EFFECT OF UNDERLOAD APPLIED AFTER AN OVERLOAD ON FATIGUE CRACK PROPAGATION FOR 12NC6 STEEL

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Abstract. Overloads and underloads perturb steady state fatigue crack growth conditions and affect the growth rates by retarding or accelerating the growth. Clear understanding of these transient effects is important for the reliable life prediction of a component subjected to random loads. We can imagine that a random loading has a mean stress on a mean magnitude which can be used to determinate the baseline fatigue crack growth rate. The main objective of this research is to analyse the underload effect in fatigue crack propagation after an overload cycle.

Keywords: fatigue crack propagation; overload-underload; retardation.

1. INTRODUCTION

Crack growth in structures is a function of the amplitude, stress ratio, frequency and random nature of the load. A major influencing parameter to be considered is the influence of load history, which is usually variable.

The overloads of low intensity, whose rate does not exceed 10%, cause an insignificant retard [2]. The more intense overloads produce a static tear in the middle of the sample. The crack then remains blocked on the surface and in the middle by the important plastic deformation and the residual compressive stresses which appear. The amount of retardation depends on the material and the loading factors.

Despite many engineering components being subjected to load spectra containing tensile or compressive underloads and in comparison with the number of investigations of the effect of overloads, there is relatively little research about their influence on fatigue crack growth rates.

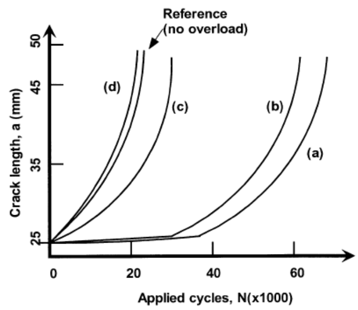


Fig.1. Crack growth behaviour for (a) overload, (b) underload – overload, (c) overload – underload and (d) underload [4]

Some recent researches of compressive loading found that it is incorrect to ignore compressive load, as they do contribute to crack growth rate [4, 5]. It is observed that even tensile underloads cause acceleration of the following constant amplitude loading, reducing the fatigue life [1].

Combined overload-underload has mixed effects, depending on the sequence. Taheri et coll [4] considered that the three load sequences, which have a significant effect on the fatigue crack growth rate, are a tensile overload, a compressive underload and a tensile followed by a compressive, which are commonly referred to as crack retardation, crack acceleration and reduction in crack retardation, respectively.

The increase of the overload amplitude τ_{ol} decreases the crack growth propagation and increases the number of cycles of delay, therefore the lifetime of the structure.

On the influence of the underload amplitude τ_{ul}, there are relatively little researches and for a negative R ratio it is considered that underload has little or no effect on the fatigue crack propagation [3].

This work is devoted to the study of fatigue crack propagation after an overload-underload sequence in order to estimate the effect on the crack growth rate and on the fatigue lifetime for cracked components under variable loading.

2. MATERIAL AND TESTING CONDITIONS

2.1 Material

The material used for the tests was a Chrome Nickel steel 12NC6. This steel is usually used for shafts and gears. The specimens used for the fatigue crack propagation study were compact tension (CT) specimens. Their dimensions (Fig. 2) are in agreement with the ASTM E647_88a normalisation.

Two heat treatments were used in order to obtain different mechanical behaviours. Each treatment begins with an austenitization at 880°C during one hour then:

- a quenching with water followed by tempering to 500 °C. Treatment named QT500,
- a cooling with air. Treatment named NA (normalizing in the air),

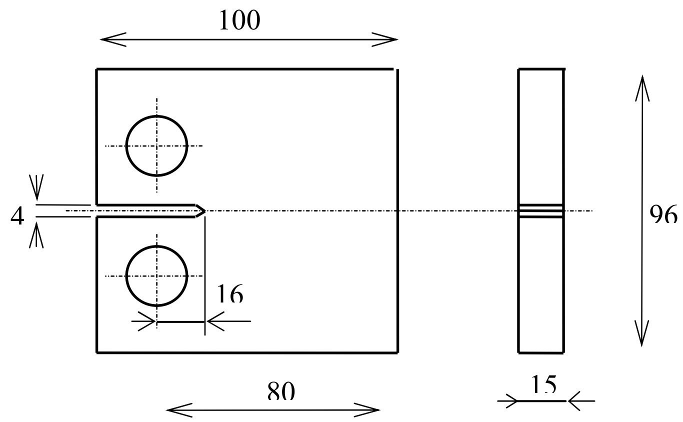


Fig. 2. Geometry of the samples (in mm)

The mechanical characteristics of 12NC6 steel are displayed in table Table 1.

Table 1. Mechanical characteristics of 12NC6 steel.

Heat treatment	$\sigma_{y\,0.2\%}$ (MPa)	σ_{ult} (MPa)	E (GPa)	Z (%)	A (%)	K (MPa)	n	$Hv_{(20)}$
QT500	900	911	216	64	16	495	0.53	275
NA	330	710	208	62	21	1017	0.41	195

2.2 Testing conditions

Crack tests (constant amplitude and overload/underload) were carried out using a servo hydraulic machine INSTRON 8500 which maximum capacity is ± 100 kN and maximum frequency is 50 Hz.

These tests were performed at room temperature. The test frequency was 30 Hz. The measurement of crack propagation length was executed on the front side of the specimen using binocular magnifying glass (20 x) set on a micrometrical table (50 mm stroke, 0.05 mm accuracy). On the reversed side, a camera visualized the specimen and enabled the operator to monitor the crack growth. A stroboscopic lamp set up on the fatigue test frequency allowed the measurement of the crack length during all the fatigue crack propagation tests.

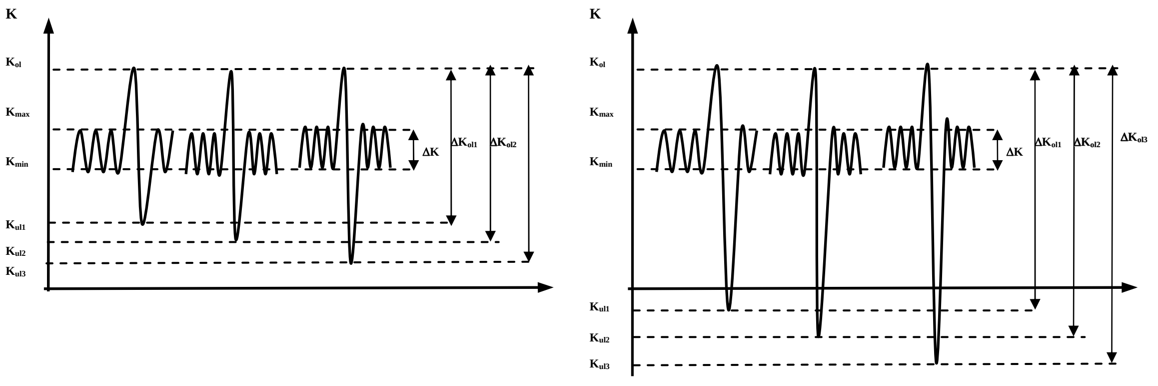
2.3 Loading conditions

The loading conditions of the experiments are presented in Table 2 and loading history is presented in Fig. 3.

Table 2. Loading conditions

Heat treatment	ΔK [MPa√m]	R	K_{max} [MPa√m]	K_{min} [MPa√m]	K_{ol} [MPa√m]	R_{ol}	K_{ul} [MPa√m]
QT500	21,6	0,28	30	8,4	60	2	K_{min} = 8,4
							6
							4
							2
							-1
							-4
							-7
NA	23,4	0,28	32,5	9,1	65	2	K_{min} = 9,1
							6
							4
							2
							-1
							-4
							-7

In order to observe the underload accelerating effect, for each heat treatment we have chosen the same overload magnitude followed by three different underload rate positive and three different underload rate negative as in Fig. 3.



a) **b)**

Fig. 3. Loading history

a) K_{ul} positive and b) K_{ul} negative

3. RESULTS AND DISCUSSION

In order to find a model which can explain the fatigue crack propagation after an overload-underload cycle, it is very important to clearly understand the load cycles interactions.

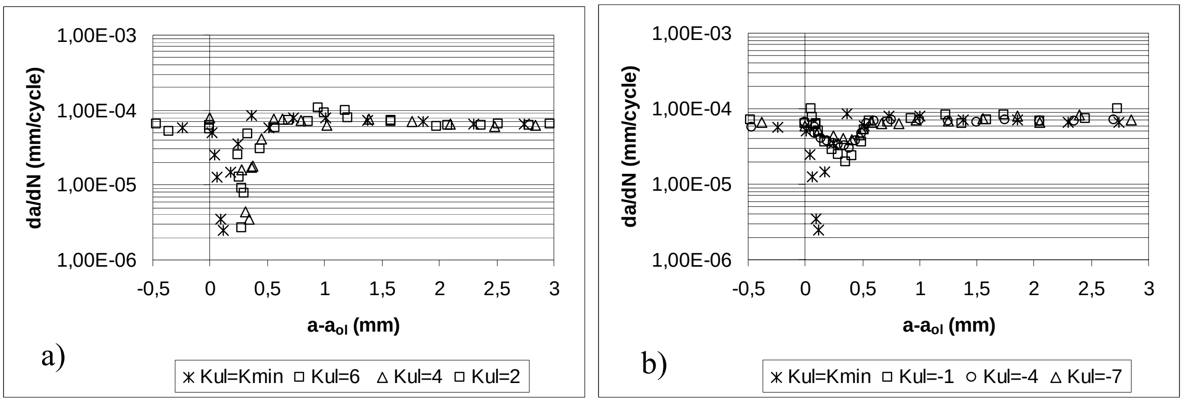


Fig. 4. Crack growth propagation da/dN versus crack length $a-a_{ol}$ for heating treatment QT500:
a) K_{ul} positive and b) K_{ul} negative

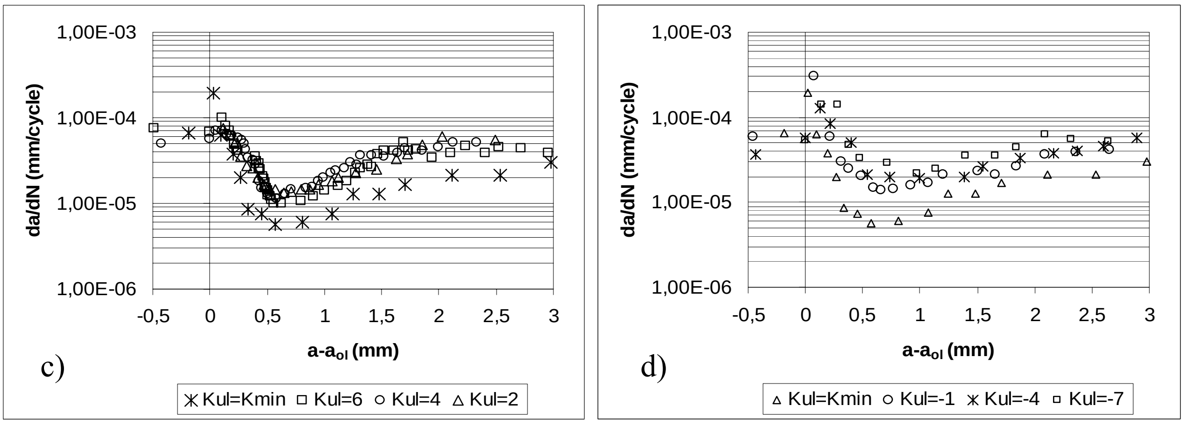


Fig. 5. Crack growth propagation da/dN versus crack length $a-a_{ol}$ for heating treatment NA:
b) K_{ul} positive and b) K_{ul} negative
c)

The tests have shown that the crack retardation effect induced by an overload is affected by an underload cycle subsequent to an overload (Fig. 4. and Fig. 5.).

The crack length affected by the delay is larger for NA treatment that for QT500. This is due to the lower yield stress σ_Y in case of NA heat treatment yielding larger monotonic overload plastic zones.

The crack length associated to the minimum fatigue crack growth rate (a_{min}) is achieved earlier for QT500. This is also due to the yield stress. Actually, the higher yield stress σ_Y induces more intensive residual compressive stresses in a smaller overload plastic zone.
Fatigue crack propagation subsequent to an overload-underload cycle can be described by three parameters: crack length affected by delay a_d, crack length associated with the minimum crack growth a_{min} and severity rate S_r [4]. Severity rate is given by the relation $S_r = (da/dN)_{min}/(da/dN)_{base}$.

For better understanding the underload effect we should verify how these parameters are sensitive to the underload cycle.

3.1 Sensitivity of a_d with the underload cycle

Fig. 6 shows that experimental crack length affected by delay a_d is not dependent on the underload rate τ_{ul}. We can notice that there is a great difference between the two heat treatments QT500 and NA. For a material with a high yield stress (QT500 σ_y = 900 MPa) the values for a_d are small with an average value of 0.5 mm. For a material with a small yield stress (NA σ_y = 330 MPa), a_d has a value definitely more important (≈ 2.1 mm).

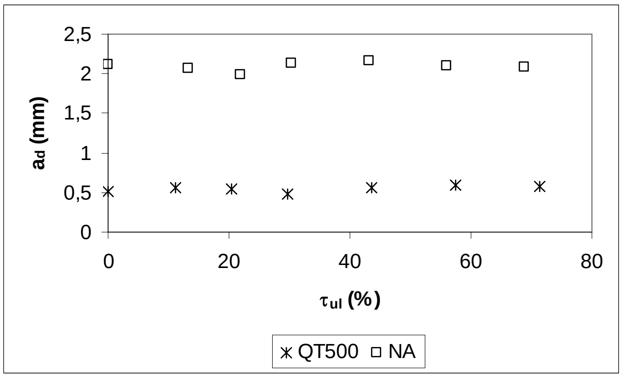


Fig. 6. Crack length affected by delay a_d vs. underload rate τ_{ul}

3.2 Sensitivity of a_{min} with the underload cycle

Fig. 7 shows that crack length associated with the minimum crack growth a_{min} is sensitive with the underload rate. We observe that as far as the underload rate τ_{ul} increases, the minimum fatigue crack growth rate occurs later. Also for the heat treatment QT500 with higher yield stress the minimal speed $(da/dN)_{min}$ is reached at a smaller distance than for the heat treatment NA with a lower yield stress, even for high underload rate τ_{ul}. It should be noted that the increase in a_{min} is weak with the rate of underload τ_{ul} but we have a continuous increase. This can be explained by the existence of a compressive plastic zone at the crack tip.

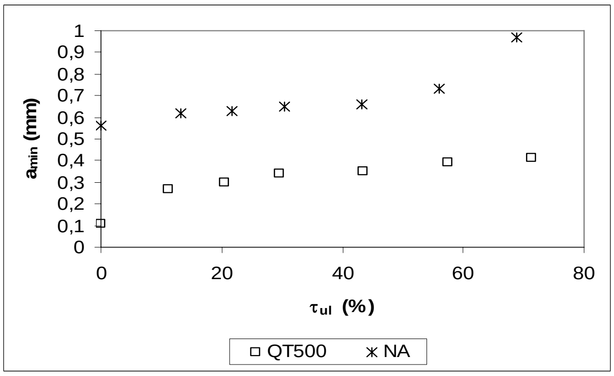


Fig. 7. Crack length associated with the minimum crack growth a_{min} rate vs. underload rate τ_{ul}

3.3 Sensitivity of S_r with the underload cycle

As it was defined before, severity rate takes into account the minimum fatigue crack growth rate after overload-underload $(da/dN)_{min}$ and the baseline fatigue crack growth rate $(da/dN)_{base}$. Fig. 8 shows that the severity ratio S_r is significantly dependent on the underload magnitude τ_{ul} whatever the heat treatment.

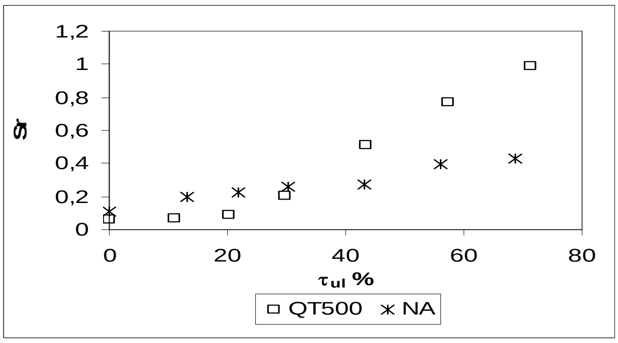


Fig. 8. Severity ratio evolution with the underload rate τ_{ul}

We can make the same remarks as previously: the increase in the underload rate, involves a reduction in the intensity of the residual stresses at crack tip, which increases the driving force of propagation. This means that the underload cycle increases the minimum fatigue crack growth rate, involving a drop in the overload cycle effect.

3.4 The lifetime of the structure

The delay affected number of cycles N_d constitutes the essential characteristic of the delay after overload-underload. This parameter indicates the lifetime of a structure. It is known that the overload has a beneficial effect over the lifetime. It is however important to take in account the effect of the underload, the real loadings being seldom constant. To estimate the lifetime of a structure becomes much more delicate then. The application of an underload after a cycle of overload, results in attenuation, more or less important of the beneficial effect of the overload or a decrease in the cycles number affected by the delay N_d.

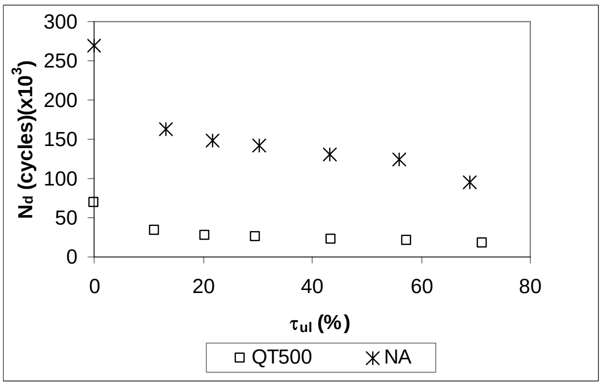


Fig.9. The delay affected number of cycles N_d with the underload rate τ_{ul}

As we can see in the Fig. 9 the delay affected number of cycles N_d is strongly affected by the magnitude of the underload cycle. We observe that, for a material with a high yield stress, the decrease in the delay affected number of cycles N_d is more important then a reduced lifetime.

4. CONCLUSIONS:

This paper has shown that the delay in the fatigue crack growth occurring after an overload cycle is strongly sensitive to an underload subsequent cycle. This effect can divide by almost tree times the amount of delay cycle number N_d.

The crack length affected by the delay a_d is not dependent on the underload magnitude, but the crack length associated with the minimum fatigue crack growth rate a_{min} and the severity ratio S_r are sensitive to the underload ratio τ_{ul}.

REFERENCES

[1] Bacila A. – "Influence des effets de surcharges et souscharges sur la propagation d'une fissure de fatigue. Modélisation et estimation de la durée de vie des éléments de construction mécanique." – PhD. Dissertation, UST Lille, 2007.
[2] Decoopman X. – "Influence des conditions de chargement sur le retard à la propagation d'une fissure de fatigue après l'application d'une surcharge" - PhD. Dissertation, UST Lille, 1999.
[3] Makabe C., A. Purnowidodo, A.J. McEvily – "Effects of surface deformation and crack closure on fatigue crack propagation after overloading and underloading" - International Journal of Fatigue 26, pp.1341–1348, 2004.
[4] Taheri F., D. Trask, N. Pegg – "Experimental and analytical investigation of fatigue characteristics of 350WT steel under constant and variable amplitude loadings" – Marine Structures 16; pp 69-91, 2003.
[5] Zitounis V., P.E. Irving - Fatigue crack acceleration effects during tensile underloads in 7010 and 8090 aluminium alloys - International Journal of Fatigue 29 (2007) 108–118.