CRACK INITIATION AND GROWTH IN A 316 L STAINLESS STEEL CYCLED BETWEEN 20°C AND 600°C IN VACUUM

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The effect of temperature on the fatigue resistance of a 316L stainless steel was investigated by performing push-pull fatigue experiments in vacuum under plastic strain amplitude control between 20°C and 600°C. It has been shown that temperature has a beneficial effect in a first period during which fatigue life increases with temperature ; in a second period the fatigue life is observed to decrease with temperature ; however the fatigue resistance at 600°C remains of the same order as at room temperature. A quantitative analysis of surface damage permitted to show that fatigue life is mainly associated with crack growth and that variations in fatigue resistance induced by temperature are directly related to a modification in the crack growth rates.

INTRODUCTION

It is now well admitted that the decrease in fatigue life and changes in damage processes observed when temperature increases are highly related to environmental effects on crack initiation and propagation. At the same time many experiments conducted on different materials in high vacuum have shown that there is little difference in the cyclic plastic strain level-life relation between room temperature and elevated temperatures at the opposite of what is observed in air. As a consequence it is frequently admitted that apart from oxidation effects not intrinsic effect of temperature exists on fatigue resistance and, moreover, that the fatigue resistance measured in air at room temperature, when environmental effects are supposed to be negligible, can also represent the intrinsic fatigue resistance at elevated temperature in the absence of oxidation effects. However very few work has been conducted in vacuum or in inert atmospheres to verify such assumptions and to study in detail the evolution of crack initiation and growth with temperature in the low cycle fatigue range. The influence of temperature on the slip mode is

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however well known, most metals with a planar slip character at low temperatures exhibiting wavy slip at temperatures higher than 0.4 T_M caused by thermal activation.

Therefore investigations in fatigue damage processes in vacuum are needed to determine the intrinsic effects of temperature on fatigue damage processes resulting from modifications in slip mode which could be masked in air with the increase in oxidation effects.

With this aim we have conducted fatigue experiments in a high vacuum on a 316L type austenitic stainless steel from room temperature to 600°C. We will report in this paper results concerning microcracking features ; other results concerning behaviour and dislocation arrangements have been published elsewhere (1,2).

EXPERIMENTAL CONDITIONS

The austenitic stainless steel studied in this work is a 316L type denoted 17-12 SPH whose composition has been indicated in previous paper (2). Cylindrical specimens with a diameter of 6 mm and a gauge length of 8 mm were used. They were heat treated in vacuum 1 hour at 1050°C then water quenched. The specimens were mechanically then electropolished before fatigue. Tension-compression fatigue tests were performed on an electromechanical machine in a high vacuum (pressure lower than 6.10^{-4} Pa) at different temperatures : 20°C, 200°C, 300°C, 400°C, 500°C and 600°C. All the tests were conducted in plastic strain controlled mode with constant plastic strain rate (2×10^{-3} s^{-1}). The cyclic plastic strain amplitudes investigated were in the range $6 \times 10^{-4} - 5 \times 10^{-3}$. The fatigue tests were performed up to failure or interrupted to quantify the evolution of damage at specimen surface by examination in a Scanning Electron Microscope. With this aim crack initiation sites and growth processes were determined, the number and the length of the distributed secondary microcracks and the length of the major crack were measured.

RESULTS AND DISCUSSION

Fatigue life

In Fig. 1 the number of cycles to failure in vacuum has been reported as a function of temperature in a semilogarithmic diagram for the three plastic strain amplitudes $\Delta\varepsilon_p/2$ investigated : 6.10^{-4}, 2.10^{-3} and 5.10^{-3}.

It appears that in a first temperature range, from 20°C to 300°C, increasing temperature favours the resistance to fatigue of the 316L stainless steel : for the three plastic levels investigated, the fatigue life is about four times higher at 300°C than at room temperature. Beyond 300°C, fatigue life decreases with temperature to reach at about 550°C the level of fatigue resistance obtained at room temperature. This improvement of the fatigue resistance is associated with an important homogenization of cyclic deformation, the intense slip bands invading the whole grains at the opposite of what is observed at room temperature (1).

Therefore, when only the extreme temperatures 20°C-600°C are investigated the fatigue resistance does not appear to be affected by temperature as it has been indicated by Coffin (3). However it is clear from our work that, at least for austenitic stainless steels, this result cannot be extrapolated to the intermediate temperatures.

This beneficial effect of temperature is masked in air by the associated increase in oxidation. Indeed, at 300°C, the effect of environment is already as important as at 600°C (4) and balances the beneficial effect of temperature associated with changes in cyclic deformation processes which therefore can only be noted in vacuo or in inert atmospheres.

Crack initiation mechanisms

A progressive evolution of crack initiation and early growth processes occurs between 20°C and 600°C : from 20°C to 300°C, microcracks initiate at the intersection of the intense slip bands with the specimen surface while intergranular damage appears at 400°C and becomes predominant at 500°C and 600°C (4).

Fig. 2 illustrates this evolution for specimens cycled to failure under a plastic strain amplitude $\Delta\varepsilon_p/2 = 2.10^{-3}$. Histograms in this figure give the percentage of the different types of microcracks classified in accordance with their microstructural path at the specimen surface : purely intergranular, purely transgranular or with a mixed mode. Up to 300°C the majority of microcracks are clearly transgranular (75 per cent) and intergranular damage appears to be negligible. At 400°C, the majority of microcracks observed at failure are located at grain boundaries, however transgranular damage still remains predominant since it controls crack growth from the early stages. At higher temperature and particularly at 600°C, fatigue damage in vacuum is clearly intergranular with 80 per cent of surface cracks following grain boundaries.

Fatigue damage features

Distributed surface damage. Another important characteristic of the temperature effects concerns differences in the microcrack density values observed on the specimens cycled to failure.

This is illustrated in Fig. 3 for $\Delta\varepsilon_p/2 = 2.\ 10^{-3}$. The number of initiated microcraks increases with temperature from 20°C to 200°C then decreases to reach a minimum value at 300°C ; above this temperature the crack density increases regularly to reach a value more than 5 times higher at 600°C than at 300°C (4 times higher than at 20°C). This marked increase in crack density, observed for temperatures higher than 300°C, is clearly related to intergranular damage processes.

Differences in crack density observed between 20°C and 200°C can be explained by the difference in fatigue life ; in fact the rate of initiation of new microcraks is of the same order at 20°C and 200°C. At the opposite the decrease observed at 300°C must be considered as significant since the fatigue life is still higher at this temperature ; the number of initiated cracks per cycle is at 300°C ten times lower than at room temperature. Therefore at 300°C the resistance to crack initiation is clearly improved.

Evolution of the major crack length. Fig. 4 shows the evolution with the fraction of life N/N_f of the largest surface crack length on specimens cycled at different temperatures under cyclic plastic amplitudes which lead to a fatigue life of about 160 000 cycles. The following conditions have been investigated : $\Delta\varepsilon_p/2 = 10^{-3}$ at 20°C and 600°C for which failure occurs in both cases at 170 000 cycles ; $\Delta\varepsilon_p/2 = 2.10^{-3}$ at 200°C and 400°C leading to failure at 150 000 cycles.

Fig. 4 shows that all the measurements are regrouped in a single $2c$-N/N_f curve. For all the temperatures investigated it must be noted that initiation occurs early in the life ($N_i/N_f < 0{,}2$) and that fatigue resistance is controlled by crack growth. Moreover these results confirm that the main crack (which growth determines the fatigue resistance) exhibit for 316L at different temperatures an homologous evolution irrespective of the mode of microcracking (transgranular or intergranular) or of surface microcrack density. This result obtained for the same material tested at different temperatures in vacuum is in good accordance with our own results on polycrystalline copper cycled at room temperature in air at different amplitudes (5) or with results of Magnin et al. on different bcc and fcc materials cycled at room temperature in air (6). In particular it is worth noticing that differences in microcrack mode from transgranular at 20°C to intergranular at 600°C cannot be associated with a decrease in fatigue resistance if only these extreme temperatures are considered. At the opposite for temperatures higher than 300°C the increase in intergranular damage is well correlated with a decrease in fatigue life.

CONCLUSION

The study of the fatigue behaviour of an austenitic stainless steel type 316L in vacuum, between 20°C and 600°C, has permitted to obtain original results about the influence of temperature on fatigue damage processes which are masked in air by the detrimental effects of oxidation. In particular a beneficial effect of temperature has been shown which is associated with a more homogeneous deformation distribution inside the grains. Above 400°C a decrease in fatigue resistance occurs related to intergranular damage ; however, the material keeps up to 600°C a better resistance than at room temperature.

An analysis of fatigue damage kinetics have shown an indentical effect of temperature on the different stages of crack growth while crack initiation is observed to occur early in the life whatever the temperature.

REFERENCES

(1) Mendez, J., Gerland, M., Alain, R. and Violan, P., To be published.

(2) Gerland, M., Aït Saadi, B. and Violan, P. "Strength of Metals and Alloys", ICSMA 8 Conference Proceedings, Edited by P.O. Kettunen, T.K. Lepistö and M.E. Lehtomen, Pergamon Press, 1988.

(3) Coffin, L.F. Jr., Metallurgical Transactions, Vol. 3, 1973, pp. 1777-1788.

(4) Violan, P., Mendez, J., Belamri, C., Gorlier, C., Driver, J. and Amzallag, C., "Fatigue à Haute Température", Proceedings of Journées Internationales de Printemps, SFM Publications, Paris, 1986.

(5) Mendez, J. and Violan, P., "Endommagement par fatigue et compteur des dommages", Proceedings of Journées de Printemps de la SF2M, Paris, 1991.

(6) Magnin, T., Ramade, C., Lepinoux, J. and Kubin, L.P., Mater. Sci. Eng., A118, 1989, pp. 41-51.

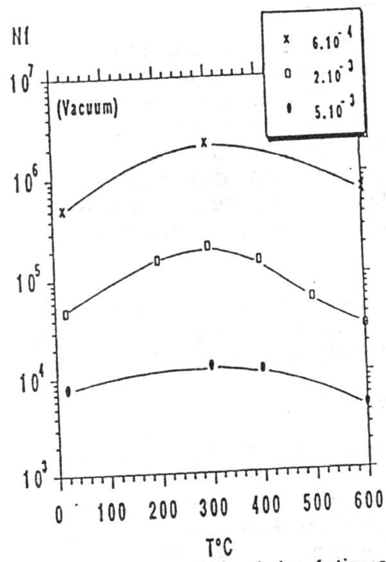

Figure 1 : Evolution of the fatigue life with temperature.

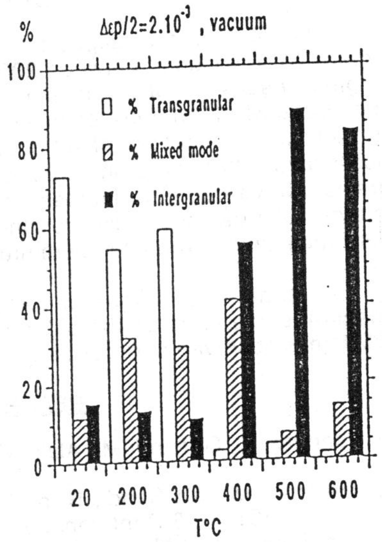

Figure 2 : Evolution of microcracking processes with temperature.

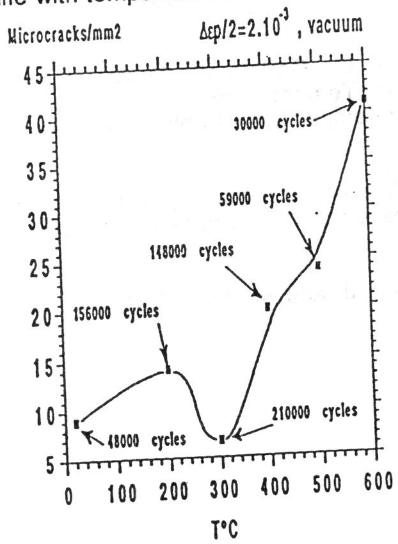

Figure 3 : Evolution of the microcrack density at failure with temperature.

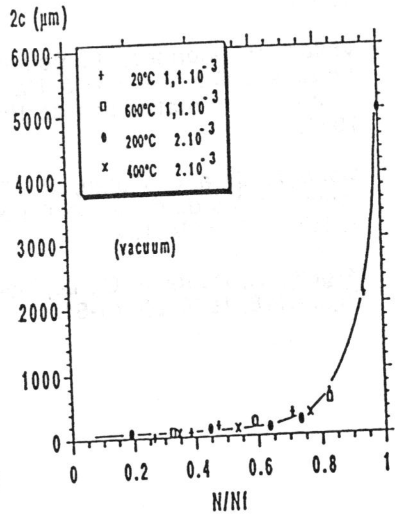

Figure 4 : Major crack surface length versus the fraction of life.