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Influence of crack length and grain boundaries on the propagation rate of short cracks in austenitic stainless steel

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Cyclic deformation experiments on austenitic stainless steel were performed using different plastic strain amplitudes. The experiments were repeatedly interrupted in order to determine the propagation rate and length of the existing cracks as well as the corresponding distance between crack tip and opposing grain boundary. The results reveal the transition between the regimes of microstructurally and mechanically short cracks as well as the nature of the barrier effect of grain boundaries for crack propagation.

Keywords: 316L steel; Microstructurally short cracks; Plastic zone; Barrier effect; Transition crack length

A crack is commonly termed a microstructurally short crack (MiSC) as long its length is comparable with the distinctive dimension of the microstructure, i.e. the grain size in a single phase material [1–5]. Characteristic for those cracks is that their propagation rate is strongly influenced by the microstructure and therefore shows strong variations due to the existence of grain boundaries, slip bands and other barriers. In 1987, Miller [1] defined the MiSC as a crack that is shorter than one grain diameter and that, above this limit, becomes a physically short crack (PSC). In 2007, Krupp [3] summarized the somewhat refined definitions of the different short cracks and stated that, prior to becoming a PSC, a MiSC would turn into a mechanically short crack (MeSC) upon reaching a transition crack length of several grain diameters; in numbers, eight to ten were mentioned. Already in 2001, Blochwitz [6] had separated the regimes of MiSC and MeSC by empirical propagation laws including a transition crack length a_t, with a propagation law of the form:

$$\frac{da}{dN} = v_I \quad for\ a \leqslant a_t \tag{1}$$

for the MiSC regime, i.e. a constant propagation rate, and a propagation law of the form:

$$\frac{da}{dN} = \frac{v_I}{a_t} a \quad for\ a > a_t \tag{2}$$

for the MeSC regime, i.e. a propagation rate linearly increasing with increasing crack length. This leads to the question of whether those two criteria are correlated in such a way that the transition crack length a_t equals a certain number of grain diameters.

For the austenitic stainless steel 316L or X2CrNiMo18-14-3, Obrtlík et al. [5] obtained transition crack lengths for several plastic strain amplitudes. Their results do not show a clear correlation between a_t and the grain size, at least not in the way that a_t equals a certain number of grain diameters. However, Obrtlík et al. did not investigate samples with different grain sizes. Having data available for the same material and plastic strain amplitude but different grain size, it was the goal of the present work to find out whether the transition crack length for a given deformation amplitude depends on the grain diameter. The data used had been measured and also partially evaluated by Mikulich et al. [7] and Blochwitz et al. [4]. The latter had actually already estimated transition crack lengths for their samples. However, they admitted that "the transition's crack length a_t cannot be estimated exactly", because "the number of measuring points … is too small". The measured quantities and some important parameters of the different studies are summarized in Table 1. In this, as well as throughout the whole paper, plastic strain amplitudes are given as $\varepsilon_{pa} = \Delta\varepsilon_{pl}/2$.

Table 2 shows the experimental outline of the data evaluated in the current study. Thereby, T-specimens and R-specimens are samples cut out along the transverse

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Table 1. Literature data for a_t and v_I in 316L steel after Refs. [4,5].

ε_{pa}	Ref.	v_I (nm cycle^{-1})	a_t (μm)	Grain size (μm)
1×10^{-4} notched	[5]	0.57	200	100
5×10^{-4} notched	[5]	2	110	100
5×10^{-4} plain	[4]	0.7–1.2	45–65	40
1×10^{-3} notched	[5]	3	95	100

Table 2. Experimental parameters (plastic strain amplitude ε_{pa}, sample notation, deformation interval ΔN, number of cycles to fracture N_f) of the data evaluated in this work.

ε_{pa}	Samples	$\Delta N \times 10^{-3}$	$N_f \times 10^{-3}$
1×10^{-4} ("small")	R1, T1	100	>900, 600
5×10^{-4} ("medium")	R2, T2, T4	30, 10 (T4)	233, 150, 148
2×10^{-3} ("large")	R3, T3	3	30, 27

and rolling direction of the initial rolled plate, respectively. For these, Blochwitz et al. [4] discovered that the average crack propagation rates differ, owing the different textures. The average grain size for all samples was 40 μm. Further experimental details can be found in Refs. [4,6]. The samples were primarily deformed with identical outer plastic strain amplitudes compared with Obrtlík et al. (5×10^{-4}, the "medium" plastic strain amplitude, and 1×10^{-4}, the "small" plastic strain amplitude). In addition, samples deformed with a plastic strain amplitude of 2×10^{-3} ("large" plastic strain amplitude) were included in the evaluation in order to check for the trend of the transition crack length decreasing with increasing plastic strain amplitude, as found by Obrtlík et al. [5]. After any deformation interval ΔN, each sample was investigated by scanning electron microscopy (SEM; Zeiss DSM 962). For all crack tips propagating in transcrystalline fashion, two quantities were obtained: the crack propagation Δa, measured as a straight distance from the old crack tip to the new one; and the distance L between the crack tip and the opposing grain boundary, measured normal to the load axis. Additionally, the overall length $2a$ of each individual crack was measured and a length of a assigned to each crack tip.

In order to overcome the limiting number of data points for the estimation of the transition crack length, as mentioned by Blochwitz et al. [4] (see citation above), the data had to be evaluated differently. Blochwitz et al. [4] only took the equivalent (see Ref. [8]) of the five largest cracks into account. An easy way of increasing the number of data points is simply to include all the measured cracks. The problem is that the data points for the smaller cracks show significantly stronger scatter. To resolve this, the following method was chosen: For each sample, all single data points, consisting of propagation rate $\Delta a/\Delta N$, crack (tip) length a and distance L, were sorted according to an increasing crack length a. Afterwards, they were divided into groups of 20 consecutive data points. For these groups, the average propagation rate and the average crack length were calculated and plotted against each other (Fig. 1).

In the case of the large plastic strain amplitude, there is no pronounced difference between R- and T-samples (Fig. 1a), which somewhat contradicts the results of Blochwitz et al. [4]. It is assumed that this is an effect of taking all the cracks into account instead of the largest cracks only. Consequently, the data were fitted according to Eqs. (1) and (2) with a single curve, as shown in Figure 1a, with the fitting parameters $v_I = 3.9$ nm cycle^{-1} and $a_t = 34$ μm. Because there is still quite a strong scatter in the individual data sets for the medium plastic strain amplitude, which is at least partly due the fact that the propagation rate depends on the distance between crack tip and opposing grain boundary, they were also fitted with one single curve, as shown in Figure 1b. In this case, the fitting parameters are $v_I = 0.4$ nm cycle^{-1} and $a_t = 38$ μm. For both plastic strain amplitudes, v_I equals the average propagation rate for all data points with $a < a_t$.

In summary of these results, the following is concluded.

1. With $a_t = 34$ μm for the large and $a_t = 38$ μm for the medium plastic strain amplitude, it is confirmed that the transition crack length decreases with increasing plastic strain amplitude although, compared with the work of Obrtlík et al. [5], the measured effect is less pronounced.
2. In the case of the directly comparable medium plastic strain amplitude, v_I significantly differs from that of Obrtlík et al. [5] (0.4 nm cycle^{-1} vs 2 nm cycle^{-1}). This is due to the use of (a) plain specimens instead

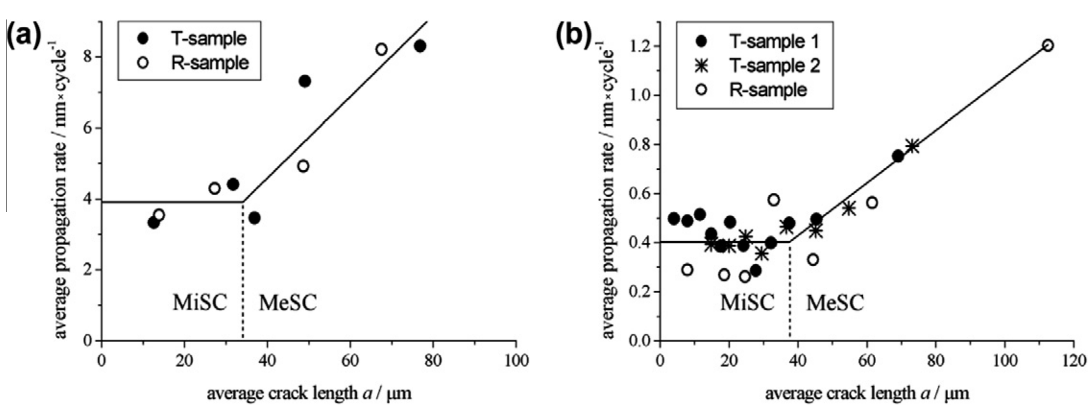

Figure 1. Average propagation rate vs average crack length for (a) the large plastic strain amplitude ($\varepsilon_{pa} = 2 \times 10^{-3}$) and (b) the medium plastic strain amplitude ($\varepsilon_{pa} = 5 \times 10^{-4}$), both with a fit according to Eqs. (1) and (2), respectively.