Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 507241

TITLE

MEASUREMENT OF RESIDUAL STRESS, PLASTICITY AND FATIGUE IN 350 WT STEELS BY NEUTRON DIFFRACTION

System Number:

Patron Number:

Requester:

Notes: Paper #38 contained in Parent Sysnum #507203

DSIS Use only:

Deliver to: DK

#507241 (38)

Measurement of Residual Stress, Plasticity and Fatigue in 350 WT Steels by Neutron Diffraction

T.M. Holden and J.H. Fox, Chalk River, ON, Canada K0J 1J0
and J. Pang and T.E. Mason, Physics Dept., Univ. of Toronto, Toronto, ON, Canada M5S 1A7

ABSTRACT

Neutron diffraction measurements have been carried out on 350 WT steel following cyclic loading to investigate the sensitivity of diffraction to fatigue loading. The first series of experiments showed that the measured line-broadening and residual strain correlated well with the degree of plastic deformation in the samples. The second series of experiments were designed to avoid plastic deformation during fatigue loading. Neither the strain nor the line-broadening were found to be correlated with fatigue parameters. A third set of experiments was designed to measure the strain response to applied stress below and above the yield point during tensile testing. The results have a bearing on the interpretation of any diffraction measurements of residual stress on engineering components.

1. Introduction

Portable diffraction techniques could provide an attractive non-destructive method of assessing the history of plastic deformation and the fatigue life of naval vessels by monitoring the residual strain or the diffraction linewidth at a sensitive location on the ship. The studies of 350 WT steel for the frigate program summarized in this paper were initiated by J.Porter to examine this possibility using the methods of neutron diffraction to measure the residual strain and linewidth. Neutron diffraction is analagous to X-ray diffraction, except that neutrons can penetrate 40 mm of steel whereas X-rays only penetrate the first few µm. This means that neutron diffraction is a probe of the whole volume of a sample and can be used to measure strain, texture and linewidth at depth, whereas X-rays from a conventional source give surface stresses, texture and linewidth.

Neutron diffraction has found increasing use over the past decade for solving industrial problems using the facilities at the NRU reactor, Chalk River operated by AECL. Since April 1st 1997 the neutron scattering program has become part of the Steacie Institute of Molecular Sciences of the National Research Council of Canada (NRCC) and is no longer part of AECL. As a result of this we have a wider mandate to serve Canadian industry with the resources of the NRCC behind us as well as preserving our contacts with expertise at Chalk River.

In this paper we summarise first the results of linewidth measurements on 350 WT steels, which showed a strong sensitivity to plastic deformation [1,2] This could have masked a dependence of width and residual stress on the fatigue parameters stress, S, and number of cycles, N, in high cycle fatigue. A second set of experiments [3] were designed to test the sensitivity to S and N in the absence of plastic deformation. We also report preliminary results of tensile test experiments on 350 WT steel at stresses below and above the yield point. These give the strain response of different crystallographic orientations of grains to the applied stress under conditions of plastic deformation. The results have a bearing on any diffraction stress measurements. They also provide test data for constitutive models of the material where the macroscopic properties of an element in a finite element array are calculated from the elastic and plastic behaviour of its constituent grains.

2. Experiments

2.1 Samples

2.1.1 Fatigue at High Maximum Stresses

The samples for the first series of experiments were cut from 350WT plate and fatigue-tested by Fleet Technology Ltd. The material exhibited an (upper) yield point of 480 MPa and an ultimate tensile strength of 546 MPa. Eleven standard hour-glass samples were fatigue-tested at stress ranges between 420 and 498 MPa with a stress ratio of 0.05. Nine of the eleven samples were tested to failure. It was noted that the diameters of the samples were reduced with respect to the pre-fatigue diameters indicating that plastic deformation had occurred. In addition to these samples a further five samples were studied whose fatigue history was not provided to us, and an unfatigued reference sample. Three of these had reduced diameters and had therefore been plastically deformed.

2.1.2 Fatigue at Low Maximum Stresses

The samples for the second series of experiments [3] were cut from a different plate of 350WT steel provided by Fleet Technology Ltd. The flow curve was measured at Chalk River and was characteristic of a carbon steel with a lower yield point of 425 MPa, an upper yield point of 470 MPa and an ultimate tensile strength of 519 MPa. The design of the second experiment required that there should be no plastic deformation to mask the fatigue effects so a symmetrical stress range was chosen with maximum values well below the yield point. With the aid of the "Atlas of Fatigue" [4] it was estimated that the stress ranges given in Table 1 would lead to the postulated number of cycles to failure. Measurements were made at 25%, 50%, 75% and 100% of these numbers of cycles in five samples together with a standard reference sample.

Table 1

Stress Range (MPa)	% of fracture strength	# of cycles
±235	45	10^6
±245	47	10^5
±255	49	5.10^4
±275	53	10^4
±295	57	10^3

2.2 Neutron Diffraction

The experiments were carried out on spectrometers at the NRU reactor at Chalk River employing neutrons of wavelength near 2Å reflected from the (331) planes of silicon and germanium monochromators. The incident and diffracted beams were highly collimated and gave instrumental linewidths of 0.26° and 0.22° for the first and second experiments respectively. To obtain high precision in the measured strains and linewidths, the maximum intensity in the peak was several thousand counts and the time to accumulate each peak was about eight hours. The samples were mounted vertically on a sample changer and the diffraction response studied was perpendicular to the direction of stress applied during the fatiguing of the samples. The peak position, 2θ, the integrated intensity and the linewidth, Δ_m, were obtained by fitting a Gaussian peak plus a sloping background to the data of counts versus angle. In a diffraction experiment, the spread of wavelengths and the finite collimation contribute to an instrumental linewidth, Δ_I .The instrumental linewidth was determined from the linewidth of the reference sample. The intrinsic linewidth due to plasticity or fatigue is found by subtracting Δ_I from Δ_m in quadrature as follows,

$$\Delta^2=\Delta^2_m-\Delta^2_I \qquad (1)$$

The lattice spacing is found from the angle of diffraction, 2θ ,with the aid of Bragg's law knowing the wavelength, λ, as follows,

$$\lambda=2d\sin(\theta) \qquad (2)$$

The strain is calculated with respect to the reference lattice spacing d_{ref} as follows,

$$\varepsilon=(d-d_{ref})/d_{ref} \qquad (3)$$

The precision of a typical linewidth measurement is about ±0.004° and the precision of the intrinsic linewidth is about ±0.015°. The precision of a strain measurement, taking into account the uncertainty in both the sample and the reference is about $\pm0.8.10^{-4}$.

2.3 Results

2.3.1 Fatigue at High Maximum Stresses

For the samples which had broken under fatigue testing the diameters decreased towards the surface of the sample, so that the plastic deformation increased as the fracture surface was approached. Measurements of linewidth and residual strain were made as a function of distance from the fracture surface and it was found that the linewidth increased as the break was approached[1]. Measurements were also made on the six unbroken samples at the mid-height of the sample and 5mm above and below the mid-height. The intrinsic linewidth and the residual strains for all these samples are plotted against the plastic deformation deduced from the diametral reduction in Figs. 1 and 2. The intrinsic widths for all samples and positions fall on a single master curve when plotted against plastic deformation. A similar master curve is observed for the compressive residual strains, although there is more scatter. It was concluded from this series of experiments that the width was a good indicator of plasticity, but that the dependence on plasticity would mask any dependence on fatigue parameters.

2.3.2 Fatigue at Low Maximum Stresses

The differences between the linewidth in the fatigued samples and the reference sample for the measurements at 25%, 50%, 75% and 100% of the nominal fatigue life are shown in Fig. 3. Note that the absolute differences are plotted rather than the differences in quadrature. This is because the widths are scattered about the reference value and are as likely to be positive as negative. Within the experimental uncertainty we have observed no change in the diffraction linewidth. Likewise, to within the experimental uncertainty there was no fatigue-induced residual strain. There was no change of sample diameter and therefore no plastic deformation.

2.3.3 Tensile Test Experiments

Standard dogbone samples were cut from the second plate, see section 2.1.2, and mounted in an automated Universal Testing Machine installed on a spectrometer at the NRU reactor, Chalk River. Measurements were made on three samples oriented so that the strains were measured along the plate transverse direction (TD), the plate rolling direction (RD) and the rolling plane- normal direction (RPN).In each case the applied stress was applied along the rolling direction. An extensometer was mounted on the sample to measure the total strain in the direction of the applied stress. The UTM was operated in a constant stress mode. At each stress the (002),(112),(220) and (222) diffraction peaks were measured and the lattice spacing ,width, and peak intensity obtained. The initial lattice spacing for each reflection was obtained by extrapolation of the initial elastic response to zero stress. Measurements were made below the yield point to obtain the diffraction elastic constants and above the yield point to a maximum stress of 475 MPa to observe the development of the intergranular strains. Figure 5 shows the axial strain response parallel to the stress direction for the (220) and (002) peaks. For the (220) case there is little departure from the linear elastic behaviour even above the yield point. However, for the (002) case there is a strong departure from the linear response above the yield point and upon unloading to zero stress there is a sizable residual tensile strain. For the (112) reflection essentially no residual strain is observed and for the (222) reflection a tensile strain is recorded. These effects are not macroscopic strains but are intergranular or Type 2 strains on the scale of the grain size. They originate in the different plastic and elastic response of grains of different crystallographic orientations to an applied stress which exceeds the yield point. The sum of all these grain stresses in a given direction would be expected to balance to zero and the observation of some positive and some negative strains indicates that this is the case qualitatively.

The response perpendicular to the applied stress has also been obtained after cycling to 475 MPa and in this case the (220) strain is compressive, $(-3.5\pm1).10^{-4}$, while the (002) transverse strain is still tensile, $(3\pm1).10^{-4}$. Recall that the strain response perpendicular to the fatigue axis in the first series of experiments, Fig.2,was also compressive so that the two very different experiments are in agreement. The intergranular residual strains in the direction of the applied stress in the unloaded state observed for all four reflections are plotted in Fig. 6 as a function of the plastic strain. Use is made in Fig. 6 of two intermediate cycles of stress versus strain not shown in Fig.4. The results clearly show that (112) exhibits the smallest intergranular strain, that (220) grains show a slightly tensile effect, (222) grains show a compressive effect and (002) grains show a strong tensile effect. When measurements are made of an engineering component, the measured strain is the sum of Type 1, macrostrains and Type 2, intergranular strains and there is no non-destructive way of distinguishing them. If this measured strain is used with the other orthogonal components, together with the appropriate diffraction elastic constants, the calculated stresses will not be the macrostresses of interest to the engineer but a combination of macrostresses and microstresses. It is important to use reflections which are least sensitive to intergranular strains or to correct the data for the intergranular part. This work forms part of the Doctoral thesis of J.W.L. Pang at the University of Toronto.

4. Discussion

The physical manifestation of fatigue damage is the appearance of slip-bands on the surface of a sample which has been highly polished. Since, in high-cycle fatigue, the applied stress never exceeds the yield point local stress-risers have to be present to generate localized plastic deformation. This, in turn, generates localized slip-bands, particularly near the sample surface. However the depth of the slip-bands is only of order 10μm. Neutron diffraction probes the whole volume of a sample, by virtue of the high penetration of the neutron . On the basis of the fraction of the total volume represented by a continuous 10μm surface region, about 1% at most, neutron diffraction is insensitive to surface-localized deformation. On the other hand, X-rays are sensitive to the surface layers because of their 2-3μm penetration. However, one still has to locate the slip-band region. Previously X-rays have been used to detect fatigue damage under special conditions. The perfection of crystal alignment is destroyed by fatigue, and this appears as an increase in the mosaic spread of the sub-grains making up a single grain. Holden [5] looked inside a fatigue crack, where slip-bands are sure to be present, with an X-ray beam of order the size of the grains and observed the development of misalignment of the sub-grain structure. Regular powder diffraction from a polycrystalline sample does not give the required result since many grains are sampled, which are nearly randomly oriented and any further sub-grain misorientation is essentially masked.

5. Acknowledgements

We wish to acknowledge the help of R. R. Hosbons in arranging for the fatigue tests and for his advice on the microstructural effects of fatigue. A.P. Clarke played an important role in distinguishing between the effects of plasticity and fatigue in the first series of experiments. J. Porter initiated this work and provided strong support for it.

6. References

[1] A .P. Clarke, T. M. Holden and J. H. Fox, Available AECL report, ANDI-100, Sept. 1995.
[2] A.P.Clarke, T.M.Holden, J.F. Porter and R. Yee, Proc. Of the 2nd Canadian Forces/CRAD Meeting on Naval Applications of Materials Technology, 1995 May 2-4..
[3] T. M. Holden and J.H. Fox, Available AECL report, ANDI-108, March 1997.
[4] H. E. Boyer, "Atlas of Fatigue", (A. S. M. :Metals Park, Ohio) 1986, p28.
[5] J. Holden, Phil. Mag. 61, 547, 1961.

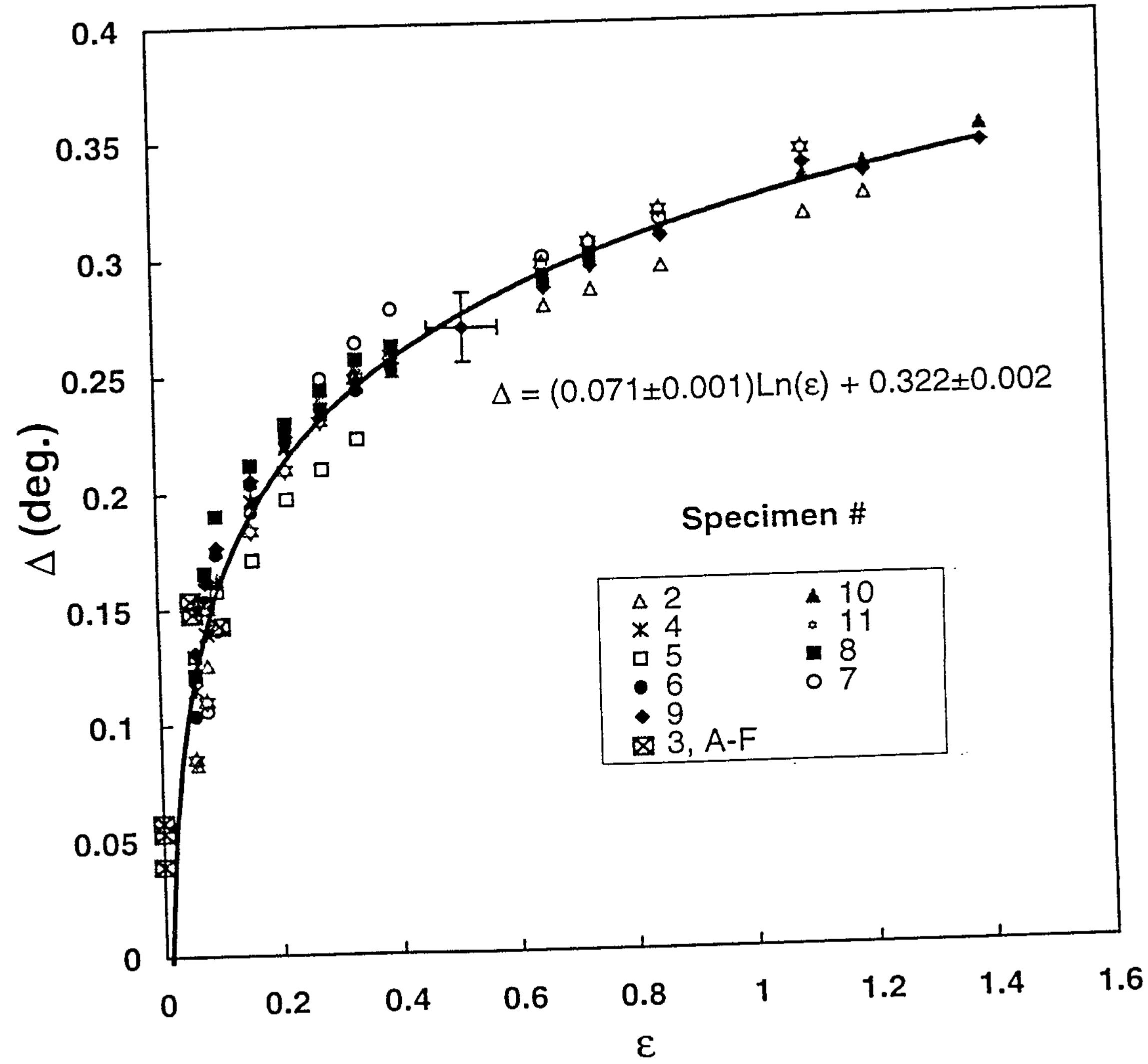


Fig. 1 Intrinsic linewidth versus plastic deformation for samples of 350WT steels fatigued at stresses close to and exceeding the yield point.

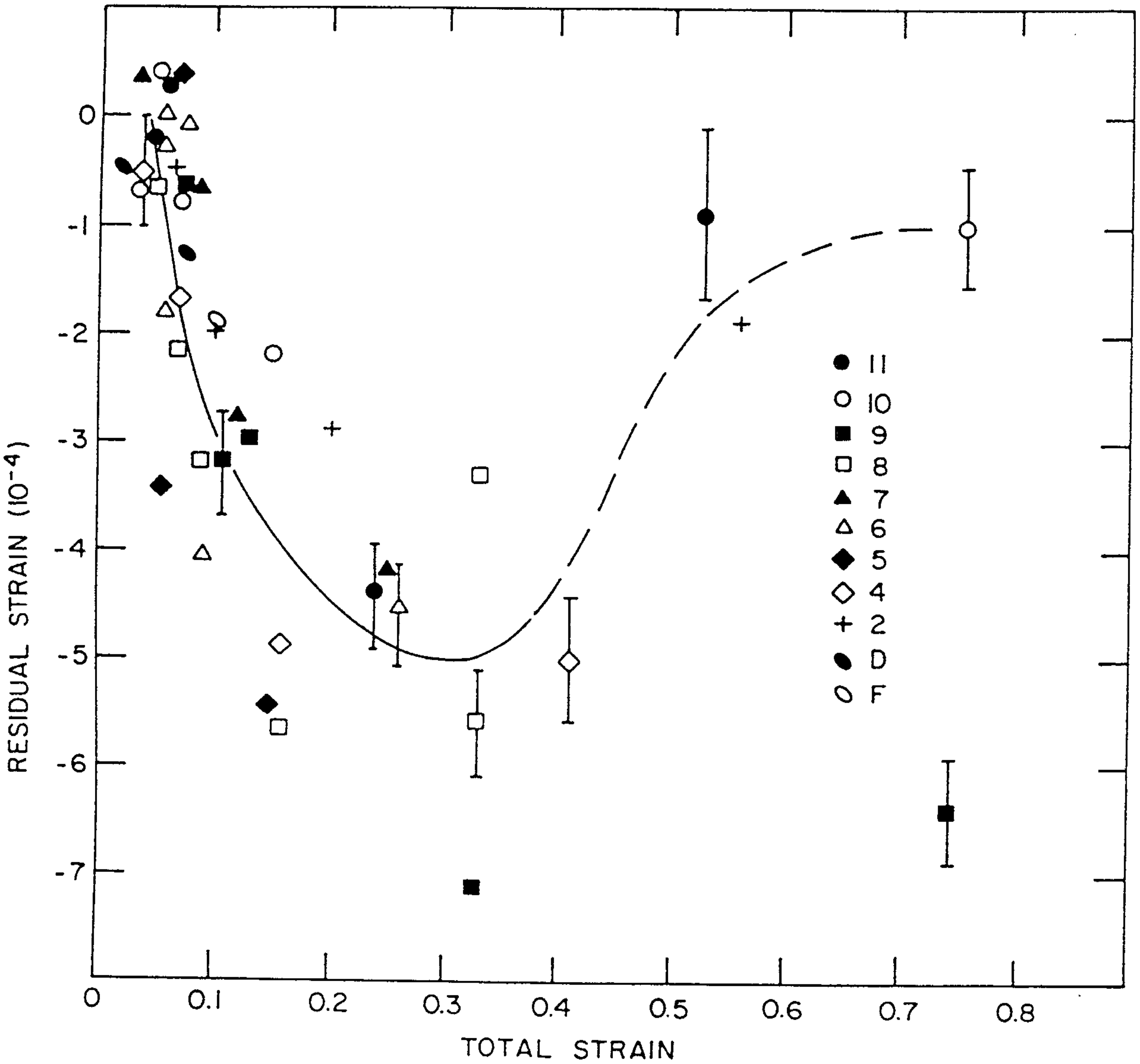


Fig.2 Residual strain versus plastic deformation for samples of 350WT steels fatigued at stresses close to and exceeding the yield point.

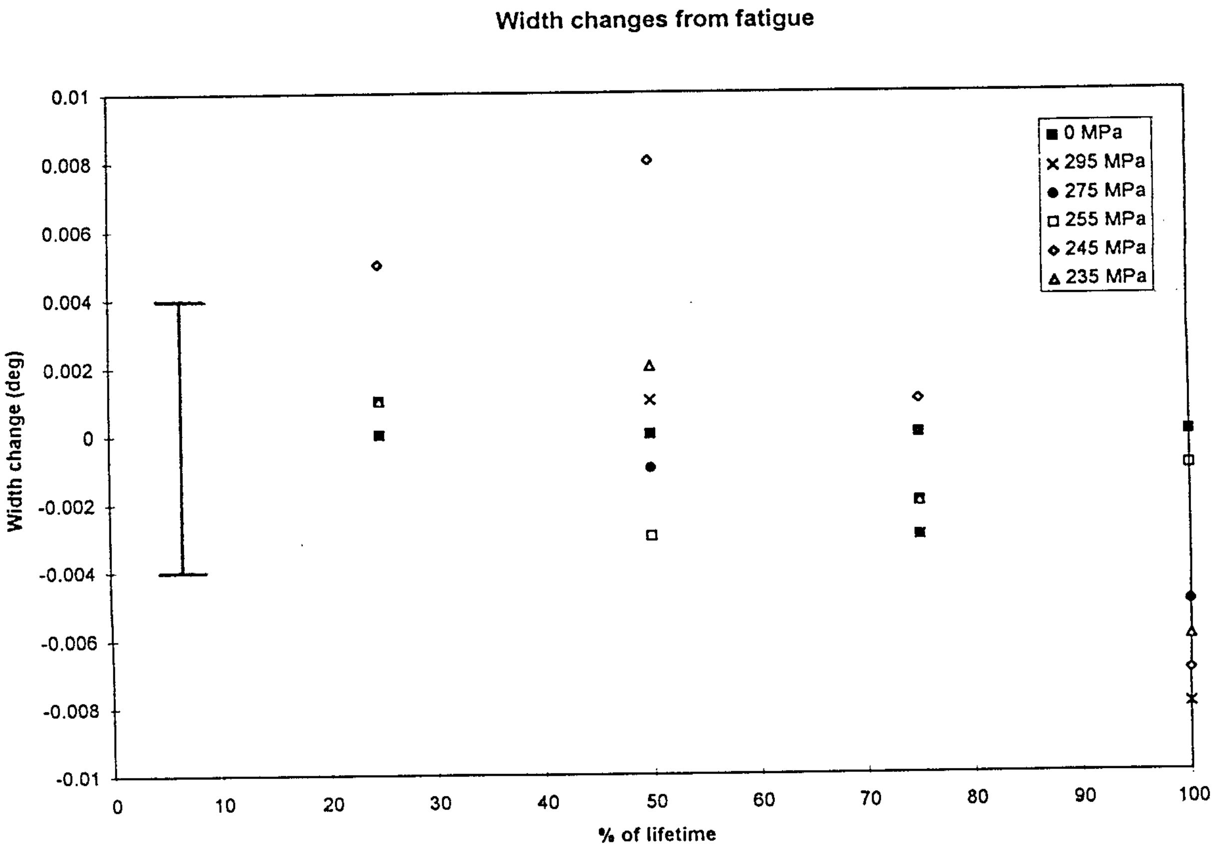


Fig. 3 Differences between linewidths of 350WT samples and a reference sample after fatiguing with no plastic deformation.

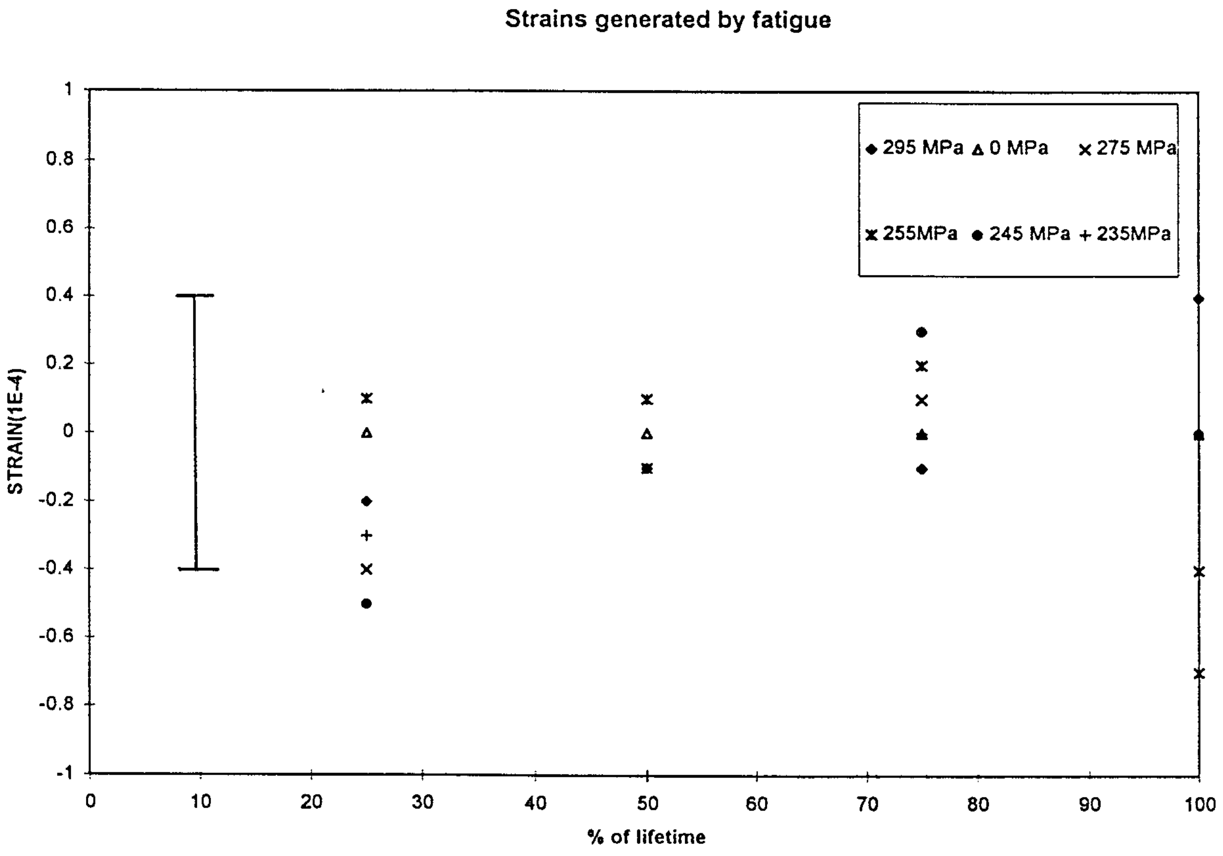
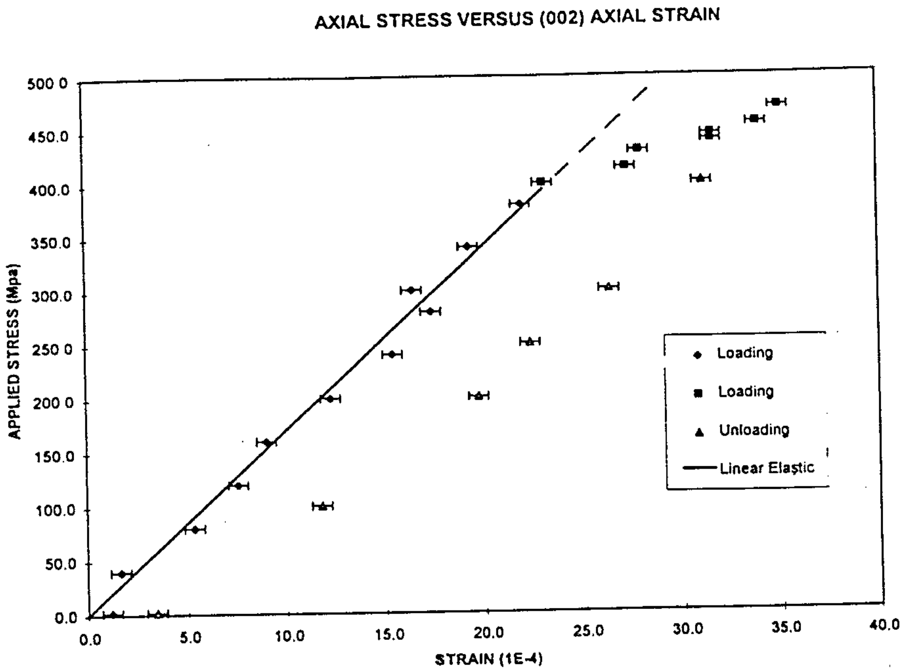


Fig. 4 Residual strains in 350WT samples with respect to a reference sample after fatiguing with no plastic deformation.


AXIAL STRESS VERSUS (002) AXIAL STRAIN

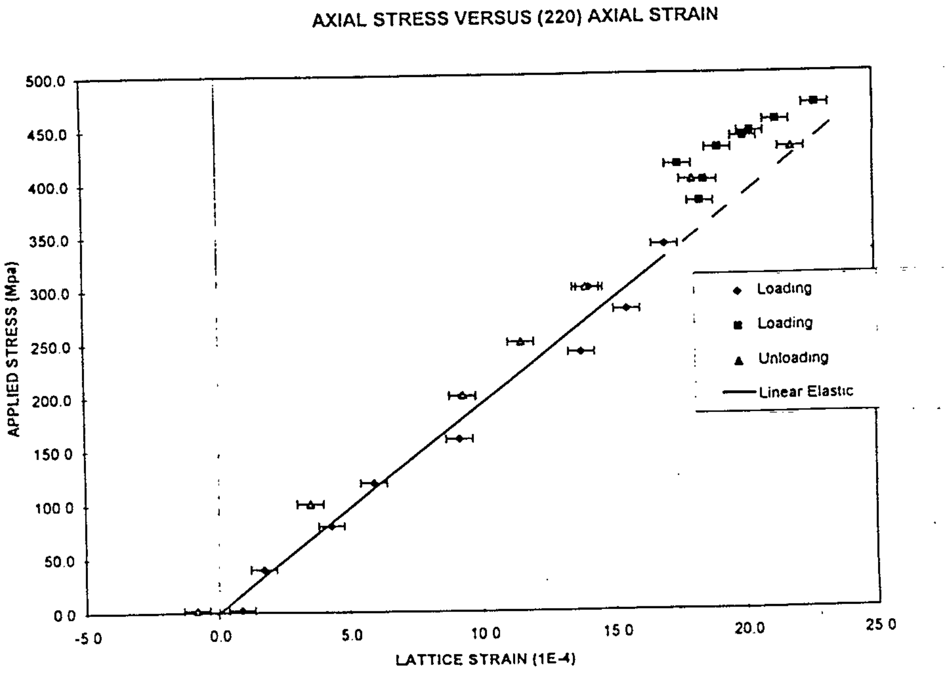

AXIAL STRESS VERSUS (220) AXIAL STRAIN

Fig. 5 Applied stress versus lattice strain for (220) and (002) grains in 350WT tensile test samples. The strain component measured is parallel to the stress axis.

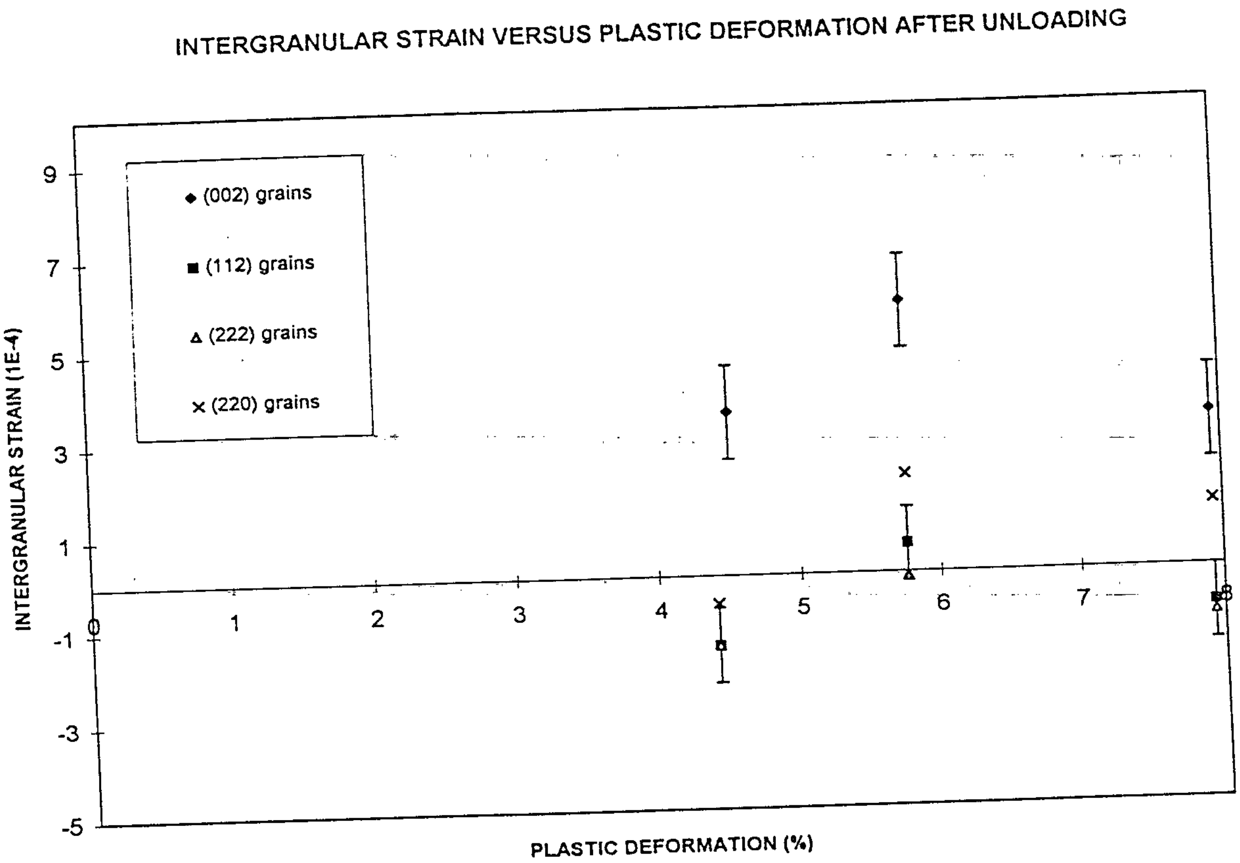


Fig. 6 Intergranular residual strain in 350 WT samples in the direction parallel to the stress axis as a function of plastic deformation.