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Selection Of Minimum Autofrettage Pressure for Steel Made Hydraulic Cylinder & Deciding Corresponding Re-Autofrettage Parameters

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Abstract: Thick cylinders are widely used in High pressure application like Hydraulic power cylinders The Autofrettage process is an important part of the material optimization process for thick walled cylinders. In Autofrettage Intentional Residual stress were created due to plastic deformation of internal cylinder wall, so that during pressure loading phase some of stresses can be reduced as Working stresses & Residual stresses were opposite in nature The right hydraulic cylinder pressure is crucial for Autofrettage. To optimize material and reduce costs, industrial hydraulic cylinder manufacturers need the right minimum pressure for Autofrettage.. In this article problem of deciding right Initial Autofrettage pressure was solved for actual Manufacturer in India. The process involves correctly analyzing the material and its properties, followed by deciding the pressure range based on an analytical method, Finite Element Analysis is then used to validate the same. Re-Aufofrettage process was also been conducted for second sample Hydraulic Cylinder.

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

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 [5]. By optimizing cylinder dimensions, residual stresses can be minimized. [1] 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. [6] 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 [8] Residual stresses are “locked-in” stresses seen in the material and they are always independent of external load [9]

Autofrettage concept is shown as per Figure1 below. In it Figure-1 (a) shows that ElasticPlastic zones during Autofrettage. Near-bore plastic zone is observed & away from bore Elastic zone is observed. [2] 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. [10] Mostly pressure with 100 MPa to 600 MPa is referred as high pressure for the [7] .So it’s very essential to decide minimum Autofrettage pressure for cylinder optimization

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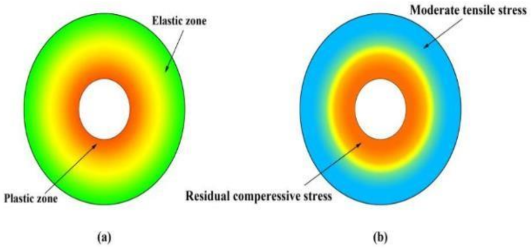

Figure 1: Autofrettage Concept for Hydraulic Cylinder: (a) Elastic & Plastic Zones Locations during Autofrettage. (b) Residual Stresses after Autofrettage after Unloading

Selection Of Cylinder & Its Properties By Testing Method

When choosing a cylinder for Autofrettage trial from a range of options, the selection process holds utmost importance. It is highly recommended to opt for a cylinder that exhibits superior production qualities for optimal results. When aiming for maximum material savings, it is essential to prioritize products that offer the highest volume. By opting for larger volume products, one can optimize material utilization, minimize scrap, and ultimately achieve significant cost reductions As per the industry guidelines, the analysis was conducted using a cylinder with a 50 mm internal diameter and a 60 mm outer diameter. The preferred length chosen for the analysis was 62 mm. These dimensions were selected based on the specific directions provided by the industry.

In such cases, testing is usually conducted to determine the cylinders' material composition and mechanical properties. As a result of chemical and mechanical properties testing received by suppliers, it appears to be 0.21% carbon Medium Carbon Steel. Cylinders mechanical properties can also be examined as per below Table-1. It is clearly seen from table that for generating residual stresses amongst cylinder minimum 383.87 N/mm^2 pressure is required.

Table 1: Major Mechanical Properties of Hydraulic Cylinder as per Test Report

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 %

Deciding Minimum Pressure For Cylinder Of Autofrettage By Analytical Method

In order to determine Autofrettage pressure, it is extremely important to confirm the yield stress of the cylinder analytically. To calculate maximum stress or thickness of cylinders for thick or thin cylinders, a number of equations were available that could be used. [3] Basically, the equations must be selected according to the material of construction & type of ends (closed or open).Here in this case the cylinder is closed & its material is ductile in nature so Clavarino's equation can be used [2] Equation can be written as per equation 1 given below.

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

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 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.

Table 2: Input Parameters for Hydraulic Cylinders.

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

According to Clavarino's equation, putting all above values into equation, we can get,

1.44(383.87-1.30 Pi)= 383.87+ 0.4Pi……………………………………………..(2)

-2.27Pi= 383.87- 552.7728……………………………………………………... (3)

So, Pi =74.4065 MPa

Which means the minimum hydraulic pressure to generate residual stress in a cylinder is 74.4065 MPa for Autofrettage.Same value of the pressure can be the base point for next trial.

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. [4]

A Finite Element Analysis was performed with ABAQUS-CAE software in order to validate the cylinder's 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 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 diameter of the cylinder.

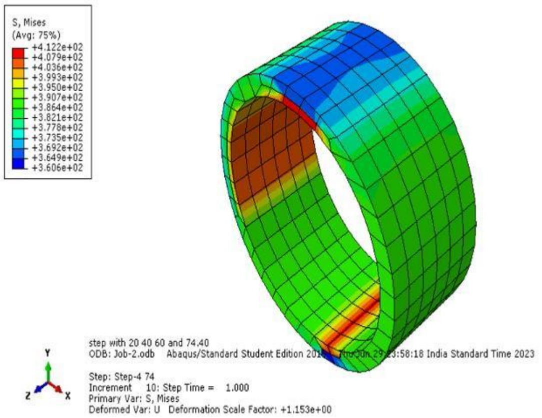

Figure 2: Maximum Stress for Hydraulic Cylinder with 74.4065 MPa Internal Hydraulic Pressure with Step Loading of 20, 40 & 60 MPa before Final Loading.

Figure-3 shows applied Internal Hydraulic Pressure of 74.4065 MPa at inner diameter With Step loading of 40 MPa followed by final loading of 74.40 MPa. This time maximum vonMisses 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.

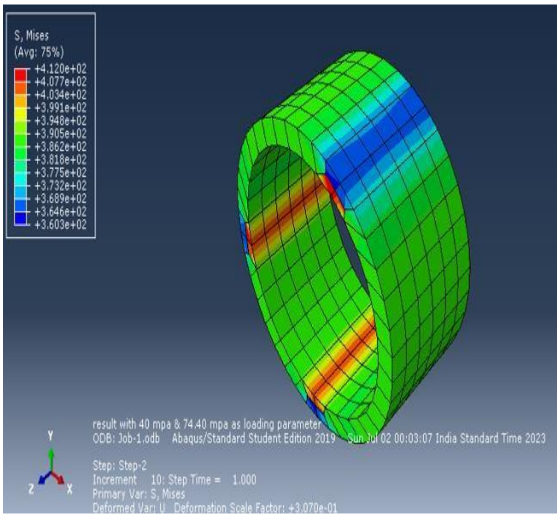

Figure 3: Maximum Stress for Hydraulic Cylinder with 74.4065 MPa Internal Hydraulic Pressure with Step Loading of 40 MPa before Final Loading.

Figure -4 shows Maximum Stress for Hydraulic cylinder with 74.4065 MPa Internal Hydraulic Pressure without any step loading. As in it no any step loading step is created in

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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.

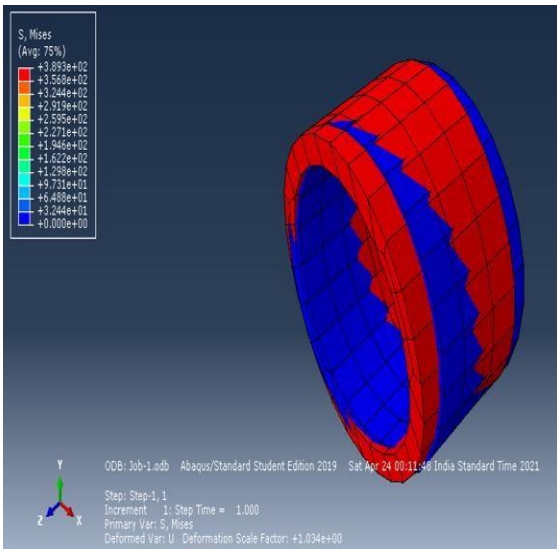

Figure 4: Maximum Stress for Hydraulic Cylinder with 74.4065 MPa Internal Hydraulic Pressure without Any Step Loading.

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 case3 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.

Table 3: Maximum Von-Mises Stress Values for Hydraulic Cylinder

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	388.10 N/mm^2

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)

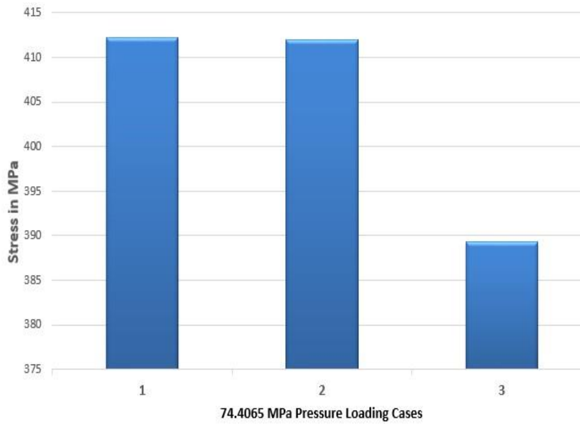

Figure 5: Variation of Maximum Stress as per Pressure Load Cases of the Hydraulic Cylinder.

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.

Table 4: Maximum Von-Mises Stress Values for Hydraulic Cylinder

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

Conclusions

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)

Future Scope

To get maximum benefit from Autofrettage in optimized manner Re-Autofrettage was suggested further to Autofrettage. In ReAutofrettage 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.

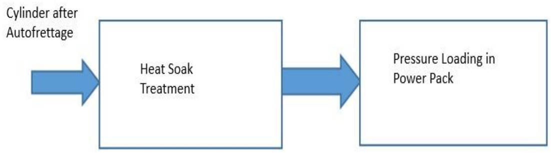

Figure 6: Stages of Re-Autofrettage

During the same Heat soak treatment for stress distribution can be adopted. After the same plastic loading of cylinder can be performed and results can be compared after residual stress analysis by hole drilling method

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