Crack propagation in fracture mechanical graded structures

B. Schramm
University of Paderborn, Pohlweg 47-49, 33098 Paderborn, Germany
schramm@fam.upb.de

H.A. Richard
University of Paderborn, Pohlweg 47-49, 33098 Paderborn, Germany
Westfälisches Umwelt Zentrum, Pohlweg 47-49, 33098 Paderborn, Germany
richard@fam.upb.de

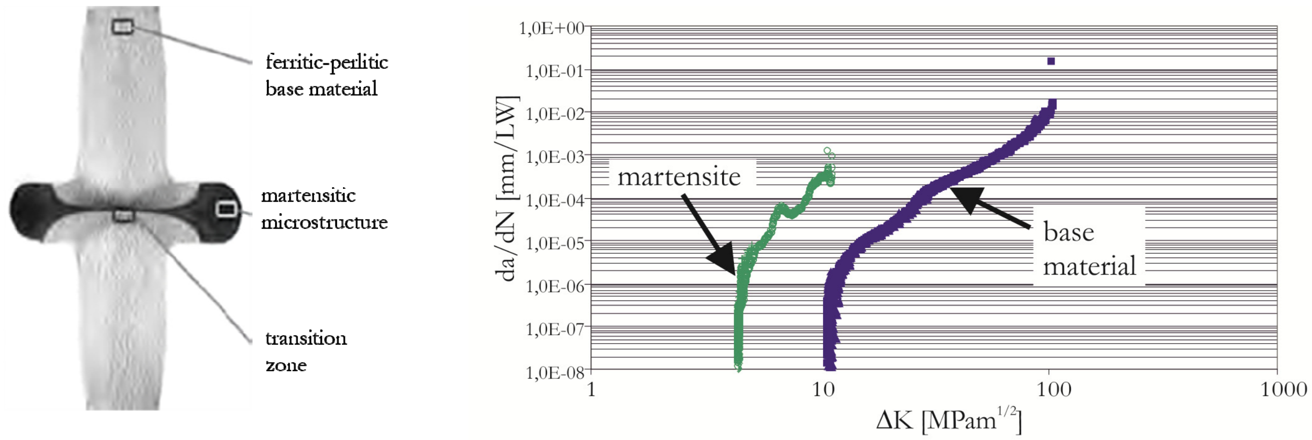
ABSTRACT. The focus of manufacturing is more and more on innovative and application-oriented products considering lightweight construction. Hence, especially functional graded materials come to the fore. Due to the application-matched functional material gradation different local demands such as absorbability, abrasion and fatigue of structures are met. However, the material gradation can also have a remarkable influence on the crack propagation behavior. Therefore, this paper examines how the crack propagation behavior changes when a crack grows through regions which are characterized by different fracture mechanical material properties (e.g. different threshold values $\Delta K_{I,th}$, different fracture toughness ΔK_{IC}). In particular, the emphasis of this paper is on the beginning of stable crack propagation, the crack velocity, the crack propagation direction as well as on the occurrence of unstable crack growth under static as well as cyclic loading. In this context, the developed TSSR-concept is presented which allows the prediction of crack propagation in fracture mechanical graded structures considering the loading situation (Mode I, Mode II and plane Mixed Mode) and the material gradation. In addition, results of experimental investigations for a mode I loading situation and numerical simulations of crack growth in such graded structures confirm the theoretical findings and clarify the influence of the material gradation on the crack propagation behavior.

KEYWORDS. Functional fracture mechanical gradation; Crack propagation direction; TSSR-concept; Experimental investigations; Numerical simulations.

INTRODUCTION

Some structures possess small inner material defects. In this case, the component life is significantly determined by the phase of stable crack growth. For the safe dimensioning as well as for the calculation of the residual life time of homogeneous and isotropic components subjected to cyclic loads methods of linear-elastic fracture mechanics (LEFM) are used. Due to the increased demand in terms of lightweight structures so-called functional graded microstructures gain in importance. Functional graded materials are generally identified by locally varying properties. They enable a large application spectrum and meet different local demands such as absorbability, abrasion and fatigue of structures.

However, for these inhomogeneous material regions the concepts of LEFM are not directly applicable. In this context, the influence of a material gradation on the crack growth as well as the possibility to extend the concepts of LEFM for the application on structures with material properties varying from location and direction have to be analyzed. The investigations were carried out by the Collaborative Research Centre (SFB/TRR 30) of the German Research Foundation and involved among other things a structure (Fig. 1a, [1]) which combines a graded microstructure with a practice-oriented geometry. The structure consists of a ferritic-perlitic base material of the heat treatable steel 51CrV4 within the unformed region of the shaft and a martensitic microstructure within the formed flanged. The different microstructures are characterized by different fracture mechanical properties in form of threshold value ΔK_{th}, fracture toughness K_{IC}, crack velocity da/dN (Fig. 1b, [2]). The elastic properties (e.g. Young's modulus E and Possion's ration ν) are not affected by the production process.



a) b)

Figure 1: a) Metallographic micrograph of the flanged shaft [1], b) crack velocity curves of different microstructures [2].

The main aim of these investigations is to understand the processes which control the crack growth in fracture mechanical graded structures, especially the influence of the material gradation on the limits of fatigue crack growth, the crack growth rate, the crack propagation direction and the lifetime of graded components. In this context the following questions are of interest:

- Under which condition is crack growth possible?
- How fast does the crack grow?
- In which direction does the crack grow in case of stable crack growth?
- When does the unstable crack growth start?
- Which residual life time can be expected for the cracked structure?

THEORETICAL INVESTIGATIONS OF FRACTURE MECHANICAL GRADED MATERIALS

Basic theoretical investigations are carried out to understand and predict the crack propagation behavior in fracture mechanical graded structures. The focus is especially on the influence of the material gradation on the limits of fatigue crack growth (stable and unstable crack growth), on the crack growth velocity da/dN as well as on the crack propagation direction.

Fig. 2 shows a structure with different fracture mechanical materials M1 and M2. In Fig. 2a the initial crack is situated in certain distance from the material gradation. Hence, there is only homogeneous and isotropic material behavior around the crack tip. Accordingly, the crack growth occurs in dependency of the present loading situation (Mode I, Mode II or Mixed Mode) for plane structures. In this case, the crack propagation concepts for homogeneous and isotropic materials, such as the MTS-concept of Erdogan and Sih [3], can be applied. In Fig. 2b the crack tip is within the material transition and sees two fracture mechanical different microstructures. Hence, a change in the crack growth rate da/dN and possibly of the direction of crack propagation might occur due to the fact that the crack takes the path of least resistance. The consequence is the existence of two potential kinking angles: the stress induced kinking angle $\varphi_{0,MTS}$ and the gradation angle φ_M itself.

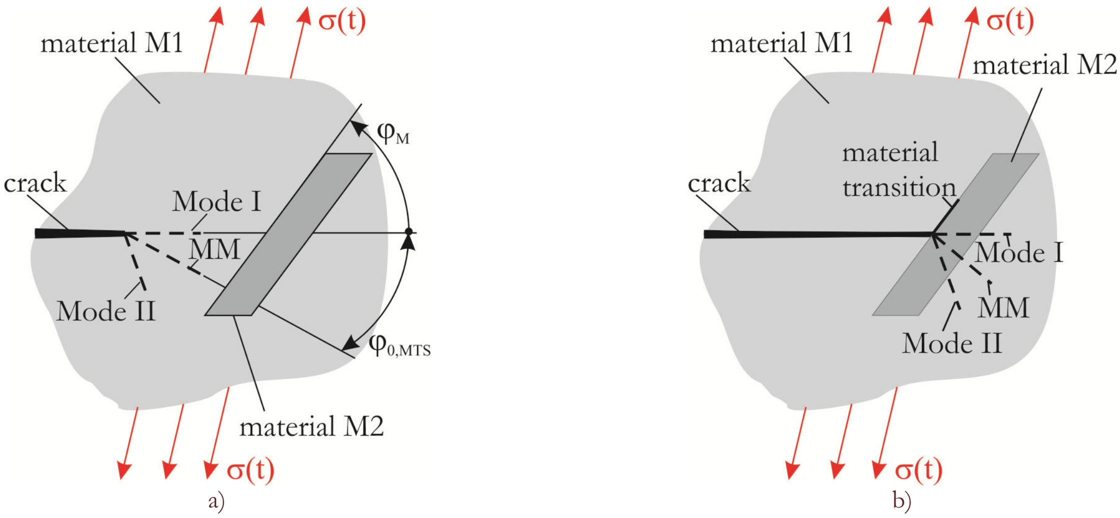


Figure 2: Fracture mechanical graded structure with potential crack propagation directions: a) crack tip with distance to material transition, b) crack tip within material transition.

Influence on the limits of fatigue crack growth and on the crack velocity

In the following, the influence of a fracture mechanical material transition is considered for a structure with the gradation angle $\varphi_M = 90°$, which is loaded cyclically with $\sigma(t)$ resulting in a pure Mode I loading situation. Fig. 3 shows the threshold value curve $\Delta K_{I,th}$ and the cyclic fracture toughness curve ΔK_{IC} for a crack growing from the fracture mechanical worse material M1 into material M2 ($\Delta K_{th,M1} < \Delta K_{th,M2}$; $\Delta K_{C,M1} < \Delta K_{C,M2}$). A homogeneous and isotropic structure consisting only of material M1 would fail at stress level A (cf. point A_1), whereas the considered graded structure doesn't fail until reaching point A_2. At stress level B stable crack growth occurs in both considered microstructures, i.e. the crack grows stable until either the cyclic fracture toughness $\Delta K_{IC,M2}$ of material M2 or the edge of the structure are reached. For the lower stress level C the crack grows until reaching the material transition (point C_1). The occurring cyclic stress intensity ΔK_I is smaller than the treshold value $\Delta K_{I,th,M2}$ of material M2, so that the crack is not able to propagate and stops within the material transition.

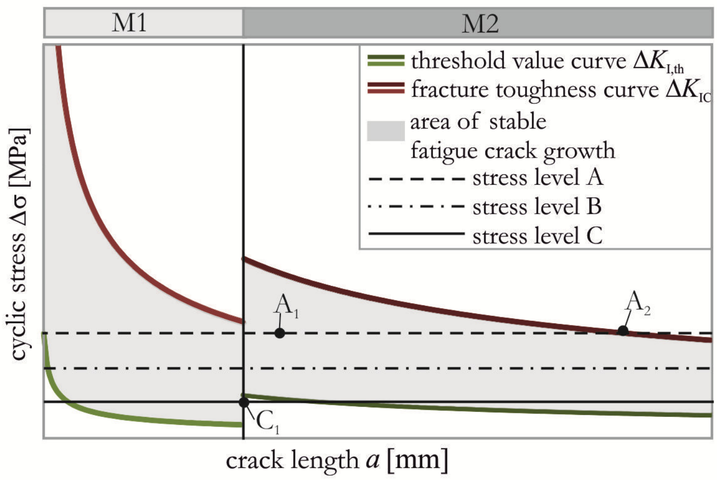
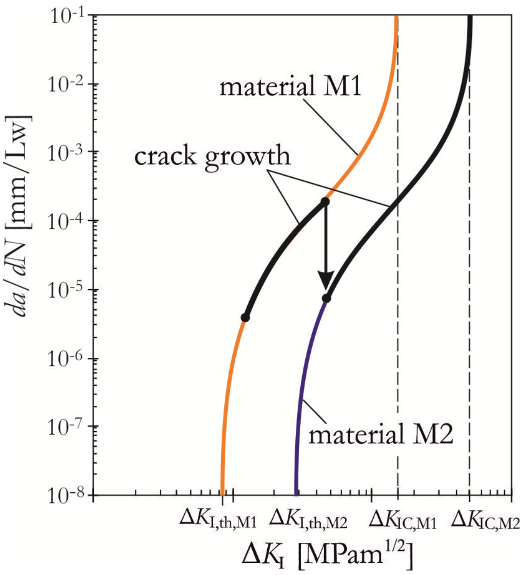


Figure 3: $\Delta\sigma$-a-diagram for a sharp material transition from M1 to M2.

It should be noted that the crack growth from a region with worse fracture mechanical material properties into a region with better properties might lead to crack arrest, if the cyclic stress intensity factor ΔK_I is at transition smaller than the threshold value $\Delta K_{I,th}$ of the subsequent material. If the gradation is oriented opposite, negative consequences for the prospective lifetime of the component are expected. With reaching the material transition the cyclic fracture toughness of the subsequent material might be exceeded resulting in the sudden failure of the structure. For further information about the influence of the gradation on the limits of stable fatigue crack growth see [4].

The change to a material with other fracture mechanical material properties is connected – besides the influence on the limits of fatigue crack growth – with a change in the crack growth rate da/dN [4, 5]. In the following, this influence is considered using principal crack growth rate curves of the materials M1 and M2 (Fig. 4). These curves have differences in the threshold value $\Delta K_{I,th}$, in the crack growth rate da/dN and in the cyclic fracture toughness ΔK_{IC}. Material M1 possesses a smaller threshold value $\Delta K_{I,th}$, a higher crack growth rate da/dN and a smaller cyclic fracture toughness ΔK_{IC} than material M2. At first, Fig. 4a considers a crack which grows within material M1. After some time the crack reaches the second material M2 leading to a change to the crack growth rate curve of M2 with the consequence of reaching the instability later as if the crack grows further within material M1. Besides the difference in the fracture mechanical limits a difference in the crack velocity can be observed: the velocity changes considerably at transition, so that the crack grows slower after reaching material M2. At the best, crack arrest occurs if the cyclic stress intensity factor ΔK_I is smaller than the threshold value $\Delta K_{I,th,M2}$ of material M2.

If the gradation is oriented opposite (Fig. 4b), i.g. the crack starts in material M2 and reaches the fracture mechanical worse material M1, the transition causes an increased crack growth rate da/dN and at the same time a reduced prospective life time. The worst imaginable case occurs if the cyclic stress intensity factor ΔK_I is at transition already larger than the cyclic fracture toughness $\Delta K_{IC,M1}$ of material M1 leading to unstable crack growth and the immediate failure of the structure.



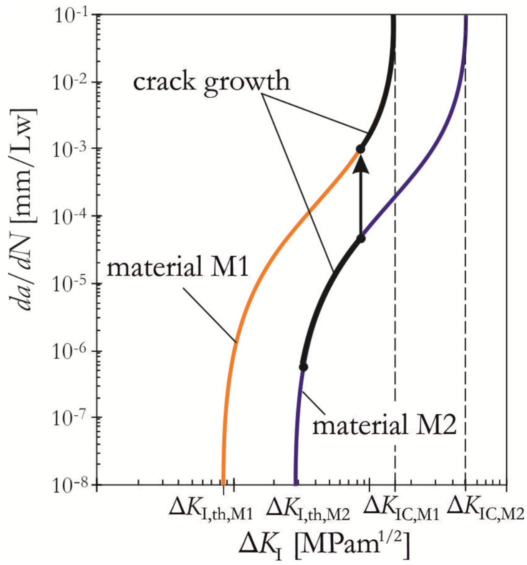


Figure 4: Influence of the fracture mechanical material gradation on the crack velocity: a) transition from material M1 to M2, b) transition from material M2 to M1.

These illustrations confirm that the fracture mechanical material gradation may have a grave impact on the fatigue behavior of components. However, they can't clarify the influence on the occurring crack propagation direction. To make a statement on the crack propagation direction the TSSR-concept is developed.

TSSR-concept for the prediction of crack propagation behavior in fracture mechanical graded structures

The developed TSSR-concept enables the determination of the beginning of stable and unstable crack growth as well as the direction of the occurring crack propagation [4, 5]. In the following, the principal application is shown for a pure Mode I stress situation and an idealized sharp material transition.

Fig. 5a shows a cracked structure consisting of the materials M1 and M2 and therefore of different fracture mechanical parameters, whereas the elastic parameters are the same for the entire structure. The cyclic load $\sigma(t)$ results in a pure Mode I stress situation at the crack tip. The gradation angle φ_M defines the position of the material transition in relation to the initial area of the crack and the crack tip. Accordingly, the crack sees two fracture mechanical different materials, so that the material functions (threshold value curve $\Delta K_{I,th}$ and cyclic fracture toughness curve ΔK_{IC}) vary in dependency of the polar-coordinate φ and the gradation angle $\varphi_M = 30°$ and show a jump for a sharp material transition (Fig. 5b). Below the threshold value curve $\Delta K_{I,th}(\varphi)$ the crack is not able to propagate, whereas above the cyclic fracture toughness curve $\Delta K_{IC}(\varphi)$ unstable crack growth occurs. The region of stable fatigue crack growth is situated between both curves.

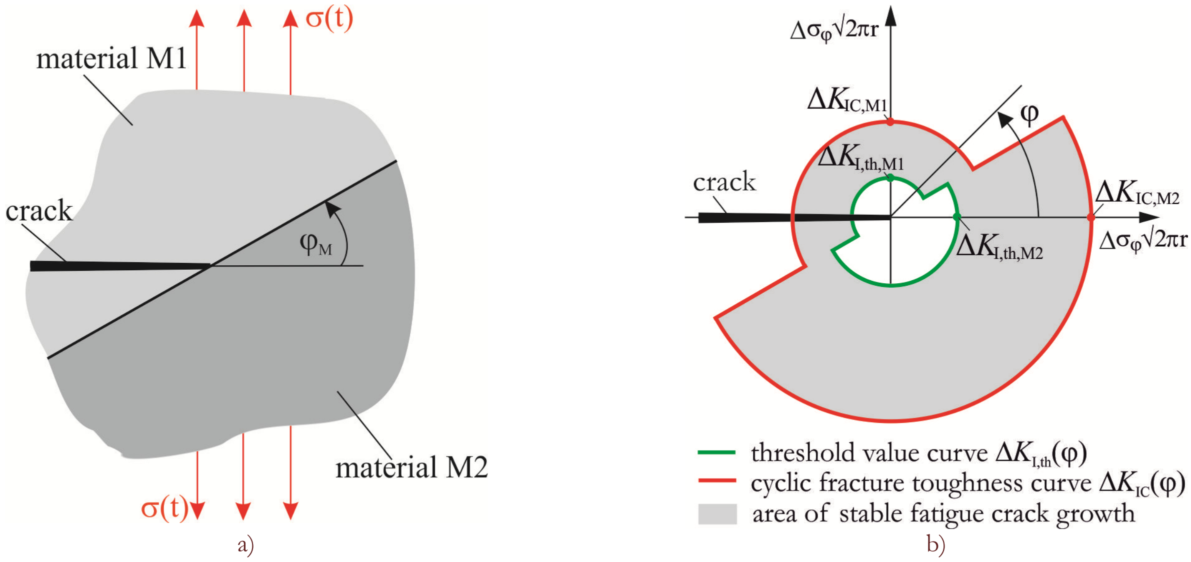


Figure 5: a) Fracture mechanical graded structure with the materials M1 and M2 and the gradation angle $\varphi_M = 30°$, b) threshold value curve and cyclic fracture toughness curve in polar coordinate system

The TSSR-concept is a modification of the MTS-concept of Erdogan and Sih for homogeneous and isotropic materials [3] and compares stress values with material values as well. Due to the fact that the fracture mechanical material properties change in dependency of the existing gradation, a material function is considered instead of a constant material value.

For the determination of the beginning and the direction of fatigue crack growth the threshold value curve $\Delta K_{I,th}(\varphi)$ is used as material function and the cyclic tangential stress $\Delta\sigma_\varphi$ (Eq. (1) with the Mixed Mode ratio $V=K_{II}/(K_I+K_{II})$) as stress function.

$$\Delta\sigma_\varphi\sqrt{2\pi r} = \Delta K_I\left(\cos^3\frac{\varphi}{2} - \frac{V}{1-V}\frac{3}{2}\sin\varphi\cdot\cos\frac{\varphi}{2}\right) \tag{1}$$

To determine the beginning of stable crack growth and the direction of propagation φ_{TSSR} the TSSR-concept looks for the cyclic stress function which has the first intersection point with the threshold value curve $\Delta K_{I,th}(\varphi)$. For this the cyclic stress function $\Delta\sigma_\varphi\sqrt{2\pi r}$ is equalized with the material function $\Delta K_{I,th}(\varphi)$ (Eq. (2)).

$$\Delta\sigma_\varphi\sqrt{2\pi r} = \Delta K_I\left(\cos^3\frac{\varphi}{2} - \frac{V}{1-V}\frac{3}{2}\sin\varphi\cdot\cos\frac{\varphi}{2}\right) = \Delta K_{I,th}(\varphi) \tag{2}$$

Transposition of this equation according to Eq. (3) and applying the potential kinking angles $\varphi_{0,MTS}$, φ_M and $\varphi_M \pm 180°$ lead to the cyclic stress intensity factors $\Delta K_I^{th}(\varphi=\varphi_{0,MTS})$, $\Delta K_I^{th}(\varphi=\varphi_M)$ and $\Delta K_I^{th}(\varphi=\varphi_M \pm 180°)$.

$$\Delta K_I^{th}(\varphi) = \frac{\Delta K_{I,th}(\varphi)}{\cos^3\frac{\varphi}{2} - \frac{V}{1-V}\frac{3}{2}\sin\varphi\cdot\cos\frac{\varphi}{2}} \tag{3}$$

These stress intensity factors define cyclic stress functions which possess points of contact with the material function at the inserted polar coordinates. The minimal value of these factors describes the first point of contact between the stress function and the material function und furthermore the beginning of stable fatigue crack growth. At the same time the occurring crack propagation direction φ_{TSSR} arises out of the used polar coordinate φ. In Fig. 6a this point can be found at the polar coordinate $\varphi = 30°$. Due to the fact that the real cyclic stress function is larger than the function which is relevant for crack propagation the crack will propagate along the fracture mechanical material transition with $\varphi_{TSSR} = \varphi_M = 30°$. The crack extension by the increment Δa is shown in Fig. 6b. Consequently, the crack propagation doesn't depend only on the existent stress situation, but also on the fracture mechanical material gradation. The new crack position and the global Mode I loading now cause a Mixed Mode stress situation which has to be considered for the determination of the further crack propagation.

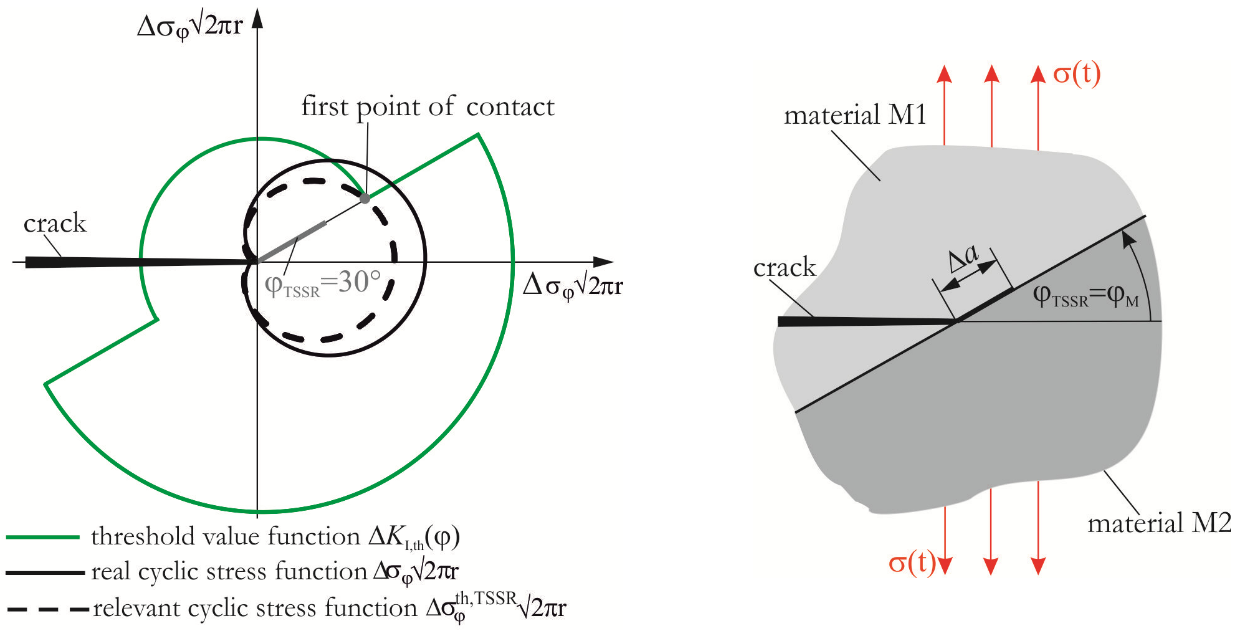


Figure 6: Crack propagation in a fracture mechanical graded structure for Mode I with the gradation angle $\varphi_M = 30°$: a) application of TSSR-concept, b) resulting crack increment Δa.

For other sample applications (further crack propagation, occurrence of unstable crack growth, different gradation angles and loading situations, continuous material transitions, expansion of the TSSR-concept to three-dimensional problems) see [4].

EXPERIMENTAL INVESTIGATIONS OF FRACTURE MECHANICAL GRADED MATERIALS

Based on the theoretical considerations experimental investigations are carried out to confirm the different influences of a fracture mechanical material gradation on the crack propagation. The studies [4, 6] are carried out with the electro-dynamic test system Electro-Puls E10000 of the company Instron according to ASTM E647-08 [7]. Previously, the compact tension specimens (CT specimens) were heat-treated resulting in a fracture mechanical material gradation.

Influence on the crack velocity

In the following, experimental results of a CT-specimen with a fracture mechanical material gradation characterized by the gradation angle $\varphi_M = 90°$ are presented. Here, the crack grows from a ferritic-perlitic microstructure towards martensitic microstructure of the heat-treatable steel 51CrV4. Fig. 7 shows the determined crack growth rate da/dN with proceeding crack growth and ΔK_{max} remaining constant. At the beginning the crack grows with a rather constant crack velocity da/dN of approximately $6.3 \cdot 10^{-5}$ mm/load cycles. This behavior is comparable to that of homogeneous and isotropic materials. However, a change of the crack velocity occurs at the crack length a ≈ 20 mm. A linear increase about an area of 4 mm is registered and clarifies the change of the fracture mechanical properties and therefore the existence of a fracture mechanical material transition. At the crack length a ≈ 24 mm the crack propagation takes place with a constant crack velocity. The crack has reached a region with isotropic and homogeneous material properties again.

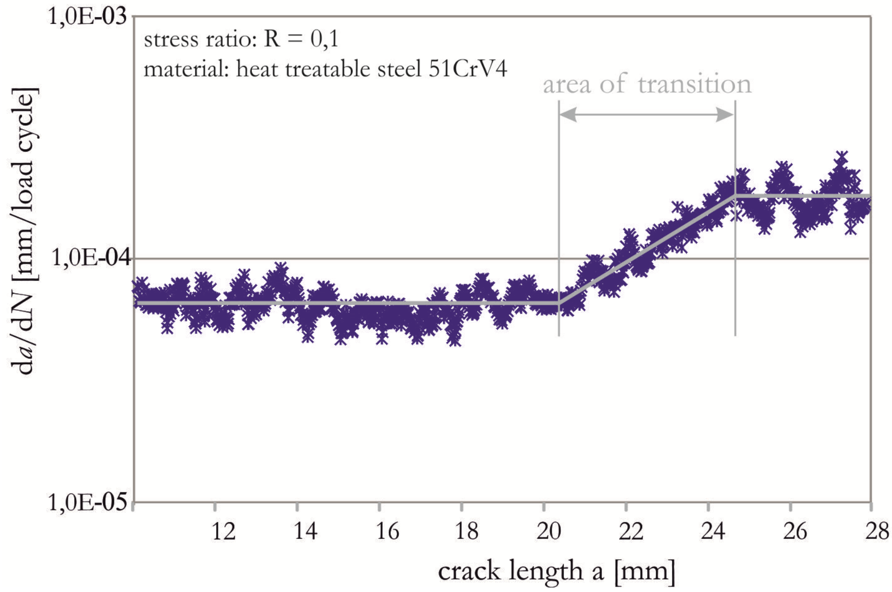


Figure 7: Crack velocity in fracture mechanically graded compact tension specimens with the gradation angle φ_M=90°.

Influence on the crack propagation direction

Fig. 8 shows a compact tension specimen with the gradation angle φ_M = 30° and a crack growing from the martensitic microstructure towards the ferritic-perlitic base material. While for homogeneous and isotropic materials and the global stress situation Mode I a crack propagation within the initial plane of the crack is expected, the application of the TSSR-concept leads to the theoretical kinking angle φ_{TSSR} = φ_M = 30° for an appropriate graded specimen. Fig. 8a shows the predicted crack propagation by the TSSR-concept.

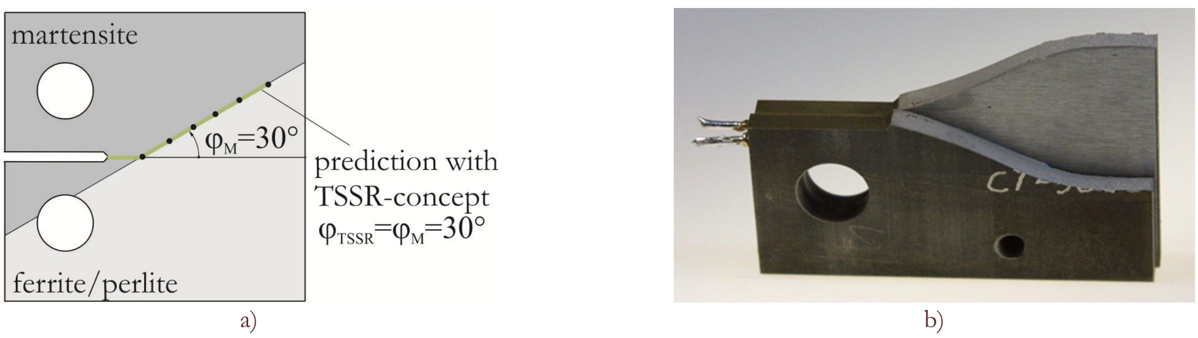


Figure 8: a) Gradation angle φ_M and theoretical kinking angle φ_{TSSR} = 30° determined by TSSR-concept, b) experimental determined kinking angle φ_0 ≈ 23°

The experimentally examined graded CT-specimens with gradation angles of φ_M ≈ 30° show kinking angles φ_0 of approximately 23°. The deviation between the experimental kinking angle φ_0 and the predicted kinking angle φ_{TSSR} is 7° and can be explained by minor differences in the material transitions caused by heat treatment and sample taking. Whereas the application of the TSSR-concept assumes a gradation angle of φ_M = 30° as well as a sharp material transition, the gradation angle and the material transition within the tested specimens may vary slightly.

Finally, it can be stated that the experimental investigations confirm that the crack propagation is not only affected by the local stress field, but also by the fracture mechanical material gradation.

NUMERICAL INVESTIGATIONS OF FRACTURE MECHANICAL GRADED MATERIALS

For lifetime prediction of components and the determination of the entire crack propagation analytical methods and programs can only be used in a restricted way due to the increasing complexity (geometry of the component, material gradation, stress situation). Hence, numerical crack propagation programs, which are usually based on the finite-element-method (FEM), are required. In the following, simulations with the two-dimensional program FRANC/FAM*, which is modified by the TSSR-concept to be able to consider the influence of the fracture mechanical gradation, and the three-dimensional program ADAPCRAKC3D are used. More information and further examples considering the crack simulation in fracture mechanical graded structures can be found in [4, 8, 9].

*2D-Simulations with FRANC/FAM**

For the two-dimensional simulations with FRANC/FAM* a CT-specimen is used which is subjected to a cyclic load and a stress ratio of R = 0.1. The application of force as well as the bearings are shown in Fig. 9a. The occurring crack propagation in the case of a homogeneous and isotropic CT-specimen is presented in Fig. 9b. The stress situation Mode I caused by the global load results in a crack propagation within the initial area of the crack.

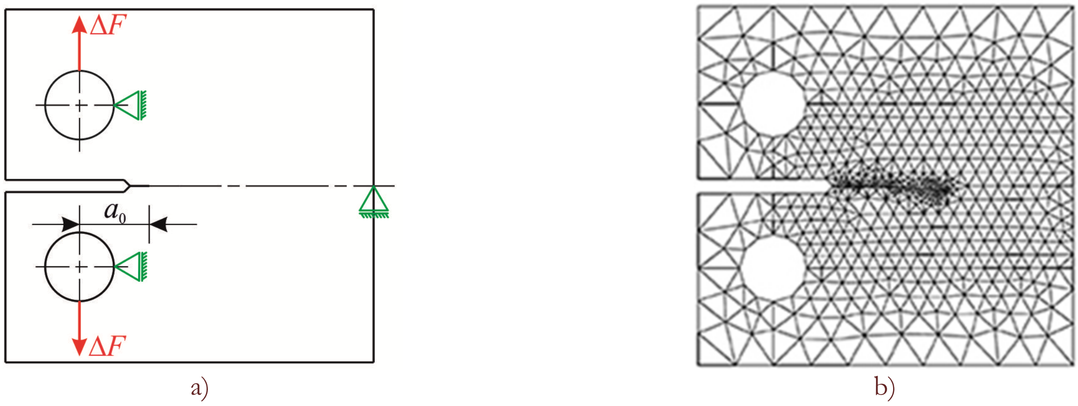


Figure 9: a) Geometry of CT-specimen and boundary conditions, b) simulated crack propagation in a homogeneous and isotropic structure for Mode I loading.

In another simulation (Fig. 10) a fracture mechanical graded CT-specimen with the gradation angle of φ_M = 60° is considered. The initial crack is within the martensitic microstructure, whereas the crack tip sees both fracture mechanical different material regions. As shown in Fig. 10a, the application of the TSSR-concept determines the gradation angle φ_M = 60° as the occurring kinking angle φ_{TSSR} for the first simulation step. Hence, the crack kinks in the first step and grows along the transition. In further simulation steps the local gradation angle $\overline{\varphi}_M$ = 0° is determined as the subsequent crack propagation direction, so that the crack propagates exclusively along the material transition.

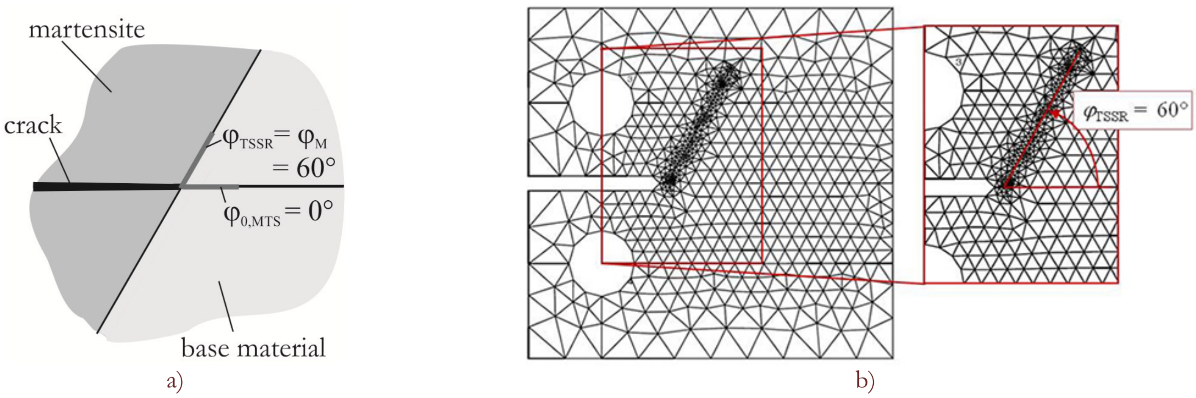


Figure 10: a) Gradation angle φ_M = 60° and prediction of TSSR-concept for Mode I loading for the first simulation step, b) simulation of the entire crack propagation along the material transition.

3D-Simulations with ADAPCRACK3D

In further simulations the crack propagation within a fracture mechanical graded flanged shaft (Fig. 1) is analyzed. First, a rather sharp material transition between martensite and ferrite-perlite is considered with the martensitic width b (Fig. 11a). Subsequently the sharp transition is replaced by a bainitic intermediate layer [8]. The initial crack is a half-elliptical surface crack. Both illustrations in Fig. 11 show that this crack grows from the ferritic-perlitic material towards the martensitic microstructure. Upon reaching the martensite unstable crack propagation and thus the failure of the flanged shaft occur. The smoother transition with the bainitic intermediate layer enables a longer crack growth and therefore more load cycles until final failure.

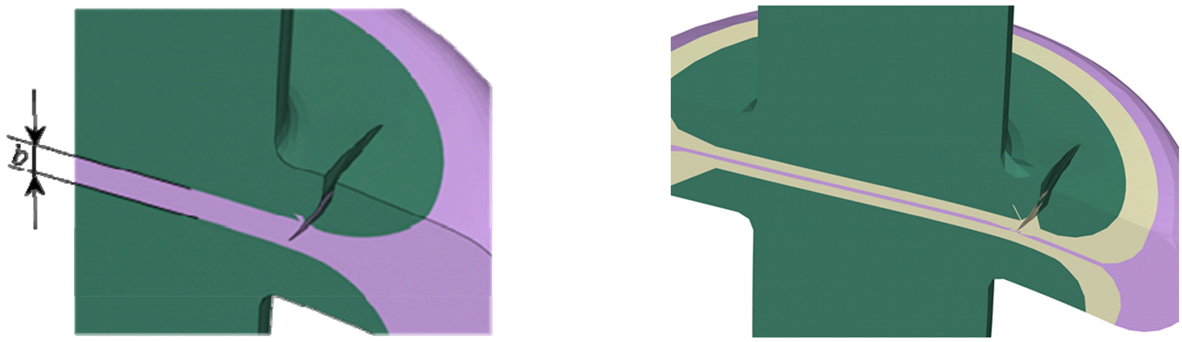


Figure 11: a) Unstable crack growth in the flanged shaft with sharp material transition between ferrite-perlite and martensite, b) unstable crack growth in the flanged shaft with smoother material transition by a bainitic intermediate layer

The crack depth - load cycles - diagram in Fig. 12 illustrates the influence of a sharp or rather smooth transition between both microstructures. For the sharp transition unstable crack propagation occurs at the crack length a_c = 10 mm and after approximately 2.500.000 load cycles. The use of a pronounced smoother transition with better fracture mechanical properties than the martensitic microstructure results in a higher critical crack depth $a_c \approx 12$ mm and increases the tolerated load cycles by the factor 1.6 compared to the sharp transition. This simulation with ADAPCRACK3D clarifies among other things that a good choice of material gradation might influence the lifetime of structure in a positive way [4, 9].

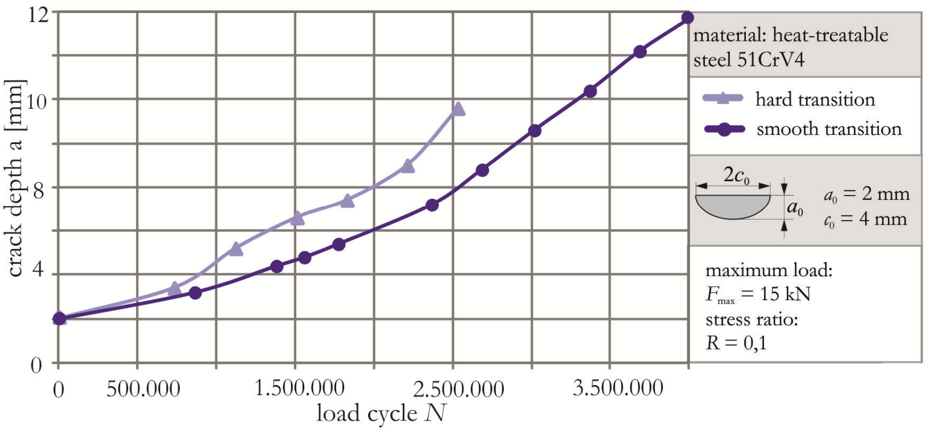


Figure 12: Interaction of crack depth a and load cycles N for sharp and smooth microstructural transition

CONCLUSION

In general, it can be concluded, that fracture mechanical material gradations can have an impact on the range of stable fatigue crack growth, on the crack velocity, on the crack propagation direction as well as on the component life time. The knowledge gained from this work can be taken into account among other things directly during the production of fracture mechanical graded structures and components. Structures are often hardened to ensure a high wear protection at the component surface. Therefore, they possess a martensitic microstructure which is rather brittle and susceptible to cracks. If a cracks grows exclusively within this martensitic region, which is characterized by worse fracture mechanical properties, the structure might fail at an early stage. However, the theoretical considerations have shown, that crack propagation might be slowed down purposefully if the crack grows into a material with better fracture mechanical properties. At the best crack arrest may occur. If these potential consequences are known, they can be taken into consideration during the production process. Based on the theoretical considerations the development of the TSSR-concept enables to describe the crack growth behavior in fracture mechanical graded structures for different gradation and loading situations. Furthermore, the developed and modified programs can be used at an early stage to influence the crack propagation behavior in a positive way and to realize a longer life time of the graded component.

ACKNOWLEDGEMENT

This contribution is based on investigations of the collaborative research centre SFB/TR TRR30, which is kindly supported by the German Research Foundation (DFG).

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