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Modeling and experimental verification of simultaneous tension and torsion in a cylindrical element with a surface layer

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ABSTRACT

This paper presents a simulative method which takes into consideration the influence of a surface layer on the stresses observed during low-cycle fatigue regions of tension and torsion and after loadings. The cyclic loading model is described for an axial-symmetric cylinder with a surface layer. The layer is divided into several zones (shells), which enable the introduction of material property changes and residual stresses as a function of the distance from the surface. This work also introduces a comparison of the evolution of residual stresses counted and measured experimentally with shot peened samples after cyclic tension and torsion. The experimental results agree well with the simulation.

1. Introduction

Improvement of machine elements by applying various surface treatments has been studied for a long time. An element with an applied surface layer which differs from the bulk material possesses composite properties, because it is characterized by zones with different structure, different elastic and plastic properties, and a large gradient of initial stress produced by the technological processes (the residual stresses). These stresses are modified in the process of use, which consequently changes not only the residual stress field, but also the properties of the material, especially in the area of the surface layer. Most often, however, the influence of the surface layer is ignored when analyzing the state of tension in an element because of its small influence on the entire element with regard to the small thickness of the surface layer.

Fatigue is an important problem in which the influence of the surface layer is essential. Crack initiation usually begins in the surface layer, and the local state of stress has an important influence [1,2]. The present investigation of elements within a surface layer produced by different technological processes shows that the sources of damage are situated in the transient zone between the surface layer and the core [3,4].

Experimental investigations show that the fatigue strength of samples depends on a complex combination of hardness and residual stresses in the layer [3]; however, for example in the nitrided case, the fatigue strength depends on the thickness of the layer to a lesser degree [4]. In another case, in the PVD layers, no relationship was found between microhardness or residual stresses and the fatigue strength [5]. At present, there are a huge number of production technologies available for the creation of surface layers, which serve to increase wear, fatigue, or corrosive strength of element. However, in some cases, the technology increases the durability of the element with regard to one property, but reduces it in another. This problem exists for the earlier-mentioned PVD technology, which increases the wear strength and reduces the fatigue strength in the case of flat elements [5]. The same technology increases the fatigue strength for elements with a notch [6]. The ability of a given technology to increase the fatigue strength depends not only on its parameters but on the geometry of the element to which the surface layer is applied and also the type of loading of the given element. Therefore, an investigation of the effect of a given technology for given elements and given loading is indispensable. Unfortunately, such investigations are very expensive, time-consuming, and labor-consuming.

Computer simulation of the process of loading an element with a surface layer provides an alternative solution. Such works have been attempted in the Surface Layer Laboratory in IFTR PAS for the low-cycle fatigue process affected by tension and compression in a cylindrical element with a surface layer [7,8] as well as the effect of the angle of torsion [9]. The aim of the present work is to evaluate the solution performance for the simultaneous problem of tension and torsion on an element with a surface layer with different core elasto-plastic material properties with isotropic–kinematic hardening and residual stresses. This problem is essential from a utilitarian point of view in regards to the fact that maximum stresses are situated in the surface layer zone.

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Nomenclature

k_1	number of shells in surface layer	$d\tau^{(i)}$	increment of tangentional stress in (i) shell of layer
k_2	number of tubes in plastic core	θ	torsion angle
g_1	thickness of shells in surface layer	$d\theta$	step of torsion angle
g_2	thickness of tubes in plastic core	ε_z	axial strain
$\sigma_\varphi^{(i)}$	circumferential stress in (i) shell of layer	$d\varepsilon_z$	step of axial strain
$d\sigma_\varphi^{(i)}$	increment of circumferential stress in (i) shell of layer	$\dot{\varepsilon}_z^{pl}$	plastic part of axial strain
$\sigma_r^{(i)}$	radial stress in (i) shell of layer	$\dot{\varepsilon}_\varphi^{pl}$	plastic part of circumferential strain
$d\sigma_r^{(i)}$	increment of radial stress in (i) shell of layer	$\alpha_{ij}(\lambda)$	kinematic hardening
$\sigma_z^{(i)}$	axial stress in (i) shell of layer	$\sigma_y(\lambda)$	isotropic hardening
$d\sigma_z^{(i)}$	increment of axial stress in (i) shell of layer	$\dot{\lambda}$	rate of plastic deformation
$\tau^{(i)}$	tangentional stress in (i) shell of layer	$\bar{r}^{(i)}$	mean radius of (i)-shell

Comparisons of numerical and experimental results, both for relaxation of residual stresses are also introduced for samples subjected to different cyclic multiaxial loading in the present work.

2. Model of simultaneous tension and torsion of a cylindrical element with a surface layer

2.1. Model of an element with a surface layer: assumptions

A correct description of an element with a surface layer, and especially a heterogeneous surface layer, should take into account the possibility of changes in individual material parameters as a function of distance from the surface. A model which includes discrete changes in material properties of the surface layer fulfils these requirements. The cylindrical element with a surface layer is modeled by a homogeneous cylinder and some number of thin-walled coaxial tubes, as well as interactions between these. A solution for the tension process was exactly described in previous work, as was the application of calculations in the case of a hardening layer [7].

The model of simultaneous tension and torsion in the element with a surface layer of elasto-plastic material is introduced in the present work. This model rests on a similar basis as the case of exclusively torsion or exclusively tension. The considered element is a cylinder of length l limited by two transverse sections perpendicular to the axis. Torsion is applied by mutual, stiff turn of transverse sections. Tension is applied by axial strain with conservation of flatness of transverse sections. The surface of the cylinder is not subject to any external influences. The material properties along the length of the cylinder do not change. The state of stress in such an element can generally be described using four components of the stress tensor; σ_ϕ, σ_r, σ_z, and $\sigma_{z\phi}$, because the two remaining components ($\sigma_{r\phi}$ and $\sigma_{rz)}$ equal zero. We accept that the residual stresses in the element, i.e., the non-zero components $\sigma_\varphi^0, \sigma_z^0$ of residual stresses in the surface layer, can exist. Residual stresses often have large values resulting from technological treatment. The stresses in the core result from equalization of stresses in the layer, and the individual component values in the core are usually about an order or two orders lower than in the layer.

The considered element consists of a homogeneous cylinder surrounded by k_1 thin-walled shells thickness g_1 which compose the surface layer. Each of the shells has different material properties and residual stresses. Let us assume, however, that they are constant on a cross-section of the given shell. The number of shells depends on the required accuracy of the approximation of the

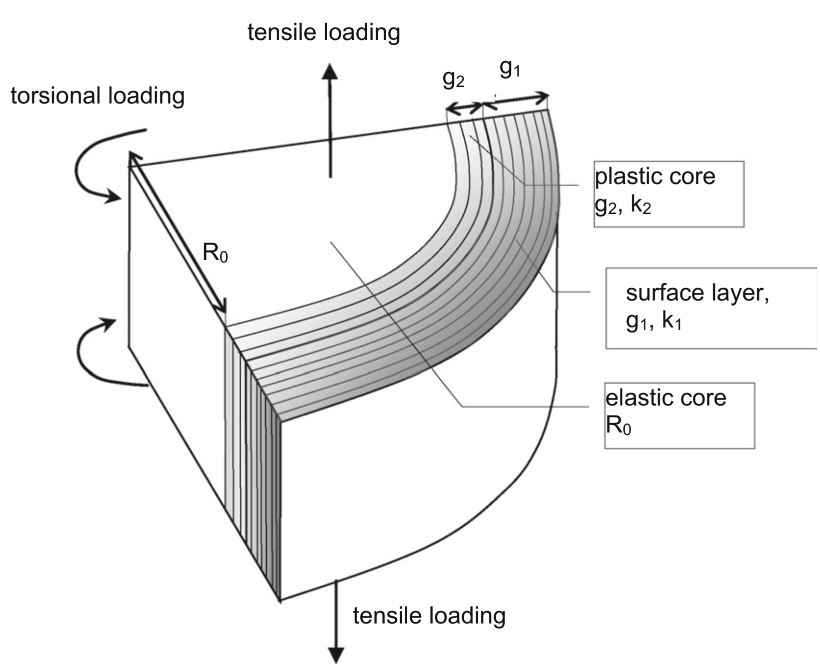

Fig. 1. Arrangement of tubes in plastic core (index$_2$) and the surface layer (index$_1$) (k_i – number, g_i – thickness of tubes).