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Functionally graded materials with a soft surface for improved indentation resistance: Layout and corresponding design principles

Tobias Ziegler *, Torsten Kraft

Fraunhofer Institute for Mechanics of Materials, Wöhlerstraße 11, D-79108 Freiburg, Germany

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A B S T R A C T

We report the finding of an optimal layout of functionally graded materials (FGM) towards indentation resistance. This optimum is characterized by a minimum in tensile surface stresses that can lead to a belated onset of cracking compared to homogeneous materials of uniform stiffness. The parameters influencing the tensile surface stresses in a FGM consisting of a soft surface layer, a stiff base material and a graded region between them have been investigated by finite element analysis and an optimum is reported for the first time. The results in general units can be used to design the gradient in any FGM from plastics to ceramics to result in low tensile surface stresses for a given load.

1. Introduction

Functionally graded materials (FGMs) have first been investigated in Japan in the 1980s during the Hope-X space plane research project and have since become a major area of research in materials science. Since the mid 1990s the amount of papers published in this area has increased from around 100 papers to almost 1000 papers per year. Applications range from design to medical applications [1] to FGMs for improved tribological properties [2,3].

A wide variety of production techniques has been developed including rapid manufacturing machines [4]. This allows for easy production with a lot of freedom in the layout, which poses the question: "How should we design FGMs for a given function?" A typical load situation is indentation into functionally graded half spaces. One of the first theoretical studies by Giannakopoulos and Suresh [5] studied the contact problem for FGMs with a graded exponential law. Ke and Wang [6] have developed a multi-layer model to numerically solve the contact problem for arbitrary variations in stiffness. This model covers the direct area of contact. Experimental evidence for benefits of graded substrates towards indentation has been given by Jitcharoen et al. [7], who showed that the creation of Hertzian cracks under indentation can be suppressed in graded materials. This gives great opportunities to design FGMs for increased usability under indentation.

Similar load cases often occur in tribological applications where the indented half space is typically moved under the indenter. For example, shoe soles or tires could increase their durability on uneven terrain. As these examples show general design rules for FGMs with improved resistance towards indentation can be applied to a wide range of materials from plastics to ceramics.

While the possible benefits of well-designed FGMs have been proven experimentally and described theoretically by Jitcharoen et al. [7], no thorough study of the parameters involved on the resulting stresses has been given up to date. Therefore, we studied this phenomenon in detail and present a finite element (FE) study of the influence of gradients in material stiffness on the stresses developing during indentation with a rigid spherical indenter. The focus is set on tensile surface stresses, which are most likely to initiate damage and lead to failure. While the actual mode of damage will most certainly depend on the type of material, we try to give insight into general principles that can be applied to a wide range of different materials. The possible applications have shown that improved indentation resistance can be useful for virtually all materials available.

For most production methods a FGM will be made from two materials with differing stiffness layered on top of each other and a graded volume in between where the stiffness smoothly changes from one material's to the other's. This layout was chosen as being most useful for engineers designing FGMs. Depending on the production method of the FGM internal stresses are likely to be present. As these strongly depend on the material and the production method employed they are left out of the current analyses. Possible residual stresses can be superimposed if necessary due to the assumed linear elasticity.

* Corresponding author. Tel.: +49 761 5142 367.
E-mail addresses: tobias.ziegler@iwm.fraunhofer.de (T. Ziegler), Torsten.Kraft@iwm.fraunhofer.de (T. Kraft).

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2. Method

Analytical solutions would be rather complex if existing at all. Therefore, we have used finite elements for the analysis. They have the advantage of being easily customizable and all information of interest is easily accessible. This includes stresses at the surface as well as inside of the FGM. FEA is especially suited for parameter analysis like the ones presented here where many calculations have to be performed.

2.1. Our setup

As we have pointed out the aim of this study is to give insights how to design a FGM for improved resistance towards indentation. As the parameter space is very large for this type of problem we had to make a number of assumptions. The emphasis was set on giving general insight that does not depend on a certain type of material. The assumptions that have been made are:

– No residual stresses exist.
– Linear elasticity is assumed together with isotropic material behaviour.
– The spherical indenter is rigid.
– Frictionless contact is assumed.

The ABAQUS/Standard finite element program was used [8]. For the parameter study a mesh with 24,524 eight-noded 2nd order axisymmetric elements was used. The indenter was taken as a rigid body. Please note that the maximum contact pressure as well as the resulting force was sensitive to the domain size in depth direction, while the tensile surface stress and the contact radius were susceptible to the domain size in radial direction. The outer boundaries were taken to be at least 50 times the contact radius to account for these findings (Fig. 1). Along KL symmetric boundary conditions have been applied. Along LM the movement was restricted along the *z*-axis. All other boundaries had no conditions applied to them.

Typically more than 100 elements were in contact during the analysis to give a sufficient resolution for the stresses inside and outside of the contact region.

The gradient depth β was defined as the depth at which the stiffness is the mean value of the two materials (see Fig. 2). For linear gradients the gradient length Δ defines the distance over which the stiffness changes from the surface material to the base material.

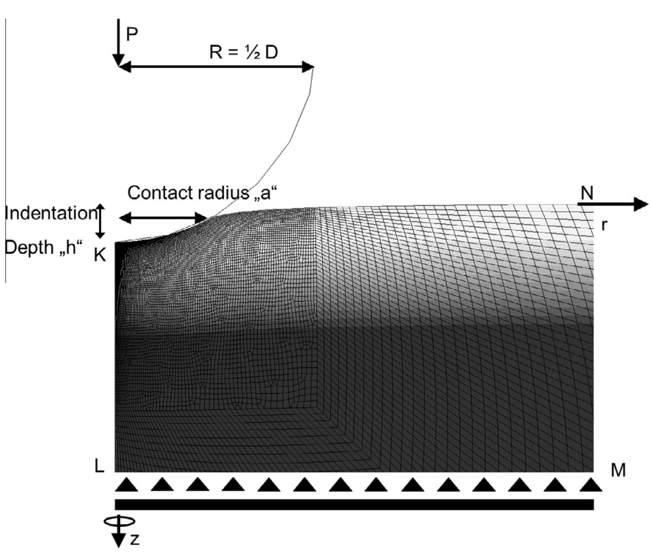

Fig. 1. Setup of the FEA. The indenter is visible on the top left and pressed down the distance "*h*" with the Force "*P*" which results in a contact radius "*a*". The four points K, L, M and N are used to define boundary conditions imposed on the setup.

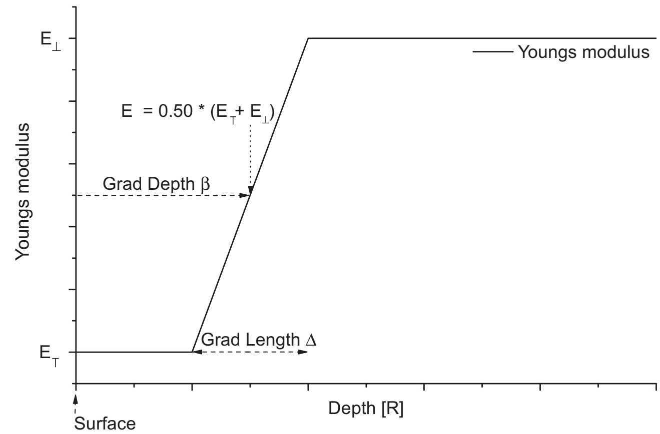

Fig. 2. The Young's modulus of the FGM is here varying linearly from $E_\top$ at the surface to $E_\perp$ at the bottom over a distance called grad Length Δ. The change in stiffness takes place at grad depth β which is defined as the depth at which the stiffness is the average of $E_\top$ and $E_\perp$.

As a convergence test the amount of elements was quadrupled and the influence on the results investigated. The resulting force was equal to the fourth digit; the contact pressure was within 1‰. The maximum principal tensile stress at the surface was along radial direction and its variation less than 1%. To model gradients in material stiffness the stiffness was set at every integration point according to its depth *z*. Thus, the resolution was not limited to element size and artificial shear stresses between layers could be avoided.

2.2. Verification

For comparison the results from Suresh et al. [9] have been reproduced. For this the Young's modulus was varied as a function of the depth $-z$ according to following equation:

$$E = E_0 e^{-\alpha z}$$

where $1/\alpha$ is a length parameter. Calculations were performed for $\alpha = -0.5; -0.25; 0; 0.25; 0.5$ all given in units of $R/2$. The resulting *P–h* curves are shown in Fig. 3. Our results for these special cases are close to the ones obtained by Suresh et al. However, for α below zero we had to apply additional boundary conditions which were not mentioned in [9] restricting movement along MN (Fig. 1). If this condition was not applied the stiff surface layer would compress the compliant base layer without curvature at the contact region.

For the Hertzian case ($\alpha = 0.0$) our result is closer to the analytical solution. More results are given in Table 1. Most results compare well except the maximum tensile principal stress $(\sigma_1)_{max}$, which is one order of magnitude higher. Although we have no proof we attribute this discrepancy to a wrong position of the decimal point.

3. Results

Now we present our results which are aimed at giving the reader a set of rules at hand how to design a FGM for optimal resistance towards indentation. For all simulations performed the material with the higher Young's modulus was always the substrate at the bottom i.e. $E_\top < E_\perp$. This was chosen because of the results from Suresh et al. [9], who found a reduction in tensile surface stresses for this setup. All resulting stresses are given relative to the bottom