INFLUENCE OF SCANDIUM ON THE KINETICS OF FATIGUE CRACK GROWTH IN 7010 AL – ALLOY

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ABSTRACT

The Influence of Scandium (Sc) addition on the fatigue crack growth rate and the fatigue crack threshold has been examined in the 7010 Aluminum alloy. The base line 7010 Aluminum alloy has been modified with Scandium addition and then subjected to a peak aging, T6 condition of heat treatment. The fatigue testing was done on a 858MTS servo hydraulic machine at a frequency of 40Hz and a stress ratio of 0.1. The fatigue crack growth study was conducted at constant amplitude loading. The threshold stress intensity factor ΔK_{th} was evaluated using the standard load shedding technique in both the conventional 7010 alloy and the Sc treated alloy. The fatigue crack growth rate da/dN versus stress intensity range ΔK curves were plotted and the Paris constants were obtained. The microstructural studies were conducted and the fracture surface study was done using Scanning electron microscopy. The investigations revealed that the Scandium addition refines the grain structure but exhibits poor fatigue crack growth resistance, as well as a lower value of ΔK_{th}. The results have been discussed in the light of microstructural observations.

1 INTRODUCTION

The 7010 alloy with suitable temper is considered to be an important aerospace material as it possesses a good combination of strength, toughness and stress corrosion cracking resistance. Over the years attempts have been made to enhance the performance of conventional 7010 alloy with appropriate addition of alloying elements [1, 2]. The addition of scandium to this alloy has been reported in the past which is known to provide an improved weldability [3]. The aerospace structures are very commonly subjected to fatigue kind of loading. No systematic work has been reported in literature so far on the effect of Sc addition on the fatigue cracking parameters such as the fatigue crack growth rate, da/dN and the fatigue threshold stress intensity factor, ΔK_{th}. The present work is an attempt to study the effect of Scandium on the fatigue crack growth kinetics in the 7010 aluminum alloy.

2 MATERIALS

2.1 Materials and microstructure

The materials used in the present investigation are a conventional 7010 Al-alloy and a Sc-modified 7010 alloy. The typical composition of the 7010 alloy is 6.3% Zn, 2.3% Mg, 1.55%Cu, 0.14% Zr, and the rest Al, whereas in the Sc modified alloy, 0.25% Sc is added keeping other additions same. The materials were available in the plate form having a thickness of around 14mm in the as rolled condition. The alloys studied were artificially aged to T6 condition. They were first solution treated at 465^{o}C and subsequently water quenched followed by ageing at 122^{o}C for 24hrs.
The specimens for microstructural studies were cut from the plate and polished on Buehler automatic polishing machine. They were initially ground on 800 grit paper and then polished on

micro cloth using 1μm diamond suspension. The final polishing was done on a chemomet cloth with masterpolish suspension. The specimens were then etched in a Keller's reagent, washed in warm distilled water and finally dried with a blower. The microstructural features were then examined in an optical microscope (Ziess), in the unetched as well as the etched conditions. The representative microstructures for the Sc treated alloy are shown in Fig.1.

2.2 *Tensile properties*

The cylindrical tensile specimens of gauge length, 45mm and diameter, 9mm were obtained as per the ASTM standard. The tensile tests were conducted on an Instron machine and various properties were evaluated. The yield strength and tensile strength of the 7010 alloy were found to be 500MPa and 566Mpa respectively whereas the %elongation was 13%. The Sc modified alloy was found to possess somewhat better strength and ductility properties as compared to the conventional 7010 alloy resulting in an yield strength = 537MPa, tensile strength = 588Mpa, and the %elongation = 14%.

3 FATIGUE CRACK GROWTH STUDIES

3.1 *Test procedure*

The fatigue testing was carried out on a servo hydraulic machine (MTS model 858) with a capacity of 25KN. Sinusoidally applied load at a constant stress ratio 'R' ($\sigma_{min}/\sigma_{max}$) = 0.1 was used for the fatigue loading. The commands and measurements of the load, crack length and the number of cycles were achieved through the controller installed with the machine. The crack growth measurements were done using compliance technique.

The compact tension (CT) type specimen geometry was used for fatigue testing. The specimens were machined from the rolled plate, maintaining an L-T orientation i.e. the longitudinal or the rolling direction has been kept perpendicular to the notch plane and the crack propagation direction is along the long transverse direction. The specimen dimensions were kept as per the ASTM standard with the width 'W' = 56.5mm, thickness 'B' = 12mm and notch length 'a_n' = 22mm. The specimens were polished (for better crack visibility) and then subjected to fatigue loading to obtain a precrack length of 2mm. The final maximum stress intensity used during precracking was 8 MPa√m.

3.2 *Threshold region*

The fatigue crack propagation threshold was measured by subjecting the precracked CT samples to a continuously decaying cyclic loading. The load shedding was done keeping the normalized stress intensity gradient, [1/K (dK/dN)] = - 0.08 as per the ASTM standard [4]. This process of K decreasing was continued till the threshold was reached. The evaluation of the crack growth rate, da/dN was done using the ASTM recommended secant method. The 'da/dN' value was continuously monitored and the test was continued until a value of around 10^{-9}m/cycle was reached. (Figs.1and 2)

The value of stress intensity factor range 'ΔK' was computed by using the following relation:

$$\Delta K = K_{max}(1-R) \qquad \text{-------------------------- (1)}$$

where R is the stress intensity ratio K_{min} / K_{max}, the K_{max} and K_{min} being the maximum and the minimum values of stress intensity factor in the fatigue cycle. The K_{max} is given by the following equation [4]

$$K_{max} = \frac{P_{max}}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \text{ -------- (2)}$$

where P is the load, B is the specimen thickness, W is the width and the factor α = a/W where 'a' is the crack length.

3.3 Paris region of crack growth

The fatigue crack growth test was conducted as per the ASTM standard E 647-95a. The test parameters were kept the same as described above except that the testing was performed at a constant amplitude loading. The resulting values of da/dN were then plotted against ΔK and the typical plots are shown in Figs.3 and 4. The linear portion of this curve i.e. the Paris region is found to obey the following equation:

$$\frac{da}{dN} = C(\Delta K)^n \qquad \text{------------------ (3)}$$

where 'C' and 'n' are the Paris constants. The fatigue crack growth behavior was subsequently studied by evaluating the Paris constants.

3.4 Fractography

The fractured specimens after the fatigue testing were carefully sectioned to appropriate sizes. The specimens were ultrasonically cleaned prior to the examination of the fracture surfaces under scanning electron microscope (SEM). The scanning was done in a Cambridge Stereoscan 360 microscope. The representative fractographs are reported in Fig 7.

4 RESULTS AND DISCUSSIONS

4.1 Fatigue Crack Growth threshold

The ΔK_{th} values were obtained from Figs.1 and 2 for the conventional 7010 alloy and the Sc modified alloy respectively. The reported ΔK_{th} values correspond to a limiting crack growth rate of 10^{-9}m /cycle and these are as follows –
$\Delta K_{th} \cong$ 5.2 MPa√m - 7010 alloy
$\Delta K_{th} \cong$ 3.1 MPa√m - Sc modified alloy.
It may be noticed that the Sc modified alloy has a considerably lower value of the ΔK_{th} as compared to the conventional alloy.

4.2 Crack growth kinetics

The Paris constants were evaluated from the linear region of the plots in Figs. 3 and 4 for the alloys investigated. The 'C' and 'n' values for the 7010 alloy are found to be 1.5×10^{-6} and 1.95 respectively; whereas for the modified alloy they are 4.75×10^{-6} and 1.954 respectively. The Paris equations for the two alloys may subsequently be written as follows -

$$\frac{da}{dN} = 1.95 \times 10^{-6} (\Delta K)^{1.95} \quad \text{- 7010 alloy} \qquad \text{-------- (4)}$$

$$\frac{da}{dN} = 4.75 \times 10^{-6} (\Delta K)^{1.954} \quad \text{-Sc modified alloy} \qquad \text{-------- (5)}$$

where ΔK is in MPa√m and da/dN in m/cycle. The fatigue crack growth rate in the two alloys has been compared by determining the da/dN values at specified ΔK levels and is reported in Table 1.

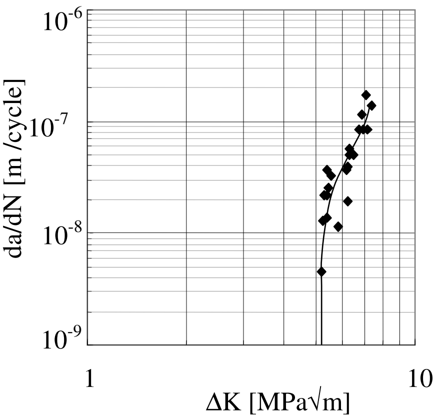

Figure1: da/dN versus ΔK for the 7010 alloy in the threshold region.

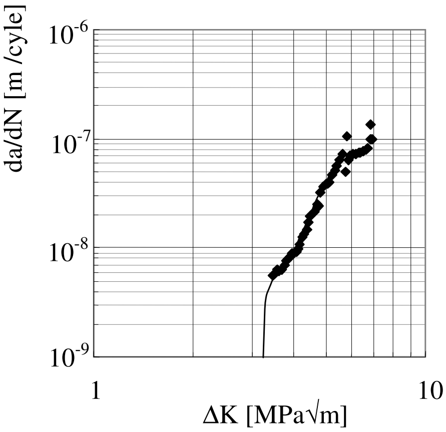

Figure 2: da/dN versus ΔK for the Sc modified alloy in the threshold region.

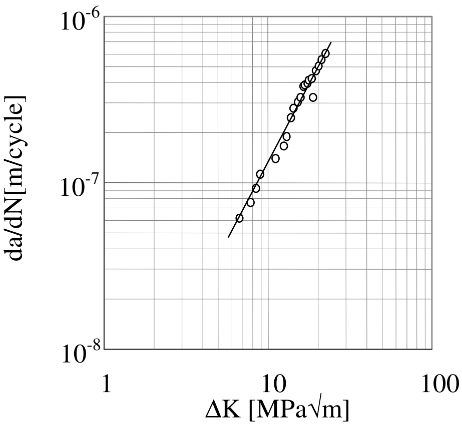

Figure 3: da/dN versus ΔK for the 7010 alloy in the Paris region.

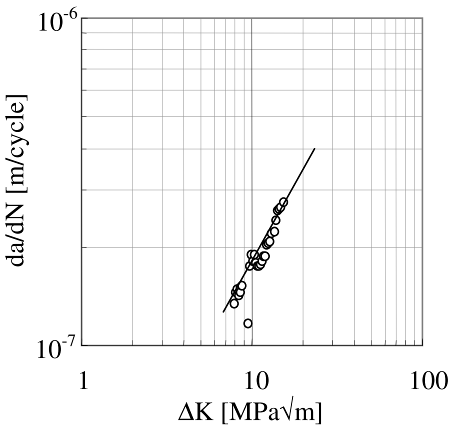

Figure 4: da/dN versus ΔK for the Sc modified alloy in the Paris region.

Table 1: The da/dN values corresponding to various ΔK.

Alloy	C	n	da/dN = C(ΔK)^n m /Cycle			
			ΔK =10 Mpa√m	ΔK =15 Mpa√m	ΔK =20 Mpa√m	ΔK =25 Mpa√m
7010	1.5 x10^{-9}	1.95	1.34x10^{-7}	2.95x10^{-7}	5.16x10^{-7}	7.98x10^{-7}
Sc modified	4.75 x10^{-9}	1.954	4.28x10^{-7}	9.44x10^{-7}	16.55x10^{-7}	25.6x10^{-7}

A comparison of fatigue crack growth rates between the two alloys from Table 1 shows that the Sc modified alloy results in a higher crack growth rate than the7010 alloy at any given ΔK level in the range of ΔK investigated i.e. between 10-25 MPa$\sqrt{m}$.

4.3 *Microstructural findings*

The microstructural examination in the Sc treated alloy has revealed elongated grains in the rolling direction as shown in Fig. 6. The average grain in this alloy in the rolled condition has about 18µm width and 200µm length and is totally unrecrystallized. In the as - cast condition of the alloy the grains are found to be equiaxed and having an average size of about 25µm [3]. A comparison with the microstructure of the conventional 7010 alloy indicated that the latter had a coarser grain structure i.e. about double the size of the modified alloy. Earlier TEM studies in the Sc modified alloy have revealed [3] the formation of secondary precipitate particles of $Al_3Sc_xZr_{1-x}$ in about 30-40nm sizes during the homogenization of the alloy. These particles restrict the grain growth and result in a fine grained structure in the modified alloy. In addition, the presence of coarse primary particles of $Al_3Sc_xZr_{1-x}$ of about 5µm size during the solidification stage of the alloy are also found to be instrumental for the nucleation of the Al – crystals resulting in fine grain structure of the modified alloy [3].

Figure 5: The unetched optical micrograph of the Sc modified alloy showing the $Al_3Sc_xZr_{1-x}$ particles↑.

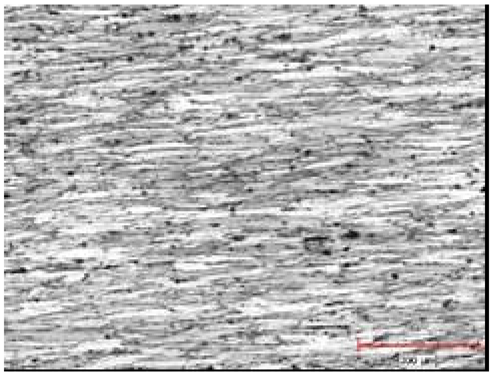

Figure 6: The optical micrograph of the Sc modified alloy showing the elongated unrecrystallized grains.

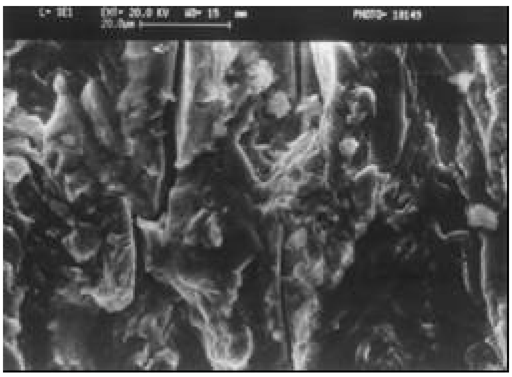

Figure 7: The SEM fractograph of the Sc modified alloy showing the cuboidal $Al_3Sc_xZr_{1-x}$ particles of about 5µm size.

Figure 8: The TEM photograph of the Sc modified alloy showing the cuboidal particle [3].

4.4 Discussions

The lower ΔK_{th} value in the Sc modified alloy may be explained in the light of the microstructural observations in this alloy. The Sc modified alloy is found to possess a refined grain structure as compared to the conventional 7010 alloy by approximately a factor of two. The ΔK_{th} is known to be influenced by the grain size and a coarse grain structure results in a higher ΔK_{th} value as compared to the fine grained structure [5]. This apparently is considered to be the reason for the reduced ΔK_{th} level in the modified alloy.

The higher crack growth rate at a given ΔK in the modified alloy as compared to the 7010 alloy is also related to their microstructural differences. The fractographic observations in the modified alloy exhibit void formations on particles of about 2-5µm sizes as may be seen from Fig. 7. Interestingly, particles of similar sizes were also noticed on the unetched surface as shown in Fig. 5. Some of the particles are of typically cuboidal shape and these have been earlier identified by TEM as coarse primary $Al_3Sc_xZr_{1-x}$ particles [3] as presented in Fig. 8. It is believed that these particles have promoted void formation on them resulting in a large void density which eventually caused enhanced rate of crack propagation in the modified alloy.

5 CONCLUSIONS

1. The addition of 0.25% Sc to a 7010 alloy has resulted in a finer grain structure leading to somewhat improved strength properties.
2. The Sc addition is found to decrease the fatigue crack propagation threshold, ΔK_{th} from 5.3Mpa√m to 3.1Mpa√m.
3. The fatigue crack propagation rate is found to increase due to Sc addition by a factor of three as compared to the conventional alloy.
4. The reduced ΔK_{th} in the Sc modified alloy is considered to be due to a finer grain structure whereas the enhanced da/dN is caused due to the void formation on coarse particles containing Sc.

6 REFERENCES

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