



Fatigue crack growth with overloads/underloads: Interaction effects and surface roughness

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ABSTRACT

The generalization of damage tolerance to variable amplitude fatigue is of prime importance in order to maintain the reliability of structures and mechanical components subjected to severe loading conditions. Engineering spectra usually contain overloads and underloads which distribution may not be random. However for predicting the life of a structure, a simplified spectrum is usually determined from the real one, in order to reduce testing periods on prototypes. Therefore it is thus important to know which cycles can contribute to crack growth and which can be neglected. This paper presents an analysis of fatigue crack growth on $M(T)$ specimens made of a medium carbon steel DIN Ck45. The specimens are subjected to repeated blocks of cycles made up of one or several (1, 2, 6 or 10) overloads (or underloads) separated by a variable number (10, 1000 or 10000) of baseline cycles. The main objective of this study is to better understand the mechanisms at the origin of interactions effects due to the presence of overloads (or underloads) at different locations of each block loading. Under constant amplitude loading, single variables ΔK and K_{\max} are required in crack growth relationships. The transferability of fatigue laws, obtained under constant amplitude loading to variable amplitude fatigue, requires at least an additional variable, whose evolution with crack length accounts for the interactions effects between cycles of different types. Results have shown that the interaction effects in fatigue crack growth are closely related to the mechanisms of crack growth: cyclic plastic behaviour of the material and fracture surface roughness. Measurements of roughness of the surface fracture were carried out in both constant amplitude and variable amplitude tests. The roughness characterization helped to determine the importance of the mechanisms on variable amplitude fatigue crack growth and determine the influence of overloads/underloads on fatigue crack growth.

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1. Introduction

Fatigue crack growth has been widely studied, since it plays an important role on the damage tolerance analysis of mechanical components and structures. The generalization of damage tolerance to variable amplitude fatigue is of prime importance in order to maintain the reliability of structures and mechanical components subjected to severe loading conditions. Engineering spectra usually contain overloads and underloads which distribution may not be random. However for predicting the life of a structure, a simplified spectrum is usually obtained from the real one, in order to reduce testing periods on prototypes. Therefore it is thus important to know which cycles can contribute to crack growth and which can be neglected. There are various methods for counting

cycles, which usually do not take into account the order of application of cycles within the loading spectrum. However, it is well known that there is a strong interaction between cycles displaying different amplitudes in fatigue crack growth. This effect is known as the overload effect [1].

Damage tolerance is based on fracture mechanics. With that concept, under constant amplitude loading, a single variable ΔK and a K_{\max} are required for the crack growth relationships. The common practice is to determine the effective stress intensity factor ($\Delta K_{\text{eff}} = K_{\max} - K_{\text{op}}$) during experiments or numerical calculations [2–4] performed at constant amplitude loading and to transfer the results to variable amplitude fatigue, cycle by cycle, without taking into account the interaction effects between the different cycles of a fatigue spectrum [5]. The interactions between cycles (overloads for example) are well known to modify significantly the fatigue life of a sample and attempts have been done to take into account such interactions [6,7]. However, they remain of limited use because of the strong dependence of these effects on

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Nomenclature

a	crack length	OL	overload
B	specimen thickness	p_i	peak height roughness
C	fatigue crack growth constant	P_{\max}	maximum load
ΔK	stress intensity factor range	P_{\min}	minimum load
ΔK_{eff}	effective stress intensity factor range	R	stress ratio
ΔP	load range	R_a	average deviation roughness
K_{\max}	maximum stress intensity factor	RBL	baseline stress ratio
K_{\min}	minimum stress intensity factor	ROL	overload stress ratio
K_{op}	opening stress intensity factor	RUL	underload stress ratio
K_{pic}	maximum stress intensity factor on overload	R_z	mean peak to valley roughness
m	Paris' equation exponent	v_i	valley height roughness
$M(T)$	middle crack tension specimen	UL	underload
N	number of cycles	W	specimen width

the material and loading conditions. Recent studies [8,9] using FEM analyses have shown that two features of the cyclic behaviour of a material are of key importance for this kind of problems, namely the Bauschinger effect and the cyclic hardening or softening capabilities of the material. The results presented in [7,10] show that the presence of consecutive overloads significantly increases the retardation effects in crack growth and that this retardation effect is smaller if the number of baseline cycles between the overloads is reduced.

The main objective of this study is to understand the mechanisms at the origin of interactions effects due to the presence of overloads (or underloads) at different locations of the block loading. A series of crack growth tests composed of baseline cycles and overloads/underloads cycles located at different time on the variable amplitude loading. The aim of this study is to observe and measure the effects governing the fatigue crack growth of the normalized DIN Ck45 steel under constant and variable amplitude loading and with different R -ratios in the Paris regime. Special emphasis is given to the effects of stress ratio on crack growth either on the baseline cycles or on the overloads/underloads including negative stress ratios. The different crack growth data obtained for the used spectra are then correlated with the surface fracture roughness. A strong effect of the stress ratio on roughness is observed for crack growth under constant amplitude loading but this remains much less pronounced for crack growth obtained in variable amplitude loading either with positive or negative stress ratio baselines.

2. Material and experimental procedures

The material tested is a normalized medium carbon steel, DIN Ck45. The chemical composition is presented in Table 1, and mechanical properties are: $\sigma_{\text{ys}} = 350$ MPa; $\sigma_{\text{u}} = 600$ MPa; $A(\%) = 25$.

Tests were carried out with a servo hydraulic testing machine (100 kN Instron) at 10 Hz frequency under load control mode at different R -ratios. The specimens used are middle-crack tension ($M(T)$ type) 10 mm thick and 60 mm width according to the Standard ASTM E 647. The central notch was 6 mm long and 0.25 mm width, made by electrical-discharge machining in order to reduce the residual compressive stresses as a consequence of milling pro-

cess. Fatigue precracking was conducted till the crack length was approximately 10 mm long. Crack growth measurements were performed with an optical microscope. The direction of loading was parallel to the rolling direction but due to the normalizing annealing condition of the steel, the grain size is similar on both directions. Temperature of laboratory ambient air was about 22 °C and relative humidity 50–60%.

The specimens were subjected to two different types of loading: first series of tests were under constant amplitude loading for a wide range of stress ratios from $0.7 > R > -3$, in the Paris regime; on the second series of tests, repeated blocks of cycles with baseline cycles and overloads/underloads. Two different baseline cycles, RBL = 0.1 and RBL = -1 were used: for both baseline stress ratio, overloads of $K_{\text{pic}} = 1.5 K_{\max}$ at ROL = 0.067 and underloads at $R = -2$ or $R = -3$ were applied. The number of baseline cycles between overloads or underloads is set to be 1000 (1k cycles) or 10 000 (10k cycles). The number of overloads (OL) and underloads (UL) consecutively applied were 1 or 6. Therefore, the specimens are subjected to repeated blocks of cycles made up of one to six overloads or underloads separated by a variable number of baseline cycles, from one thousand to ten thousand. For a better analysis of the testing programme, Table 2 and 3 show the complete series of experimental tests respectively for baseline cycles with $R = 0.1$ and $R = -1$. All tests were performed using adequate software of machine control, and Fig. 1 shows a typical result of the control imposed to the servohydraulic machine on variable amplitude tests.

For each testing condition, crack length was measured on both sides of the specimen using an optical device, and load/COD cycles were recorded continuously when overloads or underloads were applied and at regular intervals when baseline cycles are applied. The load/COD was measured at the centreline of the specimen,

Table 2
Loading with baseline cycles $R = 0.1$.

Load spectrum	Number of baseline (k cycles)	Number of OL/UL	Stress ratio ROL/RUL	Baseline (BL) [kN]	OL/UL [kN]
OL	1	1	0.067	+60/+6	+90
	10	1	0.067	+60/+6	+90
	1	6	0.067	+60/+6	+90
	10	6	0.067	+60/+6	+90
UL	1	1	-2	+40/+4	-80
	10	1	-2	+40/+4	-80
	1	6	-2	+40/+4	-80
	10	6	-2	+40/+4	-80
UL	1	1	-3	+30/+3	-90
	10	1	-3	+30/+3	-90
	1	6	-3	+30/+3	-90
	10	6	-3	+30/+3	-90

Table 1
Chemical composition of DIN Ck45 steel (%).

C	Mn	Al	Si	P	S
0.45	0.71	0.01	0.01	0.01	0.02

Table 3
Loading with baseline cycles $R = -1$.

Load spectrum	Number of baseline [k cycles]	Number of OL/UL	Stress ratio ROL/RUL	Baseline (BL) [kN]	OL/ UL [kN]
OL	1	6	0.067	+60/−60	+90
	10	6	0.067	+60/−60	+90
UL	1	6	−2	+40/−40	−80
	10	6	−2	+40/−40	−80
	1	6	−3	+30/−30	−90
	10	6	−3	+30/−30	−90

using a standard clip gage device, in order to determine the crack opening level. Load/COD data were acquired using 500 data pair of points (250 for loading and 250 for unloading) for all loading cases. Several methods have been proposed for the determination of the opening load and a procedure is recommended in ASTM E647-99. This procedure uses the compliance offset method but due to the presence of a high variability on the data, alternative methods have been used to determine the opening load. Crack opening loads were also calculated through a modified reduced differential compliance technique in order to establish clearly the crack opening levels [7]. Both the methods presented similar trends of the data. The compliance offset is drastically reduced after the application of the overloads. For the first cycle after the application of six overloads, the compliance offset is close to zero at almost the load range and only 10 000 cycles after the application of the overloads, the crack opening load is of the same level as before the application of the overloads. A detailed analysis of this procedure is available in Ref. [7].

The fatigue crack surface roughness was measured through a high-resolution LASER roughness-meter equipment (Perthometer) according to ISO 4287. The surface roughness was analyzed mapping the readings to the fatigue crack propagation direction. The roughness readings were performed for each specimen at the centre of the fracture surface. A previous study was performed with three measurements, respectively at the centre of the specimens and at both sides of the fracture surface (at 1 mm of the lateral sur-

face) but since similar results were achieved only the results at the centre of the fracture surface will be discussed.

For a standard spectrum of roughness, Fig. 2a and b shows the profile roughness measurement values, respectively for R_a (a) and R_z (b) [11]. The parameter R_a is the average deviation at the profile from the mean line in laymen's terms, being the average distance of the profile to the mean line across the length of assessment, seen in Fig. 2a. R_z is the mean peak-to valley height, with p_1, p_2 , etc., being the maximum peak-to-valley heights. These are determined within each cut-off length as shown in Fig. 2b, where five peak-to-valley heights are shown. The R_a and R_z parameters are obtained by the following equation:

$$R_a = \frac{1}{l_m} \int_0^{l_m} |y(x)| dx \tag{1}$$

$$R_z = \frac{1}{5} \left(\sum_{i=1}^5 p_i + \sum_{i=1}^5 v_i \right) \tag{2}$$

The comparison of the R_a and R_z parameters, defined above, for the fracture surfaces obtained at constant amplitude fatigue crack growth tests in vacuum and laboratory air, presented in a previous work [11] clearly shows that the R_z parameter is much more sensitive than the traditional parameter R_a .

3. Experimental results and discussion

Fatigue crack propagation rates (da/dN) vs. ΔK , or K_{max} , are obtained according to ASTM E-647:

$$\begin{aligned} \Delta P &= P_{max} - P_{min} \quad \text{for } R > 0 \\ \Delta P &= P_{max} \quad \text{for } R \leq 0 \end{aligned} \tag{3}$$

The Paris equation is given by:

$$\frac{da}{dN} = C(\Delta K)^m \tag{4}$$

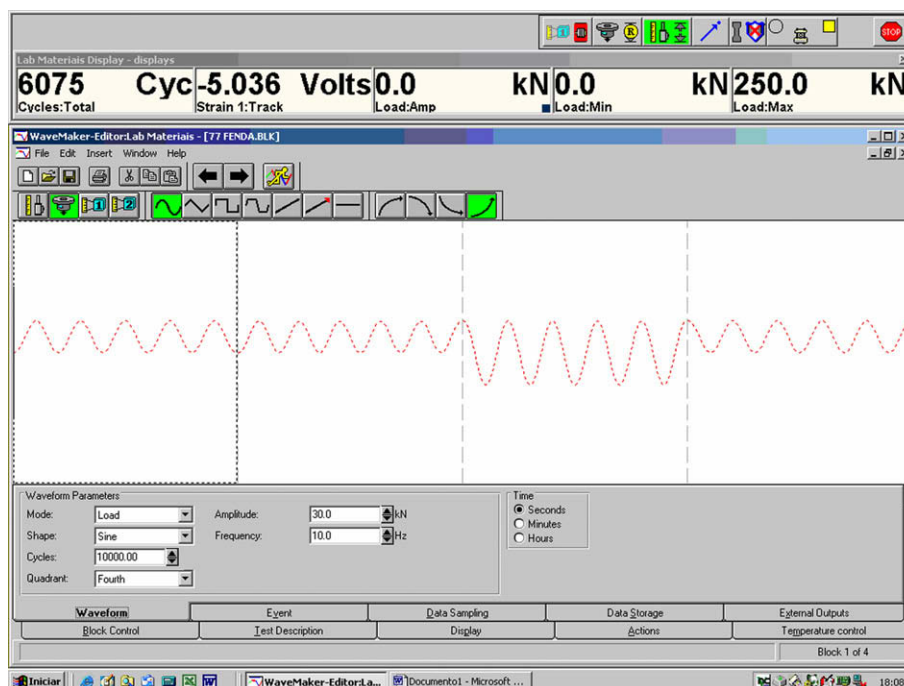


Fig. 1. Loading programme sequence.

where C and m are material constants and ΔK calculation for $M(T)$ specimens is performed according to the following equation, referred on ASTM E-647:

$$\Delta K = \frac{\Delta P}{B} \sqrt{\frac{\pi \alpha}{2W} \sec \frac{\pi \alpha}{2}} \quad (5)$$

where $\alpha = 2a/W$; W is the width and B the thickness of the specimen.

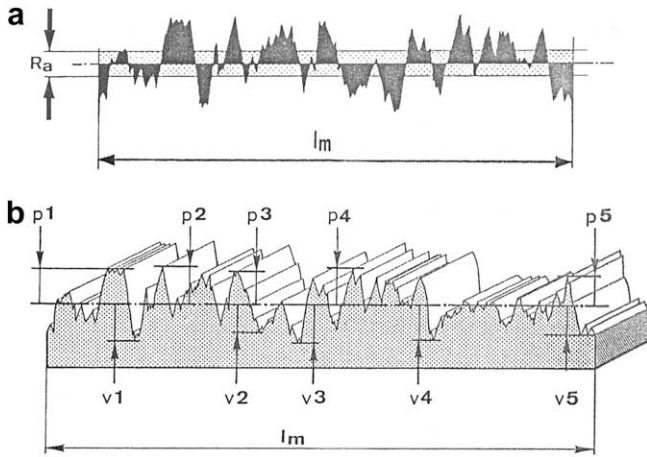


Fig. 2. Roughness spectrum from the points where (a) R_a and (b) R_z are obtained.

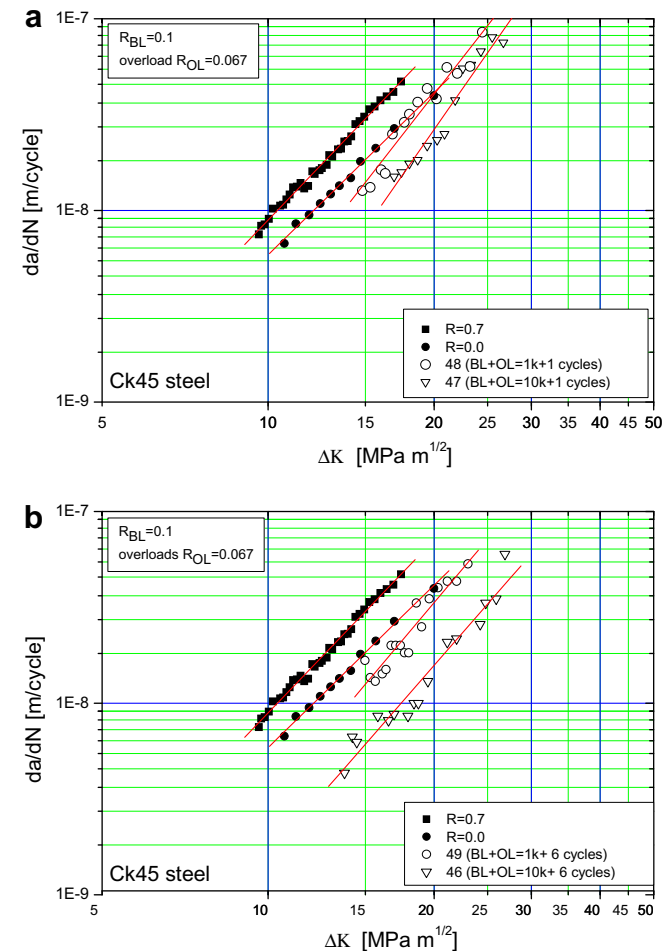


Fig. 3. Crack growth with $R_{BL}=0.1$ and overloads at stress ratio $R=0.067$ (a) one overload; (b) six overloads.

The results of fatigue crack growth tests are presented in Figs. 3 to 6. In all figures together with variable amplitude loading are also shown, for comparison purposes, constant amplitude loading results for $R=0.1$ or $R=-1$ (the same stress ratio as the baseline cycles) and $R=0.7$, the stress ratio considered for which the crack grows under closure free conditions.

Fig. 3 shows the crack growth results determined for baseline stress ratio of $R_{BL}=0.1$, two different number of baseline cycles (1000 or 10 000) and two different number of overload cycles, respectively 1 or 6, for Fig. 3a and b. The results show a significant increase of retardation effect on crack growth when 6 repeated overloads are applied.

Fig. 4 shows the crack growth results determined for baseline stress ratio of $R_{BL}=0.1$, two different number of baseline cycles (1000 or 10 000) two different number of underload cycles at $R=-3$, respectively 1 or 6, for Fig. 4a and b. The results show that a retardation effect is no more present and this effect is less influenced by the number of underloads.

One can also compare the crack growth results obtained with the effect of overloads with different baseline cycles, as shown on Fig. 5, respectively for $R_{BL}=0.1$ and $R_{BL}=-1$ on Fig. 5a and b. The retardation effect also disappears for overloads when the baseline stress ratio is fixed on $R=-1$.

If we compare now the crack growth results obtained for the two different baseline cycles, but using now underloads at stress ratio $R=-2$, as shown in Fig. 6, it is obvious that the retardation effect is observed now at the negative stress ratio baseline cycles. Similar results were obtained for underloads with $R=-3$.

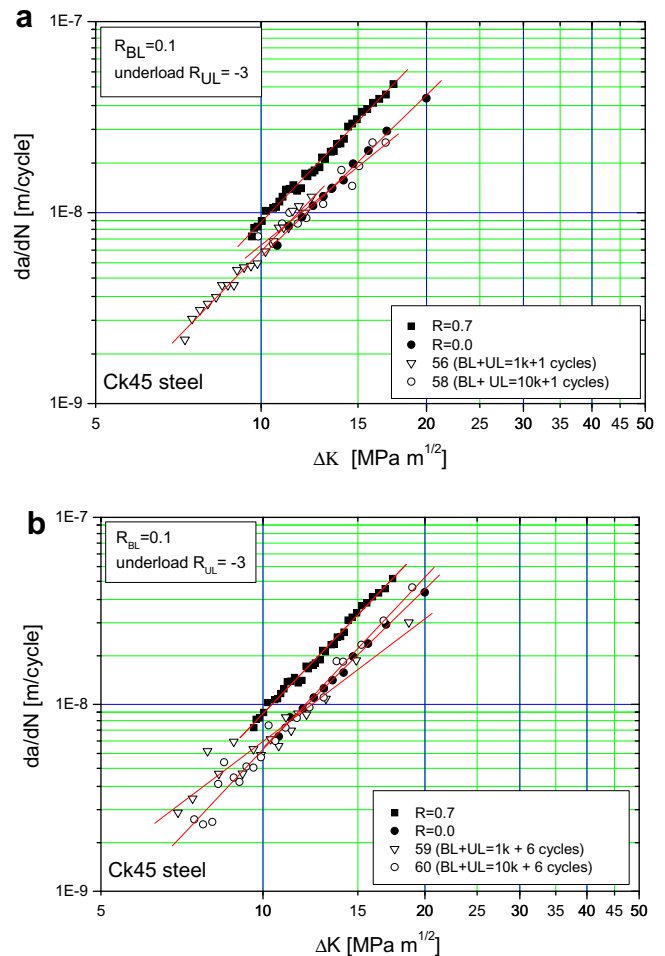


Fig. 4. Crack growth with $R_{BL}=0.1$ and underloads at stress ratio $R=-3$ (a) one underload; (b) six underloads.

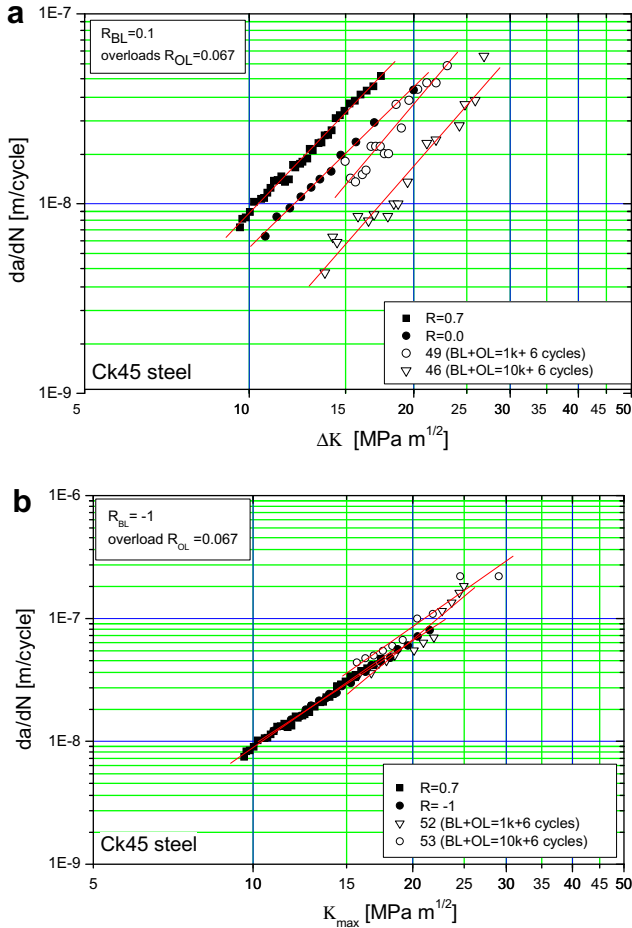


Fig. 5. Crack growth for 6 overloads on different baseline stress ratio (a) Baseline cycles $R=0.1$; (b) Baseline cycles $R=-1$.

Therefore, all results show a significant influence of the baseline stress ratio on the fatigue crack growth rates depending of the type of the overloads or underloads. An interaction effect is therefore observed and can be measured through the retardation or acceleration effects on crack growth rates. It was found [10] that the retarding effect is maximum for a given number of overloads, which depends on the cyclic plastic behaviour of the material and in particular on its Bauschinger effect. This confirms that interaction between different cycles within a spectrum is of key importance for the prediction of fatigue lives.

Crack tip blunting occurs at the crack tip, when an overload or an underload is applied, and this effect corresponds to a significant extension of the crack tip plastic zone size. The reason for an extension of the plastic zone due to an underload or to multiple overloads is similar, and corresponds to a transient phase of adaptation of the fatigue cycle at the crack tip after underloads or overloads. Before the application of an overload or an underload, the stress state and the hardening state are stationary at the crack tip and adapted to baseline cycles. In this stationary state, if the material displays the Bauschinger effect, the centre of the elastic domain is displaced toward positive stresses within the crack tip plastic zone. Therefore, if an underload is applied, the yield stress in compression being small, a large amount of reverse plasticity occurs. Consequently, and according to the Bauschinger effect of the material, the elastic domain of the material is displaced toward negative stresses, which allow crack tip blunting during subsequent baseline cycles and the displacement of the centre of the elastic domain toward positive stresses. The effect is reinforced if a higher number of underloads are applied. This displacement of

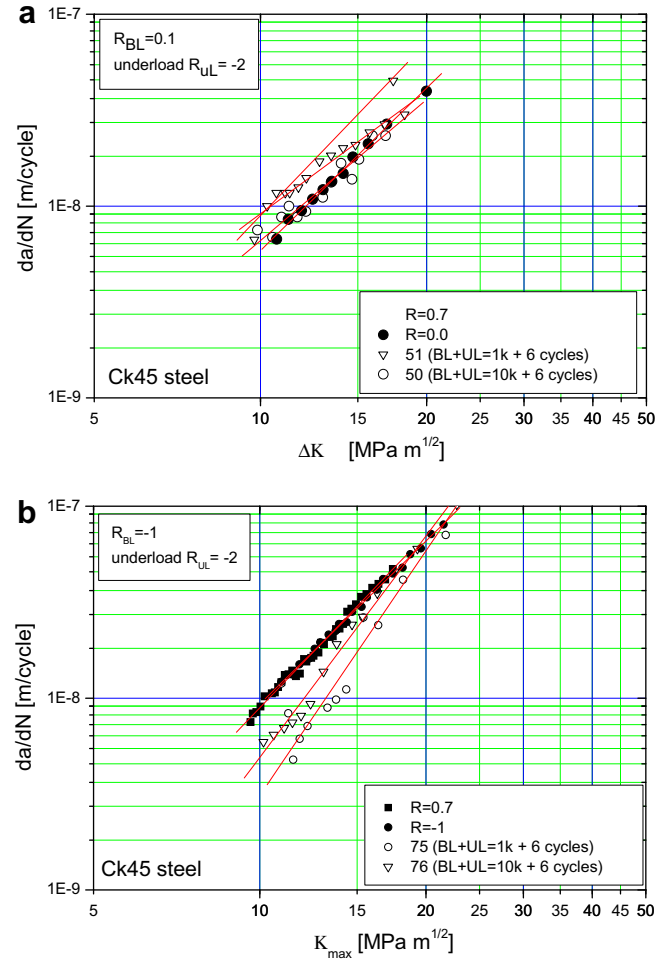


Fig. 6. Crack growth with 6 underloads at stress ratio $R_{UL} = -2$ (a) Baselines Cycles $R=0.1$; (b) Baseline cycles $R=-1$.

the centre of the elastic domain toward positive stresses results in a reduction of compressive residual stresses at crack tip and consequently to the reduction of K_{op} [10].

Roughness measurements were carried out for all the fracture surfaces. Figs. 7 and 8 show the comparison of roughness R_z parameter, defined above, for the fracture surfaces obtained at fatigue crack growth tests in constant or variable amplitude loading, respectively. On roughness analysis a constant crack length of 5 mm was chosen for all specimens, from 2.5 mm to 7.5 mm of crack growth, therefore the same R_z parameters can be compared. For constant amplitude load with the negative stress ratios $R = -1$

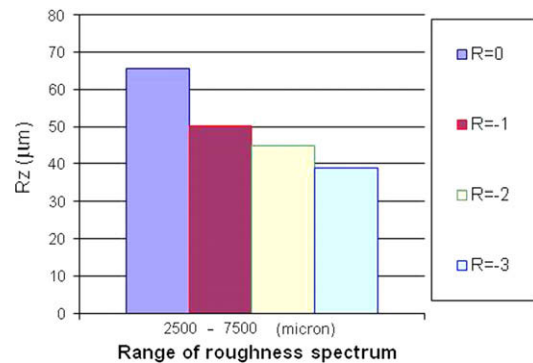


Fig. 7. Influence of $R < 0$ on fracture roughness, constant amplitude loading

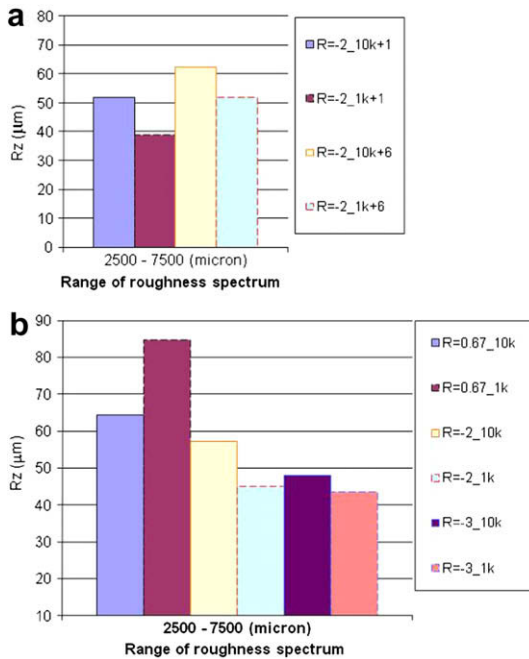


Fig. 8. Roughness under variable amplitude (a) Baseline cycles $R = 0.1$; (b) Baseline cycles $R = -1$.

to $R = -3$, shown in Fig. 7 the parameter R_z shows a significant decrease of the roughness R_a of the fracture surface due to the influence of compression loading cycles, which is consistent with results presented before [11]. The same roughness measurements were carried out for variable amplitude loading and results are shown in Fig. 8, displaying in Fig. 8a the results for baseline cycles $R = 0.1$ and Fig. 8b for baseline cycles $R = -1$. It is shown in Fig. 8a that the influence of the number of underloads is not meaningful for the R_z roughness nor the number of baseline cycles between them. In Fig. 8b it is observed a much smaller effect of compressive underloads than of overloads. This means that one of the effects of variable amplitude loading is to uniform the roughness when it is measured over a significant crack growth length. Different results may be verified when local roughness measurements are made but this study is being carried out.

4. Conclusions

Fatigue crack growth tests under loading blocks for two different baseline cycles ($RBL = 0.1$ and $RBL = -1$), composed of single

or multiple overloads or single or multiple underloads showed that:

- (1) Fatigue crack growth rate show that significant retardation effects are obtained for positive baseline stress ratios with overloads and this effect is increased with the number of consecutive overloads and with the number of baseline cycles between overloads, but this retardation effect disappears when underloads are applied.
- (2) For negative baseline stress ratios there is no evidence of retardation in fatigue crack growth rates with either single or multiple overloads, but for this baseline cycles and single or multiple underloads, the retardation effect is observed.
- (3) This confirms that interaction between different cycles within a spectrum is of key importance for the prediction of fatigue lives.
- (4) A significant effect of the stress ratio on the roughness of fracture surfaces was observed, with less roughness being measured with negative stress ratio but this effect is negligible for crack growth under variable amplitude loading.

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