# Optimization Studies of AC4CH Material in the Cylinder Block of a Diesel Engine Application

## Authors:

Bum Youl Park, Youngkun Kim, Kihyung Lee

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Keywords: refinement, diesel engine, AC4CH, weight reduction

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Bum Youl Park<sup>1</sup>, Youngkun Kim<sup>1</sup> and Kihyung Lee<sup>2,\*</sup>

- <sup>1</sup> Department of Mechanical Design Engineering, Hanyang University, 55, Hanyangdaehak-ro, Sangnok-gu, Ansan-si 15588, Gyeonggi-do, Korea; koreard@gmail.com (B.Y.P.); ygkim891@hanyang.ac.kr (Y.K.)
- <sup>2</sup> Department of Mechanical Engineering, BK21 FOUR ERICA-ACE Center, Hanyang University, Ansan-si 15588, Gyeonggi-do, Korea
- \* Correspondence: hylee@hanyang.ac.kr

**Abstract:** The reduction of the weight of the engine of a vessel or an automobile can result in improved engine efficiency and lower  $CO_2$  emissions. Therefore, this study was conducted to improve the mechanical properties of the AC4CH alloy, an alternative to cast iron for engine fabrication, through the addition of Si and Mg to aluminum. The mechanical properties of the alloy were improved through refinement of the Si structure, grain refinement, and heat treatment. In addition, the applicability of a cylinder block fabricated with the modified AC4CH alloy to a diesel engine was validated through a 300 h durability test.

Keywords: AC4CH; weight reduction; diesel engine; refinement

## 1. Introduction

As the regulations for CO<sub>2</sub> emissions have been gradually strengthened to cope with global warming, many studies have been conducted to improve the efficiency of automobiles [1]. Numerous technologies have been developed to reduce CO2 emissions, among which weight reduction has emerged as an important technical task; thus, many studies have focused on a variety of ways to reduce the weights of automobiles. The engine is one of the heaviest parts of an automobile. Generally, the weight of the engine for passenger cars is approximately 150–350 kg, and accounts for more than 10% of the total automobile weight depending on displacement. This means that if the car weight can be reduced by using a light engine material, CO<sub>2</sub> emission reductions as well as fuel efficiency can also be improved. Because diesel engines basically use a compression ignition mode, their compression ratios and explosive powers are high compared to engines that use the flame ignition mode. To withstand such explosive power, the cylinder block of a diesel engine is often fabricated using cast iron, which has excellent mechanical properties. However, cast iron is heavy, impairing the fuel efficiency and mobility of the cars [2]. In general, diesel engines have a high compression ratio, as the pressure in the combustion chamber increases up to 20 MPa during combustion. Therefore, the stiffness and mechanical properties of new engine materials need to be considered. In order to replace the existing iron cylinder block, a steel sleeve is inserted into an aluminum block to secure rigidity and a lightweight engine is being applied. However, this method has a problem of adding a process due to inserting the sleeve in the engine manufacturing process and increasing the weight due to the material of the sleeve.

Al alloys are widely used for weight reduction and mechanical improvement because they have excellent mechanical properties and casting characteristics [3,4]. To achieve such characteristics, various alloy component ratios and heat treatment methods have been standardized [5]. These standards improve the casting characteristics and mechanical characteristics of the precipitating intermetallic compound through the equilibrium state of the solid solution and eutectic reaction. Today, most Al alloys are in the form of Al-Si-Mg.



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**Copyright:** © 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). Among such alloys, AC4CH has a good melt fluidity and generates the least shrinkage cavity defects [6,7].

AC4CH alloy achieves excellent mechanical properties and heat treatment characteristics through the precipitation of Mg<sub>2</sub>Si by the addition of 6.5–7.5% Si and a small amount of Mg, 0.25–0.45%, and because it contains amounts of Fe and Mn that are lower than 0.2% and 0.1%, respectively, whereby the quantities are expressed as percentages of the aluminum content [8]. To improve the elongation and impact resistance of the AC4CH, a modification process is needed to refine the needlelike structure, which is the eutectic structure of Si with the help of Na, Sr, etc. because the acicular Si precipitated on the  $\alpha$ -phase grain boundary causes brittleness of the alloy. Therefore, once this acicular structure is changed to a round structure, brittleness can be reduced, which ultimately can increase robustness to elongation and impact.

Therefore, it is necessary to conduct research on refining the Si structure in the alloy to induce uniform solidification so that cast alloy grains can be refined as much as possible and to maintain an equilibrium between the uniform solid-solution state and the precipitation of Mg<sub>2</sub>Si. If the growth of a-Al-Si-Mg<sub>2</sub>Si structures and segregation formed inside the alloy are restricted, the mechanical properties of the alloy can be improved, and the weight reduction target could be easily achieved. Figure 1 shows the phase diagram of Al – Al-Mg<sub>2</sub>Si [9].



Figure 1. Calculated equilibrium phase diagram of the Al-Mg<sub>2</sub>Si pseudo binary section.

To obtain the desired physical properties of the aluminum alloy, the composition of the alloy was adjusted by referring to the phase diagram or heat treatment method. Table 1 shows the physical properties required for engine block fabrication with the aluminum alloy [10,11]. It is very easy to improve only one property among various physical properties. However, in the case of the hardness and elongation rate, because both have a trade-off relation, it is very difficult to improve both properties [12]. To resolve such difficulties, AC4CH alloy was prepared by the addition P, Sr, Si, Ti, B, and C to virgin aluminum, and the changes in the mechanical properties due to each element were determined. In addition, the changes in the mechanical properties due to different heat treatments were determined. The obtained results were reviewed for the application of the AC4CH alloy in the cylinder block of a diesel engine, and the optimal physical characteristics of the AC4CH alloy required for it to be applied in the cylinder block were determined. The objective of this study is to improve the mechanical properties of AC4CH alloy through Si spheroidization, grain refinement, and heat treatment. In addition, in order to reduce weight and simplify the process, a sleeveless aluminum block was manufactured and durability was verified through engine testing.

Item	Tensile Strength (T6)	Elongation	Hardness	S-DAS	Specification of Material's Ingredients
Unit	N/mm <sup>2</sup>	%	HB	μm	AC4CH
Target value	More than 200	More than 2	More than 100	17–20	AC4CH

Table 1. Physical properties of aluminum alloy required to manufacture the engine blocks.

#### 2. Experimental Methods

The elements P, Sr, Si, Ti, B, and C were added to the AC4CH alloy to improve its mechanical properties, and various heat treatments were also applied. The alloy was prepared in virgin aluminum after the addition of various elements to correctly determine the effects the added elements or heat treatments had on the mechanical properties of the aluminum. The virgin aluminum was melted in the RECRYTE®crucible at 730 °C, and polysilicon was added as the Si source. The molten metal was then stirred with the help of a graphite rod so that Si could resolve evenly. In the case of added magnesium, as it was oxidized by oxygen in the atmosphere, a magnesium ingot was inserted into the molten metal to shield the magnesium from oxygen.

## 2.1. Refinement of the Si Structure in AC4CH Alloy

The mechanical properties of AC4CH alloy, such as toughness and strength, are improved by the addition of Si and Mg. Si and Mg were added to virgin Al in this study within the range of the AC4CH alloy. The aluminum was then processed, and the structure of the alloy was monitored over time after the addition of Si. P and Sr were also added to the alloy to refine the Si grain, and changes in the microstructure were observed. The addition of P to Al led to the formation of AlP, which acted as a nucleus restricting the growth of Si particles [13]. The Sr formed  $Al_4Si_2Sr$  and could increase the tensile strength of the alloy by transforming the eutectic Si structure composed of acicular Si crystals into fine globular shapes [14]. Therefore, the optimum addition rate for different P and Sr amounts was determined. When pure P was added to AC4CH, there was a risk of explosion due to oxidation. Therefore, P should be added to the molten metal under an atmosphere devoid of oxygen in the presence of Cl or F compounds.  $P_4$  was coated on the surface of the  $C_2Cl_6$ in order to eliminate oxidation risk and increase the reaction efficiency during the addition of P in this study. P<sub>4</sub> was degraded into P<sub>3</sub> and P in the molten metal, and the degraded P was converted into PCl<sub>2</sub>, preventing oxidation of P. PCl<sub>2</sub>, meanwhile, was combined with the Al in the molten metal to produce AIP, and as a result, the restricted Si particles became coarse. The AlSr10 master alloy was used as an Sr element, and it was melted at 730 °C for approximately 2 h to ensure that it melted uniformly. When an additive, such as Sr, was added to the molten aluminum, either it was separated towards the top of the molten metal in the form of Al<sub>2</sub>Si<sub>2</sub>Sr or naturally disappeared as SrO, modifying the structure. As a large amount of time was needed to make the additive and molten metal react, the resulting microstructures were observed over time. An optimum casting temperature was also needed to ensure that the added elements completely degraded and reacted. Therefore, the structures were observed as the casting time changed to determine the changes in the grains due to the casting temperature of the AC4CH alloy.

#### 2.2. Grain Refinement of the AC4CH Alloy

Studies on refining the grain of the AC4CH alloy by the addition of various elements has been conducted. Generally, the Al-5Ti-1B master alloy has been used in these studies. However, as the eutectic reaction temperatures of Ti and B are much higher than those of the molten metal, the time and degree of degradation are different depending on the type of master alloy used. Al-1.05Ti becomes a solid-solution at 665 °C, while Al-5Ti melts at temperatures higher than approximately 1100 °C. Furthermore, whereas the melting point of Al-1B is 820 °C, it is higher than 1100 °C for Al-4B. The master alloy Al-5Ti-1B exceeded the eutectic point and became an alloy through the addition of Ti and B, and TiAl<sub>3</sub> and AlB<sub>2</sub>

crystals were precipitated coarsely during solidification [15]. As a considerable amount of time is needed to ensure complete degradation of these crystals in the molten metal, Ti and B became atomized, broke into the aluminum atom, and became incapable of acting as nuclei.

A chemical method in which Ti, B, and C were added in the form of elements was used so that the added elements were completely degraded and the grain could be refined. First, Ti was added in the form of  $K_2 TiF_6$ .  $K_2 TiF_6$  and was degraded into Ti in the molten metal according to reaction formula (1). KBF<sub>4</sub> was then added to B. KBF<sub>4</sub> was degraded into B in the molten metal using reaction formula (2). Meanwhile, elemental C was added in the form of  $C_2 Cl_6$ , which was degraded into element C through reaction (3).

$$3K_2TiF_6 + 4Al \rightarrow 6KF + 4AlF_3 + 3Ti,$$
 (1)

$$KBF_4 + Al \rightarrow KF + BF_3 + Al \rightarrow KF + AlF_3 + B, \tag{2}$$

$$C_2Cl_6 \rightarrow C_2Cl_4 + Cl_2, C_2Cl_2 \rightarrow CCl_4 + C, CCl_4 \rightarrow 2Cl_2 + C, \tag{3}$$

The degraded Ti, B, and C were combined with aluminum in the molten metal. The grain refinement characteristics were examined by measuring the grain sizes after the chemical addition of Ti, B, and C, and they were then compared with those when the Al-5Ti-1B master alloy was used. The grain sizes were measured from scanning electron microscopy (SEM) images. Prior to grain size measurement, the specimens were microground to 0.02  $\mu$ m and then electrolytically etched at 20 V for 2 min in 2% HBF<sub>4</sub>. The grain sizes were then measured from the SEM images in accordance with ASTM Standard E 112, "Standard Test Methods for Determining Average Grain Size." [16].

#### 2.3. Changes in Mechanical Properties by Heat Treatments

Tensile tests were conducted to measure the tensile strength, yield strength, and elongation of the alloy. The test specimen used in the tensile strength test was fabricated as shown in Figure 2. An MTS tensile tester was used for the tensile test. The tensile speed until the yield point was  $30 \text{ N/mm}^2$ s, and the strain increase rate was 80%/min after the yield point.



**Figure 2.** Specifications of the specimen used for the tensile test. D: Original cross-sectional area of parallel length; L: Original gauge length; R: Transition radius; P: Parallel length.

The hardness of the specimen was measured using the Brinell hardness test method. The Brinell hardness was determined by measuring the diameter of the impression on the test specimen created by applying a load with a carbide alloy bell. The Brinell hardness is proportional to the surface area of the impression left by the load divided by the test load. The diameter of the carbide alloy bell used in this study was 10 mm, and a load of 500 kg was applied to the test specimen for 15 s. The Brinell hardness was then calculated by dividing the applied force by the surface area of the impression, as in Equation (4).

$$HB = \frac{L}{A} = \frac{2L}{\pi D \left( D - \sqrt{D^2 - d^2} \right)} \tag{4}$$

where: *L*: applied load in kilogram force (kgf); *A*: Surface of indentation (mm<sup>2</sup>); *D*: diameter of the indenter (mm); *d*: diameter of indentation (mm).

The composition analysis for the AC4CH alloy prepared in this study was carried out according to ASTM E1251–17a [17]. Spark-atomic emission spectrometry (Spark-AES) was employed. Spark-AES uses a spark to generate a flame in the sample and measures the compositional elements of the alloy through the generated spectrum, which is different for the elements of the alloy. This method is mainly used to measure the aluminum content in alloys.

The secondary dendrite arm spacing (S-DAS), generated during the solidification process of the alloy, is known to greatly affect the mechanical properties off the alloy [18]. Therefore, it is necessary to minimize the growth of the S-DAS to improve the mechanical properties of the alloy. During the granulation process due to the addition of various substances, nuclei formed inside the atoms restrict the growth of the grains, while the aluminum atom is stabilized. The growth of the S-DAS during this process was mainly affected by the cooling speed during solidification. Therefore, the effect of the cooling speed on the growth of the S-DAS was examined. The growth of the S-DAS at various die temperatures and cooling speeds was determined while maintaining the temperature of the molten metal at 730 °C. For the Al alloy containing Si and Mg, heat treatments, such as the solution treatment and aging treatment, are the most commonly used during casting. The solution treatment is used to increase elongation by softening the material. Therefore, the alloy elements need to be heated to a temperature higher than that for melting the alloy into a solid solution. In contrast, the aging treatment is executed to make the alloy elements, which are in a solid solution than a saturated state, precipitate. The precipitated elements improve the hardness of the materials by precipitation hardening. Therefore, alloys were fabricated at various molten metal, mold, solution treatment, and aging treatment temperatures, as shown in Table 2, and these were compared according to different casting conditions.

Melt Mold Solution Aging Treatment Treatment Temperature Temperature 730 °C 450 °C 535 °C, 8 h 155 °C, 6 h 1st alloy 730 °C 450 °C 540 °C, 4 h 170 °C, 6 h 2nd alloy 730 °C 3rd alloy 300 °C 540 °C, 6 h 160 °C, 4 h

#### Table 2. Heat treatment conditions for each alloy.

## 2.4. Fabrication of the Engine Cylinder Block and Durability Test

An engine cylinder block was fabricated with the final modified AC4CH alloy using the sandcasting method. Sandcasting is a process in which a desired shape of a metal is obtained by pouring molten metal into a mold prepared with sand. The process flow is shown in Figure 3. After finishing the machining process, the surface roughness of the cylinder was measured to investigate the completeness. For surface roughness measurement, the average value was calculated after 5 measurements, and detailed test conditions are shown in Table 3.

Table 3. Surface roughness test condition.

Environment condition	20.4 °C, 46 % R.H
Stylus	140 mm, 60°, 2 $\mu$ m diamond tip
Cut-off	0.8 mm
Evaluation length	4.0 mm



Figure 3. Fabrication of the engine cylinder block through sandcasting.

A durability test was performed for the engine cylinder block prepared by sandcasting. The cylinder block would be operated while carrying a large load in most of the drive areas. The durability test was, therefore, executed with a 4000 rpm full load via the dynamometer for 300 h to simulate the harsh driving conditions. In a 4-stroke engine, one explosion occurs every two revolutions. Therefore,  $36 \times 10^6$  explosion strokes occur for 300 h at 4000 rpm. Since the mechanical durability verification criterion for aluminum alloy is  $10 \times 10^6$  cycles, 300 h of experiment is sufficient to verify the durability [19]. The performance of the engine cylinder block was measured every 50 h. In addition, the fuel consumption was measured by an installed flow meter. The detailed specifications of the engine are listed in Table 4.

Table 4. Specifications of the engine.

Description	Specifications
Displacement(cc)	1600
Number of cylinders	4
Bore $\times$ Stroke	76 imes 88
Compression ratio	15.5
Fuel injection system	Common rail (Piezo type)
Turbocharger type	Electrical variable geometry turbocharger
Maximum power (ps/rpm)	115/3400-4500

#### 3. Test Results and Discussion

3.1. Refinement of the Si Structure in the AC4CH Alloy

The Si grains at various melting times following the addition of Si to virgin Al are presented in Figure 4. The shorter the melting time of the Si, the greater the number of Si grains that precipitate in the form of primary crystals. The large amount of Si crystals observed might be because they were not degraded until the atom phase due to lack of energy and were precipitated during solidification, though they were melted well [20]. Therefore, Si crystallization can be minimized by increasing the melting time after the addition of Si during the alloy process. This means that instead of employing simple melting and mixing to form the alloy, the melting time should be long enough for Si to degrade into an atom phase so that a proper AC4CH alloy can form.



Figure 4. Changes in the microstructure with melting time after the addition of Si.

Following the addition of Si, P was added to the virgin Al to control the size of the Si grain. The results are presented in Figure 5. The microstructures of the alloy were compared and analyzed after the addition of Si, while the amount of P was changed 2 h after Si addition. When 30 ppm P was added, Si was formed as the primary crystal. Although P was added because it could not restrict the growth of Si grains, Si precipitated as crystals. The presence of Si grains was attributed to the brittleness of the grain boundary, which caused elongation and a deterioration in the tensile strength. When 40 ppm P was added, Si remained as the primary crystal, and irregular and thick acicular Si crystals were observed. This phenomenon might be because AIP formed incomplete and uneven nuclei, which could not restrict the growth of the Si grain [21,22]. However, when 50 ppm P was added, fine Si grains were formed, and the acicular Si crystals were dispersed. Further, when 60 ppm of P was added, grains finer than those in the case with 50 ppm P were formed, and acicular Si crystals were also modified to finer fibers. However, when 70 ppm P was added, the Si grains grew rather irregularly and precipitated, and the acicular Si crystals increased in thickness. Such phenomena might be due to the excessive modification that appeared in the hypereutectic alloy. If the amount of AIP increases excessively, coalescing between AIPs occurs. As a result, AIP loses its function as a nucleus that combines with Si, ultimately leading to the formation of large structures. These results reveal that excellent structures can be obtained when P is in the range of 50–60 ppm, as Si grain growth is restricted under these conditions.



Figure 5. Comparison of Si structures formed by adding various amounts of P to the molten alloy.

Grain refinement could not be achieved with the addition of only P; therefore, Sr was also added, and the changes in the alloy structure were examined. Figure 6 shows the Si crystals of the alloy to which varying amounts of Sr were added. Initially, 60 ppm P was added to the virgin Al to reduce the size of the Si grain; afterwards, Sr was added. When 50 ppm Sr was added, the acicular Si crystals remained almost unchanged. Furthermore, when 80 ppm Sr was added, the crystals were not evenly modified, resulting in an Si structure that was not refined, as the acicular Si crystals remained. However, when 120 ppm and 150 ppm Sr were added, although refined Si structures were confirmed in both cases, numerous fine Si crystals precipitated on the dendrite boundary surface. Finally, when more than 180 ppm Sr was added, small modified Si structures were observed. Because molten Al<sub>4</sub>Si<sub>2</sub>Sr contained a considerable amount of Sr, the Si structure was sufficiently refined, i.e., Si did not precipitate as crystals and was refined on the boundary surface of the crystal, indicating that modification of the structure was successful [23,24].



Figure 6. Comparison of Si structures obtained by adding 60 ppm P to the molten alloy and varying the amount of Sr.

The addition of Sr to molten alloy to form Al<sub>2</sub>Si<sub>2</sub>Sr resulted in the formation of a refined Si crystal [25]. However, the Sr that was bound during this reaction might have separated at the top of the molten metal or oxidized to SrO and disappeared naturally. The alloy structure might therefore have changed to a needle-like structure again or growing [26]. Therefore, changes in the structure owing to the duration of the casting time were observed and used to determine the optimal casting time after addition of Sr. Figure 7 shows the changes in the alloy structure according to the casting time after the addition of Sr. It was found that the Sr structure was the finest after 10 min following 180 ppm Sr addition, and the refined structure could be maintained for 40 min after Sr addition. However, at 60 min following Sr addition, the fine structure transformed into a needle-like structure. This might be because sufficient Al<sub>2</sub>Si<sub>2</sub>Sr could not form as the concentration of Sr reduced over time [27]. Therefore, to maintain the modified Sr structure, the casting duration should not exceed 40 min after the addition of 180 ppm Sr, and if the casting duration exceeds 40 min, additional Sr must be added to the melt so that the excellent alloy structure can be maintained.



Figure 7. Changes in Si structure with casting time.

## 3.2. Grain Refinement of the AC4CH Alloy

Various materials were added to reduce the size of the grains to refine the alloy grains. A total of 60 ppm P and 180 ppm Sr were added to the virgin Al, in which only the sizes of Si crystals were controlled to investigate the effect of the added material on the grain size. The resulting crystal sizes were measured, as shown in Figure 8. While the crystals were not modified, the size of the crystal was as small as 900  $\mu$ m and as large as 1800–2200  $\mu$ m, displaying a very irregular distribution. The larger the grain size, the more inferior the mechanical properties, and there was a possibility of defects due to gas or oxide inclusion between the grains [28].



Figure 8. Grain size of AC4CH without grain control after refinement by Si.

Figure 9 shows the results of the addition of the Al-5Ti-1B master alloy, which has been widely used to refine grains. Each of the Al-5Ti-1B master alloys at 0.05%, 0.1%, and 0.2% were added to the molten metal, and the sizes of the grains were compared. When 0.05% Al-5Ti-1B master alloy was added, the size of the grains was in the range of 800–1100  $\mu$ m. However, overall, the grains were not refined and the size of the grains was formed non-uniformly. Into 0.05% Al-5Ti-1B, 25 ppm Ti and 5 ppm B were added.

Therefore, the amount of TiAl<sub>3</sub> and AlB<sub>2</sub> that could refine the grains might be lower. In other words, although the size of the grains became smaller with no grain modification, it seems that TiAl<sub>3</sub> and AlB<sub>2</sub> do not solute [29]. Further, when 0.1% Al-5Ti-1B master alloy was added, the sizes of the grains were in the range of 600–850  $\mu$ m, which was generally large, and their sizes were not uniform. Once again, when 0.2% Al-5Ti-1B master alloy was added, the grain size was in the range of 450–550  $\mu$ m. Even with 25 ppm Ti and 5 ppm B, grain refinement was not well executed. This might not be due to lack of TiAl<sub>3</sub> and AlB<sub>2</sub>, but the melting points of precipitated TiAl<sub>3</sub> and AlB<sub>2</sub> were high, consuming more time and energy to be degraded to the atomic state; thus, it is hard to be melted into the Al atoms [30]. If a larger amount of Al-5Ti-1B master alloy had been employed, the maximum solution amount of Ti would have been in excess, resulting in the precipitation of TiAl<sub>3</sub> and AlB<sub>2</sub> on the boundary surface, which might have impaired its castability.



Figure 9. Comparison of the grain sizes of AC4CH alloy with different amounts of Al-5Ti-1B master alloy.

Figure 10 shows the grains of the AC4CH alloy into which Ti and B were chemically added. With the chemical addition method, the compound was degraded in the molten metal, and Ti and B atoms were produced. These atoms reacted with Al to produce TiAl<sub>3</sub> and AlB<sub>2</sub>.  $K_2$ TiF<sub>6</sub> at 0.014% and KBF<sub>4</sub> at 0.013% were added to adjust the Ti concentration to 25 ppm and B at 5 ppm. The grain size after the addition of Ti and B was measured as 600–750 µm. Although the size of the grains was large and uneven, the grain refinement was far better than when the Al-5Ti-1B master alloy was added.



Figure 10. Grain size control for AC4CH alloy by the chemical addition of Ti and B.

In another test, 50 ppm Ti and 10 ppm B were added in the form of 0.028% K<sub>2</sub>TiF<sub>6</sub> and 0.025% KBF<sub>4</sub>. In this case, the average grain size was 250–450  $\mu$ m. Therefore, excellently refined grains and slightly large grains were generated. This was because low quantities of TiAl<sub>3</sub> and AlB<sub>2</sub> were produced, causing deviations in the solid solution [30]. From the above results, it is clear that higher amounts of Ti and B were needed to produce sufficient

quantities of TiAl<sub>3</sub> and AlB<sub>2</sub>. Therefore, 0.06% K<sub>2</sub>TiF<sub>6</sub> and 0.05% KBF<sub>4</sub> were added to adjust the Ti concentration to 100 ppm and B concentration to 20 ppm. The resulting average size of the grains, whose size was controlled and evenly distributed, was 300–400  $\mu$ m. This might be because, with the Al-5Ti-1B master alloy, the melting points of the TiAl<sub>3</sub> and AlB<sub>2</sub> grains, which were formed in the master alloy, were high; therefore, high energy and time were required to degrade them. However, when Ti and B were added through the K<sub>2</sub>TiF<sub>6</sub> and KBF<sub>4</sub> compounds, TiAl<sub>3</sub> and AlB<sub>2</sub>, which were bound in the form of atoms, quickly released their Al atoms, forming finer and uniform grains [31].

To refine the grains, Ti and B, as well as compounds containing C, were chemically added to the AC4CH alloy to form TiAl<sub>3</sub>, AlB<sub>2</sub>, and TiC. Figure 11 shows the microscopic images after the addition of Ti, B, and C to the molten metal, and grain size refinement. In addition, 0.0085% K<sub>2</sub>TiF<sub>6</sub>, 0.013% KBF<sub>4</sub>, and 0.002% C<sub>2</sub>Cl<sub>6</sub> were added to adjust the concentrations of Ti, B, and C to 15 ppm, 5 ppm, and 1 ppm. The combination of the added materials yielded uniform grains with a grain size of 350–400 µm. Furthermore, 0.033% K<sub>2</sub>TiF<sub>6</sub>, 0.05% KBF<sub>4</sub>, and 0.008% C<sub>2</sub>Cl<sub>6</sub> were added to adjust the concentrations of Ti, B, and C to 15 ppm. This combination further improved the grain size to 200–250 µm. Specifically, the Al-5Ti-1B master alloy was added at 0.2% for refinement of the alloy, while when Ti, B, and C were added chemically, the refinement effect was maximized even with far smaller amounts.



Figure 11. Grain size control for the AC4CH alloy through the chemical addition of Ti, B, and C.

## 3.3. Refinement of the Secondary Dendrite Arm Spacing (S-DAS) by the Cooling Speed

The average S-DAS sizes were measured after fixing the temperature of the molten metal at 730 °C while changing the mold temperature. The results are illustrated in Figure 12. When the mold temperature was adjusted to 400 °C, the average S-DAS was measured as 37.54  $\mu$ m. As the mold temperature was further reduced to 370 °C, the average S-DAS also decreased to 16.23  $\mu$ m. However, when the mold temperature was further reduced to less than 300 °C, the fluidity of the molten metal decreased, resulting in a filling defect. Therefore, it was confirmed that the optimal mold temperature required to minimize the S-DAS without defect formation was 300 °C.

400 ℃ (37.54 μm)	370 ℃ ( <b>31.95</b> μm)	350 ℃ (27.31 μm)
15122 un	255.226 µm	168.50 Mar 2.853 Mar
400 ℃ (22.60 µm)	300 ℃ (16.23 μm)	
148.771 µm	5338 m 18365 m 1838 m	



#### 3.4. Changes in Mechanical Properties by Heat Treatment Methods

The process was changed at the casting stage to improve the mechanical properties of the AC4CH alloy. Tables 5 and 6 shows the measurement results for mechanical properties such as the tensile strength, yield strength, elongation, hardness, and S-DAS by varying the temperature and time of the solution treatment and aging treatment.

Testing Items	Tensile Strength (N/mm <sup>2</sup> )	Yield Strength (N/mm <sup>2</sup> )	Elongation (%)	Hardness (HBW 10/500)	S-DAS (µm)
1st alloy	317	257	8	62.5	-
2nd alloy	269	188	10.8	80	41
3rd alloy	235	129	23	87	16.09

 Table 5. Mechanical properties of alloys prepared under different process conditions.

Table 6. Composition of alloy prepared under different process conditions.

Alloy Components	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	Pb	Sn	Cr	Al
1st alloy	0.03	7.49	0.28	0.01	0.12	0.005	0.01	0.12	0.01	0.001	0.003	91.91
2nd alloy	0.08	7.16	0.26	0.02	0.18	0.09	0.02	0.11	0.01	0.001	0.001	92.05
3rd alloy	0.03	6.73	0.44	0.01	0.14	0.01	0.02	0.11	0.04	0.03	0.11	92.46

In the 1st alloy, 60 ppm P and 180 ppm Sr were added to control the Sr grain by refinement and granulation. The temperature of the molten metal was maintained at 730 °C, and the mold was heated to 450 °C for alloy preparation. The solution treatments at 535 °C for 8 h and at 155 °C for 6 h were intended to increase the precipitation of Mg<sub>2</sub>Si on the aluminum grain boundary surface. The resulting 1st alloys had an excessive amount of Si, and the tensile strength and yield strength were high while the precipitation of Mg<sub>2</sub>Si increased during heat treatment [32]. However, the elongation was low at 8% and hardness did not improve. The grain was not refined as well as the S-DAS, exhibiting small surface areas in the grain, indicating that Mg<sub>2</sub>Si might have not gone through a smooth solid solution [33]. Therefore, precipitation hardening did not contribute to hardening improvement.

For the 2nd alloy, 60 ppm P and 180 ppm Sr were added to virgin Al to reduce the size of the Si grain. Another 60 ppm Ti, 20 ppm B, and 4 ppm C were added to refine the grain to 200–250  $\mu$ m. During casting, the temperature of the molten metal was maintained at 730 °C, and the mold was preheated to 450 °C for alloy preparation. The heat treatment was

executed as a solution treatment at 540 °C for 4 h to expedite formation of the Al-Si-Mg<sub>2</sub>Si solution and to raise the degradation speed. Meanwhile, the aging treatment was carried out at 170 °C for 6 h to generate enough of the molten solution, as the alloy would not form a solution properly due to the elution at the surface of the alloy at high temperature. Furthermore, the refinement of the S-DAS was also confirmed when the grain was refined. Although the tensile strength and yield strength decreased as compared to those in the 1st alloy, the hardness was increased by 10/500 (80 HBW), and the elongation was also increased to 10.8%. This might be because hardening of the solution occurred as the amount of solution increased in Mg<sub>2</sub>Si during the refinement and aging treatments [34]. The average S-DAS was 41  $\mu$ m, which was slightly high, indicating that with grain refinement, the S-DAS could not be granulized, which could be improved through additional refinement of the S-DAS to improve the mechanical properties of the AC4CH alloy.

For the 3rd alloy, 60 ppm P and 180 ppm Sr were added to control the size of the Si grains, and an additional 60 ppm Ti, 20 ppm B, and 4 ppm C were introduced for grain refinement, which resulted in grain sizes of 200–250 µm. Based on the 1st and 2nd alloy results, the amount of Si was slightly reduced to improve the precipitation on the grain boundary surface to increase the elongation by increasing Mg<sub>2</sub>Si formation so that the hardness could be improved (Table 4). Casting was again executed after setting the temperature of the molten metal at 730 °C for fast cooling, and the mold was preheated to 300  $^{\circ}$ C to prepare the test specimens. The solution treatment duration was increased to 6 h so that Mg<sub>2</sub>Si could completely melt, and the aging temperature was reduced to 160 °C to strengthen the hardening of the solution. The casting time was also reduced to 4 h to reduce the time during which precipitation was formed on the grain boundary. The results revealed that, although the tensile strength and yield strength were slightly reduced compared to those in the 2nd test, the elongation remarkably increased to 23%. The hardness might have increased owing to increases in the refinement of the S-DAS and the amount of Mg<sub>2</sub>Si formed. In particular, the elongation remarkably increased, which was attributed to the refinement of the S-DAS. Meanwhile, Si precipitation on the grain boundary surface decreased and the dispersed structure could be achieved by the refinement of the Si and Mg<sub>2</sub>Si S-DAS, which in turn might have slightly impaired the tensile strength and yield strength [35].

Despite the remarkable increase in the elongation of the 3rd alloy, the hardness was still low. To further increase the hardness, the solution treatments were again executed at 535 °C and 540 °C for 8 h each, and the aging treatments were performed at 160 °C, 170 °C, and 180 °C for 7 h each. The heat treatments were intended to allow the added elements to become complete solutions, and the changes in the hardness for each temperature were measured.

The hardness test results for different heat treatments are tabulated in Table 7. The treatments performed for 7 h to promote the degradation of Mg<sub>2</sub>Si into a solution and to make the aging treatment sufficiently equilibrated yielded higher hardness values of more than 100 (HBW 10/500). At a solution temperature of 535 °C, the hardness value was high. However, when the solution temperature was increased to 540 °C, the Al-Si-Mg<sub>2</sub>Si alloy could not be degraded. Instead coalescence occurred, which might have impaired the hardness. The maximum hardness values were obtained at an aging temperature of 180 °C, which might be because, the higher the aging temperature, the greater the amount of Mg<sub>2</sub>Si that degrades, forming a solution that results in a higher hardness. This means that solution treatment should be executed at a temperature that does not encourage the alloy molecules to coalesce with each other. It should be noted that the hardness due to hardening of the solution was higher than that due to precipitation of Mg<sub>2</sub>Si.

Test	Solution Trea	tment	Aging Treat	Hardness	
Specimen	Temperature (°C)	Time (h)	Temperature (°C)	Time (h)	(HBW 10/500)
А	535	8	180	7	122
В	535	8	170	7	115
С	535	8	160	7	116
D	540	8	180	7	111
Е	540	8	170	7	112
F	540	8	160	7	112

Table 7. Hardness changes due to the temperature and duration of the solution and aging treatments.

## 3.5. Surface Roughness According to Cutting Speed

Surface roughness testing is essential because the metal surface changes during the cutting process such as turning, milling, grinding, lapping, boring, and honing. Surface roughness is greatly affected by the rotational speed of tool and feed rate during cutting. The surface roughness according to the rotational speed of tool and feed rate is shown in Figure 13. It was confirmed that the lower the rotational speed of the tool and the faster the feed rate, the higher the surface roughness. In particular, after the feed rate was 100 mm/min, the surface roughness increased sharply. However, when the rotational speed of the tool is 1500 rpm, the surface roughness is  $3-4 \mu m$ , even at a feed rate of 200 mm/min. Therefore, while considering the production speed, a cylinder block was manufactured with a feed rate of 200 mm/min and a tool rotational speed of 1500 rpm, and the surface roughness of each cylinder after honing is shown in Table 8. The surface roughness of each cylinder after honing is shown in Table 8. The surface roughness of each cylinder after thoning is shown in Table 8. The surface roughness of each cylinder after 13.



Figure 13. Surface roughness according to feed rate.

Table 8. Surface roughness of each cylinder.

Cylinder No.	1	2	3	4
Surface roughness (µm)	4.01	4.03	4.51	4.2

#### 3.6. Durability Test Results for the Engine

A cylinder block was fabricated using the modified AC4CH alloy chosen in this study, and a durability test for the cylinder block was performed for 300 h. After the durability test, the engine was dismantled for examination. Figure 14 shows photographs of the cylinder block dismantled after the 300 h durability test. Although the test was executed while driving the cylinder block under harsh conditions, the abrasion of the cylinder

block horning was fair, and damage or cracks were not observed. However, at the contact portion between the piston top and the second land, minute polishing occurred, which might be due to carbon precipitated between the piston and cylinder block. Still, there was no sculping due to the polishing or functional problems such as impairment of the compressive pressure. Therefore, if the modified AC4CH material were applied to the cylinder block, the durability of the engine could be secured.



Figure 14. Abrasion of the cylinder block after the durability test.

The maximum torques were measured with an engine dynamometer during the durability test, and the fuel consumption was also measured using a flowmeter. The relationship between the torque and output is given by Equation (5). The fuel consumption of the engine can be expressed as a break-specific fuel consumption (BSFC), which is the fuel consumption rate per unit output, and can be calculated by using Equation (6). The changes in the engine torque and BSFC measured during the 300 h durability test are presented in Figures 15 and 16. As the durability test progressed, the engine stabilized as the mechanical aging progressed, while decrements in the torque and BSFC gradually diminished. Specifically, the boost-up by the turbocharger started in full swing, and from 1500 rpm, when the combustion stabilized, the differences between the starting and final values of both the torque and BSFC were within 5%. Therefore, when the modified AC4CH material was used for the cylinder block, the durability of the engine cylinder black could be secured.

$$P = 2\pi NT, \tag{5}$$

$$BSFC = \frac{m_f}{P},$$
(6)

where: P: Engine power (kW); N: Engine rotational speed (rev/s); T: Engine torque (Nm);  $\dot{m}_{f}$ : mass flow of fuel (g/h).



Figure 15. Changes in the engine torque during the 300 h durability test.

**BSFC** 



Figure 16. Changes in the engine BSFC during the 300 h durability test.

## 4. Conclusions

It was proven that when  $P_4$  was chemically added to make the concentration of P 60 ppm, the grain size of Si could be controlled, whereas with 180 ppm Sr, the Si grain size became fine.

It is very important to refine the alloy structure to improve the mechanical properties of metals. When 60 ppm Ti, 20 ppm B, and 4 ppm C were added to the solution treatment of the alloy for grain refinement, the fine grains with a size range of 200–250  $\mu$ m were obtained.

S-DAS size measurement results obtained after preheating the mold to reduce dendrites, which were formed during solidification of the aluminum alloy, revealed that the S-DAS size was 16  $\mu$ m when the temperature of the molten metal was 730 °C and the mold temperature was 300 °C.

The tensile strength of the alloy was in the range of  $235-317 \text{ N/mm}^2$  under various temperature conditions. As the amounts of Si and M in the alloy were increased, the tensile strength exhibited an increasing tendency. As an effect of the heat treatment, the tensile strength increased when the aging temperature was reduced, and the heat treatment duration was shortened to increase Mg<sub>2</sub>Si precipitation.

The elongation of the cast alloy increased as the  $Mg_2Si$  was fully converted into a solution, and the Si and  $Mg_2Si$  precipitated less on the grain boundary. Heat treatment was sufficient to make  $Mg_2Si$  form a solution, and the addition of an alloy containing 6.73% Si and 0.44% Mg resulted in a maximum improvement in the elongation of 23%.

When Mg<sub>2</sub>Si was degraded and formed a complete solution to restrict precipitation during the heat treatment, the hardness increased owing to solution hardening. The best alloy hardness was achieved with the solution treatment at 535 °C for 8 h and the aging treatment at 180 °C for 7 h.

The 300 h durability test for the engine whose cylinder block had been fabricated with the modified AC4CH alloy revealed that although minute polishing occurred at the contact points between the piston top and second land, there were no functional issues. In addition, abrasion in the horning was acceptable, and damage such as cracks was not found.

The engine torque and BSFC measurement results revealed that mechanical aging progressed during the 300 h durability test, resulting in a decrease in torque and BSFC reduction. Furthermore, the differences between the torque and BSFC before and after the tests stabilized to within 5%, confirming that the durability could be secured with a cylinder block fabricated with the modified AC4CH material.

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