Introduction of Corrosion and Wear into the analytical Strength Assessment of Components used in Multiphase Boosting Technology

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1. Introduction

The worldwide steadily increasing demand for crude oil and gas leads to the need for production even in sea-covered and barely accessible areas. Often the well delivers a mixture of different phases like oil, gas and sand. Under such operating conditions it is convenient to use Multiphase Boosting Technology because there is no need of a separation before pumping. Due to this advantage, the complexity of installations in the sea-covered areas and remote locations can be kept rather simple.

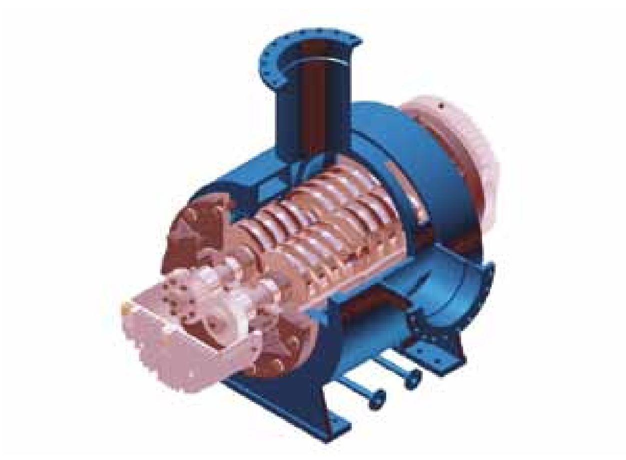

Figure 1: Multiphase twin screw pump

The employed components, like multiphase twin screw pumps, tubes or valves have to fulfil extremely high requirements concerning service life and reliability, as a failure may result in major ecological harm and economical loss.

In order to bundle the wide range of engineering disciplines related to the development of components of Multiphase Boosting Technology, the joint research “MPT-project” under the patronage of the MPT e.V. was founded. While the University of Berlin is focussing on the well characteristics, the University of Hamburg on material properties due to corrosion and wear, and the University of Hannover on the pumping process, the “Research Group for Off-Road Machines” of the Ruhr-University of Bochum is working on strength assessments of components incorporating the effects of corrosion and wear.

There are two reasons why a scientific approach for a strength assessment with the incorporation of corrosion and wear is necessary. First, the components are subjected to wear caused by e.g. transport of abrasive solids and corrosion caused by e.g. sour gas due to the multiphase flow, both in combination with dynamic stresses. Second, the common methods for strength assessments do not incorporate suitable possibilities to regard those effects.

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Due to the vast types of corrosion and wear those are identified, relevant in multiphase boosting systems. These types are grouped into different categories, depending on their effect on the strength of the components. For each category a special method for strength assessments is necessary, developed on the basis of common methods for strength assessments. Every method requires mechanical values like stress, strain or the stress intensity factor. Based on numerical and analytical methods, models are derived to describe the relevant phenomena.

2. Categorization of Corrosion and Wear

Multiphase flows can contain liquids e.g. oil or formation water, gases e.g. carbon dioxide or sour gas and solids e.g. sand. This leads to different types of corrosion and wear [7, 13, 16]. To minimize the number of different methods for strength assessments, these types are sorted due to their impact on the mechanical strength of components. One attribute is whether the component is attacked locally or globally.

Global Attack	Wear
	Erosion Corrosion
	General Corrosion
Localized Attack	Pitting Corrosion
	Stress Corrosion Cracking
	Pitting Corrosion Fatigue

Table 1: Examples of global and localized attack

Another attribute is the time behaviour of the mechanical stresses. Static stresses require a different approach than dynamically changing stresses. At least there are four groups as shown in Table 2.

	Static Stresses	Dynamic Stresses
Global Attack	1	2
Localized Attack	3	4

Table 2: Groups of Corrosion and Wear

In this paper, the Groups 2, 3 and 4 are considered. Examples for the Groups are (2) Corrosion Fatigue caused by dynamic loads and Erosion Corrosion, (3) Stress Corrosion Cracking and (4) Pitting Corrosion Fatigue.

3. New Methods of Strength Assessment

Most methods of strength assessment are organized in four steps, as shown in Figure 2 [1, 2, 3].

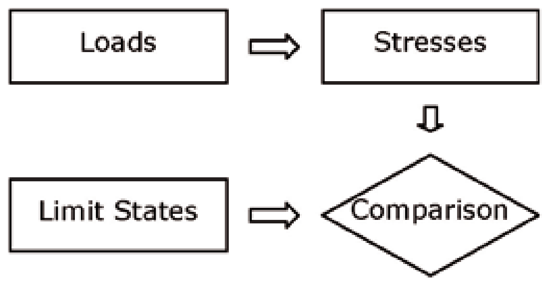

Figure 2: General method for a strength assessment

In the first step the loads like pressures or forces acting on the component have to be considered. By application of stress models the correspondent static or dynamical stresses and strains can be derived. This can be carried out for example by Finite Element Simulations. The third step is the estimation of the limit states. In the case of a fatigue assessment, for example, the allowable stress amplitude is given by the S-N Curve dependent on the aspired lifetime. The final step is the comparison of calculated stresses or strains to the corresponding limit states. The ratio of present to allowable stress represents the so-called “mechanical utilisation” [1]. This factor is not allowed to exceed a fixed value to cover possible uncertainties e.g. of loads and stresses.

As mentioned above, the different types of corrosion and wear are divided into the groups of global or localized attack which affect the strength of components in a different way.

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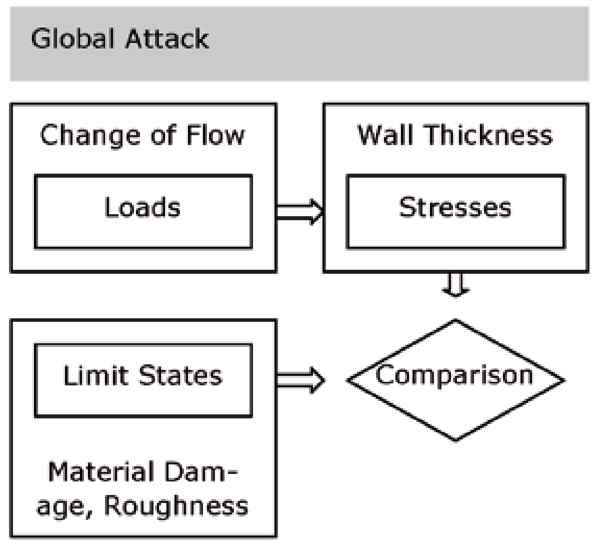

Figure 3: Effect of global attack on component strength

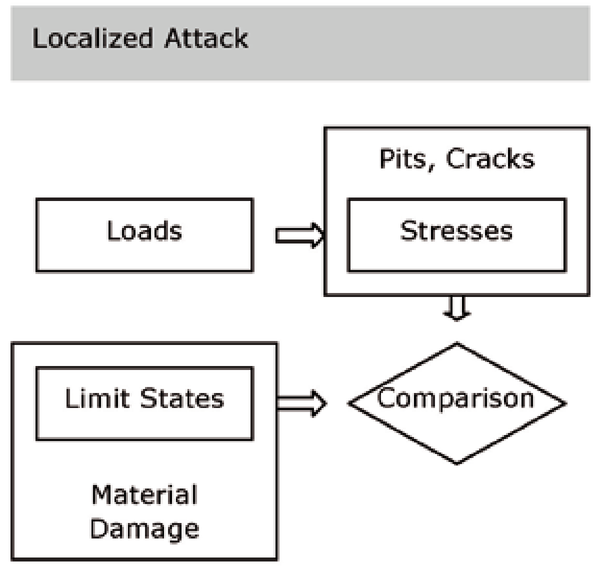

Figure 4: Effect of localized attack on component strength

The global attack on a component can affect the component strength due to a change in loads, stresses and limit states as it is shown in Figure 3. Different flow conditions arising from the loss of wall thickness cause a variation of the loads. For example twin screw pumps have gaps between the screws and the surrounding liner which can become larger due to wear by particles. This affects the backflow along the screw what leads to a change of the pressure distribution at the screw [9, 10]. The loss of wall thickness furthermore results in varying stresses, in general higher stresses and strains. A damage of the material due to chemical processes and the change of surface roughness may affect the Limit states.

Contrarily to the global attack, the effect of the localized attack on the loads can usually be neglected. For example a pit with a diameter less then 1 mm cannot change the flow conditions and the pressure distribution of the whole conveyor screw. However the small attacks considerably affect the stresses locally. These local changes have an impact on the strength of the whole component, because they can be the nucleation point for cracks, which can grow e.g. promoted by dynamic or static stresses and hydrogen embrittlement.

For the development of methods for a strength assessment it is inevitable to know how a failure may occur. According to Table 2, the typical mechanisms for groups 2, 3 and 4 are given below.

Group 3 is characterized by the combination of static stress and localized attack, known as stress corrosion cracking. The crack nucleates at a microscopic corrosive attack of the surface. The corrosive process at the crack tip leads to a loss of material strength in this region resulting in the growth of the crack. The increasing stress due to crack growth converges towards the material strength without corrosive effects. The final fracture occurs when the stress is rather close to this value. A typical example in oil and gas production is sulphide stress cracking, where the material strength is reduced by hydrogen embrittlement [16].

The combination of dynamic stresses with localized attack (Group 4) is corrosion fatigue. In this paper a special type, pitting corrosion fatigue, where the local attack is a corrosion pit, is regarded [8, 17]. As the effect of the corrosion pit depends strongly on its size, the first stage of pitting corrosion fatigue is the initiation and growth of the pit. The second stage starts with the nucleation of a crack at the corrosion pit. This crack grows due to the dynamic stresses and the corro-

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sion process and leads to the third stage - the final fracture. Damage can also occur due to dynamic loads and a global attack (Group 2). As mentioned above, the global attack affects both load and stress. Assuming that the loads are not affected, there are three stages similar to those of group 4. The first stage is the loss of wall thickness and the increase of roughness. That leads to higher stresses and the development of nucleation points for cracks all over the attacked surface. The second stage begins with the initiation of the crack resulting in the final fracture in stage three.

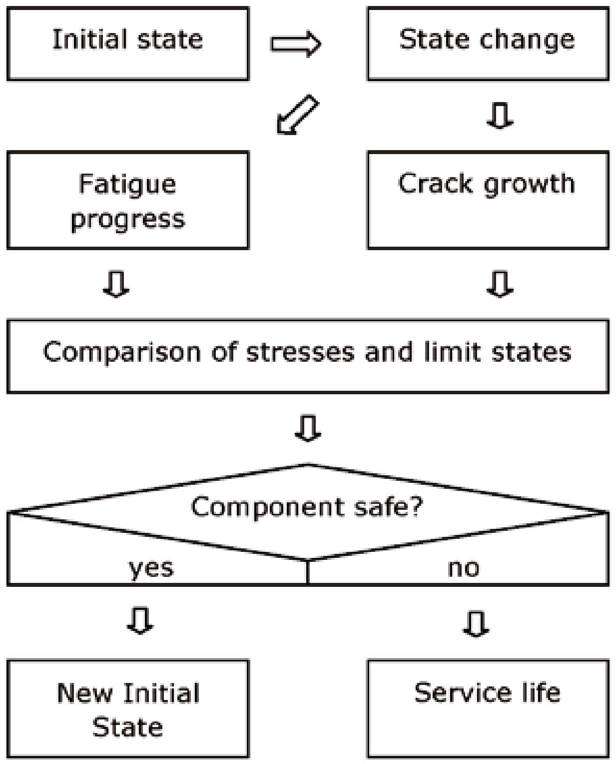

Figure 5: Graph of the new method for strength assessment incorporating corrosion and wear

The basic idea of the new method of strength assessment is to divide the service life of the components in discrete time steps. Figure 5 shows the calculation process which has to be performed for every time step. The initial state changes due to corrosion and wear, e.g. the growth of corrosion pits. Based on the changed state the progress of material fatigue due to dynamic loads (Group2 and 4, Table 2) and the growth of cracks (Group 3, Table 2) is estimated. Compared with the limit states it can be decided, weather the component is still safe. If the component is safe, the method turns to the next time step; otherwise the method ends and returns the calculated service life.

4. Models of Components of Multiphase Boosting Technology

In order to perform a strength assessment, it is necessary to develop models of the regarded components. These models should allow evaluating the input data for the method of strength assessment which is illustrated above. According to the general methodology for strength assessment (Figure 2) the models are divided into three sub-models to evaluate the loads, the stresses and the limit states. In this work models of several components were developed. These components, namely pipes, pipe elbows and conveyor screws of multiphase pumps, were chosen with the help of the project partners due to high static and dynamic loads and rather high corrosion and wear rates. The component models need some input data: Pressure, differential pressure, gas volume fraction, flow rate, material properties of the component and of the multiphase flow, and the rate of corrosion and wear. The models need the rate of corrosion and wear as input, because they do not include their progress.

4.1 Load models

Because the components are exposed to different loads, the models cover the specific loads of the considered component. The loads of pipes are pressure, forces and moments of the pipe-line and additional pressure due to slugflow. In the case of conveyor screws the loads are the pretension force and the pressure distribution which mainly depends on the operating medium and the geometry of the conveyor screw [9, 10]. By variation of the geometry of the conveyor screw it is possible to evaluate the effect of global attack (e.g. wear at the shoulder crevices) on the load. Clamping nuts are used to generate the pretension force of the conveyer screws, thus their load is the pretension force.

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4.2 Stress models

The evaluation of the component stress is performed with stress models based on the finite element method (FEM). These models consist of a basic geometry, according to the component without attack due to corrosion or wear and the attack geometry e.g. a corrosion pit or crack.

Because corrosion pits have a complex non-regular shape, their shape was simplified like pictured in figure 6 [17]. Corrosion pits have a wide range of different shapes, like shallow, deep and narrow or undercutting.

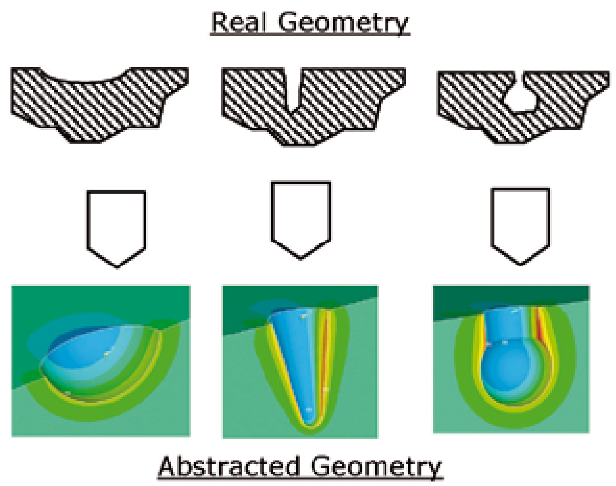


Figure 6: Simplified pit shapes

The simplified corrosion pits were used e.g. in combination with the conveyor screw (Figure 7). They were included at the tooth base of the conveyor screw. In this area the stresses reach their highest amount at the non corroded conveyor screw, so it is a kind of worst case calculation.

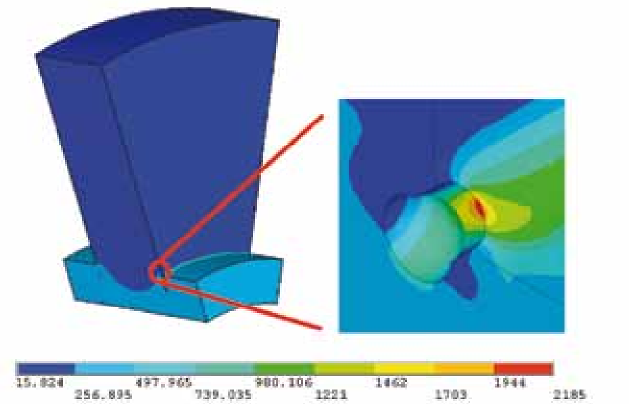


Figure 7: Stress model of a conveyor screw including a corrosion pit

Stress models of pipes consist of special piping elements and detailed sub models. The piping elements allow to quickly determining a coarse stress state of large pipe systems. The result of this calculation is used as boundary condition for detailed models of the interesting parts of the pipe system.

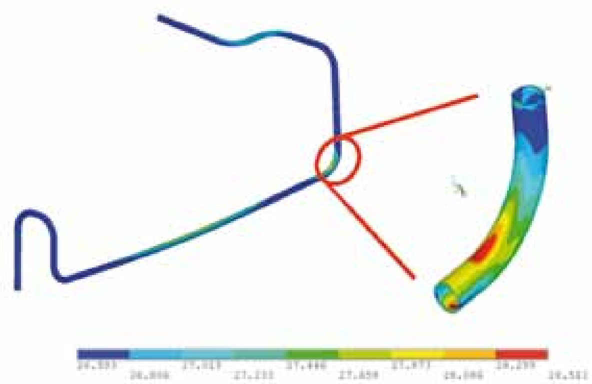


Figure 8: Stress model of a pipe bent

This method allows reducing the computing time on one hand because only the few interesting areas have a fine mesh. On the other hand it is often possible to calculate the stress state of the interesting parts with different sizes, shapes and locations of e.g. corrosion pits or wear without estimating the stress state of the pipe system again. This can be done if the attack due to corrosion or wear affects only the stress state of the detailed sub model.

4.3 Models for Limit States

Common guidelines provide models for limit states according to material properties which are used for the regarded components. These limit states do not include effects of corrosion and wear, what means that e.g. the impact of corrosion pits is exclusively regarded by evaluating the change of the stress state (Chapter 4.2). In the case of stress corrosion cracking the impact of hydrogen embrittlement was additionally integrated. This model bases on slow strain rate tests (SSRT) under corrosive conditions carried out by the project partner ISSV Hamburg. The test specimens are slowly strained and loaded with hydrogen until the rupture occurs. In this way the material strength depending on the hydrogen concentration is estimated .To calculate the local material strength at the crack tip a FEM model was developed to simulate the hydrogen distribution in the component. This FEM model is realized as a coupled field analyses in combination with the stress model of cracks and allows simulating crack growth [4, 6, 11, 12].

5 Embedment of the models in different configurations of piping systems

The loads on specific components result from the particular installation situation. According to this, the models have been connected to exemplary piping systems, consisting of pipes and multiphase-pumps. The connection of the pipes is based on the calculation of internal forces by tools from the employed FE-software. To calculate the service life of the piping system, a strength assessment for every employed component is performed using the new method explained above (Figure 5). Figure 9 shows an example of the interconnection for a simple piping system.

To connect local effects as such on the crack tip with those on the level of the piping system, the models use a multi scale approach. Table 3 displays the levels from the interconnection down to consideration of local attacks.

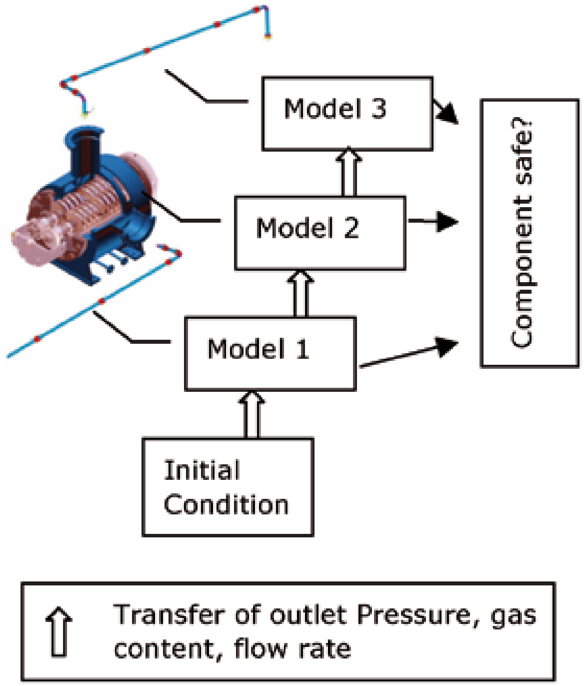


Figure 9: Interconnecting different models of components

Step	pipeline	tube	detail of a tube
Description	estimation of loads for single tubes	stress calculation considering global attack	stress calculation considering localized attack
Result		strength assessment considering global attack	strength assessment considering localized attack

Table 3: Multiscale approach of developed models

6 Studies of parameters to estimate mutable input variables

Based on the connected models of components as described in chapter 5, studies of parameters have been performed to figure out the influences of different parameters. These studies have been carried out on different levels, e.g. the examination of varied shapes of corrosion pits was made on component and on local level.

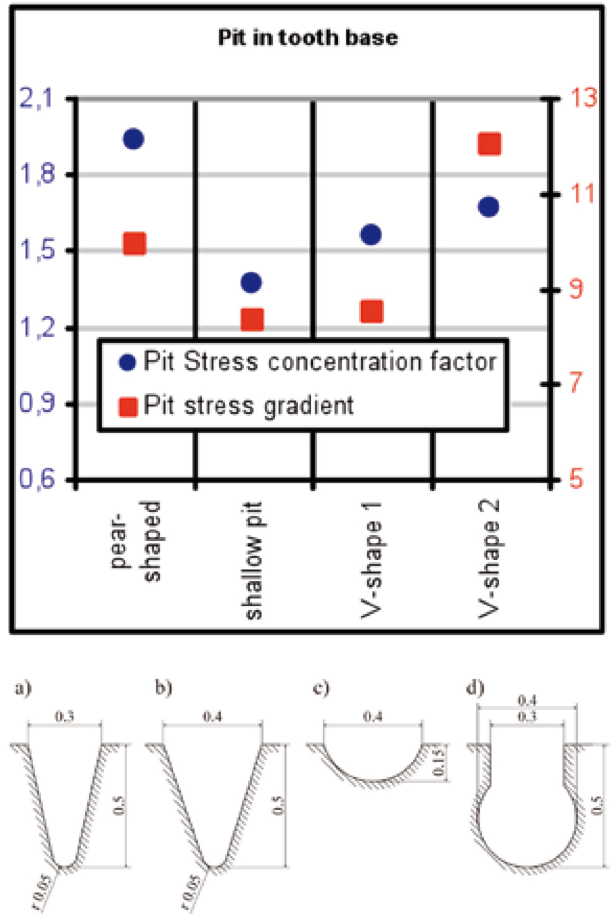
As a result there are different influences on strength assessment for each parameter. In pipes for example, wear causes decreasing of wall-thickness and increasing of stresses. On the other hand, wear has a positive effect on the strength of the screws of twin screw pumps because it leads to a decrease of loads. There are important influences on the strength of components for nearly every parameter, so that all of them have to be considered exactly within the design of a multiphase boosting system. Only the flow regime caused minor effects on the strength of components.

		tubes	conveyor screw	clamping nut
stress	static	+	0	+
	dynamic	0	+	0
	crack	+	0	+
pressure	maximum	+	+	+
	slug	0	0	0
corrosion	pit shape	0	+	0
	rate	+	+	+
wear	rate	+	-	0

\+ large impact (higher utilization)
\- small impact
0 large impact (less utilization)

Tab. 4: Overview on the study of parameters

As an example of the studies the consideration of different shapes of corrosion pits and the comparison of different kinds of loads are represented. In this analysis the wide range of possible pit shapes is put down to four basic geometries and compared in terms of their influence on strength.



a) V-shape 1, b) V-shape 2, c) shallow pit, d) pear-shaped

Figure 10: Stress concentration factors and stress gradients for variable shapes of corrosion pits [17]

The local stresses at the corrosion pit significantly depend on the shape of the pit. Figure 10 compares four corrosion pits with similar dimensions but different shapes. It becomes obvious that the general shape (pear-shape, V-shape) carries more weight than the specific details of the shape (V-shape 1, V-shape 2).

There is a substantial influence of the local stresses only in case of dynamic loads, because peaks in local stresses can cause the initiation of cracks. Dynamic loads let these cracks grow and can lead to a rupture of the component.

In case of static loads the plastification of whole sections is essential, the distribution of local stresses at the pit is less important. Therefore it is a suitable approach to consider corrosions pits as simplified geometries as shown in figure 12.

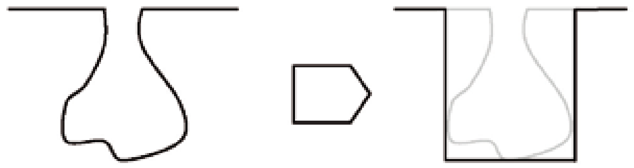


Figure. 12: Reduction of the real pit-shape to a simplified geometry in the static strength assessment

In regard to the strength-assessment of pipes several load cases in combination with different pit shapes and materials have been calculated. The load cases were combined of static loads and additional pulsating loads. For each combination it was checked which component of the load (static, dynamic, stress induced cracks) caused the calculative end of lifetime. The calculations pointed out that the dynamic loads don't determine the end of lifetime even for extreme combinations. Static loads in combination with large-area attack and local attack together with stress corrosion cracking have a greater impact.

7 Conclusions

The paper presents a new method for a strength assessment incorporating the effects of corrosion and wear. In order to handle the large number of different types of corrosion and wear, they are separated due to the kind of attack of the surface. The two major kinds are the localized and the global attack. Once separated, the effects can be implemented in a strength assessment. This has been carried out to several components of a multiphase boosting system in combination with a variation of the input parameters material, corrosion rate, pit shape and process data.

The paper presents a reasonable approach as a first step to incorporate corrosion effects and wear in the design process of components with manageable effort. This entitles the manufacturer to account for the customer's individual requirements more specifically and therefore build components more specifically and cost-effectively, as global safety margins which up to now cover possible but unknown corrosion effects may be reduced. However, further investigations have to be carried out on the one hand to make the results of the new approach become more accurate and on the other hand to simplify the necessary calculations without loosing accuracy.

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