FATIGUE ANALYSIS OF CENTRIFUGAL PUMPING EQUIPEMENT IMPELLER WITH FE-SAFE AND ABAQUS

S. Tropkin[1], A. Winkler[2], A, Devyatov[1], M. Zakirnichanya[1], R. Tlyasheva[1]
1 - Ufa State Petroleum Technological University
2 - Dassault Systemes EuroNordics AB

Abstract: *Pumping equipment is used in oil refining plants to pump oil distillation products. This equipment has to withstand heavy combined hydrodynamic and thermal loads, and recently been reported to fail due to fatigue damage. The main problem appears to be crack growth on peripheral wheel parts. The wheel sustains fatigue damage in an accumulation period which is shorter than the maintenance period recommended by the manufacturer. A study of the wheel fatigue life has been conducted. A material investigation was also carried out to verify that the damage had indeed been caused by fatigue. An analytical solution developed is viable for crack growth study only, and cannot predict fatigue life. To determine the fatigue life of the wheel, it is necessary to perform several analysis steps; first, an analysis of loads acting on the wheel based on CFD was performed using the FlowVision software. Following this step, the deduced load and time distribution was mapped to Abaqus/Standard to produce the stress state of the wheel. As a final step, the Abaqus stress field was used with fe-safe to predict the life of the wheel to crack initiation, which can be used to determine the correct maintenance interval for the pumping equipment.*

Keywords: fatigue, abaqus, fe-safe, oil&gas, pumping equipement

1. Introduction

Centrifugal pumps are one of the most commonly used equipment in oil refining plants to pump oil distillation products. Fatigue and damage tolerance properties of such equipment are factors that influence the total reliability of the technological processes and efficiency in oil & gas refining plants.

In the operation process, parts of pumps assembly have to withstand heavy combined hydrodynamic and thermal loading, and their structural integrity gradually decreases. This leads to extensive fatigue damage to the pumping equipment, which need to be analyzed. Statistical analysis in [1,2] shows that 90% of all fracture cases in pumping equipment are caused by fatigue damage due to cyclic loading. In [1,2] it is also described that cyclic loading caused the change of hydrodynamic flow, which significantly increased the load influence on the hydraulic part of the pumping equipment.

The impeller is one of the pumping equipment main parts, one of the most loaded details. Dynamical thermal and pressure loading on rotating impeller may lead to fatigue damage.

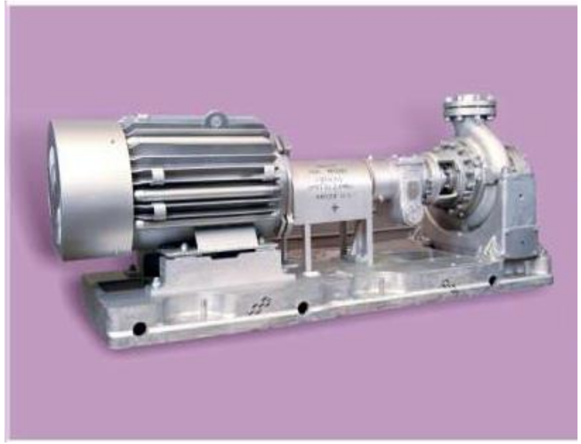


Figure 1. Pumping equipement. Design and draft.

Fatigue damage usually appear on the impeller as crack growth on peripheral parts and damages in cleaved facet form – see Figure 2. One of the most commonly used pumps, NK 210/200, sustains fatigue damage in an accumulation period, which is shorter than the maintenance period recommended by manufacturer.

Figure 2. Fatigue crack and damage on an NK210/200 impeller.

The general design rule is that impellers must be replaced at every maintenance occasion. Very often though, they have been reported to break down before the maintenance is due. This in turn leads to emergency pump stop, and may severely damages other equipment involved further along in the production chain.

An extensive study of the NK210/200 impeller was conducted [3], and the derived methodology allows for analyzing the durability of the impeller until it fractures. The method produces a prediction of the times until wheel fracture for different loads. Being based on field failures, the method becomes applicable to every day duty load analysis. However, the following shortcomings need to be mentioned:

- The method only shows the life to complete wheel fracture. It cannot predict the life until crack initiation.
- The locations of crack initiation sites cannot be predicted before the real life test.
- The method cannot be used for design improvements to achieve longer fatigue lives.

The aim of the research presented in this paper is to provide and test a methodology of impeller fatigue analysis, which can be used to determine the time of until crack initiation, and provide a verified tool which can be used in pumping equipment design process.

2. Research method

In [3] a methodology for fatigue life prediction of impeller was developed. The Methodology consist of the following steps:

1. Pump equipment operation loads analysis
2. Study of the mechanical properties of the impeller material
3. CFD analysis of the wheel operating conditions
4. FEA of the wheel stress state
5. Analytical estimation of the fatigue life

In the first step, technological records were analyzed to achieve the statistics of changes in loading. After this, the most common loading rates were determined. Usual pumping capacity varies from 18 to 98 m^3/h.

In the second step, an extensive material study was made. Digital microscopy was used to assess the origin of high cycle fatigue cracks that had developed in the wheel. Hardness measurements were used to determine stress, fatigue properties and mechanical properties of the wheel before and after its duty cycle. The study showed that the impeller could withstand the fatigue damage without abrasion or any other damage type. Collated results are presented in Figure 3.

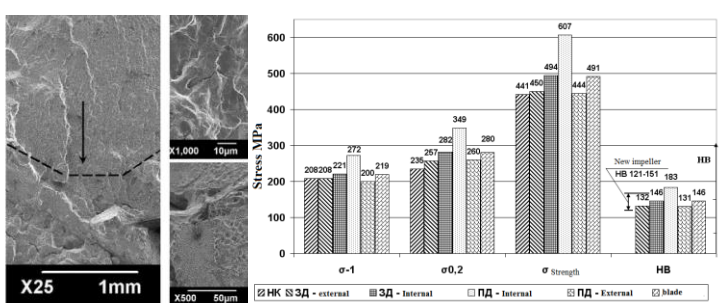


Figure 3. Fatigue damage study with digital microscope and Hardness measurement in different points of wheel.

To deduce fatigue properties of the material, one designated impeller was used to cut the test specimens from, and fatigue testing of the material conducted to produce an S-N curve. The testing adhered to the GOST 25.502-79 standard, the endurance limit defined as the stress level at 10^7 cycles of symmetrical loading. The endurance limit achieved in the tests was 206 MPa.

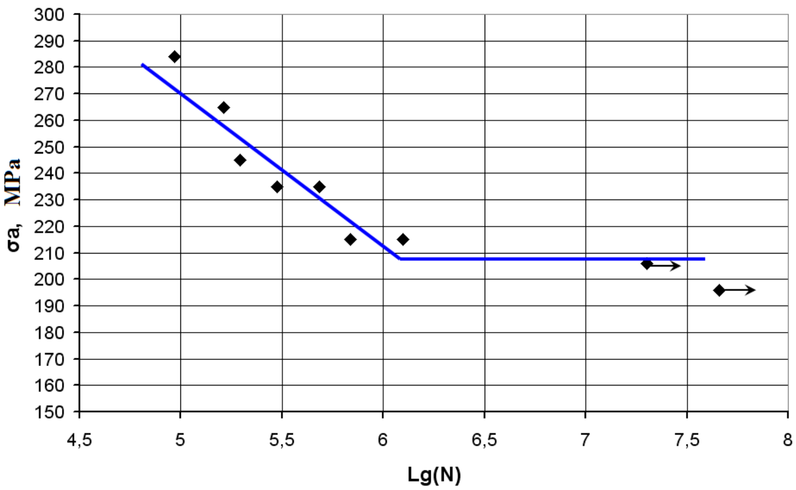


Figure 5. S-N curve of wheel material.

In the third step, a CFD study in FlowVision was conducted to produce the pressure loading history of the impeller. Study of incompressive flow of tar was performed. The analysis showed that the pressure distribution on the impeller depends on the blade position. Figure 6 shows the eight different blade positions, and maximum pressure values at the external impeller radii are shown in the graph.

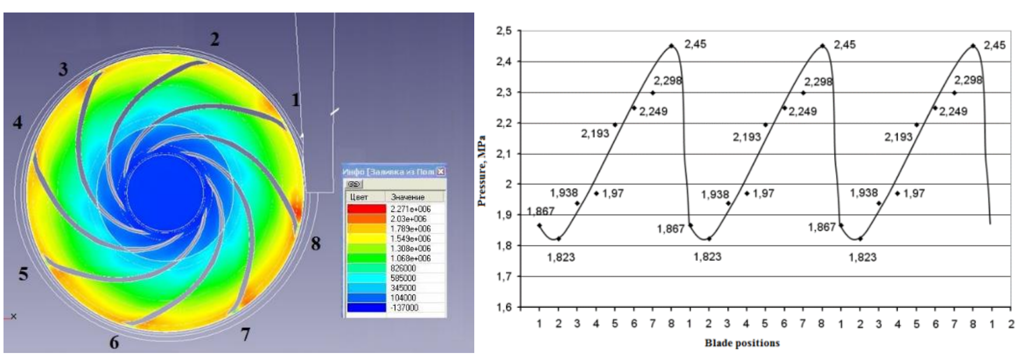


Figure 6. CFD pressure (Pa) distribution study on impeller surfaces for pumping capacity of 44,9 m^3/h.

In the fourth step the extracted pressure distribution due to hydrodynamic forces is mapped to an Abaqus model. The structural analysis consists of eight steps to simulate a full rotation of the impeller, which is loaded by pressure forces and the centrifugal force of 308 rad/s (2950 rpm). A static analysis with nlgeom=on and material model with plasticity was performed.

The resulting stress field shows that impeller did not experience plastic strains, and operates at elastic stresses with a maximum of 146 MPa. The eight solutions provide a stress history of the duty cycle, which will be used later for fatigue analysis in fe-safe.

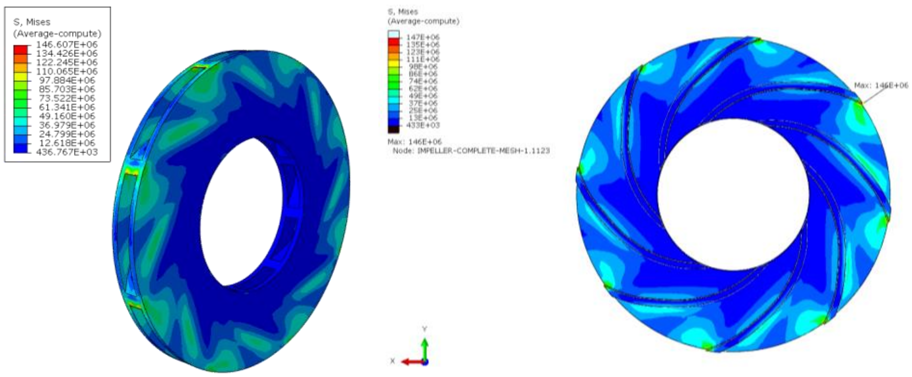


Figure 8. Stress (Pa) distribution analysis with Abaqus.

The study referred to in [3] provides an analytical solution with a chart (see Figure 9) that shows the stress levels on the impeller, which eventually lead to component fracture. The statistical information on impeller fracture yields a range from 2094 hours to 5804 hours.

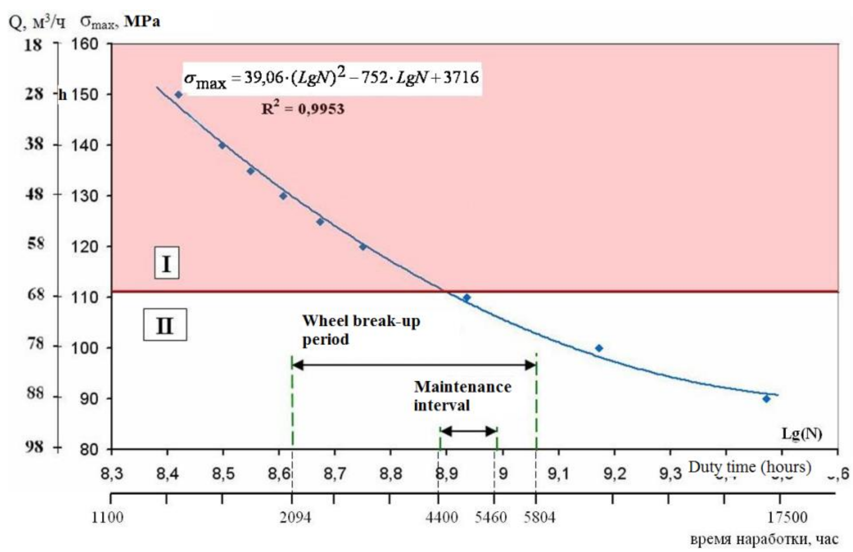


Figure 9. Wheel life chart.

In the fifth step, a fatigue analysis of the impeller was conducted in fe-safe. From a general point of view, the main difficulties encountered were:

- Obtaining reliable material data
- Understanding the manufacturing process
    - Material properties differ with each batch
    - Surface roughness is different on different areas
    - Residual stresses arise from the casting process
    - Flaws can never entirely be avoided and their locations are very hard to determine
- Recording the true duty cycle and creating a valid representation for fatigue life prediction
- Understanding the loading situation in the field

The scope of this research could not cover all of the influences mentioned above. Therefore, work was focused on obtaining viable material data and investigating the influence of surface finish (as a result of the casting process).

The steel has been specified as 25L, with a chemical composition as listed in Table 1 below. The data was acquired from the Database of Steels and Alloys (www.splav.kharkov.com).

C	Si	Mn	S	P
0.22 – 0.30	0.20 – 0.52	0.45 – 0.90	Max. 0.06	Max. 0.06

Table 1. Chemical composition for non-alloy cast steel 25L

This data made it possible to pinpoint an equivalent material, SC1025 65-35. The strain-life diagram for this material is shown in Figure 10. It is worth noting that the data presented in this diagram was reported as load controlled tests with repeats recorded until fracture, not crack initiation. The diagram is thus representative for analyses where the target is to eliminate premature fracture due to fatigue.

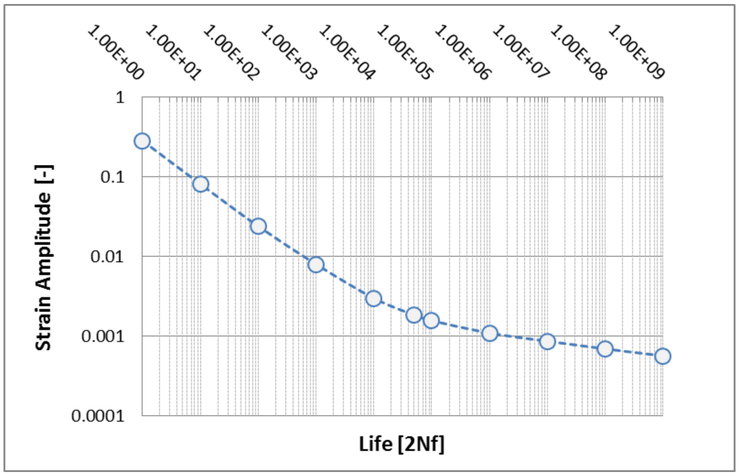


Figure 10. Strain-life diagram for 25L equivalent SC1025 65-35

The strain-life data in figure 10 was used in the subsequent fatigue analysis. The analysis was only performed for one load scenario, with a maximum pressure load level of 2.45 MPa. In total, results from 8 different load steps were used to define the history of the stress tensor.

The result of the surface finish sensitivity study is presented in Figure 11.

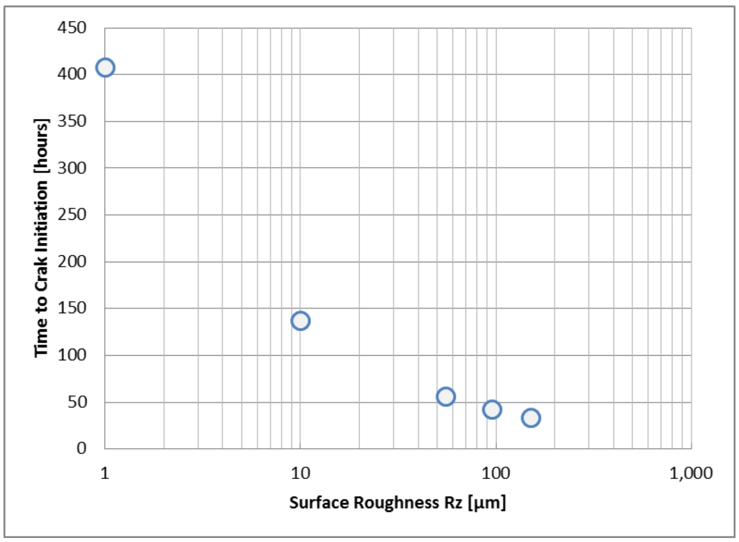


Figure 11. Time to crack Initiation as a function of surface roughness.

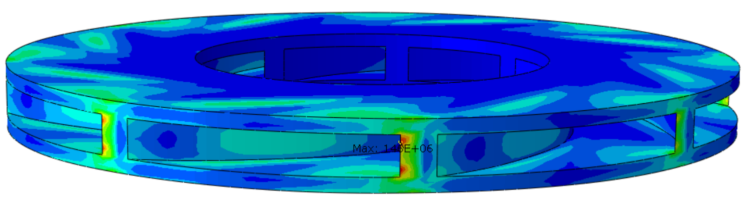
The nonlinear decrease in time until crack initiation with increasing surface roughness is distinctive. The references for the different surface finish values are presented in Table 2. The reference serves the purpose of further illustrating the influence choosing a certain casting process has on the component fatigue life performance.

Manufacturing Process	Mean Surface Roughness Rz [µm]	Predicted life to crack initiation [hours]
Pressure Casting	55	57
Chill Casting	95	42
Sand Casting	150	34

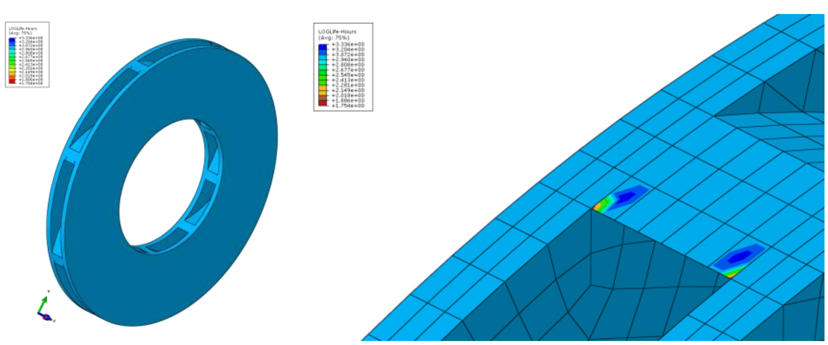
Table 2. Representative roughness values for different casting processes [4]

The duty cycle analysis predicts 1754 hours until fracture. This value falls slightly conservative of the lowest amount of duty cycles reported for impeller fracture, which was 2094 hours. As such, the result is satisfactory.

One of the key differentiators in fe-safe is the accurate crack initiation site prediction. Recall the von Mises stress distribution from step six. Note that the maximum stress is not located directly in the radii (the radii have not been modeled for simplification reasons). Fe-safe predicts that the crack will initiate in the corners, not at the point of maximum stress – see Figure 12.



Stress concentrations



Crack initiation points

Figure 12. Fatigue life analysis after post-processing in fe-safe.

The final and most important question to ask at this stage is: How much do the stresses need to be reduced for the component to last a certain life? The output variable FRF (Fatigue Reserve Factor) tells the user how much margin or deficit the component currently has with respect to a desired fatigue life – for example 2E7 repeats. In this particular case, the corners display an FRF value of 0.774. The component is therefore deemed to be under-designed – see Figure 13.

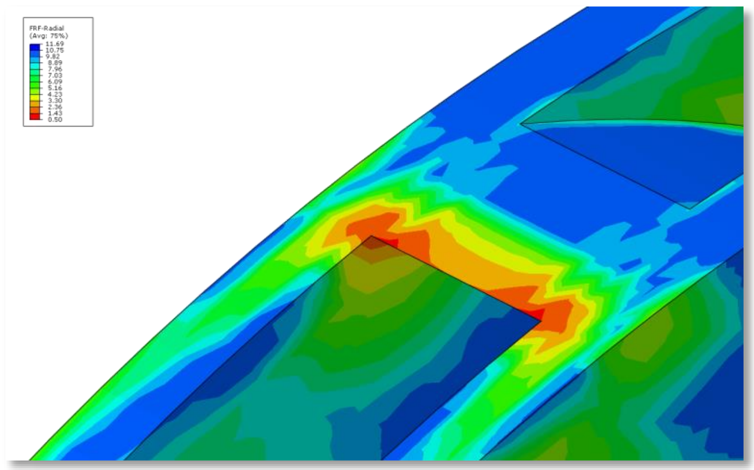


Figure 13. Resultant FRF values at critical locations in the analysed component.

The measures to improve the fatigue life would thus be to either:

- Downscale the loading accordingly.
- Alter the geometry if possible.
- Switch to a different material.

Of the above, changing the design, followed by possibly considering an alternative material are the two most likely actions to be undertaken.

3. Conclusions

Based on the work undertaken in this research, the following observations have been made:

- The life to crack initiation is much shorter than the life to component fracture, as was expected.
- fe-safe correctly predicted the crack initiation sites and also achieved correlation with the lower end of test results in the statistical fracture range.
- Surface finish plays a major role in controlling the life until crack initiation.

The main challenges encountered, which also offer opportunities for future research are:

- Hard to obtain strain-life properties for the specific steel
- No manufacturing data available (process-induced material properties)
- No technical draft data available (tolerances, surface roughness etc.)

The presented methodology shows, that the combination of modern numerical analysis software packages is capable of predicting results that fall very close to the real component life. The solution workflow will allow designers and simulation engineers to perform analyses of new designs and correctly predict crack initiation sites and maintenance intervals.

Future work has been planned to investigate automating the methodology with Isight, to provide a tool which can analyze and optimize both the geometry and fatigue properties of the components. An example model of the impeller with added detail is shown in Figure 13.

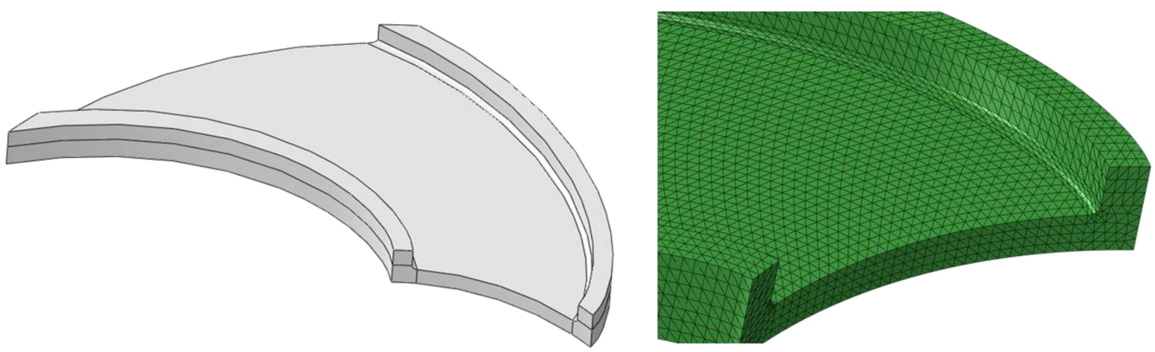


Figure 13. Impeller section geometry with added features and corresponding structural analysis mesh.

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