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On the effect of hydrogen and Fe on reproducibility of tensile properties in cast Al–Si–Mg alloys

G. Eisaabadi B. [a,b,*], P. Davami [a], N. Varahram [a], S.K. Kim [b]

[a] Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran
[b] Foundry Technology Center, Korea Institute of Industrial Technology, Incheon, South Korea

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ABSTRACT

Gas porosities and Fe-rich phases and entrapped double oxide films (hereafter: oxides) are known to be the most detrimental defects in cast Al–Si–Mg alloys. The effects of H (gas porosities) and Fe (β-Al_5FeSi phase) on reproducibility of tensile properties in Al–7Si–0.35Mg alloy have been investigated in this study. Four different casting conditions (Low H–Low Fe, Low H–High Fe, High H–Low Fe and High H–High Fe) were studied. In each case, 30 tensile test samples were prepared by casting in a metallic mold and machining (total of 120 tensile test samples). Results of tensile test were analyzed by Weibull three-parameter analyses. The microstructures of samples were studied by optical microscope. Total of 800 metallography images (200 images for each experiment) were taken and analyzed by image analysis software. Finally, the relationship between tensile properties and defects characteristics was discussed.

According to the results, Fe (β-Al_5FeSi phase) showed considerably larger negative impact on tensile properties of the alloy compared to H (pores). Results of Weibull analysis revealed that the scattering of tensile properties was mainly due to the presence of β phase within the microstructure. Results of image analysis showed that the pore area% and number of pores/cm^2 were mainly controlled by H and Fe content of the melt, respectively. Also, it was shown that Weibull modules of UTS and El% increased linearly with increasing the shape factor of pores. Furthermore, tensile properties of the examined alloy showed strong dependence to the number of pores.

1. Introduction

Al–Si–Mg cast alloys offer a good combination of mechanical properties and castability, which explains their wide use in automotive and aerospace applications [1–4]. Nevertheless, aluminum castings have been rarely used in safety-critical applications due to concerns about the variability in mechanical properties, especially in elongation and fatigue life [1,2,5]. This high level of variability is the consequence of structural defects in castings, i.e. pores, Fe-rich phases and oxides, which degrade mechanical properties [6]; they cause premature fracture in tension [2,7] and fatigue [8], resulting in low ductility, tensile strength and fatigue life [9,10]. Therefore, the presence of major structural defects results in the high level of variability in mechanical properties [10,11], as evidenced most notably by lower Weibull module [2,12–14]. Hence, the minimization and even elimination of structural defects is vital for wider use of Al–Si–Mg castings in structural applications in aerospace and automotive industries.

Another important defect which occurs in cast aluminum alloys is gas porosities. Hydrogen is the only gas that is appreciably soluble in aluminum and its alloys. Actual liquid and solid solubilities in pure aluminum just above and below the solidus are 0.69 and 0.04 ppm [15]. These values vary only slightly for most cast aluminum alloys. During cooling and solidification, precipitation of the hydrogen results in formation of primary and/or secondary voids. Many researchers [16–20] investigated the effect of porosities on mechanical properties of cast Al–Si–Mg alloys. It has been suggested that porosity is a leading cause in the reduction of mechanical properties, particularly elongation and fatigue resistance, as well as a loss of pressure tightness and a degradation of the surface appearance in cast parts [15]. Liu et al. [21] claimed that oxides have deleterious effect over the mechanical properties whereas Wang et al. [22] suggested that porosity is more detrimental than oxides.

Iron is the most common impurity that can be found in cast aluminum alloys since it cannot be removed economically [23]. In the Al–Si–Fe system there are five main Fe-rich phases: Al_3Fe, α-Al_8Fe_2Si, β-Al_5FeSi, δ-Al_4FeSi_2 and γ-Al_3FeSi [24]. In addition, Fe and Mg may result in the appearance of π-$Al_8Mg_3FeSi_6$. Therefore, α, β and π phases are normally precipitated in cast hypoeutectic and eutectic aluminum alloys containing magnesium [25]. Many researchers reported that increasing of iron content decreases the mechanical properties of cast Al–Si alloys [26–30].

* Correspondence to: Eco metal Laboratory, Foundry Technology Center, Korea Institute of Industrial Technology, 7-47, Songdo-Dong, Yeonsu-Gu, Incheon 406-840, South Korea. Tel.: +82 32 8500 417.
E-mail addresses: G_eisaabadi@mehr.sharif.ir, G_eisaabadi@kitech.re.kr, rasol121@gmail.com (G. Eisaabadi B.).

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Several researchers investigated the different interactions between pores and Fe-rich phases in cast aluminum alloys [31–34]. It has been suggested [31] that, increasing the iron content in the cast Al–A319 alloy increased the porosity, particularly shrinkage porosity. It is due to the precipitation of long and thick (needle or platelet) β-Al_5FeSi phases which are often branched into several needles. The branched morphology of β phase decreases the permeability of the interdendritic network [31,34,35] and results in reduced feeding of liquid metal through the interdendritic channels. Subsequently, the tendency for formation of extended porosity defects within the castings will be increased [35]. The nucleation of porosity on β phase is more important in sand mold castings, where the slower cooling rates favor the formation of β phase [32]. Taylor et al. [34] suggested two mechanisms for the role of iron in porosity formation. The first theory suggests that the β platelets form in the interdendritic channels during solidification and cause a physical restriction to the movement of compensatory feed liquid. This results in inadequate feeding and favors the formation of porosity. The second theory considers the β phases as active pore nucleation sites that physically constrain the growth of the pores and influenced their ultimate shape.

From the above literature survey, pores and Fe-rich phases are two of the main defects that influence the tensile properties of cast Al–Si–Mg alloys. On the other hand, these defects represent a complicated interaction with each other. Therefore, the aim of this study is to investigate the effect of these defects on tensile properties of Al–Si–Mg alloys and their effects on reproducibility of tensile properties in these alloys.

2. Experimental procedure

The alloy used in this experiment was a 2L99 alloy with a specific chemical composition of 7.2 wt% Si, 0.35 wt% Mg and 0.09 wt% Fe that was received as 5 kg ingots. The alloy was divided into two groups, with low and high Fe contents. The Fe content of low and high Fe alloys was designed to be 0.1 and 0.8 wt%, respectively. Al-20 wt% Fe master-alloy was added into the 2L99 molten alloy in order to increase the Fe content of the alloy. Table 1 shows the actual chemical composition of the investigated alloys (sample was taken from the melt), which was analyzed by ICP–AES (inductively coupled plasma–atomic emission spectroscopy).

The pattern used in this study, was tensile test bar mold shown in Fig. 1. The dimensions of the gating system are listed in Table 2. This mold was designed based on the naturally pressurized running system. According to Table 2, the runner height after filter that is indicated in Fig. 1 was 12 mm. This height was determined with considering the melt critical velocity. According to this theory, the critical velocity has been shown both theoretically and experimentally to be approximately 0.50 m/s for liquid aluminum alloys [36,37]. This states that, if the molten aluminum flows with velocity greater than 0.50 m/s, then there will be surface turbulence and the probability of oxide generation, which will then be incorporated into the bulk of the liquid metal [38].

On the other hand, it was shown that if a stream of melt falls from the height of $\boldsymbol{h}$, the melt velocity, $\boldsymbol{v}$, could be calculated by Eq. (1) [36]:

$$v = (2\boldsymbol{gh})^{1/2} \tag{1}$$

where; the gravitational acceleration ($\boldsymbol{g}$) is 9.81 m/s^2, then the distance $\boldsymbol{h}$, in millimeters, that the metal has to fall to reach the critical velocity is given by Eq. (2):

$$\boldsymbol{h} = \boldsymbol{v}^2/2\boldsymbol{g} = 0.52/(2 \times 9.8) = 12.7 \text{ mm} \tag{2}$$

since, the runner height of the mold was 12 mm (less than 12.7 mm), the velocity of free falling melt was 0.48 m/s (less than critical value). Therefore, these castings had no or very small amount of entrapped oxides. Furthermore, in all castings, a 30 ppi ceramic filter was placed in the filter print. Ardekhani and Raiszadeh [2] showed that a 30 ppi ceramic foam filter can remove almost all previously formed inclusions and oxides, and also reduce the speed of flow of the molten alloy filling the mold in order to prevent further oxide from being entrained.

In order to control the hydrogen content of the melt, in castings with Low H, a rotary fluxing and degassing machine was used to obtain a Low H content (rotor speed 150 rpm, flux

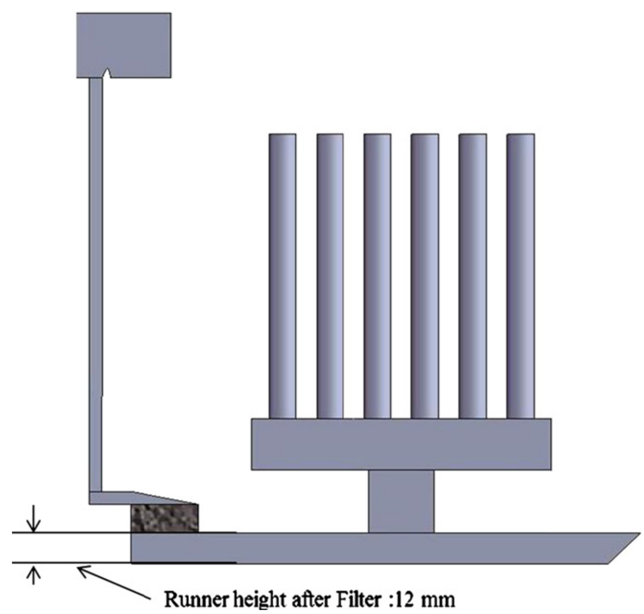

Fig. 1. Geometry of pattern used in this study (after [39]).

Table 2
Dimensions of running system component in Fig. 1 (all in millimeter) [39].

Running system component	Dimensions
Pouring basin	50 × 70 (depth 60)
Sprue cross section	Up (10 × 45), down (9 × 13)
Sprue height	320
Filter print	50 × 50 × 22
Runner cross section	Before filter (11 × 14), after filter (12 × 14)
Gate cross section	11 × 48.4
Riser	220 × 40 × 40
Tensile samples	Height 220, diameter 20

Table 1
The chemical composition of investigated alloys.

	Si	Mg	Fe	Ti	Cu	Ni	Zn	Sn	Mn	Al
Low Fe	6.98	0.35	0.09	0.15	0.01	0.013	< 0.015	< 0.005	< 0.005	Balance
High Fe	7.01	0.34	0.85	0.14	0.01	0.016	< 0.015	< 0.005	< 0.005	Balance