

# INFLUENCE OF VARYING LOAD SPECTRA ON SHORT CRACK GROWTH MODELLED BY A DISLOCATION TECHNIQUE

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## Abstract

A microstructurally short edge crack subjected to different fatigue load spectra has been studied by means of a dislocation technique. The crack was assumed to grow by emitting discrete dislocations that constitute the plastic deformation. The interaction between the developing plasticity and grain boundaries has been investigated. The discrete events of emission and annihilation of dislocations have been possible to study in detail for fatigue crack growth rates of the order of a few Burgers vectors. The simulations showed that a positive overload resulted in crack retardation, or even arrest, for the cases where the spreading of the plastic deformation is not severely hindered by a grain boundary, whereas the crack growth rate is not changed for the cases with dislocations piled up at the grain boundary. Single compressive overloads were found only to temporarily accelerate the crack. An increase in the mean load level resulted in an increase of the growth rate.

## Introduction

Short cracks are known to grow fast even below the fatigue limit for long cracks, cf. Pearson [1]. Some short cracks can continue to grow and eventually join the long crack region, while others arrest before the fatigue threshold for long cracks is reached. The growth rate is heavily dependent on the local microstructure, such as grain orientation and grain boundaries, and on the applied load spectrum, cf. Suresh [2].

Linear fracture mechanics cannot be used since it is not valid for large scale yielding situation prevailing for short cracks. For growth rates of the order of Burgers vector per load cycle, it is important to take the discrete behaviour of dislocations into account. This can be achieved by using a discrete dislocation technique developed by the authors [3]. A crack is assumed to grow by emitting discrete dislocations from the crack tip. These emitted dislocations represent the plastic deformation in an otherwise linear elastic material. The crack itself is modelled by dislocation dipoles.

## Problem formulation

A short edge crack oriented perpendicular to the free edge of a semi-infinity body is studied, cf. Fig. 1. The crack is subjected to an external load,  $\sigma$ , applied in the  $y$ -direction and is assumed to grow in mode I along the  $x$ -axis under plane strain conditions. The initial crack length is  $a_0=20\mu\text{m}$ . The material is BCC iron with a shear modulus  $\mu=80\text{GPa}$ , Poisson's ratio  $\nu=0.3$  and the size of Burgers vector  $b=0.25\text{nm}$ , cf. [4]. The crack tip is located in the vicinity of a grain boundary. The distance between the initial crack tip and the grain boundary is denoted  $l_{GB}$  and is the parameter varied in this study.

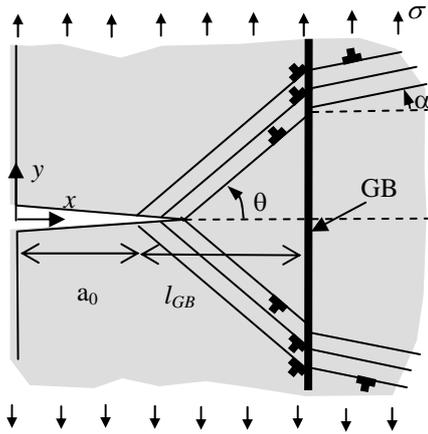


FIGURE 1. Geometry of the edge crack in the vicinity of a grain boundary, GB.

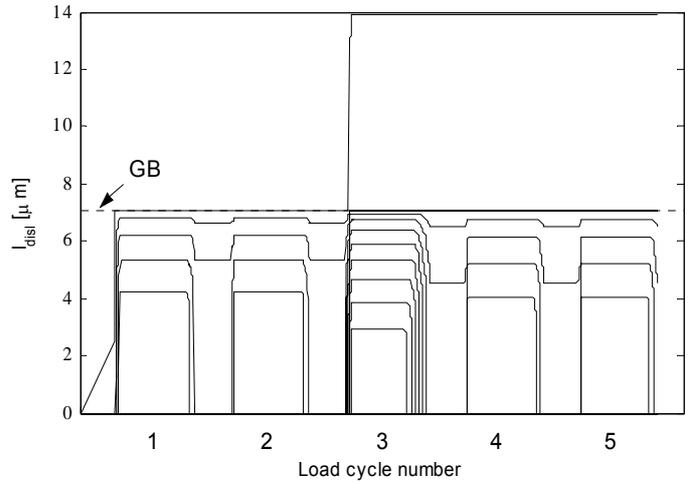


FIGURE 2. The location of the dislocations along the slip planes during a load sequence with a tensile overload for  $l_{GB}=a_0/4$ .

### Plastic zone

The crack grows by emitting dislocations, resulting in a blunting of the crack. If an emitted dislocation returns to the crack tip, the crack is resharpener but not rewelded. The emitted dislocations constitute the plastic deformation and shield the crack from the external load. A local stress intensity factor,  $k_{local}$ , is found by reducing the global stress intensity with the shielding effect, cf. Lin and Thomson [5]. The shielding effect is governed by the number of dislocations in the plastic zone, their locations relative the crack tip and the size of Burgers vector.

If  $k_{local}$  reaches a critical value  $k_e=0.506\text{MPa}\text{m}^{1/2}$ , cf. Riemelmoser [6], the crack will grow in mode I by emitting two dislocations. These dislocations glide along slip planes symmetrically oriented to the  $x$ -axis, cf. Fig. 1, as long as the resolved shear stress exceeds the lattice friction,  $\tau_{crit}=40\text{MPa}$ , cf. [6]. The angle between the  $x$ -axis and the preferred slip planes in the grain holding the crack is  $\theta=\pi/4$ , and in the neighbouring grain the angle is  $\alpha=\pi/6$ . If dislocations emitted from the crack tip reach the grain boundary, they are assumed to be trapped there. This will render in a pile-up of dislocations at the grain boundary.

Figure 2 shows the movement of the dislocations constituting the plastic zone during five load cycles for  $l_{GB}=a_0/4$ . Each line represents the distance a dislocation has moved along its slip plane,  $l_{disl}$ . When a new dislocation is emitted, its line starts at  $l_{disl}=0$ . In this example, it is seen that during the first load cycle five dislocations are emitted. The first dislocation will immediately reach the grain boundary and get trapped there, while the following dislocations will pile up. The applied positive load drives all the dislocations towards the grain boundary, but there is also a repelling force between the dislocations. Additionally, the free surface of the crack attracts the dislocation. For each load increment in the simulations a new equilibrium state has to be found where the force acting on each dislocation is balanced. As the loading is reversed some of the dislocations move back towards the crack and in this case

two of them have been annihilated when  $\sigma_{min}$  is reached. The load is then increased again and two new dislocations are emitted and thereafter they are annihilated during reversed loading. A growth rate of two dislocations per cycle is obtained and can be assumed to be stable for at least a 100 cycles, if the load sequence is not changed, according to Bjerken [7].

### Grain boundary nucleation

The spreading of the plasticity into the neighbouring grain is modelled by allowing dislocations to nucleate at the grain boundary. The dislocations always nucleate in pairs, having the same size but opposite directions, cf. Fig. 3. The nucleation criterion is chosen so that once the dislocation pair is nucleated one of them, here called the positive dislocation, will move away from the grain boundary while the negative will get stuck there. In this study, nucleation takes place when the resolved shear stress reaches the nucleation stress,  $r_{nuc} = 2.06\text{GPa}$ , at a possible nucleation site at a distance  $r_{nuc} = 9b$  from the grain boundary. Further details of the choice of nucleation criterion can be found in Bjerken and Melin [8] and Bjerken [9].

In Fig. 2, the effect of a tensile overload applied during the third load cycle is shown. The crack grows by emitting seven new dislocations and the pile up of dislocations is pronounced. This pile-up causes stresses large enough to induce nucleation of a dislocation pair at the grain boundary. The positive dislocation moves away from the grain boundary, while the negative is trapped in the grain boundary where it partly relaxes the stresses, cf. Fig. 3. After load reversal the remaining dislocations in the plastic zone give a shielding effect of the same magnitude as before the tensile overload was applied. Thus the crack growth rate of two dislocations per cycle is regained.

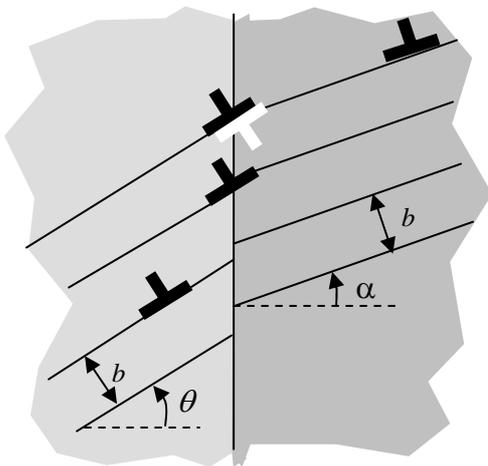


FIGURE 3. Close-up at grain boundary with a schematic dislocation arrangement. Black and white symbols represent positive and negative dislocations, respectively.

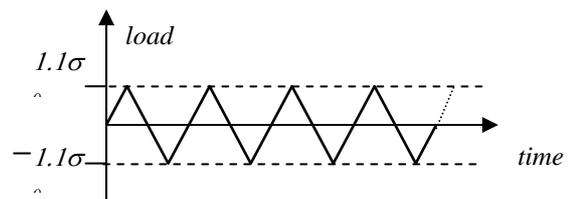


FIGURE 4. Reference load cycle (type 1).

### Load sequences

This study focus on the changes in growth rates of short cracks due to both positive and negative singular overloads, as well as an increase of the mean load level  $\sigma_{mean}=(\sigma_{max}+\sigma_{min})/2$ . The reference loading sequence (type 1) is regularly varying between  $\sigma_{max}=1.1\sigma_0$  and  $\sigma_{min}=-\sigma_0$ , where  $\sigma_0\approx 70\text{MPa}$  and is the load required to start the growth of the initial crack, cf. Fig. 4. The different load spectra that have been studied are shown schematically in Fig. 5. The load sequence of type 2 includes an tensile overload in cycle n:o 3 with  $\sigma_{max}=1.2\sigma_0$  and sequence type 3 gives a compressive overload of  $\sigma_{min}=-1.2\sigma_0$ . Type 4 is a load sequence where the third cycle has  $\sigma_{max}=-\sigma_{min}=1.2\sigma_0$ , i.e. a tensile overload followed by a compressive overload. In the load sequence of type 5, the mean load level is increased from  $\sigma_{mean}=0$  to  $\sigma_{mean}=0.1\sigma_0$ .

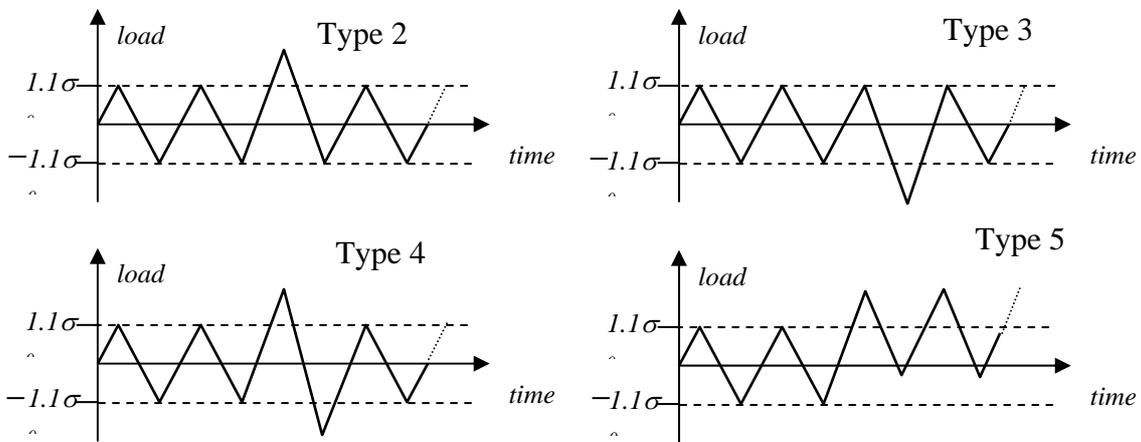


FIGURE 5. Load sequences of type 2, 3, 4 and 5, respectively.

The simulations were performed for seven different distances between the crack tip and the grain boundary, namely  $l_{GB}=a_0/100, a_0/16, a_0/8, a_0/4, a_0/2, a_0$  and for the case without a grain boundary interacting with the plastic zone. For each type of load sequence the influence of  $l_{GB}$  is investigated.

### Results and discussion

Due to the symmetry of the problem, only results referring to the upper half of the semi-infinite body,  $y>0$ , is presented. Since the crack growth rate is proportional to the number of dislocations emitted from the crack per cycle, it is convenient to normalize the crack growth by  $b/\cos\theta$ , and, thus, measure the crack growth rate in the number of dislocations emitted for  $y>0$ .

#### Reference load sequence (Type 1)

All the investigated load sequences contain 5 load cycles. In the first load cycle, for all cases, the initial crack starts to grow and the building of an initial plastic zone, consisting of emitted dislocations, is established. The larger the distance to the grain boundary, the more dislocations are emitted. The grain boundary partly hinders the spreading of the plasticity into the next grain. In the cycles to follow, the crack growth is governed by how well the plastic zone shields the crack tip from the applied load. In Fig. 6, the dashed line show the

stable crack growth rate for the different  $l_{GB}$ 's. For  $l_{GB}=a_0/100$ , the closest grain boundary, the crack was arrested after the initial cycle. When no grain boundary interacts with the plastic zone a continuous crack growth corresponding to 1 dislocation/cycle is found. This rate is obtained for  $l_{GB}=a_0$  and  $l_{GB}=a_0/16$  as well. However, for intermediate  $l_{GB}$ 's the crack growth rate is larger, 2 dislocations/cycle. The crack growth is governed by the how well the crack tip is shielded from the applied load. The shielding effect depends on the number and distribution of the dislocations in the plastic zone. For  $l_{GB}=a_0/16$  and  $l_{GB}=a_0/100$ , i.e. when the crack tip is relatively close to the grain boundary, the pile up of dislocations at the grain boundary has resulted in dislocation nucleation during the first load cycle. The spreading of the plasticity into the neighbouring grain partly relaxes the stresses created by the pile-up. However, since the nucleation always is preceded by the emission of a new dislocation from the crack tip, which joins the plastic zone, the resulting effect is an increase in the shielding of the crack tip. As the repulsive stress from the dislocation trapped in the grain boundary is reduced the dislocation next in turn can reach the grain boundary, thus reducing the number of dislocations free to move

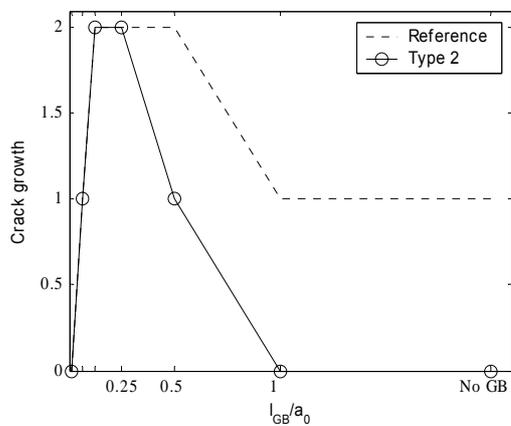


FIGURE 6. Crack growth rate during cycle n:0 5 cycles after the tensile overload in cycle n:0 3 and for the reference load cycle for the different  $l_{GB}$ 's investigated

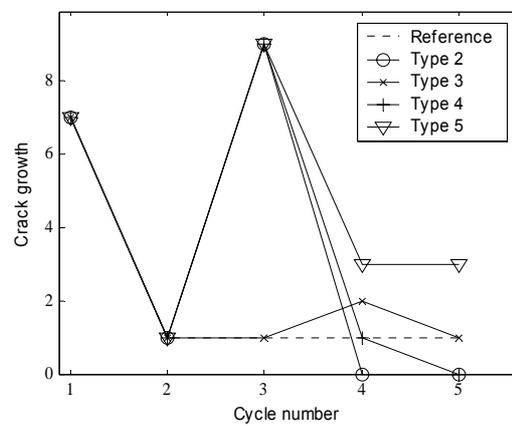


FIGURE 7. Crack growth during 5 cycles with  $l_{GB}=a_0$  for all types of load sequences.

### ***Overload in tension (Type 2)***

In Fig. 6, the crack growth rate obtained after a tensile overload is shown. For the larger  $l_{GB}$ 's the crack is retarded and even arrested, while for the smaller  $l_{GB}$ 's the crack growth rate is unchanged. The overload itself causes an increase in the crack growth rate during that very cycle, cf. Fig. 7. The number of dislocations found in the plastic zone at maximum load is larger than before the overload. During load reversal, the closer the grain boundary is, the fewer of the extra dislocations can remain in the plastic zone due to the repulsive forces from the pile-up of dislocations and the attraction from free surface.

The plastic deformation was spread into the neighbouring grain due to the overload for  $l_{GB} \leq a_0/4$  except for  $l_{GB}=a_0/16$ . In this case, grain boundary nucleation took place in the first load cycle and the stress relaxation thus obtained was large enough to prevent further nucleation at the grain boundary. However, for  $l_{GB}=a_0/100$ , the nucleation criterion was

fulfilled both during the first load cycle and during the tensile overload. In this latter case, the overload caused a temporary crack growth which was followed by a new crack arrest.

### ***Overload in compression (Type 3)***

The effect of a compressive overload was found not to change the crack growth rate more than temporarily. The compressive overload caused more dislocations to annihilate than in the reference load sequence. Thus, the shielding of the crack tip was reduced and more dislocations could be emitted during the load cycle following the compressive overload, cf. Fig. 7. Thereby the plastic zone was restored and the crack growth rate the same as for the reference sequence. For the two shortest  $l_{GB}$ :s no crack acceleration was found in cycle n:o 4, due to the limited number of dislocations free to move within the grain holding the crack. For  $l_{GB}=a_0/100$ , the crack is arrested after the first load cycle and a relatively small compressive overload will not cause crack growth. In the case of  $l_{GB}=a_0/16$ , only one dislocation was involved in the cyclic plastic zone and no more dislocations free to move was available.

### ***Overload both in tension and in compression (Type 4)***

If a tensile overload is followed by a compressive one, the same crack growth rates is found as after a single tensile overload, cf. Fig. 6, except for  $l_{GB}=a_0/2$  for which the resulting growth rate is not reduced. This difference depends on that the compressive overload causes all the extra dislocations added to the plastic zone during the tensile overload to return to the crack and annihilate, thus restoring the size and shape of the plastic zone.

It is also found that for most  $l_{GB}$ :s the crack growth rate in cycle 4 is larger than in cycle 5, cf. Fig. 7. The reasons for this behaviour are discussed in the subsection concerning single compressive overloads (type 3).

### ***Increased mean load (Type5)***

If the mean level of the applied load sequence is increased in the third load cycle and thereafter kept at that level, the crack growth rate is increased for all cases, cf. Fig. 8. The largest crack growth rates were found for the cases with grain boundaries located at an intermediate distance from the crack tip. The reference load sequence also shows large crack growth rates for the intermediate  $l_{GB}$ :s, and the reasons is that a pronounced pile-up of dislocations results in an larger number of dislocations that are annihilated during reversed loading than can be achieved for longer and very short  $l_{GB}$ :s, respectively.

## **Conclusions**

The propagation of a microstructurally short edge crack subjected to different fatigue load spectra has been simulated using a discrete dislocation technique. The stepwise changes in the crack growth rate due to varying loads were monitored in detail.

The interaction between the dislocations forming the plastic zone and a grain boundary located in front of the crack tip was found to be essential for the crack growth behaviour. The highest crack growth rates are found for the cases with intermediate distances between grain boundary and crack tip. If the plastic zone consists of a pronounced pile-up of dislocations, the cyclic plastic deformation will be large and, thus, the growth rate high.

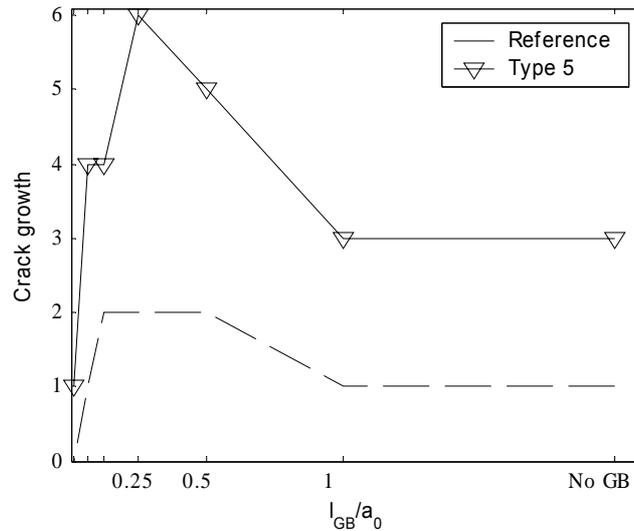


FIGURE 8. Crack growth rate due to an increased mean stress (type 5) for the different  $l_{GB}$ :s together with the growth rates obtain with the reference load sequence (dashed line).

A single tensile overload was found to cause crack retardation and even arrest for grain boundary located relatively far from the crack tip, otherwise the crack regained the growth rate prevailing before the overload was applied.

A compressive overload could not increase the crack growth rate for more than one cycle directly following the overload for any of the grain boundary distances studied.

A tensile overload followed by a compressive overload resulted in the same crack growth rates as found for the single tensile overload.

An overall increase in crack growth rate was achieved when the mean load level was increased. The largest crack acceleration was found for the cases of intermediate distance between crack tip and grain boundary.

## References

1. Pearson, S., *Engng Fract. Mech.*, vol. **7**, 235-237, 1975.
2. Suresh, S., *Fatigue of materials*, Cambridge University Press, Cambridge, UK, 1991.
3. Bjerken, C. and Melin, S., *Int. J. Fatigue*, vol. **25**, 559-566, 2003.
4. ASM Handbook, vol **2**., ASM International, USA, 1990.
5. Lin, I.-H. and Thomson, R., *Phil. Mag.* Vol. **29**, 73-97, 1974.
6. Riemelmoser, F.O., Pippan, R. and Stüwe, H.P., *Int. J. Fatigue*, vol. **85**, 157-168, 1997.

7. Bjerkén, C., The discrete nature of the growth and arrest of microstructurally short fatigue cracks modelled by a dislocation technique, Submitted to *Int. J. Fatigue*.
8. Bjerkén, C. and Melin, S., In *Proc. 9<sup>th</sup> Int. Conf. Mechanical Behaviour of Materials*, Geneva, 2003.
9. Bjerkén, C., *Modelling and simulation short fatigue cracks*, Doctoral thesis, Lund University, 2003.