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A Study of the Response of a Zr-modified 2014 Aluminium Alloy Subjected to Fatigue Loading

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Abstract

The present work illustrates the fatigue response differences of a Zr stabilized Al-Cu alloy and the corresponding unmodified one. The fatigue response of the materials has been studied in both conditions by using a fatigue test machine working at 250 Hz. The mechanisms governing fatigue life, cyclic deformation and fracture characteristics are studied as a function of the magnitude of the applied stress and intrinsic microstructural evolution. The curve representing the stress amplitude fatigue life response of the material in the Zr stabilised condition showed a classical behaviour with increasing fatigue life as cyclic stress decreases. A fatigue life of 10^7 cycles at 110 MPa was recorded. The microstructure in the as-received and deformed conditions was characterised by optical and electron microscopy techniques; the crack growth and propagation were determined by scanning electron microscopy observations. The microstructure was characterised by very small equiaxed grains in the cross section respect to the extrusion direction; fracture surfaces showed distinct regions of stable crack growth and overload and the micromechanisms of damage initiation and propagation were clearly recognised.

1. Introduction

The new generation of aerospace applications requires the development of high performance aluminium alloys characterized by very good mechanical properties. The cyclic plastic deformation of light alloys and the subsequent damage behaviour through microscopic phenomena demonstrates the crucial importance of microstructure in crack propagation and growth controlling the deformation mode of aluminium alloys [1, 2]. The complete understanding of fatigue properties of aluminium alloys leads the researchers to the development of optimal microstructure for critical applications [3].

The addition of transition elements such as zirconium forming trialuminides with low solubility and low diffusion coefficient provides a very useful instrument in the control of aluminium alloy microstructure. The small precipitates, formed by adding small quantities of Zr, develop a large coarsening resistance in the matrix in addition to high thermal stability due to their higher melting point respect to the matrix [4, 6]. Zr additions form the $L1_2$–ordered Al_3Zr phase which lead to the formation of coherent strengthening particles that stabilise alloy microstructure over a wide range of temperatures by slowing recrystallization kinetics. The Al_3Zr trialuminide particles, which are very stable against coarsening and against redissolution [7], cause a more uniform distribution of dislocations and pin grain boundaries. With a Zr concentration of more than 0.1 %, Al_3Zr particles formed from the melt as primary phase during rapid solidification act as nuclei for solidification of Al, and Zr can thus operate as grain refiner of Al [8, 9]. Also, the Al_3Zr particles provide strong obstacles to dislocation movement. Consequently, these precipitates are very effective in pinning of grain and subgrain boundaries during all thermal and mechanical processing of aluminium alloys [10].

Following these considerations the Al_3Zr intermetallic compounds are used as dispersoids or precipitates in the Al-Al_3Zr composite system. The present study is aimed to the study of fatigue response of Zr-stabilized 2014 aluminium alloy. The active strengthening mechanisms at room temperature of the studied material were identified as solid solution strengthening, grain boundary strengthening, and Al_3Zr precipitate strengthening. Strengthening due to the sub-micron grain size was the largest contribution to alloy strength, followed by precipitate strengthening and solid solution strengthening. The addition of a transition element and in particular Zr provides, on one hand the increasing of strength level at room temperature, and on the other hand the microstructural stability at higher temperatures by forming very fine stable dispersoids. These dispersoids represent very efficient nuclei for precipitation of coarse, equilibrium precipitates.

2. Experimental Procedures

The alloy used in the present work had the following chemical composition (wt.%): Cu=4.32, Mg=0.49, Zr=0.12, Si=0.68, Fe=0.23, Mn=0.77, Ti=0.03, Al=bal.; the material was supplied in form of extruded rods of 80 mm diameter ALCAN (USA). Tensile tests were performed on the commercial and modified alloys by employing an MTS 810 machine. Endurance fatigue tests were performed on a resonant electro-mechanical testing machine (TESTRONIC^{TM}) under constant loading control up to 250 Hz sine wave loading 50± 25 KN. The cyclic fatigue tests were conducted in the axial total stress-amplitude control mode under fully-reversed, push-pull, tension-compression loading such that the magnitude of negative stress amplitude equals the magnitude of positive one ($R=\sigma_{min}/\sigma_{max}=-1$). Cylindrical test specimens were machined from the as-received rods with the axis parallel to the extrusion direction, at the gauge section they measured 25 mm in length and a minimum diameter of 6 mm according to the actual standard codes (ASTM E466-72T). All mechanical tests were performed up to failure in the as-received condition.

The Zr stabilized aluminium alloy fatigue curve was compared with that for the unstabilized alloy deformed under the same conditions. TEM observations were performed in the as-received and deformed samples in order to reveal the effects of microstructure on the fatigue response of the studied alloy. Fracture surfaces of the deformed fatigue test specimens were comprehensively examined in a scanning electron microscope (JEOL JSM6500F) equipped with field emission gun to determine the macroscopic fracture mode and characterize the fine-scale topography and microscopic mechanisms governing fatigue fracture.

3. Results and Discussion

The optical microscopy observations of the 2014-Zr alloy (Figure. 1) showed very small grains as a direct result of the presence of trialuminides in the structure of the material. The effectiveness of Zr to inhibit the recrystallization in a wide range of aluminium alloys is due to the presence of spherical and coherent Al_3Zr (β') precipitates in a cubic ($L1_2$) form. The FEGSEM and TEM inspection of the as-received Zr-modified material revealed the presence of very fine precipitates within the grains as expected following the previous observations (Figure. 2).

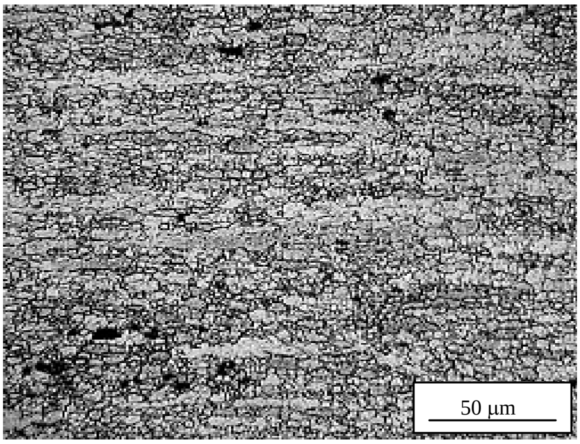

Figure 1: Microstructure of the 2014-Zr aluminium alloy showing a very fine microstructure.

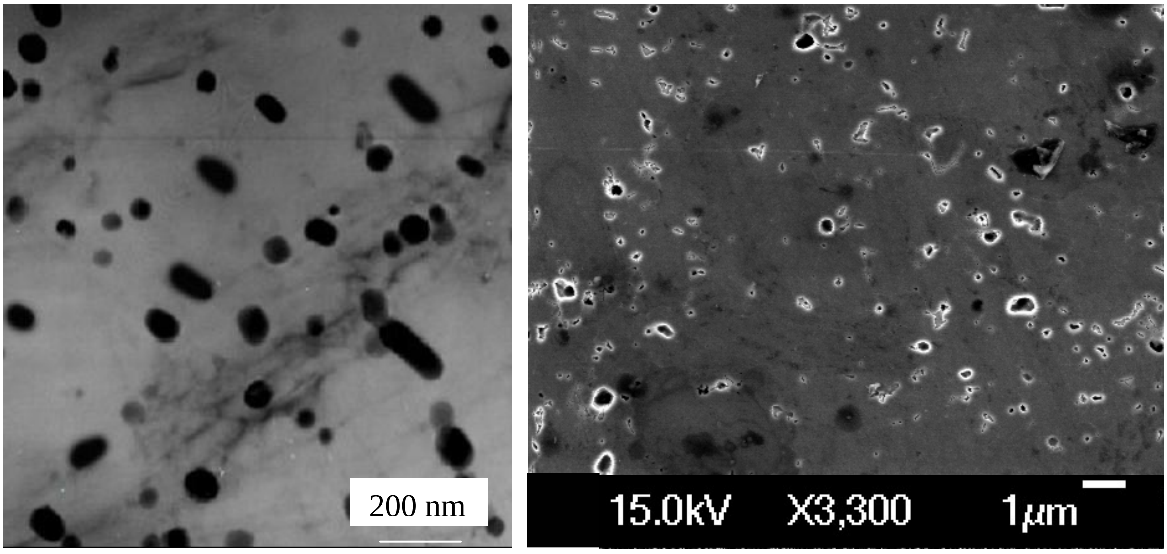

Figure 2: TEM (a) and FEGSEM (b) images of the 2014-Zr aluminium alloy showing very fine Al_3Zr precipitates.

This low misfit accompanied with very low solid solubility of Zr in Al favours the stability of the precipitates. These small precipitates act to inhibit recrystallization and pin grain boundaries through a Zener drag process. Given their small size and low misfit, the particles are probably totally coherent with the matrix, and therefore the driving force for heterogeneous precipitation is mainly the reduction of the misfit elastic energy, because of the low energy of the coherent interface. Another important effect of Zr addition is the effect associated with vacancies; in particular it reduces the concentration of the free vacancies.

The tensile properties parallel to the extrusion direction of the commercial and modified alloys are reported in Table 1.

Table 1. Comparison between tensile properties of Zr-modified (present study) and commercial 2014 alloys.

Alloy	YS (MPa)	UTS (MPa)	Elongation (%)
2014	480	530	18
2014+0.12 Zr	510	610	21

The curve representing the stress amplitude-fatigue life response of the material in the Zr stabilized and non-stabilized conditions is reported in Figure 3. The curves show a classical behaviour for the aluminium alloys, revealing a trend of increasing fatigue life with decreasing cyclic stress amplitude in both the studied materials; the difference in the number of cycles to failure, at the same stress amplitude, being more marked at higher stresses than at lower ones. Some materials, such as aluminium alloys, display fatigue limits at very high number of cycles (normally >10^6) [11, 12], many other materials do not exhibit this response, instead displaying a continuously decreasing stress-life response, even at a greater number of cycles. Following these observations it is more correct to describe the fatigue strength of these kind of alloys at a given number of cycles; the endurance limit of AA2014+Zr aluminium alloy was not so clearly recognized at 10^6 cycles as normal in many aluminium alloys, a fatigue life of 10^7 cycles at 110 MPa was recorded in the as received condition, while a fatigue life of 10^7 cycles at 100 MPa was recorded for the unstabilized alloy. The addition of a very small quantity of Zr produce an increase in fatigue resistance of the material in all the stress conditions investigated. The Zr modified alloy has more resistant to cyclic deformation than the unmodified one. The precipitation of trialuminides and the consequent more stable structure result in the increase of fatigue life of the material.

The FEGSEM was used to examine the cyclic fatigue fracture surfaces of the deformed and failed AA 2014-Zr specimens. To determine the macroscopic fracture mode, observations at low magnification were performed in order to identify the regions of microscopic crack initiation and stable crack growth as well as the regions of final failure or overload. To characterize the fine-scale topography and microscopic mechanisms governing fracture, observations at higher magnifications were performed in the zones of early microscopic crack growth to identify the size, location and number of the microscopic cracks and their progression in the material microstructure, on the other hand to study the region of overload to identify the fine-scale features reminiscent of local governing mechanisms. In both low and high cycle regimes the composite failure was characterized by small regions of stable microscopic crack growth (Figure 4).

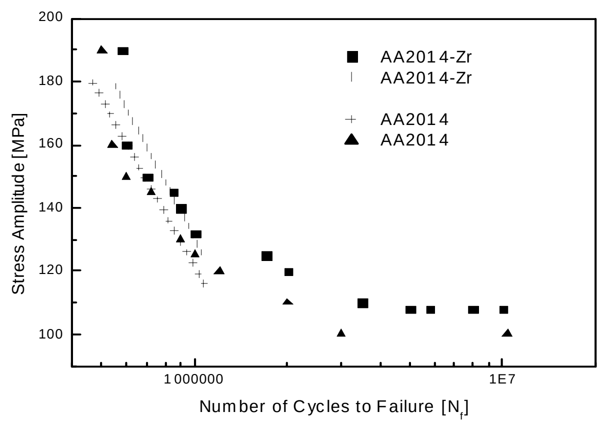

Figure 3: Fatigue endurance curve of the Zr-modified and commercial 2014 aluminium alloys.

All the fracture surfaces show distinct regions of stable crack growth and overload, the distance between the two regions resulted more marked by increasing the cyclic stress.

In this kind of materials the microcracks formed initially in direction parallel to the principal stress axis, grow and coalesce forming one or more macroscopic cracks that propagate in the same direction leading to the material failure. During crack growth, the plastic zone at the crack tip begins to increase so that many grains can be involved in the plastic deformation; the crack is able to propagate along different slip planes by simultaneous or alternating shear on two slip systems. This double slip mechanism produces a crack path normal to the load direction producing many fatigue striations shown in Figure 5.

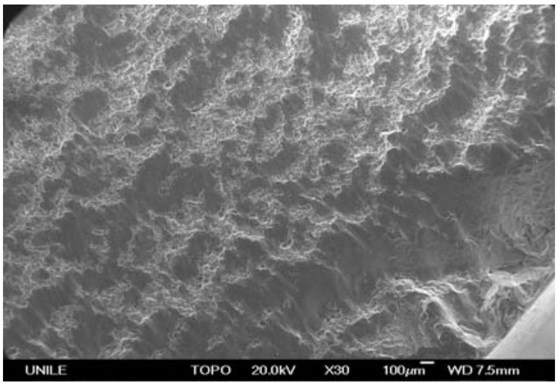

Figure 4: Stable crack growth and overload zones observed in the specimen tested at 120 MPa to failure after 2 x 10^6 cycles.

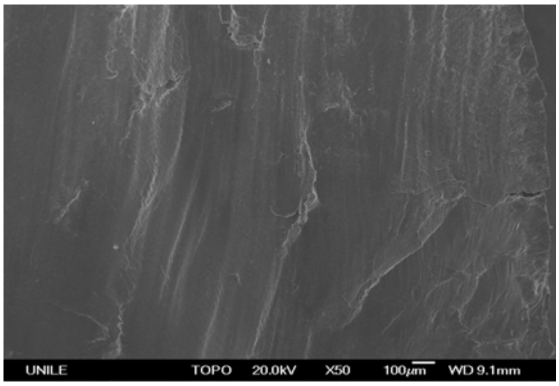

Figure 5: Typical fatigue striations observed in the specimens tested at 120 MPa to failure after 2 x 10^6 cycles.

All the crack initiation and growth is normally attributed to the incremental accumulation of microplastic damage of the material, under cyclic loading, at a localized level. The accumulation of damage at every cycle in the micro sites and the initiation of slip band activity in the grains oriented along the slip direction lead to the nucleation of many microscopic cracks; isolated areas of small voids were recognized in the regions of stable flow and crack growth (Figure 6). The nucleation of voids produce a decrease of the macroscopic response of the material, by continuing deformation, they grow and coalesce as a result of strain localization causing small increments of crack tip extension at every cycle.

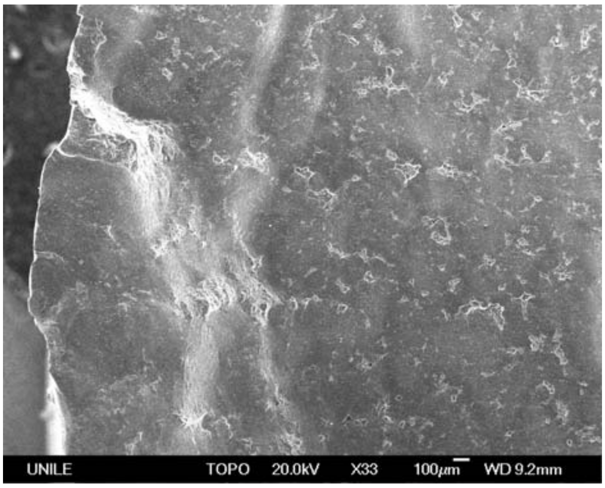

Figure 6: Small voids formation on the fracture surface of the specimen tested to failure at 125 MPa and 3.5 x 10^5 cycles.

4. Conclusions

The fatigue response of a Zr-modified 2014 aluminium alloy was analysed in the present paper. The material showed good fatigue properties with failure occurred after 2 x10^6 cycles at a stress amplitude of 125 MPa. The material microstructure in the as-received condition was studied by optical and transmission electron microscopy in order to put in evidence the very fine grain structure and the role of very fine Al_3Zr precipitates. The micro-mechanisms involved during cyclic loading were studied by means of scanning electron microscope equipped with field emission gun.

References

[1] S. Suresh, “Fatigue of Materials”, 2nd London, UK: Cambridge University Press, 1998.
[2] T.S. Srivatsan, D. Kolar, P. Magnusen, The Cyclic fatigue and final fracture behaviour of aluminum alloy 2524, Materials and Design, 23, 129-139, 2002.
[3] S.E. Stanzl-Tschegg, H. Mayer, Fatigue and fatigue crack growth of aluminium alloys at very high numbers of cycles, International Journal of Fatigue, 23, S231-S237, 2001.
[4] J. Murray, A. Peruzzi, J.P. Abriata, The Al-Zr (aluminium-zirconium) System, Journal of Phase Equilibria, 13, 3, 277-291, 1992.
[5] Z. Yin, Q. Pan, Y. Zhang, F. Jiang, Effect of minor Sc and Zr on the microstructure and mechanical properties of Al-Mg based alloys, Materials Science and Engineering A280, 151-155, 2002.
[6] A. Deschamps, Y. Brechet, Influence of quench and heating rates on the ageing response of an Al-Zn-Mg-(Zr) alloy, Materials Science and Engineering A251, 200-207, 1998.
[7] A. Waheed, G. W. Lorimer, Pinning of subgrain boundaries by Al_3Zr dispersoids during annealing in Al-Li commercial Alloys, Journal of materials science letters, 16, 1643-1646, 1997.
[8] Seong Ill Park, Seung Han, Si Kyung Choi, Hyuck Mo Lee, Phase Equilibria of Al3(Ti, V, Zr) intermetallic System, Scripta mater., 34, 11, 1697-1704, 1996.
[9] S. Z. Han, S.I. Park, J.S. Huh, Z.H. Lee, H.M. Lee, Lattice matching of DO_{23} and DO_{22} phases in Al-6at.%(Ti, V, Zr) systems, Materials Science and Engineering A230, 100-106, 1997.
[10] S. Spigarelli, M. Cabibbo, E. Evangelista, J. Bidulska, A study of the hot formability of an Al-Cu-Mg-Zr alloy, Journal of materials science, 38, 81-88, 2003.
[11] C. Bathias, D. Droullac, P. Le Francois, How and why the fatigue S-N curve does not approach a horizontal asymptote, International journal of Fatigue, 23, S143-S151, 2001.
[12] Xu-Dong Li, L. Edwards, Theoretical modelling of fatigue threshold for aluminium alloys, Engineering Fracture Mechanics, 54, 1, 35-48, 1996.