INFLUENCE OF VARIABLE AMPLITUDE LOADING ON FATIGUE CRACK PROPAGATION OF AL 7475

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ABSTRACT The fatigue crack propagation behavior of Al 7475 in an overaged (T7351) and in an underaged condition was investigated by comparing constant amplitude tests with periodically applied tensile overload tests in vacuum and in NaCl solution. The number n of intermittent baseline cycles between two overloads was varied between 100 and 20.000 cycles. In vacuum the number of n significantly affected the crack growth behavior of the underaged condition, but only minor effects were determined for the overaged condition. In NaCl solution, significant effects on the crack propagation behavior were found for the overaged condition. The results are explained on the basis of fracture surface investigations and variations in crack front geometry.

Keywords: *Al 7475, fatigue crack propagation, variable amplitude loading, crack front geometry, environmental effects*

1 INTRODUCTION

The Al-Zn-Mg-Cu alloy 7475 in the overaged condition T7351 is used in aircraft applications for highly stressed structural parts such as frames and stringers, for which also a high resistance against stress corrosion cracking is needed. Since these parts are also subjected to fatigue loading conditions during each flight, the fatigue crack propagation behavior under variable amplitude loading conditions is of importance for damage tolerant design purposes as well as for determination of safe inspection intervals.

To evaluate the influence of variable amplitude loading usually simplified loading conditions are used. In the present investigation the loading procedure consisted of periodically applied single tensile overloads (overload ratio 1.5) superimposed on constant amplitude baseline cycles with R = 0.1. The number n of intermittent baseline cycles between consecutive overloads was varied between 100 and 20.000 cycles. The effect of overloads is usually explained by crack closure considerations [1]. In a recent work on the experimental alloy X-7075 [2] the effects of overloads on crack propagation were ascribed to changes in crack front profiles. Crack closure was ruled out as the main effect because no significant differences in the overload effects were found between loading conditions with crack closure (R = 0.1) and without crack closure (R = 0.5).

The aim of the present work was to apply these findings on X-7075 to the commercial alloy 7475 in the overaged condition T7351. For comparison, also an underaged condition was investigated. The fatigue crack propagation tests were performed in vacuum and in NaCl solution.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

The alloy 7475 used in this investatigation was obtained as 36 mm thick plate from Kaiser Aluminium Europe Inc., Germany. The alloy 7475 had the chemical composition Al-5.80Zn-2.32Mg-1.68Cu-0.23Cr-0.02Mn-0.03Ti-0.07Si-0.10Fe (in wt. %). The plate was supplied in the overaged T7351 condition: After solution treatment the plate was stress relieved by stretching and artificially duplex aged 7 h 105°C and 14 h 170°C. The microstructure of this plate contained pancake shaped grains (3500 x 500 x 20 μm) and stringers of coarse intermetallic particles aligned parallel to the rolling direction. Cr dispersoids prevented recrystallization and the subgrain size was about 3 μm. The matrix contained a fine dispersion of semi-coherent η' precipitates. Besides Cr dispersoids, constituent η precipitates were present at the subgrain boundaries resulting in precipitate-free-zones (PFZ). The alloy 7475 was also tested in an underaged condition. A solution treatment of the plate material (465°C) followed by an aging treatment of 24 h at 100°C resulted in a very fine dispersion of coherent GP zones and η'' precipitates. Again, Cr dispersoids prevented recrystallzation and subgrain growth during the solution treatment. Polefigures generated from X-ray diffraction indicated that the plate had a copper type deformation texture [3]. The tensile tests (L-direction) were carried out in air on round specimens (gage length 20 mm, gage diameter 5 mm), using an initial strain rate of 8×10^{-4} s^{-1}.

Fatigue crack growth studies were carried out on 8 mm thick CT specimens (width 32 mm) in the L-T orientation under load control at 30 Hz (sinusoidal) using a computer controlled servohydraulic testing machine. Tests were performed in vacuum (< 10^{-6} Pa) and in an aqueous solution of NaCl with an inhibitor at a free corrosion potential (3.5 wt.% NaCl + 0.3% $NaCr_2O_7$ + 0.2% Na_2CrO_4). Constant amplitude tests and tests with periodically superimposed single tensile overloads (overload ratio 1.5) were carried out at R-ratio of 0.1. The number n of intermittent baseline cycles between overloads was varied between 100 and 20.000. Crack closure was measured applying conventionel back face strain technique. Crack front profiles prepared by sections perpendicular to the crack growth direction were analyzed by Light Microscopy (LM). Fracture surfaces were analyzed by Scanning Electron Microscopy (SEM).

3 EXPERIMENTAL RESULTS

In the first part of this work on the alloy 7475, the influence of the variation in the number n of intermittent baseline cycles on the crack propagation behavior was investigated for a T7351 overaged condition (7475 OA) and for an underaged microstructure taken as a reference condition (7475 UA). To exclude environmental effects, this investigation was performed in vacuum. The tensile properties of both conditions are listed in Table 1.

Table 1: Tensile Properties.

Condition	$\sigma_{0.2}$ (MPa)	UTS (MPa)	σ_F (MPa)	Tens. El. (%)	RA (%)
7475 UA	460	580	700	17	18
7475 OA	415	490	620	14	36

Figure 1 shows the effects of the variation in the number n of intermittent baseline cycles on the crack propagation rates for the overaged (7475 OA) and underaged (7475 UA) microstructures for tests performed in vacuum. The results showed significant influence of the number of n for the underaged condition, but only minor influence of the number of n for the overaged microstructure in comparison with the crack propagation behavior under constant amplitude (CA) loading. For the condition 7475 UA tensile overloads every 100 baseline cycles (n = 100) led to higher propagation rates as compared to constant amplitude loading. Periodically applied overloads every 1.000 baseline cycles (n = 1.000) resulted in much lower propagation rates as compared to constant amplitude loading and loading with n = 100. Further increase of the number of n to n = 20.000 reversed this tendency. The propagation rates for n = 20.000 were nearly the same as compared to those of constant amplitude loading. The crack front profiles at crack growth rates of da/dN = 1×10^{-9} m/cycle can be seen in Figure 2 for the underaged condition and the corresponding fracture surfaces in Figure 3 (for all fracture surfaces shown in this paper the crack propagation direction is horizontally from right to left). In comparison with constant amplitude loading (Figure 2 a) applying overloads every 100 baseline cycles resulted in a smoother crack front profile (Figure 2 b). Further increase to n = 1.000 (Figure 2 c) and to n = 20.000 (Figure 2 d) led to a significant increase in crack front profile roughness. Investigations of the fracture surfaces revealed for constant amplitude loading crack propagation mainly along single slip planes (Figure 3 a). Loading with n = 100 resulted in a flat fracture surface perpendicular to the stress axis (Figure 3 b). Overloads every 1.000 baseline cycles led to crack propagation both in the flat configuration and along single slip planes (Figure 3 c). It should be pointed out that the crack front profile of n = 1.000 appeared despite the flat areas very rough because the crack propagation along single slip planes was very pronounced (Figure 2 c). Loading with n = 20.000 resulted in intense crack propagtion along a few single slip planes (Figure 3 d) leading to the most pronounced crack front tortuosity (Figure 2 d).

In comparison with the underaged microstructure (7475 UA) the overaged condition (7475 OA) showed a much lower resistance against crack propagation (Figure 1). Only minor effects of tensile

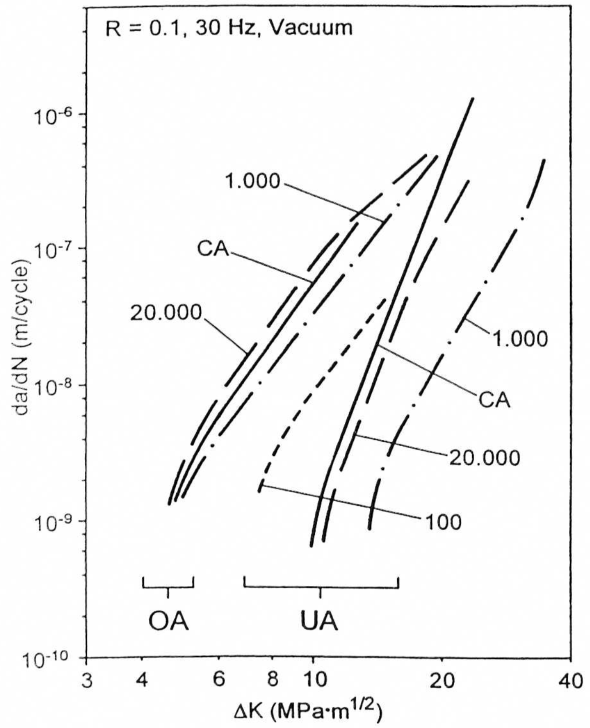
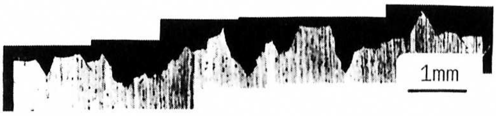


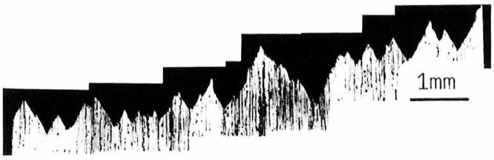
Figure 1: da/dN-ΔK curves of 7475 alloy in vacuum.

a) const. amplitude, $\Delta K = 10.2$ MPa m^{½}

b) n = 100, $\Delta K = 7.5$ MPa m^{½}

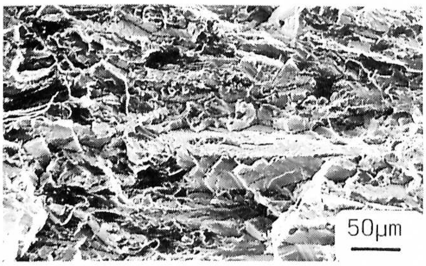


c) n = 1.000, $\Delta K = 14.7$ MPa m^{½}

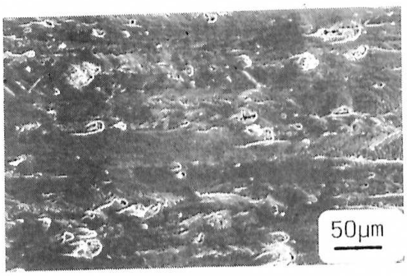


d) n = 20.000, $\Delta K = 10.6$ MPa m^{½}

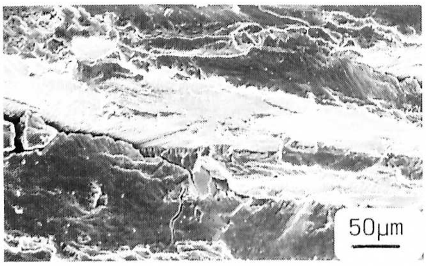
Figure 2: 7475 UA, crack front profiles (LM) at da/dN = 1 x 10^{-9} m/cycle in vacuum.



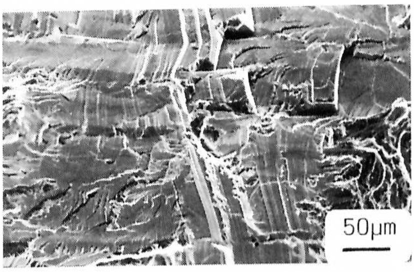
a) const. amplitude



b) n = 100

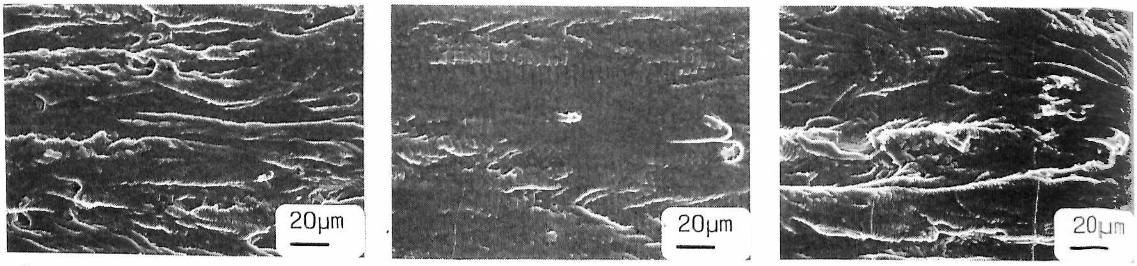


c) n = 1.000



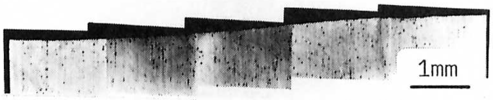
d) n = 20.000

Figure 3: 7475 UA, fracture surfaces (SEM) at da/dN = 1 x 10^{-9} m/cycle in vacuum



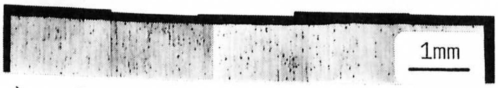
a) const. amplitude b) n = 1.000 c) n = 20.000

Figure 4: 7475 OA, fracture surfaces (SEM) at da/dN = 5 x 10^{-9} m/cycle in vacuum



a) const. amplitude, $\Delta K = 4.6$ MPa m$^{1/2}$

b) n = 1.000, $\Delta K = 4.8$ MPa m$^{1/2}$



c) n = 20.000, $\Delta K = 4.6$ MPa m$^{1/2}$

Figure 5: 7475 OA, crack front profiles (LM) at da/dN = 1 x 10^{-9} m/cycle in vacuum.

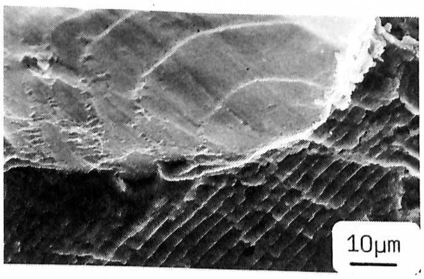


Figure 6: 7475 UA, n = 1.000

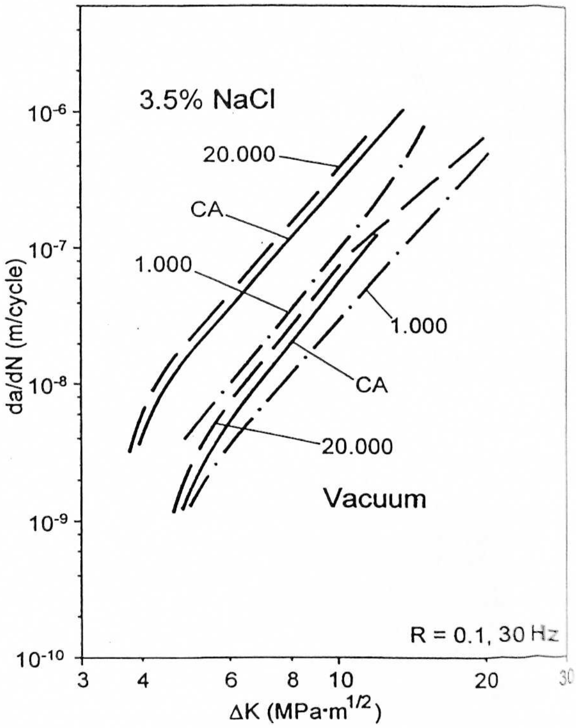
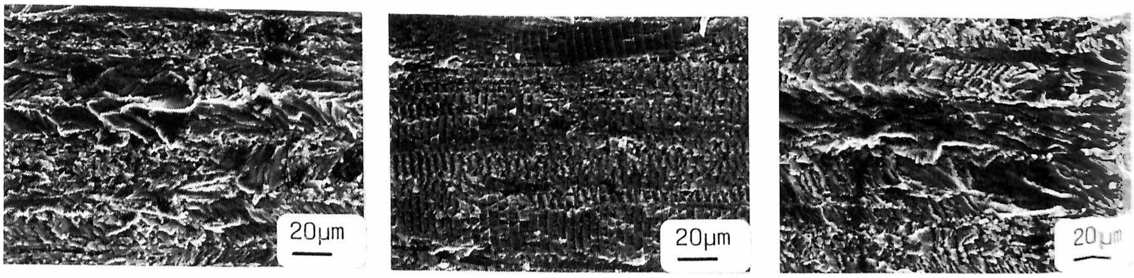


Figure 7: da/dN-ΔK curves of 7475 OA in 3.5% NaCl solution and in vacuum.



a) const. amplitude b) n = 1.000 c) n = 20.000

Figure 8: 7475 OA, fracture surfaces (SEM) at da/dN = 5 x 10^{-9} m/cycle in 3.5% NaCl solution

overloads were found with the tendency that loading with n = 1.000 resulted in slight retardation as compared to loading conditions with constant amplitude and with n = 20.000. The corresponding fracture surfaces (Figure 4) and crack front profiles (Figure 5) revealed a overall flat crack front geometry for the overaged microstructure. At low propagtion rates (da/dN = 5 x 10^{-9} m/cycle) a tendency could be seen that the loading condition with n = 1.000 resulted in a slightly smoother fracture surface (Figure 4 b) as compared to loading with constant amplitude (Figure 4 a) or n = 20.000 (Figure 4 c) which exhibited nearly the same fracture surfaces. For both microstructures (7475 UA and 7475 OA) back face strain measurements revealed crack closure levels below 10 % for all conditions tested in vacuum.

For the condition 7475 UA with n = 1.000, involving along the crack front both crack growth mechanisms, crack propagation along single slip planes and propagation in flat areas involving multiple slip, it was possible to investigate which of these two basic propagation mechanisms is showing a slower propagation rate. It can be seen very clearly from Figure 6 by analyzing the spacings of the overload markers that the crack propagation mechanism involving multiple slip exhibited a slower propagation rate.

In the second part of this work the influence of an aggressive environment was investigated for the overaged condition (7475 OA). Figure 7 shows clearly that in aggressive environment (3.5% NaCl solution) crack propagation rates were faster as compared to the inert environment (vacuum). Also the effects of overloads were more pronounced in NaCl solution as compared to vacuum tests for this overaged condition. Applying periodic tensile overloads every 1.000 baseline cycles resulted in NaCl solution in much lower propagation rates as compared to constant amplitude (CA) loading. Loading with n = 20.000 reversed this tendency and the crack propagation rates were nearly the same as for constant amplitude loading (Figure 7). The fracture surfaces in NaCl solution are shown in Figure 8 for crack propagation rates of da/dN = 5 x 10^{-9} m/cycle. The overall fracture surface appearance was flat with the tendency that applying a tensile overload every 1.000 baseline cycles (Figure 8 b) resulted in a smoother fracture surface as compared to the loading conditions with constant amplitude (Figure 8 a) and with n = 20.000 (Figure 8 c). Back face strain measurements showed crack closure values ranging between 10 % and 15 % for all three loading conditions in NaCl solution.

4 DISCUSSION

The present results concerning the crack propagation behavior in vacuum under variable amplitude loading conditions of the underaged and overaged microstructures of the alloy 7475 (Figure 1) are consistent with previous studies [2]: It was thought that the observed changes in crack propagation rates can be attributed mainly to changes in crack front geometries. Each loading condition generates ist own characteristic "equilibrium" crack front configuration. Smooth crack front geometries led to higher propagation rates in comparison with rough crack front profiles. This geometry effect is superimposed on the basic propagation rate for a specific crack propagation mechanism. It can be assumed that the basic crack propagation rate (excluding crack front profile effects) is faster for crack propagation on single slip planes as compared to propagation involving multiple slip (Figure 6). For the underaged condition (7475 UA) the GP zones and η'' precipitates are coherent with the matrix leading to a planar slip distribution ahead of the crack tip. This promotes crack propagation along single slip planes, as can be seen for constant amplitude (CA) loading (Figures 2 a and 3 a). Periodically applied tensile overloads can change the slip distribution ahead of the crack tip and the crack front profile. If the overload is applied when the crack tip is still in the severely deformed part of the plastic zone from the previous overload (n = 100), than many slip systems are activated and the crack propagates by multiple slip in a very flat configuration (Figures 2 b and 3 b). The very smooth crack front profile leads to higher propagation rates as compared to constant amplitude loading (Figure 1). If the overload is applied when the crack tip has left the severely deformed part of the plastic zone from the previous overload (n = 1.000), than the overload generates single slip bands which are even more pronounced than for constant amplitude loading. The resulting rough crack front profile leads to very slow crack propagation rates (Figure 1). It should be pointed out once more the periodically applied overloads are creating their own characteristic crack front geometry with a corresponding crack propagation rate. The individual overloads in the sequence are not changing directly the propagation rate, that means the propagation rate just before and just after an overload is the same [2]. Only the overload cycle itself is causing a larger crack advance but this contribution to the average crack propagation rate is even for n = 100 insignificant. The increase in propagation rate from n = 1.000 to n = 20.000 (Figure 1) can be explained by the fact that the difference in crack front roughness was not very pronounced (compare Figures 2 c and d) and that the crack propagated in case of n = 20.000 solely by the fast crack propagation mechanism along single slip bands (Figure 2 d and 3 d) as compared to n = 1.000 for which still some flat areas with multiple slip (slow crack propagation mechanism) were present (Figures 2 c and 3 c). Each overload in case of n = 20.000 is acting completely outside of the severe plastic deformation from the previous overload causing in combination with the strong crystallographic texture intense slip bands over long distances ahead of the crack tip.

For the overaged condition (7475 OA) semi-coherent η´ precipitates are present in the matrix enhancing a multiple slip distribution ahead of the crack tip and allowing the crack front to maintain a very straight through-thickness configuration (Figure 5). This smooth crack front geometry led to higher propagation rates as compared to the rough crack front profile of the underaged condition (Figure 1). Because the overaged microstructure exhibited already for constant amplitude (CA) loading multiple slip and and a smooth crack front profile, no significant effects of overloads on crack propagation behaviour were found in inert environment (vacuum). The tendency that the crack propagation rate was slightly slower for n = 1.000 as compared to constant ampitude loading and to n = 20.000 (Figure 1) can be explained by the fact that in case of n = 1.000 the overloads are so frequently applied that the volume ahead of the crack tip contained a higher density of less pronounced slip bands (homogeneous dislocation distribution) favouring even more the slower crack propagation mechanism by multiple slip as compared to constant amplitude loading and to n = 20.000.

In an aggressive environment (NaCl solution) the overaged condition (7475 OA) exhibited a significant effect of the variation in the number of n on the crack propagation behavior (Figure 7). Applying every 1.000 baseline cycles a tensile overload resulted in crack growth retardation in comparison with the constant amplitude loading and the variable amplitude loading condition with n = 20.000. This relatively large retardation effect can be explained by the multiple slip argument as outlined in the discussion of the vacuum results on 7475 OA in combination with hydrogen "embrittlement" due to the NaCl solution. For the loading condition with n = 1.000 the hydrogen atoms swept into the plastic zone from the crack tip surface by dislocation dragging are distributed over many more slip bands and over a much higher number of dislocations as compared to constant amplitude loading and to n = 20.000. This more homogeneous distribution of the hydrogen is causing less hydrogen embrittlement in slip bands and a slower propagation rate as compared to constant amplitude loading and to n = 20.000 for which a more pronounced slip band fracture induced by hydrogen embrittlement was observed as compared to vacuum tests (compare Figures 8 a with 4 a and Figures 8 c with 4 c). The condition with n = 1.000 exhibited nearly the same fracture surface (with the ductile overload markers visible) in NaCl solution and in vacuum (compare Figures 8 b with 4 b).

It should be pointed out once more, that crack closure considerations cannot explain the results obtained in this paper, because the crack closure levels remained the same for the different loading conditions. The higher crack closure levels in NaCl solution as compared to vacuum might be explained by hydroxide deposits at the crack tips inducing crack closure.

ACKNOWLEDGEMENT

This investigation was supported by the Deutsche Forschungsgemeinschaft.

6 REFERENCES

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