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An approach for optimization of the wall thickness (weight) of a thick-walled cylinder under axially non-uniform internal service pressure distribution

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ABSTRACT

Today, improving the weight/load carrying capacity ratio of a part is the matter of studies in most of the scientific and industrial areas.

Autofrettage dimensions, the amount of material removed from outer and inner radius while manufacturing and the service pressure applied affect the residual stress distribution throughout the wall thickness and hence the load-bearing capacity of a thick-walled cylinder. Calculation of residual stresses after autofrettage process and optimization of autofrettage outline dimensions by using the amount of service pressures applied are common issues in literature.

In this study, mandrel-cylinder tube interference dimensions were renovated by using traditional methods for swage autofrettage process of a gun barrel. Also, the residual stresses in the cylinder after autofrettage process, inside and outside material removal process and the variable service pressure throughout the cylinder applied were taken into consideration and incorporated into the design. By using the constrained optimization method, wall thickness (thus the weight) was optimized (minimized) to achieve the specified safety factor along the length of the cylinder. For the same cylinder, the results of the suggested analytical/with residual stress calculation approach were compared to analytical/without residual stress calculation results and numerical topology optimization method calculation results. Since the experimental measurement results are not yet available, it was not possible to compare them with the calculation results.

The suggested approach enabled 22.9% extra weight reduction in proportion to numerical topology optimization and enabled 4.2% extra weight reduction in proportion to analytical/without residual stress optimization.

Using this approach, the gain from residual stresses after autofrettage operation, the loss of residual stresses after material removal, and the effects of service pressures can be taken into account for each stage of design.

1. Introduction

Different amount of service pressures is applied on thick wall cylinders in accordance with the applications they used for. In order cylindrical tube to do its duty safely, internal pressure should not cause plastic deformation while using the cylinder. For making proper pressurized vessel/tube design, one should need to know the residual stress distribution of the autofrettaged cylinder while applying the service pressure. Optimization of autofrettage relies on the stress distribution which is the result of the service pressure to be applied.

After autofrettage process, an amount of material is often removed from inner and/or outer surfaces of the pressurized vessel/tube. Material removal process for heavy arm gun barrel is performed both to inner and outer surfaces to manufacture the conjunctions, to shape the outer surface of the barrel, to open the groove sets and to shape the chamber. These are the material removal and hence the weight loss possibilities of a gun barrel but it also changes the residual stress distribution along every single millimeters of the length and the radius. In this study, optimized autofrettage and subsequent residual stresses, internal and external

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material removal and distributing service pressure along the length of the barrel were taken into consideration to optimize the wall thickness (weight) of the barrel.

Davidson et al. [1] compared the results of the experiments they had performed with the theoretical results to see how the residual stresses in the mechanical autofrettage process change depending on the extreme strain and diameter ratio. Jost [2] elaborated analytically the stresses and strains that occurred during the reaming process applied by a mandrel passing through a cylinder. Jahed et al. [3] used a simple back and forth torsion test to determine the unloading behavior of the NiCrMoV12.5 steel and found that the material exhibits excellent plastic behavior during loading and nonlinear behavior during reverse loading. Parker et al. [4] summarized different models for evaluating the effect of material removal on residual stresses. They incorporated the Bauschinger effect into an analytical method for estimating residual stresses in the autofrettage process for an elastic-perfect plastic model. Ayob et al. [6], investigated autofrettaged thick wall cylinders for stress distributions at working pressures and it has been determined that the maximum equivalent stress in the working pressure occurs at the plastic-elastic transition radius of the cylinder. Ali et al. [7], using the finite element method, investigated how the factors such as the ratio of outside diameter to inside diameter of a cylindrical tube, working pressure, material model and autofrettage level affect the utility obtained from autofrettage process. Johnsen [8] implemented structural topology optimization technique for recycled aluminum material for a plane control door. Hu et al. [9] simulated the mechanical autofrettage process for a heavy arm gun barrel with a finite element program. Yıldırım [10] investigated swage autofrettage process for a heavy arm gun barrel.

2. Material and methods

Assumptions and steps;

Distributing service pressure was applied only the inner wall of the cylinder.
This was an open-end, thick walled cylinder (axial stress is accepted constant and close to zero).
The sum of the plastic strain components was equal to zero.
The value of shear stress at the mandrel-tube frictional surface was neglected because it was very small alongside the other stress components.
Mandrel exhibited elastic behavior at every moment of the autofrettage process.
The elastic-linear plastic material model was used for the cylinder.
The effect of residual stress values from autofrettage and material removal was not able to be included in the numerical topology optimization calculation.
First, autofrettage optimization was carried out and plastic-elastic transition diameter was determined. Internal diameter expansion (loading) was applied, permanent stresses were calculated after discharging the load (unloading) and no secondary-flow occurred in the cylinder inner wall after load discharge (unloading).
Optimum autofrettage dimensioning of the draft tube was then carried out for the highest service load value (400 MPa) and autofrettage residual stresses were calculated.
Material removed from the inner radius was assumed to be constant in thickness along the barrel. The outer radius was considered to be suitable for variable material removal, and the state of residual stresses after material removal was calculated.

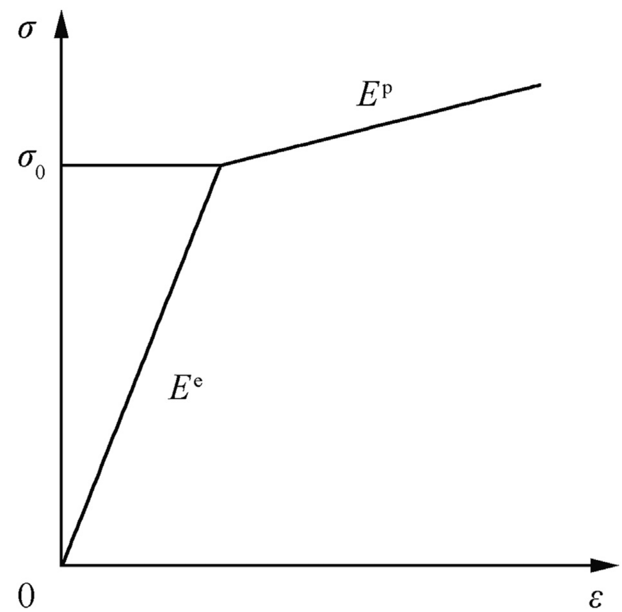

Fig. 1. Elastic-linear plastic material model.

Material removal was calculated for each millimeter of the gun barrel by using three different optimization approach and resulting optimized thicknesses were compared to each other. In the analytical thickness optimization, different levels of the safety factor of the material were used. In the numerical topology optimization, the value of the cylinder yield stress, at which, the safety factor equals 1.0, was used as the constraint value. So, Von Mises equivalent stress values were calculated and the comparison of different approaches was made for the case at which the safety factor was 1.0.

2.1. Material model

2.1.1. Elastic-linear plastic model

Elastic-linear plastic model is a more real like stress-strain model when it is compared to the elastic-perfectly plastic model (See Fig. 1). The stress-strain relation for the elastic-linear plastic model can be expressed as follows

$$\varepsilon = \frac{\sigma}{E^e} \quad (\sigma < \sigma_0) \tag{1}$$

$$\varepsilon = \frac{\sigma}{E^e} + \frac{1}{E^p}(\sigma - \sigma_0) \quad (\sigma > \sigma_0) \tag{2}$$

For use in analytical and numerical calculation, the data obtained by analyzing the result of uniaxial tensile test of the materials are shown below (See Table 1). The mandrel material is tungsten.

Table 1
Material properties.

Property	Gun barrel material	Tungsten
E^e/GPa	141	450
υ	0.29	0.28
σ_0/MPa	1086.01	–
E^p/GPa	2.36	–