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DEVELOPMENT OF A DESIGN AND OPTIMIZATION METHOD FOR HIGH PRESSURE COMPONENTS

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In this paper the development of an automated design and optimization method for high pressure cylinders is explained. To reduce the total stress in the structure during the operating state different manufacturing processes are used. By implementing standard design rules into MS EXCEL® the automated calculation of the significant stress conditions is possible. The automated calculation sequences allow a coupling with an optimization software and the investigation of computed calculated optimized parameter combinations.

Nomenclature

symbols for the calculaution of the load induced stress

σ_t = tangential load induced stress, MPa
σ_r = radial load induced stress, MPa
σ_{ax} = axial load induced stress, MPa
p_i = inside pressure, bar
r = random point in the structure, mm
r_i = inside radius, mm
r_a = outside radius, mm

symbols for the calculation of the residual stress due to autofrettage

σ_{tRA} = tangential residual stress in the plastic part of the structure, MPa
σ_{rRA} = radial residual stress in the plastic part of the structure, MPa
σ_{tR} = tangential residual stress in the elastic part of the structure, MPa
σ_{rR} = radial residual stress in the elastic part of the structure, MPa
σ_F = yield stress, MPa
D = random point in the structure, mm
D_O = outside diameter, mm
D_I = inside diameter, mm
D_p = diameter of the plastic elastic boundary fibre, mm

symbols for the calculation of the shrinkage strain in the layered structure

P_{if} = pressure in the interface between inside and outside cylinder, MPa
δ = interference between inside and outside cylinder, mm
D_{if} = shrinkage diameter, mm
E_i = elasticity modulus inside cylinder, MPa
E_o = elasticity modulus outside cylinder, MPa
υ_i = Poisson's ratio inside cylinder
υ_o = Poisson's ratio outside cylinder
σ_{tri} = tangential shrinkage strain inside cylinder, MPa
σ_{rri} = radial shrinkage strain inside cylinder, MPa
σ_{tra} = tangential shrinkage strain outside cylinder, MPa
σ_{rra} = radial shrinkage strain outside cylinder, MPa
Y_i = ratio of the shrinkage diameter and the inside diameter
Y_o = ratio of the outside diameter and the shrinkage diameter

1. Introduction

In highly stressed cylinders residual stresses are generated due to the manufacturing processes autofrettage and shrinking, which leads to a reduction of the total stress in the operating state. Thereby autofrettage is used to create compression stress at the inside diameter by plastifying a certain part of the structure. The design of layered wall cylinders causes a related effect due to an interference at the interface between the single walls [1]. In this paper the structure and application of a design and optimization tool for determination and reduction of the stress conditions in highly stressed components is explained. The tool can be used for the efficient preliminary design of the coponents. The calculation of the residual and operating stress conditions after autofrettage and shrinking of the components are implemented to the design tool. The calculations are based on standard design rules and the ASME Boiler and Pressure Vessel Code [2], that further considers the Bauschinger effect. This effect leads to a reduction of the compression strength of the material and decreases the residual stress after autofrettage. If the quotient of the tangential residual stress at the inside bore and the yield stress is more negative than –0,4 the effect is considered in the calculation and the stress is corrected [2]. Moreover the tool provides the opportunity to estimate the approximate durability based on Miner's rule. By coupling the developed calculation sheets with the free available optimization software DAKOTA® it is possible to optimize several stress conditions considering different geometric and process input parameters. For the validation of the developed calculation and optimization method the tool is applied on highly stressed components. Extensive tests have been performed in which different optima were identified. Thereby stress is reduced up to 44% and the load capacity is increased up to 30% at the same level of damage. The final design of the components is based on a finite element analysis whose results are copmpared with the analytic calculations.

2. Theory

The inside pressure in thick walled cylinders causes a triaxial state of stress in the structure in which the tangential stress has the highest tensile stress value. Thereby the tangential stress at the inside bore is higher than the one at the outside bore. The inside bore of the structure is identified as a critical point for damage due to the mentioned tangential stress. The operating stress condition is shown in Figure 1. The analytic equations 1, 2 and 3 given below enable the calculation of the operating stress conditions [1].

$$\sigma_t = p_i * \left(\frac{r_i}{r_a^2 - r_i^2} + \frac{r_a^2 * r_i^2}{r_a^2 - r_i^2} * \frac{1}{r^2} \right) \tag{1}$$

$$\sigma_r = p_i * \left(\frac{r_i}{r_a^2 - r_i^2} - \frac{r_a^2 * r_i^2}{r_a^2 - r2_i} * \frac{1}{r^2} \right) \tag{2}$$

$$\sigma_{ax} = p_i * \left(\frac{r_i^2}{r_a^2 - r_i^2} \right) \tag{3}$$

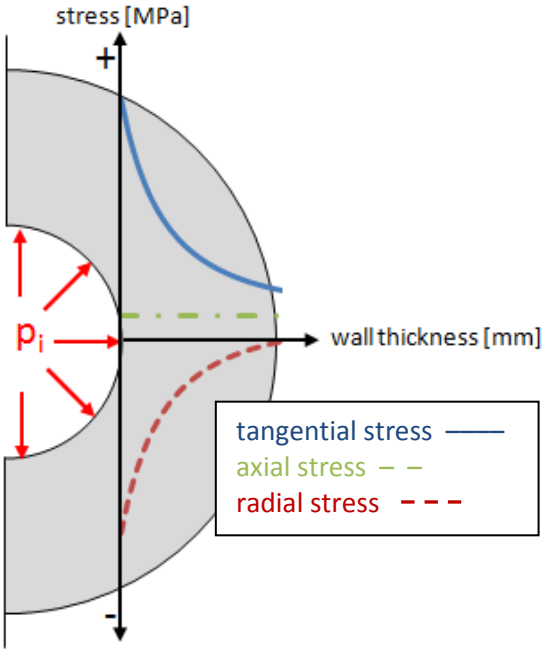


Figure 1: Operating stress condition due to inside pressure

By using autofrettage the cylinder is charged with a high pressure that plastifies a certain part of the wall from the inside bore to a certain fibre in the structure. The plastified percentage of the wall depends on the autofrettage pressure, the cylinder wall thickness and the yield stress of the material. Due to its resilient property the outside part presses on the plastic part which acts like and inside pressure on the outside part [1]. These conditions lead to a stress state shown in Figure 2.

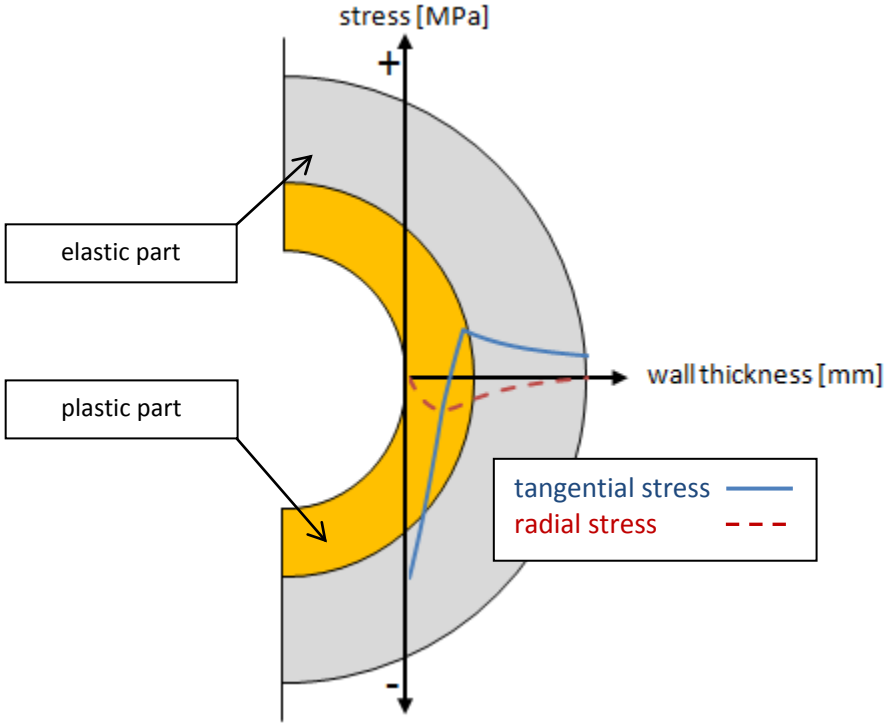


Figure 2: Residual stress conditions after autofrettage

At this point only the calculation without the consideration of the Bauschinger effect is explained. The ASME Boiler and Pressure Vessel Code [2] considers only the tangential and radial stress conditions. The calculation of the residual stress is realized separately for the elastic and plastic part of the wall. The equations 4 and 5 for the calculation of the plastic part are given below [2]:

$$\sigma_{tRA} = 1{,}15\sigma_F \left[\left(\frac{D_p^2 + D_o^2}{2D_o^2} \right) + \ln\left(\frac{D}{D_p} \right) - \left[\frac{D_t^2}{D_o^2 - D_t^2} \right] \left[\frac{D_o^2 - D_p^2}{2D_o^2} + \ln\left(\frac{D_p}{D_t} \right) \right] \left(1 + \frac{D_o^2}{D^2} \right) \right] \quad (4)$$

$$\sigma_{tRA} = 1{,}15\sigma_F \left[\left(\frac{D_p^2 - D_o^2}{2D_o^2} \right) + \ln\left(\frac{D}{D_p} \right) - \left[\frac{D_t^2}{D_o^2 - D_t^2} \right] \left[\frac{D_o^2 - D_p^2}{2D_o^2} + \ln\left(\frac{D_p}{D_t} \right) \right] \left(1 - \frac{D_o^2}{D^2} \right) \right] \quad (5)$$

The equations 6 and 7 for the calculation of the elastic part are given below [2]:

$$\sigma_{tR} = 1{,}15\sigma_F \left[\left(1 - \frac{D_o^2}{D^2} \right) \left\{ \frac{D_p^2}{2D_o^2} + \frac{D_t^2}{D_o^2 - D_t^2} * \left(\frac{D_p^2 - D_o^2}{2D_o^2} - \ln\left(\frac{D_p}{D_t} \right) \right) \right\} \right] \quad (6)$$

$$\sigma_{tR} = 1{,}15\sigma_F \left[\left(1 - \frac{D_o^2}{D^2} \right) \left\{ \frac{D_p^2}{2D_o^2} + \frac{D_t^2}{D_o^2 - D_t^2} * \left(\frac{D_p^2 - D_o^2}{2D_o^2} - \ln\left(\frac{D_p}{D_t} \right) \right) \right\} \left(1 - \frac{D_o^2}{D^2} \right) \right] \quad (7)$$

Another manufacturing process to generate stress conditions reducing the stress in the operating state is the shrinking of layered cylinders. An interference between the inside and outside cylinder in a two layer cylinder wall causes a pressure in the interface between the two layers. This pressure acts like an outside pressure on the inside cylinder and like an inside pressure on the outside cylinder. The generated stress conditions are shown in Figure 3. The pressure causes a compression stress in the inside cylinder that gets superimposed with the operating stress. The following equations 8 and 9 allow the calculation of the pressure P_{if} in the interface between the two layers [2]:

$$P_{if} = \frac{\delta}{D_{if} * A} \quad (8)$$

$$A = \frac{1}{E_i} * \left(\frac{D_t^2 + D_{if}^2}{D_{if}^2} - \nu_i \right) + \frac{1}{E_o} * \left(\frac{D_{if}^2 + D_o^2}{D_o^2 - D_{if}^2} + \nu_o \right) \quad (9)$$

The calculation of the stress conditions in the inside cylinder can be performed by the following equations 10 and 11 [2]:

$$\sigma_{tri} = -\frac{P_{if} * Y_i^2}{Y_i^2 - 1} * \left(1 + \frac{D_t^2}{D^2} \right) \quad (10)$$

$$\sigma_{rri} = -\frac{P_{if} * Y_i^2}{Y_i^2 - 1} * \left(1 - \frac{D_t^2}{D^2} \right) \quad (11)$$

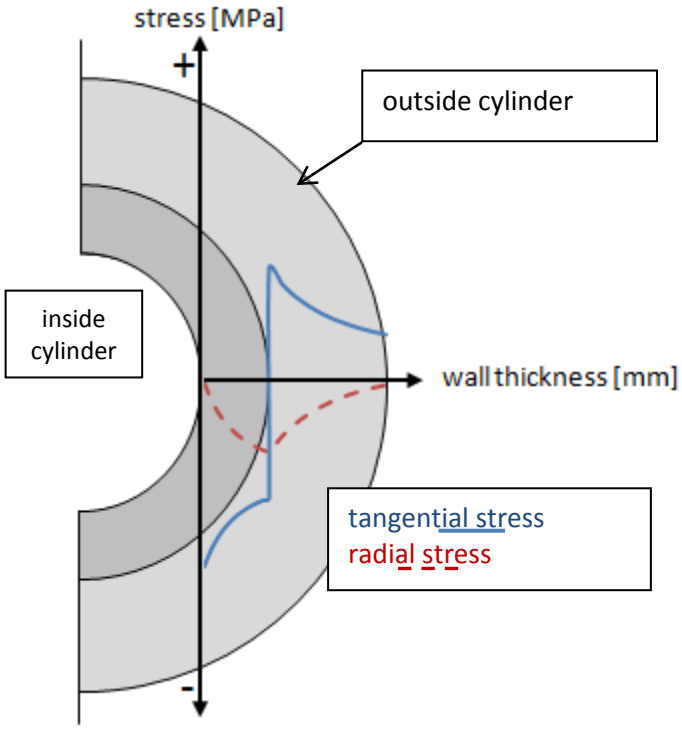


Figure 3: Stress conditions in an a two layer cylinder

The calculation of the stress conditions in the outside cylinder can be performed by the following equations 12 and 13 [2]:

$$\sigma_{tro} = -\frac{P_{if}}{Y_o^2 - 1} * \left(1 + \frac{D_o^2}{D^2}\right) \tag{12}$$

$$\sigma_{rro} = -\frac{P_{if}}{Y_o^2 - 1} * \left(1 - \frac{D_o^2}{D^2}\right) \tag{13}$$

For assembling the two cylinders the outside cylinder needs to be expanded due to the interference between the inside and outside cylinder. For manufacturing the outside cylinder is heated up to a certain temperature that expands the cylinder and enables the assembling of the two cylinders. By cooling the shrink fit down to room temperature the outside cylinder is shrinked on the inside cylinder which creates the pressure in the interface. By combining the two processes of autofrettage and shrinking it is possible two create residual stress conditions up to the value of the yield stress of the material which is the limit for residual stresses. Thereby the necessary autofrettage pressure is reduced compared with the autofrettage pressure that is used to create the same level of residual

stress in a solid wall cylinder. The calculation of the effective stress conditions after interference of the residual and operating stresses is done by simple addition of the single stress conditions.

2.1. Analytic calculation tool

By implementing the analytic equations into a calculation tool using MS EXCEL® the automated calculation of the several stress conditions is possible. For coupling the MS EXCEL® calculation sheets with the optimization software DAKOTA® and applying optimization algorithms it is necessary to have automated calculation sequences capable to edit the results after the input of different parameters [3]. The structure of the tool is shown in Figure 4. Dimensions of the cylinders or process parameters like the autofrettage depth are given to the input data sheet. On the following sheets of the tool the stress conditions are calculated and edited automatically. Furthermore the approximate durability can be estimated provided that the data from the Wöhler fatigue test is available.

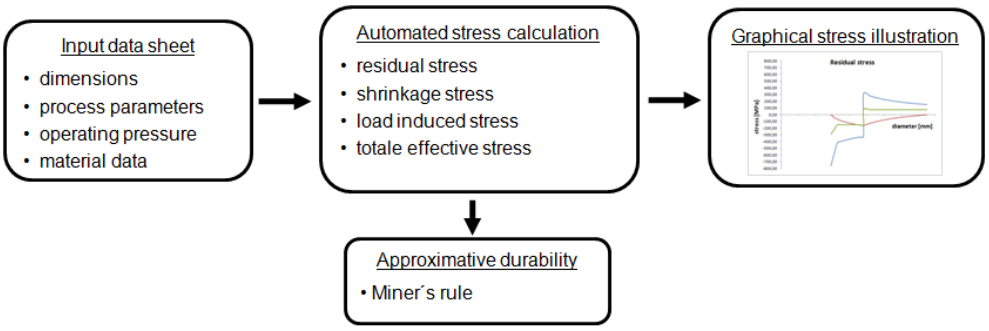


Figure 4: Structure of the calculation tool

2.2. Optimization with DAKOTA®

DAKOTA® is a free available optimization software from the Sandia National Laboratories. DAKOTA® provides several optimization algorithms and interfaces with software tools like MS EXCEL®. The optimization process runs a loop in which the settings from the DAKOTA® input file are processed into a parameter file. Certain parameter combinations are imported to the MS EXCEL® sheets and the results are automatically given to a result file. If the predetermined number of calculation sequences has been performed the break condition is fulfilled and the optimization is stopped. The parameters and results are given to an output-file in which the best parameters are listed separately. The input file contains the settings for the predetermined parameters like the lower and upper bounds of the parameter values or the number of optimization sequences. The structure of the optimization loop is shown in the following Figure 5.

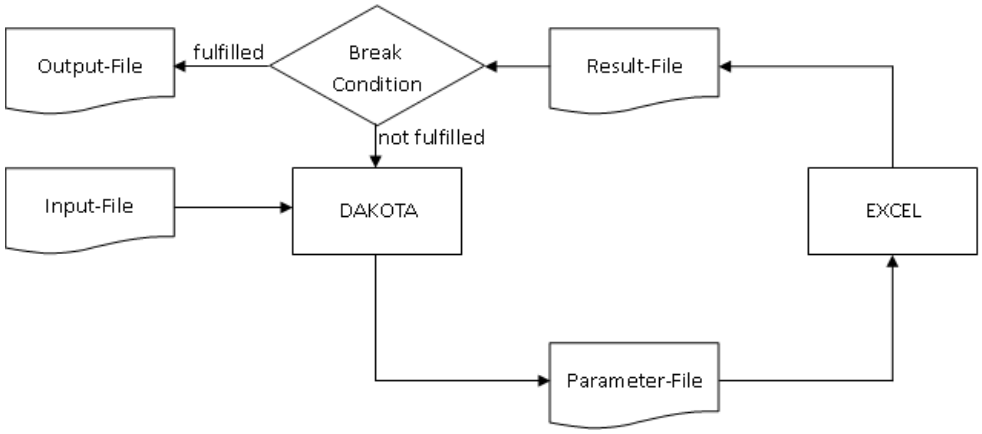


Figure 5: Optimization loop

For the optimization of the cylinders a multi-objective genetic algorithm is chosen which provides the opportunity of the optimization of two or more objective functions. The user is able to weight the single objective functions before running the optimization. Another reason to use genetic algorithms is their ability for searching reliably for a global optimum [4]. The algorithm copies an evolutionary process in which the first generation of parameters is chosen randomly in the defined parameter space. In the following generations only the "best" parameters that minimize the objective function are allowed to reproduce [3].

2.3. Optimization of high pressure cylinders

Reducing the stress conditions in the structure of high pressure cylinders is the aim of the optimization. Different input parameters like the operating pressure, the geometry of the cylinder or process parameters of autofrettage and shrinking influence the stress conditions. At this point an optimized combination of the autofrettage depth of the inside cylinder, the shrinking diameter and the interference between the two cylinder layers is searched. The inside and outside diameter of the cylinder and the material properties are supposed to be constant.

Parameter analysis can help to find a reasonable parameter space of the single input parameters defined by a lower and upper limit for the values. The optimization algorithm is performed for 20000 sequences to optimize the tangential stress at the inside bore of the inside and outside cylinder of two different versions of high pressure cylinders. By plotting the stress values of the initial situation the district of the optimized result points can be identified. The comparison of the two objective functions of version 1 is shown in Figure 6.

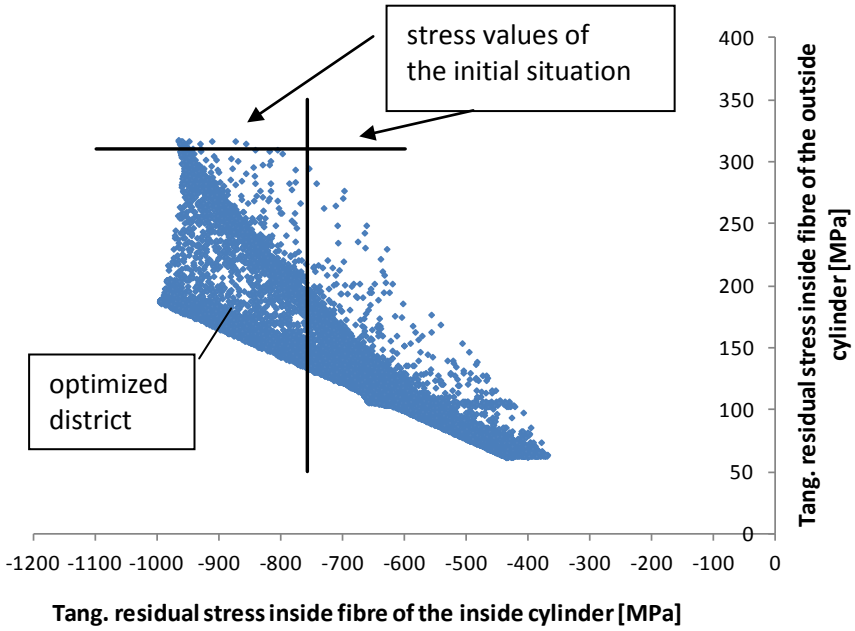


Figure 6: Results of the optimization of an autofrettaged layered cylinder version 1

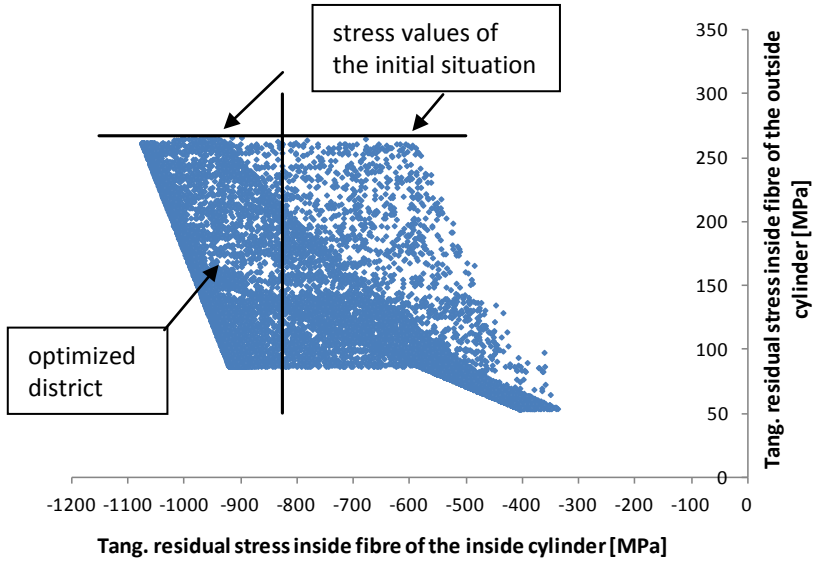


Figure 7: Results of the optimization of an autofrettaged layered cylinder version 2

Version 1 of the cylinder is designed for a lower operating pressure than version 2 and has according to this a lower wall thickness. The results after 20000 optimization sequences of version 2 designed for a higher operating pressure and wall thickness is shown in Figure 7.

By interpreting the results an optimized combination of the varied input parameters can be found. The optimized values were edited to the output-file that is created by DAKOTA®.

The combination of optimized input parameters under consideration of the defined parameter space for the two different versions is listed in table 1.

Table 1

Optimized input parameters and stress values of the objective functions

cylinders	input parameters	objective functions	
version 1	autofrettage depth inside cylinder	tang. stress inside fibre of the inside cylinder	-425 MPa
	shrinking diameter		
	interference of the cylinder layers	tang. stress inside fibre of the outside cylinder	538 MPa
version 2	autofrettage depth inside cylinder	tang. stress inside fibre of the inside cylinder	-213 MPa
	shrinking diameter		
	interference of the cylinder layers	tang. stress inside fibre of the outside cylinder	377 MPa

2.4. Compare of analytically and numerically investigated stress

For the final design of the high pressure cylinders a finite element analysis is used to detemine the stress conditions and investigate the best geometry. By comparing the results of the numerically and analytically investigated stress conditions differences are detectable. The numerically calculated compression stress in the inside cylinder is higher than the analytically calculated stress. In the outside cylinder the numerically calculated tensile stress is higher than the numerically calculated stress conditions. At the outside section of the two layers and the inside section of the outside cylinder the results deviate from each other on a lower level than in the structure. The highest deviance exists at the inside section of the inside cylinder and the transition of the plastic and elastic part of the wall. One reason for the deviation is the approval of a linear elastic material behaviour during the analytically calculation. The finite element analysis is based on an elastic plastic constitutive equation. Furthermore the analytically calculation does not consider the variation of the geometry that exists after the manufacturing process. For the design of the cylinders the analytically calculation shows conservative results for the stress conditions in the inside cylinder [5].

3. Summary

By developing automated analytic calculation sequences it is possible to determine the stress conditions in the analyzed components in a very short time. The process of finding a preliminary design of the components is accelerated and initial data for a following finite element analysis can be generated. Furthermore it is possible to couple the automated tool with an optimization software to investigate the best combination of the input parameters and minimize the stress conditions at the critical points for damage. Thereby the durability can be increased and the damage can be decreased just by varying geometrical and process parameters without changing the material or the inside and outside geometry of the components. Due to the optimization of two objective functions the chosen optimizer could help to consider a goal conflict. The conflict appears if the improvement of one objective function induces the degradation of the second function which was the case in this work. By weighting the objective functions before running the optimization sequences an optimized result under consideration of the improvement of both functions compared with the initial situation was figured out.

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