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Shrink fit design for precision gear forging dies

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ABSTRACT

The usual way to shrink fit design for precision forging of gear dies is to use thick wall cylinder theory (analytical approach) assuming that bore diameter is equal to pitch diameter by neglecting actual gear tooth shape. For more accurate determination, finite element method (FEM) can be used. The actual stresses predicted by FEM are much higher than the analytical approach, so that the design of the gear shaped die is beyond the capability of the analytical approach. In this paper, analytical approach for dies with gear teeth is modified using FEM solution sets. FEM analyses results are verified by experiments. During experiments cylinder approach is observed to be inadequate for forging loads. An easy to use set of formula and nomograms for determination of sizes of die and ring, and radial interference are presented. The solution set is verified with experiments. Proposed equations can safely be used for shrink fit design of precision forging gear dies.

1. Introduction

In precision forging, die components are subjected to high loads in a very short period of time. Components must withstand to high static and impact pressures, friction forces between surfaces, and both mechanical and thermal fatigue. Although the workpiece is plastically deformed under compressive load, forging stresses in the dies are a complex combination of tension, compression and shear. In order to increase the resistance of the die insert against internal pressure, the die insert is shrink fitted into one or more shrink rings. Interference between mating diameters of adjacent rings imposes a compressive hoop (tangential) pre-stress on the die insert. The compressive hoop stress imposed by shrink ring has a cumulative effect at the bore of the die insert. Consequently resultant tensile hoop stress on the bore, caused by the forging loads transmitted through the forging part, can be substantially reduced. Thus, allowing for maximum stress differences particularly at the bore makes it possible for higher forging pressures to be sustained.

In the case of precision gear forging dies, the die insert, shrink ring, punch, mandrel and ejector are made from one of the hot work tool steels, because of subjecting high mechanical and thermal stresses. The rest of the die components (i.e. the bolster, the clamp rings of the punch, the die, etc.) do not have to sustain so much heat and, i.e. thermal stresses, therefore they can generally be made from a high quality general purpose steel. For the sake of cost reduction, shrink fit assembly of a gear forging die is generally made from dissimilar materials having different yield stresses (S_y).

The usual way to calculate the interference allowance between the die insert and the shrink ring is to use thick wall cylinder approach (Parsons and Cole, 1968). The approach is given in detail by Lamé (1852). This approach is also used for design of precision spur gear forging dies (Eyercioglu and Dean, 1997) by considering the die assembly as a short cylinder if the facewidth of the gear is not too long. In this case, the die is considered as a cylinder with an inside (bore) diameter equal to the pitch circle of the gear and the actual gear tooth shape is neglected. It may, however, be

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Nomenclature

a	inner (bore) radius of die
b	outside radius of die
c	outside radius of ring
E	Young's modulus
m	module
n	number of teeth
p_i	internal pressure
S_y	yield stress
z	radial interference
σ_v	Von Mises (equivalent) stresses

expected that the profile of the gear tooth may cause stress concentrations which may cause premature failure of the die.

For more accurate calculation of the die assembly and the interference, finite element method has been used (Frater, 1989). Integrated analysis of cylindrical die is done by Yoh et al. (2002) where initial stress distribution is defined due to the shrink fit of stress rings. This is performed by analyzing the thick-walled multi-layer cylinders under the constant internal/external pressures caused by shrink fit. Shin and Son (1987) presented optimal design of cylindrical die with simple stress-ring. Zhang et al. (2000) compared results of the cylinder approach and FEM for cylindrical die. Oh et al. (1997) used FEM to analyze the stress patterns resulting from the high temperature and pressure in a shrink fit between a liner and a sleeve. Although many finite element analyses have been carried out on different shrink fit designs, very small number of papers available in the literature on the shrink fit design of precision gear forging dies (Kutuk et al., 2003) and a generalized solution has not been presented yet.

Kutuk et al. (2003) compared the results of thick wall cylinder approach and the finite element analysis. It was shown that, while the two methods agree well for the dies without gear teeth, FEM predicts much higher stress values than those of cylinder approach for the dies with gear teeth. It was also concluded that the design of the gear shaped die is beyond the capability of the cylindrical approach and a further study for re-optimizing the interference and other geometric parameters of the die ring assembly is required.

In this study, analytical cylinder approach for dies with gear teeth is modified by using FEM solution sets. The same FEA model which was verified in ref. (Kutuk et al., 2003) is used. The same assumptions of the ref. were made: the die and the ring are homogeneous and isotropic materials, under the maximum forging load conditions the die cavity is completely filled, i.e. the pressure distribution in the die is uniform and the length of the die is long enough to obtain a plane-stress condition. An easy to use set of formula and nomograms for determination of sizes of die and ring, and radial interference are presented. Outcomes of FEA are used to generate gear shrink fit design equations and nomograms. The proposed way of design is applied on production of gear dies. Comparison of cylinder approach with proposed design is made both numerically and experimentally.

2. Cylindrical approach

It was shown by the authors (Kutuk et al., 2003) that the design of gear shaped die is beyond the capability of the cylindrical approach. Although the analytical (thick wall cylinder) approach and finite element method agree well in the design of shrink fit cylindrical forging dies, the actual stresses predicted by finite element method was shown to be much higher than the results of the analytical approach for the dies (Kutuk et al., 2003).

As long as the interference value based on the cylinder approach is used, σ_v value occurring at the inner surface of the gear model does not vary with the module of the gear (for $m = 2$–4 mm) having same pitch diameter. If the interference is optimized the $\sigma_{v(max)}$ value for different modules varies slightly. The results of such a survey for different p' values and modules are given in Table 1 (Kutuk et al., 2003).

The results show that as long as the optimized interference value z is calculated and used, the effect of the module on the $\sigma_{v(max)}$ value is very small in the precision gear forging module range.

3. Finite element model

A 2D model of the shrink fit assembly with similar geometry to cylindrical one is constructed in Fig. 1 and gear die FE model is represented by only a portion due to its symmetry in Fig. 2. Symmetry boundary conditions are used at two sides of the model. The model is loaded by a uniform pressure value of p_i at inside of the die along the gear tooth profile.

Elements used in the model are 8-noded structural and quadrilateral plane elements. Mesh size varies at different regions of the inner surface of the gear die to approach correct stress results. Contact surface between die and the ring are modelled by contact elements of type Contac48. To ensure a continuous and converging solution of the model both die and the ring at contact surface are defined as the contactor and target with respect to each other. The friction coefficient between the die and the ring is used as 0.2 for all models. The finite element package, ANSYS is used for both modelling and solution of the problem.

Finite element gear die models were prepared for three different gear modules of 2, 3 and 4 mm. The reason why the modules are kept between 2 and 4 is that the gear module for precision forging operation is generally restricted to 2–5 mm. Smaller modules, less than 2 mm are difficult to machine on the die. On the other hand, larger modules require much

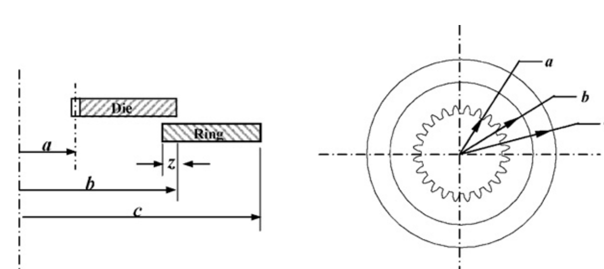

Fig. 1 – Complete shrink fit model.