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STUDY OF LOW FATIGUE CRACK GROWTH RATES IN 316 STAINLESS STEEL AND RR 58 Al ALLOY

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INTRODUCTION

The determination of the resistance of a material to fatigue crack propagation and the calculations of defect tolerance relies on the relationship between crack growth rate per cycle (da/dN) and the amplitude of the stress intensity factor ΔK. At low values of ΔK or crack growth rates, it has been shown that a threshold effect (ΔK_{th}) generally occurs. The knowledge of this threshold value is important for the establishment of safety criteria.

For a given material several factors may have an influence on ΔK_{th}. Among them, the R ratio ($R = K_{min}/K_{max}$) and the environment are known to be the most important. Other factors such as the frequency may also affect the threshold behaviour. In order to offer a firmly established experimental basis for the influence of various parameters on crack growth rate at low ΔK an extensive program has been undertaken by the French Metallurgical Society. Nine laboratories are involved in this study. The main objective of this program is to determine low crack growth rates using a series of systematic tests in which the most significant parameters are studied. Microfractographic observations were also used for the analysis of the fracture mechanisms.

This joint stùdy bears on a 316 stainless steel used in the nuclear power industry and on RR 58 T651 Al alloy used in the aircraft industry for supersonic applications.

Most of the tests are carried out using compact tension (CT) specimens except for a few tests which are performed with centre-cracked (CC) specimens. The program involves the study of the effect of initial crack length, mean stress or R ratio, frequency, wave form (sine, square, triangle) and environment (air or vacuum).

CRACK GROWTH RATE AT LOW ΔK

RR 58 T651 Al Alloy

This alloy gives rise to a true threshold ΔK_{th} in the range of crack growth rates which were determined, i.e. below approximately da/dN = 10^{-6} mm/cycle the slope of the da/dN versus ΔK curves is almost vertical. In the standard testing procedure which was used, i.e. a sine wave form, a frequency of 30-50 Hz, a R ratio of 0,01, an initial ΔK of 10 MPa $\sqrt{m}$ and a crack length (a/w) of about 0,5, CT specimens lead to ΔK_{th} = 3.5 MPa $\sqrt{m}$.

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The influence of the specimen thickness B and of the crack length (a/w) between 0,4 and 0,6 for tests carried out in these standard conditions are given in Table 1. In this table, the values of ΔK_{th} obtained with CC specimens and CT specimens for a R ratio of 0,5 are also given. These results show that the fatigue threshold ΔK_{th} is an intrinsic characteristic of the material which is independent of the crack length, the specimen thickness and the type of specimen.

The influence of frequency between 0,5 Hz and 130 Hz and of the wave shape are given in Table 2. These results indicate that these factors have only a slight influence on ΔK_{th}. It is worth noting that the threshold values measured at 0,5 Hz are systematically below those obtained at higher frequency. This frequency effect might reflect the influence of environment at low crack growth rates.

The effect of R ratio is given in Table 3. The results show that the threshold ΔK_{th} decreases when the R ratio increases. This behaviour is usually that encountered in various materials, for instance in steels [1]. The relationship, $\Delta K_{th} = K_{th0}(1-R)^{\gamma}$ given by Klesnil and Lukas [2] in order to take into account the effect of R ratio on ΔK_{th} leads for our data to $\gamma = 0,25$. This value is lower to that generally found in steels [2], where γ is closer to 1. In Table 3, ΔK_{th} obtained with R = 0,01 in vacuum is also included. The comparison with the data obtained in air clearly shows that the threshold strongly depends on the environment. This behaviour is similar to that found in steels [3].

316 Stainless Steel

For this alloy the results have not yet been completely obtained. The tests which have been presently performed on compact tension specimens show that this alloy exhibits a behaviour slightly different from that found in the Al alloy. No true threshold effect has been found for crack growth rates down to 10^{-7} mm/cycle. The da/dN versus ΔK curve exhibits a continuous slope for crack growth rates between 10^{-7} mm/cycle and 10^{-3} mm/cycle. In these conditions, it is not possible to determine a threshold value for ΔK, at least in the ΔK range which has been presently investigated. Also, at the time being, only a conventional value of ΔK corresponding to a given value for the crack growth rate can be reported. Thus, for instance, the results obtained at relatively high frequency and with R = 0,1 are given in Table 4. These partial results show that the specimen thickness between 15 and 25 mm and the wave form (triangle or square) have no effect on the crack growth rate at low ΔK.

It is worth mentioning that the experimental procedure used to determine the crack growth rate at low ΔK involved a decrease of the applied load from the initial value used to initiate the crack. It was found that this experimental procedure has to be carefully controlled in order to get significant results.

FRACTOGRAPHY

The fracture surfaces of various specimens used for the threshold determination in the Al alloy or for very low crack growth rates in the stainless steel have been observed either directly using a scanning electron microscope or indirectly using replica and transmission electron microscopy.

The various parameters studied for the measurement of crack growth rate (except vacuum) were found to have no effects on the fracture surface morphology. Thus a general description of the fracture surfaces typical of very low crack growth rates (da/dN = 10^{-7} to 10^{-6} mm/cycle) can be given.

For both alloys the fracture surfaces are always transgranular. There are some differences between the microscopic aspect of the fracture surfaces of the two investigated alloys. In the 316 stainless steel, the fractographic aspect can be characterized by the presence of a high density of relatively smooth and planar areas or facets. This morphology is particularly well defined in certain grains. These facets are separated by long, relatively straight and parallel ridges. Several sets of ridges which are probably related to different slip systems are observed in a given grain. Sometimes, they look like "striations" but the distance between two adjacent ridges is much higher than the crack advance per cycle and corresponds to several hundred of cycles. These observations suggest that decohesion of austenite along crystallographic planes like {111} could be responsible for this morphology.

In RR58 Al alloy this type of planar areas was not observed. Only wavy transgranular facets without any striations were seen. The size of these facets is larger at low crack growth rate than at higher da/dN. It has proved to be difficult to correlate the size of these facets with the grain size, mainly because of the large inhomogeneity in the grain size in commercial RR58 Al alloy.

CONCLUSIONS

This cooperative program has allowed to study the influence of many parameters on the crack growth rate at low values of ΔK. In the Al alloy which has been presently studied in more detail, an effect of the R ratio and of the environment has been found.

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Table 1 RR58-T651-Al Alloy. Influence of specimen thickness B, R ratio and Specimen type on the fatigue threshold ΔK_{th}.

	Width B (mm)					Ratio (a/w)			Specimen type R=0.5 w=5mm	
	5mm	10mm	20mm	30mm	38mm	0.4	0.5	0.6	CT	CC
ΔK_{th} (MPa$\sqrt{m}$)	4.5	3.8	3.9	4.2	3.6	3.3	3.3	3.1	2.4	2.6

Table 2 RR 58-T651 Al Alloy. Variations of ΔK_{th} with the frequency and the wave form

	Frequency			Wave Form					
				Sine		Square		Triangle	
	0.5Hz	40Hz	130Hz	40Hz	0.5Hz	30Hz	0.5Hz	40Hz	0.5Hz
ΔK_{th} (MPa$\sqrt{m}$)	3.0	3.2	3.8	3.5	3.0	3.4	3.0	3.6	2.90

Table 3 Influence of the environment (Air and Vacuum) and of the R ratio on ΔK_{th} in RR 58-T651 Al Alloy.

	Environment	R ratio ($\frac{a}{w}$) (Air)			
	Vacuum 10^{-5}Torr R = 0,01	0.01	0.1	0.5	0.6
ΔK_{th} (MPa$\sqrt{m}$)	6.1	3.5	3.2	2.6	2.3

Table 4 316 Stainless steel. Crack growth at low ΔK obtained with C.T specimens of different thickness and with two types of wave shape.

R	Frequency	da/dN (mm/cycle)	Wave shape	Specimen thickness B (mm)	ΔK MPa$\sqrt{m}$
0.1	30	10^{-6}	Triangle	15 20 25	9.2 8.7 9.3
		10^{-7}	Triangle Square	20 20	5.5 4.9