High cycle fatigue properties of stainless martensitic chromium steel springs

Pouyan Pirouznia

Feb 2012

Summary

For many materials and components like in high speed trains and airplanes fatigue failures occur in the range of over $10^7$ load cycles which is called the high cycle fatigue range. A modern version of the springs was invented which are applied in a certain application.

Ultrasonic fatigue testing (20 kHz machine) was conducted for evaluating the steel of the springs. This research explores the fundamental understanding of high cycle fatigue testing of strip steel and assesses a stainless martensitic chromium steel at the high cycle fatigue range. Finite element modeling was conducted to gain knowledge about the effect of various parameters. Significant attention was devoted to the fatigue failure initiations by SEM/EDS.

The work demonstrated that the method of investigation for high cycle fatigue test is reliable. Fatigue failure at this range was initiated by internal defects which all included non-metallic inclusion. A critical distance was defined within the strip fatigue specimen where all the fatigue failure initiated. The 3D stress field in the specimen was determined by FEM modeling and the local applied stress at the whole of the flat part of specimen and critical distance was estimated. FEM was also employed to give additional information about the effect of parameters. It was established that damping had the largest influence. The local applied stress of the fatigue test was calculated by means of FEM and SEM analysis. It was used to adjust the S-N curve which resulted in 15% lower values than the nominal applied stress.
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1 Introduction
Over 20 billion cycles of fatigue life is required for stainless martensitic chromium steel which is used as a spring. Therefore, for investigation on fatigue properties of this steel due to the high time consumption of conventional fatigue test, ultrasonic testing was conducted for this project.

1.1 Goals of study
The fundamental aim of this research was to obtain knowledge about high cycle fatigue testing and the 20kHz ultrasonic fatigue test machine for evaluating a stainless martensitic chromium steel in the high cycle range. In this thesis various parameters which could affect fatigue properties were investigated by finite element modeling of ultrasonic fatigue test (20 kHz fatigue test machine). By using FEM modeling the stress distribution could be determined which could help to estimate the local stress at internal defects initiating failure. Such a local stress could be used to correct the S-N fatigue curve for design purpose.

2 Method of investigation
This research is mainly based on literature review and finite element modeling. Regarding to find a correlation between simulation and fatigue failure, investigations of inclusions were also conducted.

2.1 Reconnaissance of key issue
By considering several scientific articles provided by KTH and Sandvik AB library, the key issues of this research were identified. Understanding of high cycle fatigue tests and its parameters were considered as the main aim of this project. During the investigations, the local applied stress was found to be an essential parameter for predicting fatigue life.

For discovering the influence of parameters on high cycle fatigue tests and estimating the local applied stress, finite element modeling was applied.

2.2 Restriction of research
Lack of time was a main restriction for this study. Achieving a proper simulation of high cycle fatigue test can be called as a main difficulty of the project.

2.3 Outline of research
A short description of each chapter is presented below.

2.3.1 Chapter 3. A stainless martensitic chromium steel
This chapter includes a specification of a stainless martensitic chromium steel which is used as a spring. Mechanical properties of this material is demonstrated at this chapter.

2.3.2 Chapter 4. Very high cycle fatigue test
The characteristics of high cycle fatigue tests which include various definitions such as the ultrasonic fatigue test machine, damping effect, specimen design and stress distribution among the specimen are presented in chapter 4.
2.3.3 **Chapter 5. Inclusion investigation**

Due to proper finishing of the test specimen, fatigue failure at high cycle range is initiated by non-metallic inclusions[1][2][3]. Therefore investigating on specifications of inclusions is essential. The critical distance is introduced in chapter 5 which is a distance through the specimen where all the fatigue failure initiated.

2.3.4 **Chapter 6. Finite element modeling**

Chapter 6 contains finite element modeling of high cycle fatigue testing and the effect of some parameters such as temperature, damping and frequency.

The local applied stress, which is the one of main aims of this project, is described in this chapter.

3 **A stainless martensitic chromium steel**

The steel grade which is used as a spring is a high strength stainless martensitic chromium steel. Specimens are produced from 1 mm thickness strip in hardened and tempered condition.

By using different finishing processes, four different types of test specimens were produced as demonstrated by table 1.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD</td>
<td>Continuously hardened and tempered, polished surface and polished edges</td>
</tr>
<tr>
<td>TE</td>
<td>Continuously hardened and tempered, tumbled</td>
</tr>
<tr>
<td>TF</td>
<td>Continuously hardened and tempered, tumbled, shot peened</td>
</tr>
<tr>
<td>TG</td>
<td>Batch hardened and tempered, tumbled</td>
</tr>
</tbody>
</table>

Batch hardening involves longer austenitizing and slower quenching time which results in different microstructure. Details of the microstructure can be found in an internal Sandvik report (110697TE).

These specimens show different behavior from their hardness aspect where TG series, regarding to batch hardened process, indicates a higher value. Their differences is demonstrated by diagram 1.

![Hardness of a stainless martensitic chromium steel](image)
At the hardness investigation, for each test specimen, 20 locations were considered which is illustrated by figure 1.

![Figure 1](image1)

Material specification is shown by table 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Property</th>
<th>Unit</th>
<th>Average amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV-microhardness</td>
<td>hardness</td>
<td>HV</td>
<td>540</td>
</tr>
<tr>
<td>Tensile</td>
<td>Elasticity modulus (Room Temperature)</td>
<td>GPa</td>
<td>212</td>
</tr>
<tr>
<td>Tensile</td>
<td>tensile strength</td>
<td>MPa</td>
<td>1670</td>
</tr>
<tr>
<td>Tensile</td>
<td>elongation (A11,3)</td>
<td>%</td>
<td>7,4</td>
</tr>
<tr>
<td>Tensile</td>
<td>Poisson’s ratio</td>
<td></td>
<td>0,27</td>
</tr>
</tbody>
</table>
4 Very high cycle fatigue test

For many materials which are used in the industry, fatigue failure occurs in the range of over $10^7$ load cycles which is called the very high cycle fatigue range[3]. By performing very high cycle fatigue testing (by ultrasonic fatigue test), material is exposed to cyclic stressing. The fatigue limit of the material can be determined in a short time. This is the primary advantage of very high cycle fatigue tests. This test can be conducted to a large variation of materials such as plastics, glasses, ceramics and metallic material [4].

The frequency of ultrasonic fatigue testing ranges from 15 kHz to 30 kHz, with a typical frequency being 20 kHz [5]. Table 3 indicates the difference in time consumption between conventional and high cycle fatigue tests. Due to this difference, fatigue result isn’t achievable by conventional fatigue test at high cycle fatigue range.

<table>
<thead>
<tr>
<th>Number of cycles</th>
<th>Ultrasonic (20 kHz)</th>
<th>Conventional (100 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\approx 10^7$ cycles</td>
<td>$\approx 9$ minutes</td>
<td>$\approx 1$ day</td>
</tr>
<tr>
<td>$\approx 10^9$ cycles</td>
<td>$\approx 14$ hours</td>
<td>$\approx 4$ months</td>
</tr>
<tr>
<td>$\approx 10^{10}$ cycles</td>
<td>$\approx 6$ days</td>
<td>$\approx 3$ years</td>
</tr>
</tbody>
</table>

As an historical view, the first high cycle fatigue machine was constructed by Mason in 1950. With the development of computer science, several laboratories have produced their own machines and designed practical test procedures. Laboratories of Willertz in the US, Stanzl in Austria, Bathias in France, Ishii and Murakami in Japan and Puskar in Slovakia, are among leading laboratories in this field. For all of these laboratories some components are the same for all machines. The three most important ones are: a high frequency generator that generates 20 kHz sinusoidal electrical signals, a transducer that transforms the electrical signal into mechanical vibration and a control unit. The progress in ultrasonic testing, enable fatigue testing with variable amplitude loading conditions, at different temperatures and in variety of environments and it enables the evaluation of fatigue properties in terms of tensile, torsion, bending, or multiaxial loading[3][6].

4.1 High cycle fatigue test concepts

4.1.1 Load ratio

Different concepts are used during fatigue testing. The stress range, amplitude, mean stress and load ratio are defined by equations 1 through 4 [7].

\[
\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} \quad \text{Eq 1.}
\]

\[
\sigma_a = \frac{\Delta \sigma}{2} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \quad \text{Eq 2.}
\]

\[
\sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \quad \text{Eq 3.}
\]

\[
R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \quad \text{Eq 4.}
\]
Figure 2 illustrates the change in stress $\sigma$ during the time $t$. The load ratio for fully reversed loading, fatigue with zero minimum stress and for a pure static load test equal -1, 0 and 1 respectively [7].

![Figure 2. Change of stress during of the time](image)

The stresses for high cycle fatigue test which are calculated by an analytical solution [5] will be referred to as the nominal applied stress in this report.

4.1.2 Longitudinal and transverse wave

In high cycle fatigue test, an electrical signal causes mechanical vibration. An elastic wave which may exist in an elastic body is defined by a longitudinal and a transverse wave. Equations 5 and 6 reveal the velocity of wave propagation for longitudinal and transverse waves [5].

Longitudinal wave

$$c = \sqrt{\frac{E(1 - v)}{(1 + v)(1 - 2v)\rho}}$$

Eq 5.

Transverse wave

$$c = \frac{E}{\sqrt{2(1 + v)\rho}}$$

Eq 6.

$c$: Velocity

$E$: Elasticity modulus

$v$: Poisson’s ratio

$\rho$: Mass density

4.1.3 Damping

Damping is a material property which influences the energy dissipation[8]. During fatigue tests at 20 kHz frequency due to material damping, the amount of dissipated energy is considerable. This phenomenon makes a cooling system essential for ultrasonic fatigue test for keeping the temperature constant. Energy dissipation in a material is caused by damping which changes the driving force through each point of specimen.

However, in spite of a large amount of research, the understanding of damping mechanisms are still quite primitive because it is not in general clear which variables are relevant to determine the damping forces[8]. By far the most common parameter is called viscous damping. This was introduced by Rayleigh [9].
The equation of motion which is normally used at finite element modeling could be presented as in equation 7[1][10].

\[
[M]\ddot{U} + [C]\dot{U} + [K]U = F
\]

Eq 7.

| M: Mass matrix |
| C: Damping matrix |
| K: Stiffness matrix |
| F: External force |

Damping of material can be demonstrated by the Rayleigh parameter which is defined by two specific factors mass (\(\alpha\)) and stiffness factor (\(\beta\))[1][11]. Damping ratio \(\xi\) can be introduced by equation 8[1] in which \(\omega\) is angular velocity[1].

\[
\xi = \frac{\alpha}{2\omega} + \frac{\beta\omega}{2}
\]

Eq 8.

Stiffness proportional factor \(\beta\) is essential at high frequency and introduces the strain rate which can be considered as a relation between mechanical properties and damping [1][3][11].

The effect of damping was not considered for the analytical solution[5] which was performed for finding the nominal applied stress. The amplitude of stress can be influenced by the damping factor. By introducing material damping into the FEM modeling, the amplitude of stress decreased significantly[3].

4.2 High cycle fatigue test machine

4.2.1 Ultrasonic machine’s equipment

As stated at the beginning of this chapter, ultrasonic fatigue machines vary between laboratories however the three following components are common for all of them[5]:

1. A power generator that transforms the 50 or 60Hz voltage signal into an ultrasonic 20 kHz electrical sinusoidal signal.

2. A piezoelectric (or magnetostrictive) transducer excited by the power generator, which transforms the electrical signal into longitudinal ultrasonic waves and mechanical vibration of the same frequency.

3. An ultrasonic horn that amplifies the displacement coming from the transducer in order to obtain the required stress amplitude in the middle section of the specimen.

The function of the system is illustrated by figure 3 which is to make the specimen vibrate in ultrasonic resonance[3][5]. Propagation of longitudinal wave appeared by this manner.
A schematic view of an ultrasonic fatigue test system and the stress-displacement field resulting from ultrasonic resonance and wave propagation is revealed by figure 4.

The installation which is shown by figure 4 is set for fully reversed loading. Since the ultrasonic fatigue test was performed at tension-compression cycles (load ratio=-1) the highest amplitude of stress is obtained at the waist of the flat specimen which is connected to the machine at the horn. At this waist position the displacement is zero while at the ends of the flat specimen, this value
reaches its maximum. These three positions are the most important nodes during ultrasonic fatigue test in order to show the reliability of the test.

In order to obtain a positive load ratio, a second horn can be attached to the free end of the flat specimen[3][5].

At this research, R=-1 was applied to the ultrasonic fatigue machine.

4.2.2 Specimen design

“Waist” shape specimen have been used through the ultrasonic fatigue tests which were performed in this study. Its smallest cross-section had 3mm width. Figure 5 illustrates the schematic view of the specimen which was used in this study.

![Figure 5. Specimen used for ultrasonic fatigue test](image)

For specimens with different section size, the amplitude of stress and strain differ at each part. The resonance amplitude which is a function of specimen geometry normally is determined numerically[5]. Waist section was designed due to the maximum stress which is one of the most important characteristics of the high cycle fatigue test’s specimen.

Fine surface finishing was conducted to minimize surface defects which resulted in fatigue failure initiated by internal defects.

Overall, the specimen which is used at high cycle fatigue test should has two major specifications. A large volume of the specimen is desired in order to have a sufficient amount of inclusions. In addition the main aim of performing high cycle fatigue test should be fulfilled which is the investigation of material’s behavior at high cycle fatigue range.

4.3 Influence of non-metallic inclusion on fatigue failure

As mentioned above, by fine finishing procedure and reducing the number of surface defect, fatigue failure initiated from internal defects. Inclusions which are streaming from melting process are the main cause of fatigue failure.

According to previous studies on influence of inclusion size, there is a critical size for inclusions which for smaller than this value fatigue failure originates from the cluster of inclusions[12].

The value of critical size can be achieved by equation 9 [13].

\[
\phi_{c,in} = C \left( 1 + \frac{120}{H_v} \right)^6
\]

Eq 9.

Where \( \phi_{c,in} \) is the critical inclusion size(\( \mu m \)) and C is a constant which for surface, interior and subsurface inclusions are 0.813, 0.969, 0.528 respectively[13].
According to equation 9, the critical size for interior inclusions to cause fatigue failure with hardness 530 Hv is 3.3 μm. Therefore, the investigation of the size of inclusions in the specimen and in cast material is one of the most important tasks of this study.

The inclusion investigation was based on Swedish Standard (SS 11 11 16)[14]. Regarding to the experimental results and literature review, there are four common non-metallic type of inclusion which normally cause fatigue failure, demonstrated by table 4.

Table 4. Common non-metallic inclusions [15]

<table>
<thead>
<tr>
<th>Type of inclusions</th>
<th>Aluminum oxide $\text{Al}_2\text{O}_3$</th>
<th>Calcium aluminate $X \text{CaO} \cdot y \text{Al}_2\text{O}_3$</th>
<th>Manganese sulfide $\text{MnS}$</th>
<th>Titanium carbonitride $\text{Ti} (\text{C}, \text{N})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specifications</td>
<td>Brittle, irregular formed particles, fractured and stretched in rolling direction to stringers (B-type inclusions)</td>
<td>Finely divided, globular particles (D-type inclusions)</td>
<td>Separate in rolling direction, stretched particles</td>
<td>Separate, cubic particles</td>
</tr>
<tr>
<td>Source</td>
<td>Deoxidation and reoxidation products</td>
<td>Reaction product of residual oxygen content</td>
<td>Specified sulfur content</td>
<td>Impurity of raw materials</td>
</tr>
</tbody>
</table>
5 Inclusion Investigation

By careful finishing process of the specimens, surface crack initiation was prevented so that fatigue failure initiated from non-metallic inclusions from the melting process[1][2][3].

Therefore, analysis of inclusion parameters such as size, shape, amount and chemical composition was performed on specimens. This task was fulfilled by using LOM (Light Optical Microscopy) and SEM/EDS.

Finding the critical distance defined as the distance within which all fatigue failures initiated, was one key task for the inclusion investigation.

Due to finishing process four different types of specimen were available which were introduced in chapter 3 (TD, TE, TF, TG).

High cycle fatigue tests were performed on the four types of specimens and their results were used for further assessments.

Table 5 lists results of the high cycle fatigue tests. This table includes the amplitude of the nominal applied stress $S$ (MPa) and the number of cycles $N_f$ at which fatigue failure occurred (all from internal non-metallic inclusions).

<table>
<thead>
<tr>
<th>NO. specimen</th>
<th>Nominal applied stress $S$(MPa)</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD-4</td>
<td>$\sigma_o + 120$</td>
<td>4,89E+09</td>
</tr>
<tr>
<td>TD-10</td>
<td>$\sigma_o + 198$</td>
<td>9,70E+07</td>
</tr>
<tr>
<td>TD-18</td>
<td>$\sigma_o + 151$</td>
<td>3,04E+08</td>
</tr>
<tr>
<td>TD-34</td>
<td>$\sigma_o + 198$</td>
<td>1,75E+07</td>
</tr>
<tr>
<td>TE-2</td>
<td>$\sigma_o + 151$</td>
<td>7,91E+07</td>
</tr>
<tr>
<td>TE-6</td>
<td>$\sigma_o + 120$</td>
<td>3,89E+08</td>
</tr>
<tr>
<td>TE-7</td>
<td>$\sigma_o + 151$</td>
<td>3,80E+07</td>
</tr>
<tr>
<td>TE-10</td>
<td>$\sigma_o + 170$</td>
<td>1,16E+07</td>
</tr>
<tr>
<td>TF-1</td>
<td>$\sigma_o + 151$</td>
<td>1,16E+08</td>
</tr>
<tr>
<td>TF-2</td>
<td>$\sigma_o + 151$</td>
<td>3,61E+07</td>
</tr>
<tr>
<td>TF-4</td>
<td>$\sigma_o + 120$</td>
<td>5,84E+07</td>
</tr>
<tr>
<td>TF-6</td>
<td>$\sigma_o + 100$</td>
<td>1,75E+09</td>
</tr>
<tr>
<td>TF-8</td>
<td>$\sigma_o + 120$</td>
<td>2,31E+08</td>
</tr>
<tr>
<td>TG-12</td>
<td>$\sigma_o + 120$</td>
<td>8,49E+08</td>
</tr>
<tr>
<td>TG-16</td>
<td>$\sigma_o + 120$</td>
<td>2,76E+09</td>
</tr>
<tr>
<td>TG-18</td>
<td>$\sigma_o + 151$</td>
<td>2,01E+08</td>
</tr>
<tr>
<td>TG-19</td>
<td>$\sigma_o + 170$</td>
<td>3,98E+08</td>
</tr>
</tbody>
</table>
5.1 LOM analysis and Critical distance

Width of the fracture surface of specimens and their failure initiation position were studied by light optical microscopy. The width of the smallest section (the waist) of the specimen is $3 \pm 0.05$ mm.

By measuring all the fracture surfaces, the width was found to vary from 2,95 mm to 3,2 mm. The fracture surface of some specimens and their width are illustrated by figure 6.

![Fracture surfaces of three specimens](image)

(a) (b) (c)

Figure 6: Fracture surfaces of three specimens (a) TD-10 , $d = 3.17$ mm (b) TE-2, $d = 3.16$ mm (c) TE-7, $d = 3.02$

The latter width range shows that all of the inclusions that lead to fatigue failure were located between the middle plane (smallest area in waist part) which has 3mm width and a plane with 3,2mm width. In this research, this distance will be called the critical distance. By assuming the middle plane as an origin, the critical distance is defined between $\pm 2.3$mm height from origin. Figure 7 shows the critical distance at ultrasonic high cycle fatigue test. From numerical solution, the amount of volume which is defined by this distance is $13,1$mm$^3$. 
Table 6 shows the height value for desired plane from middle at critical distance which was obtained numerically.

<table>
<thead>
<tr>
<th>Height from middle (mm)</th>
<th>Width of desired plane (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,00</td>
<td>3,00</td>
</tr>
<tr>
<td>0,43</td>
<td>3,00</td>
</tr>
<tr>
<td>1,01</td>
<td>3,04</td>
</tr>
<tr>
<td>1,04</td>
<td>3,05</td>
</tr>
<tr>
<td>1,07</td>
<td>3,11</td>
</tr>
<tr>
<td>1,09</td>
<td>3,13</td>
</tr>
<tr>
<td>2,11</td>
<td>3,15</td>
</tr>
<tr>
<td>2,30</td>
<td>3,20</td>
</tr>
</tbody>
</table>

The place of failure initiation was determined also by LOM. The location of several inclusions which caused fatigue failure in the shape of “fish-eye” was investigated and a schematic view of them and the middle plane (waist part) of the specimen is indicated by figure 8. Some failures initiated from the surface defects rather than inclusion. Due to the symmetry of the specimen, the right part of the plane was rebounded to the left part.

Figure 7: Critical distance at ultrasonic high cycle fatigue test
The latter figure demonstrates that there is no apparent pattern of the inclusion distribution. Despite including various type of specimen, no difference is visible.

**5.2 SEM/EDS analysis**

By performing this method some specifications of inclusion such as size and chemical composition were studied. This investigation was performed on fracture surfaces of specimens which were exposed to high cycle fatigue test. A goal was to determine the number of inclusions corresponding to their size.

SEM/EDS was conducted to discover the number of non-metallic inclusions in the continuous cast material and the finished product. The finished product refers to the 1mm specimen achieved after rolling. The inclusion classification was based on Swedish Standard (SS 11 11 16)[14]. All the samples for SEM/EDS investigation were picked from two different heat (heat no. 525101 & 520428). Sampling were done at three positions for each, illustrated by figure 9.

Numerical calculations were performed for acquiring to the number of inclusions within the volume defined by the critical distance which was introduced at chapter 5.1.

Equation 10 was obtained mathematically and it was achieved from possibility of inclusion in a specific volume. It was used for converting the number of inclusions in an area into the inclusions in a volume.
\[ N_a = d \times N_v \]
\[ N_a = \text{Number of inclusions per area} \]
\[ N_v = \text{Number of inclusions per volume} \]
\[ d = \sqrt{a \times b} \quad \text{a < range of inclusion's size < b} \]

5.2.1 Continuous cast material, Heat no.525101

Table 7 demonstrates the number of inclusions according to their classifications per cm² and cm³. Thereby it was possible to calculate also the number of inclusions within the volume defined by the critical distance. S1 and S6 corresponds to the smallest inclusion size and the largest.

<table>
<thead>
<tr>
<th>Classification of the inclusions</th>
<th>Number of inclusions/cm²</th>
<th>Number of inclusions/cm³</th>
<th>Number of inclusions/within the critical distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>410</td>
<td>4184639</td>
<td>54818</td>
</tr>
<tr>
<td>S2</td>
<td>678</td>
<td>3425421</td>
<td>44873</td>
</tr>
<tr>
<td>S3</td>
<td>172</td>
<td>442265</td>
<td>5793</td>
</tr>
<tr>
<td>S4</td>
<td>23</td>
<td>2973</td>
<td>38</td>
</tr>
<tr>
<td>S5</td>
<td>3</td>
<td>1699</td>
<td>22</td>
</tr>
<tr>
<td>S6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1278</td>
<td>8056998</td>
<td>105546</td>
</tr>
</tbody>
</table>

Inclusion distribution according to their hardness depicts by diagram 2 (a) and (b).

![Diagram 2: Oxide distribution](image)

(a) Class1 : S3, Class2 : S4, Class3 : S5  
(b) Class1 : S1, Class2 : S2

5.2.2 Finished product (Specimen) from heat no.525101

The number of inclusions in the finished product as a specimen is shown by table 8.

<table>
<thead>
<tr>
<th>Classification of the inclusions</th>
<th>Number of inclusions/Cm²</th>
<th>Number of inclusions/Cm³</th>
<th>Number of inclusions/within the critical distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>159</td>
<td>407977</td>
<td>5344</td>
</tr>
<tr>
<td>S4</td>
<td>10</td>
<td>12377</td>
<td>162</td>
</tr>
<tr>
<td>Total</td>
<td>169</td>
<td>420354</td>
<td>5505</td>
</tr>
</tbody>
</table>

Table 8: Number of inclusions in specimen that produced from heat no.525101
At this investigation there were not any inclusion with size over S4. The same oxide composition within the finished material were found compared with cast material. Hard oxides remained spherical while soft oxides were elongated and in some cases disappeared during cold rolling. The amount of soft oxide in the material after continuous casting was too small and after cold rolling, due to its shape, was not visible.

5.2.3 Continuous cast material, Heat no.520428

Another final material from continuous casting was investigated. By performing this survey, differences in the number of inclusions in different heats could be achieved. Table 9 shows the number of inclusions due to their classifications.

<table>
<thead>
<tr>
<th>Classification of the inclusions</th>
<th>Number of inclusions/cm²</th>
<th>Number of inclusions/cm³</th>
<th>Number of inclusions/within the critical distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>906</td>
<td>9247449</td>
<td>121141</td>
</tr>
<tr>
<td>S2</td>
<td>1047</td>
<td>5287247</td>
<td>69262</td>
</tr>
<tr>
<td>S3</td>
<td>620</td>
<td>1589046</td>
<td>20816</td>
</tr>
<tr>
<td>S4</td>
<td>131</td>
<td>16619</td>
<td>217</td>
</tr>
<tr>
<td>S5</td>
<td>4</td>
<td>2583</td>
<td>33</td>
</tr>
<tr>
<td>S6</td>
<td>1</td>
<td>296</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>2709</td>
<td>16143241</td>
<td>211476</td>
</tr>
</tbody>
</table>

The following diagram, diagram 3, illustrates the oxide inclusion distribution in the cast material according to their hardness.

![Diagram 3: Oxide distribution](image)

(a) Class1 : S3 , Class2 : S4 ,Class3: S5 (b) Class1 : S1 , Class2 : S2

5.2.4 Finished product (Specimen) from heat No.520428

Table 10 demonstrates the number of inclusions in the specimen which was produced from heat no.520428. According to table 10, inclusions with size over S4 were not found.
Table 10: Number of inclusions in specimen that produced from heat no.520428

<table>
<thead>
<tr>
<th>Classification of the inclusions</th>
<th>Number of inclusions/Cm²</th>
<th>Number of inclusions/Cm³</th>
<th>Number of inclusions/within the critical distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>60</td>
<td>153367</td>
<td>2009</td>
</tr>
<tr>
<td>S4</td>
<td>21</td>
<td>27209</td>
<td>356</td>
</tr>
<tr>
<td>Total</td>
<td>81</td>
<td>180576</td>
<td>2365</td>
</tr>
</tbody>
</table>

In the cast material significant amount of soft oxides are visible. On the other hand in the specimen the number of this oxide decreased apparently. This phenomenon occurred due to the cold rolling which soft oxides could be elongated and disappear gradually.

5.2.5 **Comparison between results of inclusion size distribution.**

For the comparison of inclusion size distribution see diagram 4.

The diagram for this material shows that the number of inclusions between S2 is the highest. According to upper graph, in the cast material of heat no.520428 more inclusions can be seen than in the other heat. However, in the specimen investigation the result was opposite. This was caused by the cold rolling. In heat 520428 the inclusions are softer which by cold rolling will elongate and vanish. Harder oxides were the main groups of inclusion in the final specimen. Apparently hard oxides are the common and soft oxides were elongated and deformed during cold rolling.

Within the critical distance of the specimen, there are apparently a significant number of oxides larger than the expected critical size. Therefore, for each specimen, fatigue failure is expected to initiate from the inclusion.

5.2.6 **Specification of inclusions**

Several fracture surfaces from each type of specimen were investigated by SEM/EDS analysis. Figure 10 shows an example for specimen TF8.
Specimen’s sort and its inclusion specifications is shown by table 11. It includes the normalized size of inclusion ($\sqrt{\text{Area}}$) and distance from surface.

<table>
<thead>
<tr>
<th>NO. specimen</th>
<th>$\sqrt{\text{Area}}$ normalized</th>
<th>Distance from surface (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF 1</td>
<td>1,25</td>
<td>127</td>
</tr>
<tr>
<td>TF 4</td>
<td>1,08</td>
<td>277</td>
</tr>
<tr>
<td>TF 6</td>
<td>1,77</td>
<td>300</td>
</tr>
<tr>
<td>TF 8</td>
<td>1,00</td>
<td>322</td>
</tr>
<tr>
<td>TF 9</td>
<td>0,75</td>
<td>155</td>
</tr>
<tr>
<td>TE 2</td>
<td>1,17</td>
<td>124</td>
</tr>
<tr>
<td>TE 6</td>
<td>1,93</td>
<td>106</td>
</tr>
<tr>
<td>TE 7</td>
<td>1,31</td>
<td>413</td>
</tr>
<tr>
<td>TE 10</td>
<td>2,00</td>
<td>290</td>
</tr>
<tr>
<td>TD 4</td>
<td>2,13</td>
<td>320</td>
</tr>
<tr>
<td>TD 10</td>
<td>1,68</td>
<td>330</td>
</tr>
<tr>
<td>TD 18</td>
<td>1,11</td>
<td>92</td>
</tr>
<tr>
<td>TD 34</td>
<td>0,86</td>
<td>38</td>
</tr>
<tr>
<td>TG 12</td>
<td>1,53</td>
<td>96</td>
</tr>
<tr>
<td>TG 16</td>
<td>0,64</td>
<td>34</td>
</tr>
<tr>
<td>TG 18</td>
<td>1,10</td>
<td>84</td>
</tr>
<tr>
<td>TG 19</td>
<td>1,38</td>
<td>166</td>
</tr>
</tbody>
</table>

The $\sqrt{\text{Area}}$ parameter was suggested by Murakami [16][17]. The fatigue strength of a material can be estimated by this model which is based on fracture mechanics. Murakami found that there is a strong correlation between the stress intensity threshold along the crack front and $\sqrt{\text{Area}}$ of initial inclusion[15][16]. Therefore, this model was studied in this research. The concept of area used in table 11 is the surface where the inclusion is located, surrounded by soft matrix.
6 Finite Element Modeling

By finite element modeling of ultrasonic fatigue test, various parameters that could affect fatigue properties like frequency, elasticity modulus (temperature effect), damping and specimen geometry were investigated. FEM modeling was employed to achieve the stress and strain distribution in the specimen which helps to estimate the local stress at the position of failure initiation.

A finite element modeling was performed by Marc advanced nonlinear & multiphysics software. The stress and strain distribution in the flat part of the specimen were the essential aims. While the design of screw and horn were complicated. Therefore modeling was performed only for the flat part of the specimen. Literature review of VHCF test shows that this test normally is performed at around 20 kHz natural frequency with the wave propagating from the top of the specimen[5][6]. The geometry of the specimen used in FEM modeling was obtained from the experimental specimen’s dimensions which has shown proper for achieving a resonant frequency of 20 kHz. The maximum amplitude of displacement was set to be 37.3 µm according to ultrasonic fatigue test experiment. Room temperature values for density and dynamic elasticity modulus (Young’s modulus) were used for the primary modeling but for further simulation, for finding their effect, their value had been changed. Other parameters such as Poisson’s ratio were adjusted according to material specifications demonstrated in Chapter 3. The load ratio was \( R = -1 \) and consequently, one side of the specimen should be fixed.

The damping effect on high cycle fatigue test was investigated with FEM modeling as well. Material damping could be added to modeling by the Rayleigh damping parameter defined by mass (\( \alpha \)) and stiffness factor (\( \beta \)). Stiffness proportional factor \( \beta \) is essential at high frequency and this value was set to be \( 10^{-5} \) according to experimental and literature findings[1].

The different types of specimens varied in edge appearance due to the different finishing processes illustrated by figure 11. Therefore, FEM modeling was conducted by design of flat part of specimen with sharp rectangular and rectangular with rounded edges cross-section, but the main focus of simulation was on flat part of specimen with rounded edges because most ultrasonic fatigue tests were performed on this kind of specimen. During the rest of the study, the rectangular with rounded edges is called the elliptical cross-section.

![Figure 11: cross-section of three different specimen at waist part](image)

For all of the following graphs, the numbers which are located inside of them are node numbers that had been used with the modeling program.
6.1 Modeling of elliptical and sharp rectangular cross-section specimen with one side wave propagation

The implication of modeling with one side wave propagation is that resonant frequency of 20kHz had been set into the flat part of the specimen from one side with 37.3µm displacement shown by figure 12.

![Diagram](https://example.com/diagram.png)

**Figure 12:** 20 kHz frequency from one side. d=37.3µm

### 6.1.1 Without damping effect

The effect of damping was neglected for this simulation. The principal stress distribution in the specimen with elliptical cross-section is illustrated by figure 13.

![Diagram](https://example.com/diagram.png)

**Figure 13:** Principal stress distribution for specimen with elliptical cross-section, without damping

According to figure 13 and experimental results from literature review[1], the maximum stress (723 MPa) is at the surface of the specimen in its smallest cross-section [1].
The gradient of stress is visible due to the waist shape of the smallest area. Figure 14 indicates the principal stress distribution in the specimen with rectangular cross-section.

However, the surface of the specimen at the waist part has a highest amplitude of local applied stress. The Gradient of stress at this part of the specimen in the rectangular cross section is demonstrated by figure 15.

The local applied stress amplitude in the rectangular cross-section is lower than in the elliptical one which is caused by the larger waist area. Furthermore, its value doesn’t resemble the experimental results. The same pattern of stress distribution was achieved for both types of cross-sections. In addition, ultrasonic fatigue tests mostly were performed on specimens with elliptical cross-sections. Based on this further simulation and investigation was performed only for the elliptical cross-section.
The displacement in the specimen with elliptical cross-section during $1.1 \times 10^{-4} \text{s}$ at three different points is illustrated by figure 16.

![Figure 16: Displacement of the specimen = $1.1 \times 10^{-4} \text{s}$, without damping](image)

The displacement curves for all positions are in phase and the specimen has a harmonic movement but they have different amplitude. In the middle point this value is near to zero (2.6 µm) and at the top node due to connecting to the source of wave propagation, the initial value of displacement had been applied. At the bottom point, amplitude of displacement is near to the top node (d=33.6µm) with the same phase but they have different direction which is expected from experimental tests and literature[1][3][5].

By considering figure 17, it was proven that the amplitude of displacement at different points of the specimen is not the same as the value of the top part of that. By moving from the middle part to the point with 5.6 mm distance, the displacement increased from 2.6µm to 13.1µm as well.
6.1.2 **With damping effect**

Damping is an essential factor in experimental ultrasonic fatigue test that generates energy[8]. By this simulation, the understanding of the damping effect and creating a model similar to experimental tests were our aims. In specific achieving the same maximum stress value in experiments and modeling was important.

The following figure, figure 18, indicates the displacement at different points of specimen.
The displacement curves are not in phase and the specimen doesn’t have harmonic and resonant movement. During tension and compression the top and bottom of the specimen are not moving at the same time which is the case in the experimental tests. In addition, the middle section of specimen should remain stable without any movement.

The damping force causes energy dissipation and this phenomenon appeared by phase differences and various values of displacement and decreasing the amount of maximum principle stress as well. As an evidence, each point has its unique displacement equation from which the second derivative implying acceleration is a function of F (Driving force). This different driving force for each point causes energy dissipation.

In addition, the screw part of the specimen can control damping and its effect. At the modeling part of this research, the screw was omitted due to its complication. Therefore, the damping shows its effect clearly.

Furthermore, a long computed time was needed for performing this modeling and the results and behavior of the specimen were not similar to experimental tests that have been done before.

For getting proper results and being reliable, modeling with two sides wave propagation was introduced for further investigations.

**6.2 Modeling of elliptical cross-section specimen with two sides wave propagation**

The aim of this modeling was solving the problems that occurred with one side wave propagation by means of adding resonant frequency of 20 kHz to the lower section of the specimen as shown by figure 19. The same initial value of
displacement (37.3µm) but in opposite direction from the top side was applied for achieving harmonic and resonant movement and proper displacement distribution through the specimen even with consideration of damping effect without the screw part of the specimen.

Figure 19: 20 kHz frequency from two sides. d=37.3µm for both

6.2.1 Without damping effect

For performing reliable FEM modeling similar to experimental ultrasonic fatigue tests, the concept of damping should be clarified and this purpose can be achieved by conducting modeling with and without the damping parameter. In this section FEM modeling without damping is analyzed. The Stress distribution through the specimen is represented by figure 20.

Figure 20: Principal stress distribution, two sides wave propagation, without damping
The highest range of stress is located at the waist part of the specimen and the highest amplitude is 762 MPa at its surface. The gradient of stress is illustrated by figure 21.

The top surface in figure 21 is the middle-plane of the specimen that involved the highest amplitude of principal stress. The stress varies almost 6% from the highest (762 MPa) to the lowest value (715 MPa) in this middle-plane section of the specimen.

During further investigation on this type of simulation, the strain distribution was studied through the specimen. This study will help to clarify the quality of tension and compression which help to predict the failure position. According to figure 22, four positions were chosen. The blue point was located at the center of the waist and yellow was at the top which according to the stress distribution in figure 20 has a minimum value.
Figure 22 illustrated that there is not any phase differences between different positions and harmonic displacement is expected. The locations with higher stress has a higher value of strain and vice versa. It is essential that the highest value in the strain diagram is not the highest value of strain in the whole of the specimen. Due to the waist part, a gradient of stress and strain exists which makes the highest value being located to its surface. The maximum strain rate can be calculated by using the first derivative of the highest strain equation (blue line in figure 22) demonstrated by (equations 11&12)

\[ \varepsilon = A \sin(\omega t) \quad \text{Eq 11.} \]

\[ \varepsilon = 35 \times 10^{-4} \sin(2\pi \times 2 \times 10^4 \times t) \]

\[ \dot{\varepsilon} = \frac{de}{dt} = A \cos(\omega t) \quad \text{Eq 12.} \]

\[ \dot{\varepsilon} = 439.6 \cos(2\pi \times 2 \times 10^4 \times t) \]

Furthermore, for each position, Hooke’s law (Equation 13) is valid. As an example according to the figure 21 for the middle point through specimen with 715MPa stress, due to Hooke’s law the strain value should be 0.337% and this conforms to figure 22.

Hooke’s Law

\[ \sigma = E \times \varepsilon \quad \text{Eq 13.} \]

\[ \begin{align*}
\sigma & : \text{Stress} \quad [\text{MPa}] \\
\varepsilon & : \text{Strain} \quad [\%] \\
E & : \text{Dynamic Elasticity modulus} \quad [\text{GPa}] 
\end{align*} \]

The strain distribution in figure 22 shows that the minimum value is located at the top and bottom of the specimen with the same phases which are set to the resonant frequency. Consequently the maximum tension-compression occurred at the waist section and harmonic movement was proven.

6.2.2 With damping effect

There are two purposes for conducting this simulation. By comparing this modeling to the simulation of the specimen without damping, the effect of damping could be investigated. Furthermore, as an essential aim, the most reliable and trustable simulation in comparison with experimental results, can be achieved by performing this type of modeling due to consideration of all parameters.

This modeling was performed by setting \( \beta = 10^{-5} \) as its stiffness factor in the modeling program. The following figure, figure 23 indicates the displacement of the top and bottom of the specimen.
The specimen has a resonant and proper motion in that tension-compression were applied in phase and with harmonic displacement. The principal stress distribution at the whole of the specimen and the gradient of stress in the waist part is illustrated by figure 24&25.

Figure 24: Principal stress distribution, two sides wave propagation, with damping
The proper stress distribution was achieved in that the maximum value of stress is located at the waist part of specimen. In this section, the gradient of stress is shown to vary from 621 MPa to 661 MPa (around 6%). Due to the symmetrical shape of the specimen the maximum amplitude of stress is seen at the surface sides of the waist section. In figure 26 the gradient of stress at half of the middle-plane (l = 1.5 mm) is demonstrated.

The same behavior of distribution occurred for strain with its maximum amplitude following Hook’s law. The strain gradient at the middle-plane of the specimen is shown by figure 27.
The highest amplitude of strain is 0.31% at the same position where the highest stress with value of 661 MPa was achieved. This behavior and value indicated that stress and strain have the same pattern and their maximum amplitudes are located at a position that theoretically and experiments was expected [1].

Figure 28 reveals the stress and strain distribution at different positions through the specimen at $10^{-4}$ s.
Both of them have an exact pattern and behavior. At each point, Hook’s law is also valid and they conform to that. An example of the symmetry at the specimen is shown by two points (red and white) which have the same distance from the middle. They show exactly the same stress and strain distributions, with the same amplitudes. Therefore, the red line is invisible because it is standing behind the white one.

The strain and strain rate equations for maximum (blue line) and minimum amplitude (turquoise line) according to equation 11 and 12 can be written in the following way.

\[ \varepsilon = 29 \times 10^{-4} \sin(2\pi \times 2 \times 10^4 \times t + 0.13\pi) \]  
Maximum amplitude

\[ \dot{\varepsilon} = 364.2 \cos(2\pi \times 2 \times 10^4 \times t + 0.13\pi) \]  

\[ \varepsilon = 2 \times 10^{-4} \sin(2\pi \times 2 \times 10^4 \times t) \]  
Minimum amplitude

\[ \dot{\varepsilon} = 25.12 \cos(2\pi \times 2 \times 10^4 \times t) \]

The maximum strain rate is 346.2 s\(^{-1}\) and the minimum is 25.12 s\(^{-1}\) corresponding to 0.29% and 0.02% strain. The stress and strain distributions for most of the points are in phase. The phase differences between nodes with highest and lowest amplitude is small(0.13\pi) which proportionally are located at the middle and top of the specimen. This small value occurred due to the damping factor as mentioned before but this effect is believed to be negligible.

This small value of phase differences shows that the specimen has a harmonic movement and it will not disturb the machine. Even by considering damping into this FEM modeling, proper and reliable results were achieved. Modeling by adding another source of wave propagation eliminated all the problems which had been caused by adding the damping factor and made our simulation similar to experimental results. Therefore, further investigations on the effect of other parameters like frequency and temperature were done according to this type of modeling.

6.3 Modeling of specimen with static force – Frequency effect

For finding the effect of the resonant frequency of 20kHz, modeling with static force was performed. The specimen was exposed to a tension force from two sides with 37.3\(\mu\)m displacement and thereby dynamic force caused by high frequency was neglected. The stress distribution along the specimen is shown by figure 29.
Figure 29: Modeling with static force, stress distribution \( d = 37.3 \mu m \)

The pattern of stress distribution along the specimen is the same with modeling of harmonic movement but the amplitude decreased (625 MPa) and compared to the max stress caused by dynamic force without damping (762 MPa).

This phenomenon can be clarified by the influence of frequency on dynamic force. The displacement at each point of the specimen is a function of a sinusoidal wave within a certain frequency. Dynamic force is proportional to mass and acceleration where acceleration is the second derivative of the displacement equation. Therefore, by increasing the frequency, the stress which is function of dynamic force, will increase proportionally.

\[ 6.4 \text{ Effect of temperature on amplitude of stress} \]

For simulating the effect of temperature on amplitude of stress, the elastic modulus was given three different values. A higher temperature leads to lower elasticity modulus due to lower strength at higher temperature.

As a result of performing modeling with various elasticity modulus (180, 200 and 220 GPa), it was shown that by increasing elasticity modulus the maximum amount of stress increased proportionally.

\[ 6.5 \text{ Effect of initial value of displacement on amplitude of stress} \]

Modeling with various initial value for displacement at the two ends of the specimen which are connected to 20 kHz resonance frequency were performed. According to modeling results by increasing the initial value of displacement, the stress amplitude at the middle of the specimen increased proportionally and shows a linear relation. Equation 14 is obtained from modeling (without damping).

\[ \sigma \text{ [MPa]} = 19.3 \times \text{displacement} [\mu m] \quad \text{Eq 14.} \]
6.6 Geometry of the specimen
Simulation of 20 kHz ultrasonic fatigue tests were performed for specimen with larger geometry. A lower stress amplitude was obtained which was due to smaller waist part of the specimen. By having larger specimen, the volume of material which is exposed to fatigue stress is increased, however a reliable result was not achieved.

6.7 Stress distribution in the volume defined by the critical distance
According to explanation in chapter 5-1 all the initiating inclusions were located in an area between the middle plane and a plane with 3,2 mm width located ±2,3 mm from the middle plane. During modeling with two sides wave propagation with damping which was the most trustable and reliable modeling, stress analysis was performed at this plane. The gradient of stress is illustrated by figure 30 at the plane with 3,2mm width.

![Figure 30: Stress distribution at plane with 3,2mm width, two sides wave propagation, with damping](image)

It is shown that the stress in this plane varies from 579 to 616 MPa and the stress gradient in the Z-direction (thickness direction) is negligible. The value for amplitude of the stress located in figure 30 is higher than the amplitude of stress at the plane with 3,2 mm width. This is because the program shows the highest number of this section of specimen where our desired plane is the top area of this figure and its value is smaller than the lower plane which is closer to middle-plane with highest amplitude.

The critical distance and the gradient of stress in the volume defined by the critical distance is demonstrated by figure 31 and 32. The maximum amplitude of stress is 662 MPa (illustrated by figure 25 also) located in the waist and the minimum is 579 MPa (figure 30).
Figure 31: The stress distribution in the volume defined by the critical distance.

Figure 32: 3D view of volume defined by the critical distance and its stress distribution

The stress gradient in the Z-direction is negligible and a constant value can be considered. This is due to the thin thickness of the specimen. Figure 33 shows the 3D view of the critical distance in the Z direction.
Figure 33: 3D view of volume defined by the critical distance in the Z direction (thickness)
7 Final results and discussion

The modeling and inclusion investigations were demonstrated in separate sections. More detailed results about them and final results of this research are presented in this section. Expressing the relation between modeling of high cycle fatigue test and inclusion studies are the most essential aim of this section. This relation can be expressed by finding the local applied stress which is the stress value at the location of inclusion and adjusting the S-N curve from nominal applied stress to local applied stress.

7.1 Critical distance and predicting the local applied stress

By considering fracture surfaces of high cycle fatigue tests the critical distance was found which was shown to contain a sufficient number of non-metallic inclusions. More focus was performed on this distance by modeling. The local applied stress distribution at this distance was demonstrated. According to FEM modeling results, at the critical distance, the amplitude of stress varied around 12.5% (662 to 579 MPa when applying 37.3µm initial displacement).

Due to the gradient of stress, the nominal applied stress should be replaced by a local applied stress for the position of the inclusion which initiated failure. As a main outgrowth of this study, by measuring the specimen’s fracture surface and determining the location of the inclusion, the local applied stress could be estimated which was lucrative for finding differences between local applied stress and the nominal applied stress in the S-N diagram.

By means of LOM the location of inclusion and width of the fracture surface were defined and by using this value and numerical solution the height of the desired plane from the middle plane (smallest area at waist part) was measured. The local applied stress distribution was investigated by modeling with two sides wave propagation, with damping effect. By knowing the height of the desired plane, the place of inclusion in this plane and figure 34, the amplitude of local applied stress for each inclusion could be estimated. Figure 34 is a stress distribution of the volume defined by the critical distance which was obtained from modeling with 37.3 µm initiated displacement amplitude.
Figure 34. Stress distribution and the height of critical distance.

The measured value for the local applied stress is valid for 37.3 µm as a displacement amplitude. For each specimen the nominal applied stress and the number of cycles obtained after high cycle fatigue test are known. Due to modeling, the value of stress was shown to have a linear relation to displacement value which has been set to the fatigue machine (equation 14 at chapter 6). Therefore, the amplitude of displacement can be calculated.

The local applied stress for each inclusion at 37.3 µm displacement was defined by modeling. In addition the real value of displacement for the test was clarified also. Therefore, according to the linear relation between displacement and stress, the local applied stress for each inclusion at the tested amplitude of displacement could be determined mathematically.

This research’s outcome was applied for the high cycle fatigue test result for finding a relation between S-N curve and the inclusion size. Table 12 indicates the specimen number, nominal applied stress S (MPa) and the number of cycles (N) at which failure occurred, normalized $\sqrt{\text{area}}$ of inclusion, width and height of the fracture surface from the middle plane.

Table 13 demonstrates the local applied stress achieved by comparison with modeling at 37.3 µm displacement and the nominal applied stress and this amount at the real tested displacement.

Equation 15 was used for converting the amplitude of stress at 37.3µm displacement to real displacement values.

$$\sigma_{\text{local stress}} \ [MPa] = \frac{d_{\text{desired}} [\mu m] \times \sigma_{\text{at 37.3}} [MPa]}{37.3}$$  \hspace{1cm} \text{Eq 15.}

$d_{\text{desired}} = $ Displacement of test according to high cycle fatigue test result stress
Table 12. High cycle fatigue test results

<table>
<thead>
<tr>
<th>NO. specimen</th>
<th>Nominal applied stress $S$(MPa)</th>
<th>$N_f$</th>
<th>Width(mm)</th>
<th>Height(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD-4</td>
<td>$a_0 + 120$</td>
<td>4,89E+09</td>
<td>2,13</td>
<td>3,13</td>
</tr>
<tr>
<td>TD-10</td>
<td>$a_0 + 198$</td>
<td>9,70E+07</td>
<td>1,68</td>
<td>3,17</td>
</tr>
<tr>
<td>TD-18</td>
<td>$a_0 + 151$</td>
<td>3,04E+08</td>
<td>1,11</td>
<td>3,05</td>
</tr>
<tr>
<td>TD-34</td>
<td>$a_0 + 198$</td>
<td>1,75E+07</td>
<td>0,86</td>
<td>3,04</td>
</tr>
<tr>
<td>TE-2</td>
<td>$a_0 + 151$</td>
<td>7,91E+07</td>
<td>1,17</td>
<td>3,17</td>
</tr>
<tr>
<td>TE-6</td>
<td>$a_0 + 120$</td>
<td>3,89E+08</td>
<td>1,93</td>
<td>3,10</td>
</tr>
<tr>
<td>TE-7</td>
<td>$a_0 + 151$</td>
<td>3,80E+07</td>
<td>1,31</td>
<td>3,02</td>
</tr>
<tr>
<td>TE-10</td>
<td>$a_0 + 170$</td>
<td>1,16E+07</td>
<td>2,00</td>
<td>2,97</td>
</tr>
<tr>
<td>TF-1</td>
<td>$a_0 + 151$</td>
<td>1,16E+08</td>
<td>1,25</td>
<td>3,09</td>
</tr>
<tr>
<td>TF-4</td>
<td>$a_0 + 151$</td>
<td>3,61E+07</td>
<td>1,08</td>
<td>3,00</td>
</tr>
<tr>
<td>TF-6</td>
<td>$a_0 + 120$</td>
<td>5,84E+07</td>
<td>1,77</td>
<td>3,06</td>
</tr>
<tr>
<td>TF-8</td>
<td>$a_0 + 100$</td>
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<td>1,00</td>
<td>3,04</td>
</tr>
<tr>
<td>TF-9</td>
<td>$a_0 + 120$</td>
<td>2,31E+08</td>
<td>0,75</td>
<td>3,07</td>
</tr>
<tr>
<td>TG-12</td>
<td>$a_0 + 120$</td>
<td>8,49E+08</td>
<td>1,53</td>
<td>3,03</td>
</tr>
<tr>
<td>TG-16</td>
<td>$a_0 + 120$</td>
<td>2,76E+09</td>
<td>0,64</td>
<td>3,06</td>
</tr>
<tr>
<td>TG-18</td>
<td>$a_0 + 151$</td>
<td>2,01E+08</td>
<td>1,10</td>
<td>2,97</td>
</tr>
<tr>
<td>TG-19</td>
<td>$a_0 + 170$</td>
<td>3,98E+08</td>
<td>1,36</td>
<td>3,06</td>
</tr>
</tbody>
</table>

Table 13. Values of local applied stress

<table>
<thead>
<tr>
<th>NO. specimen</th>
<th>Local applied stress by modeling at 37.3 µm displacement</th>
<th>Local applied stress by modeling at real tested displacement</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD-4</td>
<td>$a_0 + 120$</td>
<td>$a_0 + 34$</td>
<td>4,89E+09</td>
</tr>
<tr>
<td>TD-10</td>
<td>$a_0 + 96$</td>
<td>$a_0 + 78$</td>
<td>9,70E+07</td>
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<tr>
<td>TD-18</td>
<td>$a_0 + 131$</td>
<td>$a_0 + 70$</td>
<td>3,04E+08</td>
</tr>
<tr>
<td>TD-34</td>
<td>$a_0 + 145$</td>
<td>$a_0 + 125$</td>
<td>1,75E+07</td>
</tr>
<tr>
<td>TE-2</td>
<td>$a_0 + 107$</td>
<td>$a_0 + 48$</td>
<td>7,91E+07</td>
</tr>
<tr>
<td>TE-6</td>
<td>$a_0 + 145$</td>
<td>$a_0 + 55$</td>
<td>3,89E+08</td>
</tr>
<tr>
<td>TE-7</td>
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<td>$a_0 + 87$</td>
<td>3,80E+07</td>
</tr>
<tr>
<td>TE-10</td>
<td>$a_0 + 153$</td>
<td>$a_0 + 107$</td>
<td>1,16E+07</td>
</tr>
<tr>
<td>TF-1</td>
<td>$a_0 + 118$</td>
<td>$a_0 + 58$</td>
<td>1,16E+08</td>
</tr>
<tr>
<td>TF-4</td>
<td>$a_0 + 153$</td>
<td>$a_0 + 90$</td>
<td>3,61E+07</td>
</tr>
<tr>
<td>TF-6</td>
<td>$a_0 + 107$</td>
<td>$a_0 + 22$</td>
<td>5,84E+07</td>
</tr>
<tr>
<td>TF-8</td>
<td>$a_0 + 126$</td>
<td>$a_0 + 22$</td>
<td>1,75E+09</td>
</tr>
<tr>
<td>TF-9</td>
<td>$a_0 + 134$</td>
<td>$a_0 + 46$</td>
<td>2,31E+08</td>
</tr>
<tr>
<td>TG-12</td>
<td>$a_0 + 130$</td>
<td>$a_0 + 42$</td>
<td>8,49E+08</td>
</tr>
<tr>
<td>TG-16</td>
<td>$a_0 + 120$</td>
<td>$a_0 + 33$</td>
<td>2,76E+09</td>
</tr>
<tr>
<td>TG-18</td>
<td>$a_0 + 153$</td>
<td>$a_0 + 90$</td>
<td>2,01E+08</td>
</tr>
<tr>
<td>TG-19</td>
<td>$a_0 + 128$</td>
<td>$a_0 + 84$</td>
<td>3,98E+08</td>
</tr>
</tbody>
</table>
The differences in S-N curve by means of using local applied stress instead of nominal applied stress is shown by diagram 5.

It is shown that the local applied stress is significantly lower than the nominal applied stress which is used as a result of high cycle fatigue tests. This difference is about 100 MPa or 15%.

Therefore, for more accurate fatigue properties, the local applied stress should be more considered.

### 7.2 Modeling results

Modeling with two sides wave propagation and with damping effect was the most trustable simulation. A harmonic behavior of the specimen and proper stress and strain distributions were found by performing this modeling.

Due to the shape of the specimen, especially at the waist part, the gradient of stress and strain was apparent. The stress had its highest value at the middle plane of the specimen. In the mentioned plane, the stress varied up to 6% (621 to 661 MPa).

In the simulations because of the small thickness of the specimen, the value for principal stress which was used for all the results, was the same as the stress amplitude in the Y-direction. This result can be assumed as an evidence of accuracy of the simulation.
7.3 Influence of the other parameters on fatigue failure

Evaluation of some parameters that could affect the fatigue life is the aim of this part.

7.3.1 Inclusion size

The influence of the size of inclusion in the S-N curve was surveyed by means of the local applied stress. The variation of the size of the bubble in diagram 6 depicts the initiating inclusion size. The biggest bubble shows the largest inclusion which is related to TD-4 and the smallest is TG-16.

![Local stress and size distribution](image)

Diagram 6. S-N curve regarding to inclusion size distribution

According to literature[1] a higher number of cycles is needed for specimens with smaller inclusion initiating even though, according to the diagram this fact is not clearly distinguishable. Other parameters are of course of influence. Shape, composition of the inclusion, method of measurement of inclusion size, number of investigated specimens and local heating are expected to influence the result of this investigation.

7.3.2 Inclusion composition and distribution

The inclusion investigation showed that hard non-metallic inclusions were the main type of initiating inclusion in the high cycle fatigue tests. Intermediate and soft oxides were found also. A lower value of soft oxides was visible in the finished material (specimen) due to the large reduction during rolling.

An attempt was made to discover the effect of inclusion composition and its influence on the S-N curve but no influence was found.

The relation between the size of inclusion and the place was considered. It was assumed that by increasing the size of inclusion, depth of that into the material increased proportionally. This hypothesis was also not found to be fulfilled.
7.3.3 **Residual stress**

For finding a relation between inclusion position and local applied stress, the residual stress was studied at the surface of the specimens. The residual stress was determined at various depth by using different incident angle of the XRD. Diagram 7 shows the results of the residual stress test.

These points were located at 0.7, 5 and 10 µm depth from surface.

![Diagram 7. Amount of residual stress through 10µm depth](image)

TD type specimen shows a different behavior due to its polished finish. The other specimens were tumbled and compressive stresses increased through depth. From the diagram 7, it would be expected that fatigue failure initiated far from the surface however through all the fatigue failures which were investigated by LOM and SEM, some of the failures were located near to the surface. Therefore, distinguishable correlation between residual stress and location of inclusion were not found at tension compression fatigue tests.

Due to have balanced material, author predicts to have tensile stress at deeper area (> 10µm). figure 35 depicts author's assumption for distribution of residual stress through depth of specimen.
For being material stable, according to equilibrium equations, maximum compressive residual stress at specific area should be equal to maximum tensile residual stress. Therefore, value of tensile residual stress which can affect to the local applied stress is pint-sized. In conclusion, significant influence couldn't be found by residual stress.
8 Conclusions

At this research different aspects of high cycle fatigue test were studied. Understanding of high cycle fatigue test and its parameters as main goals of the research were fulfilled.

As the conclusions of this report, it can be noted that:

1. A method for high cycle fatigue testing on high strength martensitic chromium thin strip steel was investigated and found reliable.
2. The 3D stress field in a flat part of strip fatigue specimen was determined by harmonic FEM simulation, comprising a damping factor.
3. All internally initiated fatigue failures were found to be caused by non-metallic inclusion.
4. A critical distance was defined from the center of the strip fatigue specimen, within which all inclusion initiated failures occurred.
5. Significant number of hard oxide was observed in the test volume of high cycle fatigue test specimen which were in the size of initiating inclusion range.
6. The FEM simulated stress field was used together with the position of the initiating inclusions to calculate a local applied stress of fatigue test. This value was used to adjust the S-N curve.
7. The S-N curve based on the local applied stress calculated using damping is the best estimate of design data for the investigated strip steel used in a real application at any frequency.
8. Temperature, specimen design, damping parameters, frequency and initial displacement of specimen are the essential parameters for high cycle fatigue test.

9 Suggestions for future studies

For further works on this project and also on other similar cases, the following suggestions would be applicable:

1. 3D simulation of strip fatigue specimen comprising its screw part for studying the influence of screw through high cycle fatigue test.
2. More investigation on damping effect and estimating the exact number of damping parameters.
3. Further research on influence of rolling direction on fatigue properties of material.
4. Crack propagation mechanism within high cycle fatigue testing.
10 Acknowledgment

The author of this research would like to show his gratitude to Sandvik AB SMT R&D, Jörgen Westlinder specially Tomas Forsman as the project guide for providing a great opportunity to do this study work on ”High cycle fatigue properties of stainless martensitic chromium steel springs”. This research couldn’t have been done without his help and knowledge.

I would like to thank Mathias Hareland for help with the simulations and Vitaly Kazymyrovych.

Special thanks to my supervisor at KTH, Prof. Rolf Sandström with his useful advises during the period of my project work.

A lot of other persons at SMT helped me within different parts of this study and I sincerely thank all of them.
11 References


