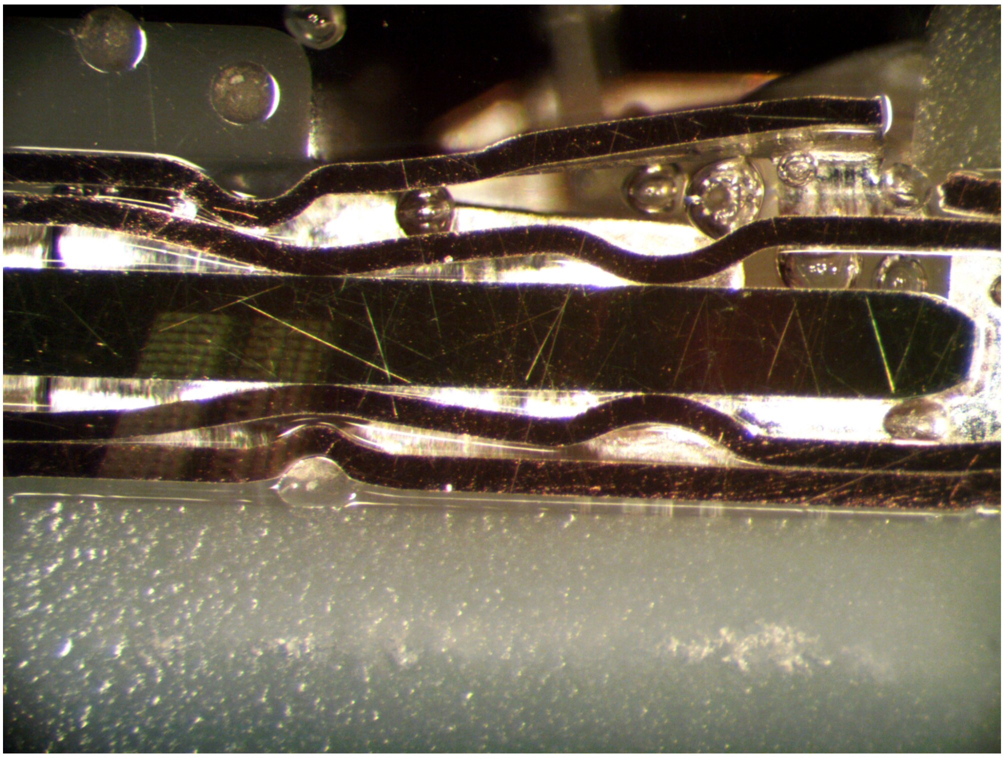


Fretting Corrosion in Electrical Connectors

The effect of temperature in electrical connectors and an evaluation of analysis methods for electrical connectors

Master Thesis in Industrial and Materials science

VILMA NORD

Department of Industrial and Materials science
Chalmers University of Technology
Gothenburg, Sweden 2020

Master thesis IMSX30

Fretting Corrosion in Electrical Connectors

The effect of temperature in electrical connectors and an evaluation of analysis methods for electrical connectors

VILMA NORD

Department of Industrial and Materials science
Chalmers University of Technology
Gothenburg, Sweden 2020

Fretting Corrosion in electrical Connectors
The effect of temperature in electrical connectors and an evaluation of analysis methods for electrical connectors
VILMA NORD

Supervisors: Mikael Lapinlampi, Volvo Cars
Håkan Ringius, Volvo Cars
Examiner: Mats Norell, Department of Industrial and Materials science

Master Thesis IMSX30
Department of Industrial and Materials science
Chalmers Univeristy of Technology
SE-412 96 Gothenburg
Phone +46 31 772 1000

The front page figure shows a picture taken in an optical microscope of a cross section of an electrical connector with terminals. The terminals can be seen going horizontally across almost the entire picture. The male terminal is the thick part in the middle and the female part is the wavy parts on either side of it. This type of contact has eight contact points per terminal four of which we can see in this picture.

Written in LaTeX
Gothenburg, Sweden 2020

Abstract

This thesis studies how fretting corrosion on electrical connector terminals are influenced by fretting as well as evaluating different analysis methods for studying fretting in industry produced electrical connectors. Fretting is a mechanism of degradation that influences surfaces meant to be stationary in regards to each other but due to for example vibrations a small relative movement exists. It is today largely unknown how temperature influence fretting and the methods currently used by Volvo cars to study this phenomenon in electrical connectors is mostly limited to optical microscopy.

A vibration rig was used to study the fretting phenomena. But before fretting tests could be done a fixture needed to be made and vibrations levels measured and analysed. Fretting tests where performed for 24h at 100 m/s^2 peak amplitude while sweeping from 100-2000 Hz. These tests where done at 8 different temperatures from -40 °C to 100 °C. Samples were thereafter analysed using optical, scanning electron and light interference microscopy.

It was found that temperature affected fretting in three ways. Firstly higher temperature resulted in higher amplitude relative motion between the terminals and larger fretting scar. Secondly temperature was found to influence the surface structure of the fretting scar. For colder temperatures more abrasive deformation was found where as for higher temperature there were more adhesive deformation. Lastly it was found that the plating thickness degraded faster at higher temperature. On another note SEM microscopy was found to be very useful when analysing fretting and provided many insights which would have been hard to achieve with only optical microscopy. The light interference microscopy however was not found useful in this thesis but this was more likely due to the instrument and not the method.

Contents

1 Introduction

Volvo car has been producing cars since 1927. The car was originally a mainly mechanical machine with no electrical components but throughout the years more and more electrical components have made their way into the car. Today we even have purely electrical vehicles on the market but also hybrid cars as well as traditional combustion engine cars with several electrical features. More electrical components naturally also lead to more electrical connectors in cars. Since many of today's electrical systems are vital to the cars basic functions as well as security systems it is important that the lifetime of these electrical systems is the same as for the car itself. In the electrical systems the connectors are a vulnerable part. One mechanism known to degrade electrical connectors and increase connection resistance is fretting corrosion. An increase in connection resistance is bad for electrical systems since it lowers the signals quality and this lowering may cause systems to malfunction or completely break down. Fretting is a type of degradation that happens as a result of relative motions often caused by vibrations. Cars have many sources of vibrations which come from vital parts of the car such as the engine and the wheels. When we cannot eliminate the cause of the problems we need to study how to minimise the damage caused by fretting. For this reason the study of fretting corrosion in general and that on electrical connectors is important since it is still an area where much is unknown.

1.1 Previous studies

There have recently been two thesis works done at Volvo Cars about fretting corrosion in electrical connectors. In 2017 Xing and Xu [1] measured relevant engine vibrations with accelerometers in a four-cylinder engine test rig. Vibrations fretting tests for 20 hours was conducted and fretting damage studied and the relative movement measured. Maximum relative movement tended to decrease during the test and they attributed this to an increases in surface roughness. Xing and Xu also attempted to measure resistance during the test but no change was found. Also they found the resonance frequencies for the fuel pump. Lastly the authors attempted to simulate the fretting wear using FEM and they found that the wear area and position was similar to that found in the microscope on real fretting tests. [1]

In 2018 Magnusson [2] measured the displacement of the terminals in comparison to the housing and found that they differed. How much it differed varied between connectors as well as male and female parts. Generally the more parts the housing contained the bigger the difference was found to be. He also tried to shift the resonance frequencies by altering the weight and rigidity of the housings but with limited success. [2]

1.2 Aim

The aim of this thesis is to study whether temperature influences fretting in one type of electrical connector as well as analysing ways to study the phenomenon of fretting corrosion using vibrations testing in an industry lab environment.

1.3 Limitations

Since this study was done in collaboration with Volvo Cars it was limited to methods and materials that could be found at Volvo Cars in Torslanda. Due to limitations in time the number of analysis methods evaluated was limited to SEM and two different optical microscopy analysis. One other limitation was the choice to study only one type of connector as well as the choice to only study temperatures between -40 °C and 100 °C.

2 Theory

The theory of fretting and of several analysis methods used will be presented in this section.

2.1 Fretting

Fretting corrosion was first discovered and correctly analysed as a mechanical phenomenon in 1911 [3]. The phenomenon was however given little attention for many years. The term fretting corrosion was termed in 1927 by English physicist Tomlinson [4] who was one of the first scientists to closely study the phenomenon. Fretting became a popular area of study in the 1950s. At this time the phenomenon had been know for several years and it had many alternative names such as ”friction oxidation” and ”wear oxidation” [5]. Fretting is defined as ”A special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force.” by the ASM in 1996 [6]. Another definition is found in a more recent paper by Park et al from 2007 [7] as ”an accelerated surface damage occurring at the interface of contacting materials subjected to small relative movement”. Fretting can be found in any application where there is small relative movement between two or more metallic surfaces. Example of such applications are ball bearing, machine elements and the focus of this study electrical contacts.

Fretting corrosion is a complex problem that is not fully understood yet. Several aspects influence the damage: such as contact conditions and dynamics, environmental conditions and material properties.[5] Fretting comes in three different forms: fretting wear, fretting corrosion and fretting fatigue. Fretting wear is when the micromotions cause wear and loss of material to one or two of the surfaces. Fretting corrosion have the added element of oxidation where the wear particles and/or the surface layer oxidise. Fretting is also known to cause fretting fatigue where cracks in the materials form as a result of stress in the material. These cracks in the surface is known to propagate further into the material under further stress. Depending on application this may weaken the structure and shorten the lifetime of the product.[5]

Micromotions is the main factor influencing fretting in electrical connectors. The relative motion is typically in the order of 1-100 μm in amplitude [8]. The frequency is determined by the driving mechanism ranging from high frequency vibrations to low frequency temperature cycling [9]. There are several other factors affecting fretting including contact normal force, contact tangential force, environmental conditions, contact material, as well as the presence of lubricants [5, 10]. When the micromotions cause oxidised wear particles they can speed up the degradation of the plating layer of the terminals by being ground in between the two surfaces. In electrical contacts these particles can also induce temporary signal losses due to the oxide not being as electrically conducting as the metals they stem from are.

The rise in contact resistance due to fretting is believed to be caused mainly by the following three processes [9]. Firstly oxidation of the surface and any wear debris give rise to the contact resistance since metal oxides generally have significantly lower electrical conductivity than their respective metals. Secondly accumulation of wear debris between the two surfaces, wear debris that accumulates between the surfaces cause the two parts to lose direct contact and only have indirect contact through the debris. This generally lowers the contact area as well as making it unstable since the debris tend to move around with the micromovements. The third mechanism is loss of contact force due to wear and loss of material in the two parts of the contact. Loss of material can also lead to a complete loss of plating exposing the core materials which in general have less stable electrical contact. [7–9]

2.2 SEM and EDX

A scanning electron microscope (SEM) is an electron microscope that produces its image by scanning the specimen sample with an electron beam and detecting electrons emitted from the sample. There are several different types of emitted electrons that can be measured but the two most common ones are secondary electrons (SE) and backscattered electrons (BE). Secondary electrons have energies in the order of 50 eV and this relatively low energy gives them very short mean free paths in solid material and only electrons from the very edge of the material can be detected. SE images therefore give good topological contrast and the small interaction volume of detectable electrons make spatial resolutions less than 1nm possible. Electrons that are reflected back via elastical scattering on the specimen surface are called backscattered electrons. The intensity of backscattered electrons are highly dependent on the atomic weight (Z-number) of the specimen. Therefore the method is useful in analytical SEM since different materials can be seen with different intensities. Even though the main strength of BE mode is its ability to differentiate different materials it can still be used to image topography within the same material. Backscattered electrons have higher energies than secondary electrons and therefore they have a longer mean free path in solid material and the detected electrons have a larger interaction volume which results in slightly lower spatial resolution than for SE images. [11]

Energy-dispersive X-ray spectroscopy (EDX) usually accompanies SEM and is used to identify which elements make up the surface as well as mapping which areas have more or less of certain elements. Since the electrons in the SEM electron beam occasionally knock out core electrons of the specimen EDS is generally a feature in most SEM instruments. When a higher level electron relax to fill the electron hole the specimen emits a photon with energy exactly correlating to the energy difference between the two electron energy levels. These energy differences vary between atoms and each atom has an X-ray fingerprint that makes it possible to identify which atoms as well as how much there are in the sample by comparing measured X-rays to known data from tables. X-ray photons have relatively long mean free paths in most metals and because of the large interaction volume that allows the spatial resolution is significantly lower for EDX than it is for SEM. [11]

2.3 Laser vibrometer

A laser vibrometer is an instrument that measures small displacements over time. When used to measure vibrations frequency and amplitude are the main data one gets from using it. Laser vibrometers consists of a laser, detector, a brag cell for phase shifts, and several optical features such as: mirrors and beam splitters guiding the light inside the vibrometer. The laser beam is split into a reference beam and a beam directed at the sample. The beam directed at the sample passes through a bragg cell to give it a phase shift. The detector then measures the doppler shift of the reflected laser beam in relation to the referance beam.[12] The doppler shift is related to the velocity of the sample as

$$f_d = 2v(t) \cdot cos(\alpha)/\lambda \tag{1}$$

where $v(t)$ is the velocity of the sample and α is the angle between the laser and velocity vector and λ is the wavelength of the laser light.

3 Electrical Contacts

An electrical contact consists of two main part the male part and the female part. When connected the male part is inserted into the female part. Each part consists of a plastic housing and one or several metal terminals. The terminal connects to the wire leading the current and the housing provides electrical insulation as well as mechanical stability for the contact. All parts used in this thesis where produced by Tyco Electronics and a cross section of the used contact can bee seen in Figure1. The terminals have a copper core and tin plating, copper is the most commonly used core material because of its good electrical conductivity [8]. Tin is also a common plating material because of its good corrosive properties as well as general low cost [13]. Other common plating materials are Silver and Gold which have superior properties but due to cost tin is often used if it is good enough. What determines what plating material is required is both the environment but also voltage and current levels. Low voltage and current requires nobler plating due to more sensitivity to resistance increase due to surface oxides [13]. More noble plating is however also commonly used in high voltage applications as well if there is a concern about the heat development than an increase in contact resistance would bring.

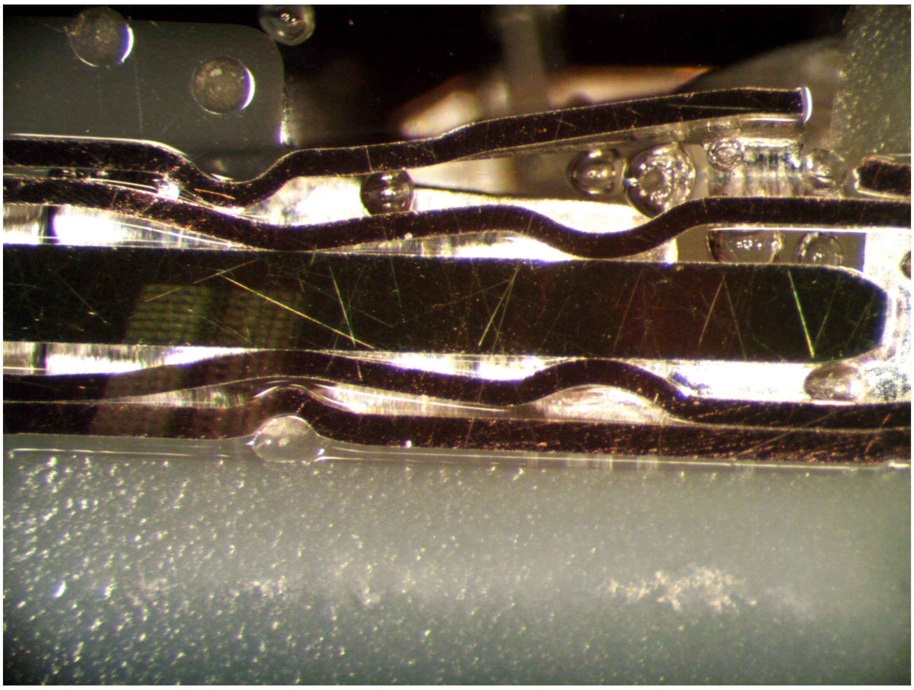


Figure 1: This figure shows a picture taken in an optical microscope of a cross section of one of the electrical connectors used in this thesis. The Terminals can be seen going horizontally across almost the entire picture. The male terminal is the thick part in the middle and the female part is the wavy parts on either side of it. This type of contact has 8 contact points per terminal four of which we can see in this picture.

The male housing used in these tests are made of 70% PBT (Polybutylene terephthalate) and reinforced with 30% Glass fibre. This is a plastic with good chemical resistance, high dielectric strength and high resistance (electric insulation) as well good strength and modulus at elevated temperature. [14, 15] It is generally accepeted as a good insulating material in electrical connectors.[16] The feamle housing is made of PA6 (Polyamide 6) reinforced with 15% Glass fibre. Just like PBT this plastic has a high electrical resistance.[17]

4 Studies of fretting in Electrical Connectors

Most studies of fretting available online are studies done not on actual connectors shaking but on individual ”terminals” where the relative movement is precisely controlled. The terminals tested come in a variety of materials but most have the configuration of the ”male” terminal in the form of a flat metal plate that is being kept stationary and a ”female” part where there is a small bump in the shape of a hemisphere on top of anther flat metal plated. This part is usually referred to as a rider and its motion is carefully controlled as it moves back and forth over the ”male” part.

Ito et al [18] and Han and Kim [19] both studied the influence of contact/normal force on fretting. Ito el al found that a higher contact force resulted in less fretting and also that a thicker tin coating resulted in higher resistance increase due to there being more tin available to form oxides. This last result is directly contradictory to how plating thickness is considered in the automotive industry. In general fretting wear is more often the cause of failure compared to fretting corrosion and therefore thicker plating is most often desirable. Han and Kim studied how normal force influenced fretting based on the gross slip vs partial slip approach. Partial slip is when the amplitude of the relative movement is small in comparison to the contact area while gross slip is when the amplitude is larger. In this definition the normal force influence how much relative movement the system can take before it moves from partial slip to gross slip. Han and Kim found that gross slip resulted in more fretting and higher oxygen content in the fretted surface. Both studies used SEM imaging in their analysis Han and Kim used top view SEM imaging to illustrate the difference in surface structure of the two different slip types. While Ito et al used SEM cross sections of their samples to image both tin oxides as well as intermetalic compounds.

Another interesting study was done by Murell and McCarthy [10] where they studied intermittances as a result of fretting. An intermittance is when the contact resistance temporarily spikes over a threshold value for when the electrical system no longer functions correctly. The effect of an intermittance varies with application and timing but they may cause both undetected malfunctions as well as complete system failure. Tests where done on both copper to copper interface as well tin to tin. Contact resistance was closely tracked. Intermittances both in height and duration as well as a time average of the resistance was tracked. They found that the number of intermittances rose with an increase in the average contact resistance. Intermittances varied in length fro 20 ns up to several ms. The majority of the intermittances however was in the 1ms order of magnitude.

Similarly to this study Park et al [7] studied the influence of temperature on fretting. Their tests where done in the temperature range of 25-100 C°. The authors measured both resistance and friction during the experiments. The approach in this study was to define contact failure at 0.01 Ω and track if the contact failed within the time span of the test and how long it took before it did. They found that contact lifetime decreased with an increase in temperature. Friction measurements as well as surface roughness calculations found surface roughness to peak at 85 °C. This was explained by the that under 85 °C temperature increase resulted in an increase in oxidation resulting in more surface roughness and over 85 °C the increased temperature softened the tin enough for the surface to become smother. It was also found that the resistance increase varied drastically for span amplitude over and under 30 μm. This may indicate that temperature influence gross slip and partial slip differently. The slopes in the over 30 μm range is different for the different temperature. However for under 30 μm the slope is approx the same for all temperatures.

5 Methods

All tests where performed using shaking rigs which can be set to a specific time, frequency spectra and peak acceleration. Different setups for mounting the connectors to the rigs where used as well as different evaluation methods. All setups and methods used will be presented and described in the following two sections followed by a summary of which setups and methods where used during which tests.

5.1 Setups overview

During this thesis three different main setups where used as well as a laser and mirror setup used for 2/3D laser vibrometer measurements. The setups for mounting the connectors to the vibrations rig where used at different stages throughout the experiments.

Setup 1

The first setup which were based on an already existing baseplate for the fixture can be seen in Figure2. As seen in the picture the setup consists of four metal blocks which holds the connectors screwed into a metal baseplate. This baseplate had several screw holes in it from old setups. Due to these old holes the desired symmetry was not satisfactory achieved. When things are vibrated very few things are absolutely rigid and since the shaking rig had a cylindrical symmetrey it can be expected that the differences in vibration amplitude will also have a cylindrical symmetry. If the four samples should be comparable after the tests it is important that they are subject to the same vibrations spectrum and this can only be achieved if they are spaced with cylindrical symmetry on the metal base. It can bee seen in Figure2 that all the connectors do not have cylindrical symmetry.

Figure 2: The first setup with the old baseplate with many holes in them. This also limited where and how the blocks holding the connectors could be placed and therefor the desired symmetry could not be reached.

Setup 2

For this setup a new baseplate was constructed, apart from not being filled with old holes this plate was also slightly smaller and thicker. This was done in an attempt to give the system more rigidity and stability. This setup can bee seen in Figure5a. We can see that there is higher symmetry here due to no longer being limited in placement and angle due to old existing holes.

Setup 3

The third setup was done on a smaller rig with a much smaller base. Due to this only one block holding the connectors would fit. This limits the amount of samples that could be produced. This setup is seen in Figure3 where the connector is the black bit with red cables sticking out. We can also see the two accelerometers used as the small metal blocks at the end of the blue cables and the temperature sensor as the end of the green cable.

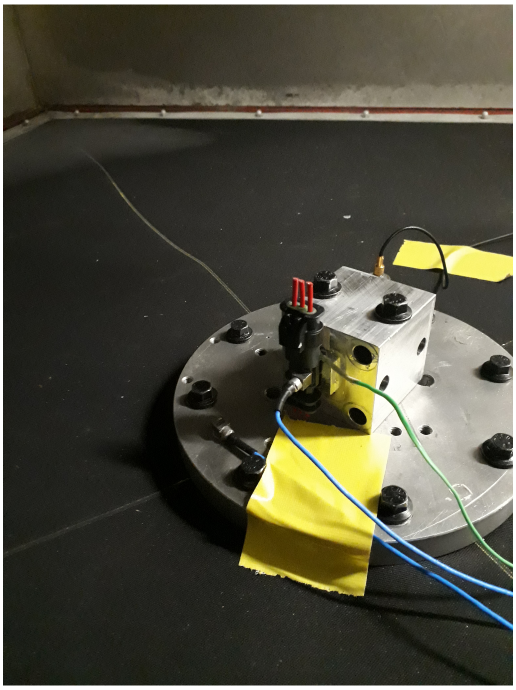


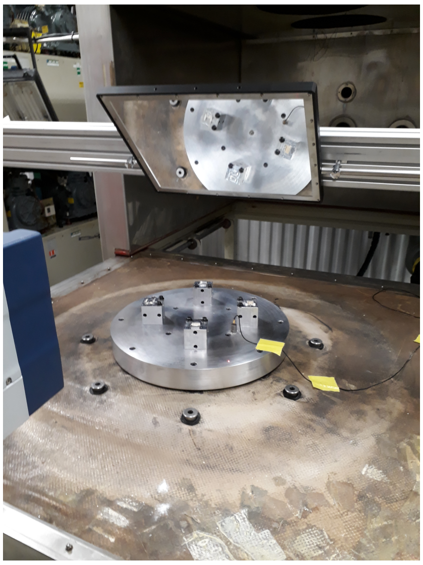
Figure 3: Photograph of the new setup inside the climate chamber with the smaller rig where only one block holding a connector would fit effectively. We see the connector as the black bit with red cables sticking out the top of it. A temperature sensor is attached at the side of the male housing (green cable) as well as one accelerometer (blue cable).

Mirror and 3D laser vibrometer setup

A 3D laser vibrometer set was used to better understand how different parts of the setup moves when vibrating. The set consisted of 3 laser vibrometers, see Figure4, and a computer with software to control the vibrometers. A setup where the lasers hit the rig via a mirror angled at 45 deg was built as seen in Figure5. The area that was measurable was greatly restricted by the size of the mirror.

The mirror and 3D laser set was only used in combination with setup 2.

Figure 4: The three lasers in the 3D laser vibrometer set. All three lasers aimed straight at the 45° mirror.



(a) Photograph of the mirror seen from the lasers.

(b) Photograph of the mirror setup seen from the side.

Figure 5: Fotos illustrating the mirror and laser setup in relation to the metal baseplate that was studied.

5.2 Measurements overview

This section explains all the measurements and analysis methods used on the three different setups.

Vibration measurements with accelerometers

Vibrations levels measurements using accelerometers where used frequently on all setups. The accelerometers can be seen in Figure2 and 3 as the blue cables ending in a small block. For all vibrations measurements using accelerometers the vibrator rig was set to do sine sweeps from 100Hz up to 2000Hz and down again. The peak amplitude response was measured at different points both on the connectors and on the base. The cables to the accelerometers are taped down due to the fact that free flying cables has been known to influence the accelerometers. When analysing the setups vibration levels on all metal blocks (connector positions) where measured to compare whether or not the four positions where similar enough for samples from them to be comparable. The accelerometers on the connectors where always glued onto the same spot of the male housing.

2D and 3D laser vibrometer measurements

2D measurements where performed which use only the centre laser which is the rightmost laser seen in Figure4. The calibration of this was much simpler than that of the 3D measurements using all three lasers. When measuring the laser scans the surface one spot at a time making high resolution measurements over a large area very time consuming. The mirror size was the biggest limiting factor in what area could be studied but for 2D measurements it was possible to study the entire base plate. The downside to only using one laser is that only movement in the z- direction is measurable.

3D measurements where performed only on a very small area since only the area that can be seen by all three lasers via the mirror can be studied. To study a larger area either a larger mirror or a different setup would have been required. The setup and calibration for the 3D measurements is also more complicated as well as time consuming compared to the 2D.

Measurements using 2/3D laser vibrometers method can only be done at one frequency at a time unlike accelerometer measurements where a sweep was used. Several different frequencies where measured, both at known resonances (from accelerometers) as well as for non resonance frequencies.

Temperature control

A climate chamber which encloses the vibration rig and the setup was used to control and change the temperature. Eight different temperatures where used -40 °C, -20 °C, 0 °C, 20 °C, 40 °C, 60 °C, 80 °C and 100 °C. The climate chamber varied a couple of degrees in temperature even after reaching ”equilibrium” at the desired temperature.

Fretting tests

All fretting tests where performed in the vibration rig with a sine sweep from 100 Hz up to 2000Hz and down again cycling for 24h with an peak acceleration of 100 m/s^2. The contact where later pulled apart and the terminals analysed in an optical microscope. The purpose of these tests is not to be comparable to what happens at any particular place in a car but to study trends. This is a simplified scenario as well as an accelerated scenario with fewer parameters to keep track of and less time consuming than in tests done in cars. The aim of this type of tests is to identify which parameters influence the fretting damage and how. The assumption is then that what is better or worse in this scenario will also be better or worse when the connector is placed in a car.

5.3 Performed tests

All tests using which setup and which measurements can be seen in table 1. The purpose of the first three tests were to evaluate and find a good fixture to perform the temperature controlled fretting tests on. The forth test was meant to be the final test but due to this test failing and the rig breaking down during the first 24h fretting cycle another rig and setup had to be procured so that the experiments could be finished, this was the purpose of test 5 in setup 3.

Table 1: A summary of all tests performed and which methods was used in which test.

Test nr	Setup nr	Acc	2/3D laser	Temp	Fretting
1	1	Yes	No	No	No
2	2	Yes	No	No	Yes
3	2+Laser	No	Yes	No	No
4	2	Yes	No	Yes	Failed
5	3	Yes	No	Yes	Yes

The fretting tests from test number 2 was only analysed in a multifocus optical microscope with the purpose of determining whether or not the rig was symmetrical enough for comparisons between positions to be valid. For test nr 5 however all samples were analysed in the multifocus optical microscope (All 384 contact points) and then one terminal (both male and female part) from the -40 °C, 40 °C and 100 °C sample was analysed using SEM microscopy (BE mode and EDS) and a Keyence VR5200 microscope that can measure surface topography.

5.4 Evaluation test, epoxy

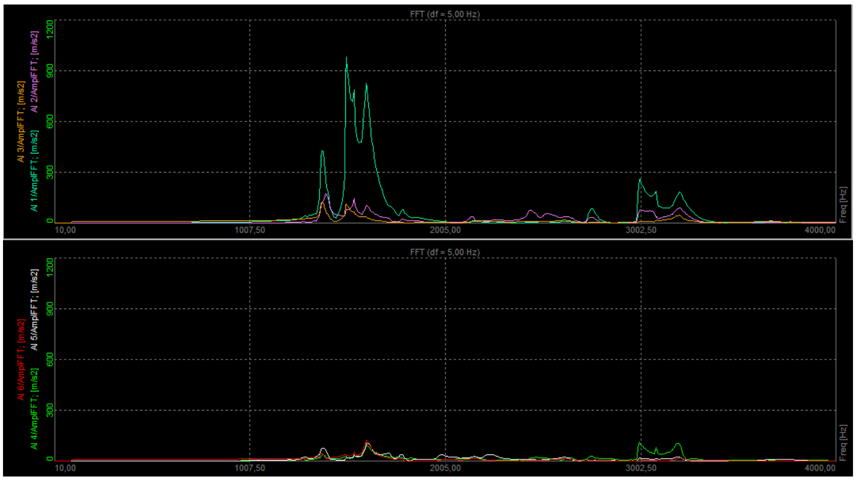
One option for evaluation the terminals without pulling the male and female parts apart is to incase the entire contact in epoxy and file it so the cross section of the fretting damage can be seen. SEM (backscattered electrons and EDS) images of all six cross sections of one test object were taken. At each cross sections all the would be contact point where examined and the thickness of plating both at the contact points and next to it was measured.

6 Results

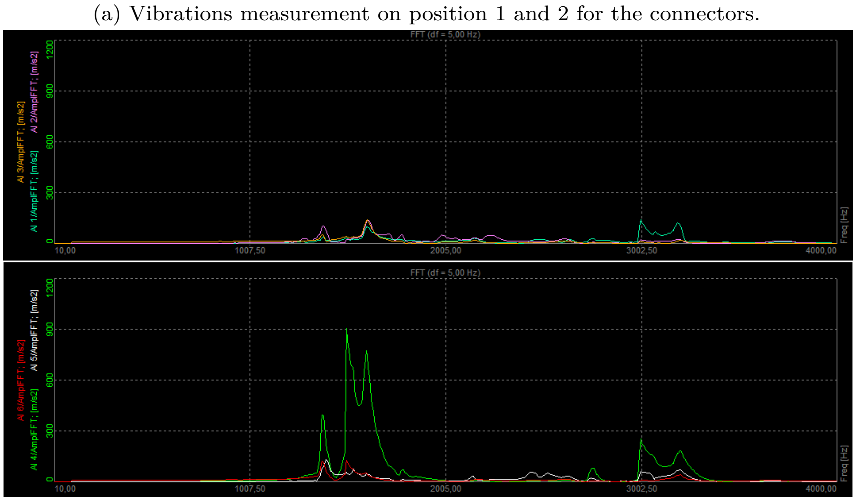
The results from all the tests described in Section 5.3, Section 5.4 and Table 1 are presented in this section.

6.1 Tests 1 and 2, Fixture evaluation and vibrations measurements.

The main results from these two tests come in the form of vibration measurements. All figures in this section display the peak acceleration on the y-axis and the frequency on the x- axis. In each of the figures there are three curves of different colours these track the acceleration in the x, y and z direction of the accelerometer. The ideal plot would be for the z-component to be constant and the x and y component to be zero for all frequencies. This would show the scenario where the rig only moves up and down and with the same amplitude for all frequencies which is what the rig is supposed to do.



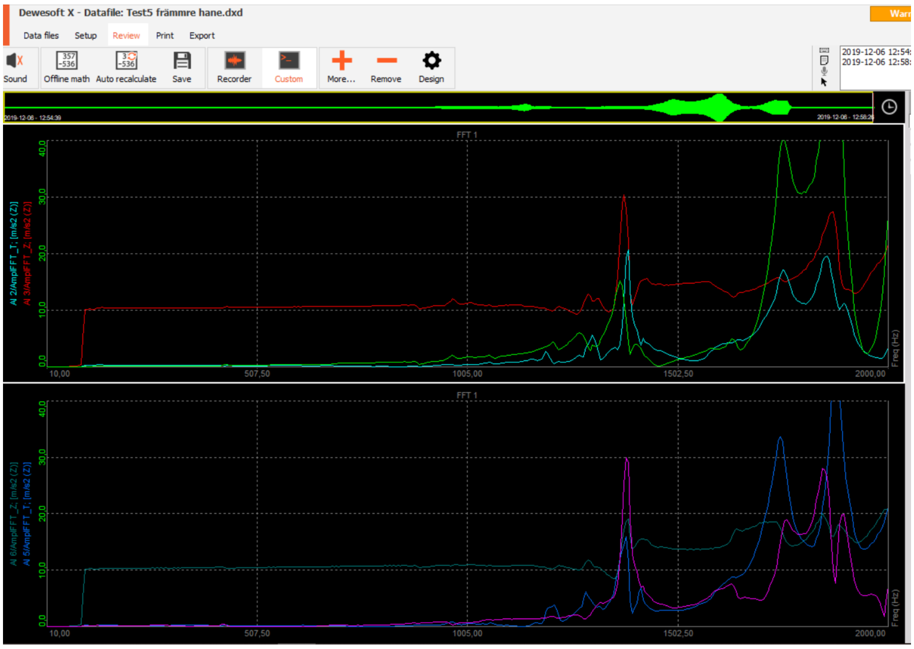
(a) Vibrations measurement on position 1 and 2 for the connectors.



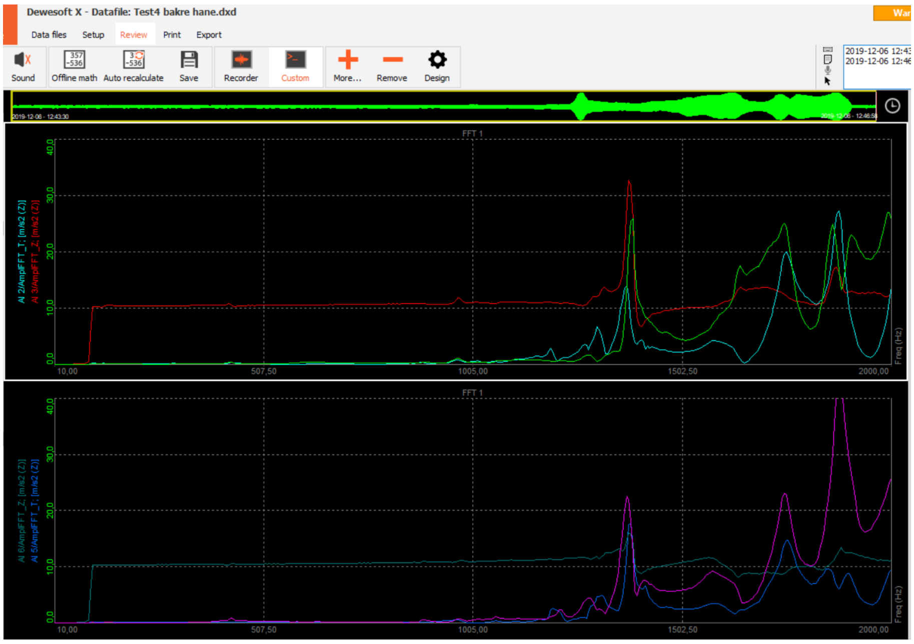
(b) Vibrations measurement on position 3 and 4 for the connectors.

Figure 6: Vibration levels results for all four positions of the connectors. We see that position 1 and 4 have much higher resonance peaks than position 2 and 3. This show that one side of the setup had much more movement for certain frequencies than the other did. In the top plot in both images the orange curve shows the z- directions and in the lower plot red is the z-direction. With this in mind we see that the unwanted sideways movement is much higher than the desired up and down movement.

Results of test 1 was that two positions on one side had 10 times higher resonance peaks at 1500Hz than the other side as seen in Figure6. The Figure shows the fourier transform of the vibrations spectrum. The relatively thin baseplate as well as all the holes where believed to be a cause for this. This was the motivation for producing setup 2 and doing test 2.



(a) Accelerometer measurements at male casing at two of the four positions. Notice the high vibration levels in the x- and y- directions when the vibration rig is supposedly only moving in the z-direction (red in top picture and turquoise in the bottom picture).



(b) Accelerometer measurements at male casing at two of the four positions. Notice the high vibration levels in the x- and y- directions when the vibration rig is supposedly only moving in the z-direction (red in top picture and turquoise in the bottom picture).

Figure 7: Vibration spectra from all four positions from test 2. We see that the extreme difference in resonance frequency amplitude of positions 1 and 4 vs 2 and 3 is no longer apparent here.

Figure7 shows the fourier transformed vibrational spectra measured at each of the four positions in test 2. We see that apart from vibration in the z-direction, which is the direction the rig supposedly vibrates in, there is also a lot of movements in the x- and y- direction. Not only is this movement unwanted but it also varies between the different positions. However the resonance peaks are now all in the same order of magnitude compared to test 1.

Results of the fretting tests on test 2 was that position 2 and 3 showed similar fretting levels while position 1 and 4 differed. This means that for further fretting tests position 2 and 3 are comparable and would allow for two samples to be tested at the same time. Due to the failure of test 4 and the subsequent change of setup these results where never used.

6.2 Test 3, Vibrations measurements using Laser vibrometers

The 2D laser vibrometer measurements showed several different vibrational behaviours that was rather unexpected. Both ”Rotational” movement (Figure 8) and out of phase movements (Figure 10) as well as ”wave” movement diagonal across the metal plate (Figure 9) was found. Different movements was found at different frequencies but together they can explain a lot of the sideways movement found by the accelerometers during test nr 2. Another result of this is proof that a 5 cm thick steel plate is in no way rigid over 1000 Hz at 100 m/s^2.

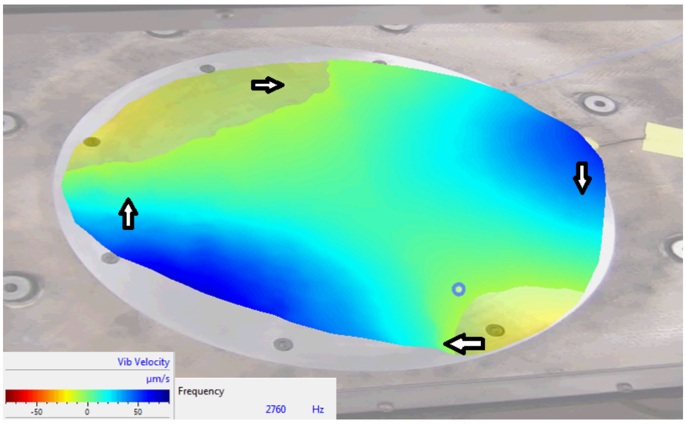


Figure 8: This figure shows the instantaneous velocity of all parts of the baseplate captured with the 2D laser vibrometer. The arrows indicate how the peaks and valleys move during one vibration cycle. In this one the two peaks and the two valleys move in a circular motion around the outer part of the plate while the middle remains mostly stationary.

There where no conclusive results from the 3D measurements due to that only a small part of the baseplate was measured. It did however confirm that there was significant movements in the x- and y-direction.

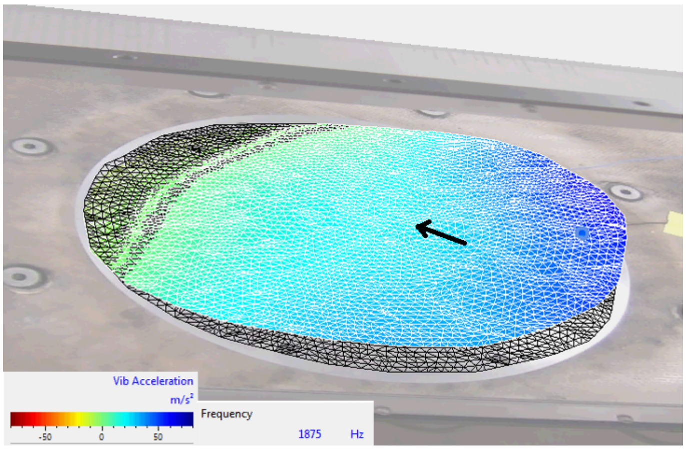


Figure 9: This figure shows the instantaneous acceleration of all parts of the baseplate captured with the 2D laser vibrometer. The arrows indicate how the peaks and valleys move during one vibration cycle. In this one there is one wave that moves diagonally across the baseplate.

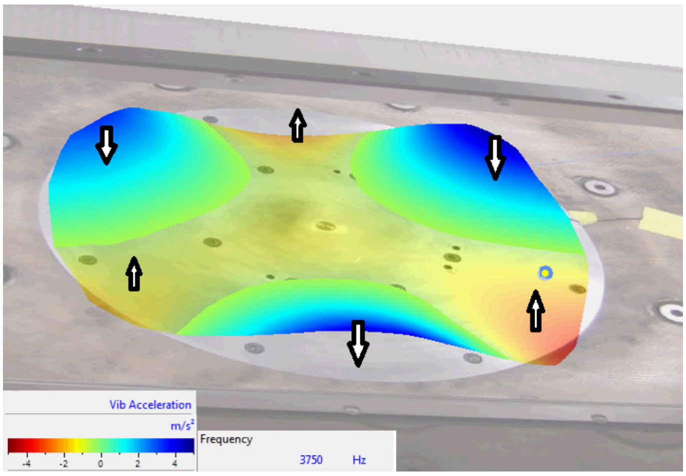


Figure 10: This figure shows the instantaneous acceleration of all parts of the baseplate captured with the 2D laser vibrometer. The arrows indicate how the peaks and valleys move during one vibration cycle. In this one the two peaks and the two valleys stay put in the same place but move only up and down. The different parts of the plate are out of phase but the paeks all follow the same movements. The nodes in between the different peaks are mostly stationary as is the middle of the plate.

6.3 Test 5, Fretting tests at different temperatures

Studying the optical microscope pictures there is a lot of variation and it is hard to get any certain results however the trend is that higher temperature have larger affected areas and that there are more cases where the plating gets so thin that the base copper material shines through. We can see this as the brown/orange colored areas in the rightmost picture in Figure 11. No contact point showed tendencies of oxidation or the corrosion side of fretting. Only fretting wear was observed. There where also found several cases where there was small holes in the plating even in ”undamaged” areas. This can bee seen as bright orange spots in Figure 12.

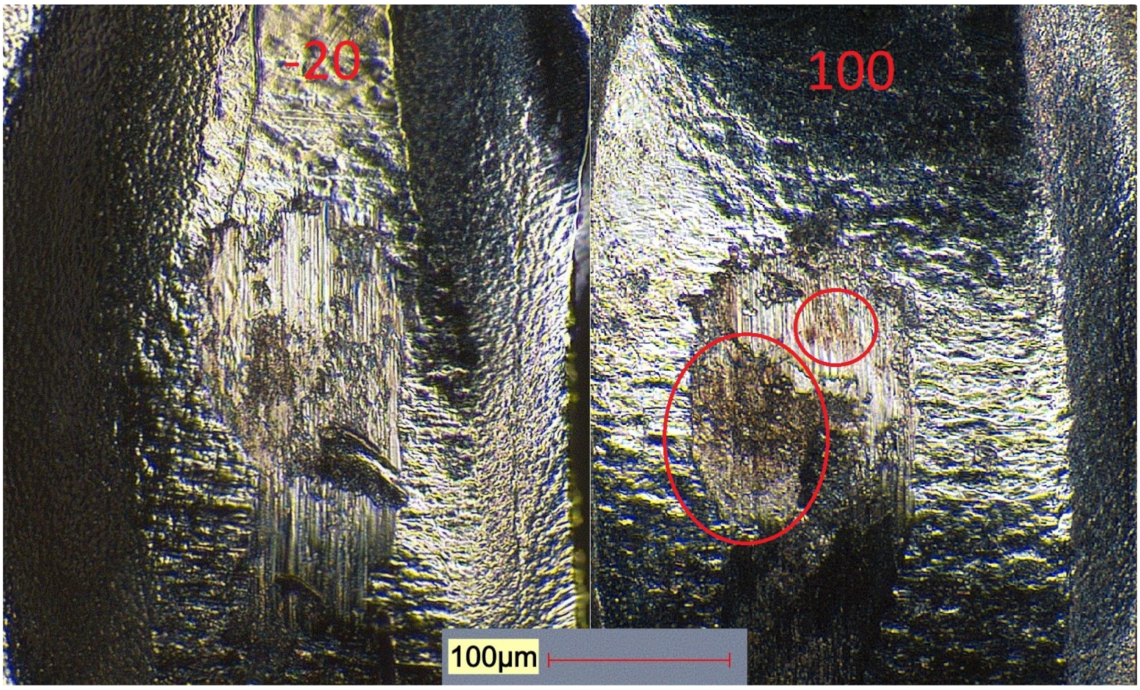


Figure 11: This figure shows two images taken with the optical microscope (both at maximum magnification) side by side. The left image shows the -20 ° C sample and the right shows the 100 ° sample. In the right image we can see that in the areas marked with the red circles the plating is no longer the silver/grey colour of tin but tends more to the orange/brown of copper. This is evidence that the plating is thin in these areas because the copper starts to shine through.

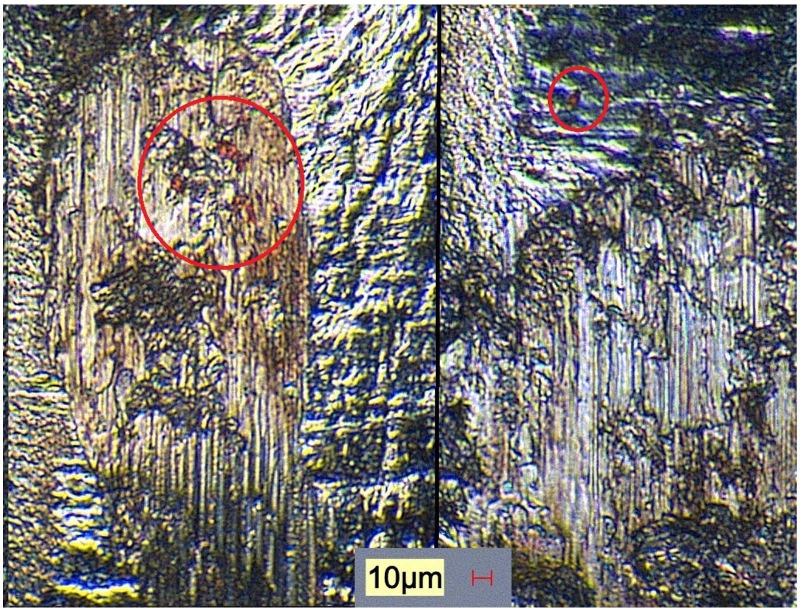


Figure 12: This figure shows two images side by side where we can see holes in the plating right through to the copper core material. The red circles mark the areas where the holes can bee seen. In the left image there are holes in the fretted area and therefore it is hard to know if they where there from the start or caused by the fretting but in the right image the hole are in an area unaffected by fretting. We can therefore conclude that the holes in the rightmost image is a result of failure in the production and not as a result of fretting.

Topography measurements

2D depth measurements couldn't tell us anything valuable due to the spatial resolution of the instrument being to low to be able to tell fretting damage apart from the general unevenness of the plating. An example of this is seen in Figure 13 where we in the top right and bottom picture cant tell the fretting damaged area apart from the rest. 1D measurements where also performed here the spatial resolution was not an issue but since the plating was so uneven there was not really possible to gain any valuable information from the topography curves. This can be seen of the bottom image of Figure 13.

Vibrations measurement

No clear trend could be seen by studying the vibrations measurements done during the fretting tests. All eight spectra have the same structure with one resonance peak at ca 1000 ±300 Hz and several smaller peaks at 1800-2000Hz. Peak position and amplitude for the first peak for all temperatures are presented in table 2. For the four lowest temperatures there is no trend but high variation. However for the 40 °C, 60 °C, 80 °C and 100 °C measurements there seemed like there could be a trend that the first peak decreased in amplitude while the other higher frequency peak increased in amplitude with higher temperature. But in general the error margin and uncertainty is too big to draw any conclusions without more data.

Table 2: Tracking of the peak position and amplitude of the first resonance peak.

Temperature [°C]	-40	-20	0	20	40	60	80	100
Peak position [Hz]	970	1085	980	1245	1190	950	810	770
Peak Amplitude [m/s^2]	243.7	245.1	207.8	302.3	282.2	164.1	152.6	130.6

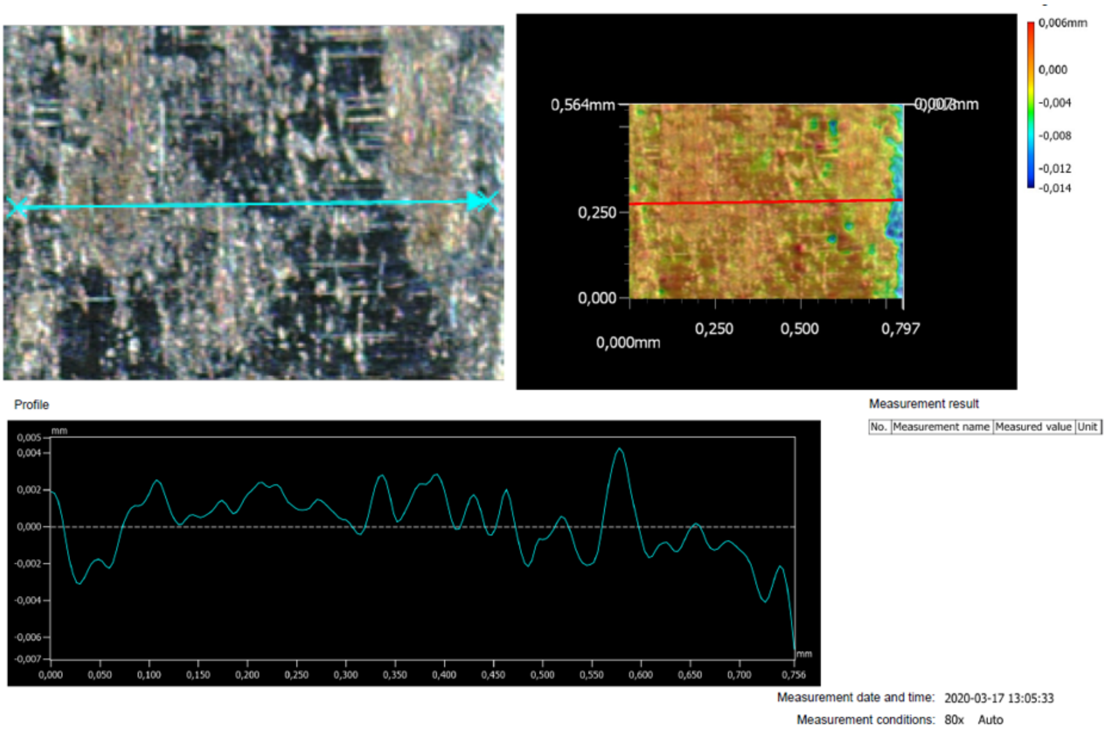


Figure 13: One image and measurement of a male terminal in the Keyence microscope. The top left shows an optical image of the studied area. Here we can see the fretting damaged area as the slightly browner and rougher parts at each side under the blue line. The top right image shows a topological mapping of the surface. Here we cannot see any significant difference between the fretted area and that beside it. The bottom image shows the height curve of the blue line in both the two top images. We see the general unevenness of the surface but we cannot tell the unevenness of the fretted area apart from that of the plating.

SEM results

The SEM images of both male and female parts of the -40 °C, 40 °C and 100 °C sample showed two clear trends. Firstly higher temperature resulted in a larger area being affected. This is an indicator that there was more relative movement for higher temperature. The second trend was that there was a difference in surface structure. The -40 °C sample, one example of which can be seen in Figure14, had a smoother surface with a lot of parallel groves in them indicating a simple polishing/ filing behaviour when the two surfaces rub against each other, this is known as abrasive deformation in tribology. The 100 °C sample, as seen in Figure16, on the other hand had a more uneven surface structure which was more patchy and had less of the parallel groves than displayed in the -40 °C sample. This is known as adhesive deformation where the two surfaces smear each other and not only simple filing. The 40 °C sample displayed a mix of the two structures, as seen in Figure15.

The "undamaged" plating did have some areas that where a lighter shade and some that where darker since BE SEM mode gives contrast based on atomic number Z this most likely is an irregularity in the plating alloy.

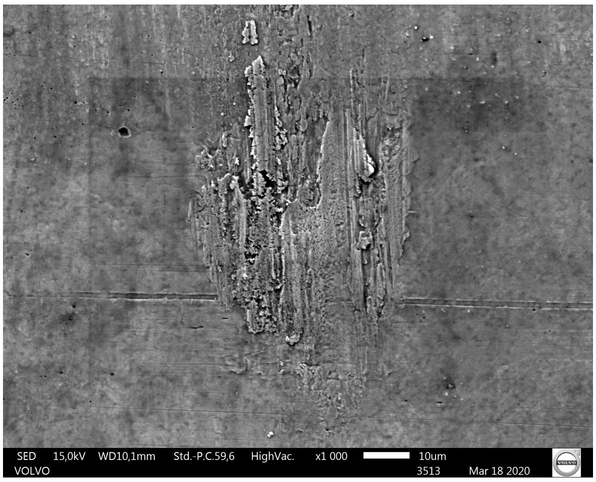


Figure 14: Top view SEM image of one of the fretted areas. This sample was fretting tested at -40 °C. We see a relatively small damaged area and mostly parallel striped groves that are characteristic for abrasive deformation.

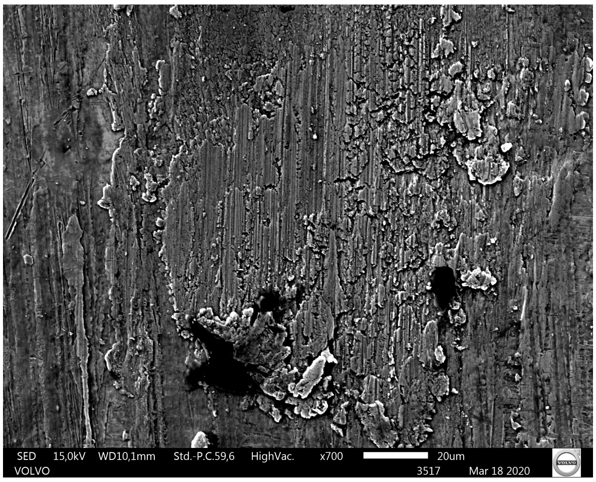


Figure 15: Top view SEM image of one of the fretted areas in the sample tested at 40 °C. We see a larger affected area than for the -40 °C sample (Figure14) and both the parallel groves characteristic to abrasive deformation as well as the more patchy structure of adhesive deformation.

EDS results indicate that the plating was worn down more for the 100 °C sample than the -40 °C sample. In the EDS mapping the 100 °C sample shows an area in the centre of the contact point where significantly less tin and more copper was found than in the surrounding undamaged material. This can be seen in Figure18 where the Tin mapping shows a darker spot and the Copper mapping shows a brighter spot in the center of the fretting affected contact spot. This was not found for the -40 °C EDS mapping as we can see in Figure17 where neither the tin or copper mapping displays any difference at the contact spot vs beside it.

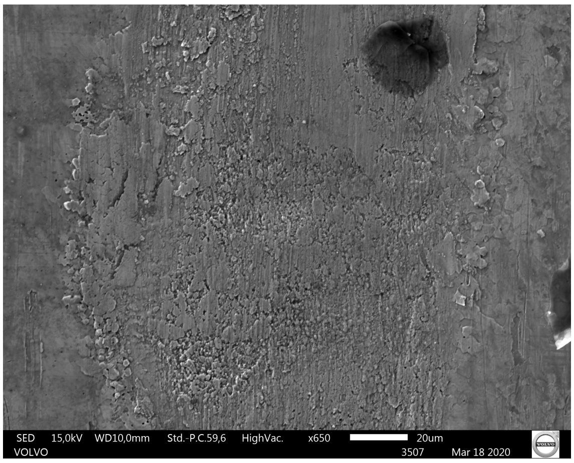


Figure 16: Top view SEM image of one of the fretted areas in the sample tested at 100 °C. We see a rather patchy surface and few of the filing groves seen in the samples from colder temperatures. This is characteristic for adhesive deformation. We can also see that there is a comparatively large area affected by the fretting.

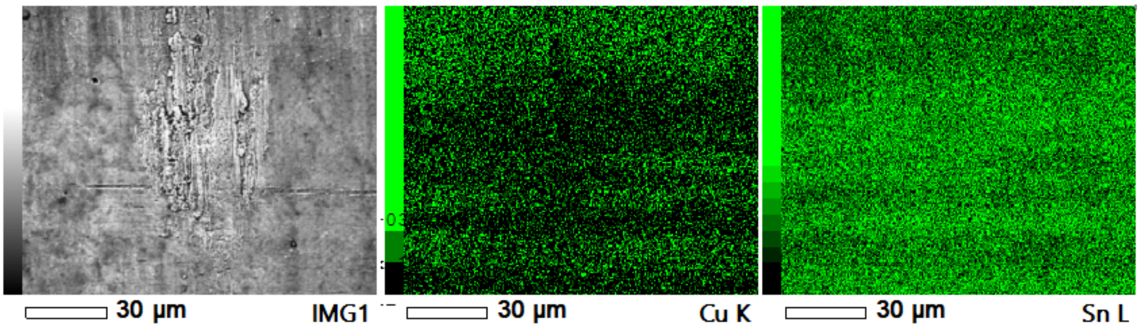


Figure 17: EDS mapping of Copper (Cu) and Tin (Sn) over the area in the SEM picture to the left. The image is of the sample from the -40 °C test. We see a slight difference in Copper and Tin concentrations in this area but since its shape (horizontal stripes covering the entire image) doent coincide with the shape and placement of the fretting scar this is most likely only an uneveness in the plating. More on this can be read about in section 6.4.

6.4 Cross sections of terminals

All 6 cross sections of the contact point of one sample with silver plated male terminals and tin plated female terminals where imaged using SEM. BE mode imaged very clearly what was plating and what was core material, see Figure19. The plating on the tin plated female was found to be very thin at the contact points 0.5-1.5 μm while being thicker at around 4 μm at other points. This might be an indication of fretting wear at the contact points or just unevenness in the plating. The plating in general was found to be very uneven and at places where there had been no contact between male and female part the female plating was found to vary between 1-4 μm, see Figure20. It was found that actually hitting the cross section of the contact point was very difficult and only 12 out o 24, which is 50%, of contact point where imaged. The difficulties with imaging the contact point is most likely not due to the method but an irregularity in their exact location on the terminals.

There was also an incasing done of an unused male terminals. Here the plating was also found to be very uneven and almost porous at some points, see Figure21.

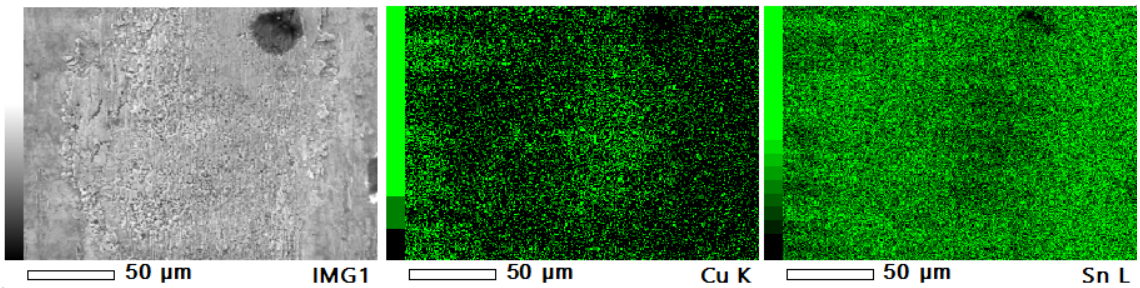


Figure 18: EDS mapping of Copper (Cu) and Tin (Sn) over the area in the SEM picture to the left. The imge is of the sample from the 100 ° C test. Here we see a higher concentration of copper (brighter green) and lower concentration of tin (darker green) in the centre of the affected area. This shows that the plating is thinner in that area.

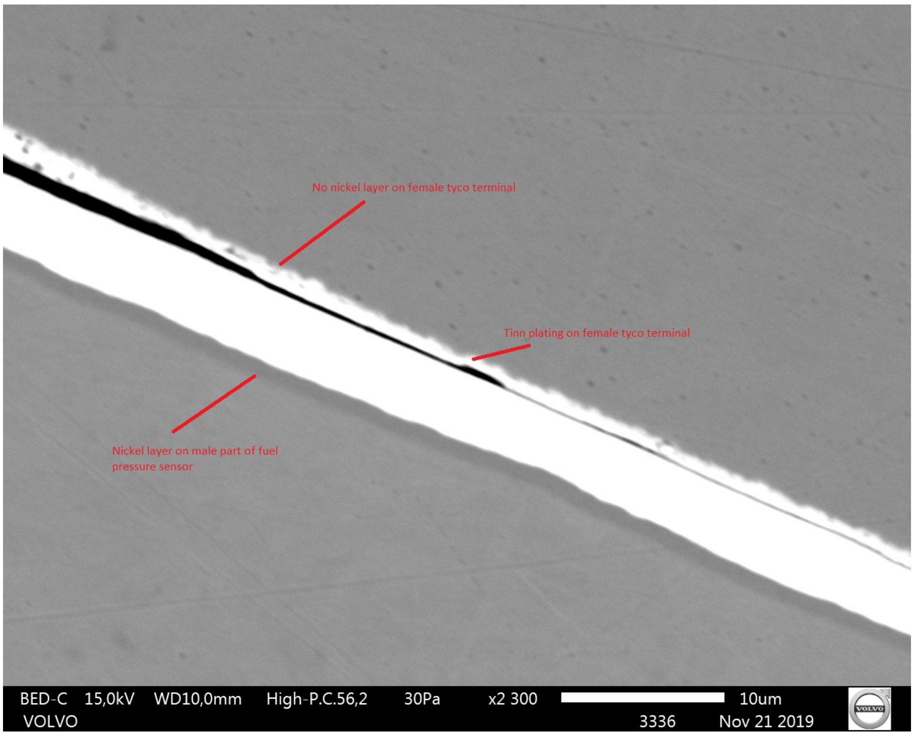


Figure 19: One of the cross section SEM images of a contact point. We can see all the different layers of plating and core materials in different shades.

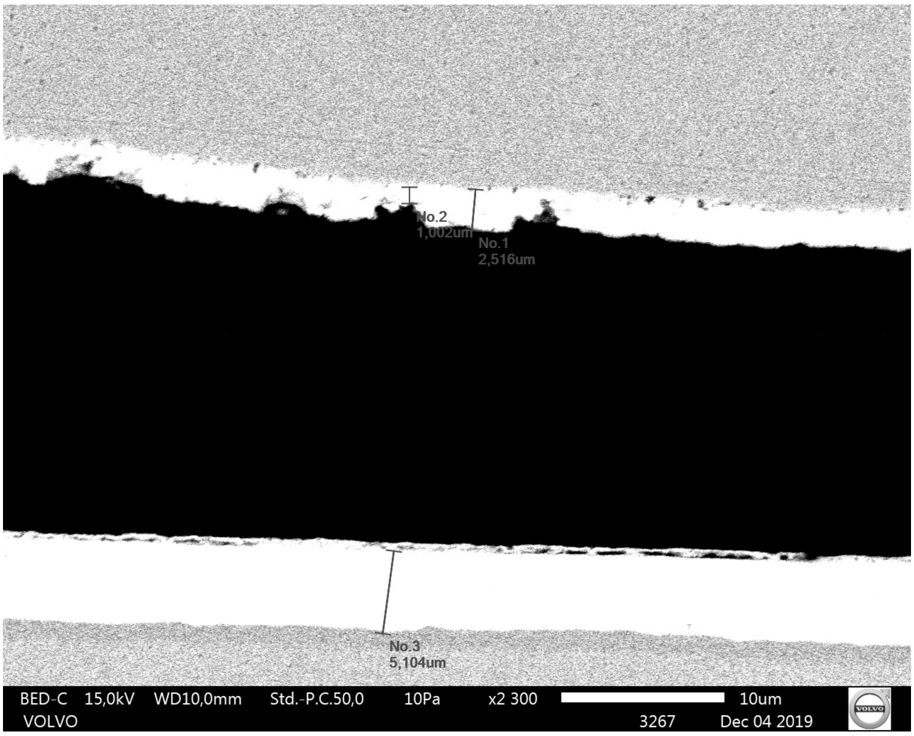


Figure 20: Cross section SEM image of connector next to one of the contact point. We see that the plating on the female terminal (Tin plated top part) is both thin and uneven.

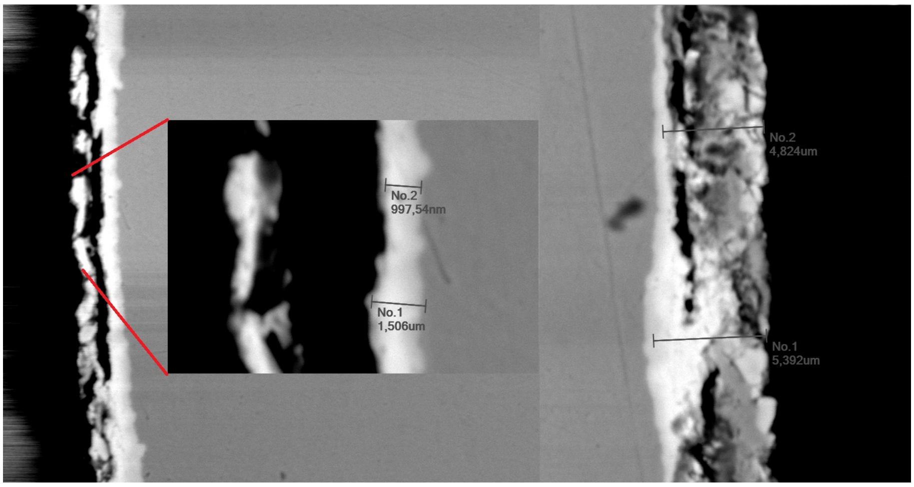


Figure 21: SEM cross section images of the two different sides of the tin plated male terminal. We see that the plating is uneven with large holes. Take note that the majority of the core material have been edited out of this picture to fit both edges into one.

7 Discussion

There are several relevant topics to discuss based on the results. Firstly section 7.1, 7.2, 7.3 and 7.4 discusses analysis methods used in this thesis and their relative merit where section 7.5 discusses the results of the fretting tests done at different temperatures.

7.1 Accelerometer measurements vs 3D vibrometer

When measuring vibrations in everyday tests accelerometers are far easier than Laser vibrometers to use due to the shorter setup time as well as lower cost. They are also more accurate at individual points than laser vibrometers but the 2D laser vibrometer tests in this study highlight the problem using accelerometers. At high frequencies almost nothing is rigid and measuring vibration levels at one point wont tell you anything about what happenes at the other points. Therefore if you have many points of interest Laser vibrometers will give you a more complete picture. Similar results can of course be obtained with several accelerometers but this approach quickly becomes impractical if there are many point of interest. For this application however accelerometers where enough for tracking vibration levels of the connectors. The main reason why one wouldn't want to use laser vibrometers is the complicated setup with three lasers that need to aim as straight as possible at the surface of study while being incredibly big in terms of dimensions as well as heavy (approximately 15kg each). Their size made it hard to angle all of them at the mirror without the centre laser blocking the two at either side.

7.2 Cross section SEM analysis

The method of taking cross section pictures in SEM was overall rather successful but very time consuming since for each cycle the sample had to pass through several different people. First to be filed down to the next desired cross section and thereafter wait for a SEM time and then also doing the microscopy. The SEM images provided valuable information both in terms of measurable plating thickness but also illustrating what materials where found where. In our test we didn't find any evidence of oxides but Ito et al [18] also used cross section SEM analysis and was able to image both oxides and Intermetalic compounds indicating that we didn't have any. Alternatively that we where less skilled compared to Ito et al and just didn't find them. It also gives a good understanding for how the connectors are designed and work in real life to see the cross sections. The main downside of this method is that it destroys the sample and that the sample cannot be studied further afterwards. The reasons this method was not used on the temperature fretting tests was twofold. Firstly due to the unfortunate events which led to setup 3 and only one connector being tested each time we didn't want to do this analysis on them as it would have destroyed them and not allowed any other analysis to be made. Secondly this process was very slow and at that point in the thesis work the time was running out and there was neither time for the process of this method or to produce the extra samples that would have been needed.

The SEM method also proved that there was a big problem with the tin plating of the terminals. The plating is as seen in figure 21 is very uneven to begin with as well as thin. This makes any kind of quantitative analysis on fretting wear almost impossible since we cant measure it before we start due to the measuring process destroying the sample and if we measure after fretting tests we can know how much wear there has been since we only know how thick the plating is now and not what it was from the start. This is one of the main differences between making experiments on industry produced connectors and perfectly evenly plated laboratory produced samples. Due to this we where only able to make qualitative analyses and not a quantitative one. But studying patterns allowed us to find a few interesting conclusions anyway.

7.3 Top view SEM and topography measurements

The top view SEM analysis was overall successful while the topography measurements with the Keyence microsccope wasn't. Top view SEM imaged the topography of the surface well and a difference in surface structure was visible in the images. This was possible due to the very high magnification achieved by SEM. What SEM doesn't show is a topography measurement i.e. height difference between different points and the possibility to calculate surface roughness. Park et al [7] successfully used a laser scanning microscop to image topography with high resolution as well as calculate the surface roughness. The Keyence VR5200 microscope used in this thesis however had too poor spatial resolution to provide any useful information on something on this small scale. We also ran into the problem that the terminals had a plating whose unevenness where on the same level as the fretted areas making them hard to distinguish from each other. It should be noted that fretting of terminals was not in the list of proposed applications by Keyence for this microscope. This is not a suggestion that Keyence microscopes are bad but only that this specific microscope was unsuitable for this purpose. As shown by Park et al measuring topography in this way shows promise as a useful method to further understand the surface structure and should be tried again but with a microscope capable of higher magnification and spatial resolution for example a light interferance microscope.

7.4 Fixture design and practical considerations in vibrations testing

In vibrations testing the fixture that attaches the test object to the vibration rig is important to consider. The difference in the results from tests 1 and 2 illustrated this. The vibrations results showed very different patterns and that of test 1 showed that there was a great asymmetry between the right and left sides of the rig. While test 2 showed much more uniform results than test 1 there was still some difference between the different positions as well as there still being significant sideways movement aside from the desired movement in the z-directions. The sideways movement was believed to come from the vibration rig itself. This was later confirmed with some non documented vibrations testing on the rig itself. The sideways movements from the rig may either be some resonance frequency of the rig itself or the years of use may have affected the rig so that the accelerating parts is no longer well calibrated or symmetrical. Even if the source of the undesired movements is the rig we see that the choice of fixture does indeed influence the results. The first baseplate had many undesired qualities compared to the second one. It was unnecessarily big in terms of radius as well as relatively thin and with several drill holes throughout. Which of these three factors that had the greatest influence in stabilising the setup with the second baseplate is impossible to tell without further study on the subject. It is however believed that a rigid and compact fixture is generally desirable.

The goal from the start was to test several connectors at once and to make that possible it was important that all of the tested connectors was subject to the same vibrations levels. Since few things are rigid at high frequencies it is therefore important to follow the vibrations rigs symmetry. The rig used in this thesis had a circular symmetry. The mounting points where spaced in circles of increasing diameter and therefore it was desired to have a cylindrically symmetric fixture in the hopes that all eigenmodes would be of a circularly symmetrical nature. The use of the 2D vibrometer showed that this was not always the case and therefore it was only two of the four positions that was found to have similar enough vibrations levels for the fretting damage to be comparable. In the end this information turned out to be useless for these expperiments since the rig broke shortly after reaching these conclutions but it may be valuable in future studies.

Another practical consideration is the accelerometer both in terms of where to put them but also the method for attaching them. The method used in this thesis was to glue them onto either the fixture itself or onto the male housing in a position close to where the male housing was glued to the fixture. While there is no particular reason to believe that gluing on the accelerometer influenced the results it also cant' be ruled out. Introducing the human factor in manually gluing both the male housing onto the fixture and then the accelerometer onto the housing is bound to end up slightly different each time. While it was attempted to be as consistent as possible this source of error may explain the variance found in the vibrations measurements done on test 5, see table 2. In this work it was chosen to attach the accelerometers to the male housing to track which vibrations the connector was subjected to. However if the goal had been to measure the connectors response to the vibration it would have been better to place them on the female housing. Furthermore if the goal had been to try and measure the relative movement one would put one accelerometer on either part of the connector. However as shown by Magnusson [2] it is not guaranteed that the relative movement of the housing would relate to the relative movement of the terminals.

7.5 Temperature influence on fretting

The results of test number 5 where fretting tests under different temperature was conducted showed that the temperature affected the fretting scar in three main ways. Firstly higher temperature resulted in larger fretting scars than lower temperature did. A larger fretting scar correlates to the relative movement of male and female terminals being of higher amplitude at higher temperature than lower temperature. The explanation for this increase in relative movement between the parts is most likely that elevated temperature softens the plastic in the male and female housing and therefore reducing the stability the housing offers the terminals. Secondly the surface structure of the fretting scar was found to be different at different temperatures at lower temperature it was found to be more abrasive deformation whilst higher temperature showed more adhesive deformation. The explanation for this result is that Tin is softer at 100 °C than at -40 °C and therefore allowing more interactions between the materials at the different sides such as smearing and material transfer. Thirdly the optical microscopy as well as EDS showed that the plating in the fretted area was thinner for higher temperatures than lower indicating that the plating is worn through faster at higher temperature. This is probably caused by the combined result of larger amplitude of the relative motion and softening of the tin at higher temperatures.

These results should be compared to the results found by Park et al in their study of fretting corrosion of tin plated contacts [7]. The main difference of their study to this is that theirs was done in a lab environment with laboratory produced contacts consisting of one slider and one perfectly flat "male" part. The relative motion was perfectly controlled both in amplitude and in frequency. The frequency of 10Hz was used for 20000 cycles this is a much lower frequency than used in this study and 20000 cycles at 10Hz lasts $\approx$33 minutes compared to the 24h the tests done in this study. The first result of this study can not be compared to the study done by Park et al since the setup was completely different. In their study the relative amplitude was one of the factors being controlled and they would therefore not see a difference in the area of the fretting scar affected by temperature as this study found shaking industry produced connectors.

The difference in surface structure was observed by them as well but approached in a different manner due to their starting terminals being flat, at least in comparison to the roughness of the fretting scar, they could calculate the surface roughness. This was not possible in our case both due to the limited spacial resolution of the Keyence VR5200 microscope available at Volvo Cars but also due to the surface roughness already present in the terminals prior to the fretting tests. Their results in terms of surface roughness was that it peaks at around 85 °C. They explain the increase in surface roughness between 25-85 °C by an increase in oxidation and the following decrease above 85 °C by the softening of the tin. Since they show no top view SEM images (only cross sections) of the fretting scar it is hard to make a direct comparison to the analysis done in this study but analysing their laser scanning microscopy images it does appear like they also have more adhesive deformation at temperatures of 100 °C and higher than they did for the lower temperature span.

Park et al [7] says nothing in their report of finding increased wear (In terms of plating thickness) in their study. Either it wasn't a parameter they chose to analyse or their tests was simply performed for too short a time for the difference to show up. The danger with wearing through the plating is mainly the exposure of a copper to copper interface which is known to be electrically unstable, hence why plating is done in the first place.

8 Conclusions

Studying fretting in real industry produced connectors is difficult as well as connecting it to research done in labs on laboratory produced connectors. However we did find in this thesis that temperature did influence the fretting in several ways both in terms of higher temperature allowing higher amplitude relative motion as well as more wear at higher temperature. Whether this increased wear was due to more relative movement at higher temperatures or the softening of Tin at higher temperature was not possible to establish but most likely both phenomenons contribute.

We also successfully managed to use SEM analysis to analyse samples of fretting both the cross section and top view SEM images provided valuable information that would have been hard to get via only optical microscopy which is the standard analysis method for fretting damaged connectors at Volvo Cars.

References

[1] Y. Xing and W. Xu, “Signal analysis of fretting damages on electrial connector systems”, (2017).

[2] M. Magnusson, “Fretting tests on connector terminals”, (2018).

[3] F. L. C. E. M. Eden W. N; Rose, “The endurance of metals”, Proceedings, Inst. Mechanical Eng, 875 (1911).

[4] G. A. Tomlinson, “The rusting of steel surfaces in contact”, Proceedings, Royal Soc., Series A **115**, 472 (1927).

[5] W. Campbell, “The current status of fretting corrosion”, in Symposium on fretting corrosion (ASTM International, 1952).

[6] “Asm handbook, fatigue and fracture”, ASM International **19**, 18 (1996).

[7] Y. W. Park, T. S. Narayanan, and K. Y. Lee, “Effect of temperature on the fretting corrosion of tin plated copper alloy contacts”, Wear **262**, 320–330 (2007).

[8] D. Chapman, *Copper in electrical contacts* (Copper Development Association Publication and European Copper Institute, July 2015).

[9] M. Antler, “Electrical effects of fretting connector contact materials: a review”, Wear **106**, 5–33 (1985).

[10] S. Murrell and S. McCarthy, “Intermittence detection in fretting corrosion studies of electrical contacts”, in Electrical contacts-1997 proceedings of the forty-third ieee holm conference on electrical contacts (IEEE, 1997), pp. 1–6.

[11] J. I. Goldstein, D. E. Newbury, J. R. Michael, N. W. Ritchie, J. H. J. Scott, and D. C. Joy, *Scanning electron microscopy and x-ray microanalysis* (Springer, 2017).

[12] P. Lutzmann, B. Göhler, C. A. Hill, and F. D. van Putten, “Laser vibration sensing at fraunhofer iosb: review and applications”, Optical Engineering **56**, 031215 (2016).

[13] G. Rules, “Amp incorporated”, (2004).

[14] G. Fellow, *Polybutylene tetraphalate - 30% glass fibre reinforced (pbt 30% gfr) material information*, `http://www.goodfellow.com/A/Polybutylene-terephthalate-30-Glass-Fiber-Reinforced.html`.

[15] N. P. Cheremisinoff, *Condensed encyclopedia of polymer engineering terms* (Butterworth-Heinemann, 2001), pp. 21–39.

[16] Omnexus, *Complete guide on polybutylene terephthalate (pbt)*, `https://omnexus.specialchem.com/selection-guide/polybutylene-terephthalate-pbt-plastic`.

[17] *Pa6 – polyamide 6 pa6 gf15*, `https://akro-plastic.com/productfilter/details/2482/`.

[18] T. Ito, M. Matsushima, K. Takata, and Y. Hattori, “Factors influencing the fretting corrosion of tin plated contacts”, IEICE transactions on electronics **90**, 1412–1416 (2007).

[19] D.-W. Han and H.-K. Kim, “Effect of normal forces on fretting corrosion of tin-coated electrical contacts”, Microelectronics reliability **79**, 321–327 (2017).