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Stress analysis of shrink-fitted joints for various fit forms via finite element method

Adnan Özel *, Şemsettin Temiz, Murat Demir Aydin, Sadri Şen

Department of Mechanical Engineering, Engineering Faculty, Atatürk University, 25240 Erzurum, Turkey

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Abstract

The stresses and deformations in the shrink-fitted hub–shaft joint for various fit forms have been analysed using finite element method. First, the results of finite element method (FEM) were compared with the results of Lame's equations along central radial line of one shrink fit type for accuracy of model and it was proved by these results. Then, the most appropriate fit type was investigated. It was observed that the most effective parameter to determine appropriate fit type is to be stepped or not for shaft and the geometries of hub of which edges were wasted have been found as more appropriate to reduce the stresses and deformations. Finally, it was also observed that the each point of the shaft or the hub at the moment of the first meeting to its partner during fit can enter the plastic region, and this situation must be taken into consideration as design parameter.
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Keywords: Shrink fit; Finite element method; Assembly

1. Introduction

There is, generally, a moment transmission problem between shaft and hub. For transmission of moment, the joining elements are placed in the interface of the two mating parts and these joining elements are classified into two groups as force-closed and form-closed joining elements according to their principle of working.

The essential principle in force-closed joining elements is to produce a pressure between the inner member, a shaft and the outer member, a hub. When the torsion moment is applied, a friction moment M_f occurs between contact surfaces. To provide the transmission, it must be $M_f \geqslant M_t$.

The pressure between hub and shaft contact surface can be produced by various method. The most widespread used are interference fits. For transmit moment, the required pressure is formed in interference fits by diameter difference. Therefore, initially, the outer diameter of shaft (d_S) is constructed greater than hollow diameter of hub (d_H). When assembling hub onto shaft, a shrinkage $\Delta d = d_S - d_H$ occurs at the interface of hub and shaft. Consequently, a contact pressure and friction force is created at the interface. After being constructed, the hollow diameter of the hub increases very small amount and the outer diameter of the shaft shrinks very small amount. Namely, attachment diameters, d will $d_H < d < d_S$.

In interference fit, hub can be mounted onto shaft by two different methods as radial and axial. In radial interference fit, hub is heated or shaft is cooled. In axial interference fit or press shrink fit, one part (hub) is mounted onto another (shaft) by axial pressing [1]. For analytical solution, in this subject, Lame's equations have been widely used in long cylinder problems [2–4]. Furthermore, experimental studies were performed [5].

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* Corresponding author. Tel.: +90 442 231 4503; fax: +90 442 236 0957.
E-mail address: aozel@atauni.edu.tr (A. Özel).

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Nomenclature

M_f	friction moment	ν_S	Poisson's ratio of shaft
M_t	torsion moment	U	strain energy
d_S	the outer diameter of shaft	V	external work
d_H	the internal diameter of hub	$\{\varepsilon\}$	strain vector
d	the nominal diameter	$[B]$	strain–displacement matrix
l	fit-length	$[D]$	elasticity matrix
D	the outer diameter of hub	$\{u\}$	nodal displacement vector
σ_t	tangential stress	$[N_n]$	matrix of shape fuctions
σ_r	radial stress	$\{\delta u\}^\mathrm{T}$	a set of arbitrary virtual displacements
p	contact pressure	$[K]$	element stiffness matrix
d_Si	internal diameter in hollow shaft	$\{F_\mathrm{e}^\mathrm{th}\}$	element thermal load vector
D_H	external diameter of hub	$[M_\mathrm{e}]$	element mass matrix
E_H	modulus of elasticity of hub	$[K_\mathrm{e}^\mathrm{f}]$	element foundation stiffness matrix
ν_H	Poisson's ratio of hub	$\{\ddot{u}\}$	acceleration vector
E_S	modulus of elasticity of shaft	$\{F_\mathrm{e}^\mathrm{pr}\}$	element pressure vector

Prasad et al. [6] analysed the stresses in hollow shaft using finite element method (FEM) for hub–shaft system with different combinations l/d (fit-length/nominal diameter), D/d (hub outer diameter/nominal diameter) and interferences. Their results are in good agreement with Lame's equation results at the centre point of the fit [6].

Zang et al. [7] applied Lame's equations and three-dimensional FE stress analysis to interference fits in ring gear-wheel connections. They found that Lame's equations do not give good results for the interference stresses and deformations of complex geometry. They also found that three-dimensional finite element analysis gives more complete and accurate results.

The finite element analysis for a tubular alumina liner, which was shrink-fitted into a heat-treated high-speed steel (HSS) sleeve and subjected to high internal pressure and high temperature, was performed. Based on the analysis a prototype alumina liner-steel sleeve was manufactured, and it was found that the alumina might be used as the structural liner for high pressures and temperatures when it was shrink-fitted into a heat-treated HSS sleeve [8].

The stresses and deformations in thin rings and disc after being interference-fitted as thermally or not are analysed. The fit-length which the plastic deformation occurs is also determined [9,10]. The behaviour of carbon face seals, used in aircraft engines and assembled via a shrink-fit procedure which generates residual stresses in both components were researched using a two-dimensional axisymmetric finite element analysis [11].

In this work, the stress and deformation analysis of shrink fitted shaft (without hollow) with six different fit forms which have the same size fit features was performed by FEM and the effects of geometry on stress and deformation were researched. It was determined that the geometry has a significant effect on the stresses and deformations at the beginning and at the ends of the fit zone.

2. Computation of stresses and deformations at shrink fit based on lame's equations

In order to compute the stresses and deformations at shrink fits, the results of elasticity theory (Lame's equations) for thick-wall cylinder subjected to both internal and external pressure are used. Although the shape of machine components used in technical are very different (for example ring gear, wheel) from the shape used in Lame's analysis and the results obtained from Lame's equations are approximate calculation, due to its practical applicability, it has been used widely.

2.1. Stresses

In thick-wall cylinder subjected to both internal and external pressure, tangential (σ_t) and radial (σ_r) stresses occur on condition that deformations are in elastic region. Assuming the cylinder subjected to internal pressure as hub and the cylinder subjected to external pressure also as shaft, the stresses can be calculate by Lame's equations as follow. The stresses in shaft:

$$\sigma_\mathrm{tS} = -p\frac{d^2}{d^2 - d_\mathrm{Si}^2}\left(1 + \frac{d_\mathrm{Si}^2}{d_\mathrm{i}^2}\right), \tag{2.1}$$

$$\sigma_\mathrm{rS} = -p\frac{d^2}{d^2 - d_\mathrm{Si}^2}\left(1 - \frac{d_\mathrm{Si}^2}{d_\mathrm{i}^2}\right), \tag{2.2}$$

where p is contact pressure existed between the two parts. d, d_Si and d_i are nominal diameter, internal diam-

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