NEAR-THRESHOLD FATIGUE CRACK PROPAGATION IN AUSTENITIC STAINLESS STEELS

C. Sarrazin-Baudoux [1] , J. Petit [1] and C. Amzallag [2]
[1] LMPM-ENSMA, UMR CNRS 6617, Poitiers/Futuroscope, France
[2] EDF-SEPTEM, Villeurbanne, France.

ABSTRACT: *This paper deals with a study of the fatigue crack propagation in the near-threshold domain and in the mid-rate range on two austenitic stainless steels type 304L and 316L widely used in nuclear industry. The aim is to reassess the propagation laws and the threshold levels to answer recent industrial safety problems related to damage tolerance. The propagation curves established at room temperature, 150°C and 300°C at R=0.1 and 0.7, are discussed in comparison to literature. The investigation of crack closure has shown a substantial contribution of this phenomenon in the near-threshold area as well at R=0.1 as at R=0.7. Propagation mechanisms are illustrated and documented by mean of SEM observations.*

INTRODUCTION

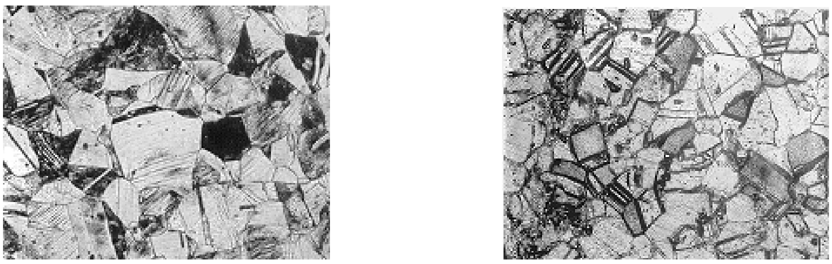
Two main concerns of the industries of production of energy in nuclear plants, is the improvement of reliability and the extension of the operative life of structures. In the recent past years, the attention has been focussed on the resistance against thermal fatigue of some critical elements of structures. The development of more accurate tool for the prediction of the fatigue life of such components required a detailed and precise knowledge of the behavior of the materials. Austenitic steels like A316L and A304L are commonly used in nuclear plants (boilers, pipes…). The objective of the present paper is to answer the industrial lack of knowledge of the near threshold crack propagation behavior of these two alloys at temperature ranging from ambient temperature up 300°C. A detailed analysis of the role of crack closure has been performed during the propagation tests so as to get information on the effective fatigue crack growth behavior in the different experimental conditions. A careful examination of the fracture surface morphology with respect to the microstructure, the temperature and the load ratio (0.1 and 0.7) has been conducted in view of a detailed analysis of the mechanisms controlling the crack growth.

EXPERIMENTALS

The materials are provided from laminated plates. Mechanical properties and microstructures are shown in table 1 and figure 1 respectively. Fatigue crack growth experiments are carried out on Compact Tension C(T) specimens machined in the LT orientation (10 mm thick and 40 mm wide) in accordance with ASTM Test Method for Measurements of Fatigue Crack Growth Rates (E 647-88) using a servo-hydraulic machine equipped with a furnace providing temperature up to 500°C.

TABLE 1: Mechanical properties

Material	Temperature	Yield stress (MPa)	Ultimate stress (MPa)	Elongation %
304L	20	231	570	76
	150	177	432	50.1
	300	142	400	44.3
316L	20	253	574	69.9
	150	185	462	50.3
	300	154	435	42.3



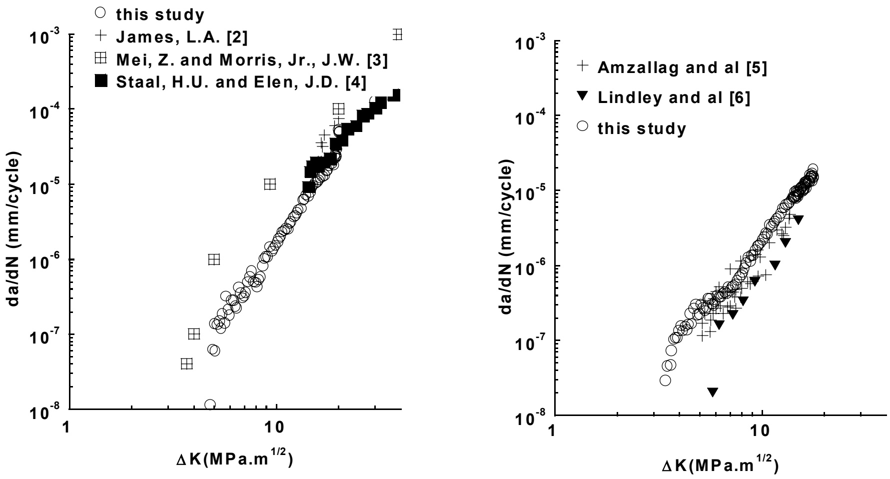
(a) 100 μm (b)

Figure 1: Microstructure of 304L (a) and 316L (b) alloys

Crack lengths are tracked using a DC (electrical) potential drop technique. The specimens are submitted to sinusoidal loading at a frequency of 35 Hz. Crack closure is detected using a capacitive displacement gauge and determined by means of the offset compliance technique [1].

CRACK PROPAGATION AT ROOM TEMPERATURE

In figures 2a and 2b are plotted the crack propagation curves established at room temperature, respectively for the 304L and 316L alloys in comparison to data provided from the literature [2-6].



(a) (b)

Figure 2: Crack Propagation curves da/dN vs ΔK at room temperature for 304L (a) and 316L (b) steels.

The few available data for the 304L are in acceptable accordance with the present results, showing a threshold ranging around 4 MPa√m. For the 316L, a larger scatter is observed with a threshold ranging from 3.3 MPa√m for the present study to 5.7 MPa√m for Lindley and al [6]. The Amzallag and al. results [5] fall between these two values which can be explained by a strong influence of the experimental procedure and primarily of the normalized ASTM K-gradient C=(1/K).(dK/da) [7]. The use of C values equal or lower than that of -0.1 mm^{-1} used in this study (which is close from the ASTM advised C value of – 0.08), leads to the more conservative curve and to the lower threshold, and consequently, should be highly recommended.

The experimental results obtained at room temperature on both alloys are gathered in the figure 3, including data at R = 0.1 and R =0.7 with and without closure correction.

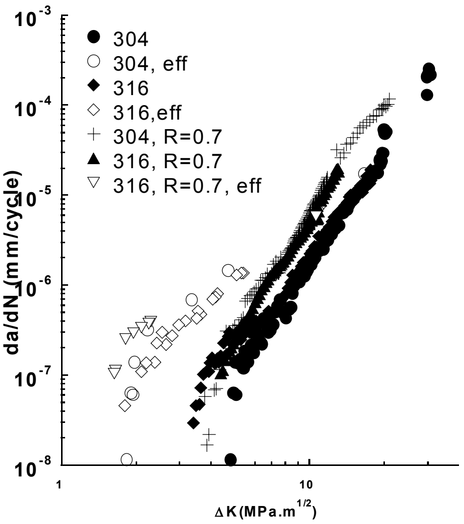
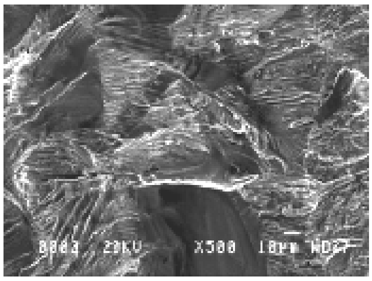


Figure 3: Crack Propagation curves da/dN vs ΔK and da/dN vs ΔK_{eff} at room temperature for 316L and 304L



(a) 304L, da/dN = 6 10^{-8} mm/cycle, ΔK = 5.1 MPa√m
(b) 316L, da/dN = 1.3 10^{-7} mm/cycle, ΔK = 4.0 MPa√m

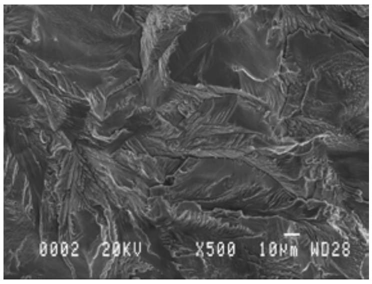


Figure 4: Fracture surface morphology in the near-threshold range.

The following remarks can be drawn :
- A similar behavior for both steels in the mid-rate range for each R ratio;
- A higher threshold range at R=0.1 for the 304L (4.8 MPa√m) than for 316L (3.3 MPa√m), associated to a more faceted crystallographic fracture surface (figure 4);
- A poor influence of the R ratio on the growth rate at a given ΔK range;
- A large contribution of crack closure at both R ratio and very similar da/dN vs ΔK_{eff} curves.
- Microfractographic surface morphology is in accordance with previous observations for the A316L alloy [7].

INFLUENCE OF TEMPERATURE

The experimental propagation curves obtained at 150°C and 300°C are compared to that at room temperature in figures 5a and 5b for the 304L alloy and in figures 6a and 6b for the 316L alloy. The main trends are:

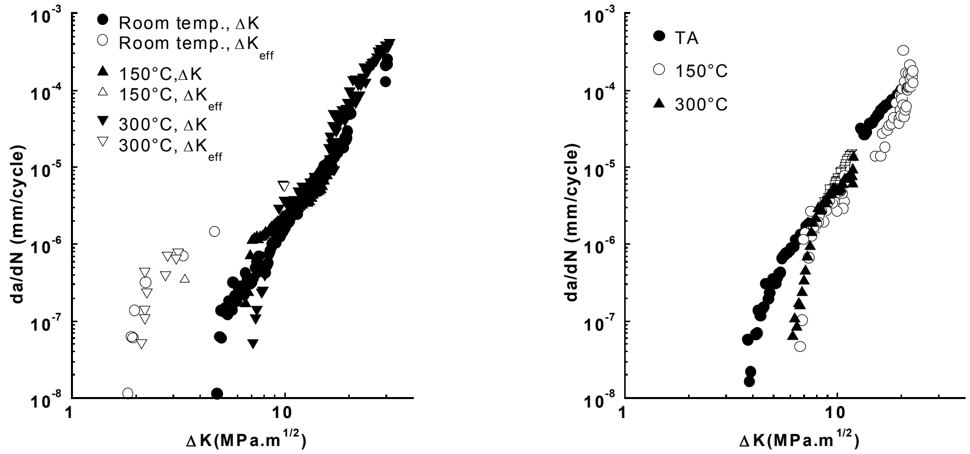
- very few difference in the crack growth curves between the two alloys and no significant influence of the R ratio at both temperatures even near the threshold.
- comparable contribution of crack closure whatever the R ratio. This result is typical of these two very ductile alloys and suggests the absence of some R_{cut} value [8] above which closure would not occur.
- The threshold range is comparable at 150°C than at 300°C (around 6.6 MPa√m for both alloys and both R ratios) but substantially higher than that at room temperature (figure 4).
- The effective threshold range for both alloys (i.e. after closure correction) is less sensitive to temperature but appears to be a bit higher at 150°C (about 3 MPa√m) than at room temperature and 300°C (about 2 MPa√m). These results suggest an increasing contribution of crack closure with increasing temperature.

SEM examination of the fracture surfaces were performed to compare the evolution of the surface morphology with respect to the growth rate on both alloys. Some illustrations are given in figure 7 for the 304L alloy tested at R=0.1 at 150°C and 300°C and for three growth rate ranges. Near the threshold very rough crystallographic surfaces as at room temperature are accordance with a substantial contribution closure. The much flatter surfaces observed at higher growth rates are in accordance with a stage II crack less sensible to the microstructure.

CONCLUSIONS

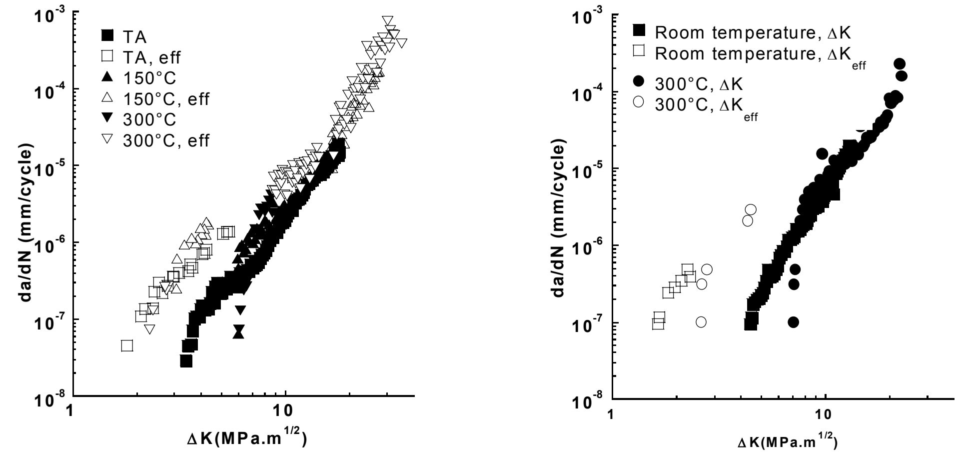
This study of fatigue crack propagation at temperature ranging from room temperature to 300°C in 304L and 316L austenitic stainless steels, leads to the following main conclusions:

- There is very little difference between the two alloys whatever the rate range and the temperature;
- The threshold range of the stress intensity factor is increasing with the temperature whatever the R ratio;
- A substantial contribution of crack closure in the near-threshold area explains the high level of the threshold whatever the R ratio.



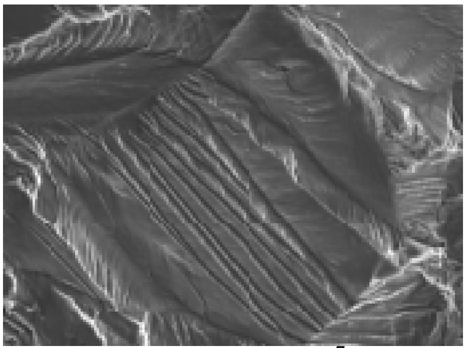
(a) (b)

Figure 5: Influence of temperature on da/dN vs ΔK and da/dN vs ΔK_{eff} curves in 304L at R=0.1 (a) and R=0.7 (b).

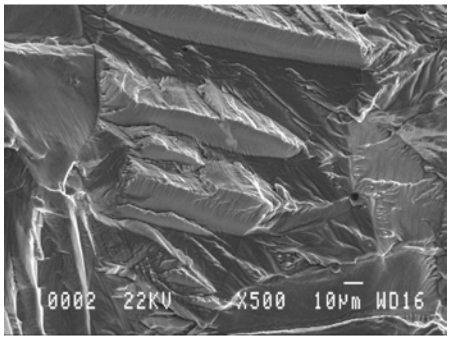


(a) (b)

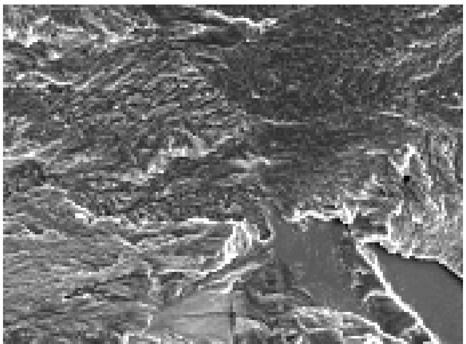
Figure 6: Influence of temperature on da/dN vs ΔK and da/dN vs ΔK_{eff} curves in 316L at R=0.1 (a) and R=0.7 (b).



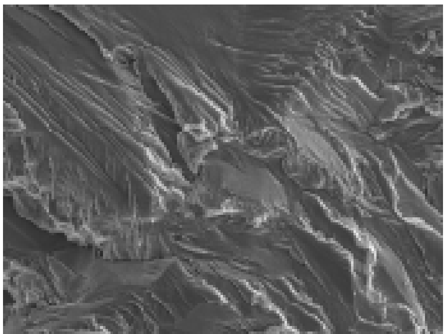
(a) 150°C, da/dN = 2 10^{-7} mm/cycle, ΔK = 6.8 MPa√m



(d) 300°C, da/dN = 3 10^{-6} mm/cycle, ΔK = 7.0 MPa√m

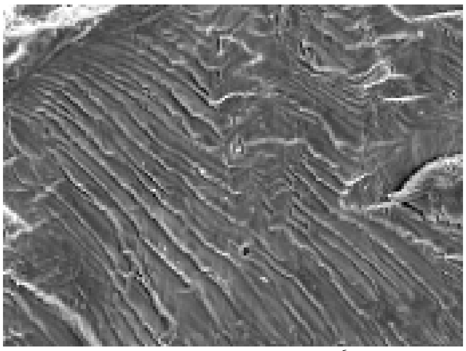


(b) 150°C, da/dN = 3. 10^{-6} mm/cycle, mm/cycle, ΔK = 12 MPa√m

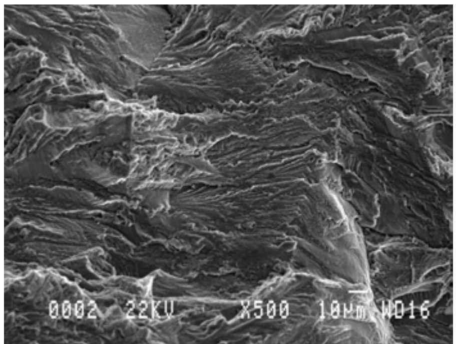


(e) 300°C, da/dN=3.10^{-6}

ΔK = 10 MPa√m

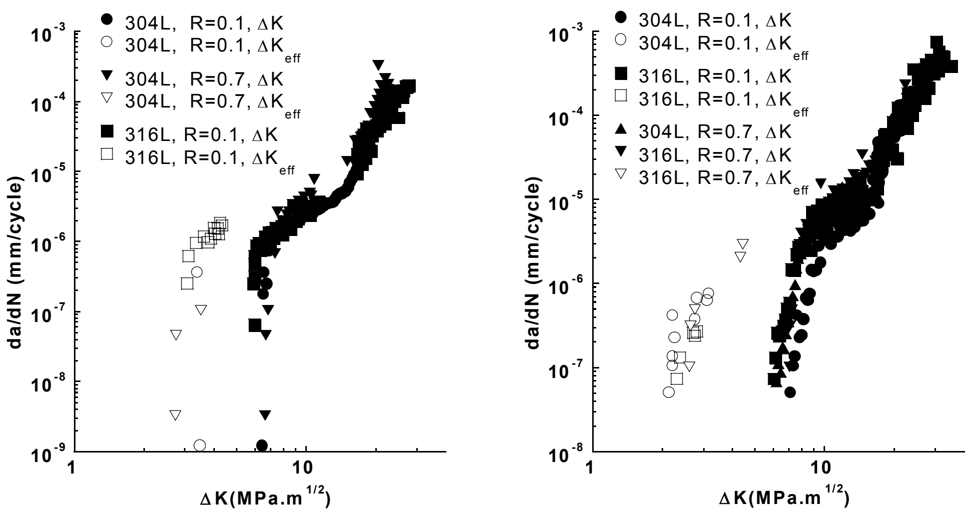


(c) 150°C, da/dN = 8. 10^{-6} mm/cycle, ΔK = 25 MPa√m



(f) 300°C, da/dN=1.5 10^{-6} mm/cycle, ΔK = 16 MPa√m

Figure 7: Comparison of fracture surfaces at 150°C and 300°C on 304L.



(a) (b)

Figure 8: Crack Propagation curves da/dN vs ΔK and da/dN vs ΔK_{eff} at 150°C (a) and 300°C (b) on 304L and 316L steel

REFERENCES

1. Sarrazin-Baudoux, C. Chabanne, Y. and Petit, J., (2000) *Fatigue crack growth thresholds, endurance limits and design,* ASTM-STP 1372, James C. Newman and Robert S. Piasick eds., American Society for Testing and Materials pub, 341.
2. James, L.A. (1976) *Atomic Energy Review* **14**, 86.
3. Huthmann, H., Livesey, V.B. and Robert, G. (1996) *Int. Jal. Ves. And Piping* **65**, 239.
4. McEvily, A.J., Gonzalez, J.L. and Hallen, J.M.(1996) *Scripta Mater*. 6, 761.
5. Lindley, T. C. and Richards, E. (1976) *Engineering Application III,* 1113.
6. Amzallag, C. et al. (1981) *Fatigue crack growth measurement and data analysis*, ASTM STP 738, S.J. Hudak, Jr. And R.J. Bucci, Eds, American Society for Testing and Materials pub., 44.
7. Meny, L. (1976) *Mécanismes de fissuration*, Rapport CEA, D.TEC/SRMA/GMAR.76.194.