CHARACTERIZATION OF THE FATIGUE BEHAVIOR OF AUSTENITIC STEEL USING HTSL-SQUID

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INTRODUCTION

The assessment of the actual fatigue damage and thus the remaining lifetime of materials is a subject of enormous scientific and economical relevance. In spite of intensive research work the quantitative evalution of fatigue damage by means of nondestructive methods in order to calculate the remaining lifetime is still impossible. This paper will describe some aspects of the cyclic deformation behavior of the metastable austenitic steel AISI 321 which is often used in power stations and chemical plant constructions. The main aim of the present investigation is to determine the fatigue damage of cyclically loaded austenitic steel specimens by detecting the plasticity induced martensite content with the help of the SQUID measuring technique [1-4].

MATERIAL

The material investigated was a metastable austenitic steel of the type X6CrNiTi1810 corresponding to the US-grade AISI 321. After the solution annealing the microstructure is characterized by a mean grainsize of about 35 μm, a small amount of Cr- and Ti-carbides and a δ-ferrite content of about 0,05 %. A typical microstructure, the chemical composition and the mechanical properties of the test material are shown in Fig. 1 and Tab. I and II.

Table I. Chemical composition (wt-%).

C	Si	Mn	P	S	Cr	Ni	Ti
0,04	0,44	1,14	0,033	0,004	17,74	9,3	0,35

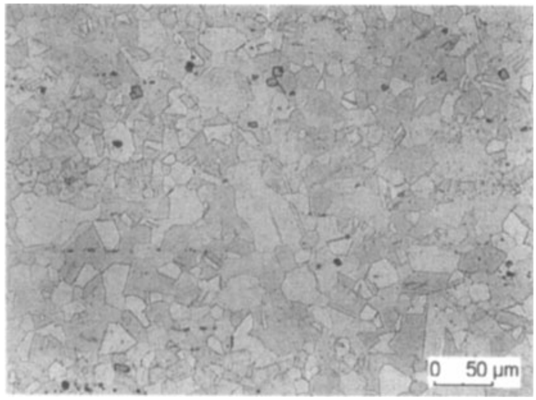

Figure 1. Micrograph of X6CrNiTi1810 (AISI 321) after solution annealing.

The investigated steel tends to transform from austenite to α`-martensite . The transformation depends on kinetic factors and requires a driving force from cooling or quasi-static and cyclic plastic deformations respectively. In order to initiate the phase transformation a certain threshold value of cumulated plastic strain has to be exceeded [5,6]. The stability of austenitic steels, i.e. the resistance against martensitic transformation mainly depends on their chemical compostion. For the determination of the existing phases at room temperature the Schaeffler-Diagram shown in Fig. 2a can be used [7]. The steel X6CrNiTi1810 is placed in the region of austenite and δ-ferrite quite close to the region of stable martensite. Thus martensitic transformation at least due to local chemical inhomogeneities could be expected. But even in the case of complete homogeneous distribution of the alloying elements and a postion outside the region - austenite, martensite, δ-ferrite- martensitic transformation could occur as a consequence of sufficiently high plastic deformation.

Fig. 2b gives a thermodynamic interpretation of the phase stability as a function of free enthalpy and temperature. To induce phase transformation a certain undercooling ΔT below T_0 is necessary. Due to plastic deformation the martensite formation starts at M_d a temperature somewhat higher than the thermodynamic defined martensite start temperature M_s. Without plastic deformation a martensite start temperature M_s of -124°C is calculated for the steel X6CrNiTi1810. The $M_{d,30}$ -temperature for the investigated material is calculated to be 25°C .

Table II. Mechanical properties.

$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	$R_{p0,2}/R_m$ [%]	Magnetic Phase [%]
214	583	60	36,7	<1

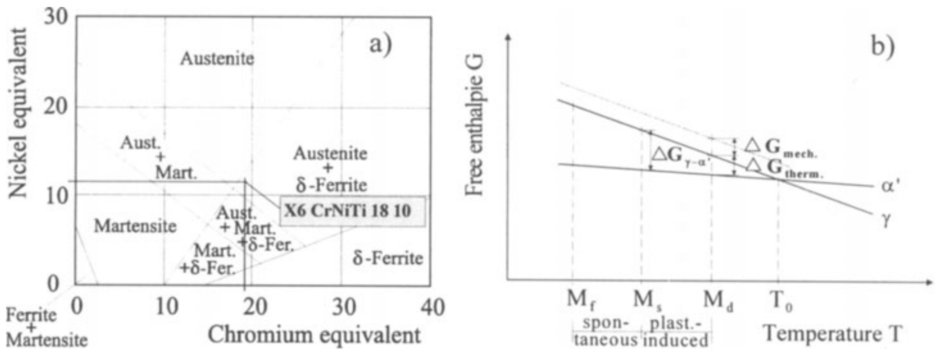

Figure 2. a) Schaeffler-Diagram; b) Free enthalpie-temperature-Diagram.

EXPERIMENTAL METHODS

The fatigue tests were performed on a 100 kN servohydraulic testing machine under stress and total strain control at room temperature and T=300°C with R= -1, a frequency of 5 Hz and triangular load-time functions. Fig. 3 shows the characteristic values of a hysteresis loop for elastic-plastic deformation with $\sigma_m > 0$ MPa. Under cyclic loading, at amplitudes above the fatigue limit, microstructural processes change the stress-strain-relationship in a characteristic manner and cause crack initiation after a certain number of cycles. It is a common agreement to use cyclic deformation curves where the plastic strain amplitude is plotted as a function of the number of cycles to describe the cyclic deformation behavior of metallic materials [8].

EXPERIMENTAL RESULTS

<u>Quasi-static:</u>

In Fig. 4 a characteristic quasi-static stress-strain curve together with the magnetic fraction as a function of the total strain is plotted. The magnetic fraction increases with increasing strain. At the same time the special etched micrographes appended to the stress-strain-curve reveal an increasing percentage of martensite (dark areas). This example clearly confirms the direct relation between the martensite fraction and the plastic strain.

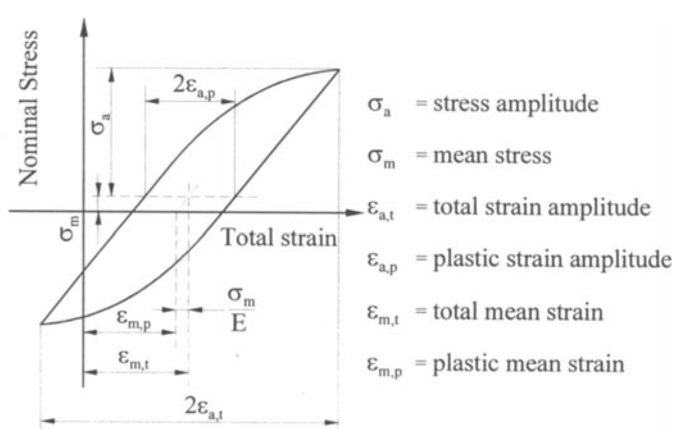

Figure 3. Hysteresis loop for elastic-plastic deformation with $\sigma_m > 0$ MPa.

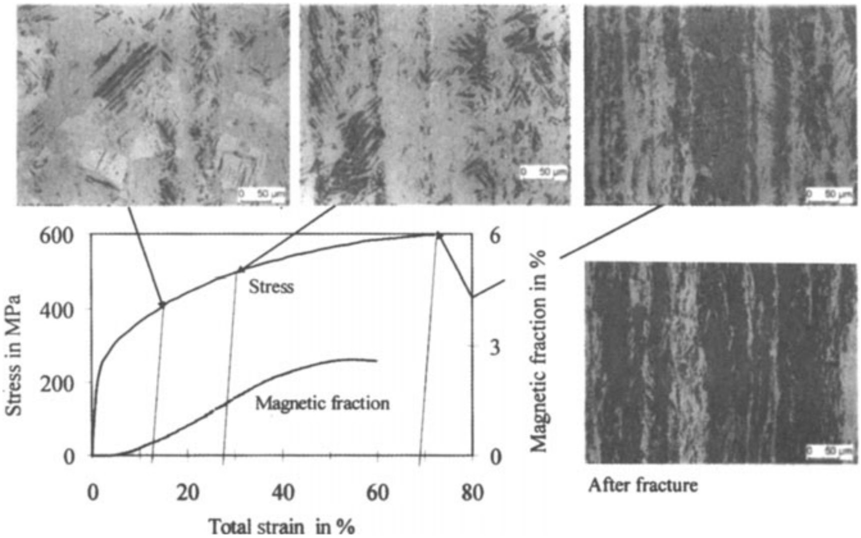

Figure 4. Quasistatic plasticity induced martensite formation at room temperature.

Cyclic deformation behavior:

Characteristic results of stress controlled fatigue tests at room temperature and T=300°C are shown in Fig. 5. The development of the plastic strain amplitude as a function of the number of cycles at constant stress amplitudes represents the microstructural changes in the tested material. The cyclic deformation curves reveal 3 different phases: primary cyclic hardening with decreasing $\varepsilon_{a,p}$, cyclic softening with increasing $\varepsilon_{a,p}$ and secondary cyclic hardening with again decreasing $\varepsilon_{a,p}$. The hardening and softening effects are more pronounced at higher stress amplitudes. As expected the secondary hardening, which is caused by plasticity induced martensite formation, is less pronounced at T=300°C. Simular results are received under total strain control. But in general the cyclic softening and hardening processes are less pronounced compared to stress controlled tests. Especially at T=300°C the plastic strain amplitude is nearly constant (Fig. 6). Eleven tests carried out with identical loading parameters illustrate the relatively small scattering band of the cyclic deformation curves of $\Delta\varepsilon_{a,p}<10^{-3}$. This point is important for the interpretation of the following Eddy Current and the SQUID-measurements.

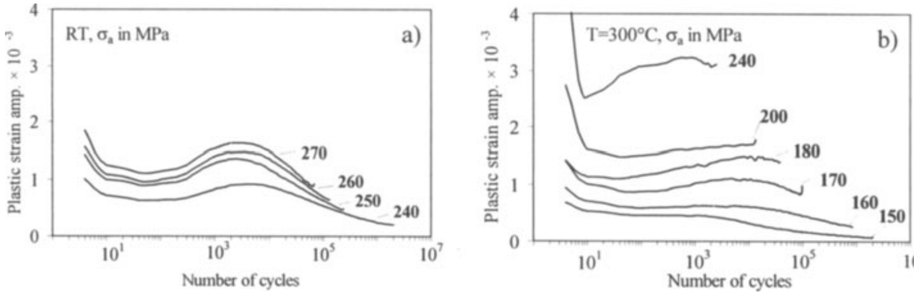

Figure 5. Influence of temperature on stress controlled cyclic deformation curves:
a) RT; b) T=300°C.

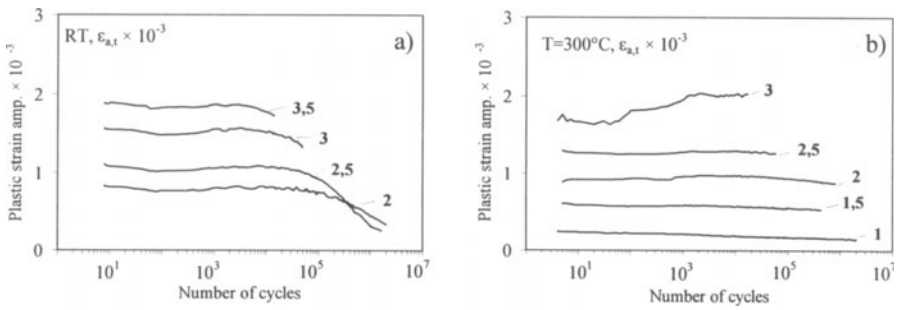

Figure 6. Influence of temperature on total strain-controlled cyclic deformation curves: a) RT; b) T=300°C.

In Fig. 7 a typical cyclic deformation curve at room temperature with cyclic hardening, softening and hardening phases is shown. In the same graph the development of the magnetic fraction is plotted. The magnetic transformation starts at about $2{\cdot}10^4$ cycles if a certain plastic strain is accumulated. This graph obviously shows that the secondary cyclic hardening is caused by the martensite formation. The dark areas in the micrographs underline the increasing amount of martensite with increasing number of cycles. Fig. 8 contains simular results for a test at T=300°C. The shape of the cyclic deformation curve corresponds to the room temperature one. But at T=300°C the amount of plasticity induced martensite is extremly small and not detectable with the Eddy Current Technique. Also in this case the micrographs appended to the cyclic deformation curve show a certain increase of martensite.

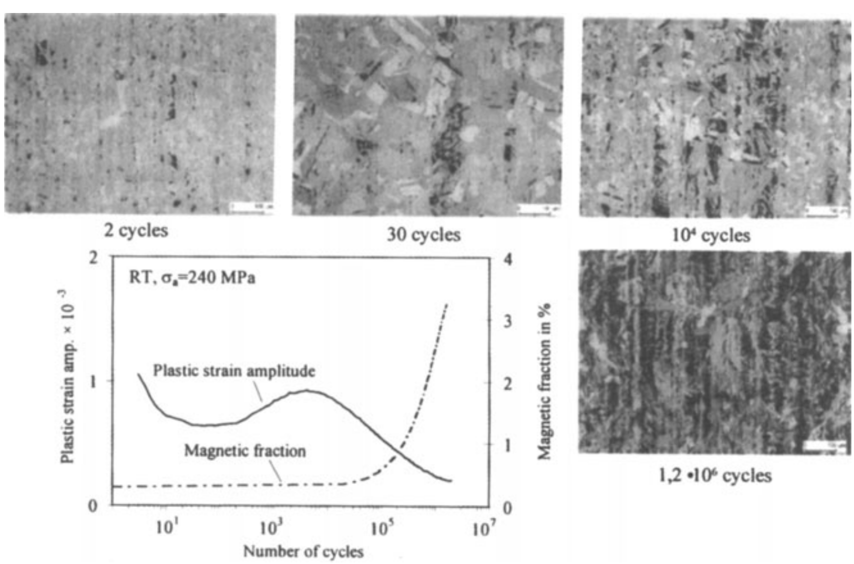

Figure 7. Cyclic plasticity induced martensite formation at room temperature.

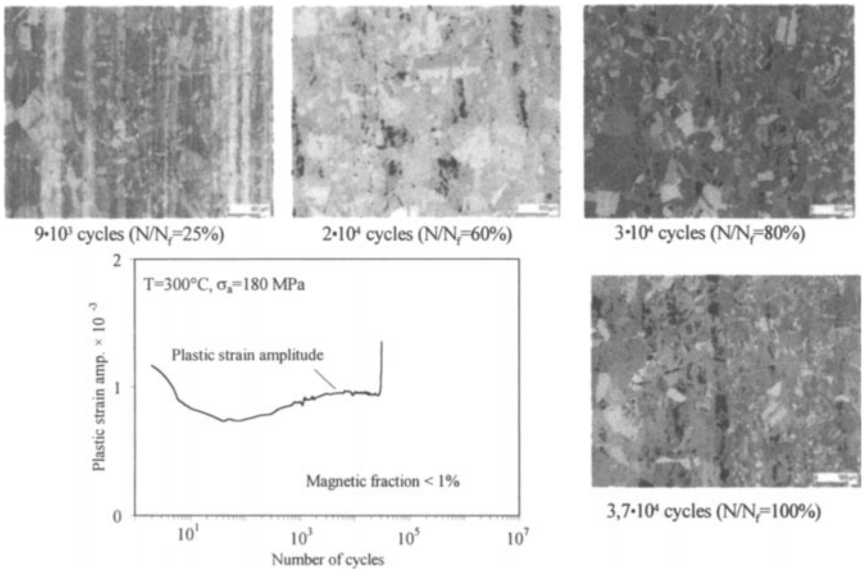

Figure 8. Cyclic plasticity induced martensite formation at T=300°C.

SQUID-measurements

In order to have a chance to measure very small amounts of plasticity induced martensite a SQUID-magnetometer developped from ISI, Forschungszentrum Jülich, Germany was used. The measuring equipment consists of a cryostat with the HTSL-SQUID, a x,y-scanning table, magnetic shielding, control unit and a data analysis system as shown in Fig. 9.

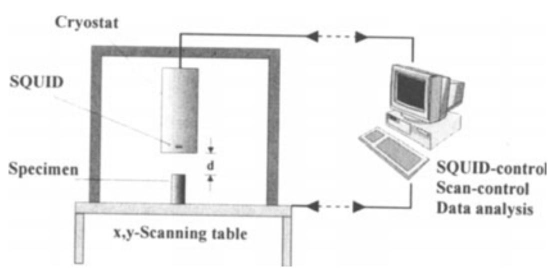

Figure 9. SQUID-magnetometer.

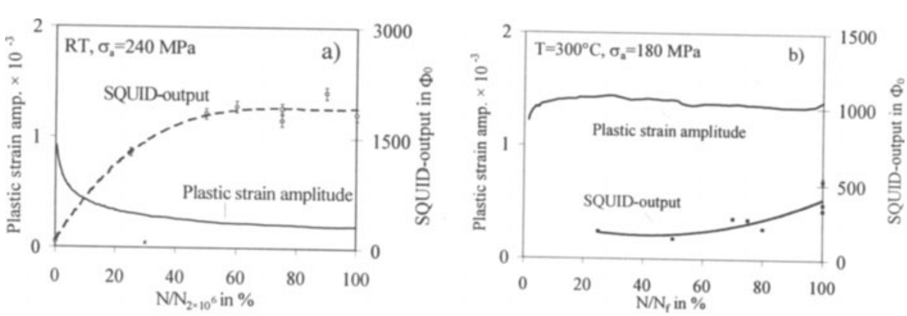

Figure 10. SQUID-magnetometer measurements: a) RT; b) T=300°C.

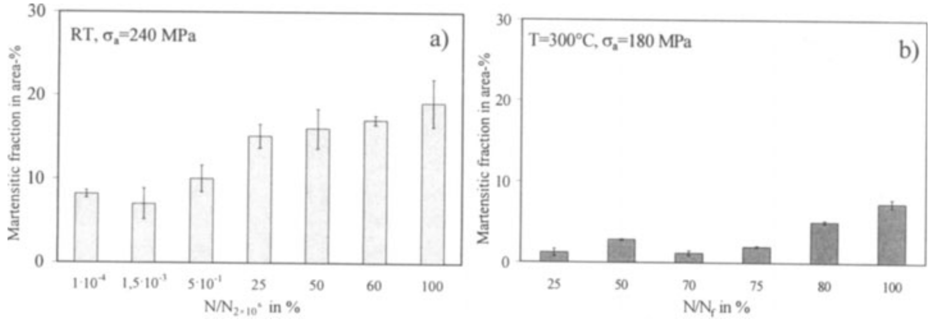

Figure 11. Quantitative microstructure analysis: a) RT; b) T=300°C.

The aime was to measure the remanent magnetization of the specimens out of a definite distance from the SQUID and to get by this an information about the amount of plasticity induced martensite in the austenitic matrix opening possibilities to estimate the actual fatigue damage.

In Fig. 10 characteristic results of the SQUID-measurements are plotted. Two sets of specimens at RT and T=300°C were investigated in defined states of magnetization. Cylindrical samples representing the actual fatigue state were taken from the gauge length of the specimens after different numbers of cycles. First experiments revealed that those specimens behave like magnetic dipols. The remanent magnetization of these specimens is plotted together with the plastic strain amplitude as a function of the life-time fraction. As expected the magnetic field values are much higher for the RT-samples than for those fatigued at T=300°C. This is caused by the much higher volume fraction of martensite at RT compared to T=300°C, additionally determined with quantitative image analysis (Fig. 11). The smaller amount of martensite is also the reason for the only slight changes of the plastic strain amplitude at T=300°C.

Fig.12 finally shows the development of the remanent magnetic field for three different specimens cycled at T=300°C and σ_a=180 MPa as a function of the life-time fraction. All specimens reveal the same tendency in respect to the SQUID-signal with increasing fatigue damages. The distance betweeen the three curves is caused by microscopic differences in the microstructure of the investigated steel.

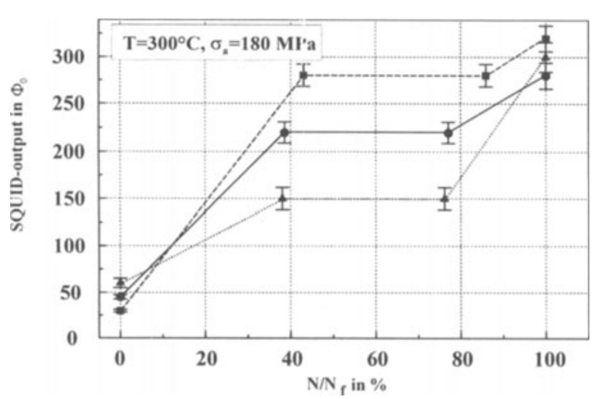

Figure 12. Continuous SQUID-magnetometer measurements.

SUMMARY

The experiments reveal characteristic cyclic deformation curves and corresponding Eddy Current and SQUID signals according to the actual fatigue state. The extremely sensitive SQUID measuring technique provides the possibility to detect phase transformations in specimens fatigued at a temperature of T=300°C in which the phase fractions of plasticity induced martensite are extremely low. This information could not be detected with other nondestructive testing techniques. Light and electron microscopic investigations additionally confirm the correlation of the nondestructively obtained results with the measured fatigue induced stress-strain state of the material.

ACKNOWLEDGEMENTS

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