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Effects of hydrogen and oxides on tensile properties of Al–Si–Mg cast alloys

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

[a] *Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran*
[b] *Eco-Metal Division, Korea Institute of Industrial Technology, Incheon, South Korea*

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ABSTRACT

Gas porosities and entrapped double oxide film (hereafter: oxides) are known to be the most detrimental defects in cast Al–Si–Mg alloys. This study investigated the effects of dissolved hydrogen (hereafter: H) and oxides on reproducibility of tensile properties in Al–7Si–0.35 Mg alloys. Also the effects of H and oxides content on the morphology of defects were studied. Four different casting conditions (low oxide–low H, low oxide–high H, high oxide–low H, high oxide–high H) were tested using tensile test bars that were cast in a metallic mold. Results of tensile test that were obtained for each casting condition were analyzed using Weibull two-parameter analysis. Microstructure and fracture surface of samples were examined by optical microscopy, SEM and EDS. Results showed that H has slightly larger negative impact on tensile properties of this alloy compared to oxides. On the other hand, oxides caused considerably higher scattering of tensile properties than H. Examination of microstructure showed that increasing of initial H of melt changed morphology of oxides from two dimensional (2-D) to three dimensional (3-D) one. It was explained through the diffusion of H into the atmosphere of oxides that expanded them. The effects of this morphological change on Von Mises stress and equivalent plastic strain was simulated by using finite element analysis. Results of finite element analysis showed that the maximum values of both Von Mises stress and equivalent plastic strain around the oxides decreased with changing their morphology from 2-D to 3-D. Also, it was shown that increasing of the H in high oxide samples, decreased the average tensile properties of test bars, but increased the reproducibility of tensile properties.

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1. Introduction

Aluminum–silicon cast alloys offer a good combination of mechanical properties and castability, which account for 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 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 modulus [2,12,13]. Hence, the minimization and even elimination of structural defects is vital for wider use of aluminum castings in structural applications in aerospace and automotive industries.

Oxides are one of the most common structural defects that exist in the microstructure of cast aluminum alloys. A general acceptance is gradually growing among researchers [14–17] that oxides play a major role in the reduction of the quality and reliability of aluminum casting alloys. Campbell [18] reported that oxides, which remain in the cast products, cause mechanical weakness and form leak paths through the walls of castings. Campbell [19] also reported that oxides appear to be the source of most of the general casting defects and act as cracks to initiate failures. Furthermore, they exert major control of the cast microstructure, including (a) grain size, (b) DAS, and (c) the modification of the eutectic silicon in the aluminum alloys.

Another important defect which occurs in cast aluminum alloys is gas porosities. H (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 [25]. These values vary only slightly for most casting alloys. During cooling and solidification, H in excess of the extremely low solid solubility may precipitate in molecular form, resulting in the formation of primary and/or secondary voids. Many researchers [20–24] investigated the effect of porosities on mechanical properties of cast Al–Si–Mg alloys. 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 [25].

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[*] Corresponding author at: 7-47, Songdo-Dong, Yeonsu-Gu, Incheon 406-840, South Korea. Tel.: +82 32 8500 412; fax: +82 32 8500 412.
E-mail address: G_eisaabadi@mehr.sharif.ir (G. Eisaabadi B.).

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Liu [26] concluded that oxides have deleterious effect over the mechanical properties whereas Wang [27] suggested that porosity is more detrimental than oxides. Mattos [28] concluded that defects related to oxides are more important in the absence of pores, because they present 2-D morphology and they have higher dependence on the loading direction while, on the other hand, pores have 3-D morphology-cavities.

Oxides introduced into an Al melt have been shown to expand as the result of diffusion of H into their interior atmosphere. Raiszadeh and Grifith [29] showed that convection or other sources of fluid flow results in continuous ruptures of oxides and diffusion of H will occur into an oxide through surface ruptures. It should be mentioned that passage of H through surface ruptures is a faster way than diffusion through the oxide layers. They showed that the diffusion of H in solution into the oxides caused their expansion. As a result of this expansion further fracturing of the oxide could occur in a continuous process, and finally the rate of passage of H will be controlled by the rate at which the film was ruptured and resealed. On the other hand, during solidification rejection of H from the growing solid causes the H content of the liquid metal to rise to twenty times its equilibrium concentration [30] and this would greatly increase the driving force for diffusion of H into the atmosphere of the oxides and their further expansion[29]. Oxides and porosities (H) have a high degree of interactions; therefore, the aim of the present study is to investigate the interaction of oxides and H in terms of mechanical properties and defects morphology in cast Al–Si–Mg alloys.

2. Experimental procedure

The alloy used in this experiment was Al–7Si–0.3Mg. The actual chemical composition of the alloy (sample was taken from the melt), which was analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES), is given in Table 1. The pattern used for this experiment was tensile test bar mold shown in Fig. 1. Each mold contained six test bars, each with a diameter of 20 mm and length of 220 mm (the details of the gating system are listed in Table 2). Four different types of castings were prepared according to Table 3.

Table 1
Chemical composition of investigated alloy.

Si	Mg	Fe	Ti	Cu	Ni	Zn	Sn	Mn	Al
6.98	0.35	0.10	0.15	0.01	0.013	<0.015	<0.005	<0.005	Balance

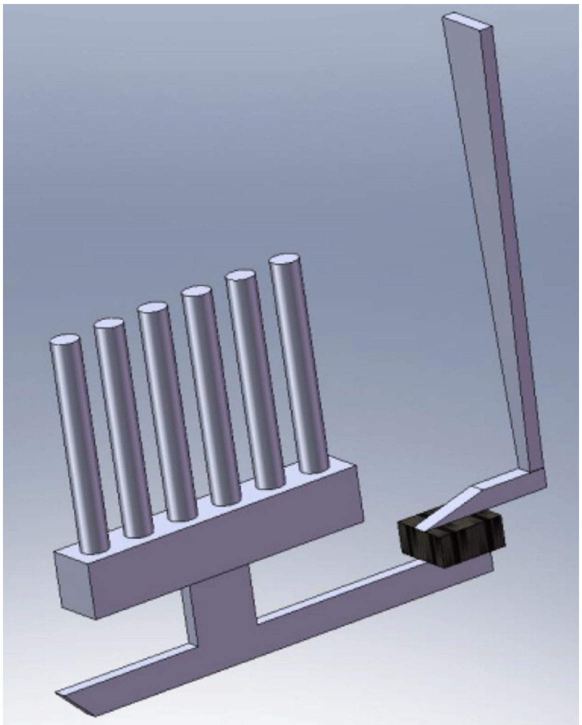

Fig. 1. Geometry of pattern used in this study (after [34]).

Table 2
Dimensions of running system component in Fig. 1 (all in millimeter) [34].

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 3
Summary of casting condition in the present study.

Designation	Experiment	Filter size (ppi)	Hydrogen (ml/100 g melt)
A	Low oxide, low H	30	0.11
B	High oxide, low H	–	0.10
C	Low oxide, high H	30	0.47
D	High oxide high H	–	0.44

For castings with low H, the melts were degassed with a rotary fluxing and degassing machine to remove H from the molten alloy to obtain a low H content (rotor speed 150 rpm, flux feed rate 18 g/min. and injection time 200 s). The H measurement instrument was a HyScan II (a product from Severn System Company). On the other hand, for castings with high H, no degassing was performed.

For castings with high oxide content, no ceramic foam filter was used in the filter print. While, for castings with low oxide content, a 30 ppi ceramic filter was placed in the filter print. The 30 ppi ceramic foam filter is thought to remove previously formed inclusions and oxides to a very large extent, and also reduce the speed of flow of the molten alloy filling the mold in order to prevent any further oxide from being entrained [2].

It was shown that if a stream of melt falls from the height of h, the melt velocity, v, could be calculated by Eq. (1) [31]:

$$v = \sqrt{2}gh \tag{1}$$

The critical velocity has been shown both theoretically and experimentally to be approximately 0.5 m/s for liquid aluminum alloys [32,33] and the acceleration due to gravity (g) is 9.81 m/s^2, then the distance h, in millimeters, that the metal has to fall to reach the critical velocity is given by:

$$h = \frac{v^2}{2g} = \frac{0.5^2}{2 \times 9.8} = 12.7\,\text{mm}$$

This is stating that if the metal falls a distance greater than 12.7 mm, then there will be surface turbulence and the probability of oxide generation, which will then be incorporated into the bulk of the liquid metal [31]. Since the runner height was 12 mm (less than 12.7 mm), in castings with a 30 ppi filter, 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. On the other hand, by removing the filter in high oxide casings the velocity of free falling melt after filter will be far beyond the critical velocity of aluminum alloys. Therefore, oxides entrapment happened in these castings.

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