Fatigue Properties of Overaged Cast Aluminium-7Silicon-0.3Magnesium Alloy

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Abstract. Over the years, Al–7Si–Mg alloys are used because of their excellent castability, high weight-to-strength ratio, good corrosion resistance and good weldability. In this paper, the fatigue behaviour of Al–7Si–0.3Mg alloys, conforming to A356, has been studied. Specimens of this material were fatigue tested in both the as cast condition, solution treated and aged conditions. The fatigue test was conducted using 3-point fatigue bending setup with the principle of low cycle fatigue failure mechanism. Overaging is found to affect the fatigue behaviour of Al-7Si-0.3Mg alloys. The fatigue properties of as cast alloys showed a three times increase upon solution treatment. Peak ageing condition further improves the fatigue value. Exposure to severe overageing conditions reduced the fatigue properties somewhat from that of the peak values but still maintained higher value than the as-cast conditions, which is constant irrespective of the overageing condition. The improved fatigue properties of heat treated samples can be generally attributed to the spheroidisation of acicular silicon particles.

1. Introduction

Presently the development of light alloys is still dominated by aluminium, with aluminium castings having an important role in the growth of the overall aluminium industry. Among the commercial aluminium castings, Al–7Si–0.3Mg is probably the most widely used alloy mainly because of its excellent stability, specific strength, corrosion resistance, and good tensile and fatigue properties. The popularity of these cast alloys, which are largely used in the automotive, aerospace and defence industries, creates a continuing increase in the demand for components with higher and more consistent mechanical properties. Car wheel rims made from cast aluminium alloys are attractive for several reasons: easy processing and manufacturing, lighter weight leading to lower fuel consumption, and the possibility of recycling the material [1].

Al-7Si-0.3Mg alloys used in automotive applications are exposed to cyclic loadings and fatigue failure. Although considerable progress has been made in understanding the mechanisms of fatigue failure, an accurate fatigue failure prediction is difficult because the different physical processes which prevail to the gradual fatigue damage accumulation during the fatigue life of a metallic component are complex and interrelated [2]. Developing with increasing number of fatigue cycles from atomic to macro-scale damage, the mechanisms entail a host of material, geometric and loading parameters [3]. Cyclic plasticity of engineering polycrystalline alloys is complex and depends on a host of parameters including type of unit cell, value of stacking fault energy, heat treatment, grain size, precipitate geometry and size, distribution and coherence to the matrix etc. [1, 5]. In precipitation hardened alloys, cyclic hardening occurs due to an increase in dislocation density and dislocation-precipitate interactions. Hence, cyclic hardening is highly favoured if the precipitates in the age-hardened alloy are not easily shearable by the dislocations [4].

In the last ten years, there were activities toward improving the understanding of the effect of some intrinsic and extrinsic factors on fatigue crack initiation and propagation in Al-Si-Mg alloy [5]. Extensive research efforts were focused on fatigue behaviour under thermal aging, modification treatment which can improve the mechanical properties of the alloy [6].The influence of microstructure on the fatigue behaviour of Al-Si-Mg alloy was also investigated.

Interactions between the dislocation and precipitates, dislocation and secondary silicon phase are investigated to understand the fatigue behaviour and performance [7]. Several works on the effect of porosity on fatigue of cast Al-Si-Mg have been done so far. Porosity has a catastrophic effect on mechanical properties of aluminium alloys. A 1% volumetric fraction of pores may reduce fatigue life by 50% and strength limit by 20% as compared to the same alloy without pores [8]. The number of cycles needed for crack nucleation depends on loading, ranging from 0% (at start up) to less than 10% of fatigue life [9]. Apart from these, the influence of stress on the crack propagation is also studied. While the time needed for crack initiation decreases with pore size, fatigue life increases when stress decreases and that for a given stress level the number of cycles to failure decreases when amount of pore introduced in the alloy increases [10].

So far, there is very little amount of work done on the influence of overaging on the fatigue behaviour of aluminium alloys. As the cast Al-7Si-Mg alloy being used in the cylinder head, wheel rim, on long time usage the alloy becomes overaged. Therefore, the fatigue behaviour of these alloys in overaged condition is very crucial.

2. Experimental

In the present work, the fatigue response of cast Al-7Si-0.3Mg alloy upon overaging condition was studied. Cylindrical fatigue test samples of 20 mm diameter and 250 mm length were machined from the cylindrical sand cast bars of 22 mm diameter and 280 mm length. The test bars were solution treated at 540±2°C in an air-circulating furnace for 4 hours and then quenched in water of 30±5°C. Then they are refrigerated at -5°C till they were aged at the effective ageing temperature of 170±2°C for 1, 2, 5, 10, 100, 1000, 10000 and 100000 hours. The long ageing times were reduced to a few hours by increasing the ageing temperature using the Arrhenius model [11], which indicates that for every 10°C temperature rise, the ageing time effectively reduces to half. The ageing schedule used for the work is given in Table 1.

Table 1: Ageing schedule used in the work.

Effective ageing time at 170°C	Actual ageing schedule
1 hr	1 hr at 170°C
2 hr	2 hr at 170°C
5 hr	5 hr at 170°C
10 hr	1.25 hr at 200°C
100 (98) hr	3.125 (3) hr at 220°C
1000 (1024) hr	1.95 (2) hr at 260°C
10000 (10240) hr	2.44 (2.5) hr at 290°C
100000 (98304) hr	3.052 (3) hr at 320°C

The fatigue test was conducted using 3-point fatigue bending setup in the Instron 8801™. The specimens were supported on two lower anvils and the load was applied at the centre of each specimen by a single upper anvil. The fixture had a span length of 18 cm. The parameters maintained throughout all the fatigue tests are: Stress ratio = 0.1, Maximum load= 3 kN, Minimum load= 0.3 kN, Average end point = 1.65 kN, Amplitude = 1.35 kN, Frequency= 40 Hz.

The structural morphology of as-cast and heat-treated samples were observed using optical microscopy. Standard metallographic techniques were used to prepare the metallographic specimens.

3. Result and Discussion

The fatigue test of the alloys was done with the principle of low cycle fatigue failure mechanism and as the aluminium is a low strength metal, it has cyclically hardened with repetitive loading and failed in brittle mode [12].

Figure 1 shows the fatigue behaviour of the as-cast and heat-treated samples. It is clear that, the fatigue property is improved during heat treatment. The solution treatment showed almost a three times improvement in fatigue properties over the as-cast samples. The highest fatigue resistance was observed at the peak ageing condition (at about 5 hour ageing time). With over-aging, the fatigue property was found to be decreased somewhat but the fatigue resistance of highly overaged alloys maintained a more-or-less steady value, which is higher than that of the as-cast sample.

This is surprising and contradictory to the results obtained for the strength-ductility behaviour of over-aged aluminium-based aerospace casting alloys [13]. The tensile strengths of these alloys were found be decreased in the overgaed conditions to values which are lower than that obtained in the as-cast condition. Clearly more works are needed to ascertain this issue.

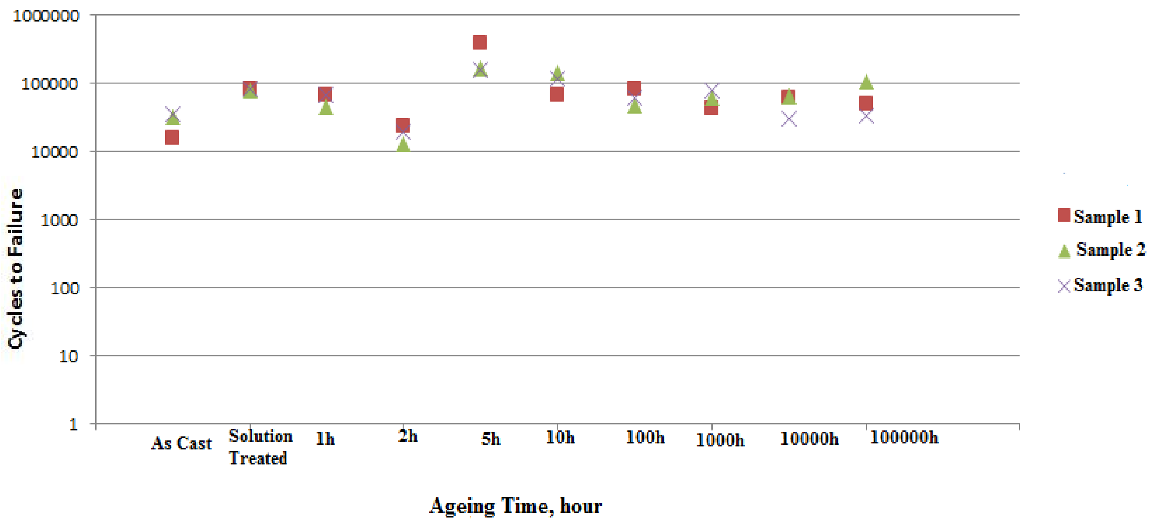

Figure 1: Fatigue response to heat treatment.

The size and shape of Si particle plays an important role in affecting the fatigue properties of the alloy. Though the surface of the as-cast samples were generally free from porosity and other defects, the presence of unmodified, coarse acicular silicon particles embedded in the α-Al matrix in the Al-7Si-0.3Mg samples (Fig. 2a) are responsible for the stress concentration in the sample. These additional stress concentrations reduced the fatigue life of as-cast samples.

Upon solution treatment, the silicon particle appeared fibrous and undissolved Al_5FeSi, dendritic structured dispersed throughout the structure [14]. Solution heat treatment also causes a substantial degree of spheroidisation and coarsening of silicon eutectics (Fig 2b), thus greatly reducing the stress concentration and improves fatigue life. Furthermore, due to low cycle fatigue (high stress) cracks nucleate by de-cohesion of internal silicon nodules (far from pores) probably located at grain

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boundaries [15]. So, the fatigue properties of ageing at 170°C for 1, 2, 5 hours are greater than those of as-cast samples.

The maximum fatigue property observed for ageing at 170°C for 5 hours. In this condition the density of the GP zone increases, because of which distortions of the lattice planes are extended to several atomic layers in the matrix. This distortion of the lattice plane causes a hindrance to the dislocation movement. Therefore, the fatigue resistance property of the alloy is further improved for under aged to peak aged conditions. The second reason for the increase in resistance to fatigue fracture behaviour of the alloy is due to the pinning and hindrance of the dislocation movement by Mg_2Si and primary silicon [16].

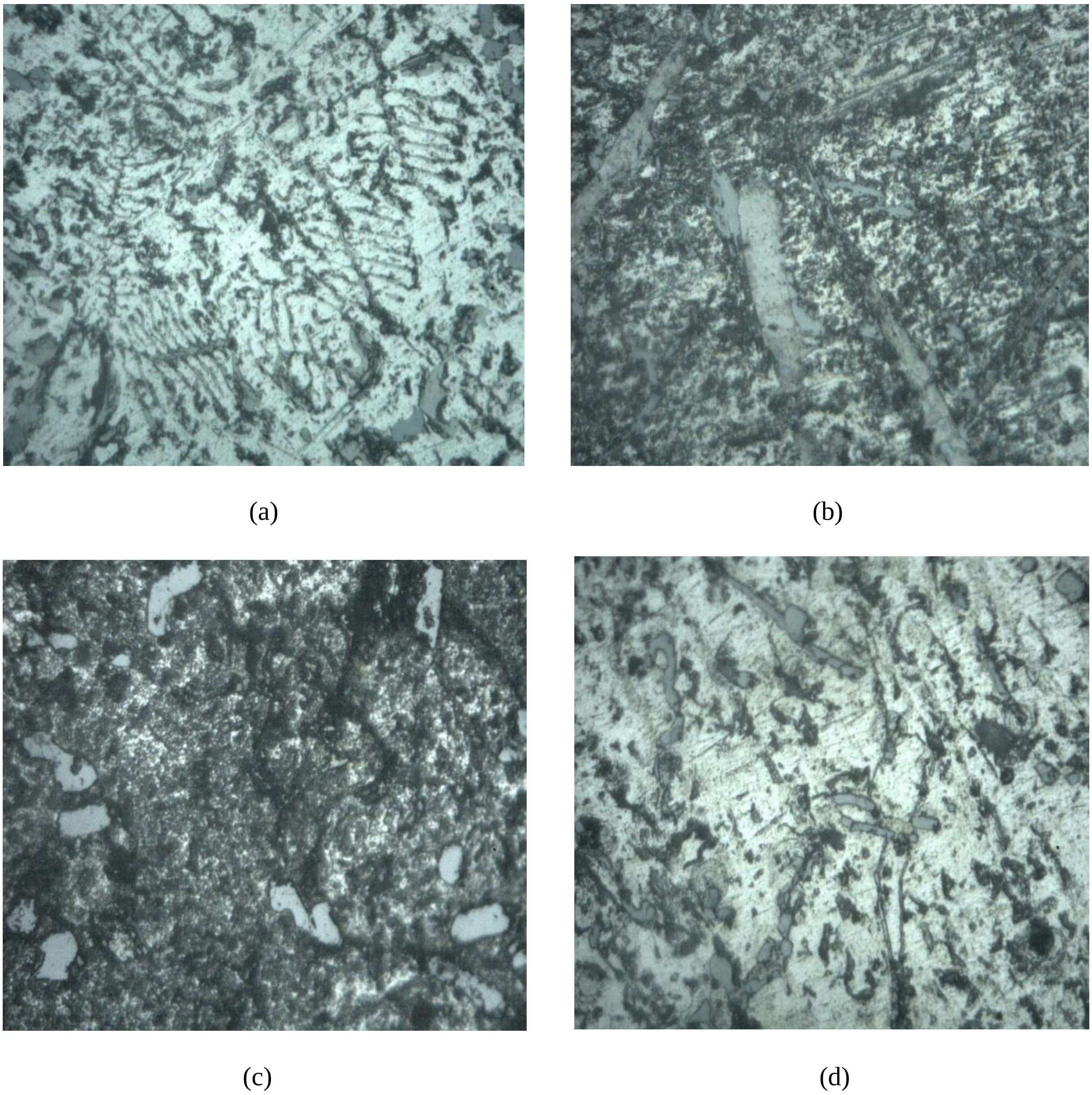

Figure 2: Optical micrograph of Al-7Si-0.3Mg alloys. (a) As-cast, (b) Solution treated, (c) Aged at 170°C for 5 hours, and (d) Aged at 170°C for 100000 hours (x500).

Upon over-aging, the fatigue properties of the samples are decreased but maintain a steady value. A decrease in the number of cycles to fail in these samples when over-aged for a longer period at higher temperatures could be attributed to further spheroidisation of silicon particles, coalescence of precipitates into larger particles and annealing of the defects in the material. This will cause fewer obstacles to the movement of dislocations. The almost constant fatigue property of the overaged samples can be attributed to the extensive grain growth and migration of silicon particle to the grain boundaries, thus deflecting the fatigue crack propagation. As the inter-dendritic crack propagation occurs alternatively in matrix and along interfaces of silicon/matrix particles, the crack propagation rate (da/dn) is almost constant.

4. Conclusion

Overaging is found to affect the fatigue behaviour of Al-7Si-0.3Mg alloys. The fatigue properties of cast alloys showed a three times increase upon solution treatment. Peak ageing condition further improves the fatigue value. Exposure to severe overageing conditions reduced the fatigue properties somewhat from that of the peak values but still maintained higher value than the as-cast conditions, which is constant irrespective of the overageing condition. The improved fatigue properties of heat treated samples can be generally attributed to the spheroidization of acicular silicon particles.

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