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Eutectic Al–Si–Cu–Fe–Mn alloys with enhanced mechanical properties at room and elevated temperature

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ABSTRACT

In this paper, we report a novel kind of eutectic Al–Si–Cu–Fe–Mn alloy with ultimate tensile strength up to 336 MPa and 144.3 MPa at room temperature and 300 °C, respectively. This kind of alloy was prepared by metal mold casting followed by T6 treatment. The microstructure is composed of eutectic and primary Si, α-Fe, Al_2Cu and α-Al phases. Iron-rich phases, which were identified as BCC type of α-Fe ($Al_{15}(Fe,Mn)_3Si_2$), exist in blocky and dendrite forms. Tiny blocky Al_2Cu crystals disperse in α-Fe dendrites or at the grain boundaries of α-Al. During T6 treatment, Cu atoms aggregate from the super-saturation solid solution to form GP zones, θ'' or θ'. Further analysis found that the enhanced mechanical properties of the experimental alloy are mainly attributed to the formation of α-Fe and copper-rich phases.

1. Introduction

Cast eutectic Al–Si alloys have been widely used in the piston of petrol engines manufacturing because of their low density, high wear resistance and low expansivity [1]. As the engines are working, the pistons contact instantaneously to the hot gas, of which the temperature may reach as high as 2200 °C. The temperature at the top of the piston is up to 300–400 °C [2]. Besides the high temperature gas, the piston also bears the gas pressure as high as 4–6 MPa for gas engine or 6–9 MPa for diesel engine. For turbine engine or heavy-duty car, the gas pressure that piston bears may further increased. Under such a severe working condition, it is vital for piston materials to possess excellent high temperature mechanical properties.

To improve the elevated temperature mechanical properties of Al–Si alloys, peoples have tried to prepare Al–Si alloys by alloying or innovative processes such as spray forming and thixoforming technologies [3,4]. For example, a kind of deforming Al–Si alloy with low iron content (<0.3 wt.% Fe) prepared through thixoforming has been reported previously, and the ultimate tensile strength (UTS) of this alloy increases up to 397 MPa after hot working [5]. Keeping G/R in the range of 100–1000 °C s/cm^2 (where G is temperature gradient and R is the growth rate of solid phase) during solidification, a serials of squeeze formed Al–Si alloys with 1.0–1.4 wt.% Ni and 14–16 wt.% Si are fabricated and exhibit a maximum UTS of 380 MPa after T6 treatment [6]. All these efforts mentioned above indeed improve the mechanical properties of Al–Si alloys. However, the production costs of these technologies are obviously higher than that of the conventional mold cast.

Alternatively, elements such as Ni, Mo, Ta, V, Sc, Cu, Fe and Mn are often added as important strengthening elements for special purpose [4,7–11]. The addition of these elements results in the improvement in tensile properties by the formation of intermetallics and solid solution strengthening of α-Al matrix. Of the above strengthening elements, the noble elements of Ni, V, Sc, etc. combined with some traditional alloying elements such as Cu and Mg were often placed emphasis on. For instance, with the addition of 2.5–4.0 wt.% Cu and 1.7–3.0 wt.% Ni, the UTS of the metal mold cast Al–Si alloy reaches 264 MPa at room temperature after T6 heat treatment [12]. Copper is an important alloying element in Al–Si alloys and imparts good heat treatability to castings owing to the large solid solubility in aluminum matrix. However, the amount of Cu is usually controlled below 3.0 wt.% due to the worry about the formation of micro-porosities which act as micro-crack sources during tensile process [13,14]. In addition, Cu inclines to aggregate in the melt owing to the large specific gravity comparing to the elements of Al and Si, which limits the precipitation strength induced by Cu from further increase inevitably.

Iron is traditionally considered as a harmful element in Al–Si alloys since the coarse and brittle lamellar β-Fe (Al_5FeSi) crystals may be formed as a primary phase when the Fe content is more than 0.5 wt.% [15]. Thereafter, it is found that α-Fe ($Al_{15}(Fe,Mn)_3Si_2$) can be formed if both the Fe and Mn are added under a certain cooling rate during the solidification [16–18]. Due to its Chinese script morphology, a certain amount of α-Fe dendrites indeed improve the elevated temperature tensile strength and retard the micro-cracks extension during tensile process [19–21]. Hence the negative effects caused by the hard, brittle iron-rich phases are partially neutralized. Owing to the relatively higher formation temperature, iron-rich phases often act as the nucleation sites of

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