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Theoretical, experimental and numerical investigations on crack growth in fracture mechanical graded structures

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ABSTRACT

Crack propagation is not only influenced by the loading situation but also by a material gradation within the structure. Therefore, it has to be examined how the crack propagation behavior changes when a crack grows through regions which are characterized by different fracture mechanical material properties. Within the scope of this paper, especially the influence of a fracture mechanical material gradation on the beginning of stable crack propagation, the crack velocity, the crack propagation direction as well as on the occurrence of unstable crack growth for statically and cyclically loaded components is discussed. In this context, a developed concept for the prediction of crack propagation in fracture mechanical graded structures, experimental investigations as well as numerical simulations of crack growth are presented. The experimental considerations clarify the influence of the material gradation and confirm the predictions of the new concept. The numerical simulations of crack growth indicate the influence of the material gradation especially on the lifetime of graded components.

1. Introduction

For the development of parts and components the fundamental goals are among other things the fail-safe, reliable as well as material specific dimensioning while considering the environmental impact, the cost effectiveness and the implementation of the lightweight concept. In this context, functional graded materials become increasingly important. These materials are characterized by local varying material properties. In this way, different requirements in regard to the fatigue behavior and the wear protection of the component can be met. For the dimensioning against fracture mechanical failure and the decision whether components with cracks can still be used, the crack propagation behavior have to be analyzed.

For homogeneous and isotropic material behavior, i.e. for materials with constant elastic and fracture mechanical material properties, these issues have been solved as far as possible. Thus, existing concepts describing the crack propagation behavior can be applied. If the fracture mechanical material behavior, however, depends on location and direction, there is need for further research.

2. Functional graded materials

Functional graded materials (FGM) are characterized by locally different properties. They are able to meet various requirements, inter alia, in terms of strength, fatigue, wear and temperature resistance. Such components consist of two

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Nomenclature

a	crack length
a_c	critical crack length
b	width of martensitic structure
CT	compact tension
DFG	German Research Foundation
da/dN	crack growth rate
E	Young's modulus
FGM	functional graded materials
K	stress intensity factor
$K_{I,max}$	maximum stress intensity factor
$\Delta K_{I,th}$	threshold value
$\Delta K_I^{th,TSSR}$	relevant (normed) cyclic stress intensity factor
K_{IC}	fracture toughness
MTS	maximum tangential stress
N	number of load cycles
R	stress ratio
t	thickness
V	mixed mode ratio
φ	polar coordinate
φ_M	gradation angle
φ_{TSSR}	kinking angle due to TSSR
$\varphi_{0,MTS}$	stress controlled kinking angle
$\Delta\sigma_\varphi$	cyclic tangential stress
$\Delta\sigma_\varphi\sqrt{2\pi r}$	cyclic tangential stress function
ν	Poisson's ratio

or more materials or phases within the structure, in which the composition, the morphology, the density, the porosity, the microstructure or the ratio of the different materials vary in spatial directions [1–4]. The uniqueness and the many benefits of these materials have always been uncontroversial, so that the development and the research in this area have been increased significantly in recent years. The advantage of functional graded materials is their multi-functionality caused by the flexibility of the material properties. In order to meet different local demands the composition and the microstructure can be tailored from one region to another [2,5–11]. This results in innovative properties that can't be achieved with conventional homogeneous materials [3]. Graded materials enable the optimum combination of different desirable properties or the utilization of the advantages of each of the present phases, inter alia strength, ductility, surface hardness, wear and impact resistance [1,2,4].

From 2006 until 2014 the Collaborative Research Centre TRR 30 of the German Research Foundation (DFG) analyzed the "process-integrated manufacturing of functionally graded structures on the basis of thermo-mechanically coupled phenomena" [4,12]. Fig. 1a shows the thermo-mechanical heat treatment used by the collaborative Research Center TRR 30 to realize a functional material gradation [9]. Here, the thermo-mechanical treatment is part of the current shape forming process leading to less costs and shorter process chains. Due to the interaction of various temperature distributions and of local different cooling rates different component geometries (e.g. symmetric, asymmetric and double flanged shafts) as well as local different microstructures can be adjusted [13,14]. The microstructural distribution is shown in Fig. 1b. The shaft region

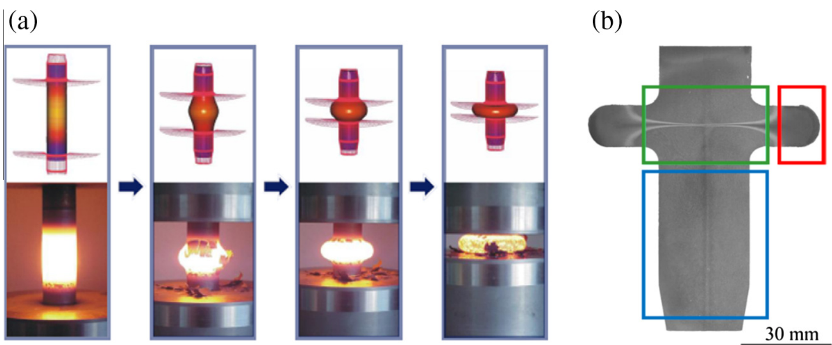

Fig. 1. (a) Thermomechanical production of the graded flanged shaft [13,14], (b) flanged shaft with material gradation [15,16].