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STUDY OF LOW-CYCLE FATIGUE IN HEAT-TREATED Al-Mg ALLOYS

N. Plaza[1], S. Pedraza[2], O. M Suarez[3]
[1.] Eugenio Maria de Hostos High School – Mayagüez
[2.] Department Mechanical Engineering- University of Puerto Rico
[3.] Department of General Engineering University of Puerto Rico

Abstract

The AA5182 Al-Mg alloy is used in applications where high formability and strength are required like container ends, can stocks, reinforcement members and automotive parts. With convenient heat treatments the alloy strength increases and it can be used in aerospace applications. In the present research Al-Mg aluminum beverage can tabs were heat treated within a temperature range between 170ºC and 450ºC beginning with solubility and then aging treatment. The tabs were tested under low-cycle fatigue conditions. The fatigue strength measured by the number of loading cycles increased in the first two hours of exposure to the aging treatment at any temperature. The maximum resistance was reached at 2.5 hours. After this time it dropped in all treatments except for the 270ºC treatment, where it decreased gradually. The fatigue strength increment could not be defined since the geometry of the tab affected the type of fracture and the number well of cycles. In the microstructure, the formation of precipitates at low temperature (aging 170 ºC and 270 ºC) caused a low fatigue resistance in the material. However at high temperatures (370ºC) the treatment facilitated precipitates dissolution reinforcing the aluminum matrix and making it more resistant.

Introduction

Al-Mg alloys as the AA 5182 are used in applications where minimum thickness, maximum strength and lowest cost are required such as inner panels, brackets and non visible supports and beverage cans easy opening ends. The Al-Mg 5000 series alloys are stronger than the 3000 series (used in the body of beverage cans) and have a good corrosion resistance and weldability combined with excellent formability[1]. One way to increase the strength of Al wrought alloy is by means of heat treatment, in which a material is subject to controlled heating and cooling cycles to improve specific mechanical properties.

Both hardness and mechanical resistance of heat treatable Al alloys is improved in some cans by the formation of precipitates[2], which are new solid phases that separate from a supersaturated solution upon heat treating. The solid solution is therefore strengthened by dispersing a harder new phase (precipitate) throughout the solution, by heat treatment (precipitation hardening). However in Al-Mg alloys precipitates may cause a reduction in strength compared to supersaturated Al Phases certaining Mg atoms in solution.

In aerospace applications not only mechanical strength is needed but also the resistance to fatigue. Fatigue is a form of failure that occurs in structures subject to cyclic stresses (e.g. bridges, aircrafts and machine

components). Under these circumstances failure occurs at a stress level considerably lower than the actual mechanical strength of the material.
One form of fatigue occurs when a mechanical part, fails after few cycles: This is low cycle fatigue process, commonly referred to as LCF[3]. Low cycle fatigue fractures are connected with the infrequent working cycles of equipment or instruments which often result from start-up and shut down operations or interruptions of their function. Important subjects represent also high temperature low cycle fatigue, thermal and thermomechanical fatigue and multiaxial elastoplastic fatigue[4]. Figure 1 shows simple example of LCF in a metallic paper clip.

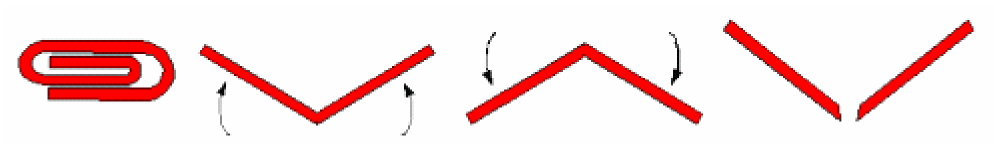

Figure 1. Low-Cycle failure of a paper clip

Experimental procedure

The objective of the present work is to study the change in the mechanical properties of AA5182 Al-Mg alloy in terms of mechanical strength, hardness and the effect of heat treatments. For this purpose we intend to determine how aging treatment affect the fatigue resistance of commercial Al-Mg alloy used in beverage cans tabs so as to propose an alternative matrix for Al- alloy matrix composite.

Tabs of AA5182 were solution heat treated at 450ºC, quenched in ice and then aged at temperatures ranging from 170ºC to 450ºC for aging times from 0 to 4 hours. AA5182 is wrought aluminum alloy that contains 4.5 wt% Mg and 0.3 wt% Mn as main alloying elements. The level of Mg makes this alloy heat treatable by solution and aging. The tabs were tested in low-cycle fatigue, by imposing a cyclic bending deformation. The treated samples were analyzed by metallographic techniques and their Hv microhardness was measured using a microidentation unit with a load of 50 g.

Optical Fatigue Test Results

Figures 2 and 3 show the number of cycles before tabs failure for aging and heat treatment samples respectively. Microhardness was measured on maxim and minimum number of fatigue cycles samples. These were samples with the sample with the highest number of cycles before fatigue failure (Hv 18.7) and the sample with the lowest number of cycles before fatigue failure (Hv 17.3).

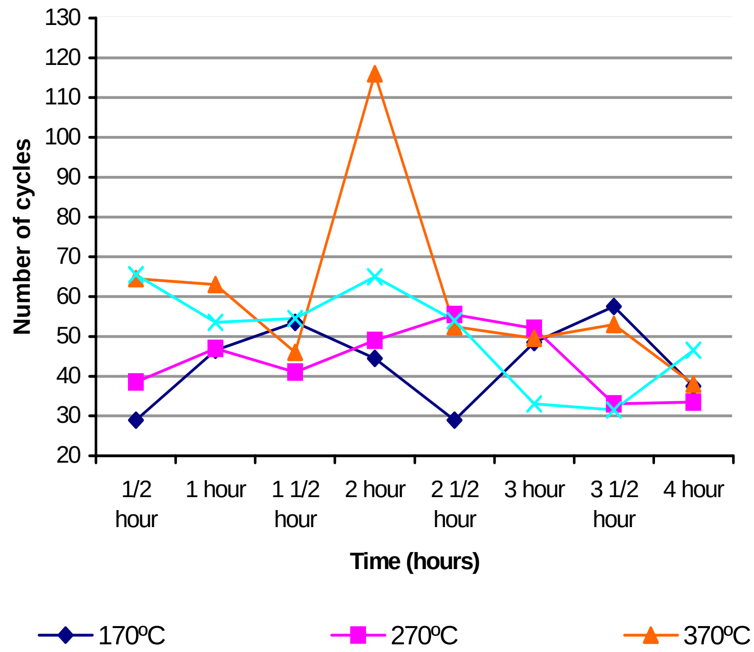

Figure 2. Number of cycles before failure as a function of aging time for different aging temperatures.

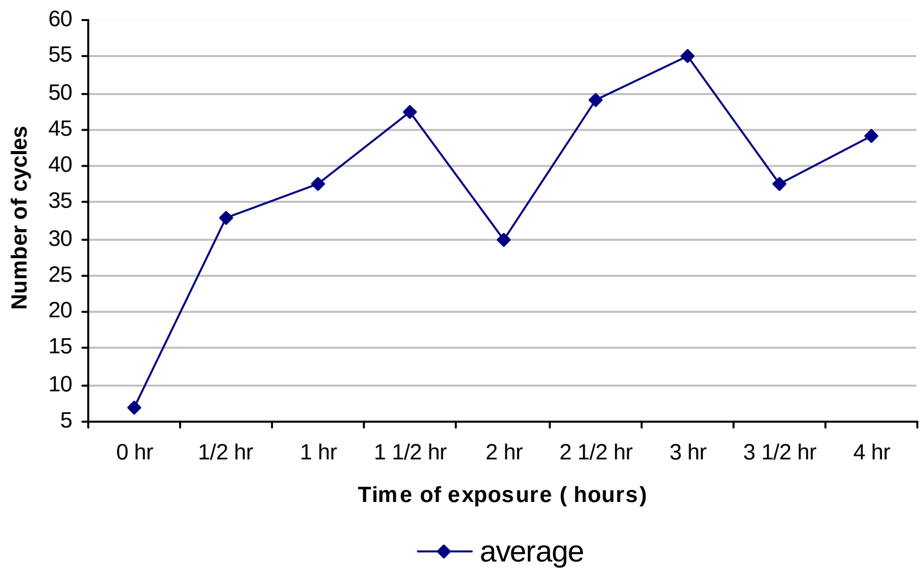

Figure 3. Tab fatigue resistance (number of cycles before failure) after a solubility treatment at 450 °C.

Optical Microscopy Results

The morphology of the fracture allowed identifying if the alloy fracture is ductile, which involves some sort of fibrous texture within the fracture and over the affected area besides plastic deformation, or brittle, which involves less fibrous aspect and cleavage. Therefore, the sample with the highest number of inflections (370ºC after two hours) had a ductile fracture and the sample with the lowest average resistance (170ºC after two hours and a half) was brittle while the samples with intermediate number of cycles presented a combination of both fracture types, as it can be seen in the figures 4, 5 and 6.

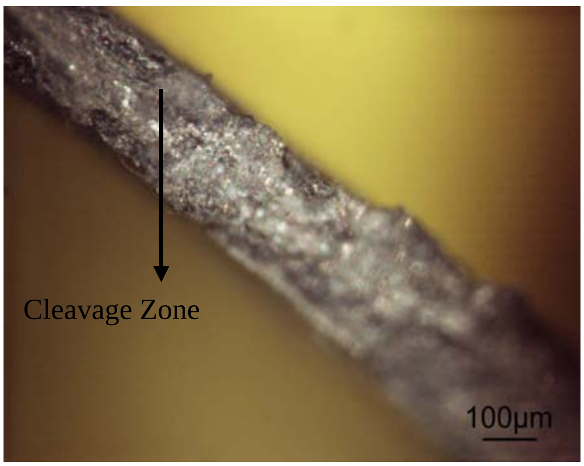

Figure 4. Fractured tab with aging at 170ºC for 2.5 hours.

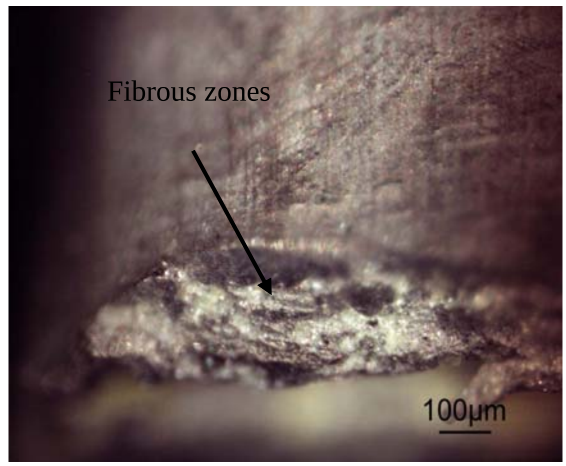

Figure 5. Fractured tab with aging at 370ºC 2 hours.

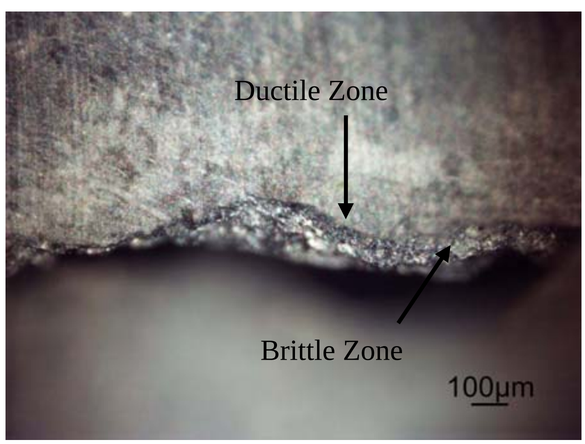

Figure 6. Fractured tab with aging to 450ºC for 2 hours.

The samples were polished for optical microscope observation. Although they were etched with Keller and hydrofluoric acid, the presence of precipitates was revealed in a suitable form as it can be observed in figure 7.

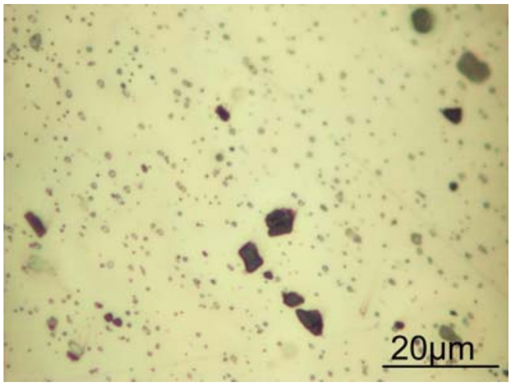

Figure 7. Microstructure of a sample that received an aging treatment at 370ºC for two hours.

Discussion

The fatigue resistance of the Al-Mg tabs varied without a visible pattern. The tabs poor symmetry and formation of precipitates did not allow a similar behavior at the moment of failure (see figure 2).

As it can be seen in figure 3, the resistance to fatigue (number of cycles before failure) for short aging times increased as aging temperature increased and then varied according to that temperature, depending on the aging time . For example, the aging for more than two hours and half shows caused a sudden change in most of the samples except for the ones that received an aging treatment at 270ºC where the fatigue strength decreased gradually.

In order to understand the behavior of each fracture it is important to comprehend the crack propagation process, i.e. before the final rupture takes place. This can be explained as follows: when the loading cycles are few some changes begin to appear among the atomic structure of the material in disperse points, which start developing submicroscopic cracks that grow as time progresses. The process is divided in three stages: crack nucleation, accompanied by plastic deformation over the fracture surface, propagation crack and final rupture. The main features in the fracture are these: a zone full of fibrous fracture and a zone with radials lines where the different levels of what are defined and characteristics fatigue beach marks are also visible (figure 8).

Most fatigue cracks begin in visible discontinuities that act as stress concentration points (tensions multipliers) like manufacture defects, holes and other microscopic discontinuities. Figure 9 shows the general crack localization on the tabs.

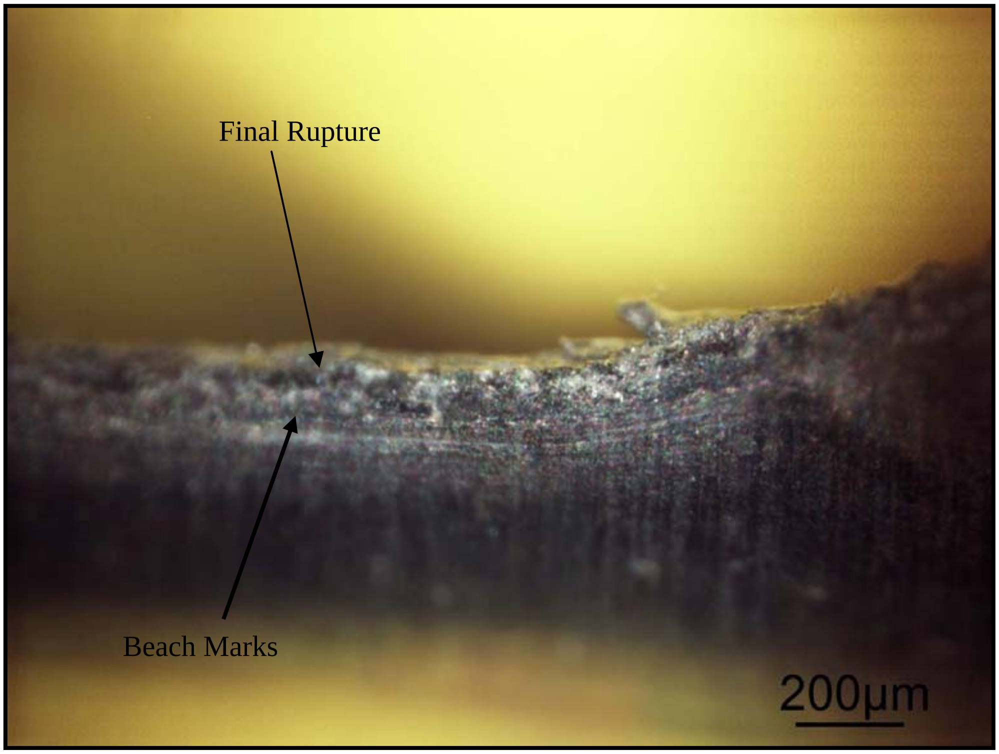

Figure 8. Development of the different zones among the surface of a tab that received an aging treatment at a temperature of 270ºC for 4 hours.

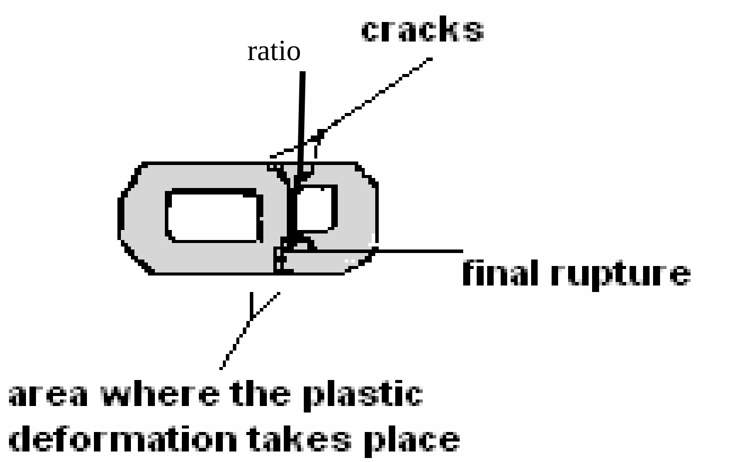

Figure 9. Effects of the geometry on the tabs.

The applied stress during the low cycle test was calculated by the following equation[5]

$$\sigma = \frac{Mo * C}{I}$$

Where M_0 = (2EIγ)/a momentum, E = 70 x 10^9 N/m^2 (elasticity module), I = 2149.67 (inertia moment), γ = 0.006375 m (deformation arc) and a = 3.56 cm (distance between the points where the force is applied). I (inertia moment) retains it original value and C = 7.75 (ratio shown on figure 9), thence the applied momentum and stress were Mo = 5.39 x 10^{14} N/m. and σ = 1.9 GN/m respectively. In fact, in figure 9 it is demonstrated that the stress concentration is higher on the pointed area so it is there where most of the fracture occurs.

Respect to the effect of the microstructure the formation of precipitates at low aging temperatures (170ºC and 270ºC) favored a low fatigue resistance in the material (figures 2 and 3). On the contrary, at high temperatures (370ºC) precipitates dissolution was favored, reinforcing the aluminum matrix (solid solution strengthening).

Conclusions

The resistance to LCF of the AA5182 Al-Mg tabs increased for all heat treatments. The lowest number of cycles occurred with the 170 ºC aging treatment and the highest, for the aging treatment at 370ºC. All samples had a sudden decrease after two hours and a half of the respective aging treatment except at 270ºC. Due to the complex tab geometry the rupture of the tabs is never alike so the resistance or the number of inflections before the material finally yield varies.

Outlook

To expand this research, it is necessary to complement the microscopy results with an analysis in atomic force microscopy study. A topographic difference could give more information about the precipitates distribution and the fracture topography.

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