Journal of Physics:
Conference Series

Simulation Research on Residual Stress of Swage Autofrettage-processed High-Pressure Cylinder

To cite this article: Lihua Sun *et al* 2023 *J. Phys.: Conf. Ser.* **2587** 012088

ICAMMT-2023 IOP Publishing
Journal of Physics: Conference Series **2587** (2023) 012088 doi:10.1088/1742-6596/2587/1/012088

Simulation Research on Residual Stress of Swage Autofrettage-processed High-Pressure Cylinder

Lihua Sun[1], Rongxuan Zhou[2], Guiqin Li*[3], Jianing Li[3], Peter Mitrouchev[4]

[1] Engineering Training Center of Changchun University of Technology, Changchun, China;

[2] School of Mechanical Engineering and Automation, Northeastern University, Shenyang, China;

[3] Shanghai Key Laboratory of Intelligent Manufacturing and Robotics, Shanghai University, Shanghai, China;

[4] University Grenoble Alpes, G-SCOP, Grenoble, France;

* Corresponding author: leeching@shu.edu.cn

Abstract: The vital component of the high-pressure pump is the high-pressure cylinder, which undergoes pulsating cyclic loads during operation. This exposure can lead to fatigue cracking and limit the pump's overall performance. To address this issue, a swage autofrettage treatment method for the high-pressure cylinder is proposed based on the principles of autofrettage technology. The structure parameters of the mandrel are designed to optimize its role in the treatment process. Subsequently, a swage autofrettage simulation model is established, considering the Bauschinger effect to analyze the distribution of residual stress about the mandrel interference percentage. The results demonstrate that the swage autofrettage treatment improves the stress distribution in the high-pressure cylinder, causing the inner wall surface to undergo a circumferential residual compressive stress. Within a specific range, the Bauschinger effect becomes more significant as the mandrel interference percentage increases. This study provides insights for enhancing the durability and performance of high-pressure cylinders while adhering to mechanical engineering standards.

1. INTRODUCTION

The high-pressure pump is a key component of the water jetting device, and the high-pressure cylinder as the core component of the high-pressure pump is prone to fatigue cracking due to long-term exposure to pulsating cyclic loads of several hundred megapascals. The autofrettage treatment of the high-pressure cylinder can introduce a beneficial residual stress field and inhibit the generation and expansion of cracks, thereby improving its bearing capacity and prolonging its service life.

Many experts and scholars have researched autofrettage technology. Hu [1] obtained residual stress results consistent with neutron diffraction measurements by numerically modeling the autofrettage procedure in a cylinder with thick walls. Li [2] obtained the optimum autofrettage pressure by simulating the residual distribution of stress within the autofrettage high-pressure cylinder while considering the Bauschinger effect. Ma [3] used a neutron diffraction instrument to measure the residual strain of high-pressure vessels under different autofrettage pressures and found that the amplitude of residual tension and plastic thickness rose as autofrettage pressure increased. Alexandrov et al. [4][5] analyzed the residual stress of autofrettage containers and found that the circumferential residual stress within the container's inner wall was dramatically reduced owing to the Bauschinger effect. Bastu [6][7] found that if the Bauschinger effect is not taken into account, the residual stresses in the high-pressure cylinder can be calculated with a large margin of error. Saeidi [8] derived the load function of a transverse semi-elliptic fracture among a cylinder with thick walls and a 1.25 inner-to-outer radius ratio to estimate the fatigue life. Although the above studies have explored the role of autofrettage, it does not provide a good insight into how to swage autofrettage affects the cylinder's residual stress distribution.

A high-pressure cylinder treatment method called swage autofrettage is put forward, and the structure parameters of the mandrel are designed according to the role of each part of the mandrel in the treatment. Finally, the swage autofrettage simulation model is established considering the Bauschinger effect to analyze the distribution of residual stress about the mandrel interference percentage.

2. SWAGE AUTOFRETTAGE SCHEME OF HIGH-PRESSURE CYLINDER

2.1 Overall scheme of swage autofrettage

The essence of autofrettage technology is to introduce a residual stress field and make reasonable use of it [9]. The high-pressure cylinder is sealed at both ends, and the piston compresses the liquid through reciprocating motion. Together with a one-way valve, it can provide a stable high-pressure jet for the waterjet system. Before the swage autofrettage treatment, the actual high-pressure cylinder is simplified by the model. The outer radius r_o of the intermediate-pressure and high-pressure cylinders is 28.6 mm, the inner radius r_i is 9.95 mm, and the length L is 92.3 mm. Since $r_o / r_i = 2.87 > 1.2$, the high-pressure cylinder belongs to a thick-walled cylinder structure. Figure 1 depicts the overall scheme, the mandrel's precise structure and dimensions are determined, and then the mandrel is slowly passed through the high-pressure cylinder using mechanical pushing or pulling, producing a locally high stress inside the cylinder to complete the strengthening.

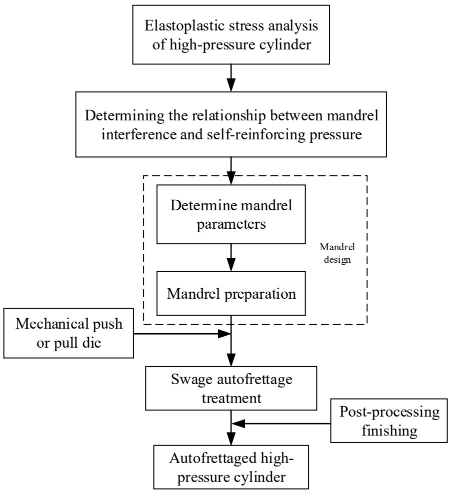


Figure 1. Swage autofrettage scheme of high-pressure cylinder

2.2 Extrusion mandrel structure design

The core component for the swage autofrettage treatment is the mandrel, whose structural shape largely determines the required pressure for pushing/pulling, the yield degree of the cylinders inside the wall, and the distribution of residual stress. Figure 2 illustrates its structure.

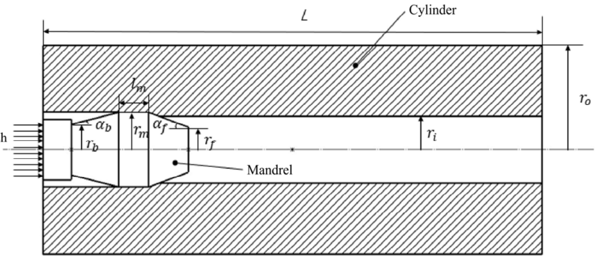


Figure 2. Mandrel structural diagram

The guide function of the front taper section of the mandrel helps to facilitate the insertion of the mandrel into the high-pressure cylinder, and the front-end radius r_f of the taper section should be slightly smaller than the cylinder's internal diameter r_i . The front taper angle α_f of the mandrel is designed as 1.5°, as it has an impact on the pushing force during the swage autofrettage process. The back taper section of the mandrel plays a role in unloading. After passing through the inside of the cylinder, the cylindrical section of the mandrel stabilizes the cylinder's rebound and generates beneficial pushing force in the forward direction. The magnitude of the beneficial pushing force is related to the back taper angle α_b, which is generally within the range of 2°~5° and is set to 3° in this article. The mandrel interference amount $\delta = d_m - d_i = 2(r_m - r_i)$ and interference percentage $I = \delta / d_i$ are defined, where d_m is the diameter of the mandrel cylindrical section, and d_i is the high-pressure cylinder bore's diameter. Table 1 displays the planned mandrel parameters.

Table 1. Mandrel design parameters

r_f / mm	r_m / mm	r_b / mm	L_m / mm	α_f /°	α_b /°
$0.99r_i$	$(1+I)r_i$	$0.99r_i$	$0.12r_m$	1.5	3

2.3 Establishment of swage autofrettage simulation analysis model

The material used in the high-pressure cylinder is 15-5PH high-strength steel which has a yield strength of 1138 MPa, a breaking strength of 1173 MPa, an elastic modulus of 195 GPa, and a Poisson's ratio of 0.27. The mandrel material is tungsten carbide with an elastic modulus of 707 GPa and Poisson's ratio of 0.24. The stress and strain data measured through the tests are nominal stresses and nominal strains, so the experimental data need to be processed to comply with the data input criteria of the ABAQUS finite element software with the following conversion formula.

$$\sigma = \sigma_{\text{nom}}\left(1+\varepsilon_{\text{nom}}\right) \tag{1}$$

$$\varepsilon = \ln\left(1+\varepsilon_{\text{nom}}\right) \tag{2}$$

$$\varepsilon^{pl} = \varepsilon - \frac{\sigma}{E} \tag{3}$$

where σ and ε are the real strain and stress, σ_{nom} and ε_{nom} are the nominal stress and nominal strain, and ε^{pl} is the true plastic strain.

The model meshes with a quadrilateral cell with a four-node bilinear axisymmetric stress-reduction integral, the mesh size can be set at 0.5 mm, and there are 6845 mesh cells altogether. To assess the stresses arising from interference with the mandrel, the interface that links the high-pressure cylinder and the mandrel is defined using a contact pair algorithm. In addition, the Cullen friction model is utilized to simulate the friction in contact that links the high-pressure cylinder and the mandrel according to the penalty equation and the friction isotropic variation condition. The model describes the relationship between friction and contact force using the coefficient μ , which is formulated as follows.

$$\sigma_{rz} = \mu\sigma_r\big|_{r=r_i} + C \tag{4}$$

where σ_{rz} is the shear stress, σ_r is the radial stress, μ is the friction coefficient, and C is the cohesive force.

Finally, the contact surfaces are modeled as rigid lines and the friction behavior follows Coulomb sliding friction. The mandrel and high-pressure cylinder's friction coefficient is adjusted to 0.015 and a finite slip algorithm is used to define the relative sliding between the master and slave surfaces. The high-pressure cylinder is displaced by the axial force exerted by the mandrel during loading, so a positional constraint along the Y-direction is applied at the outlet end of the mandrel.

3. RESULTS ANALYSIS OF SWAGE AUTOFRETTAGE SIMULATION

The residual stress cloud is obtained after the model was built for the swage autofrettage treatment of the high-pressure cylinder block (mandrel interference percentage of 2.5%), where Mises is the residual von Mises stress. The residual stresses are S11 for radial stress, S22 for axial stress, and S33 for circumferential stress. As shown in Figure 3, the high-pressure cylinder's central part has a relatively consistent stress distribution, with unstable stress distribution at the ends, and a large difference from the middle section.

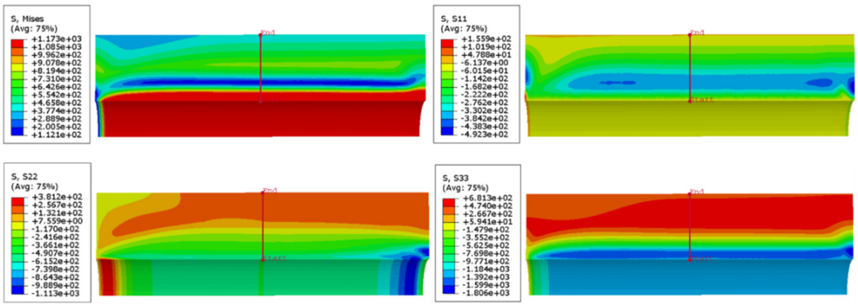
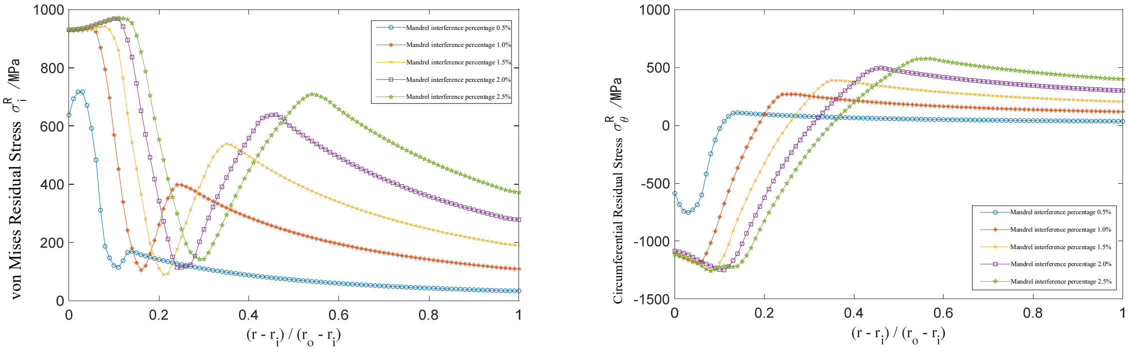


Figure 3. High-pressure cylinder swage autofrettage treatment stress nephogram

As a result of the pre-increased plastic tensile load, the compression yield stress reduction phenomenon is called the Bauschinger effect [10]. The distribution of the residual stress field in the swage autofrettage high-pressure cylinder is significantly influenced by the Bauschinger effect, so the Bauschinger effect cannot be ignored in the analysis. The effect of different mandrel interference percentages on the high-pressure cylinder's residual stresses is investigated. The high-pressure cylinder's swage autofrettage is simulated for mandrel interference percentages of 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% respectively. Considering the Bauschinger effect and friction, the simulation results for the distribution of von Mises and circumferential residual stresses over the whole wall thickness range for the central section with different mandrel interference percentages are shown in Figure 4.



a. The von Mises residual stress b. The circumferential residual stress

Figure 4. The residual stress distribution diagram

Figure 4 (a) demonstrates that the von Mises residual stress is greatest close to the interior wall, lower close to the exterior wall, and reaches a minimum within the wall thickness. As the mandrel interference percentage increases, the location of the minimum von Mises residual stress gradually moves away from the interior wall towards the exterior wall, compressing the high-pressure cylinder's surface area and enhancing residual compressional stress, but the maximum residual tensile tension near the outer wall does not increase significantly. It can be seen from Figure 4(b) that the swage autofrettage treatment formed a good circumferential residual compressive stress within the interior surface, and a relatively low residual tensile stress on the outside of the wall, and the circumferential residual stress gradually changed from the inner wall's compressive stress to the outer wall's tensile stress. The trend of circumferential residual stresses is the same for different mandrel interference percentages. With increasing mandrel interference percentage, the area of the compressed high-pressure cylinder, the range of residual compressive stresses, and the circumferential residual compressive stresses close to the interior wall all increase, while the maximum residual tensile stresses close to the exterior wall do not increase significantly. The Bauschinger effect is more significant as interior wall distortion due to plastic deformation increases with the increase in the mandrel interference percentage.

4. CONCLUSION

This study suggests a swage autofrettage method to improve the high-pressure cylinder's performance. After simplifying the high-pressure cylinder model and designing the mandrel's geometrical parameters, the swage autofrettage simulation model is established using ABAQUS software. The results show that the swage autofrettage treatment improves the stress distribution in the high-pressure cylinder, forming a good circumferential residual compressive stress within the interior surface, while the location of the minimum von Mises residual stress gradually moves closer to the inner wall. Within a certain range, the Bauschinger effect becomes more significant with the increase of the mandrel interference percentage.

ACKNOWLEDGEMENTS

This work was partly supported by the Jilin Science and Technology Development Plan Project (No. YDZ202201ZYTS537).

REFERENCES

[1] Hu, Z. Design of Two-Pass Swage Autofrettage Processes of Thick-Walled Cylinders by Computer Modeling[J]. Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science. 2019, 233(4): 1312-1333. https://doi.org/10.1177/0954406218770221.

[2] Li, G., Li, Y., Shi, J., et al. Analysis of Residual Stress for Autofrettage High-Pressure Cylinder[C]. Plymouth, United Kingdom: Springer, 2020. https://doi.org/10.1007/978-981-15-2341-0_3.

[3] Ma, Y., Zhang, S., Goodway, C., et al. A Non-Destructive Experimental Investigation of Elastic-Plastic Interfaces of Autofrettage Thick-Walled Cylindrical Aluminum High-Pressure Vessels[J]. High-Pressure Research. 2012, 32(3): 364-375. https://doi.org/10.1080/08957959.2012.702766.

[4] Alexandrov, S., Jeong, W. Descriptions of Reversed Yielding in Internally Pressurized Tubes[J]. Journal of Pressure Vessel Technology-Transactions of the Asme. 2016, 138(011204): 1-10. https://doi.org/10.1115/1.4031029.

[5] Alexandrov, S., Lyamina, E., Aoh, J. N., et al. Description of Residual Stresses in Autofrettage Open-Ended Cylinders Made of High-Strength Steel[J]. Materials, 2020, 13(13):2940. https://doi.org/10.3390/ma13132940.

[6] Bastun, V. N. The Bauschinger Effect in Transversely Isotropic Materials with Translational Strain-Hardening[J]. Strength of Materials, 2012, 44(1):1-7. https://doi.org/10.1007/s11223-012-9342-0.

[7] Lee, E. Y., Lee, Y. S., Yang, Q. M., et al. Autofrettage Process Analysis of a Compound Cylinder Based on the Elastic-Perfectly Plastic and Strain Hardening Stress-Strain Curve[J]. Journal

of Mechanical Science and Technology, 2009, 23(12):3153-3160. https://doi.org/10.1007/s12206-009-1009-9.
[8] Saeidi, G., Stress Intensity Factors Calculation for Surface Crack in Cylinders under Longitudinal Gradient Pressure Using General Point Load Weight Function [J] Fatigue and Fracture of Engineering Materials and Structures. 2014, 37(2): 184-194. https://doi.org/10.1111/ffe.12101.
[9] Parker, A. P. Autofrettage of Open-End Tubes - Pressures, Stresses, Strains, and Code Comparisons[J]. Journal of Pressure Vessel Technology-Transactions of the ASME. 2001,123(3): 271-281. https://doi.org/10.1115/1.1359209.
[10] Huang, X.P., Cui, W.C. Effect of Bauschinger Effect and Yield Criterion on Residual Stress Distribution of Autofrettage Tube[J]. Journal of Pressure Vessel Technology Transactions of the ASME. 2006, 128(2): 212-216. https://doi.org/10.1115/1.2172621.