RESIDUAL STRESSES AND HARDENING NEAR CRACK TIP REGIONS OF AUSTENITIC STEEL FATIGUE SPECIMENS.

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Austenitic stainless steel 316L is used extensively in the field of nuclear industry, and more specifically in the primary circuit of fast breeder reactors. As the normal operation temperature of the latter is about 650°C, it is very important to determine the role of residual stresses in the deformation and the fracture process in order to estimate the component's lifetimes. The plastic deformation is also an important parameter related to the residual stress relaxation and its redistribution after fatigue loading.
The aim of this work was to determine the residual stress field in cracked fatigue specimens of austenitic stainless steel 316L by neutron diffraction techniques in order to use this data for quantifying the influence of the different loading parameters on the fatigue crack growth. On the other hand, some microstructural parameters, such as the average size of coherently diffracting blocks D and the mean-square microstrain $<\varepsilon^2>^{1/2}$, were estimated by combining neutron and X-ray (synchrotron radiation) diffraction techniques. In fact, the shape and the broadening of diffraction profiles are directly correlated with the evolution and redistribution of microstructural defects .
Non-destructive neutron diffraction technique is nowadays extensively used for the determination of **internal elastic stresses** in polycrystalline materials due to the homogeneous distribution of strains across several grains, which result in a shift of the angular position of the Bragg peaks. However, the analysis of **plastic strains**, due to microstructural defects, by neutron scattering investigations still remains quite rare, in contrast to X-ray diffraction, widely used for this kind of analysis. Nevertheless, due to the high penetration of neutrons in most materials, the neutron diffraction is the only non-destructive technique, which enables to get information within a defined volume in a bulk sample and not only limited to the surface (as in the case of X-rays).
For the analysis of plastic strains by neutron scattering, experimental and theoretical methods for neutron diffraction line broadening analysis were developed [1]. These methods generally require a high instrumental resolution, which has been achieved by optimising the experimental conditions (large monochromator take-off angle and small incident beam divergence) [2]. Additionally, a new method of single peak analysis with indirect deconvolution of instrumental profile was developed to relate the diffraction profile parameters with the microstructural parameters.
Measurements were performed on two Crack Test (CT) specimens of austenitic stainless steel 316L (Fig. 1) subjected to fatigue cycling with different load ratio (R) in order to modify the dimensions of the plastic region close to the crack tip (R=0.1 and R=0.5), called in the following CT_1 et CT_2, respectively. In particular, the first sample, with R=0.1, had been subjected to 25750 fatigue cycles, while the second one (R=0.5) has been submitted to 19530 cycles. A third specimen (CT_3) was deformed by tension up to 5 mm crack opening.

1. Internal elastic stresses
In the first part of the work, we have studied the macroscopic residual stresses by neutron diffraction. Three dimensional strain measurements (x, y, z directions) were performed in the middle of the sample, along the crack opening direction y, on the "strain dedicated" G5.2 diffractometer of the LLB.

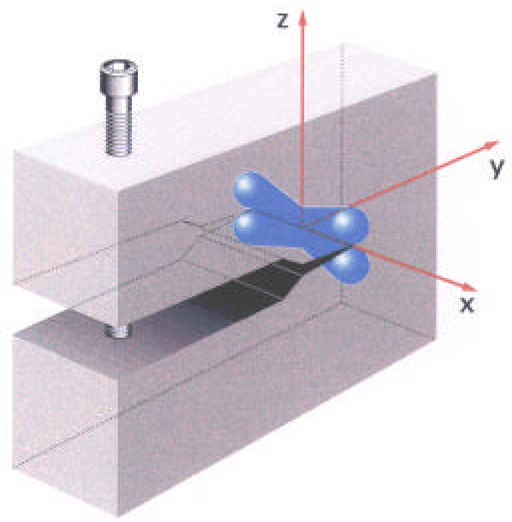

***Figure 1**: Geometry of the CT samples and measurements directions. The plastic zone near the crack tip is schematised in blue. The samples were 70 mm long in the direction of the crack growth, 45 mm high and 10 mm thick. Neutron measurements have been performed in the middle of the sample (at a depth of 5mm), along the crack opening direction y.*

For all the investigated specimens, a three dimensional stress state was observed. In particular, the residual stresses obtained for the sample with a small R (CT_1) are rather weak and they increase in the second sample (CT_2) with higher R. Experimental residual stress distribution along the crack opening direction for the third sample (CT_3) is shown in figure 2, together with a finite element calculation. As seen from the figure, the maximum stress level was observed at 2 mm from the tip, where σ_{xx} = 300 MPa, σ_{yy} = 500 MPa and σ_{zz} = 800 MPa. At the distance of 8mm from the tip, the σ_{xx} and σ_{yy} components were found to be very low, whereas the σ_{zz} component becomes large and compressive. These measurements show a good agreement with a finite elements (3 dimensional) calculation performed using CASTEM2000 code, developed at DEMT (CEA). A small disagreement between the experimental and theoretical results was observed essentially in the region of some mm near the crack tip. This can be explained by the different spatial resolution used in the neutron measurements. In fact, the size of the finite elements selected in the calculations was 0.187 mm near the crack and 1.275 mm at the edge of the sample, while the spatial resolution ("gauge volume") of neutron measurements was 1x1x1 mm^3. We note as well that the calculated values of stresses are slightly higher than measured ones. This is probably due to relaxation effects due to the plastic deformation induced by the tensile test. Another possible reason for the deviation from the maximum value can be due to the fact that the calculation does not take into account the effect of the crack propagation.

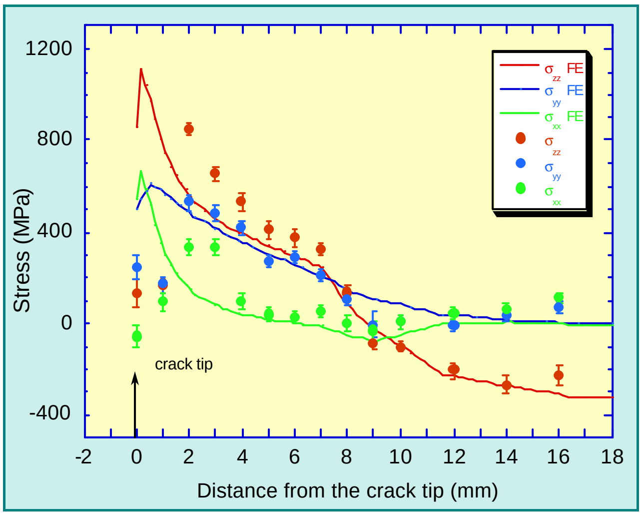

***Figure 2** : Residual stress evolution as a function of the distance from the crack tip of the CT_3 sample. Comparison between the experimental results (dots) and the values obtained by Finite Element calculation (continuous lines).*

2. Plastic strains : neutron measurements

In the second part of the work, the experimental study of microstructure and plastic deformation in the region close to the crack tip was performed by neutron and X-ray (synchrotron) diffraction. In fact, it is important to estimate the dimension of the plastic zone, created around the crack's tip, which is responsible for the stress redistribution affecting the crack propagation.

The microstrains evaluation by neutron diffraction have been performed in the middle of the sample (at a depth of 5mm) using the profile broadening analysis, based on the single-line Keijser's method [1]. The basic assumption of this approach is that the sample broadened profile can be described by the convolution of a Gauss function and a Cauchy function, depending on the strain and size, respectively. The indirect deconvolution method has been developed to extract the instrumental profile from the experimental data. The plastic zone was clearly distinguished for the CT_2 and CT_3 samples with the peak breadth considerably larger than that of reference sample. The dimension of the plastic zone (depending on the directions x, y, z) is about 2 to 3 mm for the CT_2 sample and about 4 mm for the CT_3 sample. The estimation of the plastic deformation and microstructural parameters (D and $<\varepsilon^2>^{1/2}$) was done using a previous calibration on prestrained tensile specimens, by performing neutron single line broadening analysis. For the CT_3 sample it was found that the maximum plastic strain in the directions perpendicular (z) and parallel (y) to the crack propagation is localised at 1mm from the tip and it attains about 30% (Figure 3).

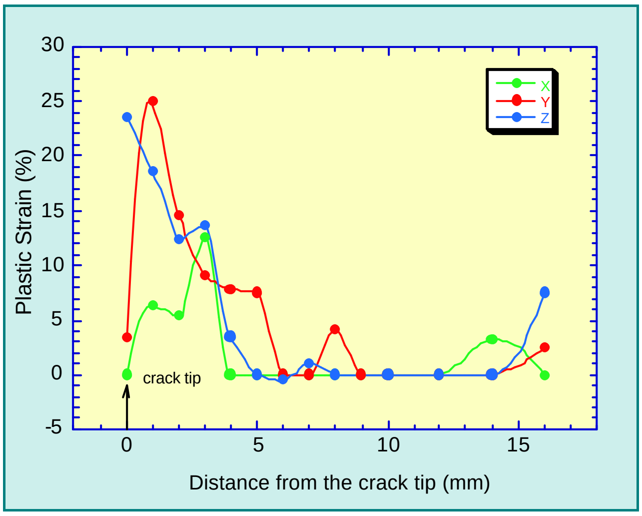

***Figure 3** : Evolution of the plastic strain as a function of the distance from the crack tip, in the sample CT_3, determined by neutron diffraction.*

3. Plastic strains : X-ray measurements

These results, obtained by a single peak broadening analysis, have been completed by a Warren-Averbach analysis using several X-ray (synchrotron radiation) Bragg reflections and higher orders. These complementary measurements were performed at the sample surface on the four circle diffractometer, WDIF4C, installed on the light guide DW22 at L.U.R.E. (Orsay). Plastic strains were determined using a recently developed theoretical model, based on the Warren-Averbach analysis and taking into account the contribution of Elastic Strain Heterogeneity (ESH) of the domains on the profiles broadening [3]. The values obtained for the mean size of the coherently diffracting blocks <L>, the mean square of the 2nd kind micro-strains $<\varepsilon_0^2>^{1/2}$ (related to the ESH effects) and the mean square of 3rd kind micro-strains $<\varepsilon_1^2>^{1/2}$ are reported in Figure 4 as a function of distance from the crack tip. As seen from the figure, the microstructural parameters obtained are quite scattered. This is probably due to the relatively large grain's size compared to the small X-rays beam dimensions and its weak divergence. In particular, the ESH and size effects are the most visible in the region close to the tip (2-3mm). In the region between 4 mm and 9 mm, we obtain very small (or zero) values of plastic deformation and negative values of <L>. This is due to the imprecision of the deconvolution as the Bragg peak breadth is very close to the instrumental width. The calculated size of coherently diffracting blocks, which is about 255Å at the crack tip, corresponds to plastic strain of 30%. The increase of distortion values at the edge of the sample shows the presence of strong plastic strains in this region.

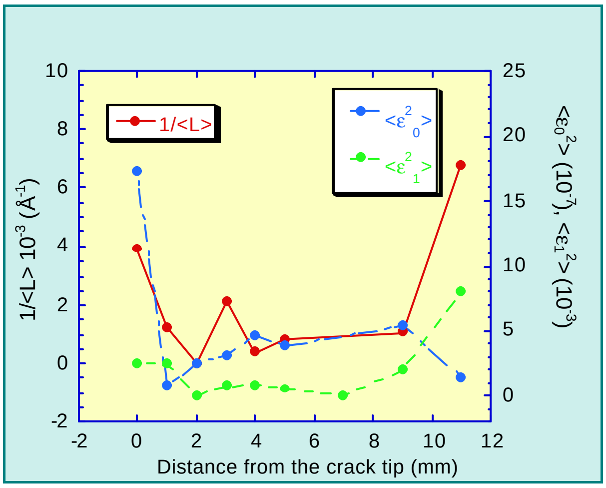

Figure 4 *: Evolution of the diffraction coherent domains size <L>, and of the microstrains* $<e^2_0>$ *(2nd order) and* $<e^2_1>$ *(3rd order) as a function of the distance from the crack trip in the CT_3 sample, determined by Warren-Averbach analysis using synchrotron radiation*

In summary, neutron diffraction has been applied to study the in-depth triaxial stress field and the hardening effect along the crack line in austenitic steel fatigued specimens. For the first time, the plastic zone close to the crack tip has been characterised by the neutron technique using diffraction line broadening analysis [4]. Complementary measurements were made using X-rays (synchrotron radiation) at the sample surface. A quantitative comparison between neutron and synchrotron results is not possible as the ESH is not taken into account in the neutron broadening analysis and the explored regions are not the same.

However, this study has shown that the neutron non-destructive technique, complementary to the X-ray technique, is a powerful tool for mechanical and microstructural characterisation of bulk samples.

References

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