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# Microstructural evolution and wear characteristics of equal channel angular pressing processed semi-solid-cast hypoeutectic aluminum alloys

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ABSTRACT

This work investigated the microstructural evolution of Al–7Si–Mg alloy cast semi-solid using a cooling slope as well as conventional casting followed by equal channel angular pressing (ECAP) in a 120° die. Feed materials were prepared for ECAP by cooling slope casting and by conventional casting. The microstructure of the processed alloys extruded was observed by optical microscope and by transmission electron microscope, and their hardness and wear resistance were evaluated. After ECAP processing, the primary α-Al phase tended to be elongated while the Si particles became fragmented and more nearly globular in shape and uniform in size than in the as-cast sample. The microstructure of the cooling slope-cast ECAPed samples was more homogenous than that of the conventionally cast ECAPed sample. The α-Al phase sub-grains were refined to sub-micrometer sizes for samples cast by both methods after ECAP. The hardness of the cooling slope-cast ECAPed sample was also higher than that of the conventionally cast ECAPed sample. The wear resistance of the alloy improved after cooling slope casting and ECAP processing.



## 1. Introduction

Semi-solid metal (SSM) processing was first discovered by Flemings and his co-worker in the early 1970s [1]. The key of the SSM is the production of slugs with a non-dendritic microstructure. To develop this microstructure, a number of methods have recently been proposed, including mechanical and electromagnetic stirring and controlled nucleation [2]. Controlled nucleation is especially interesting in that it does not need stirring and is simple and less expensive. Based on this method, the cooling slope casting process was developed: a simple semi-solid casting process with very low equipment and running costs [3,4]. In cooling slope casting, the melt with low superheat is cast via a cooling slope. The crystals nucleate by heterogeneous nucleation on the slope wall and inside the melt and are washed away from the wall by fluid motion [4–6]. The melt, containing a large number of these nuclei crystals, solidifies in the die, resulting in a fine globular microstructure.

Equal channel angular pressing (ECAP) is a severe plastic deformation processing technique first described by Segal et al. [7]. This method is used to achieve ultra fine grain in bulk aluminum alloy by inducing a large amount of shear strain into material without changing the bulk shape or dimension [8,9]. Typically, a feed material of as-cast hypoeutectic aluminum alloy with a network of dendritic α-Al phase and eutectic constituent is used in ECAP. On the other hand, fine and globular microstructure may also be the preferred structure for obtaining homogeneous microstructure after ECAP. This fine, homogenous structure can be achieved using semi-solid casting.

The goal of the present work was to produce feed material having uniform, fine and globular microstructure by cooling slope casting for ECAP processing. The study investigates the evolution of the microstructure after cooling slope casting in a combination with ECAP processing by route A, that is, the sample is not rotated between each press that sample. In addition, the hardness and wear resistance of conventional cast and cooling slope cast alloy after ECAP were studied.

## 2. Experimental procedure

The aluminum alloy used in the present studies was synthesized and its composition was similar to that of the commercially

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available A356 alloy. The chemical analysis of aluminum alloy, as measured by X-ray Fluorescence (XRF), is shown in Table 1. In the casting experiment, the material was melted in a graphite crucible set at 750 °C. The cooling slope was made with stainless steel, and its tilt angle, slope length, and slope temperature were 60°, 250 mm, and room temperature (25 °C), respectively. The solidus and liquidus temperature of diluted aluminum alloy as characterized by Differential Scanning Calorimetry (DSC) were 582 °C and 618 °C, respectively. A pouring temperature of 640 °C was selected to limit the superheating of the melt. Apparatus used in the cooling slope is shown in Fig. 1a. The casting procedure was to pour the melt onto the slope downward into a vertical mold. The mold and content were then quenched. A similar sample was cast without the cooling slope at a pouring temperature of 640 °C, which we designated as conventional casting, to investigate the effect of cooling slope on microstructure of alloy. The as-cast sample was machined into a rod shape with a diameter of 13 mm and then annealed at 540 °C for 8 h.

Then, the ECAP experiment was performed following route A for four passes with a channel angle of 120°. The cast and ECAPed alloys were characterized under optical microscope (OM) and transmission electron microscope (TEM). Hardness of samples was measured using a Vickers hardness tester (Future-Tech Copr. Japan; FV-700). Samples for microstructure studies under OM were sectioned into three surfaces, i.e., longitudinal plane (LP), vertical plane (VP) and cross-section plane, as shown in Fig. 1b. These sections were ground using SiC papers with grid size from 180 to 2000 and then polished using 1 μm–0.05 μm $Al_2O_3$ powder. The polished surfaces were etched using a 1% solution of hydrofluoric acid (HF). The ECAPed alloys were investigated for dry sliding wear behavior under a Pin-On-Disc type testing machine (TR-20, DUCOM) with a counter surface disc made of hardened (62HRc) carbon steel EN-31. The wear test was carried out in dry conditions at a room temperature of ∼25 °C and at a fixed speed of 1 m/s with applied loads of 10 N, 30 N and 50 N. The wear pins with a diameter of 12 mm and a length of 20 mm were mechanically ground and polished to 0.5 μm $Al_2O_3$ powder, cleaned in ultrasonic bath and dried in hot air; weight was recorded before and after each test. The worn surfaces of the samples were characterized by Hitachi S-3400N VP-SEM equipped with an Energy Dispersive X-ray analysis (EDX).

**Table 1**
Compositions of aluminum alloys.

| Element | Si | Mg | Cu | Fe | Mn | Ti | Al |
|---|---|---|---|---|---|---|---|
| Weight percentage (%) | 7.467 | 0.450 | 0.121 | 1.154 | 0.165 | 0.019 | Balance |

## 3. Results and discussion

### 3.1. The effect of cooling slope

Fig. 2 shows the microstructure of alloys that was cast into a vertical mild steel mold either with or without the cooling slope. The bright phase is a primary α-Al phase and the dark phase surrounding the bright phases is eutectic phase. The morphology of α-Al primary phase is almost dendritic in the sample that was cast without cooling slope (Fig. 2a–c). However, the dendrites seem to be finer from the center zone towards the thin wall zone. The differences in morphology of α-Al primary phases among the three zones is due to the different cooling rates according to position in mold. In the thin wall zone, the cooling rate was the highest due to relatively low initial temperature of the mold. Consequently, many grains with random orientations are nucleated at the thin wall zone [10]. Forced convection due to pouring could detach dendrite arms that were grown from the thin wall zone. Therefore, in the middle zone, the cooling rate was lower than in the thin wall zone, leading to the growth of dendrites at the middle zone. Besides, the cooling rate being the lowest at the center zone could induce ripening on further cooling to form coarse dendrites [11].

Fig. 2d–f shows the microstructures across a transverse section of a sample cast with a cooling slope. The morphology of primary α-Al phase is nearly globular within the middle and center zones (Fig. 2e and f), and seems to be rosette-like (Fig. 2d) in the thin wall zone. The primary α-Al phase in the center zone is somewhat coarser than that in the middle zone. The differences in morphology and size of primary α-Al phases within the three zones of the surface sample may be due to variation in cooling rate and temperature gradient across the section of the sample during solidification.

### 3.2. Annealing

Fig. 3 shows optical micrographs of the primary α-Al phase and the Si particle distribution in the cooling slope-cast sample, conventionally cast sample (Fig. 3a and b) and after annealing to soften the cooling slope-cast sample and conventionally cast sample (Fig. 3c and d). The microstructures of the cooling slope-cast sample and the conventionally cast sample consist of large grains, including the primary α-Al phase, surrounded by a network of eutectic constituents, consisting of fine, irregularly shaped Si particles (black particles) [12]. After annealing at 540 °C for 8 h, the

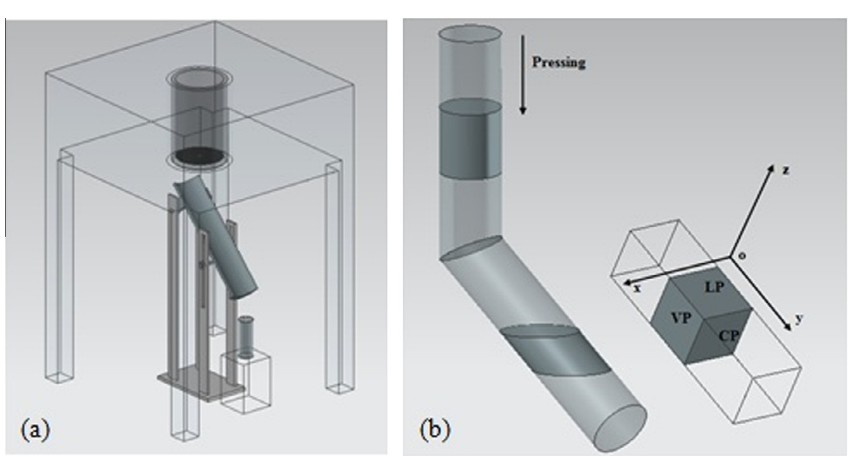


**Fig. 1.** (a) Schematic of cooling slope casting; (b) schematic of a 120° ECAP processing.