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# Crystallization characteristics of cast aluminum alloys during a unidirectional solidification process

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ABSTRACT

The crystal orientation characteristics of cast Al–Si, Al–Cu and Al–Mg alloys produced by a unidirectional solidification process are examined. Two distinct crystal orientation patterns are observed: uniform and random formation. A uniform crystal orientation is created by columnar growth of $\alpha$-Al dendrites in the alloys with low proportions of alloying element, e.g., the Al–Si alloy (with Si $<12.6\%$) and the Al–Cu and Al–Mg alloys (with Cu and Mg $<2\%$). A uniformly organized crystal orientation with [100] direction is created by columnar growth of $\alpha$-Al dendrites. With increasing proportion of alloying element ($>2\%$ Cu or Mg), the uniform crystal orientations collapse in the Al–Cu and Al–Mg alloys, owing to interruption of the columnar $\alpha$-Al dendrite growth as a result of different dynamics of the alloying atoms and the creation of a core for the eutectic phases. For the hypo-eutectic Al–Si alloys, a uniform crystal orientation is obtained. In contrast, a random orientation can be detected in the hyper-eutectic Al–Si alloy (15% Si), which results from interruption of the growth of the $\alpha$-Al dendrites due to precipitation of primary Si particles. There is no clear effect of crystal formation on ultimate tensile strength (UTS), whereas crystal orientation does influence the material ductility, with the alloys with a uniform crystal orientation being elongated beyond their UTS points and with necking occurring in the test specimens. In contrast, the alloys with a nonuniform crystal orientation are not elongated beyond their UTS points.



## 1. Introduction

As a result of the imposition of more stringent requirements regarding improvement of fuel economy and reduction of gas emissions, there is a growing trend to substitute lightweight metals for steel and cast iron in vehicles [1]. Among such lightweight materials are cast aluminum alloys. However, these alloys do not always possess suitable mechanical properties because of deficiencies arising from the presence of inappropriate microstructures and cast defects. To solve this problem, attempts have been made to create high-strength and high-ductility aluminum alloys by controlling their microstructural characteristics. One such approach is to employ heated-mold continuous casting (HMC), which involves rapid cooling under unidirectional solidification. This continuous casting technique, known as Ohno continuous casting, was developed several decades ago by Ohno [2]. It uses a different system from conventional continuous casting techniques: molten metals are poured into a heated mold before solidification by water cooling. The mold temperature is set slightly higher than the solidification temperature of the cast metal. To date, various HMC products, including Al, Bi, Cu, Co, Mg and Zn alloys, have been made by a number of investigators [3–9]. Moreover, the present authors have created several HMC aluminum alloys and have investigated their mechanical properties [10–14]. It has been found that the ultimate tensile strength $\sigma_{UTS}$ and fracture strain $\varepsilon_f$ of Al–Si–Cu (ADC12) and Al–Si–Ni–Mg–Cu (AC8A) alloys [10,11] are about twice those of the same alloys made by a conventional gravity casting (GC) process. The high tensile strength of the HMC samples results mainly from the presence of tiny spherical $\alpha$-Al grains, arising from the high cooling rate. A high ductility of more than 20% fracture strain is obtained for HMC samples such as Al–Mg–Si (AC4CH) [12] and may be a result of the uniformly oriented crystal structure. However, HMC–ADC6 [13], which has a random crystal orientation, also possesses a high ductility ($\varepsilon_f$=20%). Random crystal orientation can also be seen in some other HMC aluminum alloys, for example AC7A [14]. In fact, to date, there has been no detailed description of the crystallization characteristics of the HMC process or the effect of crystal formation on material properties. Thus, in the present work, an attempt is made to investigate systematically the crystallization characteristics of HMC samples using different aluminum alloys (Al–Si, Al–Cu and Al–Mg), and the influence of crystal formation on the mechanical properties is examined.

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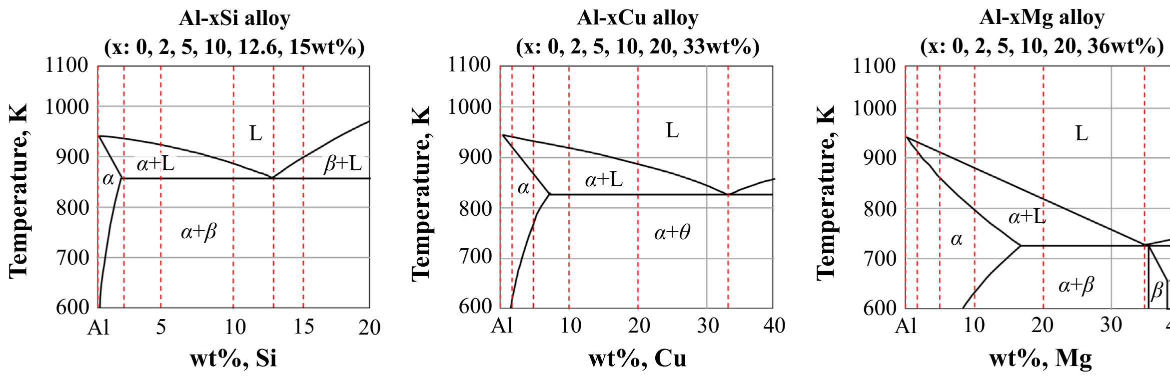


**Fig. 1.** Chemical compositions of Al–Si, Al–Cu and Al–Mg alloys.

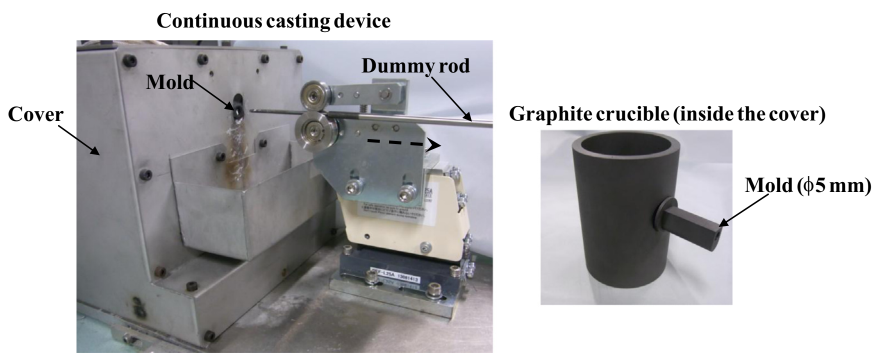


**Fig. 2.** Photographs of the HMC device and graphite mold.

## 2. Experimental procedures

Cast aluminum alloys based upon Al–*x*Si, Al–*x*Cu and Al–*x*Mg were employed. The chemical compositions of the three alloys with their phase diagrams are shown in Fig. 1. The proportions of the alloying element in each of the alloys were varied: $Si_{0-15}$, $Cu_{0-33}$ and $Mg_{0-36}$. Samples were prepared both by HMC and by GC. The HMC device comprised an electric furnace, a graphite crucible, a graphite mold and a water cooling device. The molten alloy was fed continuously into the mold at a speed of 114 mm/min via a dummy rod. Fig. 2 shows the HMC device, showing the graphite mold and dummy rod. The mold was heated to just above (by 30 K) the liquidus of the alloy. The cast sample was solidified directly by water cooling at approximately 80 ml/min. The sample shape was a round rod (⌀5 × 1000 mm). For the GC process, a typical sand-casting approach was adopted, with the melt being poured into a commercial silica-based sand mold (⌀10 × 60 mm) heated to 473 K.

Tensile properties were investigated at room temperature using dumbbell-shaped round test specimens with dimensions ⌀2 × 4 mm. The tensile tests were carried out under stroke control of 1 mm/min, using an electro-servo-hydraulic system with 50 kN capacity. The tensile stress–strain curves were monitored by a data acquisition system in conjunction with a computer through a standard load cell and strain gauge. Microstructural characteristics were examined using an optical microscope and electron backscattering diffraction analysis (EBSD).

## 3. Results and discussion

### *3.1. Microstructural characteristics*

Fig. 3 shows optical micrographs of cast samples of pure Al and the Al–Si, Al–Cu and Al–Mg alloys made by both GC and HMC. Note that for the HMC samples, the microstructure was observed on the sample surface both perpendicular and parallel to the casting direction, Fig. 3(b) and (c). The microstructural characteristics for both GC and HMC are similar (Fig. 3(a) and (b)), although they differ in size because of the different cooling rates. As can be seen, clear $\alpha$-Al phases are formed with a grain size of about 50 μm for the pure Al. With the addition of alloying elements, the microstructural characteristics are altered, with microstructure formation differing depending on the element. Acicular eutectic Si structures are embedded between the $\alpha$-Al phases in the Al–Si alloy, with the amount of Si structure increasing with increasing Si content. Primary Si crystals are precipitated in the Al–$Si_{15}$ alloy because of the existence of a hypereutectic Al–Si alloy; see the phase diagram in Fig. 1. In the case of the Al–Cu and Al–Mg alloys, eutectic phases ($CuAl_2$ and $Mg_2Al_3$) are formed between the $\alpha$-Al phases, and the volume fractions of these eutectic phases increase with increasing proportion of alloying element. There are areas of the Al–$Cu_{33}$ and Al–$Mg_{36}$ alloys that are composed almost entirely of these eutectic phases. It is also clear in Fig. 3(c) that the dendrite formation ($\alpha$-Al phase) grows in the casting direction in the hypo-eutectic Al–Si, Al–$Cu_2$ and Al–$Mg_{2-5}$ alloys, while equiaxed $\alpha$-Al phases are observed in the other samples. Fig. 4 shows scanning electron microscope (SEM) images of the eutectic structures, obtained from the HMC–Al–Si, HMC–Al–Cu and HMC–Al–Mg alloys after strong etching with Keller etchant. As can be seen, the morphology of the eutectic structures is altered. In this instance, very fine and complicated eutectic Si structures are created in the Al–Si alloys, whereas stripe-shaped Cu phases and colonies of Mg-based structures are created widely between $\alpha$-Al grains.

Fig. 5 depicts the crystal orientation maps for the HMC aluminum alloys measured on the sample surface perpendicular to the casting direction. The color level of the maps is defined according to the deviation of the measured orientation from the directions parallel to the nominal direction. It is clear that the crystal orientations show two distinct patterns for the cast Al alloys: uniform and random