ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

Design and Performance of Hydraulic Autofrettage Using Universal Testing Machine

[1]Anup Jain, [2]Swanand Khanwelkar, [3]Kumar Saurav, [4]Ameya Landge, [5]Umesh Yadav
[1,2,3,4,5]Dept. of Mechanical Engineering, Sinhgad College of Engineering, Pune, India

Abstract
Autofrettage is a pre-stressing technique used in thick walled cylinders to increase their pressure carrying capacity and fatigue life. Components such as gun barrels, automotive common rail direct injection pipe, water jet cutting components, nuclear reactors are autofrettaged. In this work an attempt is made to compare experimental results of residual hoop stress with the results of analytical calculations and numerical analysis. Hydraulic autofrettage is performed using Universal Testing Machine. Water is used as a medium to transmit pressure. Material used for cylinder is Aluminium (6082T6). Induced residual hoop stress has been measured using X-ray Diffraction Technique. An axisymmetric finite element model of a thick walled cylinder is constructed to simulate hydraulic autofrettage using ANSYS 14.5. The stress reduction, due to autofrettage, is calculated numerically.

Keywords
Hydraulic Autofrettage, Plastic Radius, Residual Hoop Stress, X-Ray Diffraction Technique

I. Introduction

Autofrettage can be explained in two steps. In step one, large internal pressure is applied to the desired component. The magnitude of this pressure is high enough to plastically deform the region close to the bore whereas the region close to the outer diameter remains in elastic range. In step two, applied pressure is removed. The outer region tries to regain its original shape but this movement is now resisted by the plastically set inner region. This induces compressive residual hoop stress. When this autofrettaged component is subjected to working pressure, the pressure has to overcome the initial compressive stress, reduce them to zero and then induce tensile stress. Thus, the same component can be used for higher pressure applications. Autofrettage has found its application in automotive, industrial, aerospace and defense system. In this work a Common Rail Direct Injection (CRDI) system is selected for the analysis. The pressure of diesel inside the common rail is in the range of 100MPa to 200MPa. The common rail has to sustain such high pressure throughout its life cycle, which can be achieved by performing autofrettage. Aluminium alloys are used to manufacture common rail. In order to replicate above application Aluminium Alloy 6082T6 having yield strength 340 MPa is used. Inner and outer diameter is 14mm and 24mm respectively. Length of the cylinder is 90mm. Working pressure is considered as 150 MPa in the analysis.

II. Methodology

The project is divided into 3 phases.

Phase 1- Analytical Calculation

After the application of autofrettage pressure, the region near the bore undergoes plastic deformation up to a certain radius. The boundary up to which the material goes in plastic region is known as plastic radius. This plastic radius c is calculated using the following equation [1]

$$c = a * \exp\left(\frac{\sqrt{3}p}{2\sigma_y}\right)$$

Hence, for the given application, substituting the values we get the plastic radius ‘c’ as 10.2572 mm.

A. Optimum Autofrettage Pressure (OAP)

OAP is the pressure, at which the maximum von-Mises Stresses induced after applying working pressure are minimum [5]. It is calculated using the following equation [2]

$$P_{optimum} = \frac{\sigma_y}{\sqrt{3}}\left[\left(1 - \frac{c^2}{b^2}\right) + 2\ln\frac{c}{a}\right]$$

Substituting the values we get,

$$P_{optimum} = 202.878 \text{ MPa}$$

Hence the optimum autofrettage pressure for a working pressure of 150 MPa is 202.878 MPa.

B. Calculating Residual Hoop Stress

When the cylinder is pressurized to the autofrettage pressure and the pressure is removed, the residual hoop stress distribution across the thickness of the cylinder can be calculated using the following equations [3].
For elastic perfectly plastic material,
Residual hoop stresses in plastic region $a \leq r \leq c$:

$$\sigma_\theta = \frac{\sigma_y}{2}\left[\frac{c^2}{b^2} + 1 - \ln\frac{c^2}{r^2} - \frac{b^2}{r^2} \times \frac{1}{k^2-1}\left(\ln\frac{c^2}{a^2} + 1 - \frac{c^2}{b^2}\right) - \frac{1}{k^2-1}\left(\ln\frac{c^2}{a^2} + 1 - \frac{c^2}{b^2}\right)\right]$$

Residual hoop stresses in elastic region $c \leq r \leq b$:

$$\sigma_\theta = \frac{\sigma_y}{2}\left[\frac{c^2}{b^2} + \frac{c^2}{r^2} - \frac{b^2}{r^2} \times \frac{1}{k^2-1}\left(\ln\frac{c^2}{a^2} + 1 - \frac{c^2}{b^2}\right) - \frac{1}{k^2-1}\left(\ln\frac{c^2}{a^2} + 1 - \frac{c^2}{b^2}\right)\right]$$

The residual hoop stress distribution across the thickness of the cylinder is shown in fig. 1.

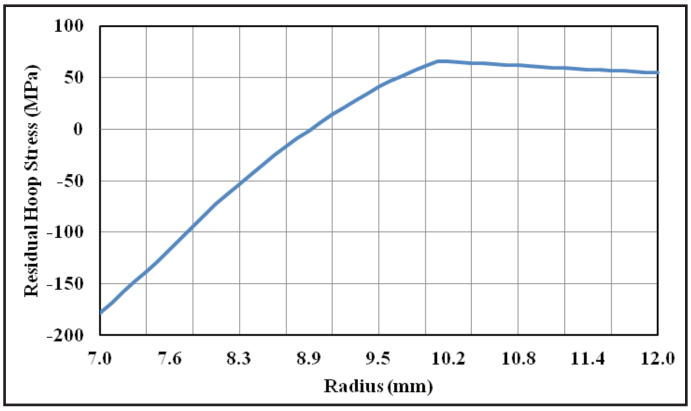

Fig. 1: Distribution of Residual Hoop Stress Along the Radius of Cylinder

Phase 2- Numerical Analysis

A 3D solid model and a 2D axisymmetric model of a thick walled cylinder are prepared in ANSYS 14.5. The analysis is performed on both the models and the results obtained for both are same. After meshing both models, following comparative results are obtained.

Table 1: Elements & Nodes in 3D & 2D Ansys model

	3D Model	2D Model
Elements	260459	1690
Nodes	1109373	5429

It can be clearly seen that the number of elements and nodes are substantially less for 2D axisymmetric model. This implies that the computation time is also less. Thus it is decided to use 2D model for further numerical analysis.

A. Engineering Data

Aluminium alloy 6082T6 with yield strength (σ_y) of 340 MPa and modulus of elasticity (E) of 60 GPa is used the cylinder.
Tensile test was performed to obtain engineering stress-strain curve for the material. True stress-strain values are obtained from nominal stress-strain values using the following relations [4]:

$$\varepsilon_{true} = \ln(1+ \varepsilon_{nominal})$$

$$\sigma_{true} = \sigma_{nominal} \times \ln(1 + \varepsilon_{nominal})$$

B. Boundary Conditions

In order to accurately model the experimental process of hydraulic autofrettage, modeling of boundary conditions is crucial. The lower surface of the cylinder is constrained in the Y direction as it rests on the base support. Internal pressure is applied on the inner surface of the cylinder to consider the autofrettage pressure. External pressure is applied on the outer surface of the cylinder to consider the atmospheric pressure.

C. Load Steps

Fig. 3 shows the load steps involved in the process of autofrettage. The time for which the load is applied does not have any effect on the induced residual stress.

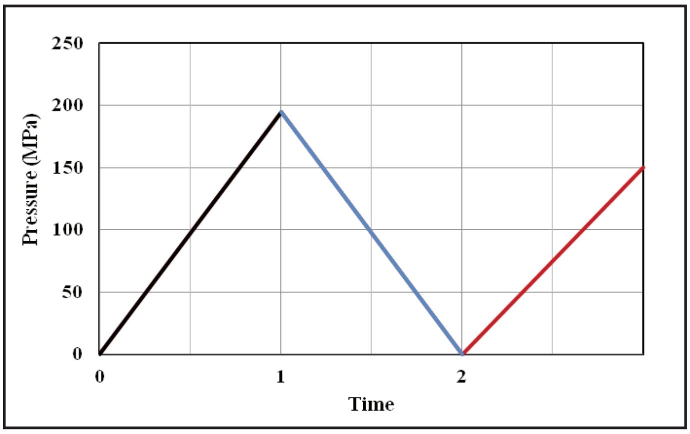

Fig. 3: Load Steps (1: Application of Autofrettage pressure, 2: Removal of Autofrettage pressure, 3: Application of Working pressure)

Convergence: The convergence study for mesh size is carried out using the value of residual hoop stress at bore. It is found that convergence occurs at mesh size of 0.5 mm; however the mesh size of 0.1 mm is used to have better accuracy of results.

D. Optimum Autofrettage Pressure (OAP)

For working pressure of 150 MPa, the autofrettage pressure is varied and the Von-Mises stress is plotted in ANSYS. It can be ssen that the value of stress is minimum at a pressure of 195 MPa. Thus by definition this is OAP as seen in fig. 4.

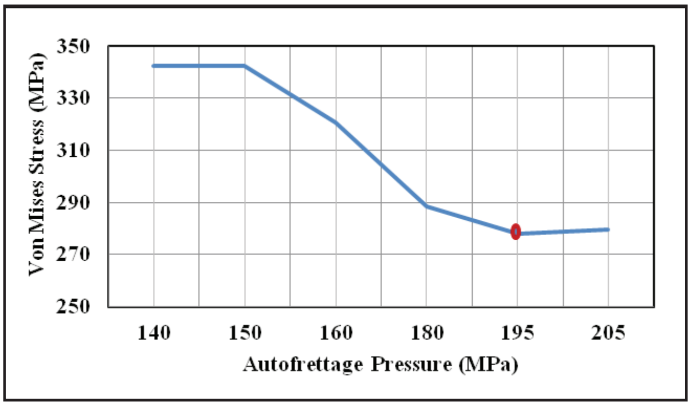

Fig. 4: Maximum Von-Mises Stress for Different Autofrettage Pressures

The residual hoop stress distribution across the thickness of the cylinder is shown in fig. 5. It is obtained by applying first two load steps.

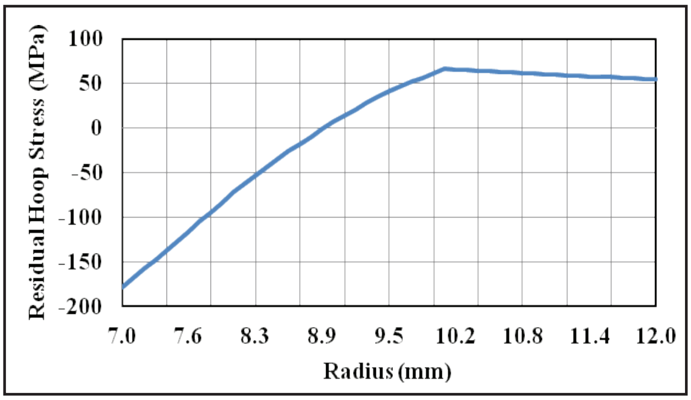

Fig. 5: Distribution of Residual Hoop Stress Along the Radius of Cylinder (Numerically)

Phase 3 - Experimentation

A. Experimental Setup

In order to perform hydraulic autofrettage the necessary components are designed and manufactured. The experimental setup consists of a base support, the cylinder to be autofrettaged and the piston. The pressure of 195 MPa to be applied to the cylinder is achieved using water as a pressure transmitting medium as it is incompressible. In order to apply the pressure on the water from the UTM a piston is designed. Since the experiment involves operation at such a high pressure it is very necessary to have proper sealing. Hence, to seal the space between the piston and cylinder and prevent leakage of pressurized water, O- rings are used. In order to sustain a pressure of 195 MPa backup rings are provided. The backup rings are made up of Polytetrafluoroethylene (PTFE) which is hard and resistant enough to withstand the pressure without any failure. The piston and the base support are provided with two slots. Each slot accommodates one O-ring and two Backup rings. The provision of two slots is provided so that even if any damage occurs to the O-ring or Backup ring of one slot, the second slot would provide safety against leakage.

B. Procedure

Fig. 6 shows the base support on which the cylinder is placed. Water is then filled in the cylinder and the piston is placed at the opposite end of cylinder. This assembly is then placed on the bed of UTM. A compressive force is applied to achieve a pressure of 195MPa. The force is then reduced back to zero. This completes the autofrettage process. The residual hoop stresses induced in the cylinder are measured using X-ray Diffraction Technique.

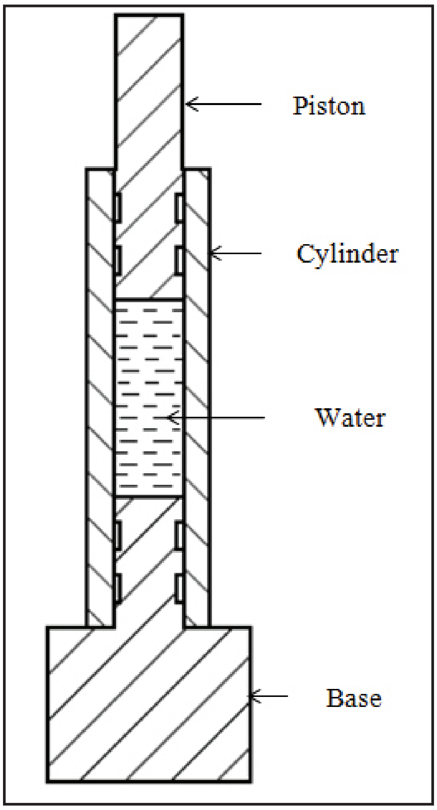

Fig. 6: Schematic of Experimental Setup

C. Calculation of Force to be Applied using UTM

The OAP to be applied is 195 MPa. The force that should be applied to achieve this is calculated as follows:

Force (F) = Pressure (P) × Area (A)

$$\therefore F = 195 \times \frac{\pi}{4} \times 14^2$$

$\therefore$ F = 30017.91 N = 30.017 kN

The residual hoop stress distribution across the thickness of the cylinder is shown in fig. 7. The values are obtained using X-ray Diffraction Technique.

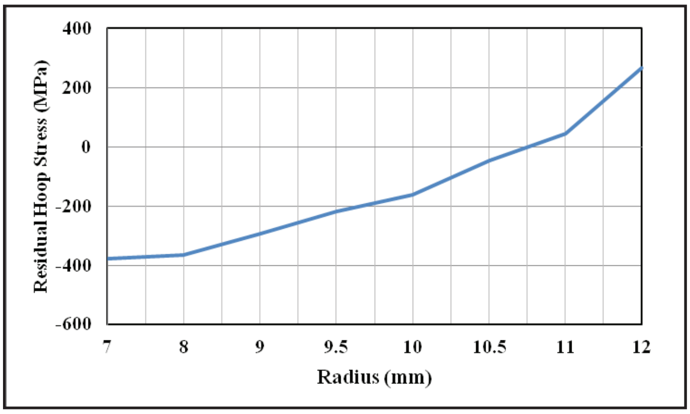

Fig. 7: Distribution of Residual Hoop Stress along the Radius of Cylinder (Experimentally)

III. Results and Discussion

1. Analytically the optimum autofrettage pressure is 202.878 MPa and numerically it is 195MPa, for an operating pressure of 150MPa.
2. Post Autofrettage the reduction of hoop stress at inner bore is 52.27%. Figure 8 shows that the process of autofrettage redistributes hoop stress. When a component is subjected to working pressure, there is a possibility of crack initiation and propagation at the inner bore. If the value of hoop stress is high at this point then the possibility increases. By autofrettaging the component we have successfully reduced the value of hoop stress at inner bore thus reducing the possibility of fatigue failure.

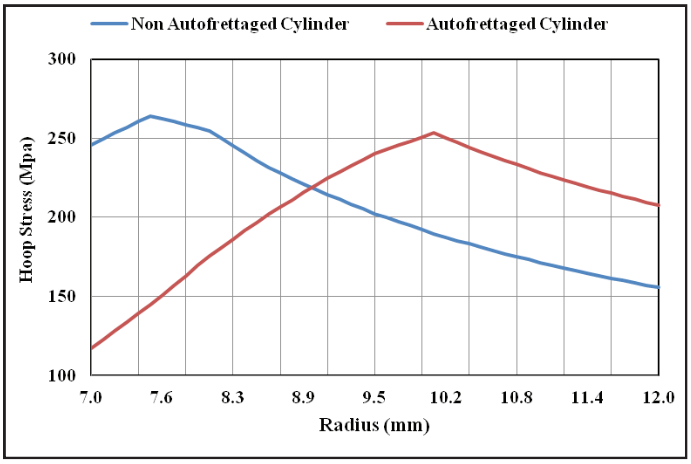

Fig. 8: Distribution of Hoop Stress in Non-Autofrettaged & Autofrettaged Cylinder on application of working pressure.

3. Post Autofrettage the reduction of Maximum Von-Mises stress is 18.75%. Figure 9 shows the values of Von-Mises Stress for an ordinary cylinder and an autofrettaged one, both subjected to the same working pressure. Considering yielding as the failure criteria, the ordinary cylinder has failed as the stress value is equal to the yield strength whereas the value of maximum stress in autofrettaged cylinder is less than yield strength. Thus it can sustain greater working pressure. It can be thus said that the pressure carrying capacity of the cylinder can be increased after performing autofrettage.

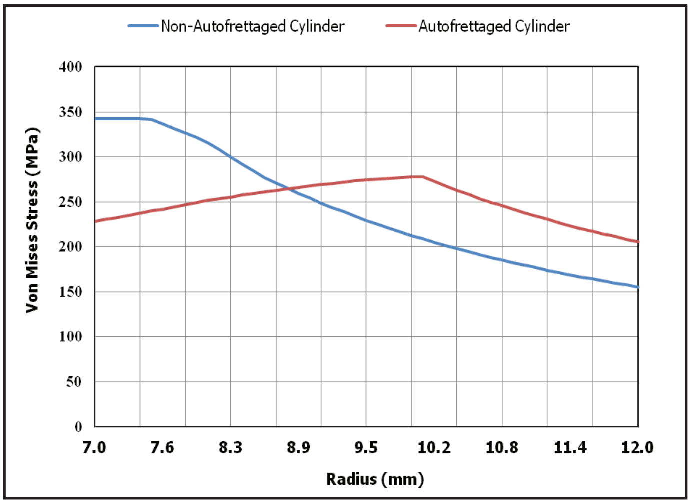

Fig. 9: Distribution of Von-Mises Stress in Non-Autofrettaged & Autofrettaged Cylinder on Application of Working Pressure

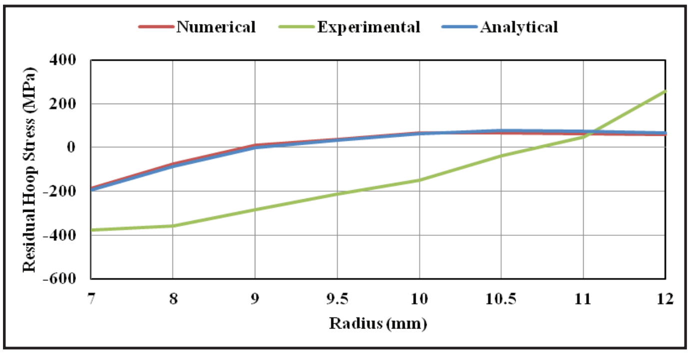

Fig. 10: Comparison of Residual Hoop Stress obtained Numerically, Experimentally & Analytically.

IV. Conclusion

The numerical results closely conform to the analytical calculations. Although both analytical and numerical results are consistent with one another, the experimental results vary substantially in terms of magnitude and also nature of distribution. Experimentally the value of residual stress at the inner bore is -377.2 MPa as compared to -192.64 MPa given by the analytical results. Thus it is 95.80 % more than what is expected. If it is considered that there are no errors in the experimentation phase as well as the measurement of residual stresses then these results are very encouraging and worthy of further academic research. In order to verify the consistency of the results, more number of experiments are needed to be carried out. The cost of measurement of residual stresses is currently very expensive, which is a major obstacle in the further research in this particular subject.

References

[1] Ruilin Zhu, Jinlai Yang,“Autofrettage of Thick Cylinders”, International Journal of Pressure Vessels and Piping, Vol. 75, pp. 443-446, 1998.

[2] Seungkee Koh,“Autofrettage of Fuel Injection Pipe”, Proc. of the Intl. Conf. on Advances In Mechanical and Automation Engineering- MAE 2014.

[3] G.H. Majzoobi, A. Ghomi,“Optimisation of autofrettage in thick- walled cylinders”, Bu-Ali Sina University, Hamadan, Iran

[4] Johnson, W., Mellor, P.B.,"Engineering plasticity", Van Nostrand Reinhold Inc., 1978.

[5] Amir Partovi, Saadat Sharrifi Shamili,“Analysis of Autofrettaged high rressure components”, Master’s Degree Thesis, ISRN: BTH-AMT-EX—2012/D-05--SE