

Development of Secondary Aluminum Alloy for Diesel Cylinder Head by Mg_2Si Precipitation Strengthening

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ABSTRACT

A secondary aluminum alloy that achieves an identical level of thermal fatigue strength to a primary aluminum alloy has been developed as a material for use in the manufacture of diesel cylinder heads, parts for which high levels of thermal fatigue strength are demanded. Conventionally, primary aluminum alloys are employed for diesel heads, and their material properties are enhanced mainly by means of the Al_2Cu precipitate. The developed alloy newly applies a precipitation strengthening mechanism that functions mainly via the Mg_2Si precipitate, realizing an equivalent level of thermal fatigue strength and high-temperature strength to a primary aluminum alloy in a secondary aluminum alloy. In addition, the softening property of the developed alloy during the solution treatment process of the heat treatment, realized by means of the material's composition design, has reduced residual stress, a factor affecting the durability and reliability of cylinder heads, by a maximum of 30%.

1. Introduction

Amid increasing calls for the reduction of CO_2 emissions and other burdens on the environment, an initial necessity for automobiles is the realization of enhanced fuel efficiency performance. In order to realize this goal, the downsizing of automotive engines is proceeding for the realization of enhanced performance and increased compactness, but this trend also necessitates the realization of enhanced thermal fatigue strength (elongation) under high-temperature environments in engine structural parts such as the cylinder head. At the same time, social demands for the reduction of energy use in the automotive manufacturing process are becoming stronger. Therefore it is normal to use secondary alloys recycled from scrap as the aluminum alloys employed in automotive engine parts.

The cylinder head is a major engine part, and its main functions are to form part of the combustion chamber, to form the path for intake and exhaust, to form the path for coolant and to support peripheral parts. The majority of cylinder heads are formed by gravity die casting (GDC) or low-pressure die casting (LPDC) of aluminum alloy, and are put to use following the application of heat treatments to help ensure the desired mechanical characteristics⁽¹⁾. Cylinder heads for use in diesel engines (diesel heads) are exposed to high cylinder pressures and high-temperature environments, making thermal fatigue strength and high-

temperature strength particular demands⁽²⁾. Figure 1 shows a representative example of the microstructure of the secondary aluminum alloys used in cylinder heads. Within the microstructure the crystallization of a primary crystal aluminum matrix phase (the “ α phase” below), a eutectic crystal Si phase, and an Al-Fe-Si intermetallic compound known as K6 can be observed. This intermetallic compound is a factor in reducing the thermal fatigue strength of secondary aluminum alloys. To help prevent the crystallization of this intermetallic compound, primary aluminum alloys, to which elements essential to pure aluminum have been added and that display good thermal fatigue strength, are used for diesel heads^{(3), (4)}. To date, no examples of the application of secondary aluminum alloys to a diesel head have been reported. Honda also used

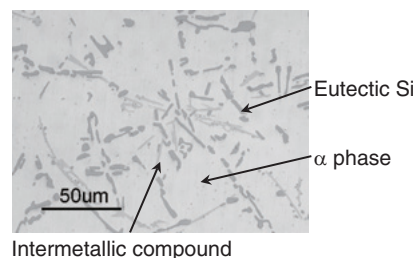


Fig. 1 Microstructures of secondary aluminum alloy for cylinder head

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primary aluminum alloy in its first diesel head for a four-wheeled vehicle. However, the primary aluminum alloy manufacturing process includes a refining process from alumina and its energy load is high. Therefore the first application of secondary aluminum alloy to a diesel head was realized.

As materials technologies employed towards this achievement, the paper will discuss the alloy composition design and the mechanism of improvement of the alloy's mechanical properties, and will consider the achieved effect in improving mechanical properties.

2. Development Goal

As indicated above, decline in thermal fatigue strength compared to primary aluminum alloys is a major issue in applying secondary aluminum alloys in order to reduce manufacturing energy. In addition, the residual stress built up when heat treatments are applied to materials used for casting complex shapes such as cylinder heads, like stress generated by such external factors as cylinder pressure when the engine is in operation, press-fitting of peripheral parts, and the tightening of the bolts, is a significant factor affecting durability and reliability, making the reduction of residual stress another important issue.

Thermal fatigue strength declines when secondary aluminum alloys are employed because cracks originating in intermetallic compounds that crystallize in the materials' microstructures tend to occur in the α phase, resulting in reduced elongation. Residual stress is high because the hardness of the material is high when the heat treatment is applied due to the use of large quantities of strengthening elements to help ensure high-temperature strength. In order to increase elongation and reduce the hardness of the material, the research discussed here decided to reduce the quantity of Cu, the main strengthening element added to the material. However, if the quantity of Cu added is reduced, the material does not achieve sufficient high-temperature strength. In order to enhance high-temperature strength, it was therefore decided to add Mg, an easily available and comparatively low-cost strengthening element, in order to recover material strength via the precipitation of fine Mg_2Si .

The project discussed here set out to develop a secondary aluminum alloy that would satisfy the criteria below, in order to make it possible for the material to realize equivalent material properties to the primary aluminum alloy (the "conventional material") used in Honda mass-production cylinder heads for diesel engines.

- (1) Equivalent level of high-temperature strength to the conventional material
- (2) Equivalent level of thermal fatigue strength to the conventional material
- (3) Equivalent or reduced level of residual stress to the conventional material

3. Material Composition Design

3.1. Concept of Material Composition Design

The material properties desired from the Al-Si-Cu-Mg heat-treated aluminum materials often employed in cylinder heads are normally obtained by means of aging precipitation strengthening of the Cu and Mg in the α phase. The mechanism of aging precipitation strengthening, shown in Fig. 2, is as follows: Atomic vacancies exist in the aluminum matrix during the solution treatment conducted as part of the T6 heat treatment, and during the aging process the strengthening elements Cu and Mg diffuse in these atomic vacancies and form precipitates. In the conventional material, the necessary material properties are obtained mainly by strengthening of the precipitate phase by Cu. Figure 3 shows the results of observation of the α phase in the microstructure of the conventional material using a transmission electron microscope (TEM). The image shows that an Al_2Cu precipitate phase with an average size of 118 nm exists in the α phase. TEM observation of the Mg_2Si phase in the α phase shows a fine Mg_2Si precipitate phase with an average size of 3.4 nm. Based on these studies of the material microstructure, it was considered that refinement of the precipitates in the α phase would represent an effective concept for maintaining high-temperature strength and increasing thermal fatigue strength in secondary aluminum alloys. The project set out to increase the number of precipitates formed by exploiting the properties of Mg, that

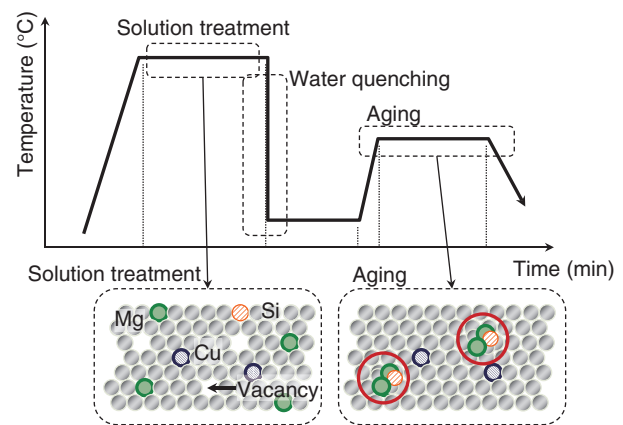


Fig. 2 Schematic illustration of Mg, Si clustering

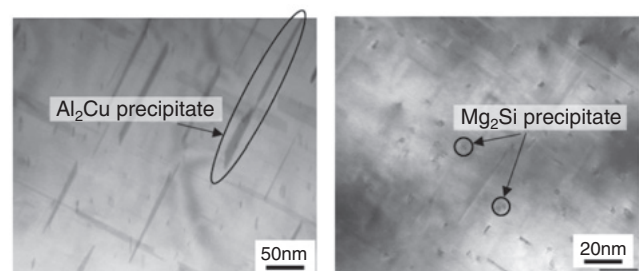


Fig. 3 Transmission electron micrograph of conventional alloy

displays a higher diffusion velocity than Cu in Al, for the refinement of the precipitates. As a result, the composition of the developed alloy used a reduced additive amount of Cu and an increased additive amount of Mg in comparison to the conventional alloy.

In addition, Cu and Mg additive amounts that would prioritize the precipitation of Mg_2Si over Al_2Cu were determined based on time-temperature-transformation curves for Mg_2Si and Al_2Cu precipitates obtained using a commercial multi-component aging precipitation simulation software (JMatPro), as shown in Fig. 4. For the developed material, the concept was to take the determined additive amounts into consideration in order to optimize the form of the precipitation phase by means of the main elements Cu and Mg, realizing the formation of fine Mg_2Si precipitates.

3.2. Test Material

To produce a test material in order to clarify the effect of aluminum alloy composition and the precipitate phase on material properties, 99.7% pure aluminum, an Al-25% master alloy, a magnesium-base master alloy, and impurity elements were added to a commercial AC2B secondary aluminum alloy, and the mixture was melted in an electric-resistance heating furnace using a graphite crucible. The melting temperature was $760^{\circ}C$ or below and the holding temperature was $720 \pm 10^{\circ}C$. In addition, the material was subjected to molten metal treatment for 12 min in Ar gas in order to exclude the effect of hydrogen gas, inclusions and oxides. Following this, the material was poured at atmospheric pressure and room temperature into a JIS boat-shaped mold pre-heated to $200^{\circ}C$ and maintained at a fixed temperature, in order to produce ingots for the manufacture of test specimens. After the application of a T6 heat treatment (conversion into a solution at $500^{\circ}C$ for 4 hr, water quenching (WQ) at $80^{\circ}C$ for 3 min, aging at $200^{\circ}C$ for 2 hr), the specimens for material properties tests were obtained from a position 10 mm from the bottom of

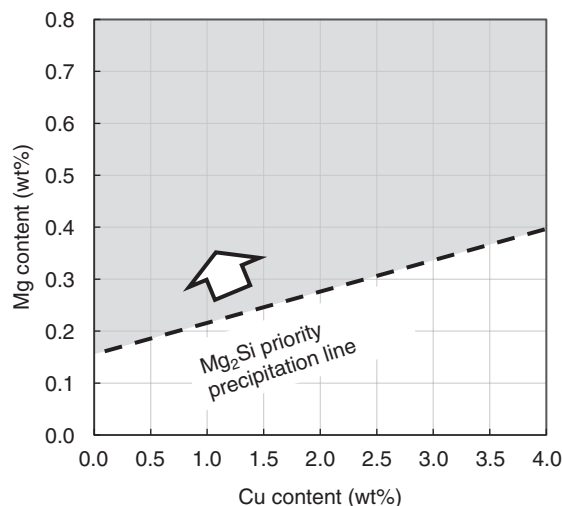


Fig. 4 Relationship of Cu, Mg content for Mg_2Si priority precipitation

the ingots. For the residual stress test, the material was cast in a dedicated mold, and melted and subjected to molten metal and heat treatments like the material used for test specimens for material properties tests. For the study of priority precipitation, a JIS 4 boat-shaped ingot identical to that used for the material properties test specimens was employed, but the material was aged for 10 min. Figure 5 shows the shapes and sizes of the test specimens used in the materials tests and the residual stress test.

3.3. Test Methods

The material properties tested were tensile strength, fatigue strength, thermal fatigue strength, and compression

	Shape and size of specimens (mm)
Tensile strength	
Fatigue strength	
Compression 0.2% proof strength	
Thermal fatigue strength	
Residual stress	

Fig. 5 Shape and size of specimens

proof strength. Average figures were determined at a range of temperatures. For residual stress, the average value was found at room temperature (RT). Table 1 shows the test temperatures for each material test. A tensile test device was used for tensile and compression testing and a test speed of 0.5 mm/min was employed. A rotary bending endurance test device was used for the fatigue strength test, and the test was conducted at a speed of rotation of 3000 rpm. The heat fatigue test used a fatigue testing machine employing an electro-hydraulic servo, and was conducted using sine waves in five-minute cycles under out-of-phase conditions such that heat deformation and mechanical deformation in the test specimens were in opposite phase. Residual stress was measured via the cutting method using a strain gauge. The study of priority precipitation employed a three-dimensional atom probe^{(5), (6)}.

3.4. Setting of Basic Composition

Table 2 shows the composition of the conventional and developed alloys. The effects of Cu and Mg, the main elements, were determined using alloys based on these compositions. The results are discussed below. First, the effect on the materials' thermal fatigue strength was judged in relation to their elongation properties. This was based on the fact that in the case of thermal fatigue strength, the range of strain is high, and in many cases the maximum strain occurs up to the plastic region. There is therefore a correlation between thermal fatigue strength and elongation.

Table 1 Test temperature conditions

	Test temperature (°C)						Soaking time (ks)
	R.T.	50	100	150	200	250	
Tensile strength	○			○	○	○	360
Fatigue strength				○	○	○	360
Compression 0.2% proof strength				○	○	○	360
Thermal fatigue strength						○	
Residual stress	○						

Table 2 Chemical composition of developed alloy (wt%)

	Si	Cu	Mg	Fe	Zn	Mn
Conventional alloy	6.5	3.0	0.2	0.10	0.01	0.01
Developed alloy	8.0	1.7	0.40	0.45	0.25	0.2

Figures 6 and 7 show the effect of the additive amount of Cu and Mg on tensile strength and elongation at room temperature, the temperature at which the tests were conducted. In the case of the effect of Cu on the material properties, tensile strength increased with an increased additive amount at a rate of 13 MPa/wt%, while elongation decreased at a rate of -0.4%/wt%. Turning to the effect

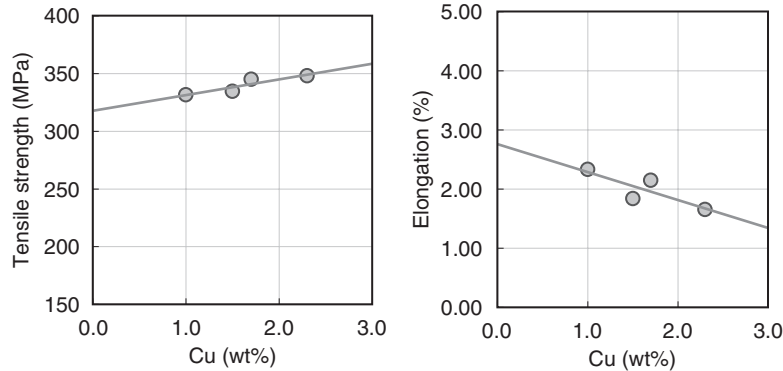


Fig. 6 Relationship between Cu content and tensile strength, elongation

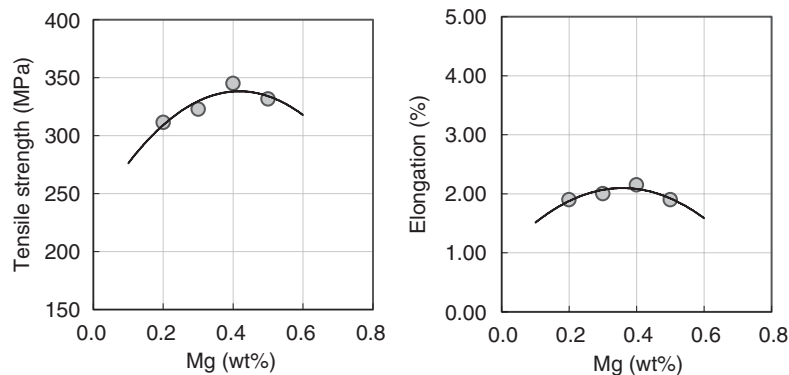


Fig. 7 Relationship between Mg content and tensile strength, elongation

of Mg on material properties, as in the case of Cu tensile strength increased with an increased additive amount, at a rate of 83 MPa/wt%. At the same time, elongation increased, in particular between 0.2wt% and 0.4wt%, at a rate of 1.25%/wt%. Based on these results, reduction of the additive amount of Cu, the main strengthening element employed in the conventional material, in order to increase elongation, and the exploitation of the effect of Mg in increasing elongation by means of its employment as the main strengthening element in place of Cu, would make it possible to increase elongation while maintaining tensile strength.

Next, the additive amounts of Cu and Mg were set in order to achieve an equivalent level of strength to the conventional material. Given that strength reached its peak at an additive amount of 0.40wt% of Mg, as shown in Fig. 7, the additive amount of Mg was set at 0.40wt%. Figure 8 shows the relationship between the additive amounts of Cu and Mg in order to achieve an equivalent level of strength to the conventional material. The additive amount of Cu was set at 1.7wt% in order to achieve this goal. The ability to realize the desired elongation at the additive amounts of Cu and Mg set with a focus on strength was also verified. Figure 9 shows the relationship between Fe content and elongation in the conventional alloy when the amount of Fe is increased. Increasing the Fe content of the material reduces elongation. This is due to the effect of the intermetallic compound discussed above. Figure 10 shows the elongation of the conventional alloy and the developed alloy with Cu and Mg additive amounts set with a focus on strength. The use of a secondary aluminum alloy results in a decline in elongation, but as indicated by the effect of Cu and Mg on elongation as shown in Figs. 6 and 7, decreasing the additive amount of Cu and increasing the additive amount of Mg increases elongation, making it possible to obtain a level of elongation equivalent to that of the conventional material.

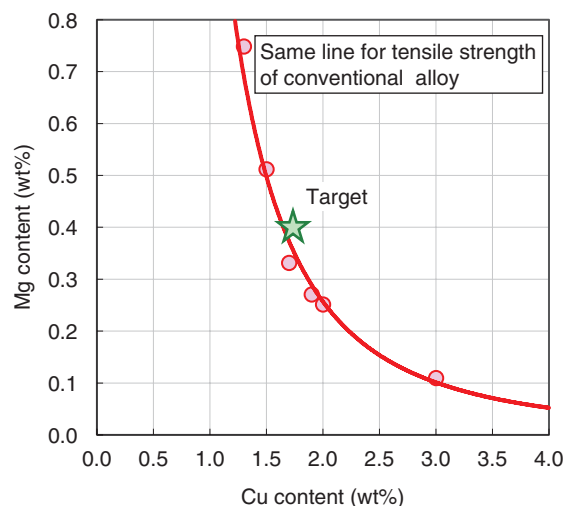


Fig. 8 Relationship between Cu, Mg content and tensile strength of conventional alloy

The composition of the alloy other than the main elements was set as follows. The additive amount of Si was set with consideration of ease of casting, in order to obtain an equivalent melting temperature and fluidity to the conventional alloy. The allowable amounts of the impurities Mn, Zn, Ti, Cr, Ni, Pb, and Sn were set at the same levels as secondary aluminum alloys, and the possibility of obtaining the desired properties at these levels was verified.

3.5. Study of Priority Precipitation of Mg_2Si

In order to verify the form of the priority precipitation of Mg_2Si , a study was conducted in order to determine whether Mg_2Si was precipitated by priority at the set additive amounts of Cu and Mg. A three-dimensional atom probe was used for the observations due to the challenge of conducting observations of the initial stages of formation of precipitates using TEM. The atom probe combined a field ion microscope (FIM) and a time-of-flight mass spectrometer (TOF-MS), making it possible to observe the distribution of atoms.

Figure 11 shows the distribution of Si, Mg and Cu atoms in a test specimen immediately following the commencement of the aging process, as observed using the three-dimensional atom probe. The results show that areas of concentration of Si and Mg atoms exist, and that these

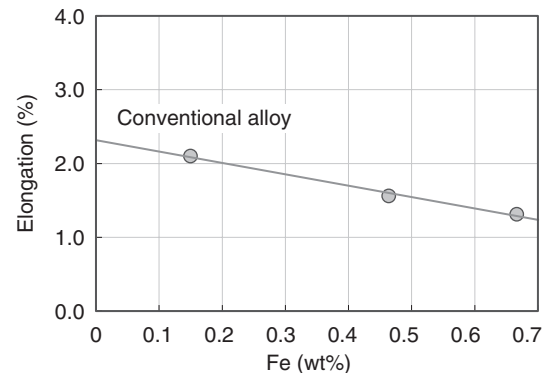


Fig. 9 Relationship between Fe content and elongation

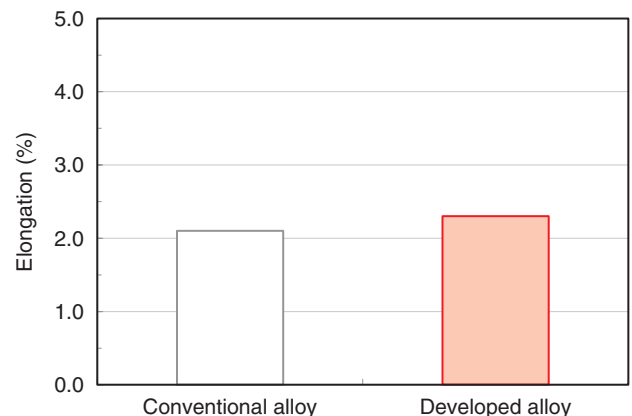


Fig. 10 Effect of elongation improvement by Cu content reduced and Mg content increased

areas correspond. No areas of concentration of Cu atoms were observed. These results indicated that at additive amounts of 1.7wt% of Cu and 0.4wt% of Mg, Mg_2Si is priority precipitated, realizing the form of precipitation projected by the development concept.

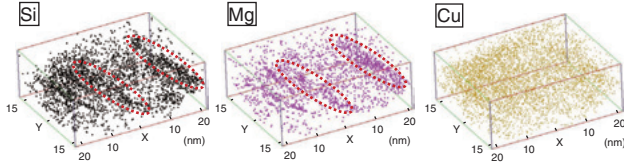


Fig. 11 Distribution of Si, Cu and Mg atoms by three-dimensional atom-probe

4. Material Properties

The developed alloy employing the composition shown in Table 2 in Section 3.4 was verified as possessing the following properties.

4.1. High-temperature Strength

Figures 12 and 13 show the results of tensile strength, fatigue strength, thermal fatigue strength, and compression proof strength. The developed alloy achieves the same levels of high-temperature tensile strength, high-temperature fatigue strength, and compression proof strength at 150°C, 200°C, and 250°C as the conventional alloy. In the case of thermal fatigue strength, the developed material displays equivalent mechanical properties to the conventional alloy in repeated tests conducted at temperatures ranging from 50°C to 250°C.

4.2. Residual Stress in a Simple Test Specimen

Simple test specimens that modeled the distribution of residual stress in a cylinder head were employed in order to compare the difference in residual stress between the alloys. Figure 14 shows the results of residual stress measurements. Residual stress, compared to the conventional alloy, is reduced by 30% in the developed alloy in both the area of occurrence of tensile stress and the area of occurrence of compression stress. Residual stress is produced by thermal strain due to differences in the temperature distribution between sections of the cylinder head, mainly during WQ from the solution treatment conducted as part of T6 heat treatment, and is affected by the hardness of the alloy when undergoing WQ from solution treatment. Figure 15 shows the Rockwell hardness of the alloy directly after WQ. Cu, Mg, and other additive elements that contributed to strengthening the α phase during the solution treatment are in a state of solid solution, but the significant reduction of the additive amount of Cu against the conventional alloy has reduced the hardness of the alloy directly after the solution treatment. This increased softness against the conventional alloy can be considered

to have reduced the material's Young's modulus, resulting in reduced residual stress. As indicated in Section 4.1, the developed alloy also displays an equivalent level of strength to the conventional alloy in the aging treatment that follows the WQ.

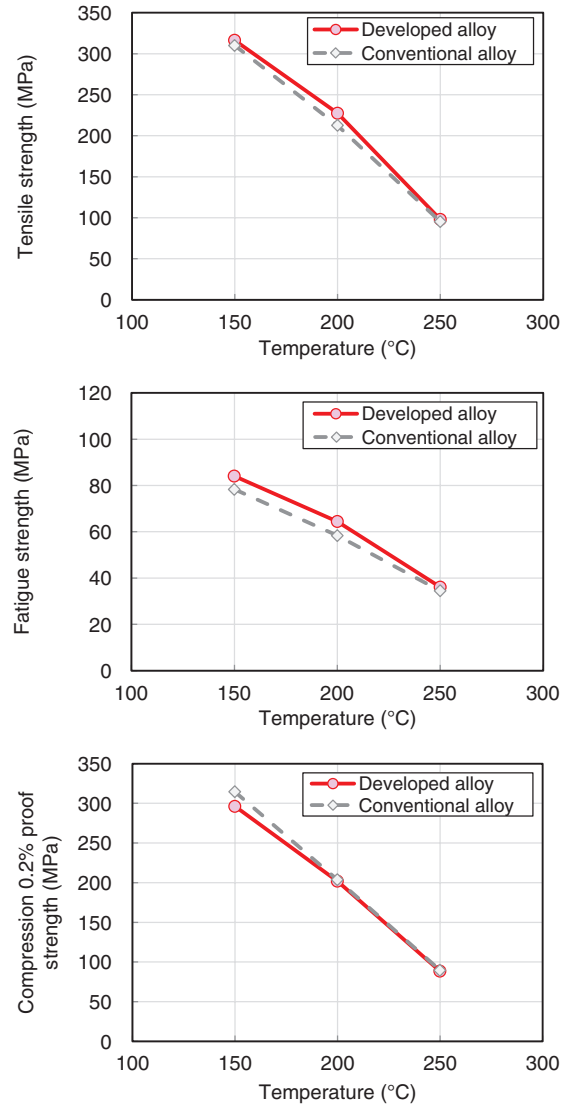


Fig. 12 Tensile strength, fatigue strength, and compression 0.2% proof strength

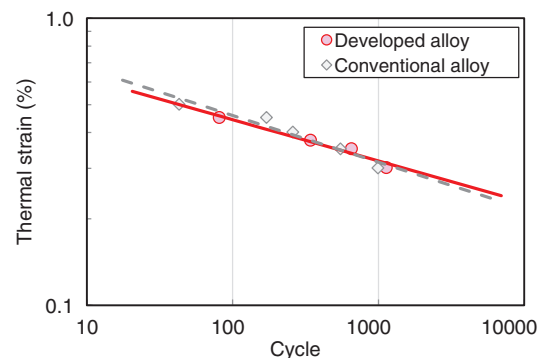


Fig. 13 Thermal fatigue strength

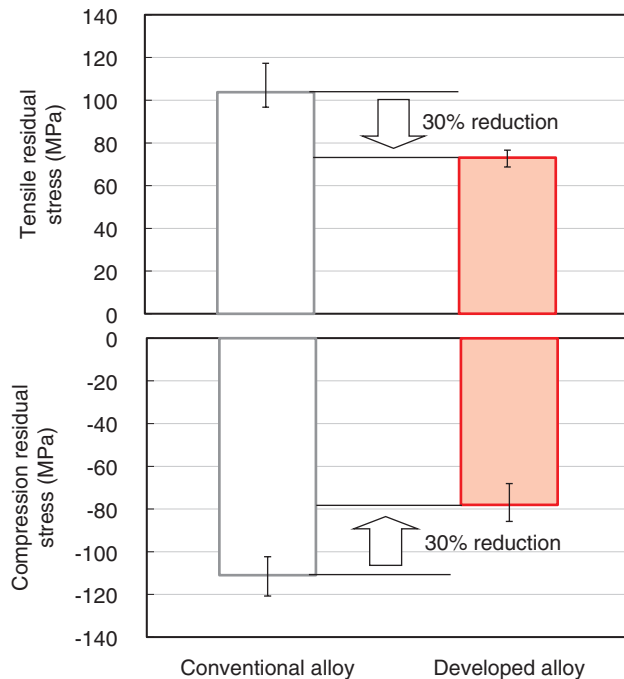


Fig. 14 Effect of developed alloy on residual stress

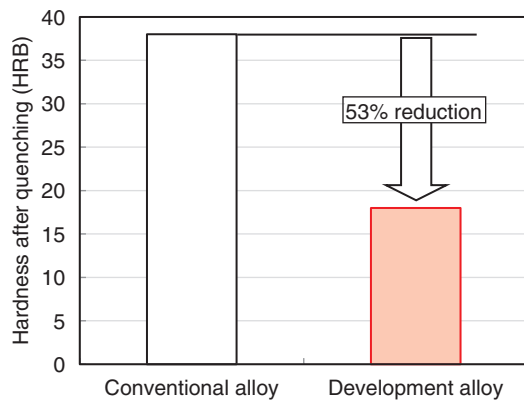


Fig. 15 Effect of developed alloy on Rockwell hardness after quenching process during T6 heat treatment

5. Conclusion

A secondary aluminum alloy has been developed that displays good thermal fatigue strength and high-temperature strength and is able to be employed in the manufacture of diesel heads. The development produced the following results:

- (1) The combination of a Cu additive amount of 1.7wt% and Mg_2Si precipitation strengthening made it possible to realize an equivalent level of high-temperature strength to the conventional alloy.
- (2) Priority precipitation of Mg_2Si made it possible to realize an equivalent level of thermal fatigue strength to the conventional alloy.

- (3) The reduction of the additive amount of Cu increased the softness of the alloy against the conventional alloy during the solution treatment conducted as part of the heat treatment, resulting in a 30% reduction in residual stress following the treatment.

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