SHORT CRACK PROPAGATION IN DUPLEX STEEL – MODELLING AND EXPERIMENTAL VERIFICATION

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ABSTRACT

The propagation behaviour of short cracks under cyclic loading in the duplex stainless steel 1.4462 was examined. Short cracks determine up to 90% of fatigue life and exhibit substantially non-uniform propagation kinetics as compared to the growth of long cracks due to their strong interactions with microstructural features. In duplex stainless steels, the composition of the hard ferrite and the ductile austenite leads to improved properties compared to the single phased materials. The different barrier effects of grain and phase boundaries present in this two-phase material on short crack propagation are quantified by means of a *Hall-Petch* analysis, using results from fatigue experiments and EBSD measurements. Furthermore, by evaluating orientation data, it was possible to identify the activated slip system(s) and conclusions concerning the crack propagation mechanisms could be drawn. The experimental findings were implemented into a mechanism-based model for two-dimensional crack propagation in stage I (operating by single slip), which is capable to take the real microstructure into account. The barrier effects of grain and phase boundaries are assigned to the respective types of boundaries according to the experimental observations. The numerical model is based on a boundary-element method, treating the plastic zones in front of the crack tip as yield strips. Each boundary element consists of a mathematical dislocation at its beginning and its end, describing a constant normal and tangential displacement in the element. Geometrical crack closure can be considered by constraints allowing only positive normal displacements within the crack elements. Crack growth simulations performed with the model have shown good agreement with experimental data. In addition, an extended numerical model for the transition of stage I crack growth on single slip systems to crack propagation on multiple slip systems is presented.

1 INTRODUCTION

In most cases, early crack propagation is determined by shear stresses on slip planes inclined by about 45° to the applied loading axis (under push-pull loading conditions), resulting in a zigzag-like crack path. Because of the strong interactions of short cracks with microstructural features (e.g. grain boundaries) and their substantially different growth mechanisms (stage I) compared to long cracks (stage II), the crack propagation rate da/dN of short cracks cannot be described by linear elastic fracture mechanics (LEFM). Also, the large plastic zone size as compared to the crack length makes it necessary to use crack growth models based on elastic-plastic mechanics. Furthermore, the fact that short cracks can grow at higher rates than predicted from LEFM may lead to non-conservative design. Therefore, a model is required that is able to take the effects of microstructure on crack propagation into account.

The new model presented in this paper treats the crack and its plastic zone as yield strips. The plastic slip ahead of the growing microcrack is blocked by grain and phase boundaries. If a critical shear stress on a slip plane in the neighbouring grain is reached, the plastic deformation and the crack can propagate into the next grain. Thus, the crack decelerates when approaching a boundary and accelerates after passing this barrier, resulting in an oscillating crack growth rate. The advantage of the numerical model over analytical ones (e.g. *Navarro* and *de los Rios* [1]) is its ability to simulate two-dimensional crack paths in a randomly generated microstructure, taking geometrically crack closure into account.

2 EXPERIMENTAL INVESTIGATIONS

In this section the experimental studies for validation and support of the presented model are summarized briefly. First, an approach to quantify the barrier strength of grain and phase boundaries is outlined. Second, two different short crack propagation mechanisms are described.

The determination of the barrier effect of grain or phase boundaries to dislocation motion is based on the idea of a dislocation pile-up in front of a boundary (*Hall* [2] and *Petch* [3]). The *Hall-Petch* parameter k_y in the *Hall-Petch* relation can be regarded as a measure for this barrier effect, but it is valid for single phase materials and monotonic loadings only. Since our examinations deal with fatigue of a two phase material, the *Hall-Petch* relation has to be extended adequately. According to *Fan et al.* [4], the extension to two (or more) phases can be derived by considering the contributions of the different boundaries (αα-, γγ-grain boundaries and αγ-phase boundaries in the case of a duplex steel) to the overall *Hall-Petch* parameter. The extension on cyclic loading was done by replacing the monotonic yield stress in the *Hall-Petch* relation by the cyclic yield stress. This approach can be considered as reasonable, if planar glide predominates because then a dislocation pile-up can occur as described by *Hall* and *Petch*. Since most duplex steels are alloyed with nitrogen, which is known to facilitate planar glide, the afore-mentioned procedure is justified. The required mean grain and phase sizes and the so-called stereological parameters (which describe the geometrical arrangement of the microstructure) were obtained by image analysis of etched sections and EBSD-Scans; the cyclic yield stresses were achieved by Incremental Step Tests (*Krupp et al.* [5]). Results are given in Table 1.

Table 1: Results of the *Hall-Petch* analysis

	γγ	αα	αγ	Duplex
microstructural cyclic yield stress $\sigma_{fl,c}[\mathrm{MPa}]$	137	198	212	196
cyclic *Hall-Petch* constant $k_c[\mathrm{MPa}\sqrt{\mathrm{mm}}]$	4.2	5.0	15.8	10.1

Concerning the growth of short cracks, two different propagation mechanisms could be distinguished: crack growth in single and in double slip. In single slip, the crack grows along one specific slip band. Crack advance in double slip takes place on two alternatingly activated slip planes (analogue to the *Neumann* mechanism for stage II crack growth). The resulting crack path can be calculated with orientation data. Fig. 1 shows examples for the different ways of short crack propagation.

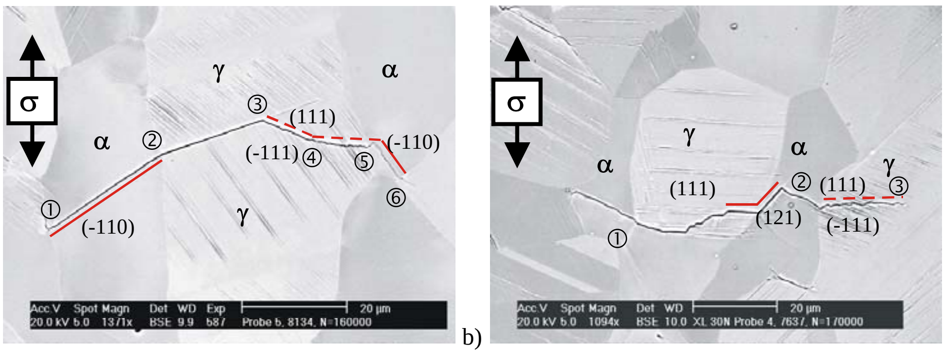
a)


Figure 1: Crack path of two short cracks

Fig. 1a shows a short crack, which has initiated at a twin boundary. The solid lines refer to parts of the crack path where the crack has grown in single slip on the indicated slip systems (between points ①,② and ⑤,⑥). The dashed lines label parts in the crack path where the crack has grown by alternating operation of two slip planes. Between points ③,④ and ④,⑤, respectively, the crack grew by activating the (111) and $(\bar{1}11)$ slip planes. At point ④ there is a transition from an inclined to a horizontal path (perpendicular to the applied stress axis). The reason for this behaviour is, that between ③,④ the involved slip planes contribute to the crack advance in equal parts, while between ④,⑤ the slip on the (111) plane is as twice as high as on the $(\bar{1}11)$ plane. A calculation shows that this should change the angle between the crack path and the horizontal direction from -19° to 3°, what indeed corresponds to the micrograph (Fig. 10).

In Fig. 1b, another example is given. Between ①,② crack growth results from the operation of different single slip systems, while between ②,③ again the denoted slip systems (111) and $(\bar{1}11)$ are activated alternatingly. Under the assumption that slip on the (111) plane is twice as high as on the $(\bar{1}11)$ plane, the calculation yields an angle of approximately –1° between the crack path and the horizontal direction and here again these angles can be found on the micrograph.

3 MODEL

The basic element of the model is a slip band consisting of a series of slip band pieces. The slip band allows tangential displacements of its two faces relative against each other. These displacements are modelled by means of mathematical edge dislocations (*Hills et al.* [6]). Plastic deformation resulting from the movement of these dislocations occurs if the shear stress on the slip band exceeds the resistance to dislocation motion. Thus, the behaviour of the plastic zone is elastic-perfectly plastic. A crack is defined as that part of the slip band which is, contrary to the rest of the slip band, allowed to open. The opening of the crack is modelled by additional dislocations perpendicular to the slip band. Hence, the crack and its plastic zones are represented by an arrangement of dislocations (Fig. 2). The dislocation distribution is calculated numerically by a boundary element method which assumes a constant displacement inside each element. Additionally, so-called "sensor elements" were introduced, which can be used to determine the state of stress at any position in the modelled structure.

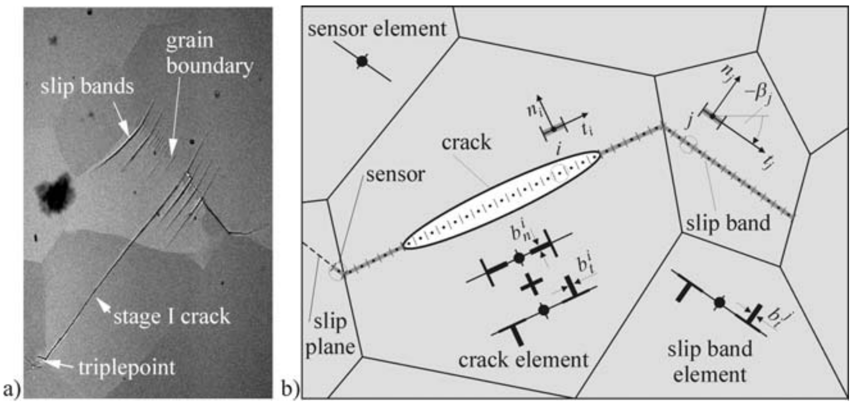


Figure 2: Stage I crack (a) and model with boundary elements (b).

By use of the boundary element method, the relative displacements of the crack and slip band faces can be calculated. Crack closure can be simulated by allowing only positive normal displacements along the crack. Analogously to the model of *Navarro* and *de los Rios* [1], the current crack propagation rate da/dN is calculated by means of a power law function

$$\frac{da}{dN} = C \cdot \Delta CTSD^{m} \,. \tag{1}$$

$\Delta CTSD$ denotes the range of crack tip slide displacement, C is a material-specific constant and m is an exponent. The crack tip opening displacement is zero because the model does not allow normal displacements in the plastic zone. According to *Wilkinson* and *Roberts* [7], eqn (1) is based on the idea that plastic sliding due to external loads causes dislocation emission at the crack tip and that during reverse loading dislocations of opposite sign are emitted. Hence, vacancies are produced leading to crack advance. For a more detailed description of the model, see *Schick* [8] and *Krupp et al.* [5].

In order to verify the crack propagation model, it was applied to crack geometries observed during fatigue experiments. Geometries of the experimentally-observed cracks were defined as crack paths. The starter cracks, obtained in the experiment, were also defined in the model and undergo cyclic loading calculations. As an example, Fig. 3 shows the simulated crack length versus number of loading cycles in comparison with experimental data for two cracks.

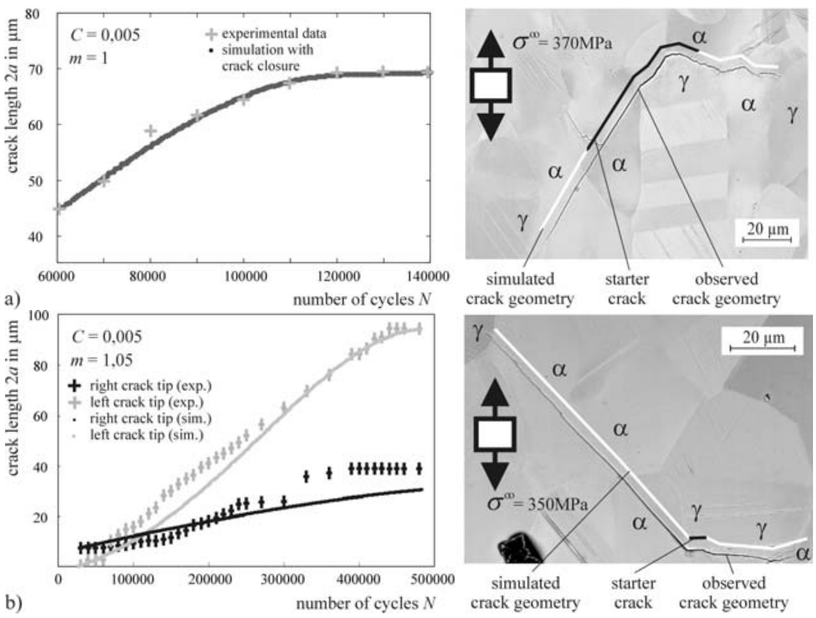
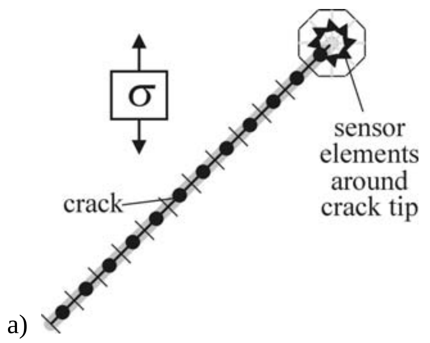


Figure 3: Crack length versus cycle number for two short cracks.

The observed deceleration of the left crack tip in Fig. 3a can be explained by a dislocation pile-up at the phase boundary. This behaviour was reproduced by the simulations. In the numerical model, the crack propagation through the boundary is allowed only if the shear stress on a slip plane in the neighbouring grain, monitored by a sensor element, exceeds a boundary-dependent critical value. In Fig. 3b, the calculated crack growth rate of the left and right crack tip also fits the experimental data. The difference in the calculated crack growth rates of the two tips is due to the difference in the resistance against shear deformation in the individual phases and due to the difference in the shear stresses acting on the crack planes, which depend on the orientation of the crack paths with respect to the loading axis. This has a strong impact on the crack tip slide displacement range and thus the crack growth rate. Therefore, the proposed model is able to describe the effect of different kinds of microstructural barriers and different phases on crack propagation in a mechanism-oriented way. In addition to the simulation of cracks with defined geometry, it is possible to simulate cracks that find their path autonomously in a virtual single- or multiphase microstructure (*Kuenkler et al.* [9]). The artificial microstructure is generated using the *Voronoi*-technique. By performing such simulations, conclusions about the influence of microstructural arrangements on crack propagation can be drawn and life-time predictions can be carried out (*Schick* [8]).

The transition of crack growth on single slip planes (stage I) to crack growth on multiple slip planes is represented simulating a stage I crack inclined by about 45° to the applied loading axis (Fig. 4a). Fig. 4b shows the shear stress distribution around the crack tip in a constant radius for a linear elastic crack (grey) and a linear elastic-perfectly plastic crack with plastic deformation on one slip plane only (black).



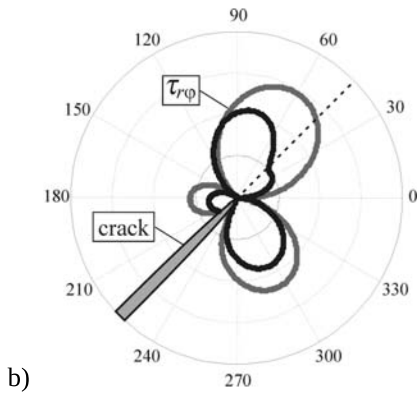


Figure 4: Elastic crack with sensor elements (a) and shear stress distribution around crack tip (b).

The stresses were found by the boundary method presented before using special sensor elements around the crack tip (Fig. 4a). The calculated elastic stress distribution is identically to the analytical solution. The stress distribution for the elastic-plastic calculation exhibits a decrease of the shear stress near the slip plane until the plastic shear stress is reached. In a larger distance from plastic deformation, the shear stress is nearly as high as for the elastic crack. Additional sensor elements representing the other slip planes of the grain are positioned at the crack tip to determine the shear stress on those slip planes (Fig. 5a). As soon as a critical stress value is recorded at one of these sensor elements, the respective slip plane is considered to become “activated” and plastic deformation occurs on this second slip plane (Fig. 5b). This is in accordance to *Lin* and *Thomson* [10], stating that a certain stress intensity has to be reached to activate additional slip systems in front of the crack tip. This happens only above a certain crack length, because the elastic shear stress increases with crack length. Accordingly, the shear stress in the elastic-plastic calculation outside the plastic zone increases. After the activation of the second slip plane, the new crack tip position results from the contribution of the plastic slip vectors (Fig. 5c). New sensor elements are now positioned at the new crack tip representing new slip planes and again these elements are activated. Hence, with growing crack length, the crack becomes deflected on a path perpendicular to the loading axis (stage II, long cracks, Fig. 5d). If the orientations of the slip planes change (because the crack tip has reached a new grain) and the crack is still relatively short, the crack possibly grows again on a single slip plane because no adequate second slip plane is available. This is in accordance with our experimental observations.

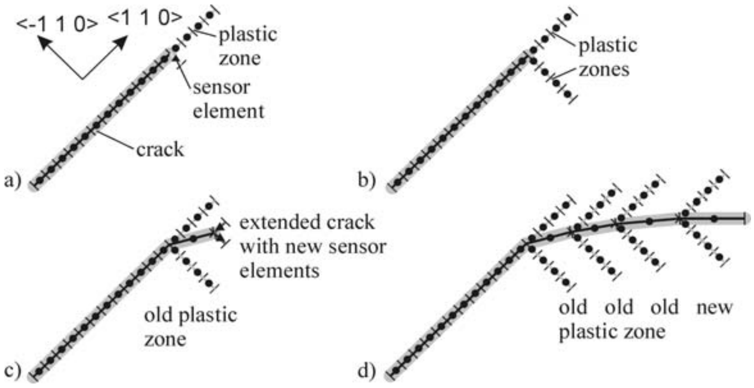


Figure 5: Transition from single slip to multiple slip.

4 CONCLUSIONS

An approach to determine the cyclic *Hall-Petch* constants in a dual phase alloy has been presented and applied. The cyclic shear stresses which are necessary for dislocation motion were obtained by this method. These values were used in a numerical model presented here to simulate stage I crack propagation. The two-dimensional model is able to reproduce fundamental phenomena of short crack propagation (e.g. dislocation pile-up, crack closure) and can be used to investigate the influence of the microstructure (e.g. texture) on crack growth. The examples demonstrate that short crack propagation can be predicted close to the experimental observed data. The model has been extended to simulate the transition from stage I crack growth on single slip planes to crack growth on multiple slip planes. It is determined that this transition depends on crack length and grain orientation. The combination of these concepts provides the possibility to simulate the whole crack propagation process from short crack growth until failure by means of a single model.

5 REFERENCES

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