Crack propagation calculations in a MMC cylindrical specimen

Guido Dhondt

MTU Aero Engines GmbH
Postfach 50 06 40
D-80976 Munich
Germany
Guido.dhondt@muc.mtu.de

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Abstract. Crack propagation calculations simulating a strain controlled cyclic loading were performed for a cylindrical specimen with a MMC (metal matrix composite) core. The analysis shows that an initial surface crack propagates through the outer titanium layer. After reaching the first fibers the crack propagation rate slightly increases but stabilizes afterwards until the first fibers break due to the attained strain level. After collapse of the first fibers the rate suddenly increases but it is expected to slowly decrease again until the next fibers break. The influence of the friction between fiber and matrix on the crack propagation results is not very significant.

1. Introduction

Titanium metal matrix composites are advanced materials consisting of a metallic titanium matrix in which high strength SiC fibers are embedded. The fibers can take up to 3000 MPa at a maximum strain of about 0.9 %. Due to the high stresses small defects can have enormous consequences for its loading capability, including sudden rupture. An accurate prediction of what happens to small defects, whether they will propagate or not and if so, at what speed, is a major challenge [1, 2].
To achieve this goal, a strain controlled LCF test is simulated for a cylindrical specimen with a MMC core and a titanium 6-2-4-2 outer layer. The MMC core is made up of SiC fibers with a diameter of 140 µm in a titanium 6-2-4-2 matrix. In the core a fiber density of 49 % is assumed. The diameter of the core is about 3 mm, the diameter of the specimen is 3.5 mm. Consequently, the thickness of the outer layer is 0.25 mm. A straight cylindrical section of 12 mm length is considered. The lower end is fixed, the upper end is uniformly moved in axial direction.

2. The model

In the model the fibers in the MMC core are equally spaced such that a fiber density of 49 % is reached. This corresponds to a distance between the fibers of 0.7209 r where r is the radius of the fiber. Throughout the specimen C3D20R elements were used: these are quadratic isoparametric serendipity elements with reduced integration which perform very well in a large range of applications. Each fiber was modeled individually using 2 elements in the cross section and 16 elements along its length. The titanium matrix and outer layer were meshed with a comparable density. This resulted in a mesh with 450,000 degrees of freedom. A typical linear elastic calculation for this mesh takes about 10,000 s with ABAQUS version 5.8.8. and 4,000 s with CalculiX CrunchiX version 0.92 (iterative solver, Cholesky preconditioning) [3]. To obtain reasonable analysis times for the crack propagation calculation it was decided to use CalculiX. A cross-sectional view on the mesh is shown in Fig. 1.

3. Cooling-down of the specimen

To get an idea of the residual stress in the specimen the cooling-down procedure was simulated. To this end, the specimen was cooled down from 600°C to 20°C, assuming full attachment between fiber and matrix in this whole temperature range. The lower end of the specimen was fixed in axial direction and freed from rigid body motions in the other directions. The upper end was forced to maintain a uniform axial displacement during the cooling process.

The analysis yielded 300 MPa tensile stress in the titanium and 600 MPa pressure stress in the fibers (Fig. 1). The shortening of the specimen was 0.0449 mm yielding a total strain of -0.374%. The thermal shrinkage of the fibers was 0.238 %. Thus, the resulting mechanical strain in the fibers after cooling down is –0.136 %. This increases the strain needed to break the fibers accordingly.

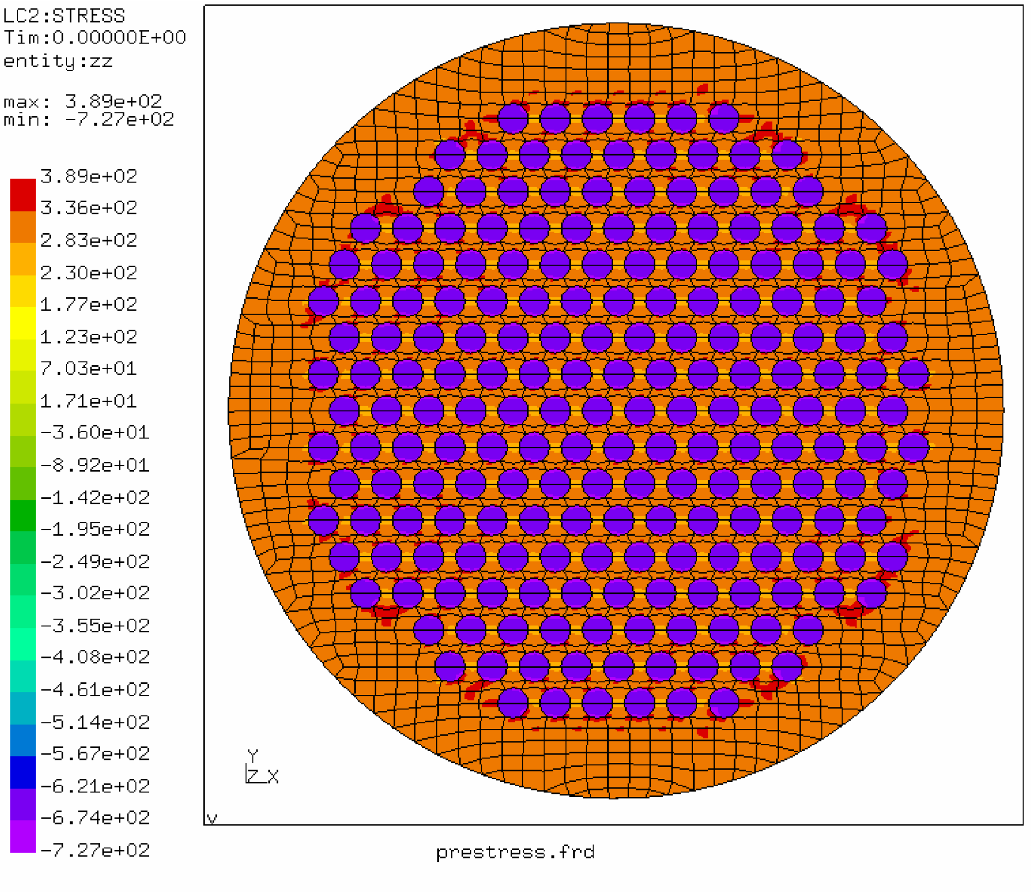

Figure 1: Residual stress in the specimen.

4. Loading of the specimen

Next, the upper end of the specimen was moved in such a way that a mean strain of 0.45 % was generated in the specimen. The resulting axial stress was about 840 MPa in the titanium and 1200 MPa in the fibers. A stress level of 840 MPa leads for a half circular crack to K-values satisfying

$$K \approx 1.04\frac{2}{p}840\sqrt{pa} = 986\sqrt{a} \quad MPa$$

Taking a threshold value of 4.3 MPa.m$^{0.5}$, this means that an initial crack with a radius as small as 0.02 mm will propagate.

5. Crack propagation

An initial half circular surface crack was inserted in the specimen (Fig. 3). The adhesion between the SiC fibers and the titanium matrix of three nodal layers symmetric about the symmetry plane of the specimen was removed. The automatic crack propagation procedure described in [4] was used.

The K-distribution along the initial crack obtained with ABAQUS and CalculiX is plotted in Figure 2. The difference is about 2 % and can be tolerated. It is caused by the iterative character of the solution procedure which was selected in CalculiX and which is appropriate for the compact nature of the structure considered. The K-values are well above threshold.

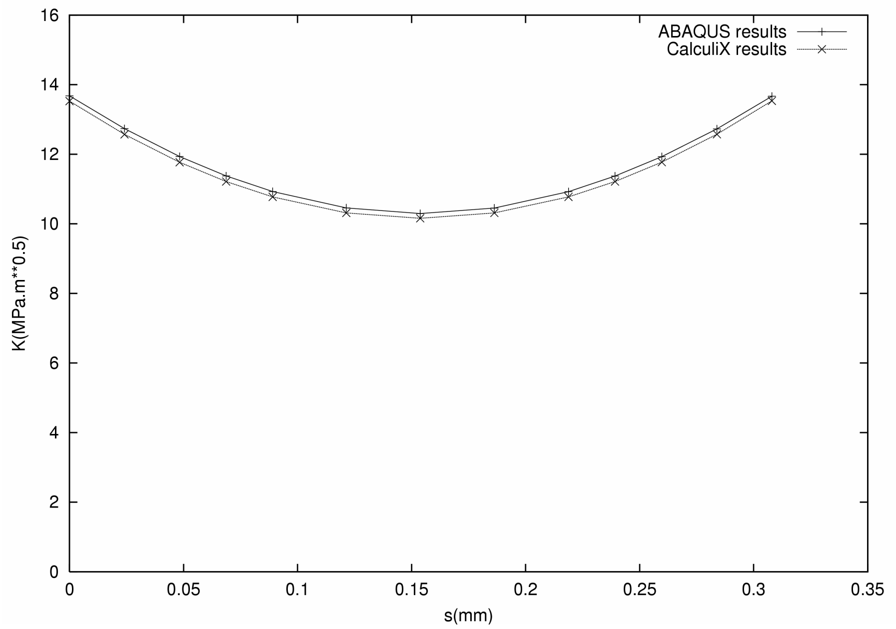

Figure 2: K-distribution along the initial crack

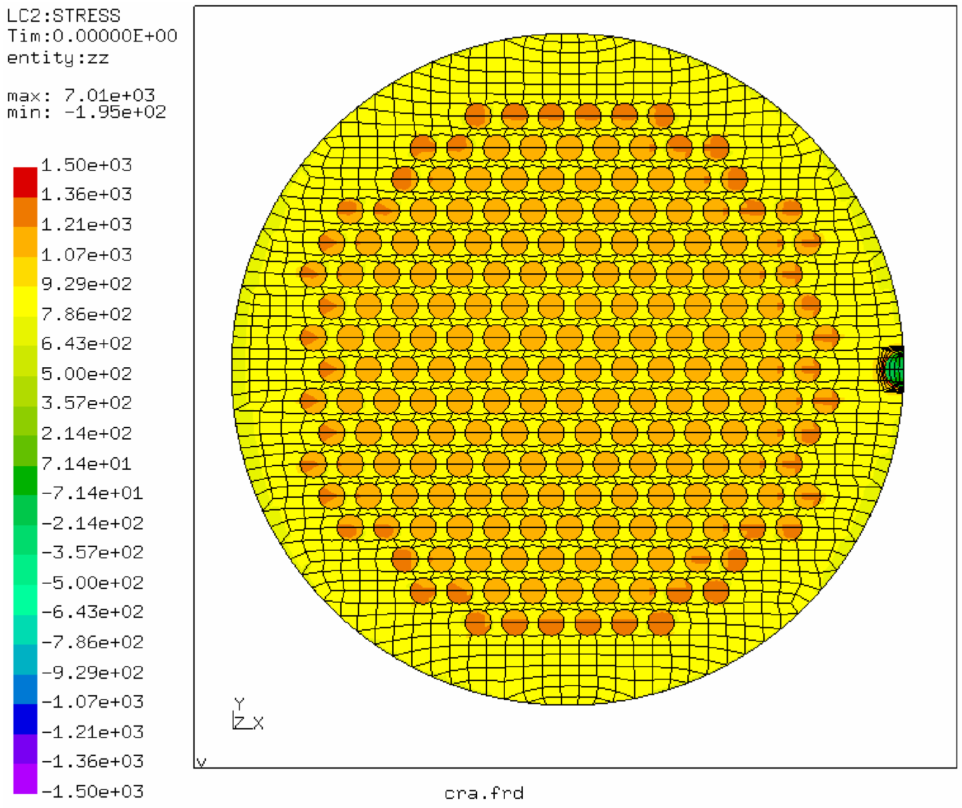

Figure 3: Axial stress (initial crack)

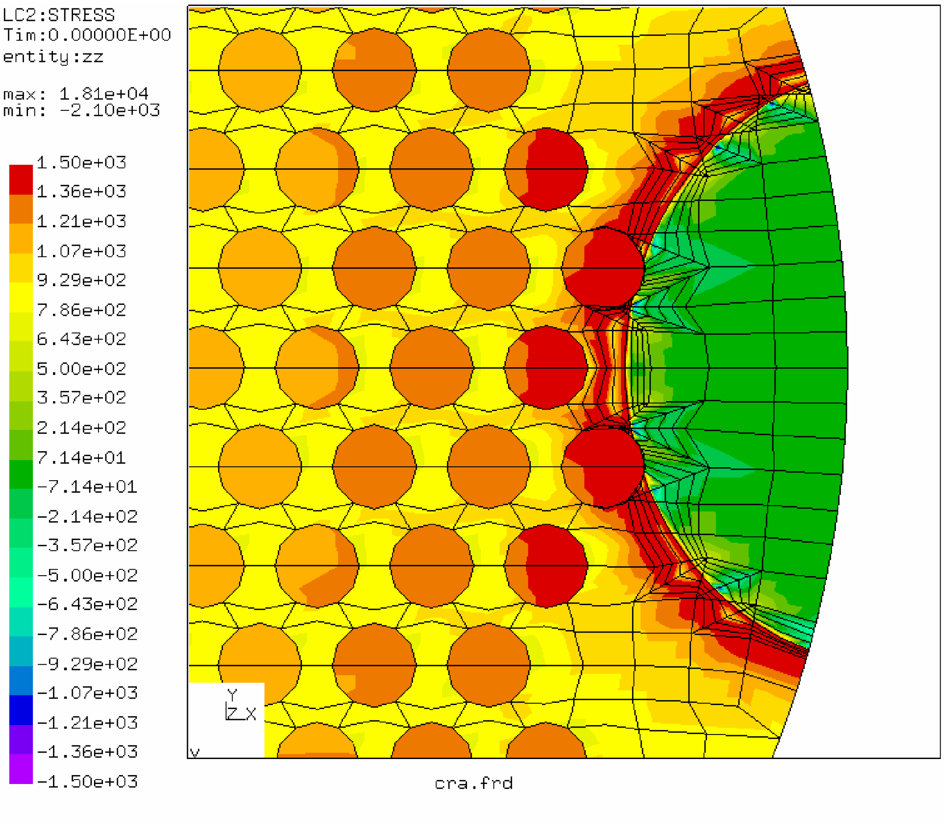

Figure 4: Axial stress (crack cuts two fibers)

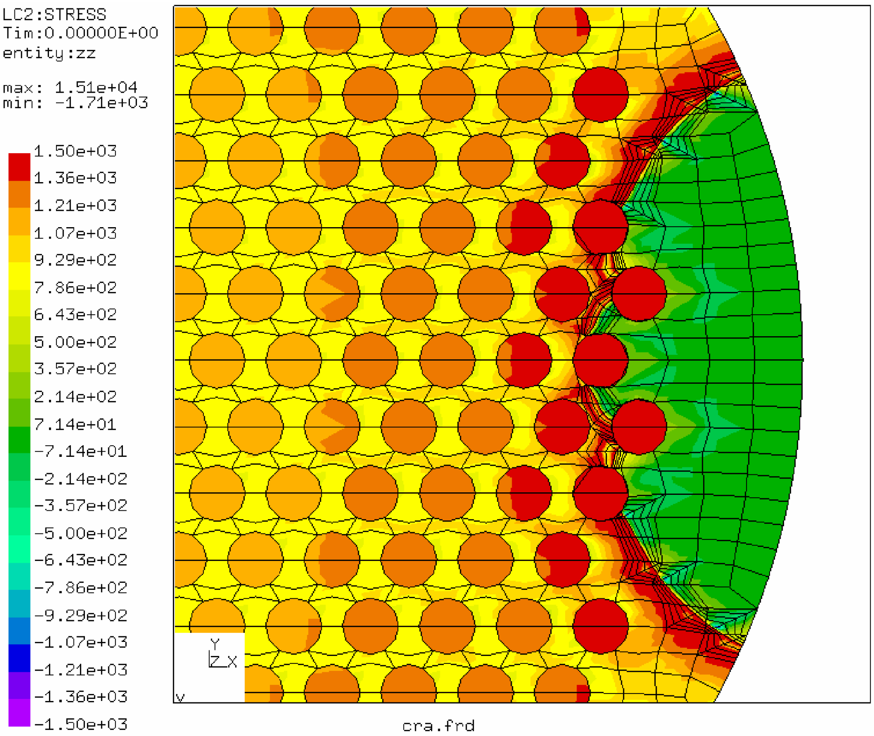

Figure 5: Axial stress (crack cuts five fibers)

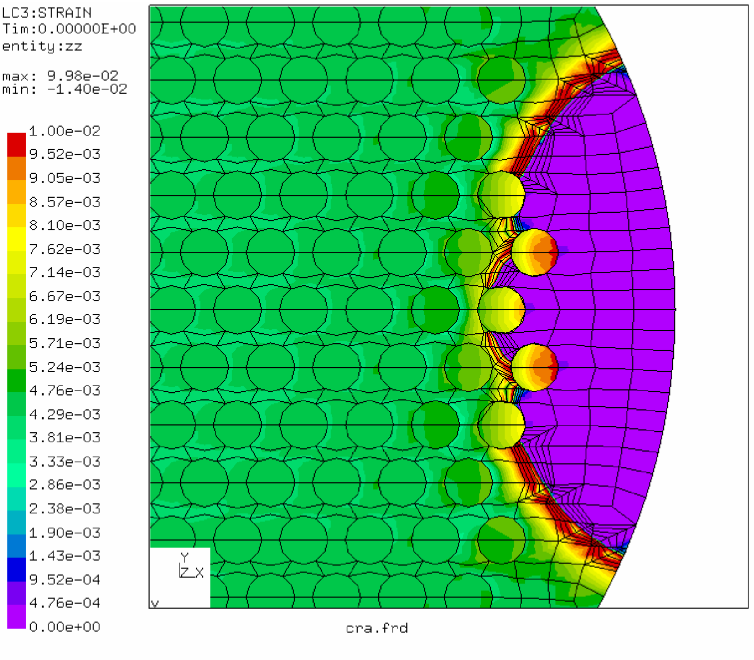

Figure 6: Axial strain (crack cuts five fibers)

Fig. 3-6 show the axial stress and strain during crack propagation, Fig. 7 shows the crack opening before fiber rupture. These are just screen shots. In total about 30 iterations were performed. At first, the crack changes its shape into a half elliptical form due to higher K-values at the free boundary. As soon as the first fibers are reached the crack front is split up into segments which have the tendency to stay perpendicular to the fibers. As soon as about five fibers are reached, the strain level in the fibers closest to the free boundary exceeds 0.9 % in more than half of the fiber and the fiber is assumed to break. This changes the strain field drastically (Fig. 8). The strain in the next fibers is increased but does not reach the strain level in the broken fibers before collapse. Thus, the crack will continue to propagate before the next fibers are broken, although at a much higher rate. Indeed, Fig. 9 shows the K-distributions immediately before the collapse of the first fibers, Figure 10 shows them immediately after: they are increased by more than 10 %. In both figures there are six K-curves. They represent the K-distribution along the crack front of each of the six crack front segments visible in Fig. 8. The labels in Fig. 9 and 10 correspond to the crack fronts in Fig. 8 (labeled 1 to 6 from the top to the bottom). The abscissa in Fig. 9 and 10 represents the distance along the crack front. Thus, the longest crack front segments have the highest K-values. They correspond to the segments cutting the free boundary of the specimen (Fig. 8).

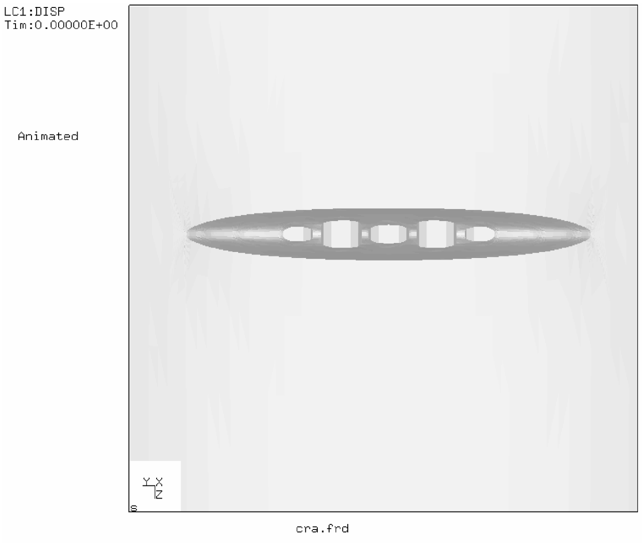

Figure 7: Crack opening (crack cuts five fibers; view looking into the crack)

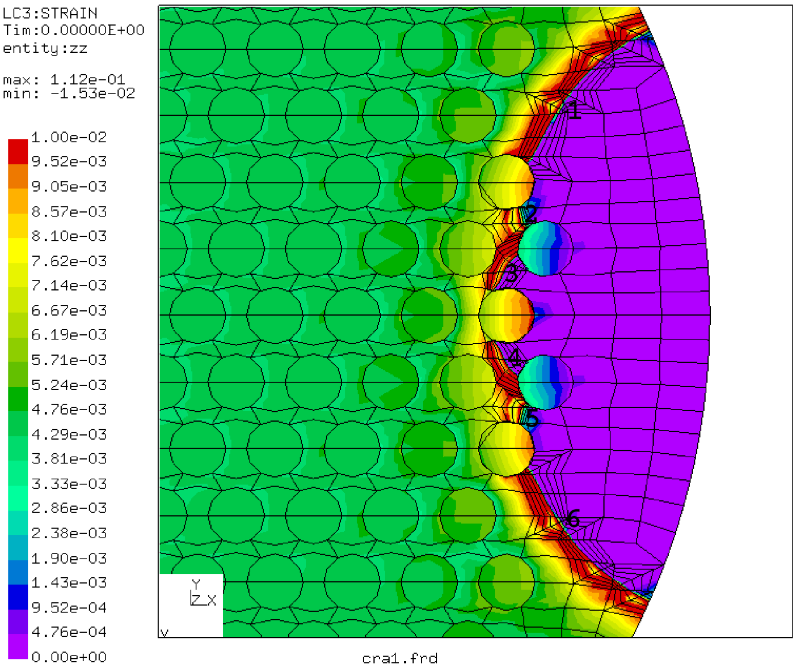

Figure 8: Axial strain (two fibers are ruptured)

The segments of medium length have the smallest K-values. They connect the fiber in the symmetry plane with its neighbors. The shortest segments have K-values in between. Thus, while moving from the free boundary to the fiber in the symmetry plane, the K-values decrease. This indicates that the crack will tend to grow fastest at the free boundary.

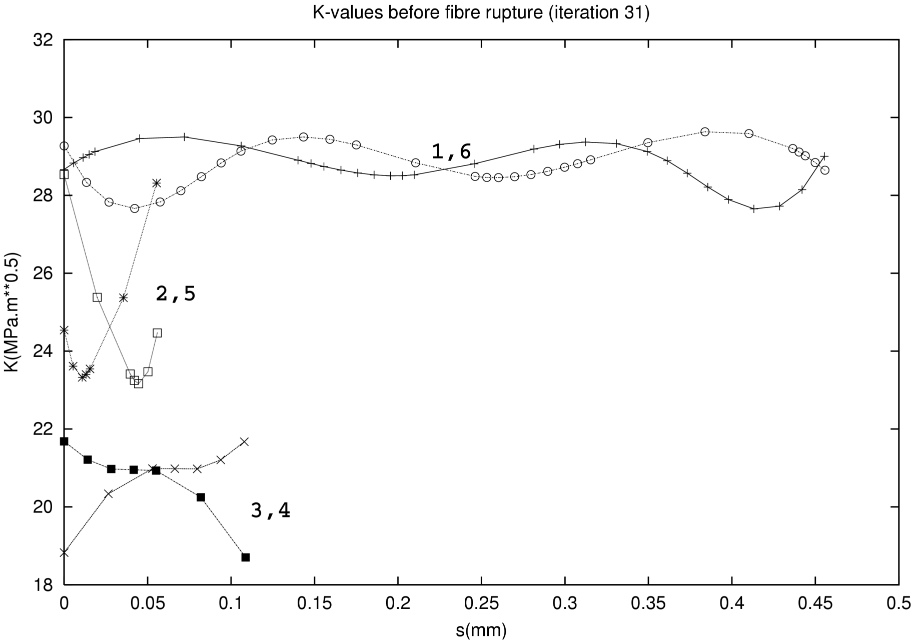

Figure 9: K-distribution before fiber rupture.
The labels correspond to the crack fronts in Figure 8.

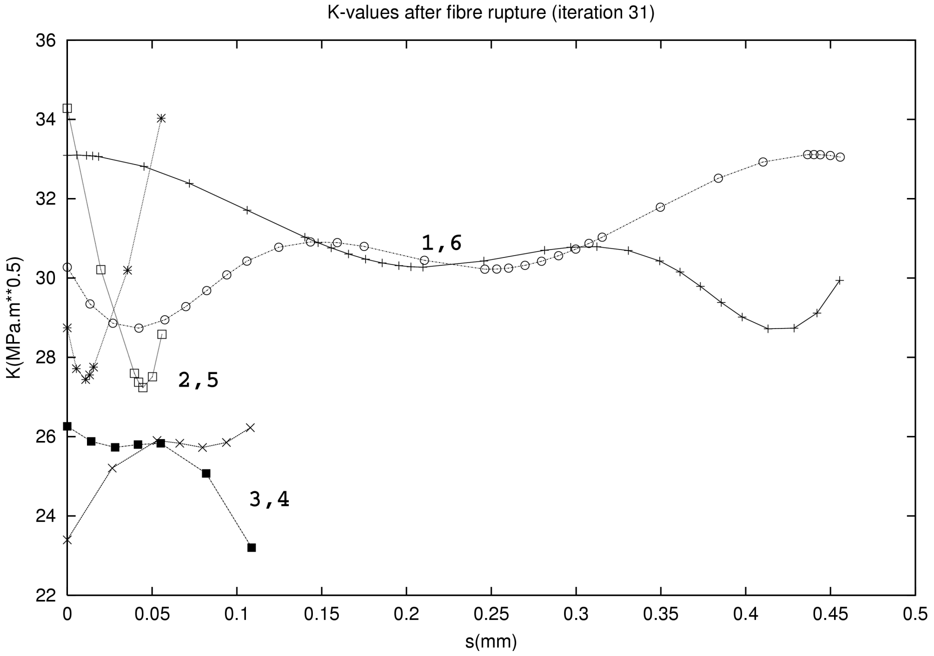

Figure 10: K-distribution after fiber rupture
The labels correspond to the crack fronts in Figure 8

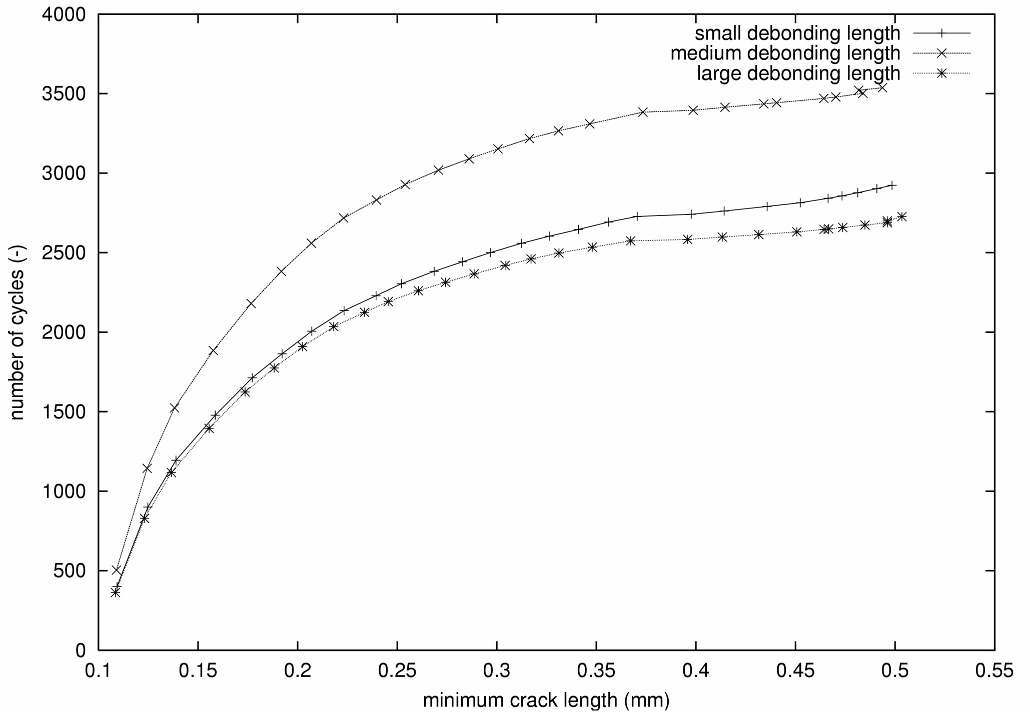

Figure 11: Life versus minimum crack length for different debonding conditions

In Figure 11 the number of cycles is plotted versus the minimum crack length up to the point where the first fibers break. The crack length along the crack front is measured as the distance from the center of the initial crack. The curve has the typical $a^{0.5}$ form up to the point where the first fibers are reached (minimum crack length about 0.37 mm). There, the crack propagation rate at first accelerates. Then, it gradually recovers the propagation rate in monolitic titanium. As soon as the first fibers break, the propagation rate will increase (corresponding to the 10 % K-increase) but is expected to recover again. However, due to the high K-values the recovery intervals will scarcely contribute to any life extension. The total life is about 3000 cycles.

Finally, the influence of the adhesion between the fibers and the matrix was analyzed. Figure 11 shows the crack propagation life for 3 (small debonding length), 13 (medium debonding length) and 23 (large debonding length) layers free of adhesion forces. Taking into account that the deviation in life between the prediction and test is usually within a factor of 2, the deviation between the different adhesion models (2600, 2800 and 3450 cycles) is moderate.

6. Conclusions and further investigations

A crack propagation calculation was performed in a cylindrical MMC specimen. The calculations have revealed that the crack smoothly propagates in between the fibers. At first the fibers bridge the crack. Then, the propagation rate is accelerated by the successive collapse of the crack bridging fibers. However, few cycles remain until complete failure of the specimen. This means that most of the crack life is spent in the homogeneous outer layer of the specimen.

7. References

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