

Microstructure Control of Al-Ce Alloys, A Review

S. El-Hadad^{a,*}, M.E. Moussa^a, E. Riedel^b, M.Ahmed^{a,b}, R. Bähr^b, A. Nofal^a

^a Central Metallurgical Research & Development Institute. P.O. Box 87 Helwan-Egypt.

^b Institute of Manufacturing Technology and Quality Management, Otto-von-Guericke-University, Universitätsplatz 2, 39106, Magdeburg, Germany.

*Corresponding author: E-mail: shimaam@yahoo.com

Received 3 November 2022

Revised 19 November 2022

Accepted 30 December 2022

Published 31 December 2022

Abstract

The recent research on Al-alloys focuses on the systems that contain intermetallic precipitates with high-temperature stability. Hence using rare earth elements to achieve this purpose minimizes the advantage of conventional casting as one of the most economical fabrication processes, an alternative way becomes mandatory. In this regard, the group of Al-Ce alloys is currently receiving attention as the most suitable high-temperature candidate among the other Al-alloys. These alloys are characterized by their stability at high temperatures. Moreover, Ce is the most abundant rare earth element, which is beneficial in economics. In the current review, the metallurgy of Al-Ce alloys and the methods used to modify their microstructures are discussed. Special attention is given to melt solidification under ultrasonic vibrations as an efficient method to control the shape and size of Al₁₁Ce₃ intermetallic particles and hence enhance the mechanical properties of the alloys. Future trends and prospects of these promising alloys are also presented.

Keywords: Al-Ce alloys; Microstructure; Mechanical properties; Microstructure control.

1. Introduction

Aluminum alloys (Al) are commonly used as structural materials because of their exceptional castability, superior mechanical characteristics, and affordability. In addition, Al alloys fill the gap between the expensive & high-performance titanium alloys and the cheap dense iron alloys. Over the years, Al alloys also played an important role in the automotive and aerospace industries due to their high strength-to-weight ratio, resistance to corrosion, and high thermal conductivity. So far, continuous efforts and research still made to improve the performance efficiency of the Al alloys. [1]. Accordingly, newly developed Al-alloys that can maintain strength and serve at temperatures reaching 300 °C, are required. However, Al-Si-(Cu/Mg) alloys, characterized by good mechanical properties, gradually lose strength at about 155 °C, which is their aging temperature. This is mainly due to the alloying elements that encourage the growth of precipitates at

elevated temperatures, following the well-known Ostwald ripening mechanism, leading to obvious changes in the microstructure and thus negatively influencing the ultimate strength [2]. Some research works mentioned that the addition of Cu enhances the strength of Al-alloys at high temperatures [3]. However, others found that the presence of Cu in Al-Si alloys encourages localized grain boundary corrosion [4].

Alloy systems like Al-Sc, Al-Zr, and Al-V that create stable L12 precipitates have received the majority of attention in recent research that aimed at creating aluminum alloys with enhanced high-temperature performance [3-5]. Following the lattice coherence with the FCC aluminum, the alloy-strengthening precipitates Al₃X (X = Sc, Zr, or V) are stabilized, producing interfacial strain that boosts the thermodynamic stability and serves as a creep-diffusion barrier [6]. This coherence degrades above the conversion temperature,

which for Al-Sc is around 300 °C [7], leading to a reduction in high-temperature properties.

Recently, Al-Ce-based alloys are used as promising alloys for elevated temperature applications. Cerium (Ce) is distinguished from the other rare earth elements by being a low-cost and available element as a byproduct of the heavy rare earth. Al-Ce alloys are highly castable and deformable, which makes them industrially processable. Besides, these alloys have better corrosion resistance than other aluminum alloys [2, 8, 9].

The elevated temperature strength of Al-10Mg-8Ce is much higher than that of common aluminum piston alloys used at elevated temperatures, such as 2618-T61 (Al-2.3Cu-1.6Mg-1.1Fe-1.1Ni, wt.%), which has an ultimate tensile strength (UTS) of 90 and 52 MPa at 260 and 315 °C, respectively [10]. The strength of Al-10Mg-8Ce is comparable to that of the commercial alloy A319-T7 (Al-8.6Si-3.8Cu-0.36Mg-0.5Fe-0.3Mn, wt.%) used in engine blocks, whose ambient temperature UTS decreases from 295 to 162 MPa at 275 °C [11, 12]. Besides, this type of alloy is typical at high-temperature applications since it keeps strength over a long time without deterioration of the alloy properties. Belov [13,14] confirmed Al-Ce-Ni as a good creep-resistant class of cast aluminum alloys when alloyed with transition metals like Fe, Cr, and Ni. In the work of Grbner et al. [15], it was found that Al-Ce-based alloys withstand prolonged exposure at elevated temperatures without losing their thermodynamic stability. Moreover, unlike several Al-alloys, cast Al-Ce alloys are not necessarily heat treated, which significantly increases the production cost in terms of energy consumption, time, and heat treatment facilities [8,11]. It was approved by Sims et al [1] that the outstanding variation in Ce solubility close to the point of eutectic, is translated to highly stable intermetallic precipitates (mainly $Al_{11}Ce_3$), which helps Al-Ce alloys to keep their mechanical properties during high-temperature service. Accordingly, raising the percentage of these intermetallic particles from 7 to 18 wt.% increases UTS retention from 40 to 50%. Therefore, this paper focuses on the microstructure control of Al-Ce alloys and their effect on their high-temperature mechanical properties.

2. Metallurgy of Al-Ce alloys

Fig. [1] shows part of the Al-Ce phase diagram that emphasizes the limited Ce solubility in the Al matrix and eutectic of Al with $Al_{11}Ce_3$ at 4 at.% Ce and 660 °C temperature [13]. The microstructures of this alloy

system are typically presented in Fig. 2 [10]. The as-cast microstructure reveals a pure Al phase and an extremely fine interlinked eutectic structure. At typical cooling rates, the measured laths' scale can be as small as 100 nm, and it doesn't show preferential orientation. At higher temperatures, these structures remain stable. The insoluble nature of cerium in the aluminum matrix traps the intermetallic making the system unable to minimize surface energy through diffusion due to this trapping and preventing the alloy to experience a conventional coarsening interaction [10,11].

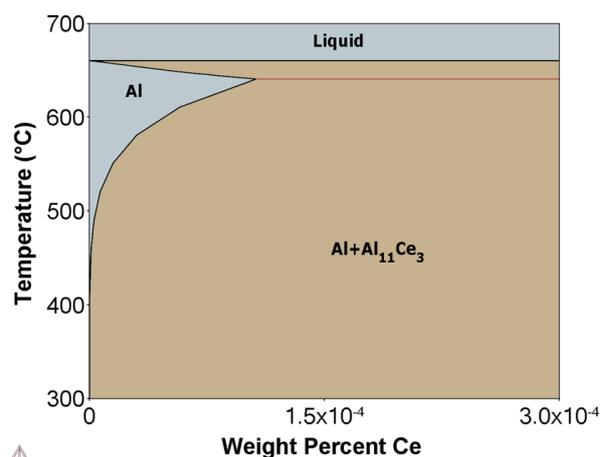


Fig. 1 Part of the phase diagram of the Al-Ce system [1].

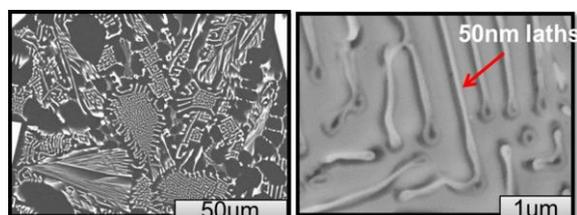


Fig. 2 Micrographs of binary Al-Ce alloy with $Al_{11}Ce_3$ intermetallic particles [10].

Based on the structure-property relationship, Fig. 3, the retention of mechanical properties at elevated temperatures is shown by comparing the ratio of the yield strength at 300 °C to room temperature to the ratio of the UTS at 300 °C to room temperature. This comparison shows that Al-Ce alloys exhibit greater thermomechanical stability than standard alloys. At 300 °C, the Ce alloys maintain more than 60% of their yield at room temperature and more than 40% of their UTS. This contrasts favorably with conventional aluminum alloys, which at 300 °C can only achieve yield and UTS retention values of at most 45% and 50%, respectively [1]. The Al-Ce alloys' higher mechanical retention values may explain how their component phases behave at high temperatures, notably Ce's solubility and diffusion.

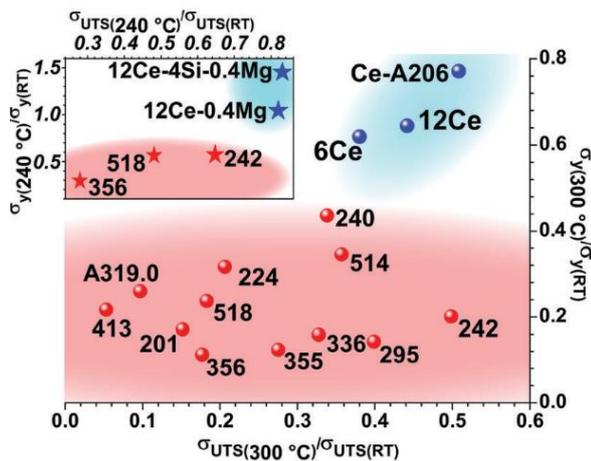


Fig. 3 Ratio of 300 °C to room temperature yield strength vs. ratio of ultimate tensile strength at 300 °C to room temperature [1].

3. Microstructure control of Al-Ce alloys

Based on the aforementioned literature, the microstructure of Al-Ce alloys can be controlled through fragmenting $Al_{11}Ce_3$ intermetallic, which in turn enhances their high-temperature strength. Several techniques have been developed to modify the intermetallic phase particles in aluminum alloys, such as rapid solidification [16], chemical modification [17], and the physical-mechanical vibrations by mechanical or magnetic stirring [18], or by applying ultrasonic treatment [19-21]. This review focuses on microstructure control during the dynamic solidification processes.

3.1. Solidification under magnetic stirring

Wang et al. [22], investigated the morphology of the eutectic phase in Al-5Ce alloy after being treated with magnetic stirring (PMS). PMS method uses the rotating magnetic field to stir melt. It was observed that the eutectic shape was altered from lamellar to fibrous via PMS at a rate of 400 rpm for 10 minutes. Micrographs (SEM) of Al-5wt.%Ce alloys that stirred before permanent mold casting at pouring temperatures of 720 °C and 630 °C, were studied. The microstructure consisted of α -Al matrix and eutectic structure that includes Al phase and $Al_{11}Ce_3$ particles. Most of $Al_{11}Ce_3$ particles were as straight plate-like lamellar structures at the pouring temperature of 720 °C. On the other side, at the temperature of 630 °C, the structures were fibrous. When the pouring temperature decreased after magnetic stirring, the structure transformed gradually from being lamellar to a fibrous structure.

Generally, stirring at a temperature below the liquidus line permits the release of partial latent heat from the α -Al phase, which efficiently increases undercooling during permanent mold casting and forms fiber structure.

3.2. Solidification under ultrasonic vibrations

El-Hadad [2] reported how the fragmentation of the $Al_{11}Ce_3$ intermetallic phase was affected by solidification under ultrasonic melt vibrations (UST) at various pouring temperatures and how the fragmented structure reflected on the strength and wear resistance of Al-10 wt.% Ce alloy. It was stated that the shearing characteristic of ultrasonic melt treatment fragmented the intermetallic compound. Additionally, $Al_{11}Ce_3$ was transformed from a coarse, linked lath-like phase to well-fragmented particles at the ultrasonic treatment temperature of 655 °C. At the pouring temperature of 655 °C along with UST, the particle size of $Al_{11}Ce_3$ dropped from about 30 μm to 3 μm as illustrated in Fig. 4. Further, after ultrasonic treatment, the fraction of area that is occupied by the intermetallic particles increased from about 31% to 40%.

At the ideal pouring temperature (655 °C), heterogeneous nucleation through cavitation occurs and creates a large number of nuclei, which are later carried by the melt and subjected to the second refining mechanism, known as dendritic fragmentation. As a result, perfect microstructure modification was achieved at the optimum UST temperature. After ultrasonic melt processing, the hardness of the conventionally cast alloy raised from 42 to 50 HV, and accordingly, the ultimate compression strength changed from 290 to 390 MPa. As depicted in Fig. 5, the fine and evenly dispersed intermetallic particles show the ideal UST temperature that boosted the alloy's wear resistance at both RT and higher temperatures.

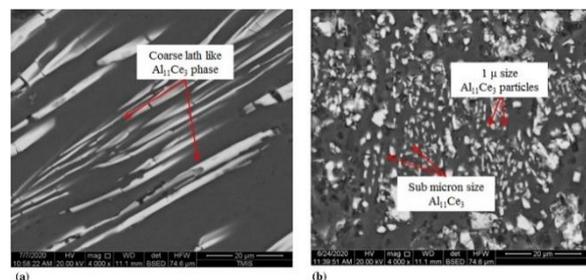


Fig. 4 SEM micrographs of a) 655 °C -no UST; and (b) 655 °C – UST. License no. 5420960115354.

- Alloys by Ultrasonication, *J. Mater. Process. Technol.* 249 (2017) 367–378.
- [20] W. Khalifa, S. El-Hadad, Y. Tsunekawa, Microstructure Evolution and Mechanical Properties of Sonoprocessed-Thixocast AC4C Billets, 71st World Foundry Congress: Advanced Sustainable Foundry, 2014
- [21] H. Huang, Y. Xu, D. Shu, Y. Han, J. Wang, and B. Sun, Effect of ultrasonic melt treatment on structure refinement of solidified high purity aluminum, *Trans. Nonferrous Metals Soc. China*, (2014) 2414–2419.
- [22] L. Wang, R. Qi, B. Ye, Y. BAI, R. Huang, H. Jiang, W. Ding, Improved Tensile Strength of Al-5Ce Alloy by Permanent Magnet Stirring, *Metallurgical and Materials Transactions A*, 51 (2020) 1972-1977.