Fatigue Properties of Sand Cast, Stircast and Extruded Al-7Si-0.3Mg Alloy with Trace Additions of Be and Mn

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Present study devotes to an understanding of the fatigue behaviour of Al-7Si-0.3Mg sand cast alloys at varying iron levels and with beryllium and manganese trace additions and when the alloy is stircast and extruded. From the stress(S)-number of cycles to failure(N)-(S-N) curves it is observed that the presence of higher amount of iron (0.76%) in sand cast alloys leads to shorter fatigue life. Beryllium and manganese additions to higher iron containing alloy (0.76%) show better fatigue properties than low (0.29%) and high (0.76%) iron containing sand cast alloys, thus countering the detrimental effect of iron. Better fatigue life of beryllium and manganese added high iron alloy is due to the presence of (Be, Mn)-Fe phases only inside α -Al dendrites. Fatigue life of stircast and extruded low iron (0.44%) alloy is superior to sand cast low (0.29%) iron alloys. Observation of fractured surfaces reveals that porosity/inclusions is the high stress concentrating point where crack originates (stage-I) and then propagates (stage-II) depending on the presence of the second phases. In the case of low iron alloys (sand and extruded stircast) crack propagates along eutectic silicon, while in the high iron alloys crack propagates through brittle β -phase. In beryllium and manganese added alloys, even though crack nucleates on (Be, Mn)-Fe phase, it will be arrested as it approaches α -Al dendrites and hence, crack has to propagate along silicon particles. Fractured surface of the stircast and extruded alloys has revealed fine fatigue fracture with striation as compared to sand cast alloys. This aspect of crack nucleation and propagation is explained schematically.

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I. Introduction

It is known that any metal subjected to cyclic or fluctuating stress will fail at a stress level much lower than the yield stress, and failures occurring under cyclic stress are termed fatigue failures. Recently automobile car wheels are semi-solid formed (SSF) using Al-7Si-0.3Mg alloy⁽¹⁾. Earlier days sports car wheels have been cast in this alloy by permanent moulding. No doubt the car wheels undergo cyclic loading and are expected to fail by fatigue. Besides wheel drums, the alloy has also been used in several critical applications which will fail by fatigue. Thus it is very important to understand the fatigue characteristics of the alloy.

Skallerud *et al.*⁽²⁾ carried out an investigation on fatigue life of cylindrical specimens of heat treated Al-7Si-0.4Mg alloy taken from cast wheels and test bars. They concluded that, presence of pores significantly reduced total life time. Wickberg *et al.*⁽³⁾ studied microstructural effects on the fatigue properties of the Al-7Si-Mg alloy. They observed reduction in fatigue strength as the volume fraction and size of porosity and β -plates increased. Healy and Beevers⁽⁴⁾ studied crack growths of a cast Al-Si-Mg alloy reinforced with 20% volume fraction of silicon carbide (SiC) particulate. One of the important conclusions was that short crack formation was associated preferentially with porosity.

However, the data available on the fatigue property of the alloy are limited and correlation with microstructure is not clearly known. The harmful effect of iron impurity of the alloy on tensile properties, impact properties and dynamic fracture toughness (K_d) has been established⁽⁵⁾⁽⁶⁾ but information available on fatigue is scanty. Although the beneficial effect of beryllium trace addition (individual/combined with manganese and/or chromium) nullifying the harmful effect of iron on tensile properties and dynamic fracture toughness has also been established⁽⁷⁾, nothing so far has been reported on the fatigue properties. Among the combined addition of beryllium with manganese or chromium, or both beryllium and manganese addition revealed better strength and ductility in addition to nullifying the harmful effect of iron⁽⁷⁾. Thus, in the present study, beryllium and manganese combined addition is selected for iron containing alloys in order to study how far the deleterious effect of iron will be nullified on fatigue.

Semi-solid forming (SSF) is a hybrid manufacturing method that incorporates both casting and forming. This process is based on the discovery of attaining thixotropic property of the material by stirring the melt during solidification where dendrites are broken and form non-dendritic structure. This type of casting is termed as "rheo-casting" (rheo means to flow) or "stir-casting" or "thixocasting". The material with non-dendritic structure can be handled by automated devices easy to near

net shapes. Even though a few investigations of SSF of Al-7Si-0.3Mg alloy have been reported⁽¹⁾⁽⁸⁾⁽⁹⁾ information on the fatigue life of extruded stircast alloy is limited. Therefore, the present investigation is devoted to the understanding of fatigue characteristics of sand cast alloys in the presence of iron impurity and with beryllium and manganese trace additions to find how far these additions neutralise the harmful effect of iron. The fatigue life of stircast and extruded alloys as compared to sand cast alloys is also studied.

II. Experimental Details

Al-Si-Mg-Fe alloys were prepared in an induction furnace using high purity aluminium, silicon and magnesium metals. Iron, beryllium, manganese and titanium were added as master alloys Al-10.63%Fe, Al-5%Be, Al-8.73%Mn and Al-5%Ti respectively. The ingots were remelted in a resistance furnace and degassed thoroughly at 730°C by bubbling nitrogen and chlorine mixture. Eutectic silicon was modified by using NaF-NaCl (30:70) salt mixture. The melt was poured at 720°C into DTD (Directorate of technical development, UK) test bar sand moulds. The chemical compositions of the alloys prepared are given in Table 1. Chemical analysis of the alloys was conducted with the Spectro-Vac DV-50 model. The fatigue specimens were machined from these DTD bars and heat treated for the T6 condition.

SSF castings were prepared by stirring the degassed melt at 10 s^{-1} for 10 min. from 590°C melt temperature to eutectic temperature and then quenching in water. The stircast alloys were soaked at 400°C for 3 h and extruded in a 250 t hydraulic press, using flat faced round die with reduction ratio of 1/3.125. The die temperature was maintained at around 220°C and coated with colloidal graphite at 175°C. Specimens for fatigue test were machined from these extruded bars. All the test specimens were heat treated for the T6 condition.

The dimensions of the fatigue specimens machined are shown in Fig. 1. The gauge length portion of the speci-

Table 1 Chemical composition of the alloys prepared (mass%).

Melt No.	Si	Mg	Fe	Ti	Be	Mn	Na	Al
1	7.51	0.35	0.29	0.17	—	—	<0.01	Bal.
2	7.20	0.30	0.76	0.16	—	—	"	Bal.
3	7.59	0.28	0.76	0.14	0.14	0.19	"	Bal.
4*	7.50	0.31	0.44	—	—	—	—	Bal.

* Extruded stircast alloy.

men was polished and the surface roughness was within 0.2–0.5 μm . The fatigue test was carried out in a Wöhler cantilever type dynamic fatigue testing machine at a frequency of 50 Hz. Stress applied at the center of the fatigue specimen was calculated to be 188.5, 170.2, 150.1, 134.6, 119.1, 111.3, 103.5, 88.0, 80.4, 72.7 and 64.9 MPa.

III. Results and Discussion

The alternating stress amplitude (S) to number of cycles to failure (N) relations (S-N curves) obtained for sand cast alloys at two different iron levels (0.29%, 0.76%) and for high iron containing beryllium and manganese added alloys as well as for extruded stircast low iron alloys are discussed:

1. Fatigue life

The S-N curve of sand cast Al-7.51Si-0.35Mg-0.29Fe alloy is shown in Fig. 2(a). The test specimen loaded at 72.7 MPa did not fail even after running 2.12 to 3.05×10^7 cycles.

From Fig. 2(b) it is observed that fatigue life of higher iron containing sand cast alloy (0.76%) is shorter compared to 0.29% iron alloy for the same applied load; i.e., the test specimen loaded at 72.7 MPa failed earlier at 1×10^7 cycles.

Trace addition of beryllium with manganese to a higher iron (0.76%) containing sand cast alloy has nul-

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Fig. 1 Dimensions of fatigue test specimen.

Fig. 2 S-N curves of sand cast Al-Si-Mg alloy at different conditions (a) 0.29% iron, (b) at 0.76% iron and (c) at 0.76% iron and with beryllium and manganese trace additions.

lifted the harmful effect of iron showing longer fatigue life than high (0.76%) as well as low iron (0.29%) sand cast alloys without any trace addition (Fig. 2(c)) i.e., the fatigue test specimen loaded at a higher applied alternating stress of 80.4 MPa for 2.12×10^7 cycles has not failed in comparison with low (0.29%) and high (0.76%) iron containing alloys.

It may further be noted that, the fatigue property of beryllium, manganese and titanium added alloys is better than the low and high iron titanium added alloys (but without beryllium and manganese trace additions). The reason may be that combined addition of beryllium, manganese and titanium acts as a better grain refiner

Table 2 Grain size of Al-Si-Mg with different alloying elements.

Alloy	Grain size, μm
0.29Fe+0.17Ti	987
0.76Fe+0.16Ti	1001
0.76Fe+0.14Be+0.19Mn+0.14Ti	746

Fig. 3 S-N curve of extruded stircast Al-7.5Si-0.31Mg-0.44Fe alloy.

(Table 2); fine equiaxed grains of $746 \mu\text{m}$ are observed with titanium, beryllium and manganese additions as against $987 \mu\text{m}$ with titanium addition alone. It was also earlier observed⁽¹⁰⁾ that beryllium addition to Al-7Si-0.3Mg alloy acted as a moderate grain refiner.

From Fig. 3 it is observed that extruded stircast alloy exhibits superior fatigue life as compared to the sand cast alloy with low iron content. The alloy did not fail at a high load of 87.2 MPa for 2.12×10^7 cycles.

2. Microstructures

The microstructure of sand cast low iron containing (0.29%) alloy is shown in Fig. 4(a). Lengthy β -FeSiAl₃ intermetallic compounds formed along the interdendritic regions are observed in high iron alloys (Fig. 4(b)). The percentages of Al, Si and Fe in β -phase analysed by wavelength dispersive X-ray analysis (WDX) are shown in Table 3. Earlier investigations have revealed that in the alloy containing above 0.4% Fe, a significant increase in maximum length of the β -phase takes place leading to drastic decrease in dynamic fracture toughness⁽⁶⁾. Similarly, in the present investigation the presence of lengthy β -phase is accounted for poor fatigue property of higher iron (0.76%) containing alloys. With beryllium and manganese additions β -phase alters its morphology to (Be, Mn)-Fe Chinese scripts and further, these altered structures are observed only inside the primary α -Al dendrites (Fig. 4(c)). The composition of the (Be, Mn)-Fe phase determined by WDX is given in Table 3. The beneficial effect of beryllium and manganese trace addition on fatigue life is mainly due to the (Be, Mn)-Fe phases seen

Fig. 4 Microstructures of sand cast modified Al-7Si-0.3Mg alloy: (a) at 0.29% iron, (b) at 0.76% iron and, (c) at 0.76% iron and with beryllium and manganese trace additions. Etchant: dil. Keller's reagent.

Table 3 Wavelength dispersive X-ray analysis of β and (Be, Mn)-Fe phases (mass%).

Phase	Al	Si	Fe	Mn	Be
β	60.3	17.98	21.69	—	—
(Be, Mn)-Fe	59.1	7.04	24.2	7.25	2.41

inside the α -Al dendrites rather than in the interdendritic regions.

It has been clearly demonstrated in an earlier investigation⁽¹⁰⁾ by conducting interrupted quench experiments that addition of beryllium to Al-7Si-0.3Mg-0.6Fe alloy forms a new compound (Be-Fe)-BeSiFe₂Al₈ inside the primary α -Al dendrite by a peritectic reaction (instead of β -FeSiAl₅ phase forming in the interdendritic regions by ternary eutectic reaction in Al-7Si-0.3Mg-0.6Fe alloy). Similarly, in the present investigation, in beryllium and manganese added high iron (0.76%) alloy, (Be, Mn)-Fe phase is observed only inside the primary α -Al dendrite and this may be due to the formation of (Be, Mn)-Fe phase by a peritectic reaction. However, further investigation is necessary to clearly understand this phenomenon.

Stircast microstructure of Al-Si-Mg alloy is shown in Fig. 5(a). Primary α -Al is observed in the form of spheroids and ellipsoids along with fine eutectic silicon. Extrusion of the stircast alloy has revealed uniform alternate bands of α -Al and eutectic silicon (Fig. 5(b)). The superior fatigue property of stircast extruded Al-Si-Mg alloy is attributed to the fine microstructures as well as

may be due to the presence of alternate α -Al and eutectic silicon bands⁽⁹⁾. An interesting observation is that, in the center of the specimen where the cyclic stress is zero ($\sigma_y=0$) the α -Al and silicon bands are not disturbed as compared to the neighbouring structure (Fig. 5(c)).

3. Fractography

Typical macro-view of the fractured fatigue test specimens of sand and extruded stircast alloys at low and high applied stresses is shown in Fig. 6. It is clear from the figures that, two distinct areas: crack initiation and propagation, and catastrophic failure are seen. Irrespective of the magnitude of applied stress or the second phases present depending on the composition of the alloy, the crack originates on pores (which is more clearly observed in SEM and discussed below). The fatigue failed area fractions are smaller for the specimens failed under high applied stress than the specimens failed under low applied stress (Table 4). However, the difference is less significant in extruded stircast alloys. It is observed that, no cracks have originated along the periphery of the specimen revealing that the surface roughness of the specimen in the gauge length portion is smooth and no machining scratches act as a stress risers to originate crack. This observation is further supported by the SEM observation discussed below.

SEM observation of fractured surface of low iron sand cast alloy has revealed more clearly that porosity is the crack initiation point (stage-I) (Fig. 7(a)). Further, the crack propagates towards the catastrophic failure area

Fig. 5 Microstructures of Al-7.5Si-0.31Mg-0.44Fe alloy: (a) stircast, (b) stircast and extruded and, (c) undisturbed silicon bands at the centre of the fatigue specimen. Etchant: dil. Keller's reagent.

Fig. 6 Macro-view of fractured fatigue test specimen: sand cast 0.29% iron alloy; (a) at 150.1 MPa applied stress, (b) at 80.4 MPa applied stress and, extruded stircast 0.44% iron alloy; (c) at 150.1 MPa applied stress and (d) at 103.5 MPa applied stress.

Table 4 Percent area of the crack initiation and propagation.

Alloy Al-Si-Mg	Load applied MPa	No. of cycles to failure	% Area of crack initiation and propagation
0.29%Fe	150.1	6.75×10^4	20
	80.4	1.2×10^4	34.8
0.76%Fe	119.1	1.1×10^5	15.6
	72.7	5.1×10^6	41.8
0.76%Fe +0.14%Be +0.19%Mn	150.1	5.4×10^4	15.9
	88.0	2.2×10^6	34.6
Extruded Stircast	150.1	9×10^6	38.6
	103.5	7.6×10^6	37.8

and surface of the specimen, apart from the crack origin (Fig. 7(a)). Thus, keeping porosity as a common point crack propagate. A view of the crack propagating area at higher magnification is shown in Fig. 7(b) where, fatigue striations are observed (indicated by arrow). As expected regular mixed mode of dimples and brittle cleavage fracture is seen in the catastrophically failed area similar to tensile fracture⁽⁵⁾.

Similar to the low iron alloy, even in the high iron alloy, porosity acts as a crack initiation point and not the brittle β -phase (Fig. 8(a)). The originated crack from the pore further propagates towards the catastrophic failure area. Observation of the crack propagating area shows fine cleavage facet features (Fig. 8(b), marked as C) along

Fig. 7 Fractographs of sand cast Al-7.51Si-0.35Mg-0.29Fe alloy: (a) a view of crack initiating on pore (indicated by arrow) and (b) fatigue striations observed in crack propagating area (indicated by arrow).

Fig. 8 Fractographs of sand cast Al-7.2Si-0.3Mg-0.76Fe alloy: (a) a view of crack initiating on pore (indicated by arrow), (b) cleavage facets (marked as C) observed in crack propagating area and, (c) cleavage fracture (marked as C) and river patterns (indicated by arrow) observed with beryllium and manganese additions.

Fig. 9 Fractographs of extruded stircast Al-7.5Si-0.31Mg-0.44Fe alloy: (a) a view of crack initiating on fine inclusion particles (indicated by arrow) and, (b) fatigue fracture with striation (indicated by arrow) seen in crack propagating area.

with micro cracks (indicated by arrow). A mixed mode of brittle cleavage and intergranular fracture is seen in the catastrophic failure area similar to tensile fracture⁽⁵⁾.

In the case of beryllium and manganese added high iron alloys, porosity is the high stress concentration area leading to crack initiation similar to low and high iron alloys without any trace additions. On closely observing the crack propagating area, cleavagelike fracture with river patterns at different plateaus are seen (Fig. 8(c), C indicates the cleavage fracture, and the arrow the river pattern).

Although pores are almost absent in extruded stircast alloy, the fine inclusion particles act as a stress concentrator where crack originates (Fig. 9(a), observed at a higher magnification and indicated by an arrow). The crack propagating area at higher magnification reveals fatigue fracture with striation (Fig. 9(b), indicated by arrow). Mixed mode of dimples and brittle cleavage fracture is seen in the catastrophic failure area while the fracture surfaces are very fine as compared to sand cast low iron alloys.

It is clear from the macro-view of the fractured specimen and SEM observations of fractured surface that the cracks originate only on pores. In the absence of pores, if inclusions are present, inclusions act as the crack initiation site irrespective of other second phase (such as eutectic silicon or β -phase) present in the alloy. Hence, porosity/inclusion may be the point of high stress concentration. The process of fatigue has been generally categorized to happen in the following stages⁽¹¹⁾: cyclic plastic deformation before crack initiation, initiation of micro crack(s), stage-I, propagation of micro crack(s) and macro crack(s), (stage-II) and final rupture (stage-III). The three stages have been observed in the present study such as; cracks initiate on pores referred to as "stage-I"; the initiated cracks from these pores propagate towards the center of the specimen up to the catastrophic failure area, referred to as "stage-II"; the catastrophic failure occurring finally as the "stage-III" process.

From Fig. 10 with microstructures observed just below the fractured surface of the fatigue failed specimen, it is

evident that a crack runs along the silicon particles (stage-II) in low iron sand cast alloys. But, in high iron containing alloys, β -phase acts as a preferential site for crack propagation (stage-II) rather than silicon particles. Presence of lengthy β -phase in high iron alloys (earlier study⁽⁶⁾ has shown that not only β -phase will grow longer in high iron alloy but also will be continuously present) will aid the crack propagation of the alloy. In beryllium and manganese added high iron alloys, although cracks are seen on (Be, Mn)-Fe Chinese scripts acting as a preferential site for crack propagation (stage-II) rather than silicon phase (similar to the observation in an earlier investigation⁽⁷⁾ in beryllium added high iron alloy in which (Be-Fe) phase acts as a site for crack nucleation and propagation), the nucleated cracks will be arrested as they approach α -Al dendrite. This may be one of the main reasons why fatigue property of beryllium and manganese added high iron containing alloys is superior to the one without these trace additions.

Based on the observations relating to the microstructure, fractography and fatigue properties of the alloy, at low and high iron levels, with beryllium and manganese trace additions and when the alloy is stircast and extruded, some salient features are summarised and explained by a schematic representation (Fig. 11). The schematic representation is shown for rotation-bending fatigue condition indicating pore locating at the maximum tensile loaded side. The first and the foremost point to be noted is the presence of porosity and inclusions which can be the high stress concentrating regions where crack originates (stage-I, Fig. 11) in preference to the second phases even including hard/brittle intermetallic compounds. Therefore, thorough degassing of the melt and providing proper and sufficient risers to feed in order to eliminate, as well as clean melt with less inclusions or pouring with filters are the essential procedures to be followed during casting so as to ensure better mechanical properties including fatigue strength of the alloy. Further, the crack nucleation and propagation depends on the presence of the second phase-eutectic silicon in the case of sand cast and extruded stircast low iron containing alloys (Fig. 11(a), (d)). The absence of pores and very

Fig. 10 Microstructures observed just below the fractured area of fatigue tested Al-Si-Mg alloy: (a) at 0.29% iron level, (b) at 0.76% iron level and, (c) at 0.76% iron level with beryllium and manganese additions.

Fig. 11 Schematic illustration of fatigue failure of Al-7Si-0.3Mg alloy at varying conditions: (a) low iron alloy, (b) high iron alloy (c) beryllium and manganese added high iron alloy and, (d) extruded stircast.

fine microconstituents in extruded stircast alloys favours improved fatigue properties (Fig. 3) as compared to the sand cast modified alloys (Fig. 2(a)). Since porosity is closed during extrusion of stircast alloys, crack originates on the fine inclusion particles (Fig. 11(d)). In high iron alloys even though the crack originates from porosity, it propagates (stage-II) through brittle β -needles/plates formed in the interdendritic regions (Fig. 11 (b)) leading to cleavage fracture and poor fatigue life (Fig. 2(b)). In beryllium and manganese added alloys, crack originates from pores. Further, the propagation of the crack perhaps may depend on the (Be, Mn)-Fe phase and since the (Be, Mn)-Fe is present only inside the α -Al dendrites, the crack that nucleates on (Be, Mn)-Fe phase will get arrested as it approaches α -Al dendrite. Therefore, crack has to propagate along the silicon particles (stage-II, Fig. 11(c)). This may be the main reason why beryllium and manganese added high iron containing alloys reveal better fatigue life when compared to high iron alloy without beryllium and manganese addition.

IV. Conclusions

(1) Fatigue life of higher iron containing (0.76%) sand cast alloys reveals less number of cycles to failure as compared to low iron alloys for the same load. Beryllium addition in combination with manganese results in better fatigue life than the high (0.76%) or low (0.29%) iron alloys.

(2) Stircast and extruded Al-Si-Mg alloys reveal lon-

ger fatigue life than the sand cast alloys and is attributed to the fine uniform microstructure.

(3) From macro and micro structural observations it is concluded that porosity/inclusions are the high stress concentration points, from which the crack originates (stage-I) irrespective of the second phases present.

(4) Further, crack propagation (stage-II) takes place on silicon particles in the case of sand cast alloys and extruded stircast alloys. But in higher iron alloys β -needles/plates are the preferential sites for crack propagation.

(5) In beryllium and manganese added alloys, even though cracks nucleates at the (Be, Mn)-Fe Chinese scripts, they will get arrested as they approach α -Al and hence cracks have to propagate along silicon particles. This may be the reason why beryllium and manganese addition has nullified the harmful effect of iron on fatigue life.

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