Parameter Control Of Autofrettage & Re-Autofrettage Of Steel Made Hydraulic Cylinder For Single & Multiple Re-Autofrettage

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Abstract
Thick cylinders are widely used in High pressure application like Hydraulic power cylinders, canon barrels, Diesel engine pump etc where high pressure is the key criteria. The Autofrettage process is an important part of the material optimization process for thick-walled cylinders. In Autofrettage, intentional residual stresses are generated by the plastic deformation of the inner wall of the cylinder so that some of the stresses can be relieved during the compression loading phase, since the working stresses and residual stresses are of opposite nature. In this article, the problem of deciding the correct initial pressure for Autofrettage was solved for a manufacturer in India. The process involves proper analysis of the material and its properties, followed by determination of the pressure range based on an analytical method, which is then validated by finite element analysis. The Re-Autofrettage process was also carried out for multiple times for same hydraulic cylinder.

Keywords: Autofrettage, Von-mises Stresses, Locked-in stresses, Residual stresses

1. Introduction
For high pressure cylinders, such as hydraulic power cylinders, thick cylinders are required. An autofrettage process is a process of generating intentional residual stresses in a hydraulic cylinder to reduce Von-mises stresses during cylinder loading (Majzoobi, 2006). By optimizing cylinder dimensions, residual stresses can be minimized. (Amin & Rayhan, 2013) To minimize working stress, residual stresses were intentionally created at the inside wall of the cylinder to get residual stresses in the opposite direction of hoop stresses (Parker & Gibson, 2001).It means by using same cylinder one can achieve higher pressure range.
The initial aim is to decide Minimum pressure for 50 mm internal diameter & 60 mm outer diameter hydraulic cylinder for Hydraulic Power applications. In many mechanical engineering applications, residual stresses are very main problem which affect applicability of the parts (Rayhan & Md. Ali, 2010) Residual stresses are "locked-in" stresses seen in the material and they are always independent of external load (Senthilmurugan & Arasu, 2016)
Autofrettage concept is shown as per Figure-1 below. In it Figure-1 (a) shows that Elastic-Plastic zones during Autofrettage. Near-bore plastic zone is observed & away from bore Elastic zone is observed. (Bhatnagar, 2013)

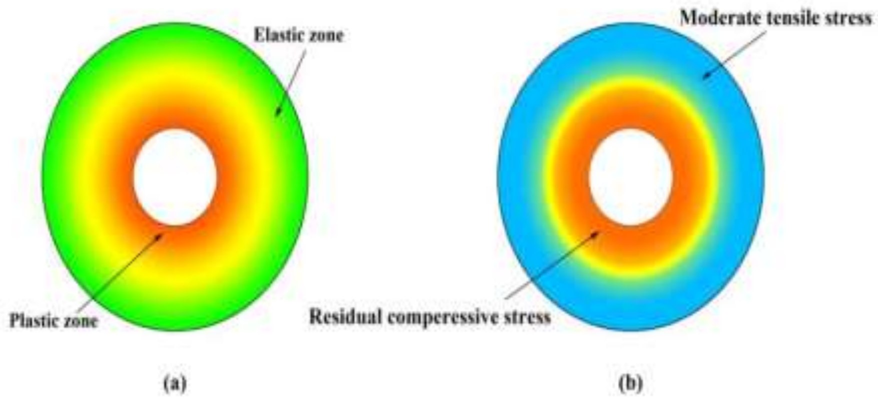

Figure 1: Representation of Autofrettage : (a) Elastic & Plastic Zones locations during Autofrettage. (b) Residual Stresses after Autofrettage after unloading

Figure-1 (b) shows residual stresses at near-bore portion of cylinder, which is outcome of Autofrettage Process. Hydraulic Autofrettage is mostly used as this process of Autofrettage persist very less damage to the surface of Hydraulic cylinders in order to get better finish in experimentation (Thumser & Bergmann, 2002) Mostly pressure with 100 MPa to 600 MPa is referred as high pressure for the operations (Rathnakumar & Martínez, 2019) So it's very essential to decide minimum Autofrettage pressure for cylinder optimization.

2. Selection of Cylinder & its properties by Testing Method.

When selecting a cylinder for the Autofrettage trial from a range of options, the selection process is of paramount importance. It is highly recommended to choose a cylinder that has superior production qualities to achieve optimal results. To achieve maximum material savings, it is important to choose products with the highest volume. By choosing higher volume products, you can optimize material utilization, minimize waste and ultimately achieve significant cost reductions. In accordance with industry guidelines, the analysis was performed using a cylinder with an inner diameter of 50 mm and an outer diameter of 60 mm. The preferred length for the analysis was 62 mm. These dimensions were chosen based on specific industry instructions.

In such cases, tests are usually carried out to determine the material composition and mechanical properties of the cylinders. The chemical and mechanical property tests carried out by the suppliers have shown that the material is 0.21% carbon steel with a medium carbon content. The mechanical properties of the cylinders can also be examined in the following Table-1. It is clear from the table that a minimum pressure of 383.87 N/mm2 is required to generate residual stresses in the cylinder.

Mechanical Properties of Hydraulic Cylinder	**Value**
Gauge Length selected	50 mm
Specimen shape	Round
Yield Load	30.03 KN
Ultimate Load	50.08 KN
Yield Stress	383.87 N/mm^2
Ultimate Stress	640.16 N/mm^2
Percentage Elongation	24.80 %

Table 1. Highlighting Major Mechanical Properties of Hydraulic Cylinder as per test Report

3. Deciding Minimum Pressure for Cylinder of Autofrettage by Analytical Method

To determine the autofrettage pressure, it is extremely important to confirm the yield stress of the cylinder analytically. To calculate the maximum stress or thickness of cylinders for thick or thin cylinders, there are a number of equations that can be used. (Bihamta & Movahhedy, 2007)) Basically, the equations must be selected according to the material of construction and the type of ends (closed or open). In this case, the cylinder is closed and its material is inherently ductile, so Clavarino's equation can be used (Bhandari, 2015) The equation can be written as given in Equation 1 below.

$$t = \frac{Di}{2}[\sqrt{[\frac{6+(1-2\mu)Pi}{6-(1+\mu)Pi}} - 1] \ldots\ldots (1)$$

Where,

t = thickness of proposed cylinders

Di= internal diameter of proposed cylinders

6 = internal stresses = Von-Mises stresses or Hoop stresses generated due to internal pressure (Pi)

Pi = Internal hydraulic pressure

μ = Poisson's ratio of proposed selected hydraulic cylinder

As discussed in article no. 2, let's determine all the parameters needed to calculate the minimum input pressure (Pi) at the cylinder to create the residual stresses internally. Input parameters can be considered as per Table-2 given below.

Cylinder Parameter	**Value of Parameter**
Internal Diameter of Hydraulic cylinder (Di)	50 mm
Outside diameter of Hydraulic cylinder (Do)	60 mm
Length of Hydraulic Cylinder	62 mm
Thickness of Hydraulic cylinder (t)	5 mm
Poisson's ratio of hydraulic cylinder	0.3

Table 2. Input Parameters for hydraulic cylinders

According to Clavarino's equation, putting all above values into equation , we can get, Pi =74.4065 MPa
Which means the minimum hydraulic pressure to generate residual stress in a hydraulic cylinder is 74.4065 MPa for Autofrettage. Same value of the pressure can be the base point for next trial.

4. Analysis of Hydraulic Cylinder by FEA Method (For same stress as per Analytical Values)

Based on the above sections , it is clear that the proposed hydraulic cylinder made of Medium Carbon Steel must have a minimum pressure of 74.4065 MPa for Autofrettage purposes. It is generally accepted in design engineering that yielding is taken as a design point for safety purposes, therefore, there is a margin of safety and stress variation for safety purposes. (Hojjati & Hassani, 2007)

A Finite Element Analysis was performed with ABAQUS-CAE software in order to validate the cylinder's stress levals by Finite Element Analysis. As compared to other software, it gives more precise results when analyzing plastic loading.Figure-2 Shows Maximum Stress for Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure. As expressed in figure-2 step loading of 20 MPa, 40 MPa, 60 MPa & Final loading pressure as applied in ABAQUS FEA software. One can easily observe that 412.2 MPa is the maximum von-misses stresses observed in the cylinder which can be noted. Specifically, maximum stress can be seen at the inner periphery of the cylinder.

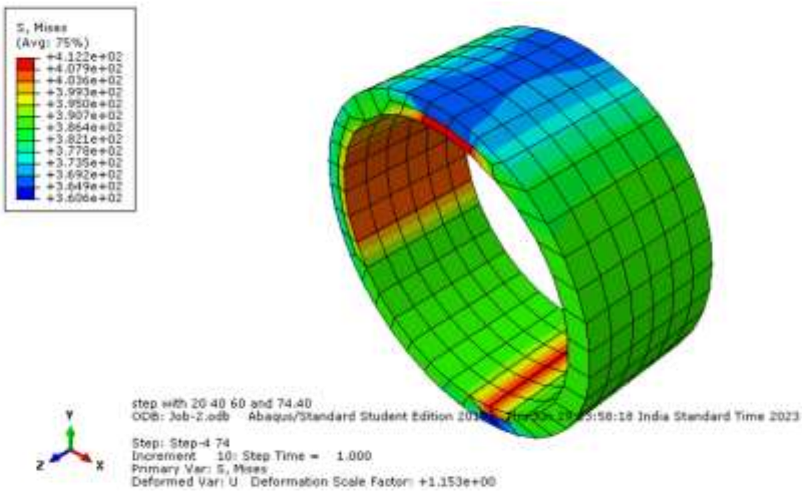

Figure 2: Maximum Stress for Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure with step loading of 20, 40 & 60 MPa before final loading.

Figure-3 shows applied Internal Hydraulic Pressure of 74.4065 MPa at inner periphery of cylinder With Step loading of 40 MPa followed by final loading of 74.40 MPa. This time maximum von-Misses stresses in the hydraulic cylinder are 412.00 MPa during ABAQUS-FEA analysis ,which are slightly lower than earlier step loading. Maximum stresses were seen at Inner Diameter of the Hydraulic cylinder.

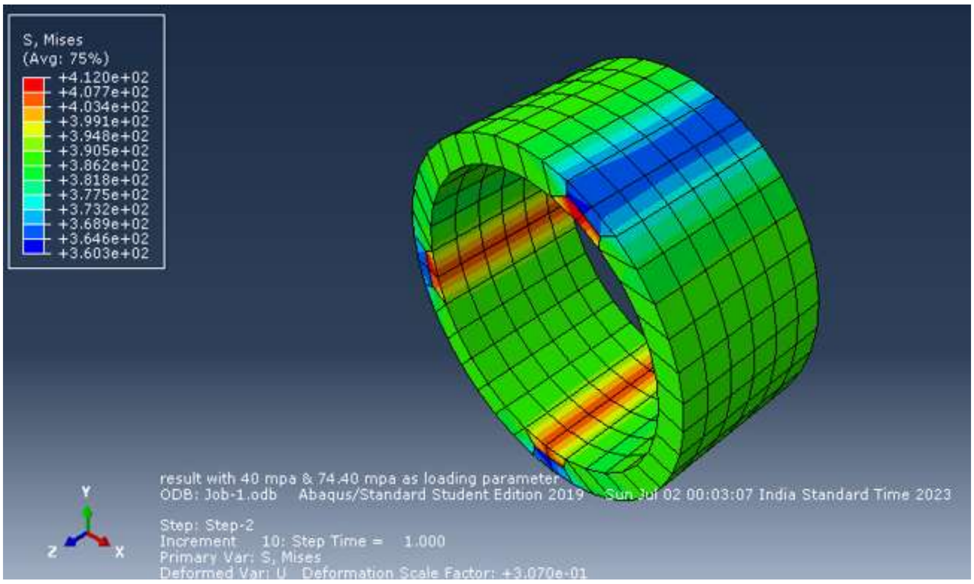

Figure 3: ABAQUS CAE Software Result showing Maximum Stress for Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure with step loading of 40 MPa before final loading.

Figure -4 shows Maximum Stress for Steel made Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure without any step loading. As in it no any step loading step is created in ABAQUS –FEA and direct loading was initiated. In direct loading step stress distribution pattern can be seen at inner diameter as well as some Von-Misses stresses at outer diameter.

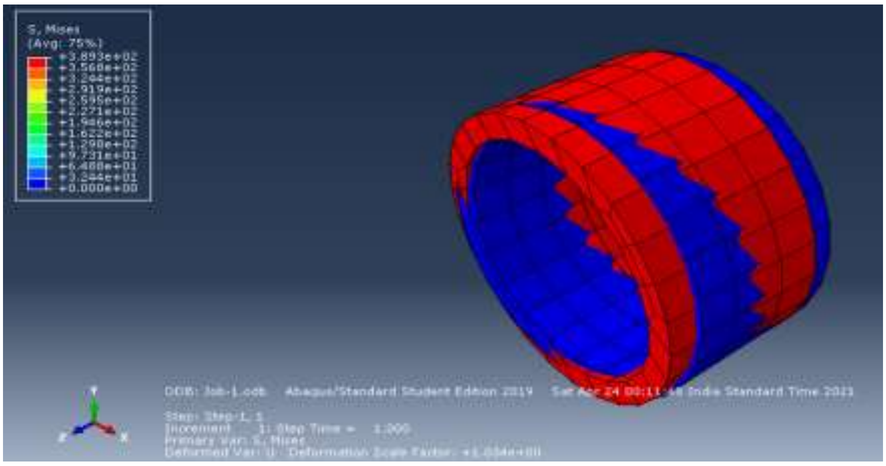

Figure 4: ABAQUS CAE Software results showing Maximum Stress for Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure without any step loading.

Table 3 shows the variation of stress patter as per step loadings & direct loading without any stress. Step loading for case 1 & case 2 are giving very close maximum stresses readings 412.2 MPa & 412.00 MPa respectively. But case-3 which is direct loading can give as much as 389.3 MPa as maximum stress. Averaging of stresses for all 3 steps can be done up to 404.50 MPa.

Loading Case	**Maximum Hydraulic Pressure in cylinder (MPa)**	**Maximum stress in cylinder**
Loading Case 1	74.4065 (With Step loading of 20,40, 60 MPa& Final Loading)	412.2 MPa
Loading Case 2	74.4065 (With Step loading of 40 MPa & Final Loading)	412.00 MPa
Loading Case 3	74.4065 (Without any step loading)	389.30 MPa
Average Maximim Stress		404.50 MPa

Table 3. Representation of Maximum stress pattern of Hydraulic cylinder after different loading pattern.

5.0 Results & Discussions

As per figure 5 graph can be drawn for case 1, case-2 & case-3 against their maximum stress patterns with stresses in MPa for 74.4065 MPa hydraulic pressure.(As per ABAQUS-FEA results)

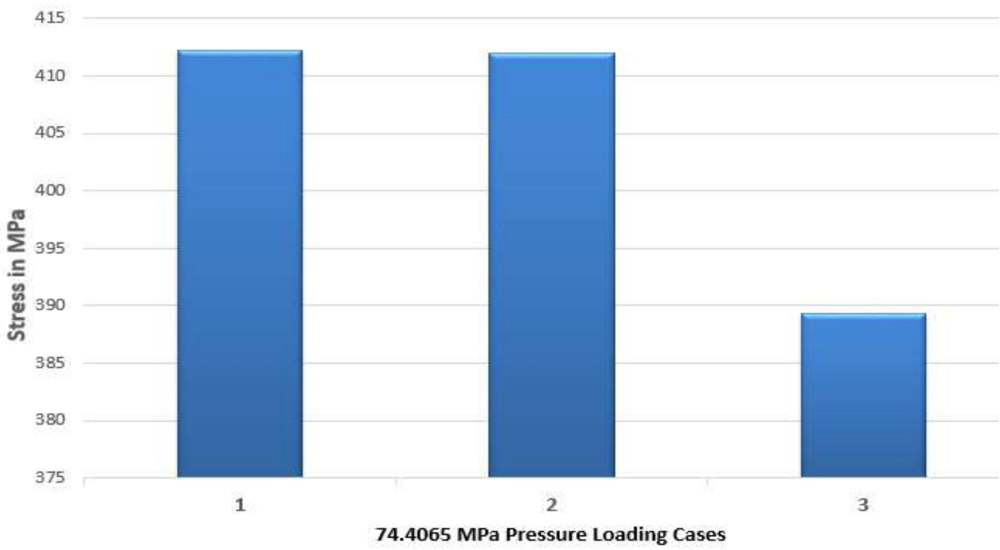

Figure-5: Variation of Maximum stress as per Pressure load cases of the hydraulic Cylinder

In it, it can be clearly seen that 404.50 MPa is the average maximum Von-Mises Stress observed during Finite Element Analysis by ABAQUS -FEA. It is evident from Table-4 that the Maximum Stress range is within the expected range when comparing Analytical versus Finite Element Analysis.

Maximum Von-Mises stress	**Value of Maximum Stress**
As per Mechanical testing of Hydraulic cylinder	383.87 N/mm^2
As per ABAQUS –CAE Results from Table-3	404.50 N/mm^2

Table 4. Comparison of Maximum Von-Mises Stress values for hydraulic cylinder

6.0 Conclusion

As per mathematical calculations 74.4065 MPa is selected as minimum pressure for Autofrettage pressure. So any pressure above that can produce permanent deformation inside the cylinder.As being a plastic zone process there is no any considerable impact of step loading was seen in ABAQUS-FEA loading. Most of the maximum Von-Misses stresses were generated near inner diameter of hydraulic cylinders.

From above Table-4 it is clearly seen that Mechanical testing & FEA testing results are inline & having only 05.37% variations.(variation of only 20.63 MPa can be observed)

5. Future Scope:

To get maximum benefit from Autofrettage in optimized manner Re-Autofrettage was suggested further to Autofrettage. In Re-Autofrettage firstly Autofrettage pressure is applied on the cylinder & then heat soak process is proposed. In heat soak process stress releasing was expected in the process before the Re-Autofrettage preaasure loading. The detailed procedure is shown as per Figure- 6.

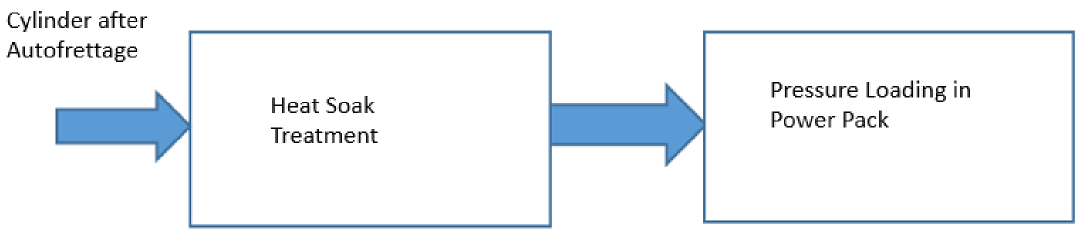

Figure 6: Stages of Re-Autofrettage and Multiple Autofrettage

During the same Heat soak treatment for stress distribution is to be carriedout. After the same plastic loading of cylinder can be performed. Simliar process is been conducted for 2 times for better material optimization. The results can be compared after residual stress analysis by hole drilling method.

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