The monitored resonant behavior of fatigue specimens of metastable austenitic stainless steel (AISI304) is correlated with its damage accumulation in the very high cycle fatigue (VHCF) regime. The resonant behavior is studied experimentally and shows a distinct transient characteristic. Microscopic examinations indicate that during VHCF a localized plastic deformation in shear bands arises on the specimen surface. Hence, this work focuses on the effect of damage accumulation in shear bands on the resonant behavior of AISI304 in the VHCF regime. A microstructural simulation model is proposed that takes into account specific mechanisms in shear bands proven by experimental results. The simulation model is solved numerically using the two-dimensional boundary element method and the resonant behavior is characterized by evaluating the force-displacement hysteresis loop. Simulation of shear bands agrees well with microscopic examinations and plastic deformation in shear bands influences the transient characteristic of the resonant behavior.


Keywords shear bands, resonant behavior, very high cycle fatigue, boundary element method

Nowadays many structural components such as railway wheels, offshore structures, load bearing parts of automobiles, etc., have to endure a very high number of loading cycles (well beyond 10 million cycles). To guarantee the safety of human, machine, and environment, the investigation of fatigue mechanisms in the very high cycle fatigue (VHCF) regime becomes more and more important. In this regime, particular attention has to be paid to the localized plastic deformation. Localization of cyclic plastic deformation in metastable austenitic stainless steel (AISI304, initially purely austenitic condition) is conducted by motion of dislocations which are arranged in shear bands.

The experimentally observed resonant behavior of AISI304 in the VHCF regime shows a distinct transient characteristic. In order to identify the microstructural changes relevant for the transient characteristic, in the present study the damage accumulation in shear bands is modeled and its effect on the resonant behavior is investigated. Therefore, specific shear band mechanisms...
are proposed and incorporated into a simulation model. The two-dimensional (2D) boundary element method (BEM) is used to solve the model numerically.

In the following paragraphs at first the results of experimental examinations in terms of the transient characteristic of the resonant behavior and microscopically analyzed changes in the microstructure are given. Then, the simulation model is presented followed by a short explanation of the numerical method. After presenting a procedure to determine the resonant behavior based on the results from simulated microstructural changes, the effect of damage accumulation in shear bands on the resonant behavior is investigated regarding the morphology of a real microstructure.

The resonant behavior of AISI304 is studied experimentally by means of a resonance testing machine, which readjusts the excitation resonant frequency during testing (stress ratio \(R = -1\)). The S–N-curve is given in Ref. 1 and points out a true fatigue limit of about 240 MPa. In Fig. 1 two separate curves for the testing frequencies over cycles are shown. The lower curve indicates the testing frequencies measured at a stress amplitude in the range of the VHCF strength (240 MPa), representing the damped resonant frequency \(f_{\text{res}}\) of the specimen-machine system. It describes a distinct transient characteristic over cyclic loading consisting of cyclic softening (decrease of \(f_{\text{res}}\)) followed by cyclic hardening (increase of \(f_{\text{res}}\)). In contrast, the upper curve indicates the testing frequencies at a stress amplitude of 50 MPa measured at distinct fatigue stages that were reached due to testing at 240 MPa. These frequencies represent the resonant frequency \(f_0\) of the sample without the damping effect of plastic deformation (note the small changes in frequency).

![Fig. 1. Damped (\(f_{\text{res}}\)) and undamped (\(f_0\)) resonant frequencies during cyclic loading of AISI304 (loading amplitude 240 MPa).](image)

In the present study confocal microscopy was used to obtain quantitatively the expansion of localization of plastic deformation in shear bands. Figure 2 shows a beginning increase in the number and markedness of visible slip markings on the specimen surface in the early stages of fatigue and stagnation after \(2 \times 10^5\) cycles. Correlation of these results with the lower curve in Fig. 1 indicates that cyclic softening (drop of \(f_{\text{res}}\)) seems to be associated to an increase of plastic deformation in shear bands and cyclic hardening (increase of \(f_{\text{res}}\)) may be related to a stagnation of plastic deformation in shear bands.

Mechanisms proposed in Ref. 2 are used to model the localization of cyclic plastic deformation in shear bands and are briefly summarized as follows. When a critical resolved shear stress is exceeded in the most critical slip system, a shear band is formed at the corresponding site in the microstructure.
Numerical investigation of the influence of shear band localization

Fig. 2. Slip marking on the specimen surface after (a) $10^4$, (b) $8 \times 10^4$, (c) $2 \times 10^5$, and (d) $2 \times 10^7$ cycles measured by means of confocal microscopy (loading amplitude 240 MPa).

The theory of dislocation pile-ups at grain boundaries enables the determination of the characteristic dislocation distribution leading to the quantitative sliding distribution along the shear band.

The cyclic slip irreversibility is taken into account by approximating the shear band by two closely located layers, where dislocation motion happens separated in compressive and tensile loading. In this way an irreversible fraction of sliding can be accounted on the layer that is inactive in each case (details see in Ref. 6).

Hardening is considered by linearly increasing the critical resolved shear stress depending on the plastic slip deformation in the shear band.

The effect of the suggested shear band model is investigated using the 2D BEM. The basic structure of the method consists of the displacement boundary integral equation being used on the external boundary $\Gamma_b$ (grain and phase boundaries), and the stress boundary integral equation being applied on the slip line faces $\Gamma_s$ (shear bands). Tractions $p_i$ and displacements $u_i$ are prescribed on the external boundary $\Gamma_b$, while stresses $\sigma_{\alpha\alpha}$ and relative displacements $\Delta u_i$ are considered on one face $\Gamma_s$ of the slip line. The displacement boundary integral equation for a solid containing a slip line is

$$c_{ij} u_i = \int_{\Gamma_b} (u^\ast_{ij} p_i - p^\ast_{ij} u_i) \, d\Gamma + \int_{\Gamma_s} p^\ast_{ij} \Delta u_i \, d\Gamma,$$

where $c_{ij}$ equals 0.5 when $\Gamma_b$ is smooth. $p^\ast_{ij}$ and $u^\ast_{ij}$ (given in Ref. 2) are the traction and the displacement fundamental solutions, respectively. Substituting Eq. (1) into Hooke’s law yields the stress boundary integral equation as

$$\sigma_{ij} = \int_{\Gamma_b} (d^\ast_{ij} p_i - s^\ast_{ij} u_i) \, d\Gamma + \int_{\Gamma_s} s^\ast_{ij} \Delta u_i \, d\Gamma,$$

where $d^\ast_{ij}$
and $s_{ij}^*$ are the stress and the higher-order stress fundamental solutions, respectively.\(^2\)

By use of the continuity condition, several homogeneous solids or substructures (each one representing a grain with its individual anisotropic elastic properties) can be combined to a continuous microstructure.\(^7\)

A prediction of the effect of microstructural changes due to plastic deformation in shear bands on the resonant behavior requires a procedure to describe the resonant behavior based on the results from the microstructural simulations. With the use of both the viscous and the hysteretic damping model\(^8\) an equivalent damping ratio $D$ and the resonant frequency ratio $\eta_{\text{res}}$ as a describing parameter for the resonant behavior can be identified. By means of energy loss per cycle $\Delta W$, stiffness $k$ of the specimen and displacement amplitude $\hat{x}$ of the force displacement hysteresis loop the ratio $\eta_{\text{res}}$ is given by $\eta_{\text{res}} = \sqrt{1 - \Delta W^2/(2\pi^2k^2\hat{x}^4)}$ where $\eta_{\text{res}}$ is basically defined as the ratio of resonant frequency of the damped system ($f_{\text{res}}$) and that of the undamped system ($f_0$) and, therefore, can also be evaluated by using the experimental results depicted in Fig. 1. Thus, the ratio $\eta_{\text{res}}$ is applicable to compare the results from experiments with those from simulations.

Applying the proposed simulation model in combination with the BEM allows for simulation of the effect of localized plastic deformation in shear bands on the resonant behavior. The examination was conducted basing on the real microstructure of AISI304 characterized by means of scanning electron microscopy (SEM) in combination with the electron backscattered diffraction (EBSD)-technique and the orientation imaging microscopy (OIM) analysis.

Figure 3 shows the SEM image and EBSD map of the observed microstructure. Grain boundaries and also markings of emerging shear bands are clearly visible in the SEM image. The crystallographic orientation of each grain is indicated by the EBSD map in Fig. 3(b). The poor image quality of the OIM analysis in single grains is a result of the deformation accumulation during cyclic loading.

Fig. 3. (a) SEM image and (b) EBSD map of the measured zone of surface grains (loading amplitude $\sigma = 240$ MPa and number of cycles $10^7$).

Contours of simulated shear stresses in most critical slip systems in the microstructure are shown in Fig. 4. Contours were chosen in each case at 240 MPa (the maximum external loading). Evolved shear bands are emphasized by thin lines which were colored from white to grey, depending upon the amount of plastic shear deformation that occurred in the respective shear band layer. Damage modeling was confined to 4 grains (labeled 1–4 in Fig. 3(a)) owing to high computational effort. It is important to note that one simulated cycle reflects the evolution of microstructural damage resulting from many cycles in the experiment. This was achieved by adapting the parameter of cyclic slip irreversibility and by increasing the cyclic hardening effect.
The comparison between surface slip markings on the SEM image (Fig. 3(a)) and simulated shear band layers (Fig. 4) illustrates a good agreement between experimentally observed and simulated damage accumulation. Due to plastic sliding deformation in shear bands shear stresses at grain boundaries are increased and shear stresses within grains are decreased.

It is shown in Fig. 4 that varying with specific polycrystalline boundary conditions the shear bands deform differently. The comparison of contour plots in the first, third, and seventh loading cycle (in Fig. 4) shows that shear stresses at the end of shear bands and thus at grain boundaries increase with increasing number of simulated cycles. This is yielded by the irreversible damage accumulation.

Figure 5 depicts the comparison of resonant frequency ratio $\eta_{\text{res}}$ from simulation and from experiment. In contrast to the results in Ref. 2 the scaling of the resonant frequency from simulation has been adjusted taking into account that in simulations only a small part of the observed microstructure is plastically modeled. In Fig. 5 a decrease of $\eta_{\text{res}}$ relates to cyclic softening and an increase to cyclic hardening.

The results show that cyclic softening and subsequent hardening arise — as simulated — from damage accumulation in shear bands. At first the mechanisms of formation and sliding cause a softening and later the mechanism of hardening is dominating. Thus, the simulated results are basically in accordance with experimental observations whereby Figs. 1 and 2 showed that cyclic softening is associated to an increase and cyclic hardening to a stagnation of plastic deformation in shear bands.
However, by comparing both curves in Fig. 5 it becomes obvious that the transient behavior of the experiment leads to a higher variation of $\eta_{\text{res}}$ than that of the simulation. Thus, the distinct transient characteristic of the metastable austenitic stainless steel can not be solely reproduced by simulation of damage accumulation in shear bands. It has to be taken into account that the metastable austenitic stainless steel exhibits deformation induced martensite formation during fatigue, which might play an important role in the transient characteristic. The mechanism of deformation induced martensite formation has not yet been considered in the model presented but is the subject of current investigations.

A simulation model is suggested that describes the damage mechanisms occurring in shear bands under VHCF condition. It is assumed that formation of a shear band occurs at sites of shear stress concentration and sliding distribution arises from the theory of dislocation pile-ups at grain boundaries. As the shear band is approximated by two closely located layers, the irreversible shear character can be represented. An increasing dislocation density in the shear bands results in material hardening. The effect of the suggested simulation model is investigated in the 2D morphology of a real microstructure by using the BEM. It comes out that simulation of slip localization in generated shear bands agrees well with SEM observation. The resonant behavior is characterized by the resonant frequency ratio $\eta_{\text{res}}$ that can be determined from the simulated force-displacement hysteresis loop with the use of both the viscous and the hysteretic damping model. The comparison of $\eta_{\text{res}}$ from simulation and experiment shows that cyclic softening and subsequent hardening in the transient regime arise from simulation of damage accumulation in shear bands. However, the variation of $\eta_{\text{res}}$ from experiment is more pronounced than that from simulation. Current work concentrates on the effect of further microstructural inhomogeneities such as deformation induced martensite in combination with damage accumulation in shear bands on the transient behavior during cyclic loading in the VHCF regime.

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