and physical properties as a piston alloy. A new alloy based on the range

of these compositions was designated as HAS14C4. The upper, middle, and lower limits of this alloy composition are shown in Table 3. Table 4 shows the mechanical and physical properties of HAS14C4 following a T5 heat treatment (250°C for 30 minutes) in comparison with those of AC8H-T7. In comparison with AC8H-T7, the thermal conductivity is about 25% lower, while the other physical properties are similar. However, the mechanical properties such as the hardness, tensile strength and fatigue strength have all improved. The thermal conductivity of HAS14C4 is equivalent to 0.256, the value for a high-performance engine piston material (A351), and the difference from AC8H-T7 is considered to be within the practically allowable range.

Photographs of the microstructures of AC8H-T7 and the upper and lower limit compositions of HAS14C4 are shown in Figs. 12-a, -b, and -c. The structure after solidification of the AC8H-T7 material contains white crystal grains of soft α -Al over a broad range, and large acicular crystals of eutectic Si is visible. On the other hand, the structure after solidification of the HAS14C4 material exhibits the distribution of extremely fine α -Al, Mg_2Si , eutectic Si and so forth. In addition, primary crystal of Si appearing in a planar form in the microstructure is distributed in larger numbers and more uniformly than in the AC8H-T7 material. This microstructure is believed to be responsible for the mechanical properties being equal to or better than those of the AC8H-T7 material.



a. DC8Z/#1 to #4 alloys



b. DC8Z/#5, 7, 8, 10 alloys

Fig. 11 Relationship between hardness and heat treatment time at 250°C

Table 3 Chemical composition of HAS14C4

	Cu %	Si %	Mg %	Zn %	Fe %	Mn %	Ni %	Al
Upper	4.0	14.0	2.0	< 2.5	< 1.1	< 0.5	< 0.5	Bal.
Middle	3.8	13.5	1.7	< 2.5	< 1.1	< 0.5	< 0.5	Bal.
Lower	3.5	13.0	1.4	< 2.5	< 1.1	< 0.5	< 0.5	Bal.

Table 4 Physical & mechanical property of HAS14C4

Physical property	Test condition	AC8H-T7	HAS14C4 250°C × 20 min.
Thermal expansion coefficient ($\times 10^{-6}$) ($^{\circ}C^{-1}$)	Room temp. ~ 100°C Room temp. ~ 200°C	19.2 ~ 20.8	19.4 ~ 20.3
Thermal conductivity ($\times 10^{-6}$) (W/m·°C)	Room temp.	135 ~ 142	100 ~ 105*
Modulus of longitudinal elasticity (MPa)	Room temp.	735 ~ 775	745
Density	—	2.68 ~ 2.74	2.68 ~ 2.79
Hardness (HRB)	—	64 ~ 68	66 ~ 68
Tensile strength (MPa)	200°C 300°C	2.12 ~ 2.60 0.74	2.30 ~ 2.80 1.29 ~ 1.42
0.2% proof strength (MPa)	200°C 300°C	1.98 ~ 2.05 0.57	1.89 ~ 2.40 1.00 ~ 1.19
Fatigue strength 10^7 cycle (MPa)	200°C 300°C	0.74 ~ 0.78 0.33	0.83 ~ 0.88 0.41

* Since the thermal conductivity of A351 is 107 which is almost equivalent to that of HAS14C4, this result is considered to be acceptable.

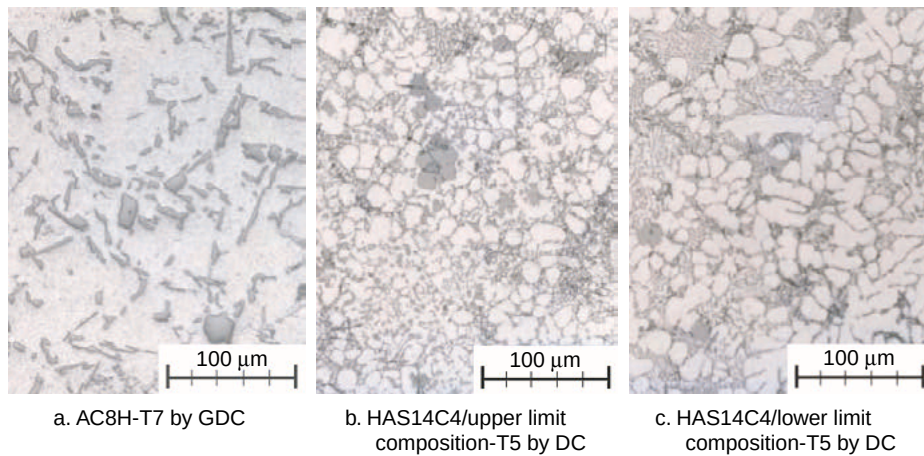


Fig. 12 Comparison of microstructures with AC8H-T7, HAS14C4/upper limit and HAS14C4/lower limit composition

4.3 Compatibility test

4.3.1 High-temperature piston fatigue strength test

A diagram of the high-temperature piston fatigue tester is shown in Fig. 13. The results of tests on an HAS14C4-T5 piston made by the DC process and on an AC8H-T7 piston made by the GDC process are shown in Fig. 14. Piston failure in the high-temperature fatigue strength test began with the formation of cracks from the pin hole which propagated toward the top of the piston pin boss in both pistons. Fig. 14 shows the change in safety factor with the number of fatigue cycles based on the maximum combustion pressure, and demonstrates that HAS14C4-T5 was superior

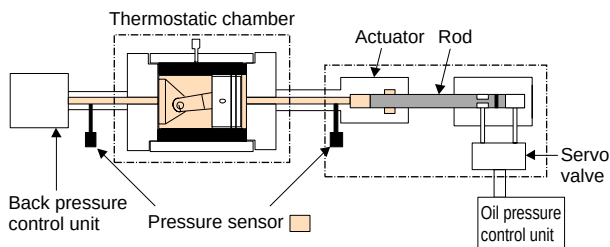


Fig. 13 Diagram of high-temperature piston fatigue tester

to AC8H-T7. This result is consistent with the results for heat degradation characteristics described in section 4.2.3.

4.3.2 Seizure limit test

(1) Piston test

The experiment on seizure limit, using a test piece cut from the piston, was performed with the chip-on-disk friction tester shown in Fig. 15. After attaching the test piece (6 x

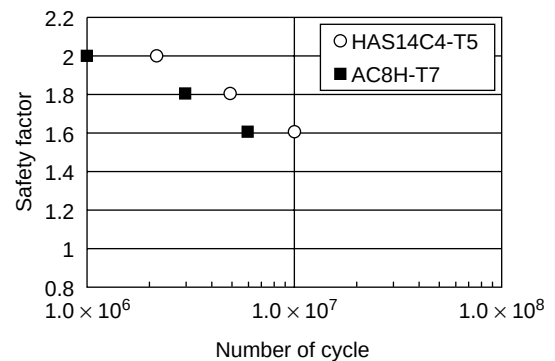


Fig. 14 Fatigue strength indicated by safety factor. Safety factor 1 equals to maximum cylinder pressure.

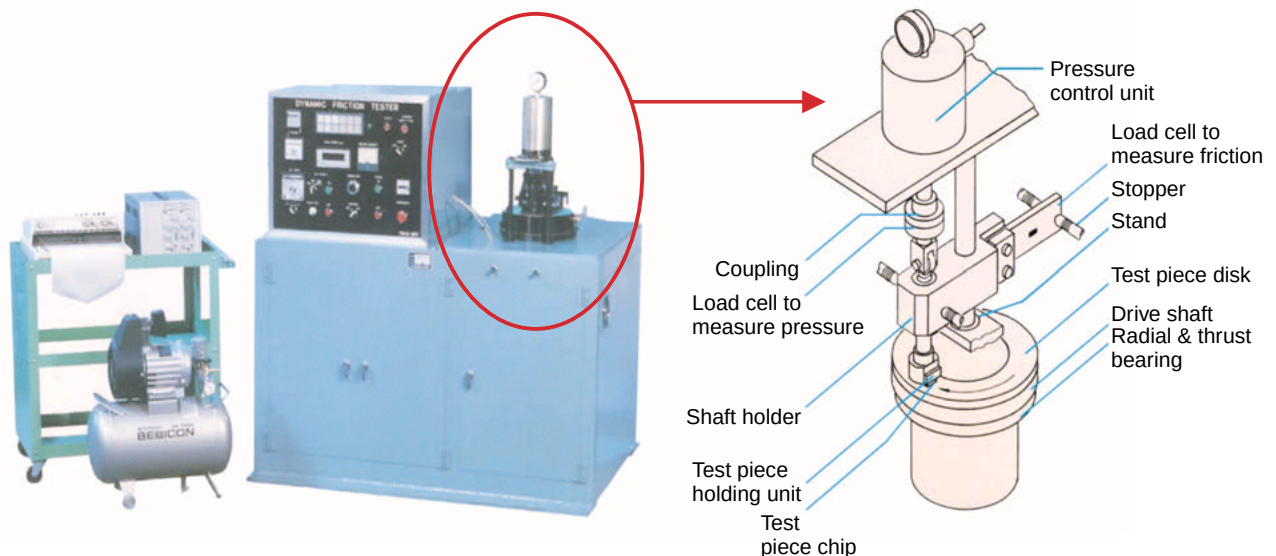


Fig. 15 Diagram and photograph of friction tester

17 mm) to the holding unit on the tester, a load was applied by the holding unit that pressed the test piece against a rotating disk made of FC250, a material equivalent to that of the cylinder liner. The rotating disk was rotated at a constant peripheral speed of 16 m/sec against the static test piece. After providing a break-in period of 3 minutes with a selected load, during which oil was dripped on to the test piece at the rate of 240 cc/min, the supply of oil was discontinued. The time till seizure was then measured. If seizure did not occur within 20 minutes, the test was terminated after 1×10^7 cycles in the same manner as a typical fatigue test, and the load at that time was determined to be the “seizure limit.”

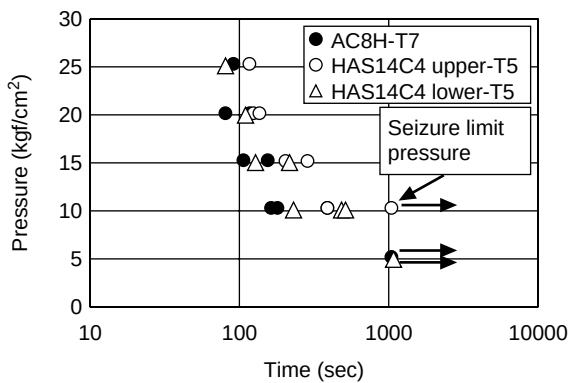


Fig. 16 Result of seizure test by friction tester

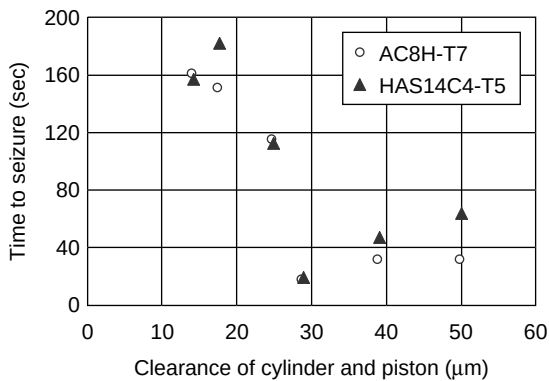


Fig. 17 Comparison of time to seizure between AC8H-T7 and HAS14C4-T5 under the dry seizure engine test

A comparison of the seizure limit for materials with upper and lower limit alloy HAS14C4-T5 compositions and AC8H-T7 is shown in Fig. 16. The newly developed material demonstrated a seizure limit superior to that of AC8H-T7. The comparison of the solidified metal microstructures described above indicates that soft α -Al crystals, which are responsible for seizure, constitute only a small proportion of the surface area of the HAS14C4-T5 material. Moreover, the microstructure of HAS14C4-T5 contains a uniform dispersion of intermetallic compounds and primary crystal of Si that contribute to the reduction of frictional resistance. These factors can be considered to be responsible for the higher seizure limit of this new material.

(2) Engine test

4-stroke general-purpose engines are often started without being filled with oil or supplied with engine oil because 2-stroke engines are more commonly used today as general-purpose engines. The resistance to seizure was evaluated by a dry seizure test assuming the first case, and by a wet seizure test assuming the second case. The engine for the dry seizure evaluation test was prepared by degreasing the cylinder bore during assembly and applying a single drop of oil. Testing was conducted by starting the engine without engine oil, immediately running the engine at 3600 rpm in the no-load state and measuring the time until seizure occurred. The test was conducted with six different values for clearance between the piston and cylinder.

The results of the dry seizure evaluation test for the AC8H-T7 and HAS14C4-T5 pistons are shown in Fig. 17. The HAS14C4-T5 piston tended to show higher seizure resistance than the AC8H-T7 piston. Photographs of the piston surface following the seizure test are shown in Fig. 18. The seizure marks on the AC8H-T7 piston were wider than those of the HAS14C4-T5 piston, and the marks from melting tended to be larger.

The engine used in the wet seizure evaluation test was assembled after applying the usual amount of oil to the cylinder bore and filling oil to the lower limit of the oil level gauge. After initially running the engine for 10 minutes at the rated load, the oil was gradually drained from the engine, and the engine was run until it stopped because of seizure. The amount of oil remaining in the engine was measured, and the appearance of the piston was observed after the engine had seized. The remaining oil in the engine at seizure was 70 cc for the AC8H-T7 piston and 58 cc for the HAS14C4-T5 piston. Photographs of the external appearance of these pistons are shown in Fig. 19. A comparison of the effects of seizure on the piston surface

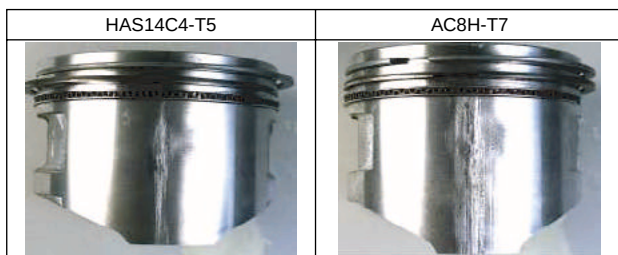


Fig. 18 Pistons after the dry seizure engine test

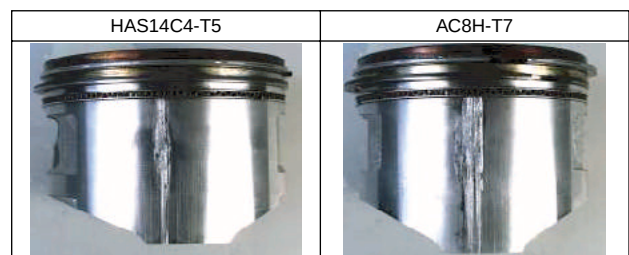


Fig. 19 Pistons after the wet seizure engine test

yielded results similar to those of the dry seizure evaluation, and the seizure resistance of the HAS14C4-T5 piston was again confirmed to be superior to that of the AC8H-T7 piston.

5. Conclusion

We have developed a new piston alloy by the DC process that offers a considerably shorter casting and heat treatment time than the conventional process to allow the use of a continuous production line. This piston alloy has mechanical properties that are equal to or better than conventional alloys used with the GDC process, under heat treatment conditions of 250°C for 30 minutes, and in seizure resistance tests it demonstrated the performance is also equal to or better than that of existing alloys.

Continuous production lines for the manufacture of general-purpose pistons are likely to be installed in the near future to enhance productivity considerably. There are great expectations for the results of research into new materials with enhanced properties and their application to manufacturing lines to improve productivity.

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