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A novel autofrettage method for strengthening and design of thick-walled cylinders

H.R. Zare, H. Darijani *

Mechanical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran

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ABSTRACT

In this paper, autofrettage of the thick-walled cylinders is investigated based on a new method named “rotational autofrettage”. The method is inspired from this fact that the cylinders under a large enough angular velocity can experience elastoplastic deformations and the residual stresses. Prior to industrial uses of cylindrical vessels, the process of autofrettage is done by applying an angular velocity which generate the residual stresses. The best angular velocity for the autofrettage operation is selected such that the equivalent and hoop stresses are more uniformly distributed throughout the wall thickness than the case of non-autofrettage. For this purpose, an exact elastoplastic analytical solution is obtained for a rotating thick-walled cylinder made of elastic-perfectly plastic material using Tresca's yield criterion with considering Bauschinger effect. In order to evaluate the performance of the proposed autofrettage approach, the results are compared with those of the routine approach of pressure autofrettage. It was observed that the stress distribution obtained from the proposed method is more uniform rather than the approach of pressure autofrettage. Finally, the optimum geometrical dimensions for a thick-walled cylinder are obtained where large internal pressures have to be withstood.

1. Introduction

Thick-walled cylinders have been widely used for various applications such as transmission and maintenance in petrochemical, nuclear and military industries because of their high pressure bearing capacity. This working condition may cause forming cracks at the inner surface because of large amount of circumferential stresses created at this area. The advantageous residual stress distribution involving compressive hoop stress can be produced near the bore of the cylinder before utilizing them to prevent this problem and increase the pressure bearing capacity. So in the working condition the internal pressure has to vanish the effect of these compressive stresses before tensile stresses can be developed which means the cylinder can contain more internal pressure and is safe in the working condition. This beneficial residual stress is created by the operation named ‘autofrettage’ or ‘self-hooping’. This operation consists of two loading and unloading phase with appropriate level that finally can create a plastic zone near the inner radius of cylinder.

Using autofrettage method dates back to the early twentieth century when a French officer (Jacob, 1907) suggested it for pre-stressing seamless gun barrels. A reliable autofrettage treatment depends on good prediction of induced residual stress in the material. The stress distribution should be specified in both loading and unloading phase whether analytically or numerically to find the residual stress distribution subsequently by superposing their effects. There are different assumptions to be supposed while determining the stress field such as the yield criterion, hardening models, material properties and so on, which directly influence the residual stress distribution and can be mentioned as the main reason of existing differences between the results presented by different investigators.

Saint-Venant [1] presented the developed mathematical relationships for the stresses resulting from overstrain in pressurized thick-walled cylinders made from elastic-plastic material which described the basic concept of autofrettage. Turner [2] suggested using sufficient internal hydrostatic pressure for producing compressive residual bore stresses. Bland [3] considered a thick-walled tube which was made from work hardening material and subjected to internal and external pressure and temperature gradient; then using Tresca's yield criterion obtained the solutions for the stresses, the elastic and plastic strains and the displacements for both loading and unloading phases from which the residual stresses and the residual displacement were calculated. Chen [4] proposed a new theoretical model for a high strength steel which could neglect the small strain hardening during loading but considered two important factors, Bauschinger effect and strain hardening during unloading and obtained a closed-form solution of residual stresses in autofrettaged tubes. The results showed the significant influence of combined Bauschinger and hardening effect on the residual stress distribution. Gao [5] used von Mises yield criterion and

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* Corresponding author at: Department of Mechanical Engineering, Shahid Bahonar University of Kerman, Jomhouri Blvd, P.O. Box 76175-133, Kerman, Iran.
E-mail addresses: hre.zare@gmail.com (H.R. Zare), darijani@uk.ac.ir (H. Darijani).

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deformation theory of Hencky while considering elastic power law plastic material model to obtain a general analytical solution for an internally pressurized open-ended thick-walled cylinder made of strain hardening material that provided a new and more theoretical basis for the autofrettage design of such cylinders. Loghman and Wahab [6] investigated the case of closed end thick-walled cylinder made of isotropic and strain-hardening material while subjected to temperature gradient in addition to internal pressure in the loading phase. They considered the unloading stage to be fully elastic and presented a numerical solution using incremental theory of plasticity and the method of successive elastic solution which was described by Mendelson [7]. Lazzarin and Livieri [8] considered the von Mises yield criterion and presented an analytical solution for the loading phase, valid for materials with linear strain hardening behavior and materials which could be described by the modified Ramberg-Osgood law. In the unloading phase they considered the Bauschinger effect as a function of pre-strain, unlike the Chen's model [4], and employed a numerical method (Runge-Kutta) to find the stress distribution (Following Bland's work [3]). They concluded that this numerical method could be applied to the real σ–ε curve also when the hardening and the Bauschinger effect depends on pre-strain.

Huang [9] introduced a general autofrettage model that benefits a strain-hardening model based on actual stress-strain curve of material which gives more accurate prediction than elastic perfectly plastic model and appropriate for different strain hardening-materials. In this model the Bauschinger effect is treated as a constant and considered von Mises yield criterion and the material supposed to be incompressible (neglects elastic part of total strain). In the plain strain state subsequently presents analytic expression of residual stress distribution. Experimental results show that the model has a stronger curve-fitting ability and gives a more accurate prediction of residual stress distribution. Hojjati and Hassani [10] used von Mises yield criterion and considered elastic unloading to investigate the optimum autofrettage pressure and the corresponding radius of a thick-walled cylinder made of strain hardening material in plane strain and plain stress state theoretically and by finite element modeling, assuming isotropic material model. They presented an explicit expression of optimum autofrettage pressure in plane strain state and showed that it could be used for plain stress state with good accuracy. The results of finite-element modeling were in good agreement with those of the theoretical analysis.

Darijani et al. [11] considered Bauschinger effect as a function of pre-strain and elastic linear hardening model to present an exact analytical solution for thick-walled cylindrical vessels. They introduced two applicable simple and reasonable method to determine the optimum autofrettage pressure for such cylinders and showed its dependency to the Bauschinger effect factor, the working pressure and the geometrical dimensions. On the other hand they presented a solution based on elastoplastic method to obtain the optimum radius ratio and autofrettage pressure for a particular working pressure. Also, they illustrated that the radius ratio and the autofrettage pressure have an inverse relationship with the Bauschinger effect. Guven [12] presented an analytical solution to find plastic strain distribution for cylindrical and spherical pressure vessels considering unified strength criterion with its associated flow rule which takes into account the intermediate principal stress and different limit strength effects, and their impact on maximum plastic strain was investigated. Sedighi and Jabbari [13] introduced a new method of wire-winding based on Direct Method (modified Variable Material Properties method) and investigated the effect of wire-winding in combination with autofrettage on strengthening thick-walled cylinder. Gao et al. [14] presented a general solution based on unified yield criterion to study the autofrettage and shakedown limit of thick-walled pressurized cylinders. Mohammad Ali Khayamian et al. [15] developed a plasticity model for materials with axially symmetric geometry could determine the loading, unloading and residual stresses in materials with asymmetric yield and hardening while assuming isotropic behavior. Davidson et al. [16,17] described swaging method of autofrettage which basically consists of passing an oversize swaging tool through the bore of the cylinder and requires greatly reduced pressure in comparison with the conventional method which utilized hydrostatic pressure; and determined residual stress distribution caused by swaging method and compared with the residual stress resulting from the conventional method. The comparison showed a little difference originating from the difference in the nature of the stress condition responsible for the inducement of overstrains in the swaging method. Mahmoudi et al. [18] investigated another method to strengthen the surface of materials based on creating beneficial residual stress which named shot peening. They studied the effect of initial residual stress in the specimen on the distribution of induced residual stress by shot peening. Correa et al. [19] investigated induction of compressive residual stress with the aim of strengthening the surface of metallic materials named Laser shock processing (LSP) method.

Elastoplastic stress distribution in a rotating cylinder has been investigated by different researchers. Hodge and Balaban [20] considered an elastic linear strain hardening material and used Tresca yield criterion and isotropic hardening model to obtain the stress distribution in the loading stage for three states: fully elastic, elastic-plastic and fully plastic cylinder in a rotating solid cylinder with slowly increasing angular speed. Also, they found the stress distribution neglecting the elastic part of total strain. Gamer and Lance [21] studied the case of rotating tube made of strain hardening material with fixed ends considering the Tresca yield criterion and its associated flow rule and linear strain hardening model obtained the stress distribution for three states: fully elastic, elastic-plastic and fully plastic. Guowei et al. [22] employed a general yield criterion which the Tresca criterion is a special case of it. Twin shear stress yield criterion considers the effect of three principal stresses while Tresca criterion considers only two of them. They determined the elastoplastic stress distribution and elastoplastic angular velocity for both plane stress and plane strain states in a rotating cylinder. In addition, the angular velocity in elastoplastic boundary was calculated by them assuming the material incompressible. The concept of imposing appropriate preload for strengthening other industrial components has been investigated by several researchers. Haag et al. [23] studied the effect of using high enough preload on strengthening and increasing the fatigue life of wires made of high strength steel. Hamilton et al. [24] investigated the impact of thermal autofrettage process on the joints with dissimilar materials to improve their operation in working condition.

In this paper, a new method for the autofrettage of the thick-walled cylinders is proposed. The loading and unloading phases of the proposed autofrettage are the applying an increasing angular velocity from zero to "ω" (loading phase) and then decrease of angular velocity from ω to zero (unloading phase). Assuming elastic-perfectly plastic material behavior and using Tresca's yield criterion, an analytical solution for the residual stress distribution is obtained with considering the Bauschinger effect. In order to reach the aim of *the hoop and equivalent stress optimization* throughout the wall thickness, the best required level of autofrettage is determined. A comparison is made between the stress distributions optimized by the proposed autofrettage method and the conventional method, pressure autofrettage. Finally, the design of thick walled cylindrical vessel is done with the aim of increasing strength-to-weight ratio and more uniform the hoop and equivalent stresses as well as preventing the failure of vessel using the proposed autofrettage method in order to withstand given working pressure.

2. Loading phase of rotational autofrettage

A thick-walled rotating cylinder with an inner radius "a" and an outer radius "b" is considered, while its rotating velocity increases slowly. As the problem is axisymmetric, cylindrical polar co-ordinates r, θ, z are employed, so the principal directions of stress and strain are radial,