MICROSTRUCTURE AND MECHANICAL PROPERTIES OF INNOVATIVE Al-Si-Mg ALLOYS

Marco Colombo, Elisabetta Gariboldi – Politecnico di Milano, Dipartimento di Meccanica

When considering structural applications, the maximum temperature of use of Aluminum alloys is limited by the degrading mechanical properties of Aluminum with temperature and, in the case of age-hardenable alloys, by the thermal stability of the precipitates formed during heat treatments. The addition of elements promoting the precipitation of coarsening-resistant particles, is one of the major and most effective ways to improve mechanical properties at elevated temperature. In this regard, transition elements and rare earths, added in fractions of unity in weight percent in the base alloy, can cause tremendous improvements in the thermal resistance of Al alloys. The present contribution focuses on specific additions made to a conventional Al-7Si-Mg casting alloy (A356). A set of alloys has been designed and cast with different Er and Zr additions. The microstructures of the alloys were characterized by means of optical micrographs, which showed the effectiveness of Er in modifying the Si eutectic, similarly to Sr, already in the as-cast state. Heat treatment cycles were performed and characterized by means of microhardness tests. It was found that, increasing the concentration of Er and Zr, the microhardness of the alloys in the peak hardness and after prolonged exposure to high temperatures was higher than that of the reference alloy.

KEYWORDS: ALUMINUM ALLOYS, THERMAL STABILITY, MECHANICAL PROPERTIES, ERBIUM, ZIRCONIUM.

INTRODUCTION:

The Al-7Si-Mg (A356) alloy is widely used in many industrial fields, because of its good mechanical properties at room and elevated temperatures, good corrosion and wear resistance and excellent castability. It has been demonstrated in different studies that proper additions of some transition elements and rare earths are very effective in strengthening hypoeutectic Al-Si based alloys at both room and elevated temperatures, changing also the eutectic morphology [1-5]. Among the transition elements, Zr results in a potentially very effective strengthening element for hypoeutectic Al-Si alloys [6]. Among rare earths, Er can lead to the formation fine precipitates, observed in commercially pure Al [7] and it acts as a modifier of the morphology of the Si eutectic phase, similarly to Sr. it has also an effect in improving the mechanical properties of Al-based alloys like A356 [1].
Literature studies have further reported synergetic effects of Er and Zr as regards strengthening of pure Al [8, 9]. Microstructurally, this family of alloy is characterized by core-shell dispersoids with improved thermal resistance [9]. The core is enriched with Er that, as a consequence of its higher diffusion coefficient, rapidly precipitate during heat treatment of the alloy. The formed Er-rich precipitates act as nucleation points for a Zr-rich layer, which forms the shell of the dispersoid. Due to the sluggish diffusion of Zr in Al, the shell acts as a barrier for dispersoid coarsening/dissolution, enhancing the thermal stability of the alloy.
Aim of the paper is to preliminary check the effect of addition of Er and of Er plus Zr on the microstructure and microhardness of a commercial A356 alloy in the as-cast, as-solution treated, peak aged and overaged conditions, comparing the results with those obtained from a commercial A356 alloy without Sr modification.

MATERIALS AND METHODS:

The chemical compositions of the alloys used in this work are reported in Table 1. By adding to the A356 different amounts of Al-15 wt % Er and Al-10 wt % Zr master alloys during castings, four alloys were obtained with final concentrations of 0.3 wt% Er, named E3, and 0.3 wt% Er plus 0.1, 0.3 and 0.5 wt% Zr, named EZ31, EZ33 and EZ35, respectively.

Tab. 1 - Chemical composition (in wt %) of the alloys used in this work.

CHEMICAL COMPOSITION OF THE STUDIED ALLOYS							
	Si	**Mg**	**Fe**	**Ti**	**B**	**Er**	**Zr**
A356	7.24	0.42	0.14	0.12	0.04	-	-
E3	7.09	0.41	0.13	0.11	0.03	0.3	-
EZ31	7.02	0.41	0.13	0.11	0.03	0.3	0.1
EZ33	6.88	0.40	0.13	0.11	0.03	0.3	0.3
EZ35	6.73	0.39	0.13	0.11	0.03	0.3	0.5

The alloys were melted in an induction furnace and held at a temperature of 800°C for 30 minutes in a protective argon atmosphere, to ensure homogenization of the melt and complete dissolution of primary aluminides present in the master alloys. The molten alloys were then poured in a permanent mold, pre-heated to a temperature of 200°C, to obtain cylindrical bars.

Samples for microstructural characterization and microhardness tests were extracted from similar positions of the cast bars, solution treated at 540 °C for 5h in an air-circulating muffle furnace, quenched in cold water (20 °C) and then aged at different temperatures (160 and 200 °C) for different times.

After aging, samples were prepared for metallographic analyses and etched in Keller's reagent.

Optical micrographs were taken and analyzed to assess the effect of Er and Zr as modifiers of the Si eutectic, measuring the roundness of Si particles in the as-cast and as-solution treated conditions. The actual development of core-shell precipitates was not directly addressed in the present work, their effects being here taken into account in the analyses of mechanical properties and microstructural stability. These latter were carried out by means of microhardness tests, performed using 2.94N indenter load.

RESULTS AND DISCUSSION:

Microstructural Characterization

The typical metallographic features of the studied alloys in the as-cast condition are shown in Fig.1. The reference A356 alloy, shown in (a), was characterized by elongated eutectic Si particles, which are detrimental for the ductility of the material. Small addition of Er, micrograph (b), had a very pronounced effect in modifying the shape of the Si phase, confirming the results reported in [1] for the same alloy.

The morphology of eutectic Si in as-cast alloys was described by means of geometric parameters such as its aspect ratio and average length, which are reported in Table 2. The addition of Er significantly reduced the average aspect ratio and length of the eutectic Si. The addition of Zr did not promote any additional spheroidization effect, but further reduced the average length of the eutectic.

The geometrical parameters of eutectic Si were also evaluated after solution treatment, and results are listed in the same Table 2. The prolonged stay at high temperature during this heat cycle coarsened the eutectic Si and enhanced its spheroidization. These effects were also observed in the base alloy. Nevertheless, while all the modified alloys showed homogeneously rounded eutectic with an average aspect ratio of 1.2-1.3 according to the specific chemical composition, the base alloy displayed an inhomogeneous geometry for Si eutectic. Aspect ratio ranging from 2 to 4 could be found in some regions, while a value of 10 or more in others. This effects could result both from the intersection of metallographic plane with differently oriented Si-structures or to their actual geometrical inhomogeneity.

The efficiency of Er in reducing the eutectic size was evident also after solution treatment, as reported in [1]. The eutectic Si average length reduced, in fact, to the 24% of that of the base alloy. On the other hand, the additional refining action visible in the as-cast condition for the EZ series alloys is lost after solution treatment.

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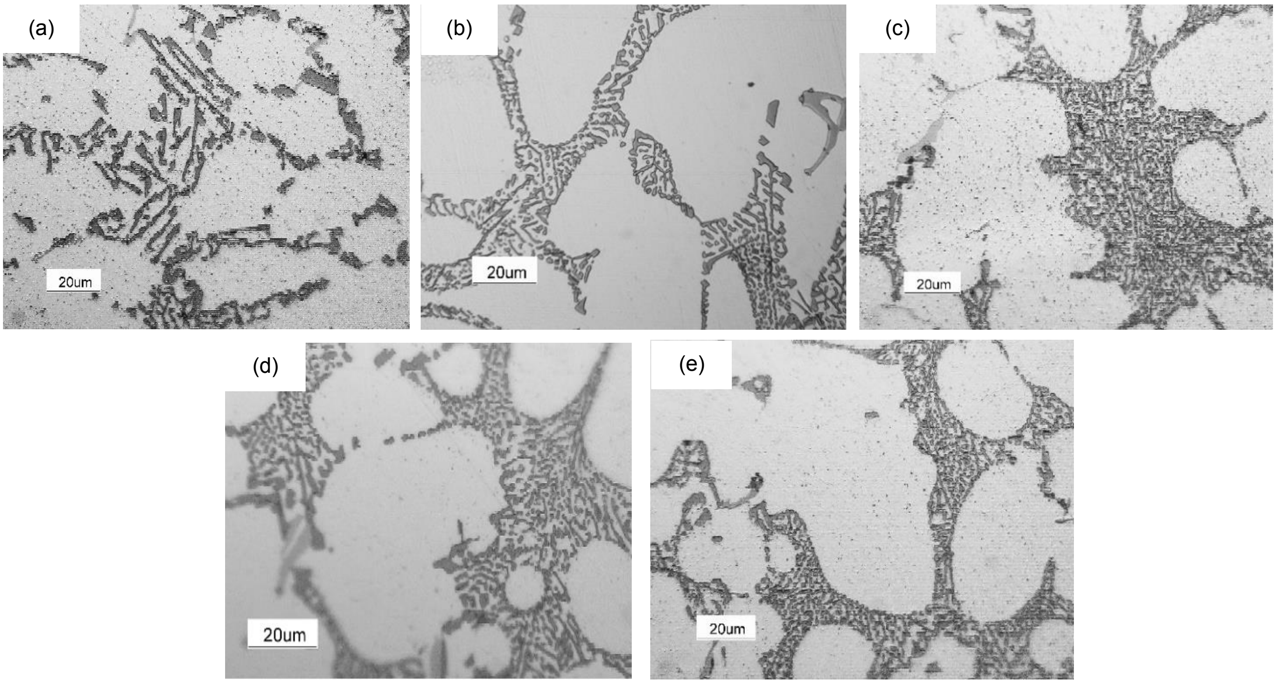

Fig.1 – Microstructure of A356 (a), E3 (b), EZ31 (c), EZ33 (d) and EZ35 (e).

Tab. 2 - Average geometrical characteristics in the as-cast condition (a.c. columns) and after solution heat treatment (s.t. columns) of eutectic Si for the studied alloys. Each value is obtained measuring at least 100 eutectic Si particles.

GEOMETRY OF EUTECTIC Si										
	A356		E3		EZ31		EZ33		EZ35	
Condition	**a.c.**	**s.t.**	**a.c.**	**s.t.**	**a.c.**	**s.t.**	**a.c.**	**s.t.**	**a.c.**	**s.t.**
Aspect Ratio	10.8	4.2	1.6	1.2	1.5	1.3	1.7	1.3	1.7	1.3
Average Length (μm)	17.2	19.2	3.5	4.5	2.4	4.5	2.4	4.5	2.3	4.5

Aging Curves

After solution heat treatment, samples extracted from the studied alloys were artificially aged at 160 and 200°C for different times; the curves describing the evolution of the alloys microhardness as a function of the aging time are shown in Figure 2. When aged at 160°C, all the modified alloys reached peak hardness in 24 hours. Peak hardness of Er-Zr-containing alloys increased with their content from 118 HV for E3 to 130HV for EZ35, with an increase of 18% with respect to that of the reference alloy (110HV). Overaging was evident for A356 alloy, while hardness remained almost constant after 80 h for modified alloys

Increasing the aging temperature to 200°C, revealed the effect of modifications on the precipitates nucleation rate and strengthening effect, EZ35 showing the fastest and more intense response to the thermal treatment, reaching the peak hardness of about 120HV, 41% higher than the reference alloy. After 50h the strength increase with respect to the reference alloy is kept at 36%. This is a preliminary confirmation of the enhanced thermal stability of E and EZ alloys with respect to the A356 alloy, even if the thermal treatments were not optimized to maximize the contribution of Al_3Er and $Al_3Er_xZr_{(1-x)}$ dispersoids.

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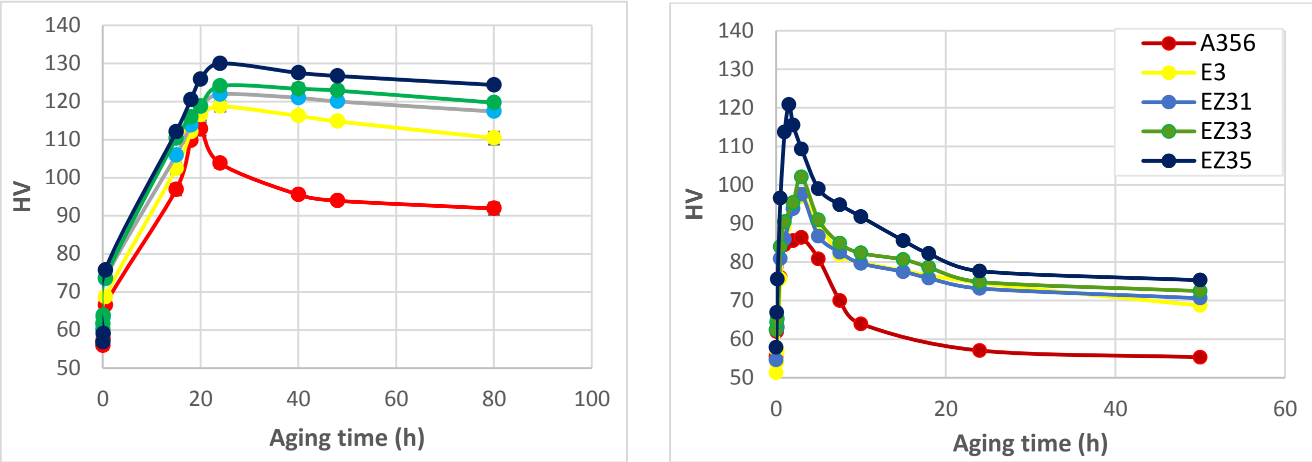

Fig.2 – Aging curves for the studied alloys at 160°C (a) and 200°C (b).

CONCLUSIONS AND FURTHER DEVELOPMENTS:

The present preliminary study was aimed at characterizing a set of potentially stronger and high-temperature stable Al-Si-Mg cast alloys, modified with small additions of Er and Zr. The analysis of the microstructures showed that these elements have a great effect in reducing the size and aspect ratio of eutectic Si, which is considered promising in increasing the ductility and the strength of the base alloy.

The mechanical properties of the alloys have been investigated in terms of microhardness, checking the effects of temperature on aging curves. At peak aging, the hardness values for the modified alloys were significantly increased with respect to the reference alloy and during overaging they showed improved thermal resistance.

Further studies will be devoted to a to a more in-depth characterization of the alloys via electron microscopy (TEM and SEM), in order to better define the role of alloying elements and to indentify suitable heat treatments to optimize both strength and thermal stability .

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