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Failure probability of ceramic coil springs

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Abstract

Ceramic springs are commercially available and a detailed reliability analysis of these components would be useful for their introduction in new applications. In this paper an analytical and a numerical analyses of the failure probability for coil springs under compression is presented. Based on analytically derived relationships and numerically calculated results, fitting functions for volume and surface flaws will be introduced which provide the prediction of the failure probability of ceramic coil springs with different spring- and material-parameters. As an example, typical mechanical properties for Si_3N_4 are chosen. It is shown that surface flaws control the strength of the investigated springs.

Keywords: Failure analysis; Fracture; Strength; Mechanical properties; Ceramic springs; Springs

1. Introduction

Springs are fundamental mechanical components which form the basis of many mechanical systems. Unlike other components, they undergo significant deformation when loaded and their compliance enables them to store readily recoverable mechanical energy. Thus, springs must possess high strength against the applied force. For that reason, high strength materials such as high carbon steels have been and are still major materials for springs.

However, in recent years the increase of efficiency in many mechanical systems has become more important and this has introduced a new demand for the conservation of more energy in springs. In addition there is need of springs in different working conditions for example at high temperature, high wear rate or high corrosion rate. One way to satisfy these demands is the introduction of new materials for springs. Ceramics have this potential with excellent resistivity to heat, low density, high strength at high temperatures and better corrosion and wear resistances compared to other materials and therefore there is a growing interest in the fabrication of ceramic springs.

The loss coefficient is an important dimensionless material parameter in cyclic loading and plays an important role in the material selection for springs.[1] It is the fraction of mechanical energy loss in a stress–strain cycle. If a material is linear loaded elastically to a stress σ with corresponding strain ε, it stores elastic strain energy per unit volume, $u = (1/2)E\varepsilon^2$, where E is the Young's modulus. If the material is unloaded (after loading), it dissipates energy Δu. The loss coefficient η per radian can be defined as $\eta = \Delta u/2\pi u$.

A high loss coefficient is desirable for damping vibrations while a low loss coefficient transmits energy more efficiently. On the other hand, since the minimum energy loss is desired, the material which is used for springs should have a low loss coefficient. A material property chart of the loss coefficient η at 30 °C plotted against the Young's modulus E is supplied for almost all kinds of material by Ashby.[2] Elastomers have the highest loss coefficient ($\eta = 1$) and advanced ceramics have the lowest with a four-order-of-magnitude reduction compared to elastomers ($\eta = 10^{-4}$). High-carbon steels have just slightly higher loss coefficients than the ceramics.

As stated before, one of the new demands placed on springs arises from the working conditions where the springs are used. At this point, the materials nowadays used for springs have some limitations with respect to temperature, corrosion and wear. With ceramics such as Al_2O_3, Si_3N_4 or SiC, it is possible to work at high temperature up to approximately 1000 °C which is not possible with most other materials. Sato et al.[3] made some experiments and broke Si_3N_4 ceramic springs at different temperatures. They observed no decrease in fracture stress until

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1000 °C and reported that the mean fracture stress at 1200 °C was only slightly less than the values obtained at lower temperatures. Furthermore, Rubesa and Danzer[4] mentioned the importance of ejection velocity of springs in the technical applications and reported advanced ceramics as interesting alternative materials to high carbon steels for the spring production according to the analytically calculated ejection velocity.

There are few references on ceramic springs in the literature. Helical ceramic springs produced from sintered vitreous-bonded alumina were reported by Chironis.[5] Hamilton et al.[6] investigated the mechanical properties of helical ceramic springs manufactured from MgO partially stabilized zirconia. They measured the spring deflection versus applied load at room temperature and also at high temperatures and observed that the material successfully obeys Hooke's law also at elevated temperatures.

Wright et al.[7] investigated the effect on the surface quality of a polymer-ceramic suspension used for the fabrication Al_2O_3 springs and windings by extrusion. The strength of Si_3N_4 coil springs at high temperatures up to 1000 °C and the influence of size on the strength of the springs by derivation of an equation to calculate the effective volumes of coil springs were examined by Sato et al.[3] It was reported that the mean strength of coil springs decreases with increasing effective volume which can be applied in design calculation.

Ceramic springs are mostly manufactured by extrusion of a polymer–ceramic suspension.[7,8] The main steps of this method are preparation of the suspension, extrusion, debinding and finally sintering. The composition of the suspension, the working temperatures and the way of removal of diluents are important parameters in order to avoid surface defects and to obtain a valuable surface quality. Furthermore, there is also a study in the literature where the springs were produced by machining the zirconia tubes.[6]

Despite the advantageous properties of ceramics, there are not too many examples of ceramic springs in the industrial applications. Firstly, manufacturing of springs from ceramics is more expensive compared to other materials. Secondly and the major reason is the brittle failure of ceramics under tension. Since even a very small defect can cause the failure of the component and there is a scatter of strength values, ceramics are less reliable in construction from the point of view of strength compared with metals. However, we are not aware of any study in the literature which gives hints to the reliability of ceramic springs. Nevertheless we think that there is a need for such a reliability analysis to provide useful information to the user about the failure probabilities of springs with different spring- and material-parameters under different loading conditions.

The main aim of this paper is an analytical and a numerical failure probability analyses of ceramic coil springs under compression. The mechanical properties of Si_3N_4 ceramics will be used as an example. Firstly, the coil springs will be shortly introduced. It will be explained how to get series of springs which meet the user specifications with a wide range of values for spring constant k, maximum displacement δ_{max} or maximum allowable force F_{max}. Afterwards, the scaling of failure probability with spring- and material parameters will be established analytically by solving the Weibull distribution function with the theoretical stress distribution in the spring. Thereafter, a numerical analysis will be performed with the finite element software ABAQUS and the post-processor STAU[9] which takes into account the effect of boundary conditions, contact stresses and multiaxial loading. Finally fitting functions for volume flaws and surface flaws will be introduced which corrects the analytical results based on the numerical solutions. This makes it possible to predict the failure probability of ceramic springs with different spring geometry and material parameters.

2. Coil springs

There are several types of springs used for different applications. In this paper, the reliability of ceramic coil springs under compression load is studied since ceramics are much stronger and more reliable under compression than under tension. Their turns are not touching in the unloaded position and they need no attachment points. If these springs are not compressed beyond their elastic limit, they obey Hooke's law, which states that the force F by which the spring is compressed is linearly proportional to the distance x from its equilibrium length:

$$F = -kx \tag{1}$$

where k is the spring constant of the spring.

There are four types of commonly used springs, namely plain, plain-ground, squared and squared-ground springs. They differ from each other by their ends.[1] Here the investigated spring type is a plain spring which is shown in Fig. 1. This type of spring is used because it is the easiest to be treated for the analytical failure probability calculation.

The spring parameters shown in Fig. 1 are:

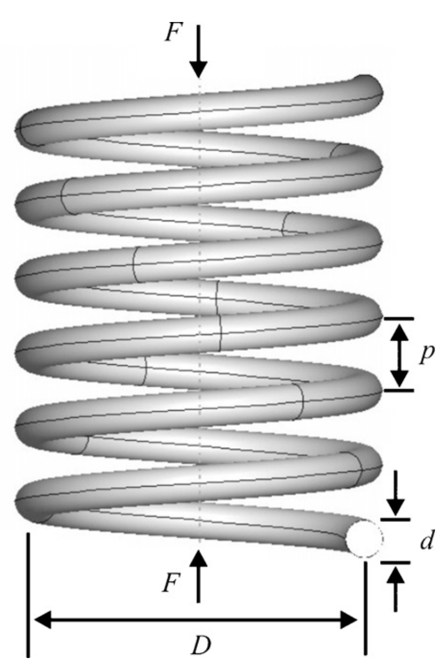

Fig. 1. Schematic representation of plain type coil spring with used spring parameters.