EFFECTS OF PERIODICALLY APPLIED OVERLOADS ON THE FATIGUE CRACK PROPAGATION BEHAVIOR OF HIGH-STRENGTH AL-ALLOYS

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Abstract

The fatigue crack growth behavior of a high-purity X-7075 with equiaxed grain sizes of 40 and 100 μm and of a very fine grained IN 905 XL alloy was studied at R = 0.1 and 0.5 in vacuum, comparing constant amplitude tests with periodically applied tensile overload tests. The number n of baseline cycles between consecutive overloads was varied between 1000 and 20000. The results showed for X-7075 that with increasing numbers of n significant crack growth retardation occurred at both R-ratios as compared to constant amplitude loading, together with increasingly rough crack front profiles and no measurable crack closure at R = 0.5. With decreasing grain size the crack profiles became less tortuous, resulting in completely flat profiles for the ultrafine grained IN 905 XL at constant amplitude as well as for overload tests, together with almost no crack growth retardation. The results of the present study therefore suggest that the crack growth behavior under periodically applied overloads seems to be influenced to a significant part by variations in crack front geometries.

Introduction

The influence of periodically applied tensile overloads superimposed on constant amplitude fatigue loading has been studied in the past for a number of different alloy systems (1-3). The experimental findings consistently showed that significant crack propagation retardation as compared to constant amplitude loading can occur if the number n of intermittent baseline cycles between consecutive overlaods was increased, while for low numbers of n either no effect or even crack growth acceleration was observed (1,3). However, the reasons for the pronounced retardation phenomena are still discussed in controversial ways. While in (1) a combined effect of variations in crack tip blunting and mean stress with increasing number of n was assumed as the dominating factor, others considered variations in crack closure levels as significant parameters (2). Furthermore, recently published results (3) showed pronounced increases in through-thickness crack front tortuosity with increasing numbers of intermittent baseline cycles between overloads, which were thought to contribute to the observed retardation behavior in addition to other possible parameters, including crack closure variations.

The purpose of the present study therefore was mainly to further investigate possible contributions of crack front geometry variations on the effects of periodically applied tensile overloads on the fatigue crack propagation behavior by investigating Al-alloys with different grain sizes at low and high R-ratios and therefore different amounts of closure.

Experimental Procedure

The tests were performed on a high-purity X-7075 alloy without Cr-dispersoids (Al-5.8Zn-2.6Mg-1.5Cu in wt.%) and on a mechanically alloyed IN 905 XL alloy (Al-3.9Mg-1.3Li-

1.2C-0.4 O in wt.%). Alloy X-7075 was used with two equiaxed grain sizes of 40 μm (FG) and 100 μm (CG) produced by thermomechanical treatments (cold rolling), both in an underaged condition (24h 100°C). Alloy IN 905 XL was studied as a forged rectangular bar (cross section: 80 x 140 mm) with a final heat treatment of 4h 450°C followed by air cooling (4). All mechanical tests were performed at room temperature with the loading axis being parallel to the rolling direction (X-7075) or parallel to the S-direction (80 mm) for IN 905 XL. Tensile properties were carried out in air on round specimens with the gage length being 5 times the gage diameter, using an initial strain rate of $8 \times 10^{-4}\ s^{-1}$ (3,4).

Fatigue crack growth tests were performed in vacuum on CT-specimens (8 mm thick, 32 mm wide) under load control at 30 Hz (sinusoidal) using a computer controlled servohydraulic testing machine. The macroscopic crack growth direction was parallel to the T-direction (X-7075) or to the L-direction (IN 905 XL). Constant amplitude tests and those with periodically superimposed tensile overloads (overload ratio 1.5) were carried out at R-ratios of 0.1 and 0.5. The number n of intermittent baseline cycles between overloads was varied between 1000 and 20000. Crack closure was measured for some selected specimens applying conventional back face strain technique. Crack front profiles in the through-thickness direction, taken from sections perpendicular to the crack growth direction, were analyzed by light-micrographs.

Experimental Results

The microstructure of X-7075 consisted of fully recrystallized equiaxed grains, hardened by coherent η" precipitates (5). That of IN 905 XL was an elongated pancake like layered structure with alternating regions containing small dispersoids (oxides and carbides) resulting in small equiaxed grains with sizes of about 1μm and regions without dispersoids and therefore larger elongated grains (details can be found in (4)). The tensile properties of X-7075 and IN 905 XL are summarized in Table I. It should be noted that the yield stress of IN 905 XL seems to be mainly affected by the small grain size (4).

Table I. Tensile Properties

Alloy	Grain Size	$\sigma_{0.2}$ (MPa)	UTS (MPa)	σ_F (MPa)	TE (%)	ε_F
X-7075	CG	413	532	738	18	0.42
X-7075	FG	416	534	820	20	0.61
IN 905 XL*		365	460	525	8.7	0.15

* from Ref. (4)

The effects of a variation in the number n of intermittent baseline cycles on the crack propagation behavior for the coarse grained X-7075 alloy are shown in Fig. 1 for $R = 0.1$ and in Fig. 2 for $R = 0.5$. The results exhibited significant crack growth retardation with increasing numbers of n in comparison to constant amplitude loading at both R-ratios, except for $n = 1000$ at $R = 0.5$ where no effect was found (Fig. 2). Examples of corresponding crack front profiles at growth rates of about 10^{-9} m/cycle are summarized in Figs. 3 and 4 for R-ratios of 0.1 and 0.5, respectively. At $R = 0.1$ the profile roughness increased with increasing numbers of n in comparison to the constant amplitude profile, showing however more rounded off peaks and valleys. At $R = 0.5$ the profile for $n = 1000$ was fairly smooth (Fig. 4b), while at higher numbers of n (5000 and above) the profiles again became very tortuous (Fig. 4c).

Investigations of fracture surfaces in the ΔK regime corresponding to growth rates of about 10^{-9} m/cycle revealed always very rough fracture morphologies for those specimens which showed crack growth retardation under periodically applied overloads (Figs. 1 and 2) and concomitant rough profiles (Figs. 3 and 4). Crack propagation in these specimens occurred

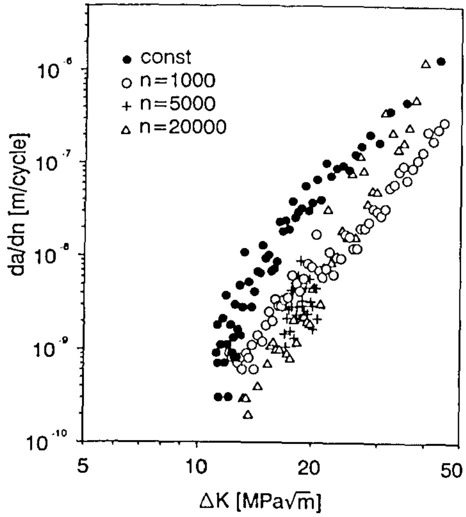


Fig. 1: X-7075, CG, R = 0.1 (3)

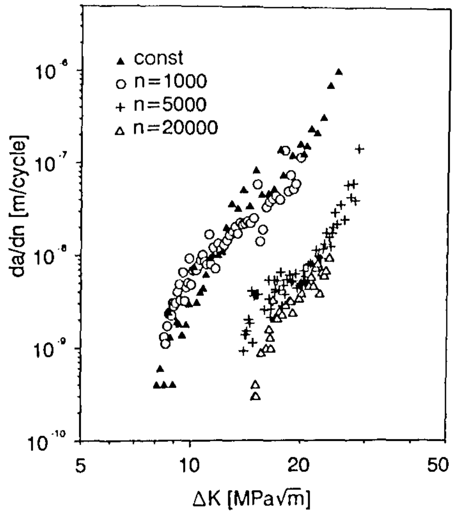


Fig. 2: X-7075, CG, R = 0.5 (3)

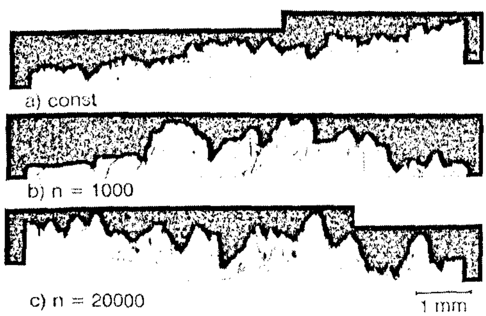


Fig. 3: X-7075, CG, Profiles, R = 0.1, da/dN ≈ 10^{-9} m/cycle (3)

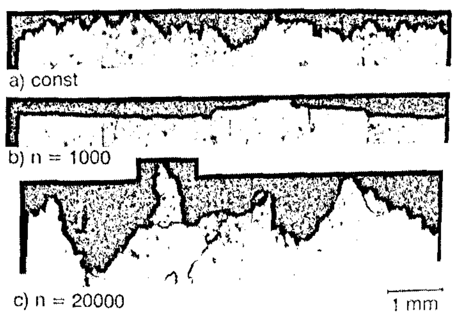
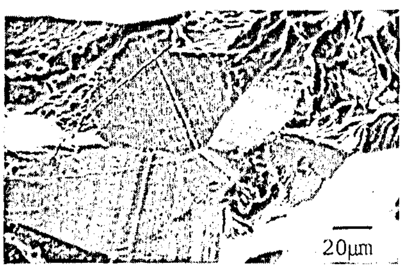
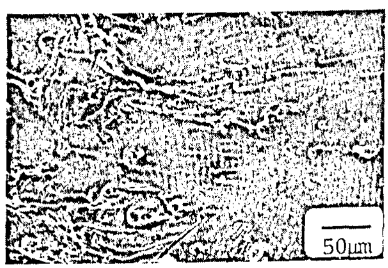


Fig. 4: X-7075, CG, Profiles, R = 0.5, da/dN ≈ 10^{-9} m/cycle (3)



a) R = 0.1, ΔK = 12.4 MPa·m$^{1/2}$

→ CPD



b) R = 0.5, ΔK = 10 MPa·m$^{1/2}$

Fig. 5: X-7075, CG, Fracture surfaces (SEM), n = 1000 (6)

mostly along pronounced slip bands under varying orientations from grain to grain (Fig. 5a). The grain in the upper part of Fig. 5a shows faint overload markers, indicating the significant deviation of the local growth direction with regard to the macroscopic propagation direction. By contrast, the fracture surfaces of specimens which showed no retardation effect (e.g. Fig. 2, $n = 1000$), together with smooth profiles (Fig. 4b), exhibited a very flat appearance (Fig. 5b). On these fracture surfaces the overload markings were always rather straight over many grains and nearly perpendicular to the macroscopic crack growth direction.

The effects of periodically applied overloads on the crack propagation behavior of the fine grained X-7075 alloy are shown in Figs. 6 and 7 for $R = 0.1$ and 0.5, respectively. The overall behavior was similar as found for the coarse grained alloy. However, at $R = 0.1$ the curve for $n = 1000$ showed crack acceleration in the low ΔK regime as compared to constant amplitude loading and retardation only at higher ΔK values (Fig. 6). At $R = 0.5$ the overload test with $n = 5000$ exhibited comparable growth rates in the low ΔK regime as found for constant amplitude loading while crack growth retardation was only observed at higher ΔK values (Fig. 7). In contrast, the coarse grained material exhibited crack growth retardation in both cases over the whole ΔK region (Figs. 1 and 2).

The corresponding crack front profiles for the fine grained X-7075 alloy were found to be very rough for overload tests which resulted in crack growth retardation, for example at $R = 0.1$ for $n = 5000$ and for $n = 20000$ (Fig. 8c), and at $R = 0.5$ for $n = 20000$ (Fig. 9c), while the profiles for lower numbers of n were fairly flat as compared to their respective constant amplitude counterparts (Fig. 8b and 9b). Fracture surface studies confirmed the findings of the coarse grained alloy, exhibiting a fairly smooth fracture morphology (Fig. 10a) for all loading conditions where no retardation was observed. The overload markers in Fig. 10a are again fairly straight over many grains and almost perpendicular to the macroscopic crack growth direction. At higher numbers of n the fracture surfaces became again very rough. It can be seen from Fig. 10b that the local crack fronts were severely bowed out, presumably because of pinning at a crystallographic unfavorably oriented grain (center of Fig. 10b). Along this ligament the crack was forced considerably out of the previous crack plane, resulting in local crack growth retardation, as can be seen from the more closely spaced overload markers in Fig. 10b.

The crack propagation results for the extremely fine grained IN 905 XL are summarized in Figs. 11 and 12 at R-ratios of 0.1 and 0.5, respectively. Besides considerably increased growth rates in comparison to X-7075, this alloy revealed almost no retardation effects for periodically applied overloads, regardless of R-ratio. It should be noted that the measured data points from overload tests with n-values of 1000 were omitted since they overlapped with the constant amplitude curves. A comparison of the curves for $R = 0.1$ and 0.5 exhibited almost no effect with regard to a variation in R-ratio (Figs. 11 and 12). The corresponding crack front profiles of IN 905 XL were almost perfectly flat for constant amplitude as well as for periodically applied overload tests (Fig. 13). Fracture surface studies revealed very smooth and regularly spaced overload markers over the whole fracture surface of each specimen, as can be seen in Fig. 14.

Compliance measurements at $R = 0.5$ did not show any indications of crack closure for the coarse or fine grained X-7075 or for IN 905 XL, neither under constant amplitude nor under periodically applied overload testing. At $R = 0.1$ also no closure was observed for IN 905 XL, while small amounts of closure were found for X-7075. For example, the coarse grained X-7075 tested with $n = 5000$ intermittent baseline cycles, which showed crack growth retardation (Fig. 1), exhibited a K_{cl}/K_{max} ratio of 0.17 at ΔK of 17.7 $MPa \cdot m^{1/2}$. Correcting this ΔK-value for closure resulted in an effective ΔK of 16.3 $MPa \cdot m^{1/2}$ which is still far higher than even the concomitant uncorrected constant amplitude ΔK-value of about 13 $MPa \cdot m^{1/2}$ (Fig. 1).

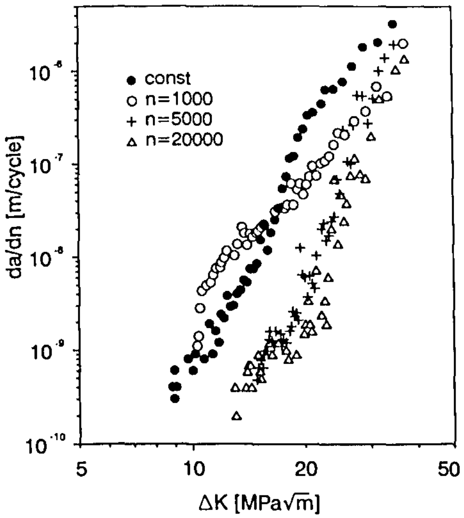


Fig. 6: X-7075, FG, R = 0.1 (3)

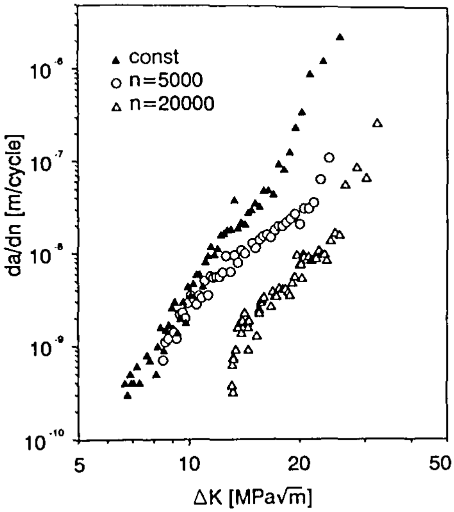


Fig. 7: X-7075, FG, R = 0.5 (6)

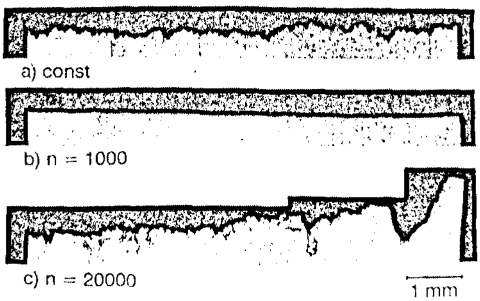


Fig. 8: X-7075, FG, Profiles, R = 0.1, da/dN ≈ 10^{-9} m/cycle (3)

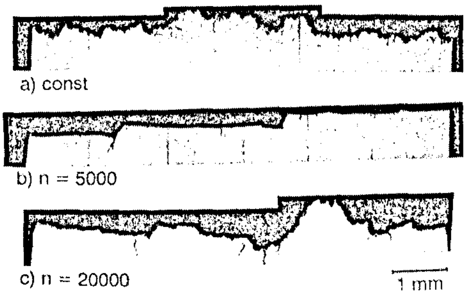
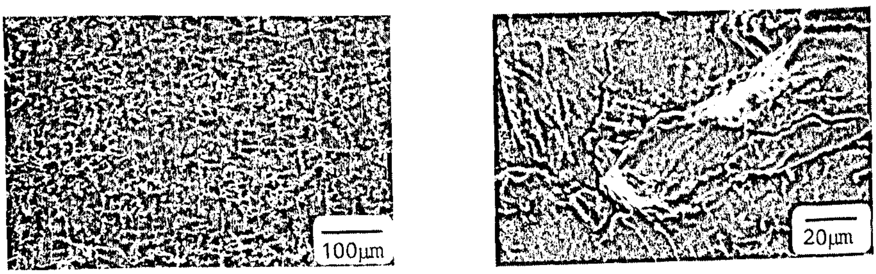


Fig. 9: X-7075, FG, Profiles, R = 0.5, da/dN ≈ 10^{-9} m/cycle (6)



a) n = 1000 b) n = 5000

Fig. 10: X-7075, FG, R = 0.1, Fracture surfaces (SEM), ΔK = 16 MPa·$m^{1/2}$ (6)

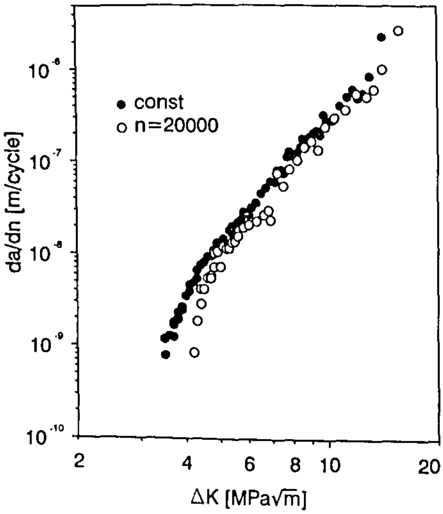


Fig. 11: IN 905 XL, R = 0.1

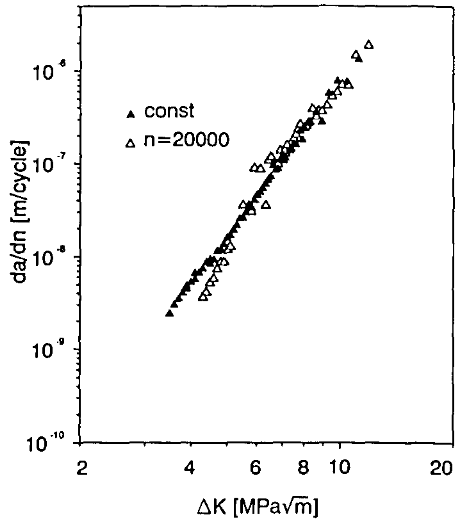


Fig. 12: IN 905 XL, R = 0.5

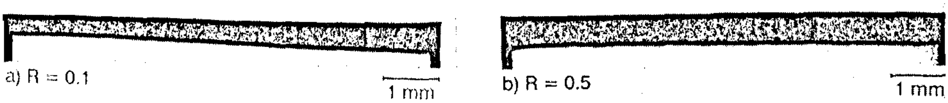
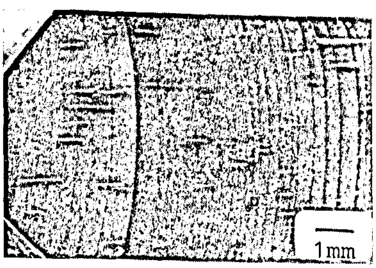
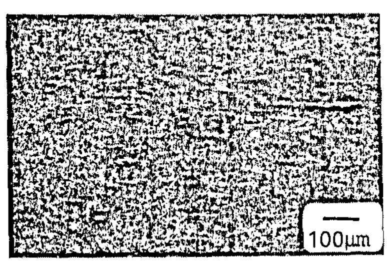


Fig. 13: IN 905 XL, Crack front profiles (LM), n = 20000, da/dN ≈ $4 \cdot 10^{-9}$ m/cycle



a) Overview



b) Higher magnification of a)

Fig. 14: IN 905 XL, Fracture surface (SEM), R = 0.1, n = 20000

Discussion

The fatigue crack growth behavior is mainly influenced by the following three parameters (7): fracture properties (e.g. ductility), crack front geometry, and roughness induced crack closure. Since at R = 0.5 no closure was observed and since the crack growth behavior at low and high R-ratios for each alloy was qualitatively similar, crack closure variations cannot account for the observed crack growth variations as a function of intermittent baseline cycles. It is thought therefore that the observed variations in crack growth behavior are mainly influenced by the different crack front profiles. It is known from constant amplitude as well as from periodically applied tensile overload tests that smooth crack front geometries contribute to higher propagation rates in comparison to rough crack front profiles (3,4,7). However, it is anticipated that other parameters, such as for example differences in mean stresses or in residual compressive stresses at the crack tip (1), might also contribute to the observed variations in crack propagation behavior.

The results for the coarse and the fine grained X-7075 showed considerable crack growth retardation with increasing numbers n of intermittent baseline cycles as compared to constant amplitude loading at both R-ratios (Figs. 1,2,6,7), together with increasingly rough crack front profiles (Figs. 3,4,8,9). For lower numbers of n either no effect on crack growth rates was observed (Figs. 2,7) or even crack acceleration (Fig. 6) together with significantly smoother crack front profiles (Figs. 4b,8b,9b) as compared to constant amplitude tests. These flat crack front profiles seem to be a result of the frequently applied overloads, which can activate a high number of different slip systems ahead of the crack tip, thus allowing the overall crack front to maintain a very smooth configuration with only minor deviations out of the main crack plane. Increasing the number of intermittent baseline cycles between consecutive overloads would permit the local crack segments within individual grains to propagate over longer distances along previously activated slip systems out of the main crack plane into less strain hardened regions. This would explain the pronounced rough profiles (e.g. Fig. 3c), the significant deviations of the local crack growth direction with regard to the main growth direction (Fig. 5a), and the heavily bowed out overload markers (Fig. 10b). The concomitant lower growth rates (e.g. Fig. 2) are thought to result from unfractured grains between more favorably oriented grains. These unfractured ligaments seem to be effective barriers against propagation of the main crack front.

The occurrence of flat crack front profiles was found to depend on R-ratio. At the high R-ratio flat profiles occurred at lower numbers of n (compare Figs. 3 and 4) probably due to the high overload stresses at R = 0.5, which is thought to activate additional less favorably oriented slip systems in comparison to tests at the lower R-ratio. This would explain the absence of crack growth retardation at the high R-ratio for the coarse grained X-7075 at n = 1000 (Fig. 2). In addition, it was observed that flat crack front profiles extended to higher numbers of n at the high R-ratio (Fig. 9b) in accordance with the observed coinciding crack propagation rates between constant amplitude and periodically applied overload tests up to n-values of 5000 (Fig. 7), presumably also due to the higher stresses at the higher R-ratio.

With decreasing grain size the crack growth rates increased for constant amplitude as well as for overload tests at both R-ratios (e.g. Figs. 1,6,11), and the concomitant crack front profiles became less tortuous (e.g. Figs. 3c,8c,13a). The decreasing profile roughness seems to be due to the decreasing length for propagating local crack segments out of the main crack plane because of the grain size reduction. Thus for the extremely fine grained IN 905 XL completely flat crack front profiles were observed for constant amplitude as well as for overload tests (Fig. 13), and therefore no retardation behavior was found, regardless of R-ratio (Figs. 11 and 12).

Conclusions

1. An increased crack front profile tortuousity with increasing numbers of intermittent baseline cycles between overloads seems to be mainly responsible for the observed crack propagation retardation behavior of the coarse and the fine grained X-7075 alloy at low and high R-ratios as compared to the respective constant amplitude tests.

2. Crack closure variations cannot explain the observed crack propagation behavior under periodically applied overloads since at $R = 0.5$ no closure could be detected and since the crack growth behavior for each alloy was quantitatively similar at low and high R-ratios.

3. With decreasing grain size the decreasing crack front tortuousity seems to contribute to the concomitant decreasing amount of retardation with increasing numbers of intermittent baseline cycles between oberloads. Thus for the extremely fine grained IN 905 XL alloy no crack growth retardation was observed with increasing numbers of n which is thought to result from the completely smooth crack front profiles found for this alloy for constant amplitude as well as for periodically applied overload tests.

4. The present results support the importance of crack front profile variations by explaining the propagation behavior under periodically applied overloads.

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