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Effect of Mg on the fracture characteristics of cast Al–7Si–Mg alloys

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Abstract

The fracture behavior of Al–7Si–Mg cast alloys mainly depends on the size and shape of eutectic silicon particles and iron-rich intermetallics. These can be altered by many ways such as, chemical modification, cooling rate, magnesium content and iron-rich intermetallics. Magnesium increases the matrix strength, but decreases the ductility. Further, cast Al–7Si–Mg alloys can be strengthened by heat treatment processes to attain desirable mechanical properties. Crack tortuosity, crack branching factor (CBF) and tendency of crack propagation through eutectic regions are quantified in order to study the formation and growth of fatigue crack. The crack propagation in the Al–Si–Mg alloys depends on the morphology of silicon particles, cell size and Mg content. The fracture toughness values measured are found to decrease with increase in magnesium content at the optimized T-6 heat treated condition.

Keywords: Al–7Si–Mg cast alloy; Eutectic silicon; Fracture toughness; Fatigue crack

1. Introduction

Cast Al–Si–Mg alloys have wide spread applications for making structural components in automotive, aerospace and general engineering industries due to their excellent castability, corrosion resistance and high specific strength [1]. When these components are in service, they fail under severe conditions. The significant point is that many discontinuities or cracks are present in many large fabricated structures, even though these structures may have been "inspected". Methods of inspection or non-destructive testing are gradually improving, with the result that smaller and smaller discontinuities are becoming detectable. An overwhelming amount of research on brittle fracture in structures of all types has shown that numerous factors (e.g., service temperature, material toughness, design, welding, residual stresses, fatigue, etc.) can contribute to brittle fractures in large welded structures. However, the development of fracture mechanics has shown that there are three primary factors, namely material toughness, crack size and stress level that control the susceptibility of a structure to brittle fracture [2]. Magnesium in Al–Si cast alloys is intentionally added to increase the tensile strength on heat treatment and it predominantly affects the microstructure [3]. According to Joenoes and Gruzleski [4], magnesium neither clearly refines nor clearly coarsens the eutectic, but definitely reduces the degree of homogeneity of the microstructure. Al–7Si–Mg alloys form dendrites during solidification and fracture occurs generally in ductile manner by void initiation at eutectic silicon particles and inclusions [5].

Gall et al. [6] have concluded by SEM fractographic studies, that the interface debonding dominated the fatigue crack growth process at a maximum stress intensity factor, K_{max} less than 6 MPa m$^{1/2}$, but fracture of Si particles dominated at K_{max} greater than 6 MPa m$^{1/2}$. Lee et al. [7,8] have showed that decohesion of Si particles from Al matrix is the predominant failure mechanism in Sr-modified Al–Si–Mg cast alloy with small (∼1.5 μm) Si particles. But in the unmodified Al–Si–Mg alloy castings having larger Si particles (∼3.8 μm), the predominant fatigue mechanism is the fracture of Si particles. Mixed mode of Si particle cracking and interface decohesion is also observed in the case of alloy containing Si particles in the size range of 2.5–5.5 μm. Thus, it is evident that microstructure has a significant effect on the fatigue and fracture mechanisms in Al–7Si–Mg cast alloys, i.e., microstructures containing small dendrite cells and Si particles, develop damage at a low rate, thus requiring a large strain to reach the critical level for fracture. On the other hand, coarse microstructures with large cell sizes, large and elongated Si particles tend to crack at low strains, thus lowering the ductility [9].

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Table 1
Chemical composition of A356 alloy

Alloy	Si	Mg	Zn	Cu	Fe	Mn	Be	Ti	Others	Remaining
A356	7.0	0.35	<0.05	<0.05	<0.11	<0.03	–	<0.20	<0.05	Al

The mechanical properties of cast Al–7Si–Mg alloys depend on size and morphology of eutectic Si particles, dendrite arm spacing and cell size. As dendrite cell size decreases, tensile strength and elongation increases. Iron is the most common element in Al–7Si–Mg casting alloys affecting the fracture toughness due to the formation of needle-like Fe–Al based intermetallic compounds [10]. In order to achieve good toughness, morphologies of eutectic silicon and iron-rich intermetallic compounds should be modified. The morphology of eutectic silicon can be modified by ‘chemical modification’ and proper heat treatment [9], whereas the morphology and volume of iron-rich intermetallics can be controlled by adjusting the Mg content. A T-6 heat treatment provides two beneficial effects: it improves ductility and fracture toughness through spheroidisation and coarsening of eutectic silicon particles in the microstructures, and yields higher alloy strength through the formation of a large number of fine β''-Mg_2Si precipitates which are coherent with the matrix and strengthens the soft α aluminium matrix [3].

In order to study crack growth and its formation, crack tortuosity (CT), crack branching factor (CBF) and tendency of cracking through eutectic regions are quantified. Crack tortuosity is used to describe the meandering of a crack in a microstructure. The crack branching phenomenon is characterized by a crack branching factor, which is defined as (length of all branched cracks alongside main crack/projected length of main crack in the notch direction) × 100%. The tendency of cracking through eutectic regions is analyzed by comparing the crack-intercepted density (CID) and line-intercepted density (LID) of eutectic silicon particles. The CID has been taken as the number of eutectic silicon particles intercepted by main crack per unit projected crack length, and the LID is measured along a straight line parallel to the notch direction [11–13].

This paper summarizes the results of the investigation of the plain-strain fracture toughness and the growth and formation of fatigue pre-crack in Al–7Si–Mg cast alloys by carrying out standard ASTM E-399 K_{IC} tests performed on these alloys [14]. The materials and the test methods, as well as the fracture toughness results are discussed. The results of the limited fractrographic studies were performed on the fractured surfaces and correlated with the fracture toughness results.

2. Experimental procedure

2.1. Materials and melt procedure

Around 10 kg of A356 foundry ingots of composition shown in Table 1 were melted in a clay bound graphite crucible placed in an electrical pit type furnace under a conventional ‘Coverall 11’ flux. When the melt temperature was around 740 °C, required amount of Mg was added in the form of Al–10Mg master alloy.

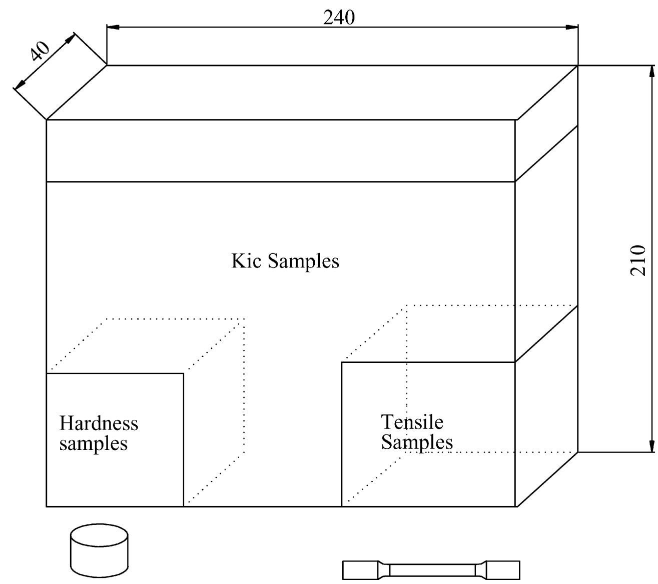

Fig. 1. Dimensions of plate type casting showing location of samples machined out for mechanical tests.

Weight loss due to addition and holding time was also taken into account while adding Mg in to the melt. For modification, required amount of Al–10% Sr master alloy was added into the melt at around 740 °C so as to get 0.02% Sr in the melt. The melt was then held for about 10 min to allow full dissolution of strontium into the melt. The melt was then degassed by purging nitrogen gas into the melt for about 15 min. The treated molten metal was poured into a plate type permanent mould of dimensions 240 mm × 210 mm × 40 mm. Fig. 1 shows the plate casting and the locations from which the samples were drawn for various studies. While pouring, the melt temperature was kept around 720 °C. Five different casting compositions were produced as shown in Table 2.

2.2. Hardness, tensile and fracture toughness testing

Hardness, tensile and fracture toughness samples were machined out from the plate castings as shown in Fig. 1. The dimensions of the cylindrical tensile specimens and K_{IC} fracture toughness Compact Tension specimens were shown in

Table 2
Alloy composition and code

Code	Composition	Condition
A	Al–7Si–0.3Mg	Unmodified
B	Al–7Si–0.3Mg	Sr-modified
C	Al–7Si–0.5Mg	Sr-modified
D	Al–7Si–0.7Mg	Sr-modified
E	Al–7Si–1.0Mg	Sr-modified