

# Effect of Strain Level on the Behavior of Intermetallics and Texture of Al-Si-Cu-Mg Alloy Modified with Transition Metals

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## ABSTRACT

The uniaxial compression test was used to assess the influence of strain amount on the behavior of precipitates and texture of the Al-7%Si-1%Cu-0.5%Mg alloy, modified with micro-additions of V, Zr and Ti. As revealed through metallographic examinations, fracturing and re-orientation of the second-phase particles increased with increasing compression strain. However, the intermetallic particles experienced substantially more frequent cracking than the eutectic silicon. The crystallographic texture was measured and correlated with deformation behavior of the alloy. The weak texture of 11<211> and 111<110> components, detected after casting transformed to a mixture of 1<110>, 112<110> and 111<110> components after room-temperature compression deformation. The intensity of the texture components depended on the strain amount. It is concluded that the texture formation in the studied alloy is controlled by the precipitates formed during solidification of the alloy.

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## INTRODUCTION

The lightweighting of the motorized vehicle increases the demand for Al-alloys as materials for automotive engine parts and other structural components [1, 2]. However, to replace the ferrous parts and improve the engine efficiency, high strength Al-alloys are needed which can sustain high temperature loads and have a comparable strength to ferrous alloys. In the last few decades, numerous studies have been performed to improve the elevated temperature properties of aluminum alloys by introducing transition metals. Sepehrband *et al.* [3] and Mahmudi *et al.* [4] reported the influence of 0.15 wt.% Zr additions on the aging behavior and mechanical properties (hardness, tensile strength and wear resistance) of A319 cast aluminum alloy. The effect of the addition of Zr and Ti in Aluminum alloys was also studied [5], and it was found that phase morphology and the types of phases formed during either casting or heat treatment processes controlled the high temperature properties. It is also evident that increasing the Zr content (1-2.5%) in Al-Si piston alloy reduces the tendency to form primary silicon and enhances the elevated temperature performance of the alloys [6]. Other investigations [7, 8, 9] also showed that V could enhance the alloy performance by forming Al<sub>3</sub>V or Al<sub>10</sub>V, which was formed in the master alloys, and used to prepare the studied alloy. However, increasing the transition metal content above the solubility limit increases the tendency of feeding blockage during die casting, and form casting defects [10]. Ti,

V and Zr have similar effects on microstructure and mechanical properties in Al-Si alloys, and can replace each other [8]. Therefore, multiple numbers of transition metals could be introduced in Al-Si alloys to improve the high temperature properties. Thus, Al-Si-Cu-Mg alloy was modified with the addition of Ti-V-Zr to get the benefit of thermally stable precipitates which improve the high temperature performance of the alloy [11, 12, 13, 14].

Our recent characterization studies of the Al-Si-Cu-Mg alloy modified with additions of Ti-V-Zr covered the microstructure and mechanical properties in as-cast and T6 heat treated states [15, 16, 17, 18, 19, 20, 21]. However, the crystallographic texture analysis of the modified alloy has not yet been investigated. The crystallographic texture is one of the key characteristics that determine the micro-plastic deformation in metals. Depending on processing route, the orientations of the crystals change from random to preferentially align in a particular direction. Any aggregate characterized by a condition in which the distribution of crystal orientations is non-random, is said to have a preferred orientation or texture. The rotation of the grains could be hindered by the second phase particles which depend on the alloy chemical composition and processing parameters [22, 23]. Okayasu *et al.* [24] reported that depending on the casting processes, such as gravity casting, die casting or centrifugal casting, crystals could be oriented along the solidification direction which

affects the properties of the materials, though generally casting can form a random crystal orientation. It was indicated in the literature that increasing the silicon content in the Al alloy matrix increased the amount of secondary phases, primarily the eutectic or primary silicon, which led to texture and affected the properties of the alloys [25, 26]. Most of the studies on texture evolution in aluminum alloys were performed for wrought grades after rolling or extrusion [27, 28]. Benum and Nes [29] and Kashihara and Inagaki [30] studied the effect of precipitates on texture evolution in aluminum alloys during rolling followed by solution treatment and aging. They reported that precipitates can control the formation of texture by a pinning effect at grain boundaries. A recent study focused on the effect of precipitates on work hardening and texture changes during compression in cast Al-Si-Cu-Mg alloy modified with additions of Ti-V-Zr. However, the effect of strain on texture and behavior of precipitates in as-cast alloy is not reported yet. Thus, in the present paper, a cast Al-Si-Cu-Mg alloy modified with additions of Ti-V-Zr was compressed using different strain levels to investigate the influence of strain on the microstructure and texture changes. This information will be helpful in the proper design of engine parts as the engine operation causes cyclic loading during engine heat-up and cool-down that results in expansion of the inter-valve regions during engine heat-up that induces local compressive stresses.

## EXPERIMENTAL DETAILS

A hypoeutectic Al-7%Si-1%Cu-0.5%Mg cast alloy, modified with micro-additions of transition metals V, Zr, and Ti, with chemical composition listed in Table 1, was used as a test material in the present study. The alloy was cast at a temperature of 730°C into an ASTM B108 steel mold. The details about the alloy preparation and casting were described separately [15]

The compression tests were performed following the ASTM E9M-09 standard at a room temperature of 25°C using a computerized United tensile testing machine. The cylindrical specimens with a diameter of 5 mm and height of 8 mm were compressed at strains of 4.7, 9.8, 17.2 and 28.1% at a strain rate of  $10^{-3} \text{ s}^{-1}$ .

The texture measurements of the alloy both before and after compression tests were performed using a PANalytical X-ray diffractometer on polished samples cross-sectioned through the center of the loading axis. The extractions of the sample and texture measurement are described in [16]. The experiment was conducted by measuring incomplete pole figures of (111), (100), (220) and (311) for  $\psi$  between 0° and 75° in the back-reflection mode using CuK $\alpha$  radiation at 45 kV and 40 mA [16, 31]. Based on the measured pole figures (PF), orientation distribution functions (ODF) were calculated using MTEX software.

After compression tests, the samples were subjected to quantitative microstructural analysis. Following cutting along the loading axis, samples from each group were prepared according to the standard metallographic technique as reported in [18]. The microstructure was observed using a Nikon EPIPHOT 200 light optical microscope, equipped with a quantitative image analyzer coupled with CLEMEX software. The average values reported are based on analysis of at least 10 images.

Table 1. Chemical composition of cast aluminum alloys used in the present study.

| Alloying elements | Wt.% |
|-------------------|------|
| Si                | 7.0  |
| Cu                | 1.0  |
| Fe                | 0.12 |
| Mg                | 0.50 |
| Ti                | 0.11 |
| Zr                | 0.20 |
| V                 | 0.25 |
| Al                | Bal. |

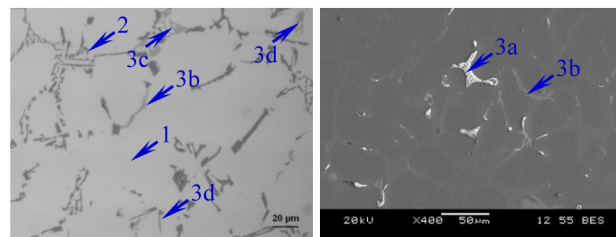


Figure 1. Microstructure of Al-Si-Cu-Mg alloy modified with addition of Ti-V-Zr in as-cast state. Note: 1-  $\alpha$ -Al, 2- eutectic silicon precipitates, 3- intermetallics.

## RESULTS AND DISCUSSION

### Effect of Strain on Microstructure

Figure 1 shows the typical microstructure of the Al-Si-Cu-Mg alloy modified with additions of Ti-V-Zr, consisting of  $\alpha$ -Al (#1), unmodified eutectic silicon (#2) and intermetallics (#3). The SEM/EDX analysis identified the intermetallics as the Cu-rich phase of  $\text{Al}_2\text{Cu}$  (#3a), the Mg-rich phase of  $\text{Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_6$  (#3b) and the Fe-rich phase of  $\text{Al}_8\text{FeMg}_3\text{Si}_6$  (#3c). At the same time, the Ti-, V- and Zr- containing phases were identified with needle-like shapes, generally referred to as  $\text{Al}(\text{TiVZr})\text{Si}$  (#3d) [20, 9]. It is believed that those micro-size phases containing Ti-V-Zr most likely contributed to the strength retention at elevated temperatures as they are more thermally stable than Cu- and Mg-based phases [20].

As seen in Figure 2, the true stress-true strain curves of the alloy in the as-cast state depict compressive yield strength of 166 MPa and a compressive ultimate strength of 384 MPa. For this study, the compression tests were stopped at 4.7, 9.8, 17.2 and 28.1% strain to observe changes in alloy microstructure. It is seen in Figure 3 that the number fraction of cracked eutectic silicon particles ( $f_{\text{si}}$ ) increased gradually with increasing strain while the number fraction of cracked intermetallics ( $f_{\text{in}}$ ) increased and reached near saturation after 9.8% deformation. The obtained  $f_{\text{si}}$  was 0.08 for the sample deformed at 4.7% strain. With increasing strain from 4.7 to 28.1%, the  $f_{\text{si}}$  rose to 0.71. In contrast, the  $f_{\text{in}}$  achieved significantly higher fraction at all strains. At 4.7% the intermetallics achieved a  $f_{\text{in}}$  of 0.4 which grew up to 0.9 with increasing strain to 28.1%.

The cracking frequency of particles in Al-Si alloys was affected by testing temperature, the size, shape, aspect ratio, deformation conditions, internal stresses developed during deformation, secondary dendrite arm spacing of the matrix and the interfacial bonding between matrix and particles [18]. As material containing second phase particles goes through plastic deformation, interfacial stress