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ENVIRONMENTALLY ASSISTED CRACKING BEHAVIOR OF 7010 ALLOY

ABSTRACT

In this study, the environmentally cracking (EAC) behavior of 7010 Al-alloy was examined using slow strain rate technique (SSRT). This study brings out the developments on the heat treatment and alloying to improve the EAC resistance of 7010 Al-alloy. The effect of microstructures including the grain boundary precipitates, coarse metallic particles and recystallized grains on the EAC behavior of 7010 Al-alloy has been examined

INTRODUCTION

High strength Al-alloys have wide spectrum of applications from automobile to aerospace industries. Hence, development of high strength Al-alloys continues to be an important area of research. 7xxx alloys are developed mainly for this purpose. For successful application of these alloys, they should possess not only high strength but also exhibit high resistance to environmentally assisted cracking (EAC). Unfortunately, susceptibility of Al-alloys to EAC is directly proportional to their strength levels. Hence, a better understanding of EAC mechanism(s) is vital for the development of Al-alloys. In order to achieve high strength levels, 7010 Al-alloy has been developed as a substitute for the well known 7075 Al-alloy. Studies on the former are, however, scanty. Only a few authors, namely Puiggali et al., [1] and Robinson [2] have studied the EAC behavior of 7010 Al-alloy. Hence, a systematic work was carried out to understand the EAC behavior of this alloy [3-7].

ENVIRONMENTALLY ASSISTED CRACKING

Effect of heat treatment

Puiggali et al., [1] report that an improvement in the EAC resistance of 7010 Al-alloy can achieved by over aging. They measured fracture energy of smooth tensile samples from slow strain rate tensile curves. At slow strain rates, for example at 10^{-6}/s, the relative fracture energy increased from 60% to 80% when T651 alloy was compared with T7451 aged alloy. The rise in value due to heat treatment became even more striking when the testing strain rate was reduced one order lower than this, indicating how the EAC resistance can be improved by over aging. Robinson [2] work, carried out under constant load test on smooth bar samples, on 7010 forgings subjected to two-step over aging and RRA (RRA retrogression and re-aging) tempered treatments show that this alloy was susceptible to EAC. However, K_{1SCC} measurements made on notched samples showed an improvement in EAC resistance due to RRA treatment.

A detailed examination on the effect of multistep aging heat treatment on EAC behavior of 7010 Al-alloy was studied [3]. The multistep aging treatment is advantages over RRA treatment by the fact that the former can be applied to even thick plates, while the latter is restricted to thin sheets. The data from this publication is presented in Table 1. In air, the peak aged alloy exhibited 10 % elongation (E) and reduction in area (RA) and 561 MPa ultimate tensile strength (UTS). However, in 3.5 wt% NaCl solution, the peak aged alloy suffered a significant loss in ductility and strength. Thus, %E and %RA of the alloy decreased to 3 and the UTS to 515 MPa. On the contrary, the over aged alloy showed high ductility in air as well as 3.5 wt% NaCl solution, with only a 10 % loss of its peak strength. Thus, the alloy exhibited 10% E, 28% RA and 504 MPa UTS when tested in air. In 3.5 wt% NaCl, the over aged alloy exhibited 10% E, 24 % RA and 491 MPa UTS. This work notably showed that a higher percentage elongation of peak aged and over aged alloys could be achieved than that was reported by Puiggali et al., [1]. The EAC index was further quantified form the SSRT results in air and 3.5 wt% NaCl solution. It was found that the over aged alloy exhibited a far more superior resistance to EAC as compared to that of the peak aged alloy.

Table 1. *SSRT data of 7010 Al-alloys in peak aged and over aged conditions tested in air and 3.5 wt% NaCl solution at 10^{-6}/s strain rate*

Temper	% Elongation		% Reduction in Area		Ultimate Tensile Strength (MPa)	
	Air	3.5 wt% NaCl	Air	3.5 wt% NaCl	Air	3.5 wt% NaCl
Peak aged	10	3	10	3	561	515
Overaged	10	10	28	24	504	491

Effect of microstructure

The role of microstructure on the EAC behavior was studied by analyzing the fracture surface of the failed SSRT samples. Scanning electron microscope (SEM) fractographs of peak aged 7010 Al-alloy showed that the recrystallized grains were predominantly attacked along the grain boundary (Fig.1 (a)) leading to intergranular cleavage failure, while the over aged alloy exhibited predominantly ductile failure (Fig.1 (b)) [3]. Only the peak aged alloy was found to be sensitive to cracking along recrystallized grains, although the over aged alloy also contained recrystallized grains (Fig. 2(a) and (b)). Since the grain boundary area in peak aged alloy is most susceptible for cracking, the authors felt that the difference in the morphology and chemistry of grain boundary precipitates (GBPs) in both heat treated conditions are likely to affect the EAC. To follow this, they carried out transmission electron microscope (TEM) studies. TEM photographs revealed that in the peak aged alloy, the GBPs continuously decorated the grain boundaries (Fig.3(a)), whereas in the over aged alloy the GBPs were found to be coarse and disconnected (Fig.3(b)). The GBPs were mainly η particles having the chemistry of $MgZn_2$ [8]. These precipitates were considered anodic to the Al matrix and suggested to undergo selective dissolution in corrosive environment. For this reason, the grain boundaries of peak aged alloy, where η precipitates lie in a continuous manner, suffered severe cracking in 3.5 wt% NaCl medium. As the grain boundary

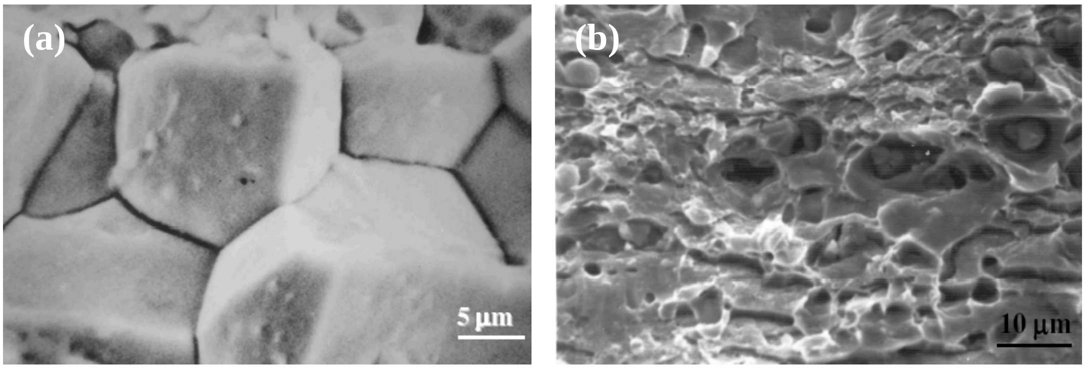

Fig. 1. SEM fractographs of 7010 Al-alloy in: (a) peak aged condition, shows typical intergranular cracking of recrystallized grains; and (b) over aged condition, shows predominant ductile fracture

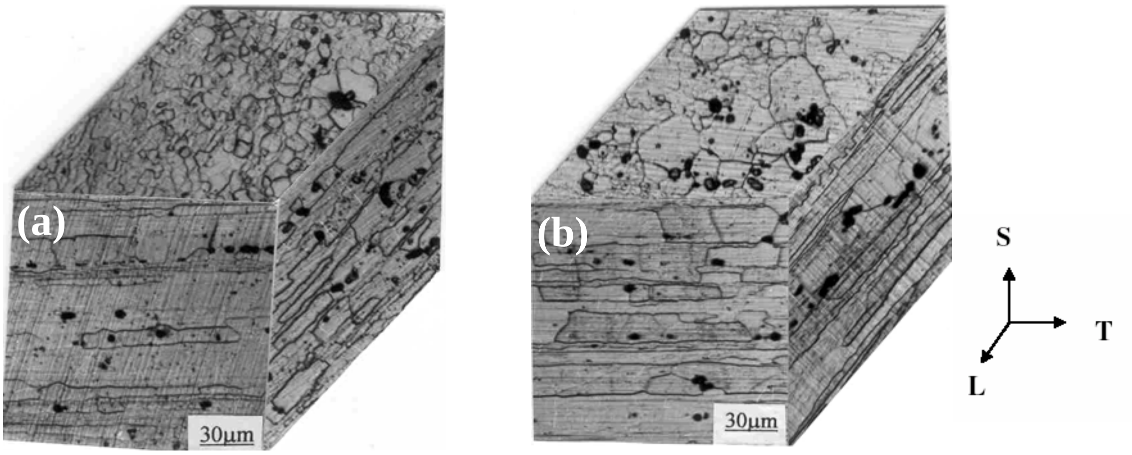

Fig. 2. Optical micrographs of 7010 Al-alloy in: (a) peak aged condition; and (b) over aged condition, shows elongated pancake shaped grains and equiaxed recrystallized grains along the long-transverse direction

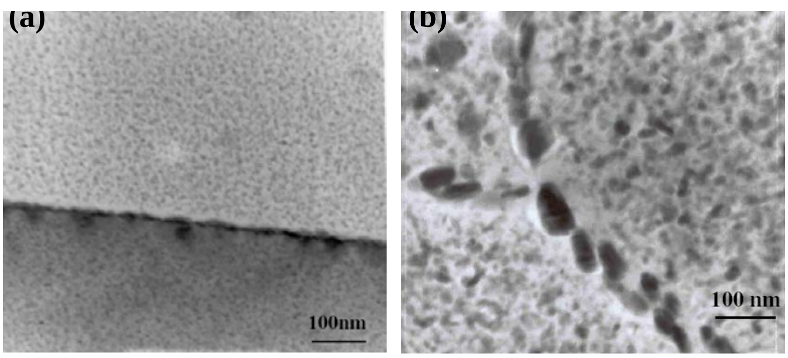

Fig. 3. TEM micrographs of 7010 Al-alloy in: (a) peak aged condition, shows fine precipitates in the matrix and continuous grain boundary precipitates ; and (b) over aged condition, shows coarse precipitates in the matrix and broken network of coarse grain boundary precipitates

precipitates were separated in the over aged condition, the over aged alloy offered more resistance to cracking. Further, the higher Cu of GBPs of over aged alloy than that of peak aged alloy made $MgZn_2$ precipitates noble and thereby minimized the dissolution of these precipitates. Puiggali et al., [1] also seem to concur with this view.

Effect of coarse intermetallic particles

Puiggali et al., [1] reported that particles are responsible for crack initiation in the over aged alloy. In this study it was observed that the Al-Cu-Mg intermetallic particles to influence the crack initiation [7]. Even in 7050 Al-alloy coarse intermetallic particles seemed to affect EAC [9]. But what is interesting is that the peak aged alloy seemed to have little affected by the coarse intermetallic particles, though these particles affect the film breakdown of the surrounding Al-alloy matrix in both the cases (Fig. 4(a) and (b)). Hence, further investigation was carried out [7]. The potency of the particles to influence cracking was based on the following arguments. The selective dealloying of spherical shaped particles and Cu enrichment on their surface, as shown by Fig. 4, can affect the cracking following ways.

(i) The dealloyed Cu layer on the particle can induce a cleavage fracture in the particle itself [10]. This fracture event can be responsible for the crack initiation on the alloy.

(ii) The Cu rich surface of the coarse intermetallic particles could also develop high galvanic potential difference with the alloy matrix. This in turn can induce film break-down in the Al-alloy matrix and thus become the cause of crack initiation in the matrix.

Whatsoever be the mechanism involved in initiating the crack, the difference in time taken to complete EAC test (to failure) between the two aging conditions was mainly responsible for the effect of spherical on EAC. High EAC resistance of the over aged alloy had automatically resulted in a much longer exposure of the tensile sample to the environment than that was possible for the peak aged alloy. Indeed the EAC tests for peak aged alloy were completed within 10 h, while the test for over aged sample took about 36 h to complete. Further it was observed that the alloys required longer than 10 h for pitting at open circuit potential (Fig. 5a, b) and by that time peak aged samples failed in the SSR test.

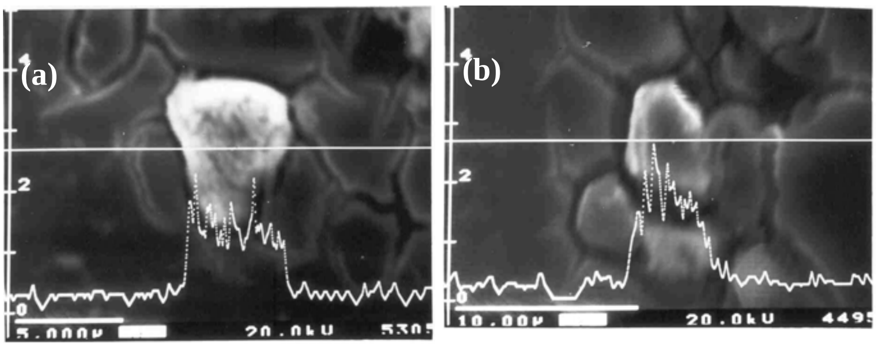

Fig. 4. SEM micrographs of 7010 Al alloy in: (a) peak aged condition and(b) over aged condition, show passive film break-down in the vicinity of spherical intermetallic particles, when exposed to 3.5% NaCl solution for 24 h (WDX Cu scans show the spherical intermetallic particles are rich in Cu)

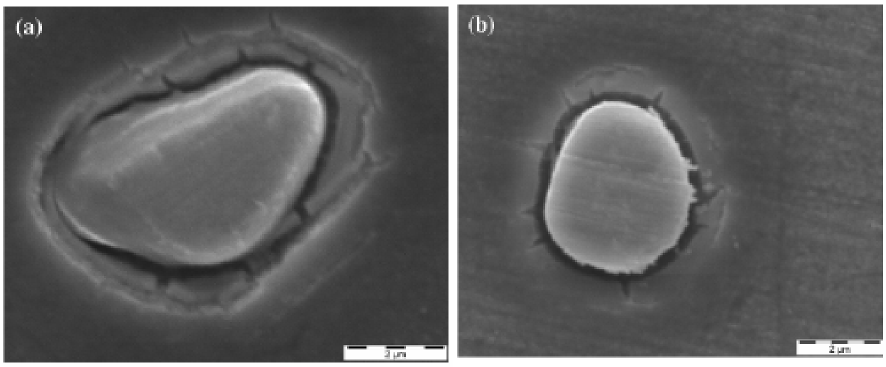

Fig 5. SEM micrograph of (a) peak aged (b) over aged, 7010 Al alloys exposed to 3.5% NaCl solution for 10h, shows no significant film break-down along the grain boundary

Effect of recrystallization

Since recrystallized grains were found to be the weakest zones of intergranular stress corrosion cracking (IGSCC), the EAC resistance of Sc containing alloys were examined [5], as Sc is known to improve the strength levels and inhibit recrystallization tendency (Fig. 6) of Al-alloys [11-14]. Interestingly, the alloy containing 0.25 wt. % Sc showed higher EAC resistance even in the peak aged condition (Table 2). Thus, the alloy exhibited 12.5 %E, 16.4 %RA and 560 MPa UTS when tested in 3.5 wt% NaCl solution at 10^{-6}/s strain rate. Comparing with the base alloy, 0.25 wt.% Sc containing alloy exhibited about 4 fold increase in %E and 5 fold increase in % RA, in spite of the latter exhibiting a 10 % higher UTS than the former. Due to a sharp reduction in recrystallization, the Sc containing alloy exhibited mixed mode of failure (quasi-cleavage) (Fig. 7).

Table 2. *SSRT data of base 7010 Al-alloy and 0.25 wt.% Sc containing alloy in peak aged conditions tested in air and 3.5 wt% NaCl solution at 10^{-6}/s strain rate*

Alloy	% Elongation		% Reduction in Area		Ultimate Tensile Strength (MPa)	
	Air	3.5 wt% NaCl	Air	3.5 wt% NaCl	Air	3.5 wt% NaCl
Base	10	3	10	3	561	515
0.25 wt.% Sc added	13.4	12.5	15.8	16.4	560	560

CONCLUSIONS

The recrystallized grains in 7010 Al-alloy were found to be more susceptible towards intergranular cracking. Preferential dissolution of $MgZn_2$ precipitates assisted by its continuous nature along the grain boundary makes the grain boundary an easy path for the crack growth. Both the above conditions were modified by over aging treatment, but with about 10% loss in UTS. Coarse intermetallic particles facilitate SCC cracks in over aged alloy and minimizing them can further enhance its EAC resistance. As far the peak aged alloy is concerned, recrystallized grains are the weakest areas of cracking and inhibiting recrystallization through 0.25 wt. % Sc addition significantly improves the EAC resistance.

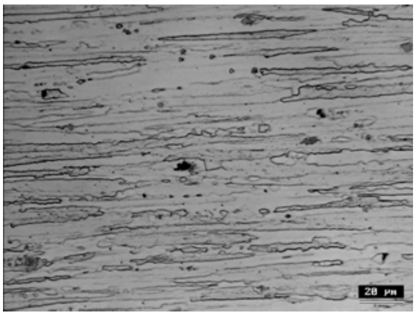

Fig. 6. Optical micrograph of 0.25 wt.% Sc containing 7010 Al-alloy in peak aged condition, shows fibrous non-recrystallized grains

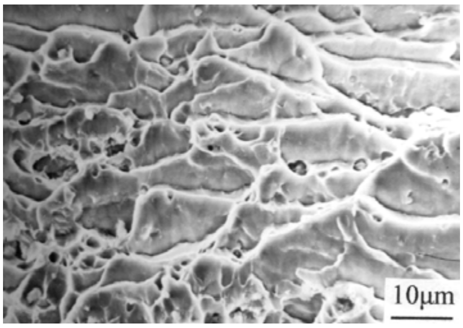

Fig. 7. SEM fractograph of 0.25 wt.% Sc containing 7010 Al-alloy shows a predominant ductile failure

REFERENCES

1. M. Puiggali, A. Zielinski, J.M. Olive, E. Renauld, D. Desjardins, M. Cid, Corro. Sci., (1998), 40, 805.
2. J.S. Robinson, Mater. Sci. Forum, (2000),pp. 331-337, 1653.
3. [M. Bobby-Kannan, V.S. Raja, R. Raman and A .K. Mukhopadhyay, Corrosion, (2003), 59, 881.
4. M. Bobby Kannan, V.S. Raja, and A .K. Mukhopadhyay, Scripta Mater., (2004), 51, 1075.
5. M. Bobby Kannan, V.S. Raja, A .K. Mukhopadhyay and P. Schmuki, Metall. and Mater. Trans. *A*, (2005), 36,3257.
6. M. Bobby Kannan, “Role of multistep aging and scandium addition on the environmentally assisted cracking and exfoliation behavior of 7010 Al-alloy” Ph.D. thesis, Indian Institute of Technology Bombay, India, May 2005.
7. M. Bobby Kannan, V.S. Raja, J. Materials Sc., (Accepted).
8. A.K. Mukhopadhyay, G.M. Reddy, K.S. Prasad, S.V. Kamat, A. Dutta and C.Mondal, "Influence of scandium addition on the microstructure and properties of AA7010 alloy sheets", J.T.Staley Honorary Symposium on Al Alloys, Advances in the Metallurgy of Al Alloys, ASM International (Indianapolis, USA, November 5-8, (2001), 63.
9. D. Najjar, T. Magnin, J.J. Warner, Mater Sci Eng A, (1997), 238, 293.
10. RC Newman, T Shahrabi, K. Sieradzki., Scripta Metall., (1989), 23, 71.
11. L.A. Willey: US Patent 3619181, (1971).
12. Y. Wu, F.H. (Sam) Froes, C. Li, and A. Alvarez, Metall. and Mater. Trans. A, (1999), 30, 1017.
13. Y. Zhi-min, Y. Lei, P. Qing-lin, and J. Feng, Trans. of the Nonferrous Metals Soc. of China, 2001,11, 822.
14. Y.W. Riddle, and T.H. Sanders Jr., Mater. Sci. Forum, (2000), pp. 331-337, 799.