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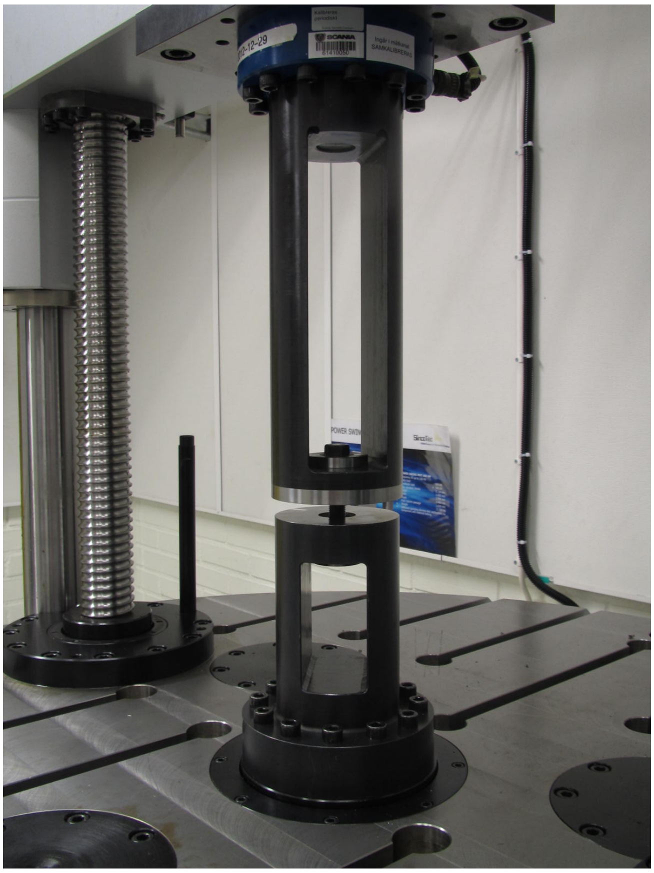

Establishing Fatigue Properties of Ultra High Strength Steel Bolt Materials

Master of Science Thesis in Product Development

David Thor

Department of Product and Production Development
Division of Product Devlopment
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Cover:
Fatigue testing fixture used to test the bolts in this thesis.

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Abstract

To transfer large loads with less weight, stronger steels need to be developed, these materials can then be used to create fasteners such as bolts. For many years have higher metric strength classes of bolts i.e. above 10.9 been regarded to have low fatigue resistance. With new materials, bolts such as 14.9 and 15.8 can be manufactured, these new strength classes has been fatigue tested in this thesis. The tests were conducted in a resonance-testing machine at Scania in Södertälje.

The main results are shown as Wöhler curves, and a Haigh diagram. From the bolts used in this thesis there is only one that seems viable to use in production for Scania while other needs more research before making any conclusions.

Before these new materials are taking into production there are more tests that need to be done, e.g. hydrogen embitterment tests and test-assemblies.

Keywords: Ultra high strength steel bolts, Fatigue test,

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Preface

This report is the result of my master thesis at the master degree programme, product and production development. This thesis was carried out in collaboration with Scania CV AB during the spring of 2013

I would like to thank my supervisors Erik Tolf and Lars Gunnarson at Scania CV, without their invaluable help this thesis would never have been finished. Thanks also to Henrik Nordin at Scania for helping me with wheatstone bridges and the Sincotec Powerswing.

I would also like to thank my supervisor and examiner at Chalmers, Göran Brännare.

1 Introduction

With the current trends towards lower fuel consumption and carbon emissions, Scania develops trucks and busses and with engines and transmissions that in the future needs to translate larger torques as well as the vehicles weight needs to be reduced. That implies that components and joints need to translate larger loads per area. Scania uses today bolts with strength class 10.9 i.e. minimum yield strength 940 Mpa. Materials has been developed which allows rational manufacturing of bolts with strength classes 15.8 and 14.9 i.e. the yield strength as been increased with approximately 30%. This can be used for reduction of dimension and consequently lower weight or higher loads with same dimensions. The properties of these new bolt materials needs to be established before theses new ultra high strength bolts can be used in a complete product.

1.1 Problem statement

There are no reliable fatigue data for these new strength classes. Scania has three possible suppliers for ultra high strength steel bolts, the manufacturers tests their bolts in different ways, which makes the comparison between the bolts impossible. To establish fatigue properties and make a fair comparison, they have to be tested in the same way, in the same machine.

1.2 Purpose

The purpose of this thesis is to establish the fatigue properties for ultra high strength bolt materials and compare with strength class 10.9 and explain the results. In addition a literature review was made to establish the parameters that influence the fatigue resistance of steels and more specifically bolts. This provides information so a conclusion about the material can be made instead of the component.

1.3 Scope

The literature review covers metals resistance to fatigue, theory of bolted joints. The bolts that have been tested was delivered from three different suppliers.
A total of 137 bolts has been tested with constant amplitude tests to create Wöhler curves. Metric strength classification 10.9 is used as a reference.

This thesis will not take in to account bending stresses that occur in bolted joints.

2 Literature Review

The theory chapter introduces fatigue, bolted joints, and material properties to increase the knowledge to understand the conclusions.

2.1 Fatigue

During cyclic loading small plastic deformation may occur where the highest stress appears, these plastic deformations increases over time and initiates a crack. With increasing number of load cycles the crack grows, and after a certain time the crack will cause failure in the component. The crack usually grows along the plane of maximum stress and along the grain boundaries (Davis 1996).

The development of a crack is usually divided in two phases, first is the crack initiation the second is the crack growth phase. During high-cycle fatigue testing of steel the crack initiation time accounts for most of the fatigue life for the component.

To determine a materials fatigue properties it has to be tested. This is usually done by adding a pulsating load with constant amplitude. Identical specimens are then tested at several different amplitudes and the numbers of cycles to fracture are recorded. The fatigue test data are then usually plotted on a semi-log coordinates, this is called a Wöhler diagram or a S-N diagram (Lee 2005). To this data a curve can be adapted, this is called the Wöhler curve or the S-N curve. Fatigue limit for steels can be decided by these curves, the fatigue limit is the amplitude where no fatigue fractures occur.

According to ASM handbook the fatigue resistance of steel depends on a number of factors.

Strength Level.

Below hardness level 400 Vickers the fatigue limit can be estimated to be half the ultimate tensile strength (David 1990). Higher strength level can then be expected to results in higher fatigue resistance

Ductility

Ductility is usually associated with low cycle fatigue (<1000 cycles), and should not influence the infinite fatigue life. There is however exceptions, where you have millions of small amplitude cycles and once in a while a large cycle, then a ductile material should provide good resistance to fatigue (Davis 1990).

Cleanliness

Cleanliness refers to the fraction of non-metallic inclusions in the material. These inclusions usually affect the fatigue resistance of steel. These inclusions are rarely the prime cause for fatigue fractures (David 1990).

Surface Condition

Surface conditions such as surface roughness and surface imperfection can reduce the fatigue resistance of steel. The influence of surface condition on fatigue is most apparent for high strength steels (David 1990)

Residual stress

Residual stresses induced in the bolts thread from rolling the threads after heat treatment increases the fatigue resistance (Stephens, R et al. 2005)

Composition

Carbon content can be increased to increase the fatigue limit, this is most apparent above hardness levels of 460 Vickers and higher. Other alloying elements usually don't increase fatigue resistance but is used to achieve the hardness levels (Davis 1990).

2.2 Bolted Joints

Bolted joints are one of the most common fasteners, the technique is old and standardized. Properly dimensioned joints can handle a high load, which saves both weight and cost compared to improperly dimensioned joints (Broberg 1983).

When preloading, the bolt gets a tensile force F_b. The joint members are subjected to an equally large compression force F_j. These forces are introduced during preloading and are usually denoted by F_p (Blickford & Nassar 1998), figure 2.1 is a joint diagram that shows the relation between force and deflection.

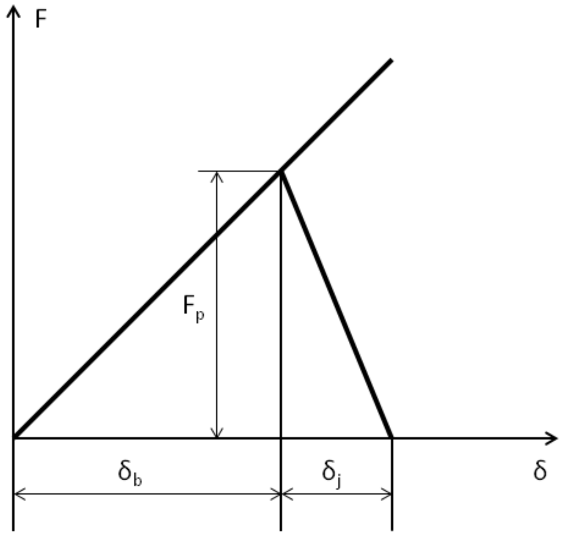

Figure 2.1 – Force deflection diagram of a assembled joint, without external force

When external force F_e is applied to the bolted joint the force relation between F_b and F_j changes, Figure 2.2 shows the relation between forces when applying external load.

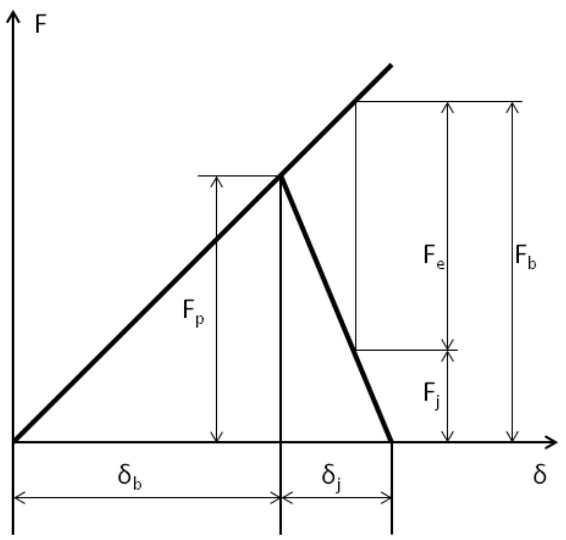

Figure 2.2 – Force deflection diagram for bolt with external load applied.

The more external load that is put on the joint, the less force will clamp the joint material. The external load that is so high that the clamping force Fj falls to zero is a called the critical load (Bickford & Nassar, 1998). If the external forces are higher than the critical load the joint material cannot absorb part of the load, hence the forces will be absorbed entirely by the bolt. If the load is cyclic and above critical load it can lead to rapid fatigue failure.

The recommendation for threads rolled after heat treatment (RTAHT) from VDI for 10^7 load cycles is similar to the rolled before heat treatment (RTBHT), the difference is a factor that depends on the level of preload. Equation 1 is for RTBHT and equation 2 is for RTAHT.

$$\sigma_a = 0.75\left(\frac{180}{d} + 52\right) \qquad 1$$

$$\sigma_a = 0.75\left(\frac{180}{d} + 52\right)\left(2 - \frac{R_m}{R_{p0.2}}\right) \qquad 2$$

Where d is the nominal thread diameter, $R_{p0.2}$ the yield strength, R_m the mean stress. In this thesis the testing has been performed with the minimum stress constant not the mean stress. By rewriting equation 2, the amplitude can be expressed as a function of the minimum stress, as shown in Equation 3.

$$\sigma_a = \frac{0.75\left(\frac{180}{d}+52\right)\left(2R_{p0,2}-\sigma_{min}\right)}{0.75\left(\frac{180}{d}+52\right)+R_{p0,2}} \qquad 3$$

Important to note is that these equations are valid for metric strength class 8.8-12.9, but gives a good comparison for ultra high strength steel bolts.
Calculating the fatigue resistance for $2e^6$ cycles can be done accordingly to equation 4

$$S_2 = S_1\left(\frac{N_1}{N_2}\right)^{1/m} \qquad 4$$

Where S_1 and S_2 is the fatigue limit at N_1 respectively N_2 and m is the fatigue exponent, normally the fatigue exponent is between 3-8 (Olsson, 2013). For bolts the calculations should be done with fatigue exponent of 4 (Bergqvist, 2010). From these equations recommended fatigue limits at $2e^6$ cycles can be gathered, and with these compare to the results from this thesis. The fatigue limit for RTBHT is accordingly to this reasoning 72,7MPa, and for RTAHT (with σ_{min} 70% of $R_{p0,2}$) 87,6 MPa.

2.3 Material Properties

To understand the displayed results knowledge in material properties of steel is required. There are several factors that determine a steels resistance to fatigue failure, some of these factors are Tensile residual stresses, Grain size, Composition and Microstructure.

2.3.1 Martensite

Martensite is formed when steel is rapidly cooled (quenching) from austenite, this traps carbon atoms in the crystal structure by not allowing the carbon atoms to have time to diffuse. Martensitic's mechanical property comes from the carbon atoms ability to prevent dislocation by reducing the number of slip planes. Martensite is the hardest microstructure for steel, and is the most common microstructure for steel bolts.

2.3.2 Bainite

Bainite is a microstructure that forms when quenching from austenite to a temperature between 250-500 degrees Celsius, transformation to bainite occurs at this temperature. When sufficient bainite has formed, the steel is cooled to room temperature (Bhadeshia & Honeycombe, 2006). Bainite and martensite has similar properties and microstructure, bainite is in-between martensite and pearlite in terms of hardness

Metals at hardness levels above Rc 40, about 385 Vickers, a bainitic structure that is austempered shows better fatigue properties then a quenched and tempered structure with the same hardness (Key to Metals 2013). This is due to the thin carbide films that are formed during tempering of martensite, which induces stress concentration effects.

3 Test Material

The tools and specimens used in this thesis are explained in this section.

3.1 Fatigue Testing Machine

The equipment used to test the bolts were a resonance machine from Sincotec, Sincotec PowerSwing 150kN. It has a working frequency of 50 hertz, and a maximum load of 150kN. The controlling software for the powerswing is Emotion II. Figure 3.1 Shows the Powerswing. The machine from Sincotec was chosen because of its high working frequency, with 50hz the long run out test would only take approximately 11 hours.

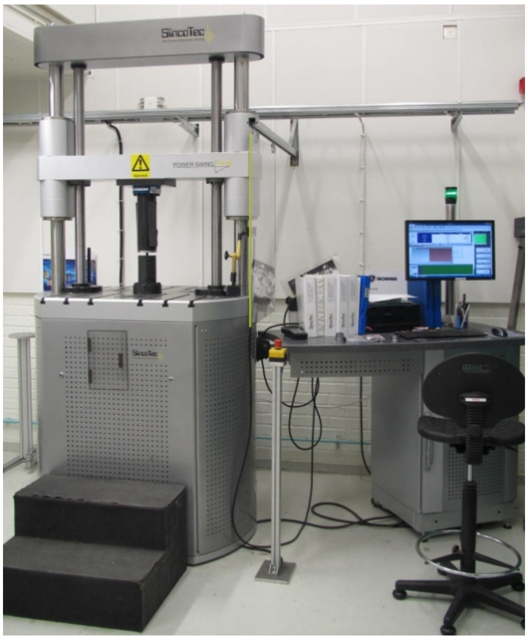

Figure 3.1 – Sincotest Powerswing 150kN, the used fatigue testing machine in this thesis.

3.2 Test Fixture

The test fixture was designed accordingly to SS-ISO 3800.To be able to test several different sizes of bolts in the future, a fixture with inserts were the logical option. The fixture was manufactured in 2541 steel that was tempered and annealed to achieve HRC between 36-40. The inserts were tempered and annealed to HRC 50. The fixture can be seen in figure 3.2.

A load verification stud was manufactured according to ISO 3800 with a diameter of D=M16x1.5. To be able to measure the alignment of the load four strain gauges was glued to the stud at 90° on a common centerline around the axis.

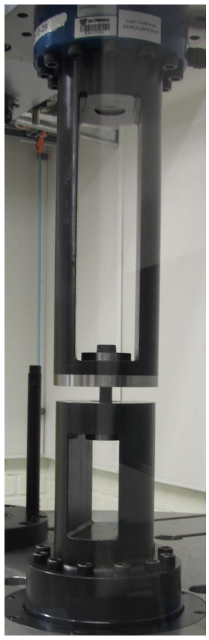

Figure 3.2 – The test fixture used for the bolts.

3.3 Bolts

The bolts tested in this report are all M14x1.5, 70mm threaded length, except for the reference, which is 65.5mm. The bolts are provided from three different manufacturers, The bolts tested in this report are Bolt 1, Bolt 2, Bolt 3 and for reference Bolt 4.

3.3.1 Bolt 1

B1 has a martensitic microstructure, with Vickers hardness 512.Figure 3.3 shows the microstructure of B1. According to specification B1 has tensile strength 1400MPa and $R_{p0,2}$ 1280MPa. When performing Stress-Strain tests the measured tensile strength were 1504-1528MPa and $R_{p0,2}$ 1333-1352MPa

The radius under the bolt head is 520µm and the radius in the thread bottom is 166µm, this is shown in figure 3.4 respectively 3.5. The threads are rolled after heat treatment.

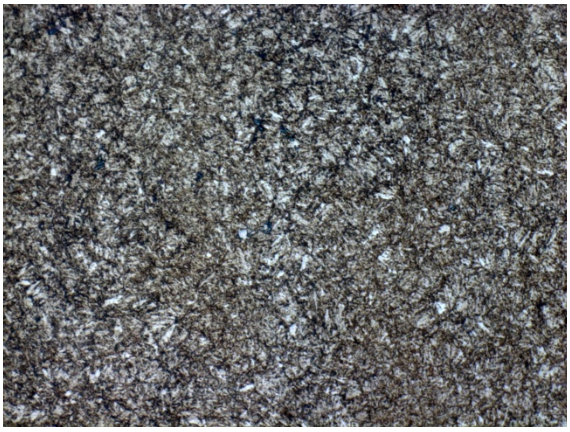

Figure 3.3 – Microscopic image of the microstructure in bolt 1

Figure 3.4 – The head radius of B1, as can be seen it is undercut.

Figure 3.5 – The thread root radius of B1

3.3.2 Bolt 2

B2 has a martensitic microstructure, with Vicker hardness 473.Figure 3.6 shows the microstructure of the bolt. According to specification B2 has tensile strength 1360MPa and $R_{p0,2}$ 1260MPa. When performing Stress-Strain tests the measured tensile strength were 1409-1423MPa and $R_{p0,2}$ 1310-1323MPa. The radius under the bolt head is 733µm and the radius in the thread bottom is 200µm, this is shown in figure 3.7 and 3.8. The threads are rolled before heat treatment.

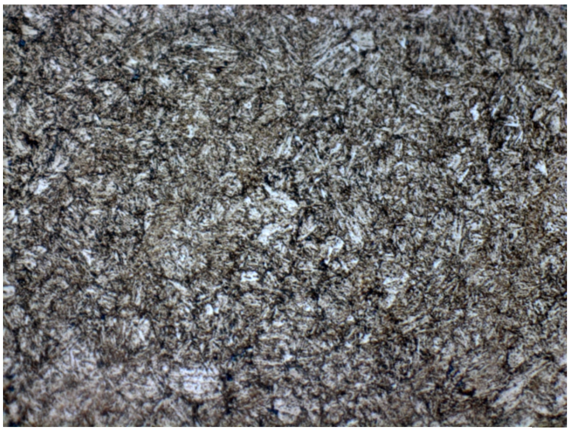

Figure 3.6 – Microscopic image of the microstructure in bolt 2

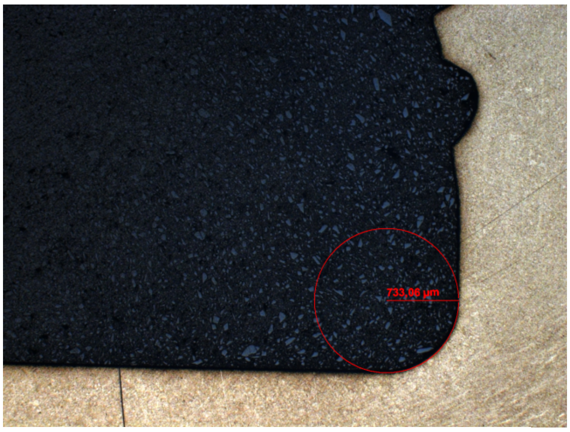

Figure 3.7 – The head radius of B2,

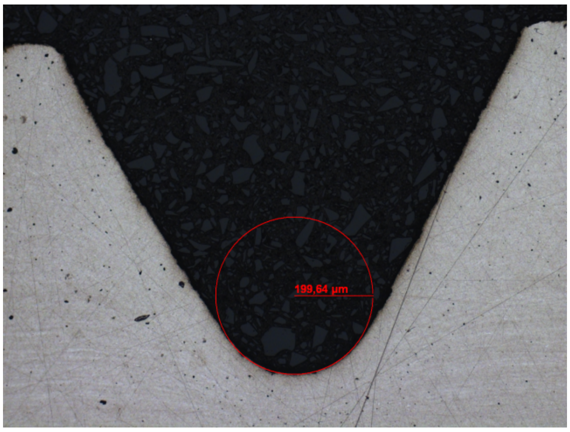

Figure 3.8 – The thread root radius of B2

3.3.3 Bolt 3

B3 has a bainitic structure, they claim bainite has lower internal stress in crystal lattice that induce advantages such as higher ductility, higher fatigue life and less distortions compared to martensite. The Vicker hardness of B3 is 522. Figure 3.9 shows the microstructure of B3. According to specification the bolt has tensile strength 1500MPa and $R_{p0,2}$ 1200MPa. When performing Stress-Strain tests the measured tensile strength were 1608-1631MPa and $R_{p0,2}$ 1463-1489MPa

The radius under the bolt head is 1200µm and the radius in the thread bottom is 212µm, this is shown in figure 3.10 and 3.11. The threads are rolled after heat treatment, which induces residual stresses that should increase fatigue resistance.

Figure 3.9 – Microscopic image of the microstructure in bolt 3

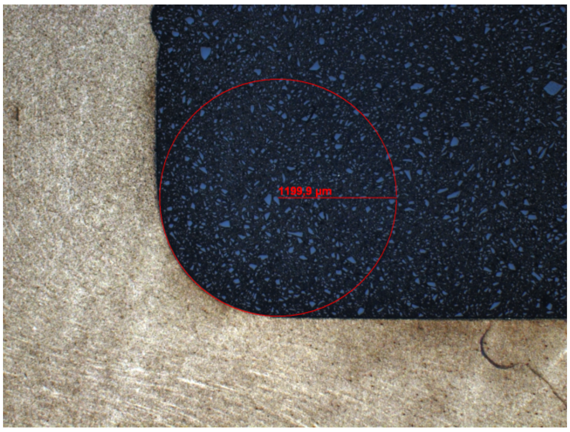

Figure 3.10 – The head radius of B3,

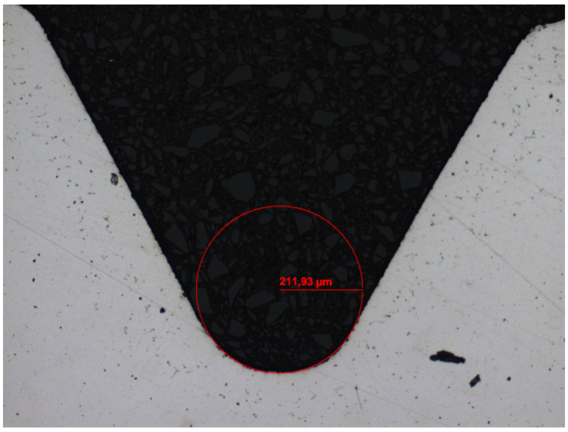

Figure 3.11 – The thread root radius of B3

3.3.4 Bolt 4

B4 has a martensitic microstructure, with Vickers hardness 383. Figure 3.12 shows the microstructure of B4. According to specification B4 has tensile strength 1000MPa and $R_{p0,2}$ 940MPa. When performing Stress-Strain tests the measured tensile strength were 1106-1145 MPa and $R_{p0,2}$ 1088-1127 MPa. The radius under the bolt head is 1589µm and the radius in the thread bottom is 194µm, this is shown in figure 3.13 and 3.14. The threads are rolled after heat treatment.

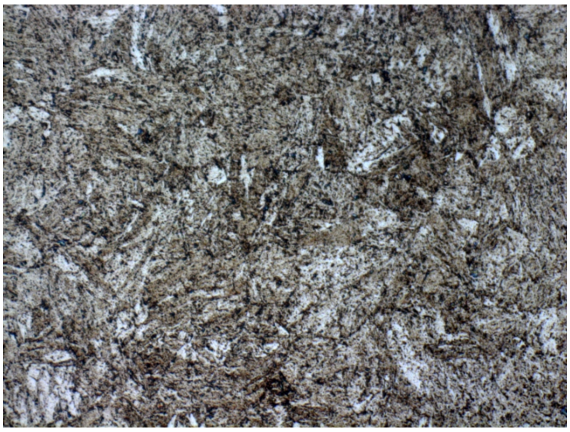

Figure 3.12 – Microscopic image of the microstructure in bolt 4

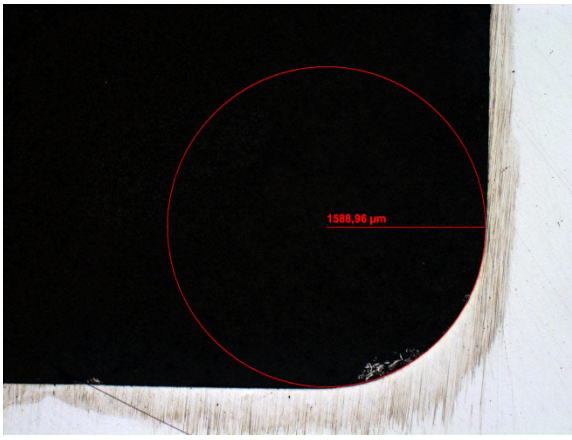

Figure 3.13 – The head radius of B4,

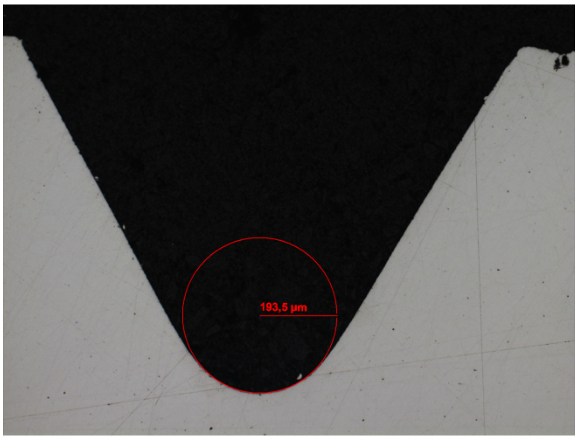

Figure 3.14 – The thread root radius of B4

3.3.5 Chemical Composition

To check for differences in the material compositions a chemical analysis was ordered from a company that performs these with high precision. Both B1 and B2 are made of steel from japan. One hypothesis was that the material used by B1 and B2 was from the same manufacturer, but looking at the chemical composition there are a few remarkable differences between B1 and B2. The main difference is the nickel and chrome content, where B2 has more of the named alloy metals.

Table 3.1 shows the content of each element in the different bolts. The values in the tables are shown as percentage.

	C	Si	Mn	P	S	Cr	Ni	Mo	Ti
B3	0,421	0,08	0,72	0,008	0,01	1,07	0,03	0,22	<0,003
B2	0,379	0,06	0,43	0,007	0,008	1,08	0,47	1,04	0,041
B1	0,458	0,11	0,5	0,006	0,002	0,31	0,27	1,05	0,06
B4	0,228	0,08	0,89	0,009	0,006	0,3	0,03	<0,01	0,031

	Nb	Cu	V	Al	Fe
B3	0,002	0,02	0	0,022	97,36
B2	0,005	0,03	0,08	0,037	96,3
B1	0,003	0,03	0,16	0,033	96,97
B4	<0,002	0,02	0,01	0,037	98,3

4 Test Procedure

The norm when conducting fatigue tests is to use fully reversed loading, this specify that loading alternates about a zero mean stress (Lee 2005). During fatigue testing in the fixture, there is no preload from clamping, therefore during the tests all external forces will be applied to the bolt. To get relevant data the bolts were tested as they are intended to be used, therefore the lowest load a bolt was subjected too was constant. This method represent the preloading bolts would encounter during normal use.

The testing method described in ISO 3800 was used, where you have 4 different amplitudes to decide the finite life range, with replicates at each level. To find the infinite life, 6 specimens where tested with the staircase method. This method is also described by Japan Society of Mechanical Engineers and Nakazawa H. And Kodama, S. The bolts were tested at two different lowest loads, to be able to compare the influence of preloading, and if the ultra high strength steel bolts can replace 10.9 in situations where fatigue is an issue.

During the tests a load verification stud was used to frequently verify that the load conditions has not changed. The verification stud was rotated four times when measuring, this removes any individual differences between the strain gauges.

To make sure that the temperature in the bolts did not increase more than allowed, K-elements were glued to a few bolts and were monitored during testing. According to ISO 3800 the maximum rise in temperature allowed is 50°C above room temperature.

To prepare the bolts for fatigue testing they were thoroughly cleaned, and coated with oil. This is to remove all loose chips and fragments still left from manufacturing and transport, the small fragments could induce a crack initiation in the bolt thread. The bolts were stored in plastic jars after cleaning and oiling.

When a fractured occurred the nuts were inspected for damage before either being reused or put in a lathe to machine off the damage. The bolts were inspected as where the damage had occurred, some of the bolts were put under a stereo microscope to look at the crack propagation. The bolts were then stored in plastic bags marked with bolt, load level, load cycles.

The results from the tests was analyzed using UTM2 which is a Scania developed application that plots test data on log-linear coordinates with polynomial curve of degree three.

5 Results

From the data set produced in the Sincotec Powerswing, eight Wöhler curves have been created. They have been created in the application UTM2, which through least square method adapts a polynomial curve of degree three to the data points. The key findings is shown by two different diagrams, one where all bolts have minimum loads as 70% of their own yield strength, one where all bolts have the same minimum load which is 50% of the yield strength for the ultra high strength steel bolts and 70% of the B4. There is also a curve for B4 with 50% of the yield strength, which is used to draw a trend line in the Haigh diagram.

The verification stud that was used to verify that the fixture does not induce to much bending stresses showed the bending stress to be 0.9%. The allowed limit for bending according to ISO 3800 is 6%.

The K-elements that were glued to the bolts showed the increase of temperature to be a maximum of 5° celcius. The temperature increase was therefore not affecting the results in any way.

5.1 Wöhler Diagram 70 %

The results from the 70% series show that the reference B4 has the highest fatigue resistance at 120MPa. B3 has a fatigue resistance of 62.8MPa. B2 has a fatigue resistance of 83.5MPa. B1 has a fatigue resistance of 81.6MPa. The diagram can be seen in figure 5.1

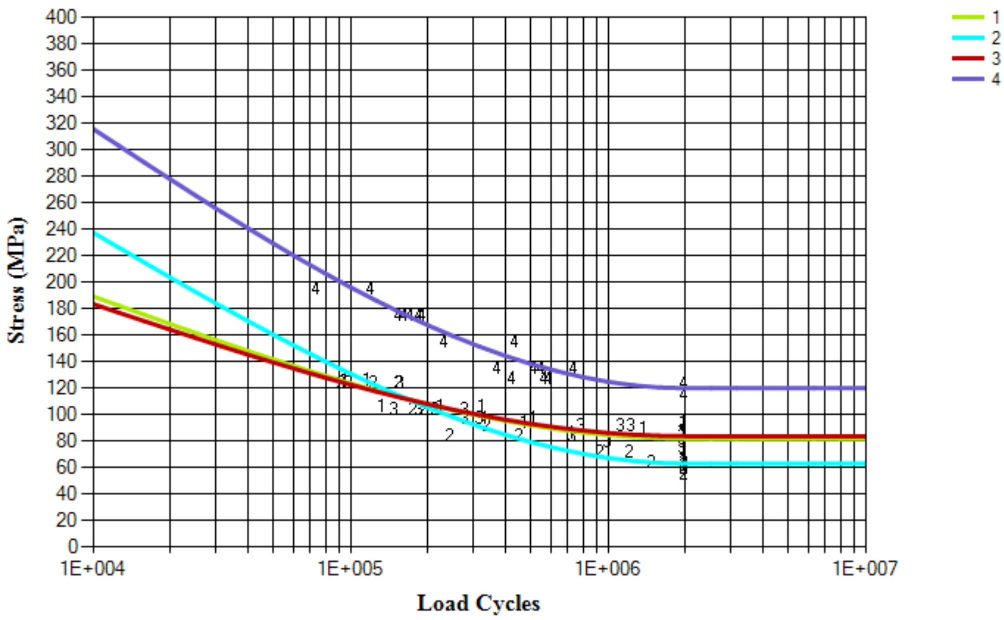

Figure 5.1 - Wöhler diagram for the 70% series. The green curve (1) is representing Bolt 1, cyan curve (2) represents Bolt 3, red curve (3) represents Bolt 2. Bolt 4 is represented as the purple curve

5.2 Wöhler Diagram 50 %

The results from the 50% series is shown in figure 5.2. There are a few changes from the 70% but not any dramatic changes. B4 still has the highest fatigue resistance at122MPa. B3, 87,6MPa. B2, 86,6MPa. B1, 101MPa.

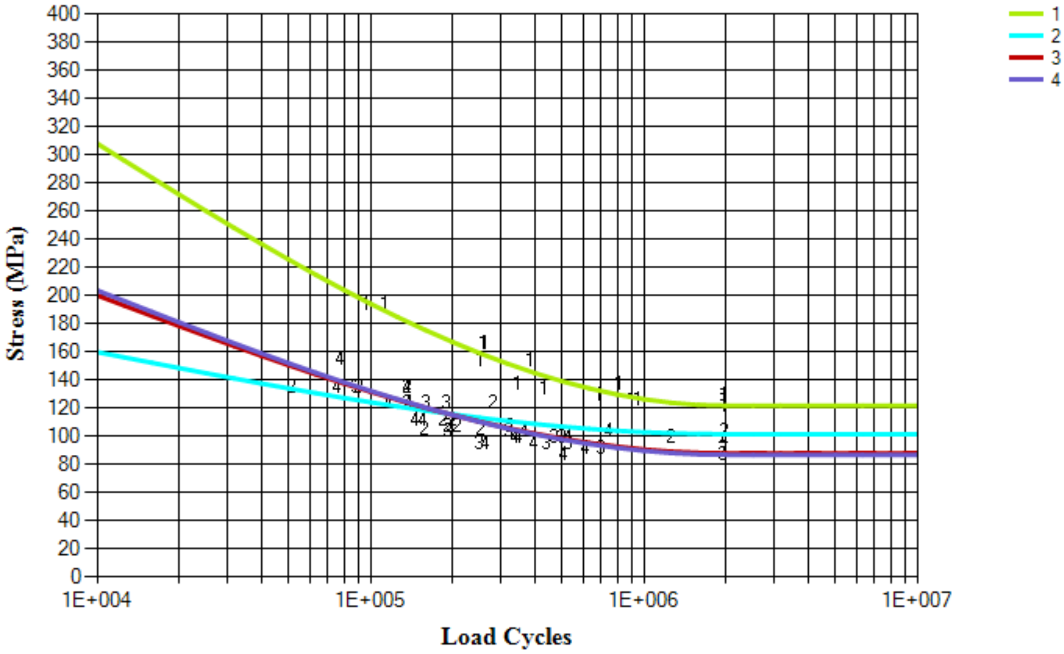

Figure 5.2 – Wöhler diagram for the 50% series. The green curve (1) is representing Bolt 4, cyan curve (2) represents Bolt 1, red curve (3) represents Bolt 2. Bolt 3 is represented as the purple curve

5.3 Wöhler Diagram Same Min Load

Combining the 50% for ultra high strength steel and 70% for the reference B4 a Wöhler diagram with the same lowest load for all the bolts can be made. Figure 5.3 shows this diagram, which could be used to evaluate if its possible to replace a 10.9 bolt with an ultra high strength bolt when there is a fatigue fracture in a 10.9.

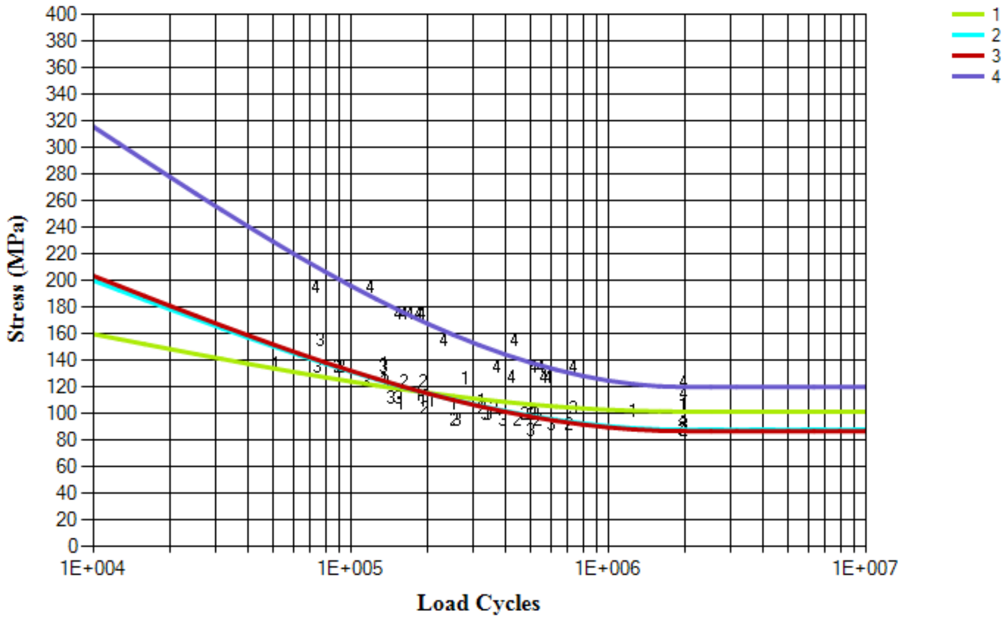

Figure 5.3 - Wöhler diagram for the same minimum load. The green curve (1) is representing Bolt 1, cyan curve (2) represents Bolt 3, red curve (3) represents Bolt 2. Bolt 4 is represented as the purple curve

5.4 Haigh Diagram

To show the bolts relation between preload and fatigue limit a Haigh diagram is plotted in figure 5.4. In the Haigh diagram, there are two grey vertical lines, which represent a working point for the bolts when assembled.

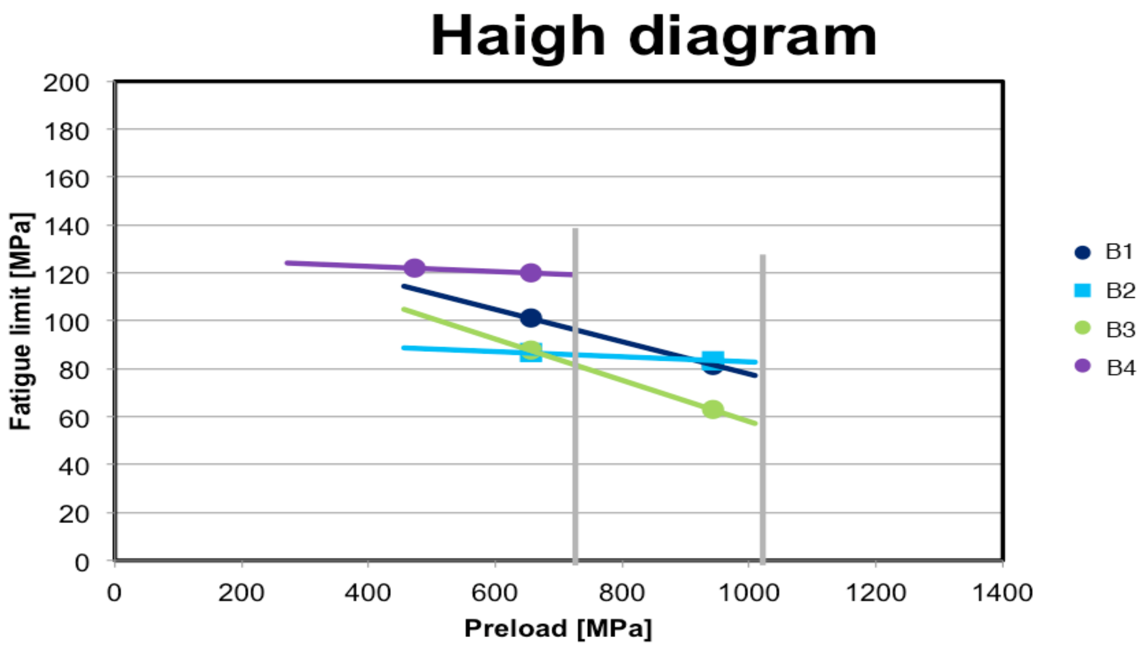

Figure 5.4 – Haigh diagram for the Ultra high strength steel bolts and the reference B4.

5.5 Thread roots

To try and explain the factors influencing the bolts fatigue limit, and to be able to make some conclusions about the materials a plot of fatigue limit and thread root radius is shown in figure 5.5. This figure shows the relation between mean stress and fatigue limit as the vertical distance between the data points.

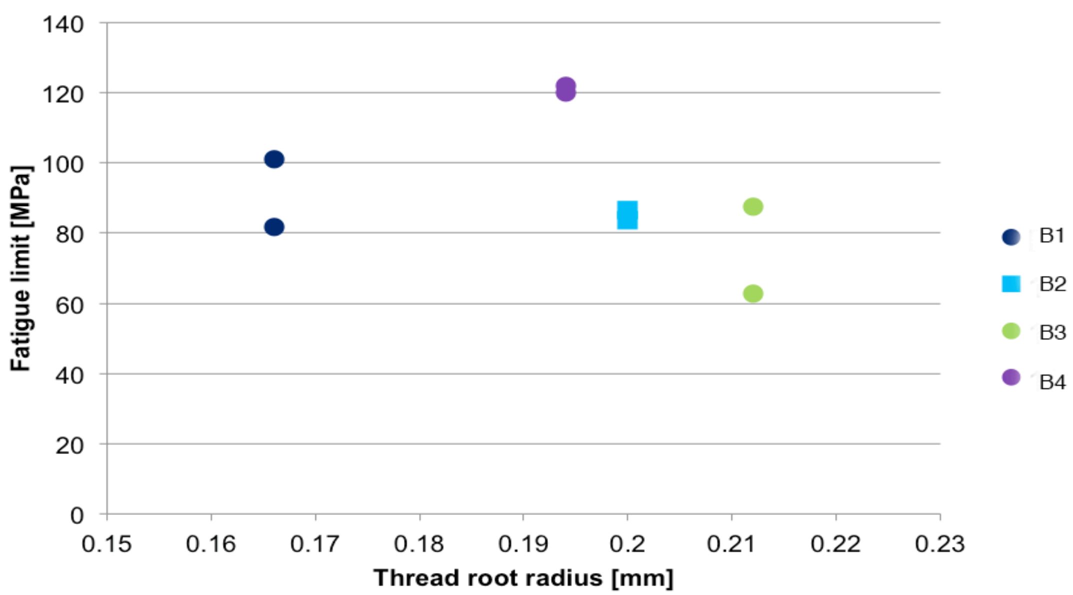

Figure 5.5 – Fatigue limit vs thread root radius plotted for the bolts.

There are more factors that could influence the fatigue resistance of the bolts. Figure 5.6 shows the four different bolt thread roots with magnification 500, clearly visible is that B4 has a more even surface then ultra high strength steel ones. It’s hard to quantify this small surface defects, but they are an important factor for the fatigue.

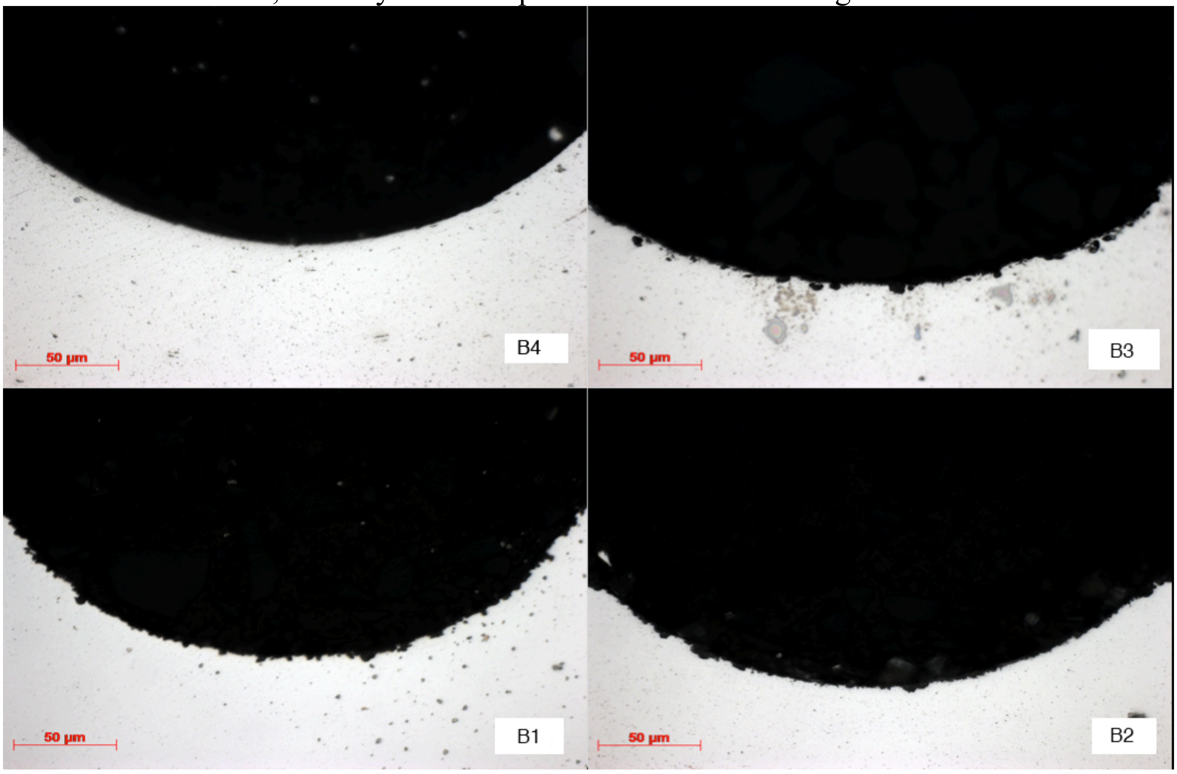

Figure 5.6 – Image of the thread roots and their surface structure.

6 Discussion

From the results it may look like the UHSS bolts are week when comparing to the B4. This is somewhat skewed since the B4 is an excellent bolt. Instead of comparing to the B4 one should compare with recommended design data for different type of bolts. From VDI2230 equation 5.5/19 with M14 and life length calculations for $2e^6$ cycles gives fatigue limit as 72,7MPa for bolts rolled before heat treatment and 87,6MPa for bolts rolled after heat treatment.

The results for B4 at 50% of its yield stress do not look like it is correct. B4 has threads rolled after heat treatment that should make the threads affected by mean stress. For the 50% load all fractures occurred in the bolt head radius, this explains why there is no difference between 70% and 50% loading for the 10.9. The head is manufactured before heat treatment and the threads are rolled after heat treatment, this makes the thread affected by a mean stress but not the head. Thus when the bolts head radius fractures no visible relation between mean stress and fatigue limit can be seen.

The results for the B1 are not straight off comparable with the other bolts. The B1 had a lot of fractures at the bolt head radius, which makes the fatigue limit for B1 lower then if it should have fractured in the threads. This should make the bolt less affected by the mean stress, but in the Haigh diagram a relation between mean stress and fatigue can be seen. This relation shows that the threads are somewhat increasing the fatigue limit of the B1 but how much and if any at the higher loads are impossible to say. To be able to make a decision if the B1 material are viable as an Ultra high strength steel bolt, more tests has to be done.

FEA modeling shows a theoretical difference of 10% in stress concentration between root radius 0.16mm and 0.2mm (Stephens, R et al. 2005). Same study showed a 40% difference in fatigue limit at mean stress 70% of yield strength when comparing threads rolled before and after heat treatment. At 50% of yield strength they had 70% difference in fatigue limit. If these values are applied to this thesis the B2 can be considered stronger than then B4. If this is correct then it could be useful to change from 10.9 to 14.9 when experiencing a fatigue fracture.

The figures of the thread roots where you can see the surface conditions are quite troublesome, Scania's bolt expert Anders Johansson stated that the reason for the difference could be something small such that the manufacturers have the wrong oil when rolling the threads. This should be investigated further, if its possible to manufacture this strong bolts with a smooth surface in the thread root.

Overall the fatigue data from the Sincotec 150kN are high. Swerea has conducted a research comparing B1 and a 10.9 bolt. They show the fatigue force to be 53±6,4MPa, for a mean stress of 0.7xRp. Comparing this with 81,6±7,5 from the Sincotec machine. It's hard to compare between the findings in this report and the findings from Swerea. They have chosen to use a fixed mean stress and vary the amplitude, while a fixed lowest stress was used in this report. Another difference is that Swerea has used values from stress-strain tests on the material, for this report nominal values were chosen. This difference in choosing actual values and nominal values makes the comparison easier in this particular case.
Swerea has chosen 0.7*Rp=0.7*1445=1011.5MPa as mean stress. In this report 0.7*Rp=0.7*1260=882, the mean stress then varies some but for example, with amplitude 104MPa the mean stress would be 882+104=986, which makes the difference of choosing actual values from nominal values low in this case.

The report from Swerea also showed some interesting results, the 10.9 bolt they used as a reference has a lower fatigue resistance then the B1. This is completely opposite of what has been shown in this report. This shows the difference between different bolts that has the same metric strength classification, and also proves that every bolt needs to be fatigue tested regardless of what strength classification they have.

7 Conclusions

From the results of this thesis there is one ultra high strength steel bolt that are good enough to be used in production at Scania, however it cannot be used as a replacement for 10.9 where the clamping force is sufficient but you still get a fatigue fracture.

B2 has a high enough fatigue resistance to be used in production, however there should be more tests done to verify quality between batches. If the fatigue limit needs to be raised for some reason there is always the option of rolling the threads after heat treatment and therefore increase the fatigue resistance. It was shown that it might not be such a benefit to roll coarse threads after heat treatment, as it is to roll fine threads, this concludes that if needed to increase the fatigue limit a fine thread bolt should be used with threads rolled after heat treatment.

The bolt B1 is not good enough in these tests, however there were a lot of head radius fractures, which might decrease the fatigue resistance. It is therefore not possible to make a conclusion about the material, only the bolt itself. More tests need to be done which is also described in recommendations

The ultra high strength steel from B3 have a low fatigue resistance compared to B1 and B2. This is really confusing because B3 has a large thread root radius and is rolled after heat treatment, there really are more factors favoring the bolt then vice versa. However the B3 has a greater ductility then the other bolts, which indicates that a non-uniform loading, could favor this bolt i.e. if the load consists of several smaller amplitudes then once in a while large amplitude, then the ductility should provide a better fatigue resistance. B3 has the highest yield strength at around 1500MPa, which makes performance engines where you change bolts after each race a great for application. This makes the B3 not viable to use in production for Scania.

8 Recommendation

The fatigue properties of the B1 material has to be investigated, a batch of B1 rolled before heat treatment with a large head radius should be ordered. These can then be compared to the B2, and then you could make a proper statement about the fatigue resistance between the different bolt materials.

Before taking these bolts into production the results from the hydrogen embrittlement tests should be analyzed to see that they could withstand this issue.

To test the hypothesis that a M16 10.9 can be replaced with a M14 14.9, there should be fatigue tests done on M16 bolts. The results from those tests can then be directly compared to the results in this theses, and give information if it is viable to change or not.

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