THE EFFECT OF A5TB REFINER ON THE FATIGUE STRENGTH OF 6063AL ALLOY

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ABSTRACT

The study focuses on the influence of aluminium titanium boron (A5TB) master alloy on the fatigue behaviour of 6063Al alloy. Cylindrical cast rods of 6063Al alloy containing different proportions of A5TB ranging from 0 - 0.11 wt.% were produced and were machined to conform to a standard fatigue specimen. The test specimens prepared were tested for fatigue strength at various stress levels, and results obtained were compared. The resistance to fatigue failure was observed to decrease as the stress level increased. It was also noted that irrespective of stress level, the optimum fatigue strength was obtained when the A5TB content was about 0.06 wt.%. It was found that 6063Al alloy to which A5TB master alloy have been added was most suitable for the design of components meant to operate under cyclic loading at low stresses below about 3.02 kN/m2.

Refiner, Fatigue, Aluminium Alloy, Cyclic Loading, Stress level

INTRODUCTION

Fatigue is a progressive failure of a part under repeated, cyclic or fluctuating loads whose peak values are considerably smaller than the loads estimated to be safe, based on static fracture analyses (Madayag, 1968; Coffin, 1979; and Matin, 2003).

Many of the sources of cyclic stress arising in structural elements, power generation, aircraft, machines and ground vehicles are mechanical stresses which arise as a result of start-stop operations which then have effect on the machine part from geometric effects such as notches. Repeated loading and unloading cause cyclic stress on machine parts and some structures. This lead to high-cycle fatigue (fatigue which occurs over a long time before fracture). Combination of thermal stresses with mechanical stress however has been found to lead to low-cycle fatigue (fatigue failure at low number of cycles) (Starink et al, 2000).

Fatigue failure follows three sequences namely, the initial damage on the submicroscopic scale, crack initiation and propagation and the final rupture. The failure can emanate from simple or compound fatigue due to simple or multiple cracks respectively. Generally, the failure may be due to Microstructural changes can be effected by heat-treatment, mechanical working or grain refinement. A16063 alloy is a well known heat-treatable alloy which has useful strength and toughness properties in both T4 and T6 tempers (T4 refers to solution heat treated, quenched and naturally aged to a substantial stable property level while T6 is a stronger condition produced by artificial ageing (WIPO, 2006). However, A16063 is also known to be widely used in its unheat-treated form for structural applications such as window frames and machine parts. In extruded condition, only the grain refinement (if used) and the homogenization treatment when properly carried out confer upon it its strength.

such factors which among others include bad design practice, material defects, geometrical discontinuities and introduction of residual stresses (Madayag, 1968). Fatigue strength therefore greatly influences the life span of a material exposed to cyclic loading.

The fatigue strength and life of materials are affected among others by temperature, frequency of the stress cycle, strain rate, wave-shape effects, multiaxial loading, residual stresses and metallurgical factor (Madayag, 1968; Mager, et al, 1977; Coffin, 1979; Starink et al, 2000; Jayce et al, 2003). In addition to these, factors like microstructure and grain size have been identified to also affect fatigue life of components (Breen and Wene, 1979; Raja et al, 1999). Fine-grained materials are noted to have longer fatigue lives while intergranular cracks are easily formed in large-grained materials. Secondary intermetallic particles and dispersoids, grains and grain boundaries are introduced into materials to slow down crack propagation rates (Sanders and Staley, 1979). Microstructural effects such as compositional variations, precipitation strengthening and solid-solution strengthening improve fatigue life of components (Landgrof, 1979; Morere et al, 2000).
Titanium is one of the important refiners of aluminium alloys. Titanium, not more than 0.25% in the melt and which is normally added in the form of master alloy Aluminium 5% Titanium Boron (A5TB) is found to be an important grain refiner during solidification of ingot and it is also useful against intergranular corrosion when present within 0.06-0.20% (WIPO, 2006). Although 6063Al alloy is a very important structural material in household machinery, cyclic stress has been one of the stresses that this material is exposed to in usage. Knowledge of its fatigue behaviour is therefore of significance to its choice for the production of engineering components. The effect of the addition of Titanium on the fatigue strength of Al 6063 during

solidification is of interest. This work therefore focuses on the effect of A5TB addition on the fatigue strength of 6063Al with the aim of finding the right proportion suitable to enhance the fatigue strength of Al 6063.

Experimental Technique

Sample Preparation

The various elemental composition of the aluminium alloy was carried out using the Spectrometer and the results are presented in Table 1.

Table 1: The Result of Spectrochemical Analysis of 6063 Al Alloy.

ELEMENT	COMPOSITION (%)	ELEMENT	COMPOSITION (%)
Silicon	0.4255	Zinc	0.0383
Iron	0.2421	Chromium	0.0053
Copper	0.0517	Titanium	0.0065
Manganese	0.0319	Calcium	0.0003
Magnesium	0.4515	Aluminium	98.7468

Five batches of the 6063Al alloy containing A5TB master alloy in varying proportions ranging from 0.3kg/tonne – 1.30kg/tonne were formulated as presented in Table 2. The choice of this proportion is based on the fact that complete columnar grain refinement is achieved at 0.7 kg/tonne (Loong and Heathcock, 1989; Easton and StJohn, 2000).

For each batch, calculated amount of 6063Al was charged into an Electric furnace, melted and raised to 750°C. The calculated required quantity of A5TB was added to the charge, stirred for about 30 seconds and held at this temperature for about 3.5 minutes (Loong, 1989). Thereafter, it was immediately cast into cylindrical rods of 1.4 cm diameter and 3.5 cm long and were machined into standard fatigue specimens. Similar specimens were likewisely prepared from the unrefined 6063Al alloy.

Table 2: The Composition of the Charge for Different Alloy Batches.

BATCH	WEIGHT PERCENT OF REFINER	
	(kg/tonne)	(wt. %)
As received	0.00	0.00
Batch 1	0.30	0.03
Batch 2	0.50	0.05
Batch 3	0.70	0.07
Batch 4	1.00	0.10
Batch 5	1.30	0.13

Determination of Testing Loads and Bending Angles for the Fatigue Test

The machine applies load to a specimen in form of bending moment. The testing loads and the bending angles are calculated through equation (1) (Avery, 1975):

$$M = K_2 B$$

eqn. (1)

where M is the bending moment acting along the axis of the specimen (N.mm), K_2 is the flexural rigidity of the specimen and B is the bending angle imposed on the specimen (in degrees).

For the bending angle B, considering the parallel and the tapered portion of the neck, the flexural rigidity of the specimen is calculated through the expression:

$$K_2 = \frac{198E}{10^4}$$

eqn. (2)

where E = Elastic modulus of the specimen. Substituting equation (2) into equation (1), we have

$$M = \frac{198EB}{10^4}$$

eqn. (3)

For a material subjected to pure bending,

$$\frac{\sigma}{R} = \frac{M}{I}$$

eqn. (4)

Where, σ = bending stress (N/mm^2), R is the minimum gauge radius of the specimen i.e. the distance from the neutral axis of the specimen under test (mm), M = bending moment acting along the axis of the specimen (N.mm) and I = moment of inertia (mm^4).

From equation (4), $$M = \frac{\sigma I}{R}$$

eqn. (5)

But for a circular section, $$I = \frac{\pi D^4}{64}$$

eqn. (6)

Hence (5) becomes,

$$M \quad \frac{\sigma \pi D^3}{32}$$

eqn. (7)

where D=diameter of the specimen. Combining equations (3) and (7) gives

$$\frac{198EB}{10^4} = \frac{\sigma \pi D^3}{32}$$

eqn. (8)

This implies that: $B = \frac{10^4 \sigma \pi D^3}{63.36\, E}$. For Aluminium 6063 alloy,
$E = 70$ GPa $= 70 \times 10^3$ N/mm^2. Substituting this for values in equation (9),

$$B = 7.08 \times 10^{-3} \sigma D$$

eqn. (9)

By varying the load and hence the stress, the various bending angles can be determined. As earlier established, the gauge diameter for each of the sample was used in calculating the bending angle. The choice of varying stress level in fatigue testing depends on the ultimate tensile stress (UTS) of the material since dynamic loading is under consideration (Madayag, 1968).

For Aluminium 6063 alloy, the UTS is 150 kN/m^2 and this forms the basis for various stress level. Since the fatigue machine applies reverse load of equal magnitude but differs in sign, for which reason, only half of calculated percentage of the UTS is used in calculating the bending angle.

Fatigue Testing

Fatigue test was performed at five different stress levels. Fifteen as-received specimens prepared were tested for fatigue using three specimens for each stress level. A specimen was loaded at a time on the Avery Denison 7505 Fatigue Testing Machine having determined the bending angle for 2.01 kN/m^2 stress level so that the eccentric is accordingly adjusted. The number of cycles for each run was recorded and the average value calculated. The procedure was repeated for another set of three specimens for each of 3.01, 150, 200 and 250 stress levels. The prepared samples from each of the five batches were similarly tested for each of the five stress levels. The same number of samples prepared from each of the five batches was similarly tested at the same stress levels.

RESULTS AND DISCUSSION

Results

The results of the fatigue strength for different stress levels for as received and refined Aluminium 6063 Al alloy are presented in Fig. 1, showing the number of cycles to failure (N) for the unrefined 6063 Al alloy and alloys containing different proportions of titanium boron (A5TB) master alloy. Fig. 2 shows the variation of N with the Ti-B content of the prepared alloy.

It is generally observed that the number of cycles of stress to fatigue failure (N) increases as the applied alternating stress decreases. For example, for the unrefined 6063Al, at 7.03 kN/m^2 stress level, the value of N is 1100 while at stress level of 5.02 kN/m^2 the value of N rises to 2100 (Fig. 1). The N value almost doubles for just a difference of about 2 kN/m^2 stress level. Similarly for the sample containing 0.03% A5TB, the N value of 300 is recorded for the applied stress level of 7.03 kN/m^2 while N value of 1400 is recorded at 5.02 kN/m^2 stress (Fig. 2). The number of cycles N in the later translates to about 4 times the magnitude of the former. Similar trend is observed in the rest alloys containing different Ti-B master alloy (Fig. 1). The number of cycles to failure N initially decreases as the Ti-B master alloy is added and later slightly rises and falls again as the content of A5TB in 6036Al increases. This is observed at many stress levels except at 2.01 and 3.01 kN/m^2 at which the number of cycles to failure N shows initial gradual increase before attaining peak values (Fig. 2).

Discussion

Generally, the number of cycles of stress which a metal can endure before failure increases with decreasing stress level (Dieter, 1988). This is also demonstrated by the 6063Al to which no addition of Ti-B is made (Fig. 1). At stress level of 7.02 kN/m^2, the N value is 1100 and this value keeps increasing to 7750 as the stress level decreases to 2.01 kN/m^2. When the 6063Al alloy was subjected to cyclic loading, crack initiation first develops before propagation. The initiation and subsequent rate of propagation depends on the frequency and the magnitude of the applied stress. Since the only variable in this respect is the applied stress level, the reason for this observation might be that at low stress levels, the initiation of cracks and subsequent crack propagation rate were slow probably due to the fact that the stresses are below the required stresses to propagate the surface crack to failure (Coffin, 1979). For this reason, high N values are recorded for low stress levels while low N values are recorded for high stress levels. Similar explanation can also be extended to 6063Al alloy containing various A5TB contents.

It is however observed that an addition of 0.03 wt.% A5TB master alloy to 6063Al caused a drop in the value of N at some stress levels, indicating a reduction in the fatigue strength (Fig. 2). Comparing results obtained when 0.03% A5TB was added (Fig. 2) with those obtained when no refiner was added (Fig. 1), a decrease of 800 cycles, 700 cycles and 650 cycles were recorded for 7.03, 5.02 and 4.02 stress levels, respectively. This is contrary to the known report that fine grained alloys have higher fatigue strength compared to coarse grained ones (Rollason, 1982). The reason for this deviation at high stress levels is not very certain. It has however been reported that hydrogen porosity in Alumimium alloys appears as angular interdendritic cavities or as comparatively small spheroidal pores. Interdendritic porosity results from the rejection of hydrogen from the solid to the liquid metal during solidification until the solution pressure of the hydrogen in the liquid exceeds 1 atmosphere (Rajan *et al,* 1999). The possible entrapment of hydrogen porosities in the solidified alloy could have contributed to poor fatigue strength exhibited at the high applied stress level. On the other hand, the addition of 0.03 wt.% of master alloy caused significant increases in the values of N at the low applied stresses. This observation supports the report that there is improved fatigue strength with fine grained crystals (Rajan *et al*, 1999).

The influence of the added A5TB to 6063Al is better appreciated by the characteristics of number of cycles to failure N against the A5TB content for various stress levels Fig. 2. At lower stress levels of 2.01 kN/m^{2}and 3.01 kN/m^2, the resistance to fatigue keeps rising as the refiner contents increases to about 0.06 wt.% (Fig. 2). Beyond this value, the fatigue strength sharply decreases to the minimum when the A5TB content in the alloy reaches 0.11 wt.%. However, for high stress level of 4.02, 5.02 and 7.01 kN/m2, the values of N were very low. As the A5TB content rises from zero, the fatigue strength initially falls and picks up at 0.05 wt.% refiner addition and got to the peak at about 0.06% A5TB content for the three stress levels. In excess of 0.06% A5TB content, the fatigue strength starts to fall gradually until a minimum value is attained at 0.11 wt.% A5TB content is attained irrespective of the value of the stress level (Fig. 2).

This observation in which peak fatigue strength is attained at about 0.06 wt.% A5TB may be due to the formation of optimum grain sizes at this concentration of A5TB in 6063Al alloy. This may be due to the formation of optimum grain sizes at about 0.06 wt.% alloy addition which upon further increase to 0.11 wt.%, grain sizes become coarse. This may probably be attributed to the report that excess refiners beyond the optimum point may lead to gravity separation of intermetallic compound thus, reducing the fatigue strength (Loong and Heathcock, 1989). An increase in the amount of refiner has been found to cause an increase in localized porosity in the casting, while complete removal of grain refiner caused hot cracking (Easton and StJohn, 2000). It has also been confirmed that as the quantity of refiner increases, the amount of hot cracking decreases; while the amount of localized porosity increases (Boot *et al*, 2002). Therefore, there is an optimum amount of refiner required for a particular aluminium alloy to obtain castings with optimum quality. It is known that localized porosities serve as stress concentrations and points of crack initiation and thus will reduce fatigue strength (Dieter, 1988). Therefore, the reduction in strength may also have been due to the fact that grain refinement in excess of 0.06 wt.% up to about 0.11 wt.% A5TB might have led to the increase in defects such as porosity in the refined 6063Al.

This study has also conformed to the report that as against the behaviour of steel and Aluminium-magnesium alloys under fatigue loading, no definite fatigue limit has been found on the stress S versus number of cycles N curves (Rollason, 1982). Grain refinement of Aluminium and its alloys using A5TB master alloy is a common industrial practice to produce fine equi-axed structure in the casting. The grain refinement leads to improved yield strength, high toughness, good machinability and excellent deep drawability (Cibula and Ruddle, 1947; McCartney, 1989).

Reduction in grain size raises the fatigue strength of a X-7075 Al aluminium alloy (American Society of Metals, 1978) is against 1.35x10^6 cycles at 30μm grain size. It has also been shown that slip in fine-grained Al-Zn-Mg-Zr alloy is less intense and crack initiation is delayed. For the same plastic-strain amplitude, the number of cycles to initiate failure for the fine-grained alloy exceeded the cycles to failure for the coarse grained (American Society of Metals, 1978). The improved fatigue strength at 1.02 and 2.02 KN/m^2 applied stresses for the Al 6063 alloy may therefore be due to grain refinement.

From the foregoing, it may be said that grain-refining 6063Al alloy containing about 0.03 wt.% - 0.11 wt.% A5TB master alloy may not really be very suitable for use in the design of components that will be subjected to fatigue stress in the neighbourhood of 4.00 kN/m^2 - 7.03 kN/m^2 . However, it may be utilized for components that will operate under a stress level that is below 4.00 kN/m^2.

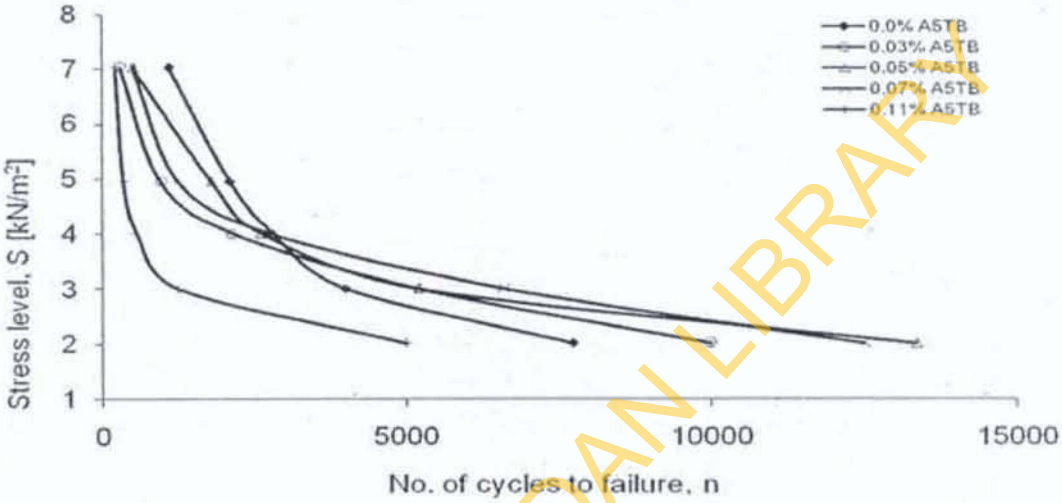

Fig. 1: S - N curve for Al6063 alloy with different A5TB refiner concentration

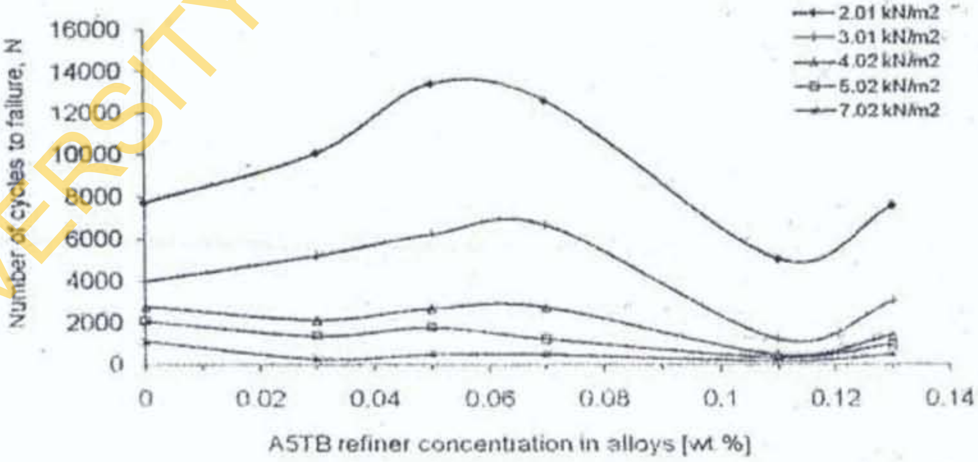

Fig. 2: Number of cycles to failure for 6063Al alloys containing different A5TB refiner content at different stress levels.

CONCLUSIONS

A5TB alloy content in the range of 0.3 wt.% - about 0.06 wt.% is considered beneficial to the grain refinement of 6063Al with increasing fatigue strength as its content increases within this range. 6063Al alloy exhibits optimum fatigue strength when the A5TB content is about 0.06 wt.% at all stress levels investigated. In excess of about 0.06 wt.% and up to 0.11 wt.%, the resistance to fatigue failure keeps decreasing irrespective of the stress level. 6063Al alloy containing A5TB is best suited for the design of components meant to operate at low stress level of up to about 3.02 kN/m^2 and the best operating performance against fatigue is obtainable when A5TB content is about 0.06 wt.%.

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