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Material Properties of Various Cast Aluminum Alloys Made Using a Heated Mold Continuous Casting Technique with and without Ultrasonic Vibration

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Abstract: This work was carried out to develop high-quality cast aluminum alloys using a new casting technology. For this purpose, commercial Al alloys were created by heated mold continuous casting (HMC) with ultrasonic vibration (UV). With the HMC process, the grain size and the crystal orientation of the Al alloys were controlled, *i.e.*, fine grains with a uniformly organized lattice formation. In addition, an attempt was made to modify the microstructural formation by cavitation. These microstructural characteristics made excellent mechanical properties. Using UV in the continuous casting process, more fine and spherical grains were slightly disordered, which was detected using electron backscattered diffraction. The mechanical properties of the UV HMC Al alloys were slightly higher than those for the related cast Al alloys without UV. Moreover, the severe vibration caused higher mechanical properties. The lattice and dislocation characteristics of the cast samples made with and without UV processes were analyzed systematically using electron backscattered diffraction.

Keywords: aluminum alloy; ultrasonic vibration; heated mold continuous casting; mechanical property; microstructural characteristic

1. Introduction

In recent years, high fuel efficiency in the automotive industry has been required because of environmental issues. To achieve this, a reduction in exhaust gases, such as carbon dioxide and nitrogen oxide, is required, as the number of automobiles has increased to more than one billion across the world. Automobiles consist of a number of related parts, many of which have been made using cast iron and steel. It is expected that Fe-based automotive parts will eventually all be replaced with more lightweight metals, e.g., aluminum alloys. The specific weight of Fe is approximately 7.8 g/cm^3, which is more than 2.8 times higher than that for Al. Recently, the number of automotive parts made of Al alloy has increased. Al–Si–Cu-based cast aluminum alloys (ADC12) have high mechanical properties and good castability, so these alloys have been used for automotive parts with complicated shapes, e.g., cylinder blocks, transmission cases, and converter housings. Like ADC12, Al–Si alloys (ADC1) have good castability, and these alloys are employed for frames and front panels. Al–Mg alloys (ADC6) offer good corrosion resistance for most kinds of environmental exposure because of a highly protective barrier of oxide film on the alloy surface. As the Al–Mg alloys do not rust strongly on exposure to the environment, the alloys are employed for wincer holders. However, these alloys do not have high castability. Similar to Al–Mg alloys, Al–Cu–Si alloys have poor castability (AC2A), while AC2A alloys have good machinability and high fracture toughness. These alloys are therefore used for high-strength engine parts. Al–Si–Ni–Cu–Mg alloys (AC8A) have been utilized for high-performance pistons because the alloys have high tensile strength, high wear resistance, and low thermal expansion at high temperature. Al–Si–Mg alloys (AC4CH) have good castability, good corrosion resistance, and high fracture toughness. AC4CH alloys have been employed for various engine parts and wheels.

To produce automotive parts with high-quality cast aluminum alloys, various casting technologies have been employed, e.g., die-casting, semi-solid casting, squeezed casting, pore-free casting, vacuumed casting, and continuous casting. Although the quality of cast aluminum alloys has been improved, their mechanical properties (strength and ductility) are not high enough compared to cast iron and steel. Since the application of cast aluminum alloys for the manufacture of safety-critical parts in automobiles has been considerably restricted, further improvement of their mechanical properties is required.

It is generally considered that small grains with spherical shapes are significantly important to make excellent mechanical properties. To obtain such microstructural characteristics, some practical techniques of rapid solidification, high casting flow, and addition of fine nucleating elements are employed. Moreover, in recent years, new technologies have been proposed with mechanical modifications, including electromagnetic vibration [1], mechanical vibration, and mechanical shearing processes.

Aghayani and Niroumand [2] examined the effects of ultrasonic vibration (UV) treatment on microstructural features and tensile strength. The melt alloy in sand molds was subjected to ultrasonic waves of different power levels for 5 min at a frequency of approximately 20 kHz and a maximum power of 600 W. Strong effects on the size and sphericity of α–Al dendrites were obvious. In addition, high applied ultrasonic power resulted in small, more rounded and uniformly distributed α–grain and eutectic particles. Feng *et al.* [3] attempted to apply UV to a melt hypereutectic Al–23%Si alloy in a horn crucible. With this process, hydrogen bubbles were removed, the primary silicon particles were

refined, the α–Al dendritic crystal was formed with an equiaxial crystal, and the eutectic lamellar spacing increased. A similar approach using hypereutectic Al–Si alloys was carried out by Abramov *et al.* [4]. In their study, primarily Si plates were disconnected and broken, forming spheriodized crystals under ultrasonic treatment, which made alloys with high plasticity and high strength. Taghavi *et al.* [5] also proposed mechanical vibration for producing semi-solid slurry with thixotropic microstructures in an Al–6.58%Si alloy (A356). In their work, the influences of vibration frequency and time on the size and morphology of the α–Al phase were investigated, where thixotropic microstructures together with small and spherical α–Al phases were obtained by severe vibrations. That is, the size of the primary solid phase decreased with increasing vibration times to 15 min, but the size increased with increasing vibration times of more than 15 min. Furthermore, the increment of frequency and vibration time up to 15 min led to an increase in the density of A356 aluminum alloys: a high density of 2.68 g/cm^3 was obtained at 50 Hz [6]. The effect of the UV process during the casting process on material properties in 7050 aluminum alloy was examined [7], and a finer microstructure that made a high-strength alloy was obtained. It was also considered that pure metals have poorer ultrasonic tractability than their alloys, while very high purity aluminum substantially refines the microstructure, resulting in better mechanical properties [8]. The UV treatment has not only been an advantage to make excellent solidification structures, but has also reduced defects, e.g., pores. Xu *et al.* attempted to degas aluminum A356 alloy using UV at a frequency of 20 kHz and vibration intensities up to 1500 W [9]. Up to data, Puga *et al.* [10,11] have examined the mechanical properties of grain refined Al alloys using ultrasonic treatments. In their work, tensile properties were improved significantly due to the ultrasonic vibration, e.g., ultimate tensile strength of their Al-Si-Cu alloy with UV is about 1.5 times higher than that without UV [12].

From the above previous work, it appears that a number of experimental works have been conducted to produce high-quality cast Al alloys using the UV process [3]. However, the present authors believe that there is still a requirement for new casting technologies using UV devices. This is because, in the previous studies, UV was conducted only to the melt in crucibles and molds. Although several researchers have done excellent studies to understand the UV effect on the mechanical properties for Al alloys, we believe that there is still opportunity to study the vibration effects on the material properties. This is because the associated examinations have been executed under limited vibration conditions, e.g., a few vibration amplitudes and frequencies.

Until now, the authors have attempted to make high-quality cast Al alloy using heated mold continuous casting (HMC). These HMC aluminum alloys have excellent mechanical properties (tensile and fatigue strength), where tensile strength and fatigue strength are more than twice as high as those for the same alloys created by conventional gravity castings. This is because of the tiny microstructures and uniformly organized crystal orientations. On the basis of previous work, we believe that the mechanical properties of the cast Al alloys could be further improved by the following hybrid casting technology: the HMC process using UV. Thus, in the present study, an attempt was made to develop a new hybrid casting process. With this casting system, the mechanical properties of several Al alloys were investigated, and the material properties analyzed by considering lattice and strain characteristics.

2. Experimental Procedures

2.1. Material Preparation

In the present study, several aluminum alloys (AC2A, AC4CH, AC8A, ADC1, and ADC6) and pure aluminum (99.9% Al) were selected. The main chemical composition of those aluminum alloys are indicated in Table 1. The Al alloys have been employed in various automotive parts as mentioned in the previous section, while the pure aluminum has been used for electric wire.

Table 1. Chemical composition of cast aluminum alloys (wt%).

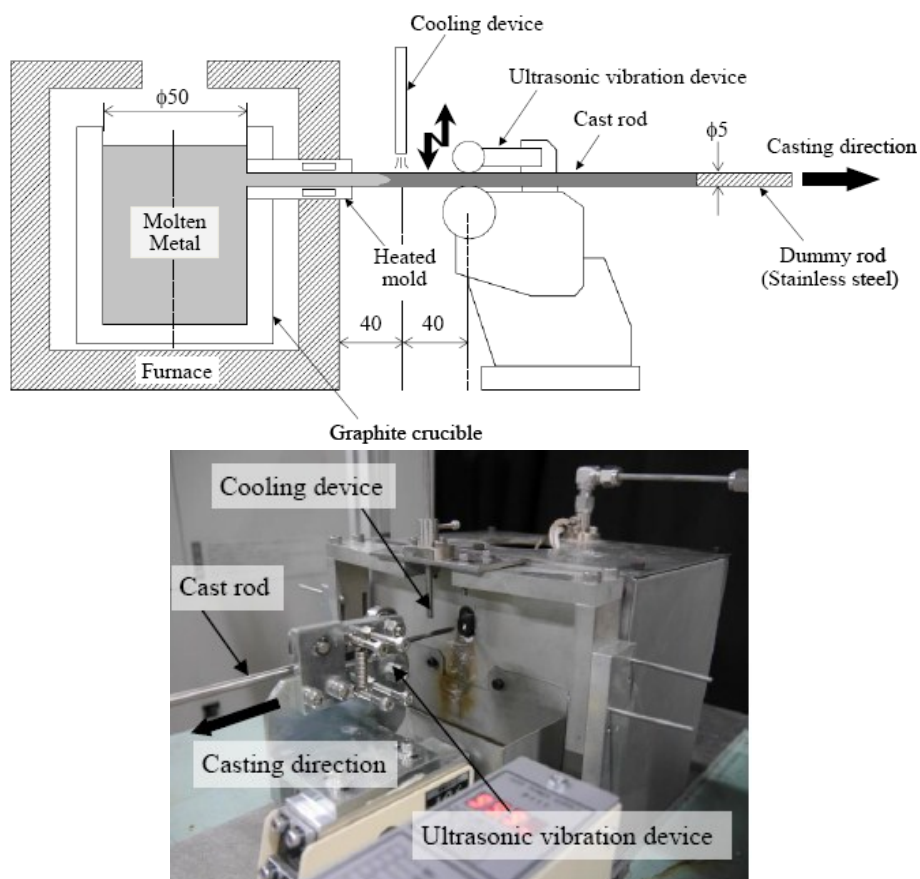|	Cu	Si	Mg	Zn	Fe	Mn	Al
AC2A	3.0–4.5	4.0–6.0	<0.25	<0.55	<0.8	<0.55	bal.
AC4CH	<0.1	6.5–7.5	0.25–0.45	<0.1	<0.2	<0.1	bal.
AC8A	0.8–1.3	11.0–13.0	0.7–1.3	<0.15	<0.8	<0.15	bal.
ADC1	<1.0	11.0–13.0	<0.3	<0.5	0.6–1.0	<0.3	bal.
ADC6	<0.1	<1.0	2.6–4.0	<0.4	<0.6	0.4–0.6	bal.

Figure 1. Schematic illustration and photograph for the heated mold continuous casting (HMC) device with ultrasonic vibration system.

In this work, a heated mold continuous casting (HMC) process with and without ultrasonic vibration (UV: PEF–L25A, SANKI Corp. LTD, Tokyo, Japan) was newly proposed. Figure 1 illustrates the schematic diagram for the casting system. The specification of the UV device is as

follows: electric voltage 0–240 V and frequency 60–400 Hz. Vibration was applied directly under various conditions (0–400 Hz and 120–240 V) to the cast rod at 80 mm from the heated mold during the solidification process, where the temperature of the cast rod is approximately 523 K. In this case, severe vibration was made to the liquid or semi-sold of the cast Al alloy. The HMC arrangement consists of a furnace with a graphite crucible, a graphite mold of 5 mm in diameter, a cooling device, and a dummy rod (SUS304) for withdrawal of the cast sample. The graphite mold was jointed directly to the crucible. The cooling system was set just out of the mold, where water cooling is carried out to make rapid solidification. Approximately 200 g of each cast material, cutting to small blocks, e.g., 20 × 20 × 20 mm, was melted in the crucible before the casting process. The molten metal and mold were heated to just above the liquidus of the cast materials. The melts in the crucible were fed continuously into the mold at 1.9 mm/s, *i.e.*, casting speed. To understand clearly the material properties of the HMC–Al alloys with and without UV, the material properties of the cast aluminum alloys, made by gravity casting (GC), were further examined. In the GC process, the melt was poured directly into a metal mold (600 × 90 × 40 mm) using a ladle.

2.2. Experimental Details

Tensile tests were conducted at room temperature using an electro-servo-hydraulic system with 50 kN capacity. The tensile load and tensile strain were monitored during the tensile tests using a commercial load cell and strain gauge, respectively, where the tensile loading was conducted at 1 mm/min to fracture.

Microstructural characteristics were investigated using optical microscope, energy–dispersive X–ray spectroscopy (EDX, X'Pert Pro, PANalytical, Westborough, MA, USA), electron backscatter diffraction (EBSD, JSM-7000F, JEOL Ltd., Tokyo, Japan) and transmission electron microscope (TEM, JEM-2010, JEOL Ltd., Tokyo, Japan). EDX analysis was carried out with an acceleration voltage of 20 kV using a JSM–6510 scanning electron microscope (JEOL Ltd., Tokyo, Japan). EBSD analysis was conducted to examine the crystal orientation characteristics and internal strain, in which a high-resolution JSM–7000F SEM with HKL Channel 5 software (Oxford Instruments HKL, Hobro, Denmark) was employed with an acceleration voltage 15 kV, beam current 5 nA and step size 0.5–20 μm. The samples for this analysis were prepared with sectioning to less than 5 mm thick and with mirror flatness. The TEM observation was carried out using a HD-2700 with an acceleration voltage of 200 kV. The TEM samples were prepared by conventional methods, such as mechanical thinning followed by ion thinning to about 100 nm thickness.

3. Results and Discussion

3.1. Material Characteristics of HMC–Al Alloys

Figure 2 shows the optical micrographs for various cast samples created by gravity casting and the continuous casting with and without ultrasonic vibration. It can be seen that the microstructures for all Al alloys basically consist of α–Al phases and various eutectic structures although those eutectic phases are different depending on the alloy. Coarse α–Al phases and largely grown needle shape eutectic structures are observed in between the grain boundaries for the gravity cast (GC) samples,

while small α–Al grains with fine eutectic structures are created in the heated mold continuous cast (HMC) samples. Such different grain size is made by the different cooling rate arising from the different alloy elements (solid-liquid coexisting region). To quantify this, the secondary dendrite arm spacings (SDAS) with standard deviation (S.D.) for all samples were examined, and the obtained data are summarized in Table 2. In this case, SDAS was determined by the average SDAS measurements of more than 100 dendrite cells. As seen, SDAS for HMC is overall smaller than that for GC. Note that the different SDAS is observed for the HMC samples depending on the Al alloy despite the same cooling process. The cooling rates (CR), estimated by $CR = 2 \times 10^4 \ SDAS^{-2.67}$ [13], are 6.4 K/s for GC-AC8A, 135.1 K/s for HMC-AC8A, 0.9 K/s for GC-ADC6 and 23.6 K/s for HMC-ADC6. This is caused by different alloy elements. Figure 2 also depicts the optical micrographs for the HMC samples with ultrasonic vibration (pure aluminum, AC4CH and ADC6). The α–Al grains seem to be altered by UV to make a finer spherical shape. This occurrence was similarly reported in the previous work [8].

Table 2. Secondary dendrite arm spacing (SDAS) of cast aluminum alloys.

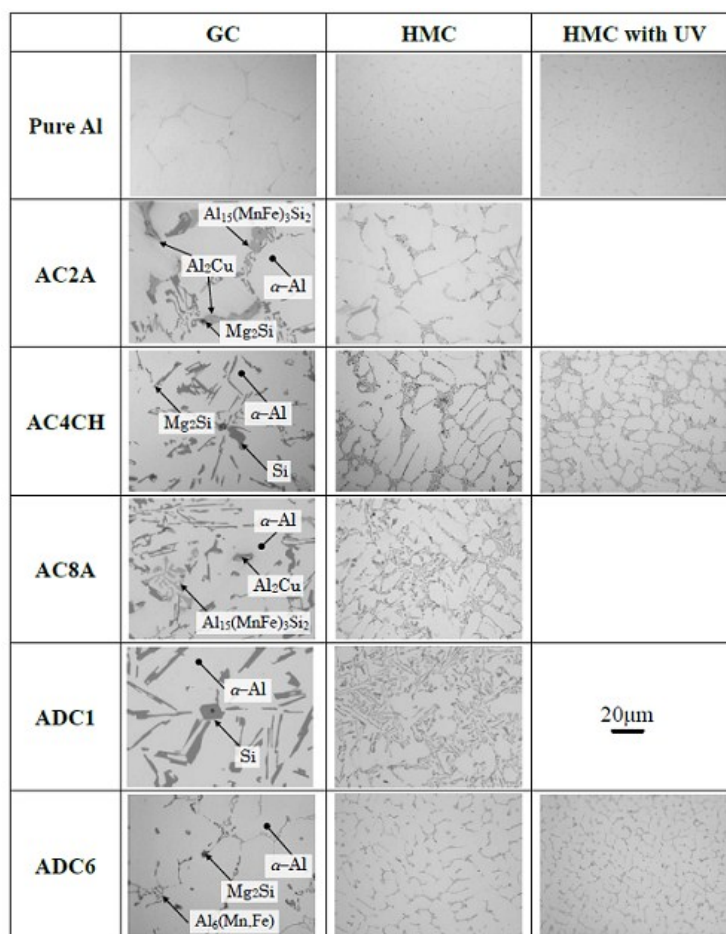|	SDAS, μm (S.D.)				
	AC2A	AC4CH	AC8A	ADC1	ADC6
GC	33.2 (4.7)	42.6 (6.3)	20.4 (4.8)	28.5 (5.1)	41.7 (6.4)
HMC	13.8 (1.6)	13.8 (1.6)	6.5 (0.9)	8.0 (1.4)	12.5 (1.6)

Figure 2. Optical micrographs of cast aluminum alloys. HMC = heated mold continuous casting; GC = gravity casting.
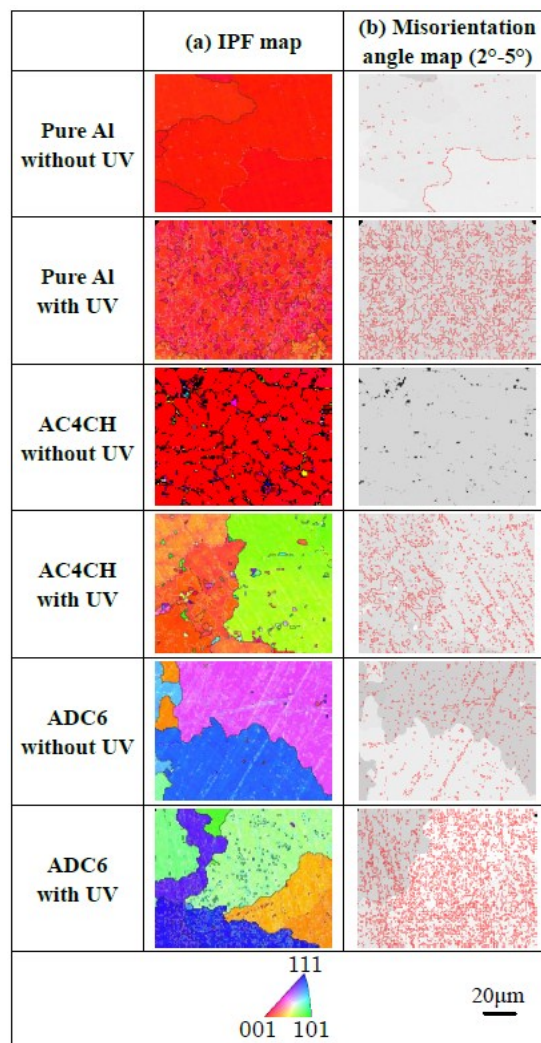
Figure 3. Electron backscatter diffraction (EBSD) analysis of pure aluminum, AC4CH and ADC6 with and without ultrasonic vibration process: (**a**) crystal orientation maps (IPF) and (**b**) misorientation angle maps.

Figure 3 presents the crystal orientation maps (IPF) examined by the EBSD analysis. In this case, the observation was conducted in the face perpendicular to the casting direction. The color level of each pixel in this map was determined according to the deviation of the measured orientation, as indicated in the stereographic projection. The black color lines in the IPF maps are defined with the misorientation angle of more than 5°, respectively. Although the crystal orientation is disordered for HMC–ADC6, that for pure aluminum and AC4CH shows a relatively uniform lattice orientation. It should be pointed out that we also analyzed the crystal orientation for the other aluminum alloys, such as AC2A, AC8A, and ADC1, and their crystal orientations were found to be of a uniform structure, like AC4CH and the pure aluminum one. Such uniform crystal structure over a large area in the HMC samples can be created by the unidirectional solidification process. On the other hand, the reason for the disordered lattice structure for ADC6 has not yet been clarified, which will be discussed in the future. Figure 3 further presents IPF and misorientation angle (MO) maps for HMC–pure aluminum, HMC–AC4CH and –ADC6 with the UV process. The red solid lines in the MO maps indicate misorientation angles of more than 2° and less than 5°. As can be seen, the density of the

misorientaiton angle (2°–5°) increases apparently after the UV process for all samples, *i.e.*, high density of radish zone. Note, the radish zone should be related to the high misorientation angle arising from the internal strain. From this, it is considered that the UV process (severe vibration) makes the high internal strain. Note, the severity of the misorientation angle is sometimes scattered depending on the area of the related samples.
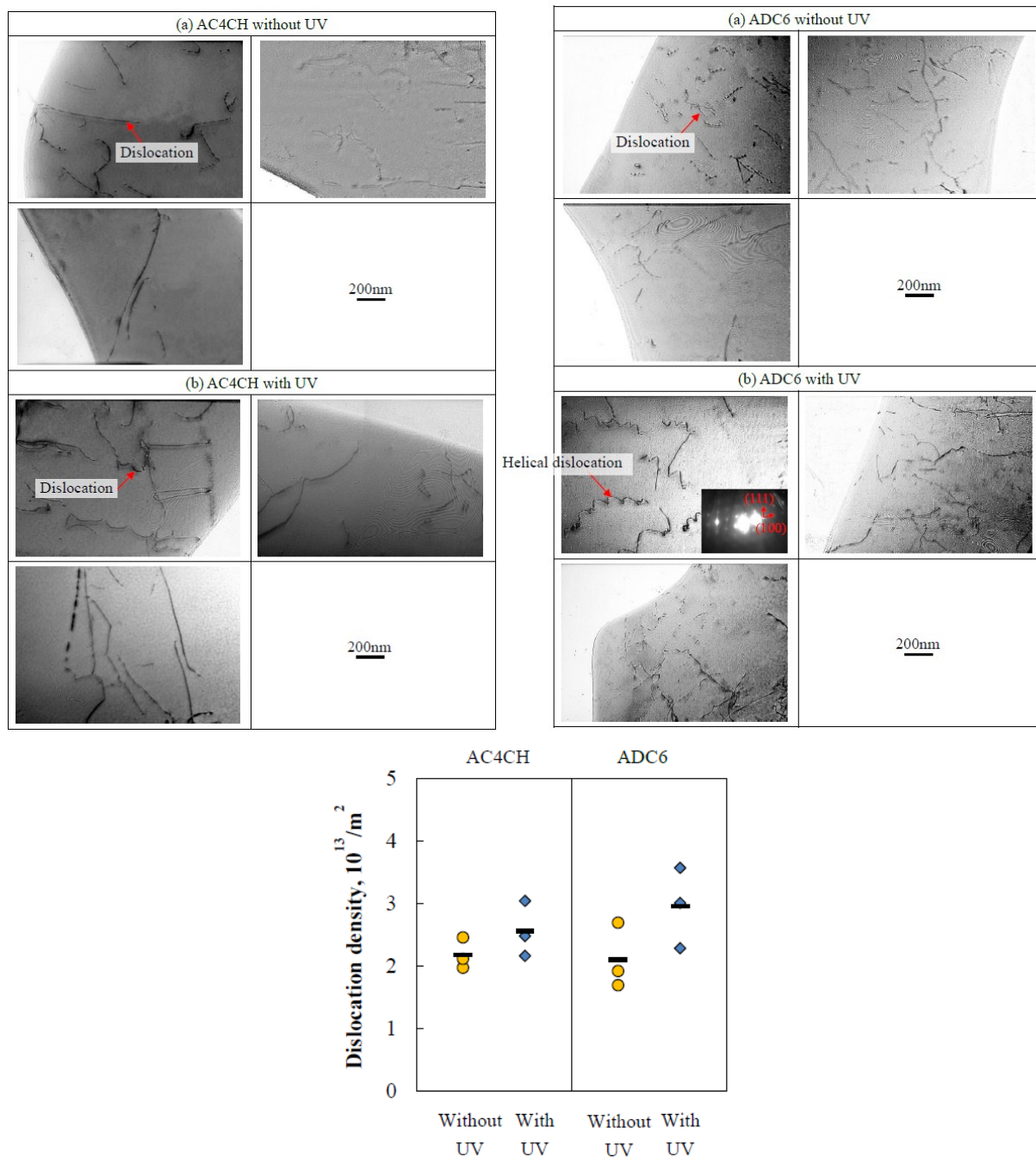

Figure 4. Transmission electron microscope (TEM) images of the AC4CH and ADC6 samples with and without ultrasonic vibration process.

Figure 4 displays TEM images of the ADC6 samples with and without UV process. It is obvious that the dislocation of the cell boundaries is observed in the HMC–sample with and without UV process. An increment of the dislocation density is clarified in the cast samples with the ultrasonic

vibration process. To quantify this, the dislocation density was measured by the total dislocation length L (m) in a cube of side l (m), which is divided by the volume of the cube l^3 (m^3), where the dislocation density is L/l^3 (m^{-2}). The mean dislocation density value measured is 2.1 m^{-2} for the without UV process of ADC6, which is much lower than those for the UV–HMC samples, e.g., 3.0 m^{-2}. It is interesting to mention that spiral dislocation loops, *i.e.*, helical dislocation, can be seen in the UV samples. This would have been made by the force arising from the vibration, and these spiral dislocations are found to be related to the direction of the <100>. Such helical dislocations are associated with screw dislocation [14].

Figure 5 shows the stress–strain curves for the GC and HMC samples, and the obtained ultimate tensile strength (σ_{UTS}) and strain to failure (ε_f) from the S–S curves are summarized in Figure 6. It is clear first that different trends of tensile properties are obtained depending on the aluminum alloy, and overall tensile properties for the HMC samples are higher than those for the GC ones. Such high ultimate tensile strength of the HMC samples is related to the tiny grains, as shown in Figure 2. In particular, HMC–AC8A shows the highest UTS value, which is closed to 400 MPa, and this level is almost twice as high as that for GC–AC8A. In addition, high fracture strain is detected for the HMC samples compared to the GC samples. This can be influenced by the microstructural characteristics: tiny gain and regularly organized crystal orientation. Even though the crystal orientation is not uniformly organized completely for ADC6, high strain values were obtained for HMC–ADC6. This may be influenced by less alloy elements, *i.e.*, Si < 0.1 and Fe < 0.6, embedded in between the α–Al grains, which cannot strongly interrupt the dislocation movement as loaded.
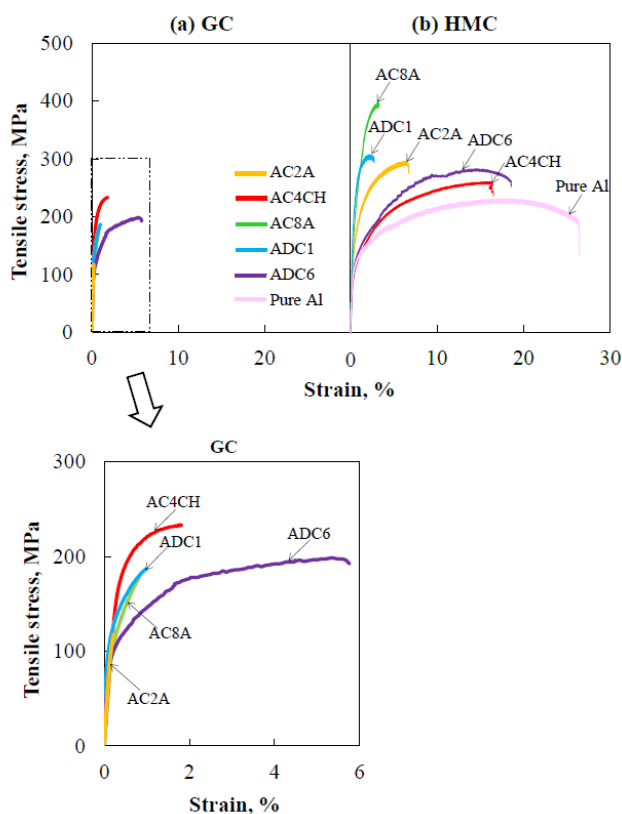

Figure 5. Representative tensile stress versus tensile strain curves for cast aluminum alloys: (**a**) GC and (**b**) HMC.
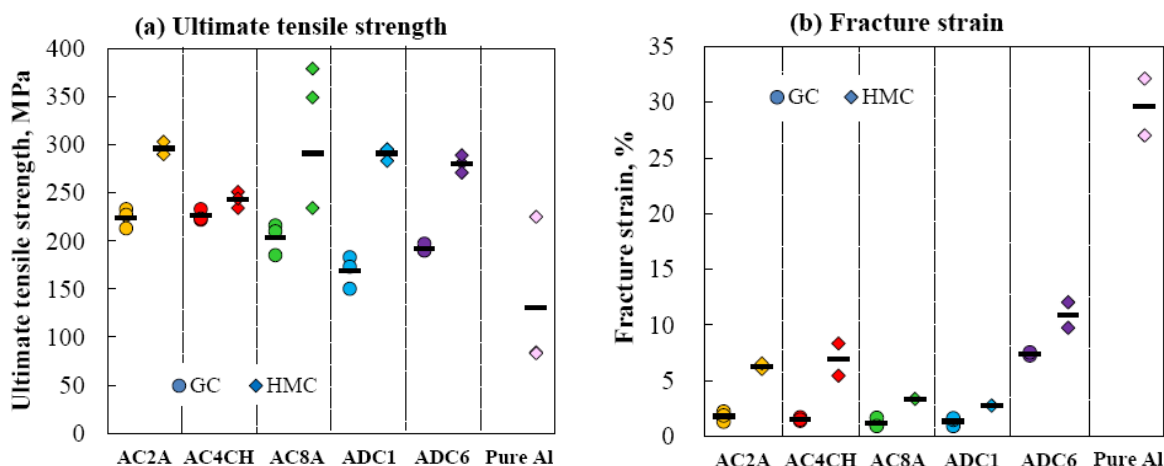
Figure 6. Tensile properties of cast aluminum alloys: (**a**) ultimate tensile strength and (**b**) fracture strain.

On the basis of the crystal orientation for our HMC samples, it was considered that excellent electric conductivity (EC) of the HMC samples could be obtained. To verify this, the EC values for our cast samples were measured by a LCR meter (ZM2353, NF Corporation, Kanagawa, Japan) using the samples of ϕ1 mm × 100 mm, machined from the original cast sample. Moreover, to identify this more clearly, the EC measurements for other materials, such as wrought pure copper, pure iron, Fe–0.8%C, SUS304 and wrought pure aluminum, were executed. Figure 7 shows the electric conductivity (EC) of all samples, which are indicated with the rate of electric conductivity based upon the pure copper one. It is clear that the electric conductivity for the wrought pure aluminum is about 40% lower than that for the pure Cu, while that is higher than that for the Fe ones (pure Fe, Fe–0.8%C and SUS304). The electric conductivity for the HMC–pure aluminum is about 10% higher compared to that for the wrought pure aluminum. This may be attributed to the uniformly organized crystal orientation as mentioned above. As for the aluminum alloys (HMC–AC4CH and –ADC6), their EC values are lower than those for the pure aluminum. With the UV process for HMC–AC4CH and –ADC6, the EC level decreases about 25%, compared to that for the same sample without UV. This would have been affected by the randomly distributed lattice structure.
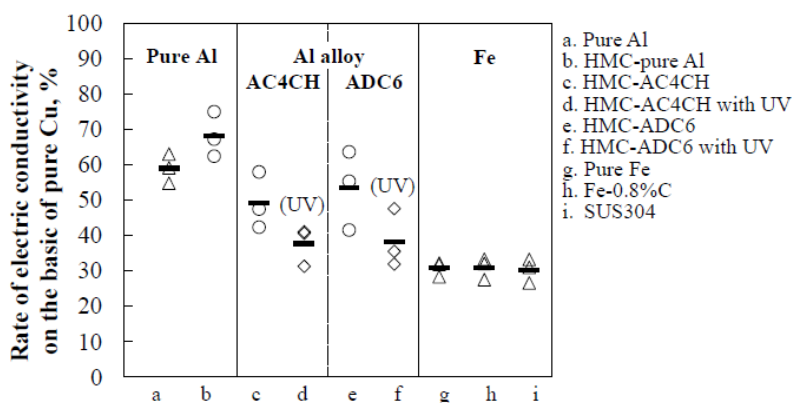

Figure 7. Rate of the electric conductivity for various materials on the basis of that for pure copper (HMC: heated mold continuous casting).

3.2. Material Characteristics of HMC–Al Alloys with Ultrasonic Vibration

Figure 8 displays Vickers hardness of HMC–AC4CH and –ADC6 alloys as a function of the vibration frequency and amplitude. As seen, the hardness levels of both samples are widely scattered, but it seems to increase the hardness for ADC6 with increasing the UV frequency (400 Hz). Furthermore, the high hardness was obtained for ADC6 at the high amplitude of the vibration (240 V). From this result, it may be considered that the ultrasonic vibration can enhance the hardness level, which is similarly reported in a previous study by Abramov *et al.* [8]. They reported that the high hardness is obtained for the high purity aluminum with the UV treatment, which is about 14% higher than that for the related sample before the UV process [8]. Because of the scattered hardness data, further examination of their mechanical properties was conducted.
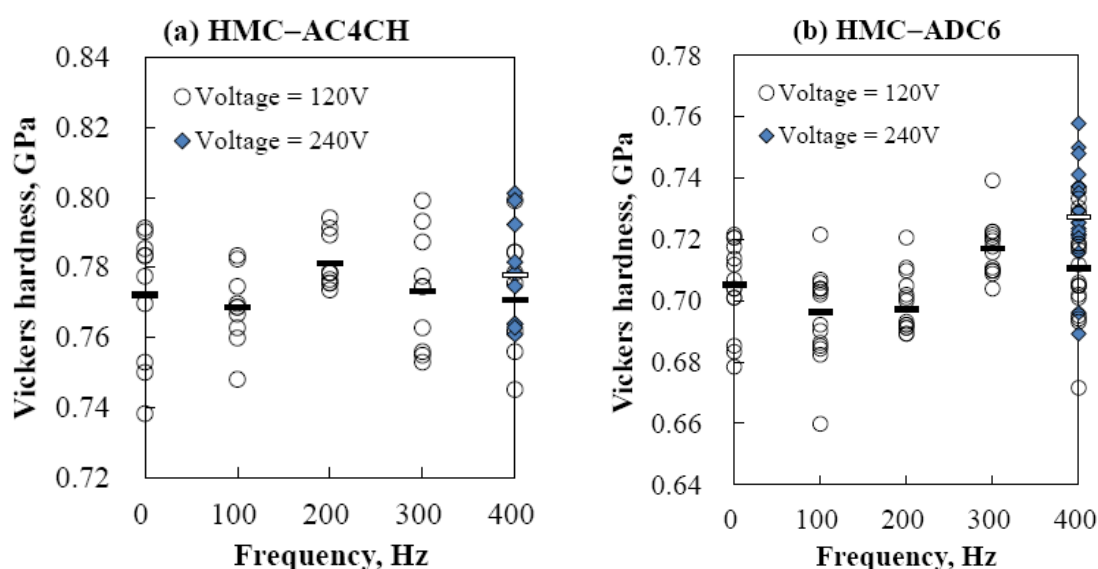

Figure 8. Variation of Vickers hardness as a function of vibration frequency and vibration amplitude of: (**a**) HMC–AC4CH and (**b**) HMC–ADC6.

Figure 9 depicts the representative tensile stress-versus-strain curves for HMC–AC4CH and HMC–ADC6 with and without the UV process, and, based upon their stress-strain curves, ultimate tensile strength, and 0.2% proof strength for both AC4CH and ADC6 samples and also summarized in Figure 9. As seen, tensile strength slightly increases for both UV samples. The mean σ_{UTS} and $\sigma_{0.2}$ for the UV samples are a few percent higher than those for the same Al alloy without UV. Such increment of the tensile strength would be caused by the change of their microstructural characteristics, as mentioned above. Note, due to the scattered data, no clear difference in the material ductility is detected. The reason behind this will be dealt with in the future.
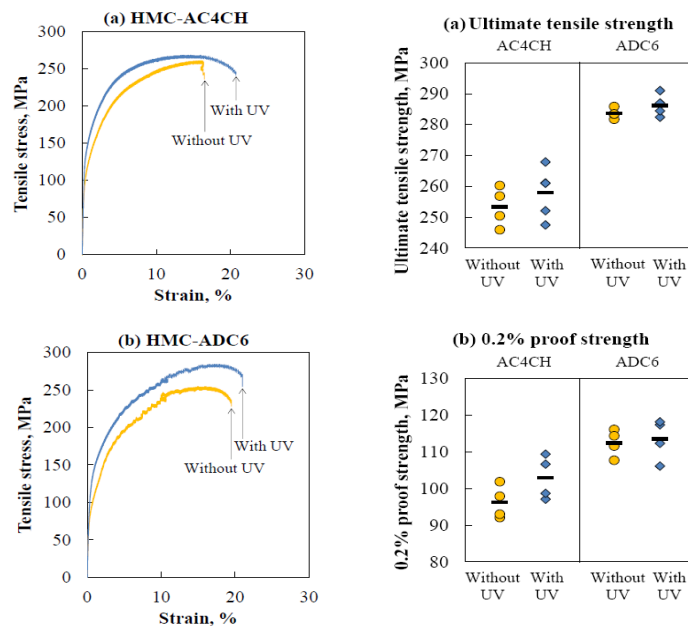
Figure 9. (**a**) Tensile properties of HMC–AC4CH and (**b**) HMC–ADC6 with and without ultrasonic vibration (HMC: heated mold continuous casting).

4. Conclusions

The effects of ultrasonic vibration on the mechanical properties of various cast aluminum alloys, produced by the heated mold continuous process with and without ultrasonic vibration, were studied. In this approach, an attempt was made to modify the microstructural formation by cavitation. Based upon the results obtained, the following conclusions can be drawn.

Electrical conductivity for the HMC–pure aluminum is about 10% higher than that for the wrought pure aluminum. This is attributed to the uniformly organized crystal orientation. The EC level for the HMC–Al alloys decreases about 25% with the UV process, which is affected by the randomly distributed lattice structure arising from the vibration during the solidification process.

Vickers hardness of the HMC–ADC6 alloys increases with increasing UV frequency (400 Hz). Furthermore, high hardness is obtained for the cast Al alloys vibrated at a high amplitude (240 V).

Tensile strength (σ_{UTS} and $\sigma_{0.2}$) for the HMC–Al alloys increases slightly as the UV process is conducted. Such increment of the mechanical properties is caused by the change of their microstructural and lattice characteristics, in which internal strain increases in fine grains, because of the disordered lattice structure. From this work, it could be clarified that the UV process can make changes to the mechanical properties.

Author Contributions

M. Okayasu is the head of this research project, and he has designed originally the testing machine and the materials by his research fund. Moreover, he has made the manuscript based upon the experimental data, obtained by his excellent students. Y. Miyamoto and K. Morinaka have conducted mainly the experimental works, and they have also systematically analyzed to clarify their research results. They worked hard very much until they have obtained and verified their experimental results.

Conflicts of Interest

The authors declare no conflict of interest.

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