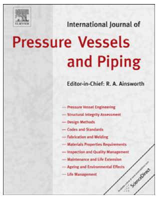
International Journal of Pressure Vessels and Piping 149 (2017) 66–74

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp



Effective parameters on fatigue life of wire-wound autofrettaged pressure vessels

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A R T I C L E I N F O

Article history:
Received 27 December 2014
Received in revised form
7 December 2016
Accepted 11 December 2016
Available online 12 December 2016

Keywords:
Fatigue life
Pressure-vessel reinforcement
Residual stress
Wire-winding
Autofrettage

A B S T R A C T

In this paper, fatigue life of wire-wound autofrettaged vessels is investigated. The mutual and simultaneous effects of cylinder thickness, autofrettage pressure, number of wire layers, wire-winding stress, and working pressure are studied in several cases. The vessel cylinder is made of high strength steel, DIN1.6959, and actual behavior in loading, unloading and reloading is considered. Modified Variable Material Properties method is used to calculate residual stresses in autofrettage process. For wire-winding, since tangent and/or Young's modulus could be changed in autofrettage unloading step or during reverse yielding according to material behavior, a capable approach is applied. Moreover, the fatigue life is determined by using ASME code equations for tick-walled pressure vessels. The results show that by combination of wire-winding and autofrettage techniques, in addition to ability of reducing production costs, infinite fatigue life could be accessible. Furthermore, optimum autofrettage pressure has significant effects on fatigue life and wire-winding efficacy.

1. Introduction

Wire-winding, autofrettage and shrink fit are three common techniques used in order to increase fatigue life and maximum allowable working pressure in thick-walled pressure vessels. In all of them, residual compressive hoop stress is introduced in inner part of vessel cylinder. The combination of these techniques could increase this desirable residual stress and also the advantages of pressure vessel reinforcement.

In autofrettage process, a high pressure is applied to internal surface of a cylinder, which would cause partially plastic deformation in cylinder wall. After releasing the internal pressure, residual compressive hoop stress at the inner part of cylinder is resulted. The effects of material parameters in autofrettage residual stress have been analyzed in the different studies [1-6]. A reliable calculation method should be able to consider all parameters under different conditions for accurate prediction of residual stresses. Variable Material Properties (VMP) method is an iterative elastic solution for axisymmetric boundary value problems under plane stress and plane strain conditions which is proposed by Jahed and Dubey [2]. Farrahi et al. [7] modified VMP method for open-end and closed-end conditions and they named it as Direct Method. Also, Parker et al. [8,9] solved autofrettage problem under open-end and closed-end conditions indirectly, which is known as Hencky program.

In wire-winding process, steel wires with rectangular cross section are wound around a cylinder with tension stress which causes to introduce residual compressive hoop and radial stresses in cylinder. Moreover, preventing rapid failure is one of the most important advantages of wire-winding technique. There are different methods and hypothesis in order to wind and analyze vessels [10-14]. Alegre et al. [15] presented a new procedure for simulation of a wire-wound thick-walled vessel. ASME Code Section VIII Division 3, Article KD-9 has provided design requirements for wire-wound high pressure vessels [16]. While all of the existing analytical methods for wire-winding were applicable for a vessel with constant Young's modulus and elastic behavior, Sedighi et al. [17] proposed a new wire-winding method based on Direct Method, which can be used to calculate residual stresses for a wire-wound vessel with variable tangent and/or Young's modulus.

Reasonable fatigue life is one of the most important objectives in pressure vessel designing. Alegre et al. [18] studied fatigue design of wire-wound pressure vessel by using ASME-API 579 procedure [19]. A theory of autofrettage is proposed by Rees [20] with applications to creep and fatigue. Jahed et al. [21] studied fatigue life prediction of autofrettage tubes by using actual material behavior.

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http://dx.doi.org/10.1016/j.ijpvp.2016.12.003
0308-0161/

Combination of wire-winding and autofrettage techniques could increase desirable compressive residual hoop stress in thick-walled vessels and eliminate their disadvantages. As a result, a higher maximum allowable working pressure and fatigue life would be accessible. In some respects, autofrettage is a more convenient process in comparison with wire-winding. For instance, wire-winding process takes more time and wire could be ruptured during the process. Also, there are some difficulties for starting and finishing the winding process and setting the wires next to each other and regularly in the layers. But maximum available compressive hoop stress is limited in autofrettage process. On the other hand, wire-winding is a safe technique that introduces unlimited compressive residual stress in whole of the cylinder wall and prevents rapid failure.

In this paper, the effective parameters on fatigue life of wire-wound autofrettaged vessels are studied by considering actual behavior in loading, unloading and reloading of vessel material, DIN1.6959. According to the material behavior, after autofrettage process tangent and/or Young's modulus could be changed depending on loading plastic strain. So, a capable method is needed to calculate residual stress after wire-winding of an autofrettaged vessel. For this purpose, an approach based on authors' previous work [17] is used. Moreover, the fatigue life is determined by using ASME code equations for thick-walled pressure vessels. In the following, first governing equations and problem definition will be presented. Then, in the results and discussion section, the effect of five different parameters including thickness of cylinder, autofrettage pressure, number of wire layers, wire-winding stress, and working pressure will be studied mutually.

2. Governing equations and problem definition

First of all, applied equations for prediction of fatigue life in a wire-wound autofrettaged vessel are reviewed. In this way, Direct Method for autofrettage process, the method used for wire-winding, and ASME code equations for fatigue life prediction are presented respectively. Then geometrical dimensions, working conditions, material properties and applied approach will be explained.

2.1Autofrettage, Direct Method

VMP method is an iterative elastic solution for axisymmetric boundary value problems which have inelastic solution under plane stress and plane strain conditions. It is a powerful method which can employ different actual material behavior in loading and unloading steps. Jahed and Dubey [2] presented VMP method based on the following revised constitutive relation:

$$\varepsilon_{ij} = \frac{1+\nu_{eff}}{E_{eff}}\sigma_{ij} - \frac{\nu_{eff}}{E_{eff}}\sigma_{kk}\delta_{ij} \tag{1}$$

where ε_{ij} and σ_{ij} are the strain and stress components, respectively. Also ν_{eff} and E_{eff} are the effective Poisson's ratio and effective Young's modulus which are depended on the final state of stress, uniaxial stress-strain curve, Poisson's ratio, and Young's modulus. There are different methods which can be used to obtain the complete distribution of ν_{eff} and E_{eff} [2].

If cylinder cross section of an autofrettaged thick-walled vessel is divided into several infinitesimal strips, it will be assumed that the material properties, ν_{eff} and E_{eff}, remain constant for points of a strip in each solution. At the beginning of the next iteration, the values of them should be updated. Fig. 1 shows an isolated strip on cross section of a thick-walled vessel [2], where P is internal pressure, r_1 and r_2 are internal and external radius and P_1 and P_2 are internal and external pressures of each strip.

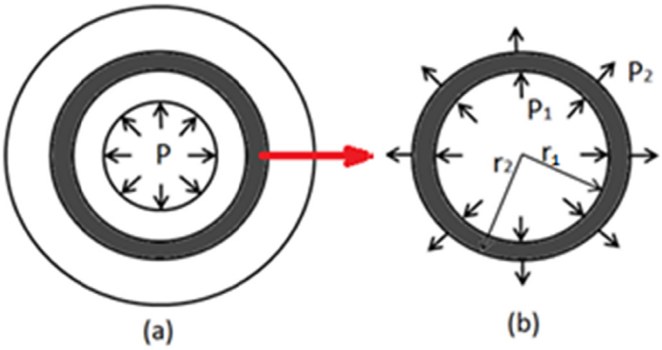

Fig. 1. Cross section of thick-walled vessel cylinder: (a) pressurized cylinder, (b) an isolated strip.

Farrahi et al. [7] modified VMP formulation for autofrettage of thick-walled vessel under open-end and closed-end conditions and called it Direct Method. In this method, the inside and outside displacements for each strip, u_1 and u_2, are related to its inside and outside pressures and constant axial strain, ε_z^*, as the following:

$$\begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} - \begin{Bmatrix} \nu_{eff}\ \varepsilon_z^*\ r_1 \\ \nu_{eff}\ \varepsilon_z^*\ r_2 \end{Bmatrix} \tag{2}$$

where $[c]$ is coefficient matrix and constant axial strain, ε_z^* could be determined for different end conditions [7]. After loading step, the unloading stress-strain curve of each strip should be defined according to the plastic strain and material behavior. The unloading process is the same as the loading process with new stress-strain curve for each strip. In order to calculate residual stress distribution, results from the second step should be subtracted from those of loading [7].

2.2. Wire-winding

For wire-winding of an autofrettaged cylinder, a method based on authors' previous work is applied [17]. In this method, wire layers are wound layer by layer and for each layer, a new individual strip should be defined. This strip assumed as a thin-walled vessel. If the new layer is wound with a hoop stress equal to S_w, then pressure between this layer and the last wound layer, P_w, could be calculated by using Eq.(3):

$$P_w = \frac{2\ t\ S_w}{2R_w - 2\ t} \tag{3}$$

where t is the thickness of the wire layer and R_w is instantaneous applied outside radius. The hoop stress in this new layer is S_w and the radial and axial stresses are zero. To calculate residual stress in the vessel, which is caused by this layer, P_w could be applied to the cylinder and the wound layers as an external pressure under open-end condition. The calculated residual stresses should be added to the previous residual stresses.

By continuing this approach, other new layers could be wound and finally, residual stresses of wire-winding process are obtained for the vessel under elastic (with constant or variable Young's modulus) or plastic behavior [17]. Then, stress distribution could be calculated under working condition (by applying internal working pressure).