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Paper

AUTOFRETTAGE - BASIC INFORMATION AND PRACTICAL APPLICATION ON COMPONENTS FOR WATERJET CUTTING

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ABSTRACT

The Autofrettage is an important procedure for components which are exposed to high and ultra high pressures. Depending on geometry and strength of material, different degrees of wall thickness permanent deformation are calculated. Introduction of residual stresses into the wall of high pressure components by permanent deformation is essential for reduction of operating stresses and leads to essential extension of life time.

Especially for components in waterjet cutting units like cylinder, check valve and cutting valve parts, the Autofrettage is mandatory. On behalf of diagrams the determination of the optimum Autofrettage pressure is illustrated. For Autofrettage treatment pressure ratings between 600 MPa and 1,000 MPa are applied. The advantages of Autofrettage procedure are illustrated on stress versus wall thickness diagrams and verified by fatigue testing under cyclic pressure load conditions.

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1. INTRODUCTION

The design and calculation of high pressure components have an essential impact on equipment reliability and safety on high pressure pumps for waterjet cutting application. Under operating conditions the high pressure components have to withstand high cyclic load. Introduction of residual stresses into the wall of high pressure component is essential for reduction of operating stresses and leads to essential extension of life time. Basis for design and calculation of high pressure components are the mechanical material properties, considering static and dynamic load conditions.

In the literature there are only a few investigations available about dynamic load conditions and the impact of Autofrettage on dynamic loaded components. In order to fulfill operation requirements, a continuous improvement of theoretical description about fatigue behavior of autofrettaged components has to be performed. Reliable and accurate life time calculation procedures allow to minimize fatigue testing efforts and test material costs. Nevertheless fatigue testing is required for verification of theoretical investigations.

This presentation should demonstrate the trend of fatigue behavior of test cylinder under internal pulsating pressure considering Autofrettage and residual stresses. An important target is the investigation of the impact of degree of plastic deformation on the fatigue life time. For this reason test specimen are loaded under pulsating internal pressure until leakage. Woehler diagrams, respectively design curves are recorded for different degrees of Autofrettage depth.

2. BASIC INFORMATION ON AUTOFRETTAGE

Due to Autofrettage procedure the advantage of material cold hardening is used in order to increase the yield strength by plastic deformation. If a thick walled tube is loaded with internal pressure, a triaxial stress condition with tangential, radial and longitudinal stress is generated. Autofrettage is standard practice on thick walled high pressure tubes and fittings in order to improve the fatigue life of components at pulsating pressure. Furthermore the stresses at the inside of cylinder are reduced due to residual compressive tangential hoop stress originated by Autofrettage. The result is a higher safety factor against yielding at operating conditions.

Depending on the input data, the optimum Autofrettage pressure causes a permanent deformation of 20% to 35% of the cylinder wall. If the internal pressure is increased in a thick walled cylinder, the deformation imposed on the cylinder material at first is purely elastic until the elastic pressure limit is reached. As long as the deformations follow the Hooke´s law, they are reversible when the internal pressure is released. The elastic theory calculation of the triaxial principal stresses in tangential, radial and axial direction of a thick walled cylinder under internal pressure, is based on the equilibrium of forces. The formulas for stress calculation and deformation are well described in ASME Code and Buchter.

For the calculation of the equivalent stress and tensile elastic limit the Von Mises criterion is applied. Plastic deformation of thick walled cylinder is produced under precise internal pressure control. The yielding process in the cylinder wall begins at pressure increase over elastic limit starting from the internal fiber. The extension of yield region is concentrically to the cylinder bore. By increasing the pressure further, the full plastic condition can be reached causing plastic deformation also on the external fiber. Due to different reasons this condition is only considered for burst tests and safety factor evaluation. For Autofrettage pressure calculation Prager and Hodge have developed a procedure, which can be applied to the partial plastification as well as to the full plastic condition of wall thickness.

By integration and logical conversion the end formula for the Autofrettage pressure is obtained. When the internal pressure is released after Autofrettage procedure, the plastic deformation in the wall remains, while the elastic external region springs back and the yielded region is set into a so called residual stress condition, as shown in Figure 1. The elastic forces act as an external pressure on the plastically deformed region, the developing residual stresses are compressive stresses. On the other hand, the plastic region avoids the return of the elastic region into its original neutral condition. The plastic region acts as internal pressure on the external region, still under elastic deformation, and therefore creates residual tensile stresses.

The curves of maximum stresses in Figure 2 are the result of a computer iterative calculation for different continuous increased Autofrettage pressures, starting from plastification pressure on the inner fiber of the cylinder up to the value for full plastification of wall thickness.

The optimum Autofrettage pressure is considered to be determined were the equivalent stress at interface fiber under operating pressure is a minimum in this diagram. Because in this case the load on the material is minimized and the safety factor against yielding under operation condition is the maximum possible. Fatigue testing has been performed already at different Universities, research laboratories and manufacturers.

3. AUTOFRETTAGE FOR HIGH PRESSURE COMPONENTS

For standard high pressure intensifier pumps used for waterjet application the nominal values for operating pressures are between 250 and 400 MPa at a maximum ambient temperature of 35°C. Lifetime of the pumps is influenced by design and production processes of high pressure components on the one hand, and by the number of load cycles on the other hand.

The duration of the load cycle can be increased by the design of the intensifier e.g. diameter of the plunger and length of stroke. The ability to create a constant high pressure throughout the compression stroke has a positive effect on the lifetime. Figures 3 and 4 show typical high pressure heads of an intensifier pump used as pressure generating unit for waterjet cutting equipment. At this intensifiers the high pressure cylinder, valve body and internal parts of suction and pressure check valves are autofrettaged.

Autofrettage procedure is performed by increasing the internal pressure in the thick walled cylinder to a precalculated limit, mainly depending on material strength, geometry and operating conditions. For optimisation a multiple step computer calculation is used with the target to minimize the equivalent stress in the wall calculated according to Von Mises under operating conditions. Depending on the input data, the optimum Autofrettage pressure, which is between 600 and 1,000 MPa, causes a permanent deformation of 20% to 35% of the cylinder wall.

As a standard during Autofrettage the pressure and strain on tube are recorded. For documentation a pressure/strain diagram is provided indicating also the elastic limit and the percentage of cylinder wall plastification. Due to a certain range of material yield strength and tolerances on geometry two limit curves are precalculated before Autofrettage performance. To avoid expensive tests with original high pressure comonents for long term testing and material comparisons a special test specimen has been developed.

4. DESCRIPTION OF TEST PROCEDURE

The requirement of pulsating load condition is generated by a high pressure pump and by pneumatic actuated high pressure on/off valves. The high pressure pump provides the relevant test pressure at room temperature. During testing the number of pressure cycles and operating hours are automatically counted and recorded. Figure 5 shows the schematic of the pulsation equipment. The counting signal is connected to the valve command signal. Each valve opening stroke is therefore considered as a cycle. In case of failure of test specimen the entire system is automatically stopped due to pressure drop cased by leakage.

5. EXECUTION OF TEST PROCEDURE

Fatigue testing of different materials show a very significant improvement of fatigue strength and fatigue life due to Autofrettage treatment and specific surface finishing. For this reason it was determined to find an optimum by variation of these parameters. Target of testing was, to verify the influence of residual stresses due to Autofrettage, respectively to demonstrate the increase of life time by applying different Autofrettage depths on test specimen. Test tubes have been autofrettaged to different ranges of plastification. After Autofrettage, the testing tubes have been loaded with pulsating internal pressure until failure in a leak before burst condition. The applied pulsating test pressures were 200, 300 and 400 MPa.

All results are illustrated in double logarithmic Woehler diagrams. Due to the high expenses for testing, the accurate fatigue strength was not exactly determined. Therefore the relevant design cycles for fatigue strength is defined with $2.1 \cdot 10^6$ cycles. The fit function of the design curve respectively 50% failure probability Woehler curve is selected as a simple exponential equation.

6. TEST RESULTS

In Figures 6 to 9 the test results are summarized in the relevant Woehler curves. The curves show the fatigue test results versus Autofrettage depth at the applied pulsating test pressure of 200, 300 and 400 MPa.

The test results in Figures 10 and 11 clearly show the significant increase of fatigue life due to increased Autofrettage depth. Due to the Autofrettage procedure, the maximum of stresses are changed from inside diameter into the wall. The fracture surface analysis indicates that the crack initiation started at the inner surface. Therefore the relation to the tangential strength has been verified.

7. CONCLUSION

The life time of high pressure components is significantly improved by increasing Autofrettage depth. Fatigue strength and life time of pressurized thick walled cylinders are strongly influenced by the tangential stress.

Due to Autofrettage, the tangential stress on inner surface is changed to compressive stress. The increased life time can be explained by the reduction of tangential stress at inner diameter. But it has to be also considered that the stresses in wall thickness and on outside diameter are increased due to Autofrettage and limited by reverse yielding.

Depending on Autofrettage pressure cracks might be generated at both, inner and outer surface. Therefore, too high stresses on outside diameter should be avoided in order to avoid cracks. Nevertheless for high pressure cylinder, which have fatigue or life time problems due to pulsating pressure, the life time can be increased by considering a higher Autofrettage depth.

8. REFERENCES

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9. GRAPHICS

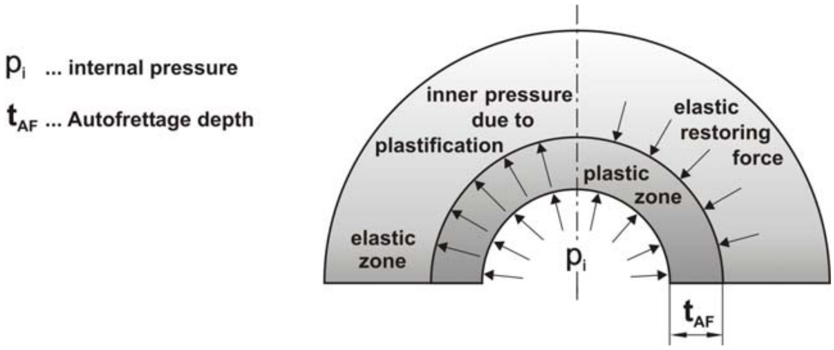

Figure 1. Model of Autofrettage

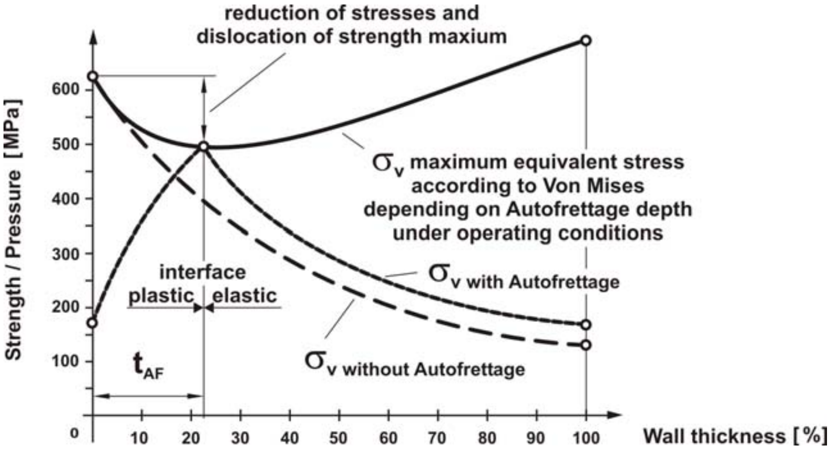

Figure 2. Stresses due to Autofrettage

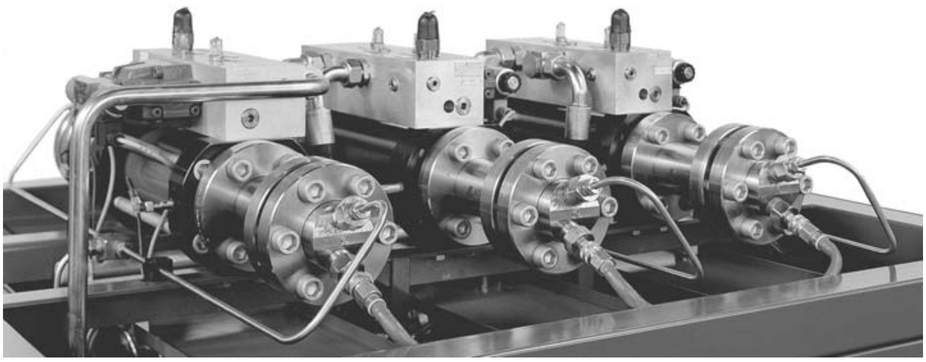

Figure 3. Standard high pressure intensifiers

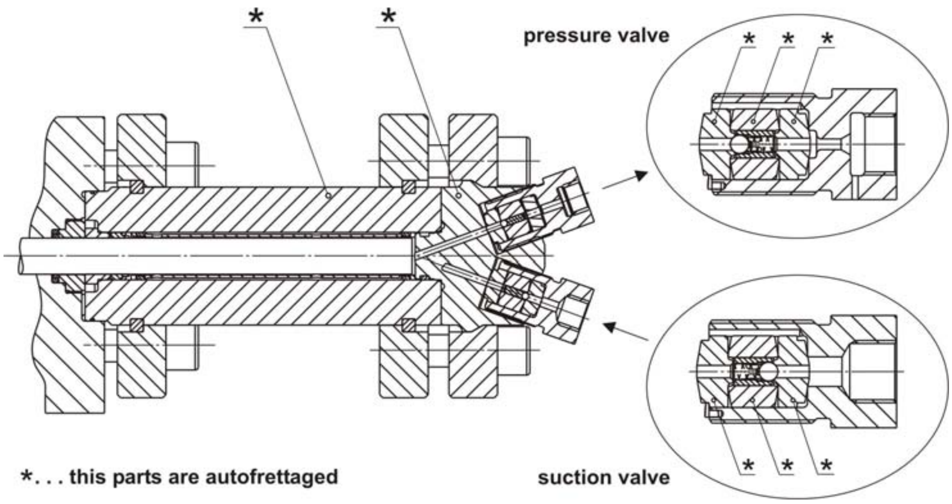

Figure 4. Autofrettaged parts on high pressure intensifier

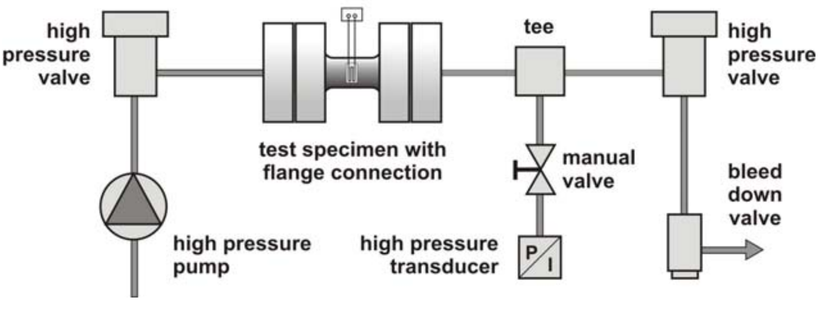

Figure 5. Schematic of the pulsation testing equipment

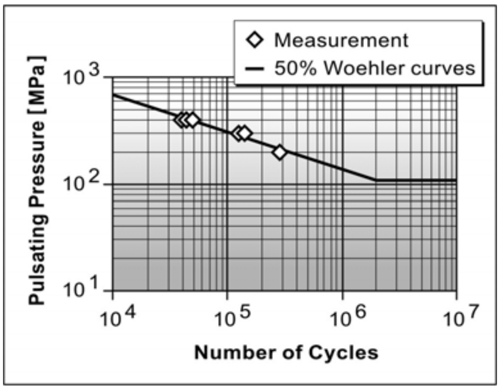

Figure 6. Curves without Autofrettage

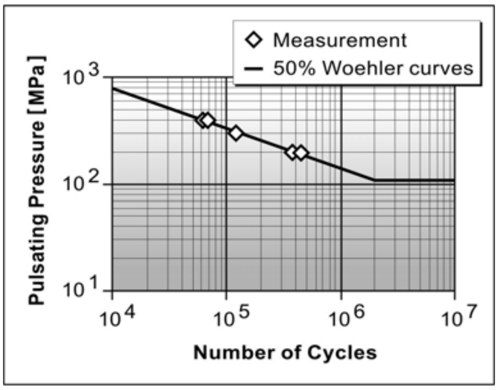

Figure 7. Autofrettage depth 20.4%

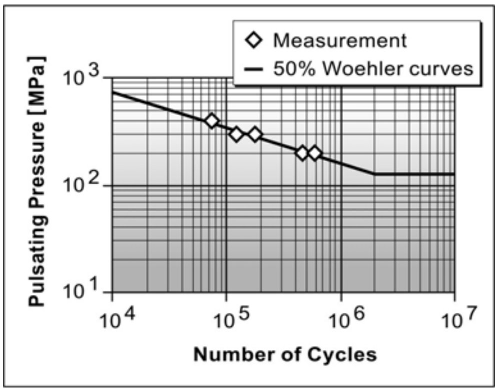

Figure 8. Autofrettage depth 42.2%

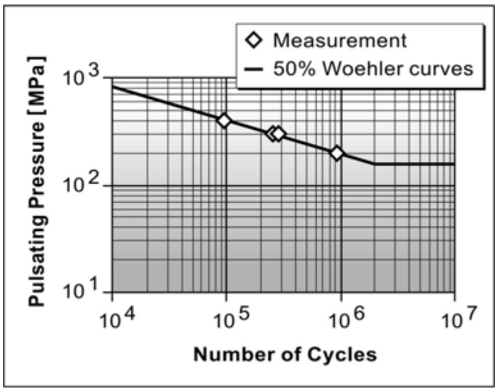

Figure 9. Autofrettage depth 78.8%

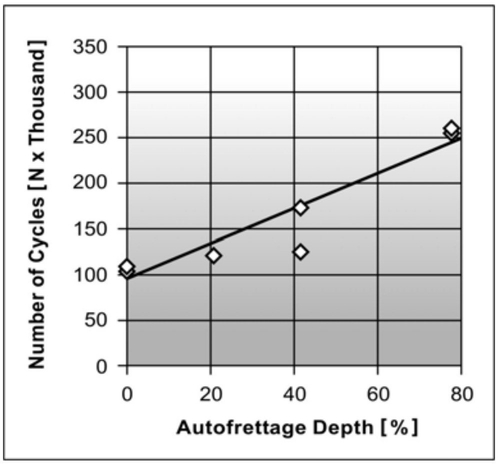

Figure 10. Cycles at 300 MPa

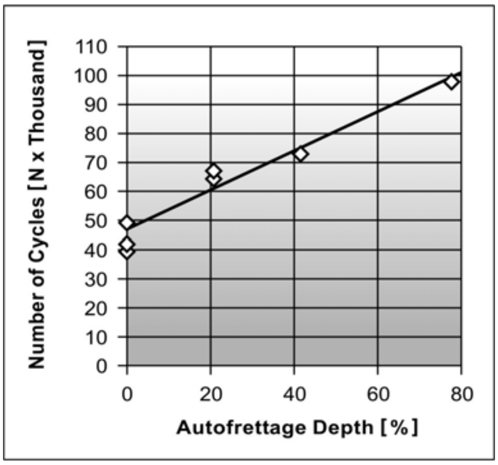

Figure 11. Ccycles at 400 MPa