Fatigue testing of scratched flapper valve steel

Utmattningsprovning av repat ventilstål

Vighneish Selvaraj Nadar
Abstract:

A flapper valve is made from a hardened and tempered high strength strip steel which opens and shuts as it is subjected to very high cyclic loads. Steel strip of which flapper valves are made from can encounter a surface defect which are anticipated to influence fatigue life negatively. In this study, the influence of surface scratches on fatigue life of flapper valve strip was investigated. The analysis was carried out by using thirty samples that were blanked out of eight different steel strips in the transverse direction. Of these samples, fifteen of them had scratches on the surface and fifteen did not, all these samples were fatigue tested by constant amplitude method. An S-N curve was plotted based upon the values and results from the fatigue test, considering the curve as the nerve center in relation with fractrographic studies using the Scanning electron microscope. Therefore this master thesis work aims to explain the influence of scratches on fatigue life of flapper valve strip and suggest future improvements based on the findings.
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Abbreviations:

U specimen: Test specimens without scratch.

M specimen: Test specimen with scratch.

M+ specimen: Test specimen having a scratch but not exactly at the centre of specimen.

Mnl scratch: Manually induced scratch on test specimen.

SEM: Scanning Electron microscope.

OM: Optical Microscope.

UHB: Bohler Uddeholm.
1 Introduction

Flapper valve strip is used in refrigerators, compressors, air conditioners and heat pumps. This stainless steel is manufactured in precision strips or coils which are then fabricated to a multitude of final products of which our focus is on “Flapper Valve”.

![Flapper valve strip steel](image)

**Figure 1 Flapper valve strip steel**

This valve steel component is required to work for long life times without failure. The main objective of this thesis work is to conduct fatigue life comparison between samples with and without scratches and then study the influence of these scratches on the fatigue life of the steel strip.

This thesis work is carried out with Bohler Uddeholm Precision Strip Steel AB, Sweden. The work material is martensitic stainless steel produced by Bohlers Uddeholm Precision Strip AB. The fatigue testing of these stainless steel was carried out at an associated lab.

1.1 Flapper valve

The valve strip in its production phase can experience a surface defect which may affect the performance of the end product- “Flapper valves”. These surface defects have been termed as “scratches” due to their slender appearance. Since they are quite difficult to identify during visual inspection, these scratches are thought to be a danger in relation to quality. These scratches can act as develop an initiation point for a fracture on flapper valve this will cause a breakdown of the unit within which it is installed. Scratches also lead to lower production yields due to scrapping of finished material affected by scratches.
1.1.1 Materials used to manufacture flapper valve:

Materials used to make flapper valves are numerous such as cast iron, carbon steel, stainless steel, special spring steels, bronze, metallic composites (stainless steel/ copper) and they can also be lined or coated with a metallic coating or synthetic rubber which covers the inner metallic part [1] [2] [3]. Hence a flapper valve may be used as a stand – alone metallic part or one with a cover of rubber or coatings. Though there may be various materials available for flapper valve ready forms of supply are stainless steel, bronze or carbon steel. Among these materials the most common grades are AISI 1095 type of carbon steel and AISI 420 type of martensitic stainless steel [4]. Our focus is upon a strip that is composed of high quality martensitic chromium stainless steel alloyed with molybdenum to give better corrosion resistance and higher fatigue strength resulting in a compressor with longer life.

1.1.2 Working conditions:

The working conditions of this type of valve material usually involve high pressure and corrosive environments. Steels are suitable for this application due to their high tensile strength, high fatigue strength under bending and impact stress conditions in addition to the enhanced corrosion resistance offered by presence of molybdenum.

1.1.3 Heat treatment:

A heat treatment process is done to give suitable microstructure resulting in optimum tensile, fatigue strength, high degree of flatness and an excellent surface finish through in – line polishing. Heat treatment is carried out in hardening and tempering furnaces with an intermediate lead bath for quenching.

1.1.4 Surface requirements:

The surfaces of these flapper valves need to be very smooth, brightly – polished, free from scratches and other detrimental surface defects. Fatigue fractures can initiate from surface imperfections and therefore they are controlled to reduce the risk of catastrophic failures. Unfortunately, these flapper valves can contain scratches and these scratches are predicted to be formed during the hardening process.
1.2 Fatigue:

Refrigerator, heat pump and air conditioning compressor manufactures are aiming for better energy efficiency paralleled with improvements in compression, volumetric and mechanical efficiency. When practical compressor tests were made it was certain that valve components are the most critically loaded compressor parts and their durability is dependent on fatigue properties of the whole valve system and applied stresses [5].

The efficiency of a valve in a compressor is affected by many factors like material, design of valve, loading geometry, ambient atmosphere etc. Studies of failed valves showed that most of valves failed due to fatigue [6]. Fatigue is the failure caused in a component as a result of cyclic stresses [7]. When a material is subjected to repeated load (cyclic) stresses below the ultimate tensile strength it results in a crack initiation and then propagation called fatigue [8].

![S-N curve (Wohler diagram)](image)

The life of compressor is influenced by various factors like valve material, design, treatment, geometrical factors i.e. area of contact at stop or area of valve seat, valve speed, displacement, Positioning between valve reed and valve seat (valve overhang) [5].

The applied load cycle is of various types. They are axial (tension-compression) where tensile stresses are usually considered to be positive and compressive stresses are considered negative, plain bending, rotating bending, torsional (twisting) and combined loads [9]. There are three basic factors necessary to cause fatigue 1. Maximum tensile stress of sufficiently high value, 2. Large
enough variation or fluctuation in applied stress, 3. Sufficiently large number of cycles of applied stress [10].

Figure 3. Fluctuating and reversed stress.
Fatigue causes brittle like failures in ductile materials with little plastic deformation occurring before fracture. The whole process occurs by the initiation and propagation of a crack and normally the fracture surface is close to the perpendicular direction of maximum tensile stress [8]. Failure does not occur when the component is loaded initially; instead, failure occurs when a certain number of similar load fluctuations have been experienced. The fatigue load can be fluctuating or reversed. Fluctuating bending is the most common in flapper valve applications.
Mean stress: \( S_m = \frac{s_{\text{max}} + s_{\text{min}}}{2} \)

Stress amplitude: \( S_a = \frac{s_{\text{max}} - s_{\text{min}}}{2} \)

Stress ratio: \( R_s = \frac{s_{\text{max}}}{s_{\text{min}}} \)

Range of stress: \( \Delta S = s_{\text{max}} - s_{\text{min}} \)

**Figure 4** Diagrammatic representation of cyclic loading and fatigue terms involved.

1.2.1 Impact and bending fatigue:

A Compressor valve is subjected to two types of fatigue loading namely bending and impact fatigue. Bending fatigue failure can be downplayed by designing the valve with minimized bending stress.

Impact fatigue is caused by constant, repeated impact against the seats and is characterized by tearing off chips from the edges.

**Figure 5.** Schematic representation of flapper valve.
Figure 6 Valve reed of refrigeration compressor after failure.

Impact fatigue life is affected by chemical composition of the steel. There is no correlation between static mechanical properties and impact strength. Tensile strength, surface condition and temperature show minor influence on impact fatigue strength. With the measurements of damping velocity, we can conclude that there is correlation between damping velocity and impact strength of martensitic steel [11].

For the creation of impact fatigue the fundamental importance is the obliquity of impact. Obliquity of impact is caused by flexural and torsional vibrations of specimen. These vibrations are damped in the steels which show high damping capacity and angle of obliquity will be small. This reveals that local, high impact stress peaks will be avoided, so the measured fatigue limit will be higher [11].

A large plastic zone is present in stainless steel UHB 716 relative to carbon steel UHB 20, so fatigue crack initiation at certain stress level will be more retarded in 716 than in 20, hence higher impact strength in 716. The primary fatigue crack was radially oriented and located outside the contact ring with the seat where mechanical load due to impact cannot be expected, this says that fatigue cracks were created by propagating stress waves [12].
1.2.2 Fatigue life:
Fatigue life is number of cycles to failure at a specified stress level, fatigue strength also called as endurance limit is the stress below which failure does not occur. As the applied stress level is decreased the number of cycles to failure increases. Normally fatigue strength increases as the static tensile strength increases [10].

Fatigue life ($N_f$) = Total fatigue cycles to failure or in words number of stress cycles at which fatigue failure occurs.

Total life = crack initiation + crack growth.

$$N_f = N_i + N_p$$

Crack initiation ($N_i$): it is the first stage, number of cycles required to initiate a crack. It is a result of dislocation pile-ups and/or imperfections such as surface scratches, voids.

Crack propagation ($N_p$): number of cycles required to grow the crack to a critical size in a stable manner. Generally controlled by stress level. Prediction of crack is one of the important aspects of fatigue because most of the materials contain flaws.

Fast fracture: when the crack length reaches a critical value ($a_c$), very rapid critical growth occurs. Since rapid fracture occurs instantaneously it’s not included in the fatigue life expression [8].

The duration of all the three phases depends upon various factors like fundamental raw material characteristics, orientation of applied stress, magnitude, processing history etc [7].

Some of metals for example: aluminium, austenitic stainless steel and copper do not typically have a standard endurance limit. For such materials the fatigue limit starts to increase as the stress level decreases [7]. The fatigue life of steel can be enhanced by introduction of residual compressive stress on its surface, when talking about flapper valve steel these compressive stresses are introduced by means of tumbling [13]. Fatigue life can be reduced by 10-50% if ferrite appears in the surface layer of the steel [14]. Surface properties and edge preparation are of vital importance of fatigue life of valves because all fatigue failures in reverse bending and tensile fatigue start from the specimen are from surface or the edge [15].
In high strength materials, when subjected to dynamic loading crack initiation takes the major part of the total fatigue life. This initiation stage depends on the stress field intensity at the tip of crack or defect. In reality, whenever the stress exceeds the yield strength of the material, a region of plasticity is created near the crack tip. The effective crack length will be equal to initial crack length and plastic zone radius.

A flapper valve with higher fatigue strength is a very important factor for compressor designs. Bending fatigue and impact fatigue strength are the most important properties for flapper valve. Flapper valve with high bending fatigue strength should possess high tensile strength and high ductility and the one with high impact fatigue strength should have high tensile, high ductility and high damping capacity [4]. Valves in actual operation are exposed to more of bending fatigue than tensile fatigue but why the latter is also important is the well defined state of stress in tension [15]. Degree of reduction of fatigue strength depends on the composition and condition of steel and also on the corrosive agent but is more pronounced, the higher the hardness [14].

1.3 Defects in flapper valves and their influence on fatigue life:
In valve compressors, fatigue fractures contribute a large proportion of the failures. A flapper valve practically contains external or internal defects which produce stress peaks. Surface scratches, rolling defects, blanking marks, structural inhomogeneities which are higher than stress that is experimentally measured on its surface, lead to the formation of fatigue crack or a fatigue cracking can also be initiated from local plastic deformation that is caused from the elevation of stress level at external or internal notch sites.

The initiation stage is considered to be at an end when crack growth is controlled by normal stress perpendicular to the plane of crack. After some point the fatigue crack grows up to a certain length where the fracture toughness of the material is reached and the valve breaks. Normally these fatigue failures must have been initiated from the defects that were created during the production of valve used in compressors which can be divided mainly into two stages as follows:

1. Bulk vs surface.

2. Manufacturing of steel vs fabrication of component.
The most severe and common ones are the defects originating from valve fabrication out of strip steel for example:

- Edge cracks
- Blanking marks and burrs.

Some defects serve as starting point for fatigue fracture and they occur on the surfaces like

- Corrosion pits
- Rolling defects
- Transverse scratches.

All these defects happen to occur on the surface, where the damaging effect of notch is the highest. Hard oxide inclusions were the crack starters of metallurgical origin, and these kinds of inclusions cannot be excluded completely. Higher service life of valve steel can be achieved by eliminating some of the severe defects [16].

1.3.1 Defects caused during the manufacturing of valve used in compressors:
As said earlier it can be divided into two stages,

1.3.1.1 Defects originating from strip manufacture:
Surface defects like scratches and rolling defects can affect the service life of a valve component. Fatigue fracture can be initiated from a longitudinal scratch if present and are perpendicular to the maximum stress under loading. Improper tumbling and also high operating stresses can also be a cause of fracture. The surface of a valve may also contain a rolling defect. Stable crack growth is always there in a failure which was caused by fatigue fracture that had started from rolling defects. Another cause of cracking which can be counted is a surface scratch; a heavy transverse scratch has a negative influence on service life.

1.3.1.2 Defects originated during fabrication of valve component:
Production of valve from a steel strip is accomplished by blanking. Usually a blanked edge contains cracks, burrs, jagged notches. Ineffective blanking may result in such defects reaching a size of 100 µm. Tumbling is done during which the surface of the valve, and the blanked edge are
improved along with surface roughness being reduced. Surface roughness is greater at edge and less on surfaces. Compressive stresses are also introduced that can reduce the applied tensile stress. The problem is because of the complex valve designs for example: slots or holes. It has been proven that refrigerator compressor valves without slots gave significantly longer service life than the modified compressor with slots. Slots or holes in the valve component which are made actually to reduce the flexural resistance of the component and tend to reduce the service life [16].

1.3.2 Way of loading and temperature:
Reversed load gives higher fatigue value than fluctuating load and fatigue strength under bending stress is higher than axial stress. Fatigue strength increases with declining temperature; this effect is small for high strength steels. As the temperature is lowered, the notch sensitivity rises [14].

1.3.3 Surface treatment and edge finish:
Fatigue strength can be increased or decreased by various types of surface treatments some of such are shot peening and tumbling depending on the material and surface treatments [13]. Even though shot peening and tumbling result in better state of surface stress and fatigue strength, they tend to cause a rough surface which in itself is a negative influence. An even, rounded edge is an advantage in terms of fatigue strength tumbling a valve after blanking is basically done to remove the burrs and scratches from the edge [14]. Rounding of the edges as a result of tumbling operation is very important because the probability of fracture initiation from the edge is evidently very high [15].

1.3.4 Residual stress:
The blanked edge has a residual tensile stress which is converted to compressive stress during the tumbling process because residual compressive stress on the surface can improve bending fatigue strength and can reduce tensile stress [14]. As said, compressive stress enhances fatigue strength while increased surface roughness and corrosion have negative effect [9]. As mentioned in the previous topic, compressive residual stresses with low stress relaxation rates and good surface finish can be introduced by various surface treatments for example tumbling and shot peening [13]. High compressive residual stress can enhance the resistance to crack initiation and propagation. The amount of residual stress introduced near the surface by tumbling or shot peening strongly depends on type and ductility of material and material conditions [4]. Tumbling gives
better bending fatigue properties than impact fatigue, this diminishing effect of tumbling of impact fatigue is because of small “penetration depth” of tumbling operation [17].

1.3.5 Shape of the test specimen:
The size of the component undergoing stress also has some consequences; the greater volume put under the same stress, the greater the probability of fracture initiation. Thin strips would be expected to exhibit much more fatigue strength than thicker strips at a prescribed tensile strength. Anyhow in practical application the thin valve are anticipated to present a more convoluted pattern of movement than a thick one, hence they suffer additional stresses that in turn produces a shorter life. Stress concentrations lead to reduction in fatigue strength [14].

1.3.6 Tensile properties:
Higher tensile strength equals higher fatigue strength [14]. As a general concept increase in tensile strength increases the defect sensitivity of a material. In the case of high strength steels, ductility is generally low and with increasing tensile strength it decreases further. Consequently this increases the localized stress concentrations around the defects, which may exceed the contribution of tensile strength. Therefore, an increase in tensile strength will obviously increase the overall fatigue load resistance which in turn increases the bending fatigue strength. Impact fatigue fracture is caused by transformed stress waves hence the increase in tensile strength will increase the impact fatigue strength [13].

1.3.7 Specimen orientation:
A sample banked out in the strip rolling direction will always display better fatigue strength than the one taken transversely. This may be sometimes because of slag inclusions, texture and surface topography. The difference in fatigue strength in both directions is approximately 5 % [14]. The texture in the strip material affects both E-modulus and tensile strength and since impact fatigue strength is related to tensile strength and E-modulus and bending fatigue strength is directly related to tensile strength. An increase in orientation angles shows a slight increase in bending and impact fatigue strength. When the specimen is oriented at an angle of 90°, one can expect a combination of greater impact and bending fatigue strength [18]. The manufacturing process of a strip involving
a polishing operation leaves the strip with longitudinal marks which results in somewhat lower fatigue strength in the transverse direction than in the rolling direction. Tumbling removes these oriented marks and in turn improves the transverse properties even if the resulting surface has a very less roughness [15].

![Figure 7 Orientations in steel strip.](image)

1.3.8 Non-Metallic Inclusions:
Steel contains non-metallic inclusions like oxides and sulphides. Various parameters should be considered when taking non-metallic inclusions into account i.e. composition, shape, size, amount and position. Hard and brittle slag inclusions can be identified as initiators for fatigue cracks. The closer these inclusions are to the surface, the greater the notch effect. Fracture can also be initiated from plastic inclusions of the MnS or MnO-SiO2 type, these type of inclusions are in the form of thin bands that are oriented parallel to rolling direction [16]. When the sulphur content is low there is not much influence on the tensile and reversed bending fatigue strength. Oxide inclusions can initiate fatigue fracture provided that their shape is suitable, their size exceeds critical value and that they appear in the highly stressed region. Critical oxide inclusion size, in a highly stressed region diminishes with total number of oxides i.e. low content of large oxides should give high fatigue strength [14]. Oxide inclusions have a deleterious influence on fatigue strength [19].

1.3.9 Composition and microstructure:
Alloy steels have better fatigue properties than carbon steel in dry air and at high tensile strength. Diminishing grain size give higher fatigue strength and the grain size is determined by hardening
and tempering procedures. It is diminished by inhomogeneities occurring in the form of segregation and surface decarburization. It is more pronounced at higher tensile strengths. Hence, it is important the valve steel needs to be fine grained and there should be no surface decarburization. Small carbides that are evenly dispersed in the structure do not diminish the fatigue strength [14]. A small amount of retained austenite in a martensitic structure increases the impact fatigue strength but no effect was found in bending fatigue properties, this is because the small amount of retained austenite acts as a shock absorber during the impact loading where they are less pronounced in conventional bending fatigue because the load applied there is much smoother [17].

1.4 Mechanical testing:
There are various forms of mechanical testing of strip steel, among which are reversed bending, fluctuating tensile and impact fatigue test. Generally UMG test machine is used for reversed bending (R=-1), Amsler high frequency pulsator are usually used to test fatigue strips under axial stress (R=0). The pulsator follows the resonance principle and has an electromagnetic system that gives a driving force [6]. Usually bending and tensile fatigue testing samples are blanked out of the steel strip with their axis in the rolling direction. The edges are then machined and after which they are subsequently polished.

For special cases like corrosion fatigue testing, rotating bending is employed and here the specimens are taken from the bar stock. Fluctuating load has a higher fatigue value than reversed load. Fatigue strength under bending stress is higher than the one under axial stress [14].

Most fatigue tests are carried out at what is called as “constant amplitude” which states that the maximum and minimum stresses are constant for each cycle of test. Fatigue test are time consuming and expensive, each data point represents several hours of testing.

1.4.1 Stair case method:
The fatigue limit is statistically distributed property and several methods are used for its evaluation. The stair case method is the most reliable of these methods [6]. Probability of fracture can be defined as the ratio of total number of specimen that has failed to the total number of specimens that have been tested. The main interest is limited to the median value of fatigue strength and the method can reduce the number of specimens required for the test. The method is not fair enough
for small or large percentage points if the distribution is not normal. The first test is started at a stress level based upon the estimated mean value of the fatigue strength. If the failure occurs before the pre-assigned cycle life, then the next specimen is made to be tested at a lower level. If the specimen in question does not fail within the pre-assigned number of cycles, then the specimen is tested at a higher stress level. The intervals between the stress levels must be almost equal to standard deviation. But then again this is not a strict rule and also the interval should not be more than twice the standard deviation. The stress level of the upcoming test is being lowered or raised based upon the preceding test, so this is how usually the test continues.

The disadvantage of this method is that one specimen can be tested at one single time. If in case more than thirty specimens should be tested then the test will take very long time. Then the total number of specimens is split into subgroups of equal size. Each group can be then tested individually and simultaneously, this method of grouping samples and testing them is called a modified stair case method [9].

1.4.2 Constant amplitude axial fatigue test:
This method of fatigue testing is particularly for axial notched and unnotched specimens that are subjected to constant amplitude. The significance of this method is that it is used to determine the effect of variations in surface condition, geometry, material, stress etc. on fatigue resistance of metallic materials subjected to direct stress for large number of cycles.
1.4.2.1 Specimen design:

![Diagram of test specimen dimensions]

0.3-0.6

20±1

160±2

10±5

As surface

**Figure 8 Dimension specification of test specimen.**

The specimen has a continuous radius between ends, this is to ensure failure within the test section. The grip sections cross sectional area should be a minimum at least 1.5 times, but in most of materials and specimens at least four times the test section area. The radius of blending fillets should be at least eight times the specimen test section width.

1.4.2.2 Specimen preparation:

Method of specimen preparation and condition of test specimen are of prime importance because improper specimen preparation can greatly affect the test results. Regardless of the machining, grinding or polishing method used, the final metal removal should always be in direction parallel to the longitudinal axis of the specimen. Fillet undercutting and introduction of residual stress are
the two most important effects that has to be avoided by specimen machining practices. Proper inspection can avoid fillet underecutting and by careful control of machining procedures surface residual stress can be minimized as well. Surface residual stress can be determined by X-ray-diffraction peak shift or by similar techniques but their value has to be reported along specific directions i.e. longitudinal or transverse.

1.4.2.3 Storage:
If the specimens are subjected to corrosion at room temperature, then they should be preserved in an inert medium. Appropriate solvents should be used later to remove the storage medium from the specimen before testing, so that they don’t give any adverse effects on the life of specimens.

1.4.2.4 Inspection:
Low power magnifications up to 20x, or visual inspection should be conducted on all the specimens. In order to remove surface oil films, finger prints etc., the specimens should be cleaned with solvents prior testing and abnormalities like cracks, machining marks, gouges, undercuts etc. are not acceptable.

1.4.2.5 Mounting and alignment verification of specimen:
Misalignment due to twist(rotation of grips), or a displacement in their axis of symmetry should be prevented. Specimen fixtures should be aligned in a way that the major axis of the specimen coincides with the load axis all throughout the cycle. For all the specimens the accuracy of alignment is to be kept consistent. A trial test specimen is usually used to ensure the alignment of all sorts of specimens.

For rectangular cross section specimens, by placing longitudinal strain gauges on either side of trial specimen at a minimum width location, the alignment is verified. The trial specimen should be rotated longitudinal axis, installed and checked in both the orientations with the fixtures. The bending stress(strains) so determined on the specimens should be limited to less than 5% of maximum or minimum stresses(strains).
1.4.2.6 Test termination:
Tests have to be continued until the specimen failure criterion is attained or a predetermined number of cycles has been applied to specimen. In this case, failure can be defined as complete separation, or as a visible crack at a specific magnification [20].

2 Aim of thesis work:
This thesis work is carried out in Böhler Uddeholm Precision Strip AB, Sweden. The work material is martensitic stainless steel produced by Böhler Uddeholm Precision Strip AB and is used for flapper valves. The fatigue testing of these stainless steel is carried out at an associated lab.

Main objectives of this thesis work are listed below:

- To investigate the influence of scratches on fatigue life of steel strip.
- To perform fatigue life tests on sample with and without scratches and compare fatigue life between both set of samples.

3 Materials and methods:

3.1 Stainless steel strip material:
UHB stainless steel 716 is a stainless steel grade designed for medium and thinner range of flapper valve components in which toughness, impact strength, corrosion resistance, hardness and bending fatigue etc. are essential. It is used at elevated temperatures (180-400°C) or in corrosive atmosphere. The 13% chromium steel is delivered in the tempered condition and has been proven to offer superior bending fatigue and impact fatigue properties. Manufactured steel strip should possess optimal external and internal properties. External properties include surface finish, flatness, straightness and internal properties have to do with mechanical properties, structure and inclusion content and composition [6].
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Table 1 Nominal Chemical composition of UHB stainless steel 716

UHB stainless steel 716 strip in the finished condition from various batches was chosen as the material. The steel strip accommodates scratches of varying depths ranging from 0 to 3 µm in the rolling direction, these scratches are presumed to be created by foreign particles. Then a section of the steel strip housing scratches were marked as samples. The samples were cleaned with alcohol later to find out the scratches for studying them under a microscope.

### 3.2 Depth vs frequency measurement:

Before taking the sample to the confocal microscope, a further size reduction of the sample is done in order to place them in the confocal specimen holder. In the confocal microscope there are various objective magnifications available like 10x, 20x, 50x, 100x. Using these magnifications, the scratches are viewed at a greater exposure and by focusing the scratch, the exact dimensions of the scratch (width, depth, intensity) are revealed.

![Figure 9 Confocal microscope images of a single scratch in the steel strip.](image-url)
Graph 1 Depth vs frequency.

The above graph shows overall distribution of the depth of scratches of all finished samples, plotted against their frequency of occurrence.

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In the above table, both the depth and width of scratches are taken into account and presented diagrammatically with their values and shape. They are tabulated in an ascending order in accordance to their probability of fracture initiation.
Graph 2 Frequency vs width/depth

The above graph portrays the width/depth values derived from the previous table. The numbers from one to five show the priority from sharp to blunt scratches respectively.

By using all these learnings, the focus was totally upon preparing samples from the steel strip consisting of the categories of scratches which were critical, dangerous and may negatively influence fatigue properties. The samples marked and blanked out from the steel strip normal to the rolling direction and a total of 30 specimens were collected, 15 of them including scratches and 15 without. They were then sent for fatigue testing. The dimensions of the samples are marked as per the standards of constant amplitude axial fatigue test.

3.3 Fatigue life comparison by fatigue testing:

The test specimen is taken out of the steel strip by means of spark erosion after which the neck of the specimen will be 13 mm, so in order to do more size reduction in neck of the specimen milling is done on either side and width is reduced further to 11mm.
Figure 9 Image of steel strip after the test specimen is blanked out by spark erosion.

The next step is the preparation of edges, this is done in order to ensure that fracture of the specimen does not initiate from the edges. Test specimen preparation process also involved grinding of edges in longitudinal direction which is done with seven grades of aluminium oxide paper.

After grinding, the thickness and width of the specimen are measured using a micrometer with an accuracy level of ± 0.002 mm. One end of the specimen is glued with a metal foil sheet and the end which is open is checked for perpendicular alignment with the help of a digital protractor against the machine. Finally, the test specimen is run at a particular stress level which corresponds to the number of cycles.

The fatigue testing machine is totally controlled with the help of a system which maintains the stress level (MPa), number of cycles, force (kN) and frequency (Hz) monitoring the test specimen constantly.

As an initial step, fourteen of samples were run at (X) MPa stress level, i.e. seven “U” samples and seven “M”, "M+" samples, fracture for these set of specimens initiated prematurely and the fracture did not initiate from the scratch. Because of the fact that stress level is inversely proportional to number of cycles the stress level was decreased to (X-100) MPa and two samples, i.e. one “U” and one “M” sample that belonged to the same batch of steel strip as in previous case, were processed at (X-100) MPa. But then again there was no enormous change in no of cycles and again, the fracture did not initiate from scratch. The stress level was decreased further to (X-300) MPa and at this stress level most of the samples were run outs (number of cycles at which the test is discontinued) in our case it is 2 million cycles.
In order to verify when the fracture actually initiates, these run out samples were processed for another 2 million cycles at the same stress level i.e. (X-300)MPa, at which some of the samples failed but a few samples again turned to be run outs i.e. they survived until 4 million cycles. Based on the results at previous stress level, the stress was increased slightly to (X-200)MPa to find out the fatigue limit of the material, but again the same pattern was observed repeatedly few samples at this stress level were run outs. So, those run outs were again tested for 4 million cycles at which few samples survived and few failed. The surprising fact was that all the samples that fractured, the fracture initiated at slag inclusions instead of scratches because the intensity of slag inclusions were higher compared to the depth of scratches.

3.4 Manual indentation of scratch in the specimen

With regard to previous experiments and results, to verify that fracture cannot initiate from scratches present on the surface and because some samples had "M+" type of scratches, scratches were induced manually in some specimens exactly in the centre, that were deeper than the slag inclusions and these specimens were axially fatigue tested.

This manual indentation on the specimen was created with the help of metal scriber tip. Using this metal scriber tip scratches of varying depths were introduced on a piece of metal strip. The samples were then taken to optical profilometer to measure the depth, by doing this one can ensure that these induced scratches have greater depth than the slag already present in the steel strip. Considering the same procedure, scratches were induced on the surface on a set of specimens few in the transverse direction and some along the rolling direction.

The optical profilometer images below show the depth of scratches which were induced on the surface of the specimens by using metal scriber tips and the depth of all the scratches induced were at a range of 10-20µm. The reason for inducing such a range of scratch depth is in accordance to the depth of slag inclusions determined from SEM images. We just wanted to determine if the specimens had scratches deeper than that of slag inclusions, will they cause fracture initiation fracture initiation in preference to the slag inclusions. This was true.
Figure 10 Three-dimensional view of manually induced scratch.

Figure 11 Optical profilometer image measuring the depth of scratch more than 20µm.
Figure 12 Optical profilometer image showing a scratch more than 14µm.

Figure 13 Optical profilometer image showing a scratch more than 16µm.
3.5 Fractography:
The test specimens that failed during the fatigue testing were then taken to SEM for studying the fracture surfaces. The procedure that was followed before taking the samples to SEM, lab involved reducing the size of the samples so that they could fit the specimen holder. They had to be cleaned with ethanol to ensure the surface was free from contamination, and then they were placed in ultrasonic cleaning machine to remove all the wear debris. This process took about fifteen minutes. Lastly the samples were placed in the heater for drying purpose.

4 Results and discussion:

4.1 Fatigue life measurements:
In order to compare fatigue life between the “U” and “M” specimens at various stress levels force controlled constant amplitude axial fatigue testing (for procedure see section 3.3) was carried out at room temperature in a dry, non-corrosive atmosphere. To determine the fatigue limit at $2 \times 10^6$ loading cycles, thirty specimens had to be tested as described in the method. The fatigue limit was defined as the stress at which the specimens failed within $2 \times 10^6$ loading cycles. All the thirty specimens were tested to plot the above S-N curve as in the graph. The edges of all specimens were prepared as mentioned in (section 3.3) and dimensions as in Figure 8 Dimension specification of test specimen.

<table>
<thead>
<tr>
<th>BATCH NUMBER</th>
<th>CROSS-SECTION (mm)</th>
<th>STRESS LEVEL MAX/MIN (MPa)</th>
<th>NO OF CYCLES TO BREAK</th>
</tr>
</thead>
<tbody>
<tr>
<td>III, U</td>
<td>9.713 x 0.633</td>
<td>X/0</td>
<td>42269</td>
</tr>
<tr>
<td>V, U</td>
<td>9.728 x 0.409</td>
<td>X/0</td>
<td>59935</td>
</tr>
<tr>
<td>IV, U</td>
<td>9.668 x 0.409</td>
<td>X/0</td>
<td>34496</td>
</tr>
<tr>
<td>XI, U</td>
<td>9.719 x 0.385</td>
<td>X/0</td>
<td>15599</td>
</tr>
<tr>
<td>XI, 2U</td>
<td>9.693 x 0.385</td>
<td>X/0</td>
<td>33887</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>-----</td>
<td>-------</td>
<td>-----</td>
</tr>
<tr>
<td>VII, U</td>
<td>9.732 x 0.598</td>
<td>X/0</td>
<td>26910</td>
</tr>
<tr>
<td>VII, 2U</td>
<td>9.716 x 0.598</td>
<td>X/0</td>
<td>33658</td>
</tr>
<tr>
<td>III, M+</td>
<td>9.723 x 0.636</td>
<td>X/0</td>
<td>23781</td>
</tr>
<tr>
<td>IV, M</td>
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<td>X/0</td>
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</tr>
<tr>
<td>V, M+</td>
<td>9.684 x 0.408</td>
<td>X/0</td>
<td>33200</td>
</tr>
<tr>
<td>XI, m+</td>
<td>9.679 x 0.387</td>
<td>X/0</td>
<td>25455</td>
</tr>
<tr>
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<td>9.685 x 0.599</td>
<td>X/0</td>
<td>61728</td>
</tr>
<tr>
<td>VII, 2m+</td>
<td>9.728 x 0.598</td>
<td>X/0</td>
<td>46524</td>
</tr>
<tr>
<td>VII, 3m+</td>
<td>9.712 x 0.597</td>
<td>X/0</td>
<td>39811</td>
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<tr>
<td>VI, u</td>
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<td>X-100/0</td>
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<tr>
<td>VI, 3m</td>
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<td>X-100/0</td>
<td>66591</td>
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<td>X, 3m+</td>
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<td>79043</td>
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<td>4000000</td>
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<td>X-200/0</td>
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<tr>
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<td>167478</td>
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<td>X, 2u</td>
<td>9.771 x 0.602</td>
<td>X-200/0</td>
<td>2099878</td>
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### Table 3 Showing test parameters, number of cycles and batch number of test specimens

<table>
<thead>
<tr>
<th>Description</th>
<th>Power (MPa)</th>
<th>Number of Cycles to Failure (log scale)</th>
<th>Batch Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, 2m</td>
<td>9.757 x 0.602</td>
<td>X-200/0</td>
<td>2091592</td>
</tr>
<tr>
<td>XV, u</td>
<td>9.748 x 0.305</td>
<td>X-200/0</td>
<td>4000000</td>
</tr>
<tr>
<td>XIX, u</td>
<td>9.739 x 0.307</td>
<td>X-200/0</td>
<td>4000000</td>
</tr>
<tr>
<td>XIX, m+</td>
<td>9.728 x 0.308</td>
<td>X-200/0</td>
<td>2106859</td>
</tr>
<tr>
<td>XV, m</td>
<td>9.662 x 0.308</td>
<td>X-200/0</td>
<td>4000000</td>
</tr>
<tr>
<td>Mnl scratch</td>
<td>9.748 x 0.305</td>
<td>X-200/0</td>
<td>4050622</td>
</tr>
<tr>
<td>2012-RR-02, Mnl scratch</td>
<td>9.405 x 0.198</td>
<td>X-200/0</td>
<td>310210</td>
</tr>
</tbody>
</table>

### Graph 3 Showing fatigue life comparison between specimens with and without scratch
Tensile fatigue testing was carried out on UHB stainless steel 716, and all the steel strips were of varied thickness as seen in Table 3. As one can see from the graph a comparative study on fatigue life between U and M specimens. The test specimen are being processed at a particular stress level that can be seen in the Y axis and the corresponding life cycle for the particular stress level can be seen in the X axis. The graph comprises values of 31 specimens in transverse direction among which 15 had a scratch on their surface and 15 of them did not and 1 specimen was in the longitudinal direction and a scratch was made on the surface manually with the help of a metal scriber tip as discussed earlier in section 3.4.

Things that can be concluded from the graph are there was no difference in the life between the “U” and “M” specimens because both the set of specimens failed because of slag inclusions, so the scratch present in the “M” specimens almost didn’t matter. A study of fracture surface and the endurance limit of the material would be 1020 MPa.

4.2 Study of fracture surface:
Fractography of the samples which failed during the fatigue testing are studied in the help SEM.

![Figure 14](image.png)  
Figure 14 One broken half of test specimen and part of specimen observed in SEM.
The primary fatigue crack is generated near the surface or near the outer edge. However, in both cases the radial orientation of primary fatigue crack is established. This radial orientation of the primary cracks proves that circumferential (tangential) stress component is one of the principal stress components responsible for failure.

The initiation stage represents the main part of the valve fatigue life [14]. The initiated primary fatigue crack acts as a macroscopic stress raiser, once the crack has initiated the successive growth is relatively fast and leads to sudden final failure.

Figure 15  Typical representation and position of SEM images.
Figure 16 SEM Image showing the radial crack initiating from slag inclusion.

The black circled region in the above image is the initiation point of fatigue fracture and the black arrows are progression marks revealing crack growth, they are propagating straight in the radial direction i.e. Initiation has started near the surface and they have proceeded into the material. The dotted curve in the image tells us about the shape of the fatigue crack i.e. half penny shaped.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12.60</td>
<td>44.32</td>
</tr>
<tr>
<td>O</td>
<td>8.88</td>
<td>23.46</td>
</tr>
<tr>
<td>Al</td>
<td>5.40</td>
<td>8.46</td>
</tr>
<tr>
<td>Si</td>
<td>3.12</td>
<td>4.69</td>
</tr>
<tr>
<td>S</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td>Ca</td>
<td>16.34</td>
<td>17.23</td>
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<tr>
<td>Cr</td>
<td>0.45</td>
<td>0.37</td>
</tr>
<tr>
<td>Fe</td>
<td>1.56</td>
<td>1.18</td>
</tr>
</tbody>
</table>
The above image illustrates the exact fracture initiation point BSD (back scattered view) at a higher magnification and it can be seen that there is an hard and brittle oxide slag inclusion which served as a fatigue crack starter and an area of stable crack growth can be observed around the inclusion. When a spot analysis was performed on the initiation point (spectrum1) the chemical composition tell us that the slag is calcium oxide rich and also has traces of aluminium oxide and silicon oxide.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>5.53</td>
<td>10.60</td>
</tr>
<tr>
<td>O K</td>
<td>32.81</td>
<td>47.18</td>
</tr>
<tr>
<td>Mg K</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>Al K</td>
<td>31.33</td>
<td>26.72</td>
</tr>
<tr>
<td>Si K</td>
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<td>0.44</td>
</tr>
<tr>
<td>Ca K</td>
<td>10.06</td>
<td>5.78</td>
</tr>
<tr>
<td>Cr K</td>
<td>3.70</td>
<td>1.64</td>
</tr>
<tr>
<td>Fe K</td>
<td>16.43</td>
<td>6.77</td>
</tr>
<tr>
<td>Totals</td>
<td>101.34</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 17** EDS Image showing high intensity of aluminium oxide

This image is also of the same steel strip but spot analysis was performed at a different point (spectrum3) since there was presence of slag inclusions of greater width and the chemical composition of the slag tells that it has nonmetallic inclusions like aluminium oxide rich and also contains calcium oxide. The closer these inclusions are to the surface, the greater their notch effect. Oxide inclusions have deleterious influence on fatigue strength.
Figure 18  SEM Images showing crack initiation at brittle oxide inclusion.

The circled region in the above image is the initiation point of fatigue fracture. Even this specimen exhibited the radial orientation of primary fatigue cracks. The primary crack initiation is similar to the one shown in fig 18. Fatigue crack was growing in radial direction perpendicular to the valve surface. The dotted curve in the image tells us about the shape of the fatigue crack and its limit and it almost looks like a half penny shaped crack as in the previous case. The arrow pointing in the other half of the material indicates that the remaining portion underwent ductile failure and when the image was taken to higher magnification we could see dimples present because the loading mode was axial.

In the below highly magnified BSD image the dimensions of the slag inclusions as one can see from the image the cavity is 12.87µm deep and 47.15µm in width.
The above image shows again an oxide slag inclusion of Al₂O₃-type which served as a fatigue crack starter, since they are close to the surface the notch effect is higher, the slag is aluminium oxide rich and has traces of magnesium sulphide. Sulphides are less harmful than oxides.
Figure 19  SEM image of “U” specimen with quite large inclusion.

In the above figure, the fatigue fracture is again because of non-metallic inclusions in the material. This slag inclusion is 4.9µm deep from surface.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C K</td>
<td>8.69</td>
<td>33.16</td>
</tr>
<tr>
<td>O K</td>
<td>11.56</td>
<td>33.13</td>
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<tr>
<td>Al K</td>
<td>5.59</td>
<td>9.49</td>
</tr>
<tr>
<td>Si K</td>
<td>1.01</td>
<td>1.65</td>
</tr>
<tr>
<td>S K</td>
<td>2.50</td>
<td>3.57</td>
</tr>
<tr>
<td>Ca K</td>
<td>7.86</td>
<td>8.99</td>
</tr>
<tr>
<td>Cr K</td>
<td>2.26</td>
<td>1.99</td>
</tr>
<tr>
<td>Mn K</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td>Fe K</td>
<td>9.15</td>
<td>7.51</td>
</tr>
<tr>
<td>Cu K</td>
<td>0.25</td>
<td>0.18</td>
</tr>
</tbody>
</table>
In the above image, when EDS analysis was performed on a spot at far away from the surface we could see traces of manganese sulphide, silica and high percentages of aluminium and calcium oxide as usual.

Fig 22 are cases where the slag inclusive particle which are way deeper and the cause for the fatigue fracture has fallen out from the material and hence the initiation points are clearly visible as a hole.
Figure 20  Particle fallen out image of “M” specimens
Figure 21  Images portraying width and depth values of heavy slag inclusions

Figure 22  Image showing fatigue crack which started at manually induced surface scratch
One of many samples where the fracture happened from a scratch that was induced manually using a metal pencil tip as described earlier. Primary crack initiation is similar to the ones described in fig 18, 19. Fatigue crack was growing in radial direction perpendicular to the valve surface as in previous studies.

**Figure 23** SEM Images of sample that failed due to manually intended scratch
One other sample in which a scratch was induced manually by the same procedure as the previous specimen, failed from the scratch near the edge and the white arrow indicate the fatigue fracture initiation point. Fatigue failure had been caused, it is a very well-known fact that the severe surface notches act as effective stress raisers.

The above image shows a much more closer view of the fracture initiation point from a manually induced scratch.
Figure 24 SEM images of specimens which had a scratch but failed because of heavy slag

The white arrows in the images explains that there were scratches already present in the specimen but the fracture has happened due to heavy slag inclusions as we can see the ductile fracture with dimples present above marked with black arrow.
The above image shows a fracture initiation that has started but not progressed to final failure, since fatigue cracks started at some other internal defects and which had higher notch effect than stress raiser found in the surface.

Figure 25 Crack growth, Fatigue striations at lower magnification

Figure 26 Fatigue striations at higher magnifications.
These scanning electron microscope fractographs, showed that most of cracks initiated below the surface, such fatigue cracks had started from internal defects (non-metallic inclusions) since they had higher notch effect than the stress raisers (scratches) found in the surface, examples for this fact are seen in images starting from fig 19 to 22. These non-metallic inclusions have a deleterious influence on the material, the depth and width of such slag was also analyzed in this study. One other cause of fatigue fracture is scratches which were induced in some specimens examples for this is seen in Figure 22.

5 Recommendations and future work

This study focused on fatigue life comparison of samples with and without scratch against the rolling direction by fatigue testing. However recommendations can be made to improve the fatigue testing methods. In this study, simulation and testing of the test samples was done only for tensile fatigue, similarly Impact and bending fatigue also needs to be investigated.

Samples selected for fatigue testing with scratches, had only a limited range of depth values which was based upon frequency vs. depth graph, samples with higher depth should also be considered for testing. The thickness of test samples varied; investigation based on uniform thickness of samples would also be of interest. A lower level of slag inclusions can reduce the probability of fatigue fracture and hence should be taken into consideration for optimizing fatigue life, a detailed study about the source and occurrence of such inclusions will be advantageous.

6 Conclusions:

From, UHB stainless steel 716 test specimens blanked out against the rolling direction which had a scratch depth as in Graph 2 Frequency vs width/depth, following conclusions are made:

- Fatigue life comparison on U and M specimens shows that the scratches existing in the selected group of specimens did not have any deleterious influence on tensile fatigue life because of heavy slag inclusions which were present within the material.
- The slag inclusions in the material seemed to influence the initiation of fatigue fracture in preference to the scratches being analyzed.
• When scratches were made manually in specimens more than the minimal depth of inclusions, failure happened to develop from scratches, therefore for failure to initiate from a scratch the depth criterion plays a decisive role.
• From fractographic studies we can say that, brittle oxidic slag inclusions acted as the fatigue crack starter in all of the failure specimens.

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Jens Bergström, examiner at Karlstad University, Sweden.

Pavel Krakhmalev, supervisor at Karlstad University, Sweden.

Christer Burman, supervisor at Karlstad University, Sweden.
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International compressor engineering conference, Available: 
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1173&context=icec


http://www.asminternational.org/portal/site/www/.


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