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Shrink fit with solid inclusion and functionally graded hub

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ABSTRACT

Since in a shrink fit the transferable moment essentially depends on the interface pressure between inclusion and hub, the interface pressure should be as large as possible. This may be facilitated by a partially plastic design, which however also has some drawbacks like a possible permanent redistribution of the stresses after operating at high angular speeds and temperatures. In contrast to that, in the present study the use of a functionally graded hub in an elastically designed interference fit with solid inclusion is proposed. It is shown that for an appropriate grading not only the weight of the hub can be reduced noticeably as compared to a homogeneous hub, but also that particularly a much better performance at rotation can be achieved, which predominates over marginal disadvantages at high temperatures. The generally valid analytical results provide a comprehensive means for the practicing engineer for the design of this kind of shrink fits.

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1. Introduction

As shrink fits are a simple and cost-effective means of transfer of moment, they frequently are found in mechanical engineering: examples are shrunk-on rings, armature bandages in rotating machines, or tires of railway wheels [1], to mention but a few. Hence, due to their importance, many studies of their behavior were performed by (semi-) analytical as well as numerical methods. Since under certain circumstances a partially plastic design for better utilization of the material is admissible, often not only elastic but also elastic–plastic states were taken into consideration. For both cases, an application-oriented basic survey of the design of shrink fits can be found in the monograph by Kollmann [2]. Later on, special attention was paid to the widely-used thermal assembly process, see, e.g., the studies by Cordts [3], Mack [4,5], Bengeri and Mack [6], Mack and Bengeri [7], Sen and Aksakal [8], Doležel et al. [1], and Lorenzo et al. [9]. Moreover, several investigations on (transient) heating during operation were performed (e.g. [10–14]), and also effects of various material laws and/or geometrical properties were studied in a number of papers (e.g. [15–20]); in some of these investigations rotation of the shrink fit was taken into account, too. Furthermore, special design procedures were proposed [21].

Since for given geometry of the shrink fit and friction coefficient at the interface between inclusion and hub the transferable moment depends solely on the interface pressure, the latter should be as large as possible. However, maximizing the interface pressure under all operating conditions is limited by several constraints.

As was mentioned above, a possibility to achieve a high interface pressure is to admit partially plastic behavior; if however purely elastic behavior is required a priori – e.g., if the shrink fit shall be easily dismountable without permanent deformation –, an elastic–plastic design cannot be chosen, of course. Nevertheless, the most important issue is a reduction of the interface pressure with increasing angular speed and/or heating during operation. This reduction may be a transient one (which is particularly pronounced for a high rate of the outer surface temperature, see [13]), or in case of an elastic–plastic design also a permanent one, accompanied by a permanent redistribution of the stresses in the entire device. And a further point, which becomes increasingly important in engineering design, is to minimize the weight of the device while maintaining a good or even excellent performance of the shrink fit.

Hence, an interesting alternative (or at least supplement) to admitting partial plasticization might be the use of a functionally graded material (FGM), particularly for the hub. As is well known, in a machine part of FGM the material properties like modulus of elasticity, density, coefficient of thermal expansion, and yield stress vary continuously and can - to a certain extent - be tailored in an appropriate way (for survey articles on this topic see, e.g., [22–25]). Thus, the aim of the present study is to analytically investigate the essential features of a purely elastic shrink fit with

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solid inclusion and functionally graded hub, taking both rotation and an elevated temperature into account. The material properties are presupposed to vary according to a power law in the radial direction; in particular, the case of radially decreasing density of the hub is considered. The latter property may be achieved, e.g., by using a steel/aluminum FGM, which can be produced by a powder metallurgical process, i.e. by appropriate mixing of the respective pure powders, cold pressing, and subsequent sintering (for details see [26]). Then, for a sufficiently large ratio of outer surface radius to interface radius a considerably better performance at rotation may be achieved, accompanied by a substantial saving of weight as compared to a homogeneous hub. These two significant advantages must be weighted against the fact that a marginally worse evolution of the interface pressure with increasing temperature may occur. It is the intention of this paper to thoroughly discuss these effects and to support the practicing engineer in deciding whether a shrink fit with FGM-hub might be advantageous for the specific application under consideration.

The paper is organized as follows: in Section 2, the statement of the problem is given, and the governing equations are derived. In Section 3, the stress distribution is discussed, and particularly the interface pressure under various operating conditions is studied. Finally, some concluding remarks are made in Section 4.

2. Statement of the problem and governing equations

2.1. Statement of the problem

The subject of the investigation is a cylindrically symmetric shrink fit with homogeneous solid inclusion ($0 \leqslant r \leqslant a$) and an FGM-hub ($a \leqslant r \leqslant b$) with free cylindrical outer surface,

$$r = b: \quad \sigma_{r,h} = 0; \tag{1}$$

it is presupposed that the axial length c of the device under consideration is much smaller than the diameter of the inclusion (see Fig. 1), and therefore a treatment as a plane stress problem is feasible [2,21], so that

$$\sigma_{z,i} = 0, \quad \sigma_{z,h} = 0, \tag{2}$$

where the indices i and h are here and in the following assigned to the inclusion and the hub, respectively. As a matter of course, the radial displacement u has to comply with the condition

$$r = 0: \quad u_i = 0, \tag{3}$$

and the relations

$$r = a: \quad \sigma_{r,i} = \sigma_{r,h}, \tag{4}$$

$$r = a: \quad u_h - u_i = d \tag{5}$$

with the interference d hold.

A purely elastic design of the shrink fit under all operating conditions is required, and slowly varying angular speed is presupposed.

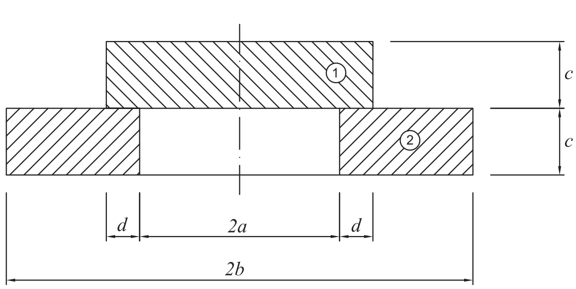

Fig. 1. Sketch of the shrink fit (prior to the assembly); ① inclusion, ② hub.

2.2. Governing equations

First, the basic equations shall be summarized. Taking a variable density $\rho = \rho(r)$ into account, the equation of motion in radial direction reads

$$\frac{d(r\sigma_r)}{dr} - \sigma_\theta = -\rho(r)\omega^2 r^2. \tag{6}$$

For small deformations, the geometric relations are

$$\epsilon_r = \frac{du}{dr}, \quad \epsilon_\theta = \frac{u}{r}. \tag{7}$$

Furthermore, considering a variable modulus of elasticity $E = E(r)$ and variable coefficient of thermal expansion $\alpha = \alpha(r)$, but constant Poisson's ratio ν (as discussed below), the generalized Hooke's law reads

$$\epsilon_r = \frac{1}{E(r)}(\sigma_r - \nu\sigma_\theta) + \alpha(r)T, \tag{8}$$

$$\epsilon_\theta = \frac{1}{E(r)}(\sigma_\theta - \nu\sigma_r) + \alpha(r)T, \tag{9}$$

where T means the difference of absolute and reference temperature.

Next, for the FGM-hub the dependence of ρ, E, and α on the radial coordinate must be specified: as was already mentioned in the Introduction, a power law is presumed (compare e.g. related studies for disks by Horgan and Chan [27] or Tutuncu and Temel [28]). The basic grading law is however not postulated for the volume fractions of the constituents (e.g. [29]), but for the modulus of elasticity, and the dependence of the other physical quantities on r then is derived by the rule of mixture. The reason for this is that in this case a closed-form solution of the differential equations can be found, and therefore a purely analytical discussion of the problem is possible.

The general linear rule of mixture reads [29]

$$Pr_{eff}(r) = Pr_1 V_1(r) + Pr_2 V_2(r); \tag{10}$$

there, Pr_{eff} means an effective material property, and V_j is the volume fraction of material j with property Pr_j, $j = 1, 2$. In the following, it is further postulated that the material at the inner surface of the hub (denoted by the index s) is pure constituent s of the FGM (i.e., $V_s(a) = 1$) and the same material as used for the homogeneous inclusion. If the index l denotes the second constituent of the FGM-hub, it is obviously

$$V_l(r) = 1 - V_s(r). \tag{11}$$

Now, presuming that in the hub the modulus of elasticity varies according to

$$E(r) = E_s\left(\frac{r}{a}\right)^m, \tag{12}$$

there follows from (10)–(12) that the volume fraction of constituent s should vary with r according to

$$V_s(r) = \frac{E_s\left(\frac{r}{a}\right)^m - E_l}{E_s - E_l}. \tag{13}$$

Then, applying the rule of mixture (10) to the density $\rho(r)$, the coefficient of thermal expansion $\alpha(r)$, and also to the uniaxial yield limit $\sigma_y(r)$, respectively, one finds

$$Pr_{eff}(r) = A_{pr}\left(\frac{r}{a}\right)^m + B_{pr} \tag{14}$$

with

$$A_{pr} = \frac{E_s(Pr_s - Pr_l)}{E_s - E_l}, \quad B_{pr} = \frac{E_s Pr_l - E_l Pr_s}{E_s - E_l}, \tag{15}$$

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