LUT UNIVERSITY
LUT School of Energy Systems
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*Jaakko Colliander*

# COMPARISON OF STEEL MATERIALS TO REPLACE THE CURRENT TROLLEY RAIL OF HIGH DUTY CLASS CRANES

Lappeenranta 18.3.2020

Examiner(s): Professor Harri Eskelinen
M.Sc Jari Jaakkola

**TIIVISTELMÄ**

LUT-Yliopisto
LUT School of Energy Systems
LUT Kone

Jaakko Colliander

**Comparison of Steel Materials to Replace the Current Trolley Rail of High Duty Class Cranes**

Diplomityö

2020

60 sivua, 21 kuvaa ja 11 taulukkoa

Tarkastajat:Professori Harri Eskelinen
DI Jari Jaakkola

Hakusanat: hitsaus, tribologia, lujat teräkset, kovat teräkset, kuluminen, nosturi, kisko

Tässä diplomityössä tutkitaan miksi korkean käyttöluokan nosturien lattakiskot ovat joissain harvoissa tapauksissa kuluneet aaltomaiselle kuopalle. Tarkoituksena on löytää sopiva hitsausprosessi, jolla voidaan hitsata teräsmateriaalia, joka olisi nykyisin käytettyä kiskoa kovempaa. Rautateillä on huomattu, että vaihtamalla kisko kovempaan materiaaliin saadaan kiskon kuluminen nimismiehen kiharalle loppumaan.

Tämä diplomityö alkaa tutkimalla vikaantumishistoriaa ja pyrkii löytämään yhtäläisyyksiä nostureista, joissa kuluminen on tapahtunut liian nopeasti. Jonkin verran korrelaatiota on havaittavissa nosturin lyhyen jännevälin ja nopean kulumisen kanssa, mutta koska vikaantuneita nostureita on vain muutama ja kaikkea tarvittavaa tietoa ei ole saatavilla mittaustietojen puuttuessa luotettavaa analyysia ei voitu suorittaa.

Vikaantumishistorian lisäksi tutkitaan kulumisen teoriaa ja pyritään löytämään kirjallisuudesta mahdollisia syitä kiskon kulumiselle. Todennäköisimmäksi syyksi kulumiselle todetaan pyörän olevan liian kova verrattuna kiskoon.

Kiskomateriaalin kovuuden kasvaessa hitsaaminen hankaloituu, tämän vuoksi tutkitaan hitsaamisen teoriaa ja suoritetaan hitsauskokeita, joissa pyritään löytämään sopiva hitsausprosessi sopivalle materiaalille.

Lopulta materiaaliksi valitaan SB500 ja sopivia hitsausprosesseja on kaksi, riippuen vaadittavasta iskusitkeysluokasta. Jos J0 riittää voidaan hitsaus suorittaa nopeasti, mutta jos nosturin käyttöympäristö tai asiakas vaatii J2 luokkaa täytyy hitsaus suorittaa useammalla palolla.

**ABSTRACT**

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**Comparison of Steel Material to Replace the Current Trolley Rail of High Duty Class Cranes**

Master's thesis

2020

60 pages, 21 figures and 11 tables

Examiners: Professor Harri Eskelinen
M.Sc Jari Jaakkola

Keywords: Welding, tribology, high strength steels, hard steels, wear, crane, rail

This thesis studies why flat rails on cranes with a high duty class have on a few rare occasions corrugated. The goal of this thesis is to find a suitable welding procedure for a suitable steel material that would be harder than the currently used flat rail. On railroads in has been noticed that using a harder rail removes corrugation.

This thesis begins by studying the failure log of the cranes where the rails have worn too quickly and tries to find similarities between the cranes. Some correlation is found between cranes with a short span wearing faster, but as there are only a few cases that have worn quickly and those do not have all the details available a reliable analysis cannot be conducted.

In addition to the failure log, theory of wear is studied in order to find possible root causes for the wear from literature. The hardness of the wheel when compared to the rail is discovered as the most probable reason for the corrugation.

As the hardness of the rail material is increased, welding becomes increasingly difficult to complete with an acceptable result. Therefore, the theory of welding is studied, and welding tests are conducted in order to find an acceptable welding procedure for an acceptable material.

In the end SB500 is selected as the new material, with two optional welding procedures, depending the required impact toughness class. If J0 class will suffice the rail can be welded quickly, but if J2 is required by the crane's environment or the customer, welding with multiple passes must be conducted.

**ACKNOWLEDGEMENTS**

Thank you Jari Jaakkola and Harri Eskelinen for active participation and guidance. Special thanks to Seppo Huhtasaari for professional work during our welding testing.

*Jaakko Colliander*

Jaakko Colliander

Lappeenranta 18.3.2020

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| d | Material thickness [mm] |
| E | Welding energy [KJ/mm] |
| $F_2/F_3$ | Welding geometry factor |
| I | Welding current [A] |
| Q | Heat input [KJ/mm] |
| $t_0$ | Preheating temperature |
| $t_{8/5}$ | Cooling time from 800 °C to 500 °C |
| U | Electric tension [V] |
| v | Welding speed [m/min] |
| | |
| η | Efficiency factor |
| | |
| AR | As rolled |
| CET | Carbon Equivalent Value SEW088 |
| CEV | Carbon Equivalent Value IIW |
| DQ | Direct Quenching |
| FCAW | Flux Cored Arc Welding |
| HAZ | Heat Affected Zone |
| MAG | Metal Active Gas |
| MIG | Metal Inert Gas |
| Pcm | Critical Metal Parameter |
| QT | Quenched and Tempered |
| TIG | Tungsten Inert Gas |
| TMCP | Thermo-mechanical controller process |
| USC | Units of Cracking Susceptibility |

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# 1 INTRODUCTION

Konecranes is the world leader in manufacturing lifting equipment with over 17 000 employees at 600 locations in more than 50 countries. Konecranes provides lifting solutions and services for manufacturing and process industry, shipyards, ports and terminals. Annual sales from 2018 were slightly over 3 billion euros.

Three different business units are active at Konecranes, service, industrial equipment and port solutions. Service business provides repair and maintenance and spare parts including full scale modernizations. Industrial equipment provides hoist, cranes and material handling solutions to a variety of industries, including paper and forest, waste to energy, automotive and metal production. Port solutions offers full range of products for shipyards, ports and terminals. Including equipment for container handling, bulk material handling and heavy-duty lift trucks.

Konecranes is committed to improving the safety and productivity of its customers' operations. To keep achieving this goal Konecranes must keep up to date on all technological advancements that could be applied towards the goal. (Konecranes, 2019)

## 1.1 Background and Motivation

It has been noticed that at some applications trolley rails are wearing out much faster than they should be. The wear has only occurred on cranes with a high duty class, which means the cranes are used non-stop all year and mostly carrying loads near the specified maximum. These cranes where the problems have occurred are all in ISO duty class M8, which is defined as 24-hour operation having maximum load 63% of the time. The rail is supposed to last the entire lifetime of the crane so between 15 and 30 years could be considered a minimum. In the cases where the wear has been faster than expected it has generally taken about five years for the wear to appear, and the fastest one taking only one year. Previous study has been concluded on the matter where three different solutions were studied, replacing the current rail with a harder material, replacing the wheel with a softer material or use a tribological coating on the rail to improve its durability. Out of these the harder rail was selected as the one to be studied further in this thesis, a separate study for changing the wheel is also being conducted at Konecranes, but not as a part of this thesis. The rail currently in use is standard structural steel with a typical hardness of 150 – 190 HB and the wheel is made from high alloyed steel and flame hardened to higher hardness when compared to the rail.

### 1.1.1 Research Problem

The wear type on the rail is corrugation, where the surface of the rail wears out by a pattern of small wavy bumps. The root cause of the wear is unknown, but the assumption is that it is due to fatigue caused by excessive surface pressure between the rail and the wheel. The reason for the excessive surface pressure is unknown. The problem can be fixed by replacing the trolley rail with a harder steel material, but those can be problematic to weld. The research problem of is this thesis is, can we find a suitable welding procedure for a suitable hard steel material that will stop the corrugation of trolley rails in cranes with high duty class?

### 1.1.2 Objective

The objective of this thesis is to select a steel material to replace the current rail and find a welding procedure that is able to provide acceptable end results, both mechanically and financially.

## 1.2 Goals and limitations

The purpose of this thesis is to compare several rail materials and select the best one to replace the current rail material used. The new rail material should be hard enough, so that the wear moves from the rail to the wheel, since changing the wheel is quick and cheap when compared to replacing the rail, but ultimately lifetime of both should be optimized. Also, the corrugation should stop, and the wear should become uniform across the rail and the wheel. As weldability tends to decrease with increased hardness, the selected material should be easy enough to weld to avoid further problems in manufacturing, so weld tests will be conducted on the materials as a part of this thesis to determine an acceptable welding procedure for the selected material. Availability and price of the rail should also be on a reasonable level.

As of now this problem has been limited to cranes used in high duty class applications, and the hoisting trolley used in those cranes is different than other trolleys, this thesis will be limited to this one trolley type. Wear has also been limited to flat rails, so this thesis will only focus on flat rails.

## 1.3 Structure

This thesis will begin by studying the theory behind the wear and suggest probable causes that could be behind the wear. The third chapter will introduce different types of rail materials that will be studied and proposed to fix the problem. The fourth chapter will study the welding of the harder and stronger steels in general. The fifth chapter will explain weld testing and analyze the results of the testing. At the end a summary of the rail materials will be concluded, and the best rail material will be selected accompanied with an acceptable welding procedure.

## 1.4 Failure log

There are seven cases where the rails have worn quickly in a corrugated pattern. Table 1 shows some basic data for the cranes where rail corrugation has been reported.

*Table 1 Failure Log*

| No | Rail | Rail hardness | Wheel Hardness | Span | Load | Duty Class | Temperature |
|---|---|---|---|---|---|---|---|
| 1 | FL70x40 | Unknown | Unknown | 19,8m | 10t | M8 | 0-40 |
| 2 | FL60x40 | Unknown | 53-55 | 19m | 16t | M8 | 0-50 |
| 3 | FL70x40 | Unknown | Unknown | 20,75m | 9,5t | M8 | -20 - +40 |
| 4 | FL50x30 | 170HB | 54-55 | 9,95m | 6,3t | M8 | 0-40 |
| 5 | FL70x40 | Unknown | Unknown | 28,28m | 11t | M8 | 0-40 |
| 6 | FL60x40 | Unknown | Unknown | 17,77m | 12t | M8 | 0-40 |
| 7 | FL50x30 | Unknown | Unknown | 19,4 | 7,5t | M8 | -20 -+40C |

Typically, it has taken around five to seven years of use for the problem to become visible. Except for cranes four, six and five, which are the extreme cases with only one year of use for cranes four and six and nine years of use for crane five. Based on this minimal data available, there seems to be quite a clear correlation between span and lifetime of the rail, where the rails of a crane with a shorter span wear more quickly. This is rather obvious as with a shorter span a single section of rail is under more frequent stress and it makes sense that it would wear more quickly. Crane six is an outlier when compared to the others as it has worn much faster than other cranes with similar loads and spans. We can also see from the table that load seems to have no significant impact as the cranes with similar spans and varying loads have worn at a similar pace. Most likely rail hardness and wheel hardness would have an impact on the wear rate, but unfortunately the data was not available outside a few cases. Collecting and storing this data is something that requires improvement in the future. The standard material certificates for the rails from suppliers are not including data for hardness at all, so that test is not done unless specified separately. But what we can see from the few cases where data is available, is that wheel hardness was on the upper limit of 55 HRC, which might suggest that the maximum allowed hardness for the wheels is just too hard. Some correlation also exists between rail width and lifetime for rail, where a wider rail lasts a longer time, which is natural due to the bigger surface area which results in less stress. But to make an analysis using this data is rather unreliable as there can be several factors in play and with only seven failed cases it is very difficult to make any solid conclusions.

Hardness measurement have been taken from the rail of the crane 4 and there it has been stated that the undamaged section of the rail has a hardness of around 170 HB, which is a typical hardness for the material. But in the damaged sections the hardness has increased to 230 to 300 HB as a result of work hardening. From the wheels of this particular use case, no hardness measurements have been taken after the crane has been installed to determine how much work hardening happens in the wheels during regular operation. But according to tests done for a guide roller using the same material as trolley wheel, just without flame hardening. It was found out that they would work harden from 250 HB to 365 - 452 HB. So the rail has hardened 60 – 130 HB, or 35 – 75% and the wheels have hardened 115 – 202 HB or 45 – 80%. Now as the wheel was not hardened in this case, it cannot really be used as a direct comparison, and this would require further testing. But at least for this case the wheel work hardens slightly more than the rail during use, which will make hardness difference higher than in the initial stage further increasing the problem.

This chapter introduced the problem, its background and a summary of all the known cases of rail failure.  The next chapter will focus on the theory behind the rail wear and tries to assess possible root causes for the wear.

# 2 RAIL WEAR

This chapter will study the theory behind the wearing and tries to assess possible root causes for the rail wear. There have only been a few cases of quickly worn rails against delivered high duty class cranes and there has been no thorough study concluded on these few cases. In the absence of details, assumptions will be necessary in order to speculate what could be the possible root cause.

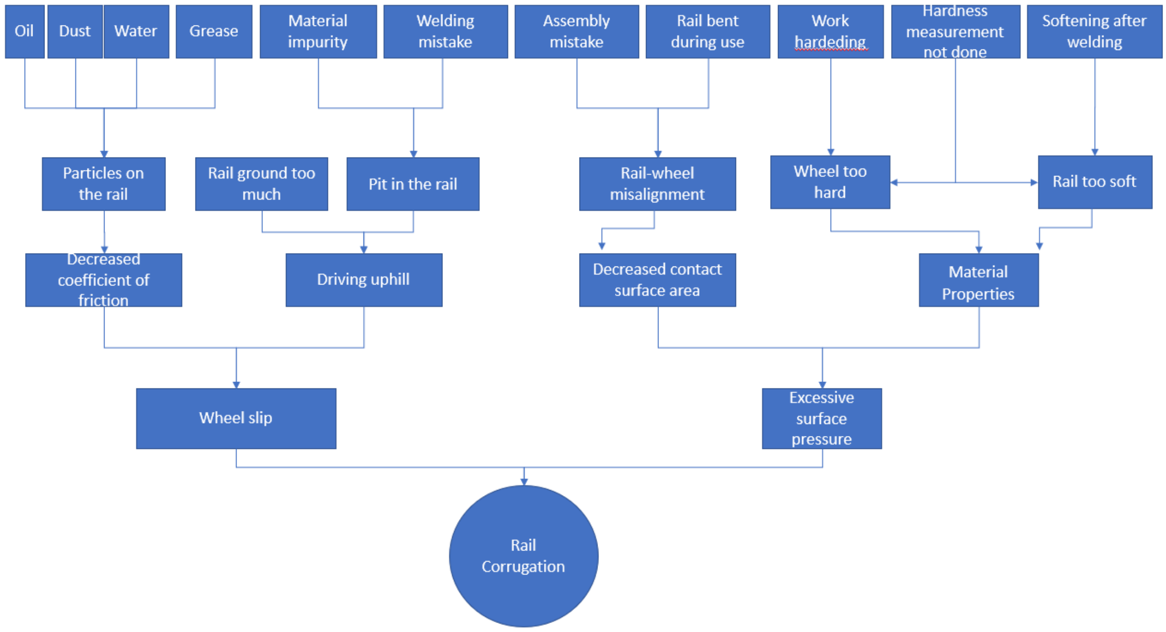


Figure 1 Failure diagram

Figure 1 shows a failure diagram for the causes that can lead to rail corrugation, these will be explained with more details in the following chapter.

## 2.1 Tribology

Rail corrugation is a common phenomenon from rail roads, but even the railroad industry has been unable to identify a solid root cause. Trains are a lot heavier and they move at a much faster speed than the trolley of the crane. The wheel geometry is also different between the two, but we can assume that the root cause for the two will be the same. In trains the corrugation is mainly found in curves and near stations, in curves the corrugation is found more often on the inside track which experiences higher forces than the outside track. The parts near the stations experience a lot of accelerating and decelerating. Cranes do not have any curves in them, but they do experience constant accelerating and decelerating. (Grassle, 2009, pp. 581-596)

In trains the wheel hardness is typically around 260 – 300 HB and rails are slightly harder than the wheels on the straight tracks, and in the curves sometimes bainitic or martensitic rails are used with a hardness up to 390 HB. (Straffelini, 2015, pp. 253-254)

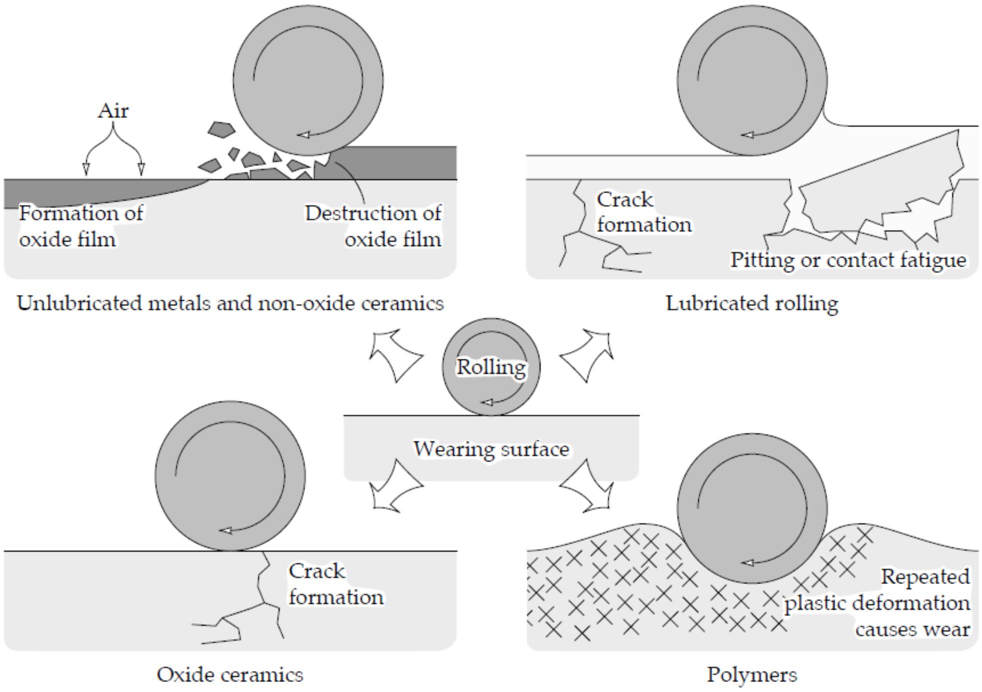


Figure 2 Wear types for rolling contact *(Stachowiak & Batchelor, 2014, p. 629)*

Figure 2 illustrates the different wear types that occur in case of rolling contact. When the wheel rolls on the surface of the rail it is called rolling contact, if the wheel slips on the surface of the rail it is called sliding contact.

The rail will oxidize over time under the influence of air and as the wheel will roll over the rail the oxidized layer will wear off. This wear type is common for all metals and other materials which can form this oxide layer. For the wheel, it is under near constant stress so there may not be enough time for the oxide layer to form. The same can also be true for parts of the rail, especially on cranes with shorter spans. However, the wear type caused by oxidation would be a smooth surface and not corrugated, so for this case this is not the root cause. Oxidation could be minimized or avoided by using lubrication but in this case, it is not a viable solution. (Straffelini, 2015, pp. 31-33)

The top right-hand corner of Figure 2 illustrates a case under lubricated rolling, so for this case it is not relevant. The same can be said about the bottom left-hand corner, this kind of crack formation only happens for very brittle materials or under extreme surface pressure. The bottom right-hand corner illustrates a case when one material is much harder than the other, the softer material will begin to lose its shape quite quickly. If the deformation of the softer material causes the geometry to change in a way that increases its surface area the deformation may slow down or stop. This wear pattern seems to fit this case the best. (Stachowiak & Batchelor, 2014, p. 629)

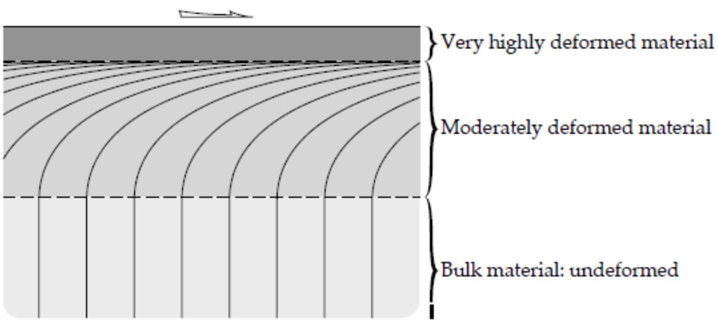


Figure 3 Deformation caused by sliding contact *(Stachowiak & Batchelor, 2014, p. 622)*

Figure 3 illustrates how sliding impacts the material below the surface. When the cross section of a badly worn material is studied, severe deformation can also be found under the surface of the material, where the cells have elongated to the direction of the sliding. These boundary zones are ideal spots where fatigue wearing may begin. In a crane though, the sliding does not always happen in the same direction as the sliding will depend on the direction where the trolley is driving. Unfortunately, no existing study was found on this kind of back and forth sliding, so we cannot know how the material would behave under such stress. (Stachowiak & Batchelor, 2014, pp. 622-623)

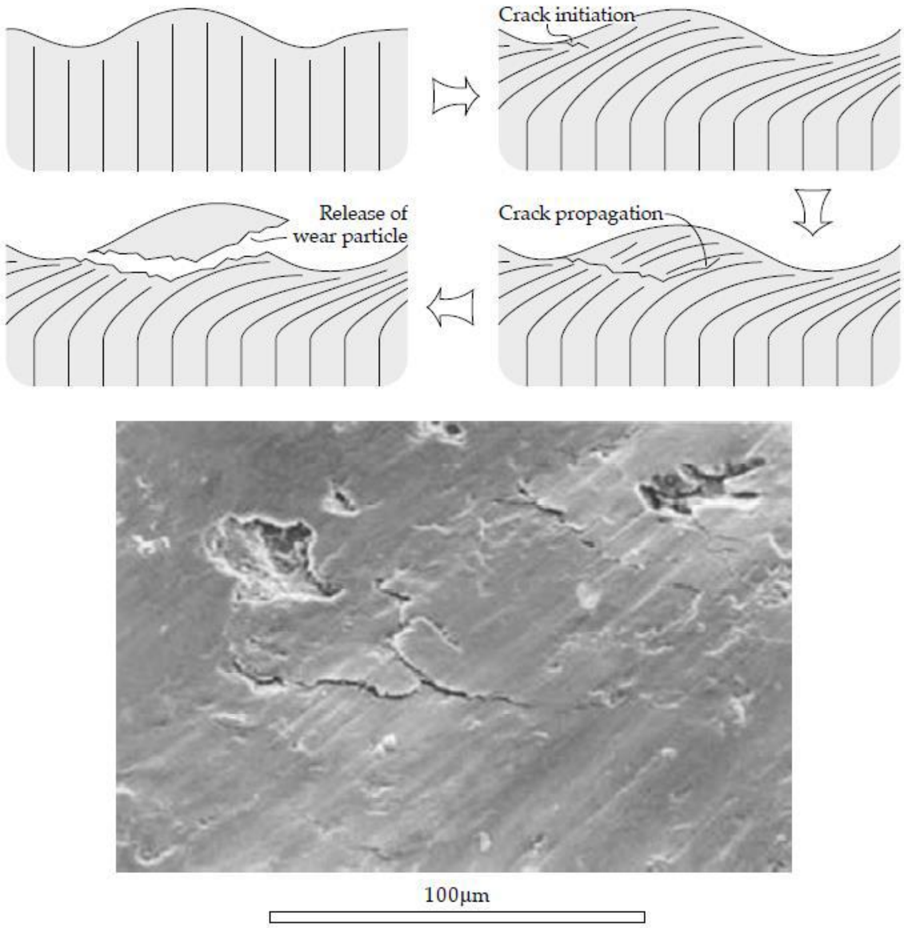


Figure 4 Wear caused by growth of surface-initiated cracks *(Stachowiak & Batchelor, 2014, p. 624)*

Figure 4 shows a minor crack on the surface of the material will slowly grow until it removes a small particle. Studies have shown that chemically active materials are more sensitive to sliding wear than noble metals. This is due to the fact that noble materials do not form oxide layers, which prevent the material from recovering and the cracks from closing back up.

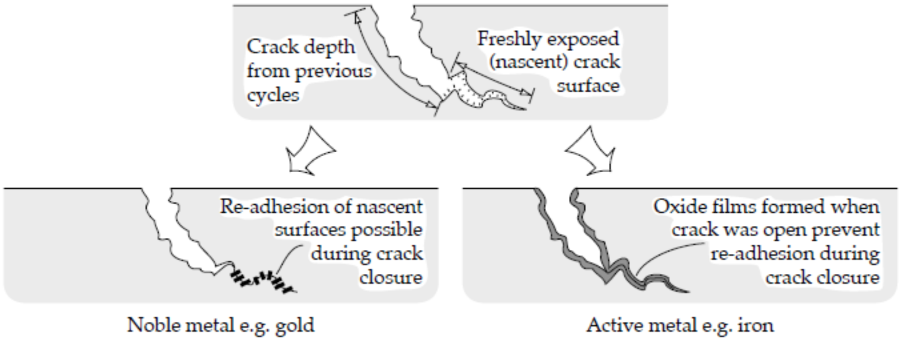


Figure 5 Effect of oxide film on crack propagation *(Stachowiak & Batchelor, 2014, p. 626)*

Figure 5 illustrates how active materials form an oxide film around fresh cracks rather quickly. The oxide layer prevents the re-adhesion of the crack and as a result the crack will continue growing. Noble metals do not form oxide films and it is possible for the cracks to close back up and slow down the wearing. It is possible to prevent the oxide films from forming either by using noble metals or by reducing the amount of oxygen in the atmosphere. (Stachowiak & Batchelor, 2014, pp. 624-627)

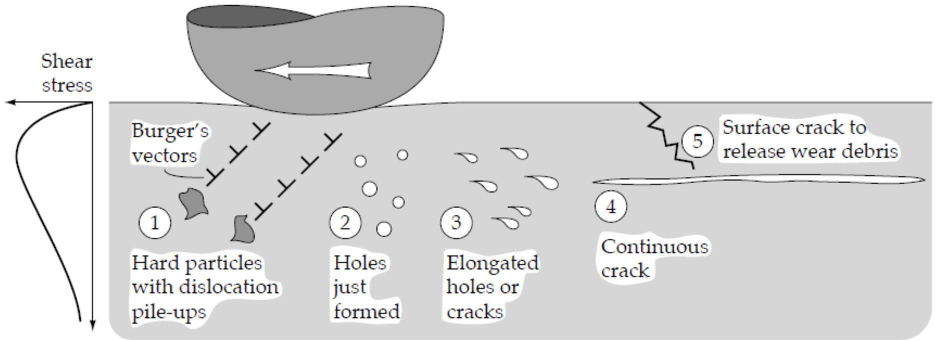


Figure 6 Crack formation under the surface *(Stachowiak & Batchelor, 2014, p. 627)*

It is also possible for crack propagation to start under the surface of the material and continue its growth there. Most materials have some sort of impurities in them, which allow crack propagation to begin, these are demonstrated in bullet 1 of Figure 6. These impurities are concentration points for stress and will slowly develop cracks that will continue growing parallel to the surface until at some point they turn towards the surface to release a wear particle. If all impurities could be removed from the material it could have a huge impact on the lifetime of the material. Under laboratory conditions it has been possible to achieve ten

times longer lifetime with completely pure materials, when compared to same material with impurities. (Stachowiak & Batchelor, 2014, pp. 626-627)
A relatively newly discovered phenomenon called plastic ratchetting is also related to sliding wearing. In plastic ratchetting small thin films of material are breaking off the material's surface. Ratchetting happens when contact pressure exceeds the elastic shakedown limit and is most common when one material is much harder than the other. The phenomenon is illustrated in Figure 7. (Johnson, 1995, pp. 162-170)

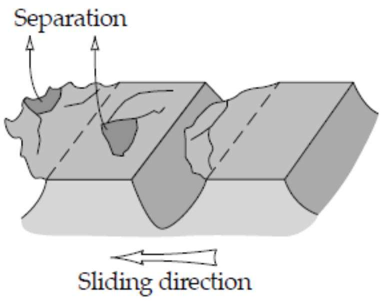


Figure 7 Plastic ratchetting *(Stachowiak & Batchelor, 2014, p. 628)*

## 2.2 Causes for Rail Wear

Sliding or slipping the wheel on the rail's surface will increase the wear of the rail. While there are no visual observations of excessive slipping during the usage of the cranes in driving wheels there is always some degree of slipping present. When considering the operational environment, it is more than likely that water, dust, chemicals or any kind of substance will end up on the rail's surface that can cause the coefficient of friction to decrease and thus increase the chances that the wheel will slip. To minimize the issue the trolleys are always equipped with rail brushes to help cleaning the rail while the trolley is moving, but those are not able to remove all the smallest particles from the rail. (Straffelini, 2015, pp. 130-131)

It has been noticed that localized temperature increases have a big impact on wearing, when two materials were scrubbed against each other at a speed of 3 m/s, it was noticed that quick localized heat increases up to 800 °C lasting only 0,1 ms would happen. It was suggested that these were caused by small deformations on the surface of the materials, this is illustrated in Figure 8. (Stachowiak & Batchelor, 2014, pp. 513-515)

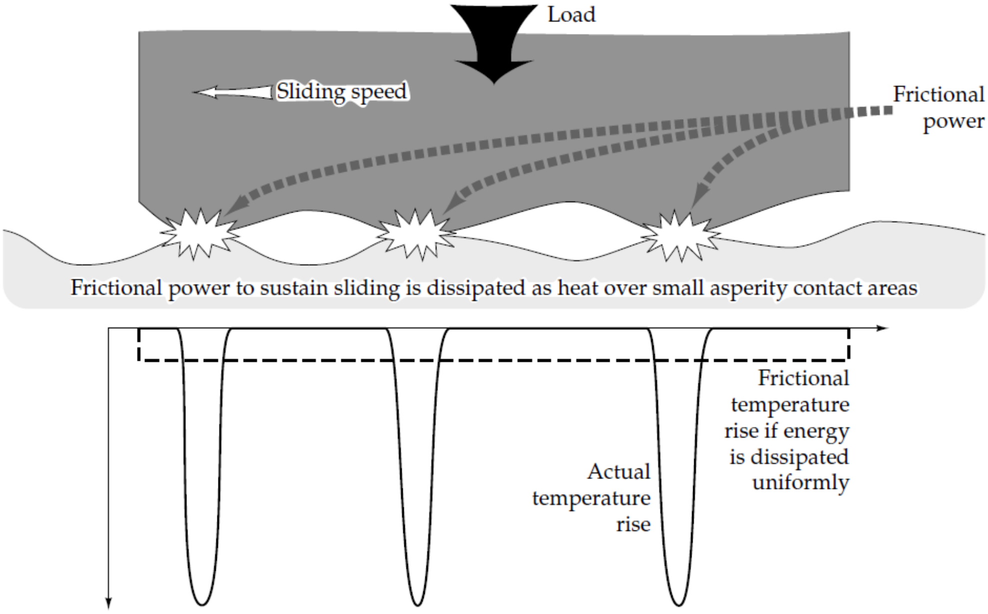


Figure 8 Effect of surface abnormalities on temperature increases *(Stachowiak & Batchelor, 2014, p. 513)*

These local temperature increases can also lead to heat expansion, and a small hump may form on the surface of the rail as illustrated in Figure 9. This kind of hump can cause a stress concentration point on the rail where fatigue may begin. It is also good to understand that trolleys do not move at a speed of 3 m/s, as the maximum speed for the trolley is 80m/min → 1,33 m/s, also the metals used in this test are different than the ones used in the rail and the wheel, and perhaps the most important point is the surface area and friction coefficient when comparing the wheel and rail contact with two sheets of metal. The friction coefficient between the wheel and the rail will be minimal, so it is safe to assume that as such this phenomenon will not happen on the rails of the crane. However, the slipping of the wheel will cause a heat increase on the rail adding to the overall stress. (Straffelini, 2015, pp. 53-55)

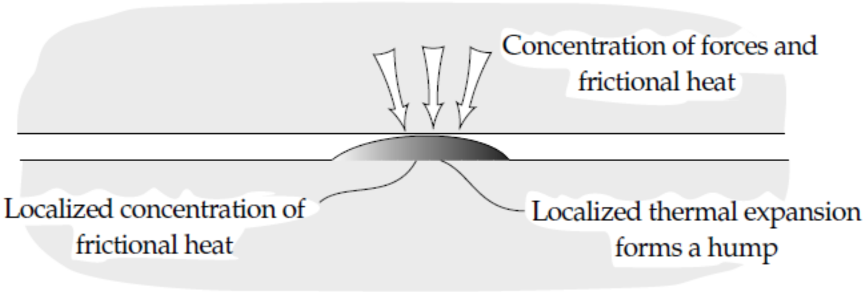


Figure 9 Hump caused by heat expansion *(Stachowiak & Batchelor, 2014, p. 514)*

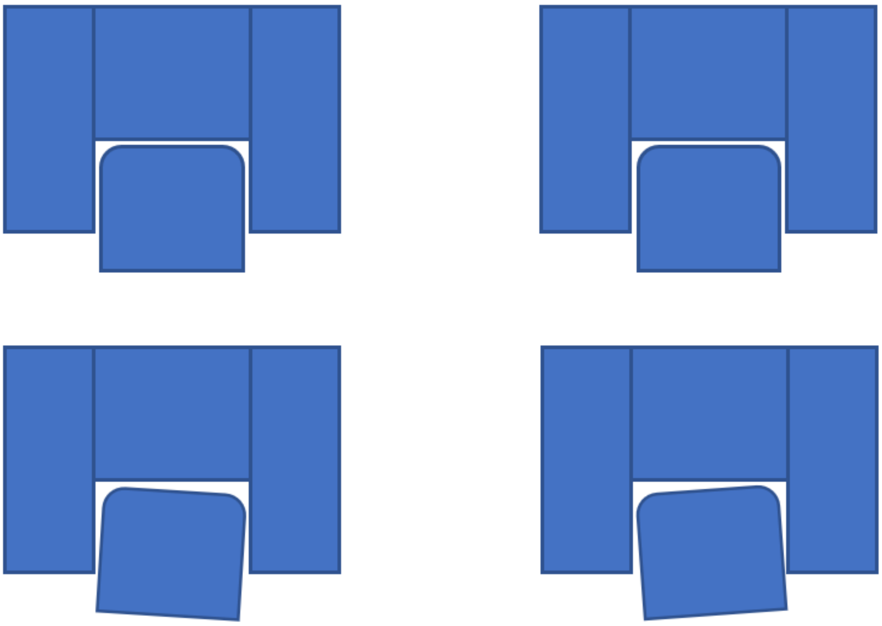

Figure 10 Twisted rail

The top half of Figure 10 shows the ideal position of the rail and the wheel, where the rail is nicely horizontal and aligned with the wheel. The bottom half shows a situation where the crane may end up if the bridge bends under the load, of course the wheels may follow the bend, but not necessarily with the same ratio. This kind of misalignment can cause huge stresses on the wheel and the rail as the surface area will decrease and it can also cause the side of the flange to hit the side of the rail.

Figure 11 Rail after grinding

After the rail pieces have been welded together the surface is ground until it is smooth and flat. Sometimes the welding is not perfect and small gaps are left under the weld or sometimes they are found on the side the rail and visible to the naked eye as shown in Figure 11. These small gaps cause stress concentrations and can increase crack propagation. Sometimes the surface has been ground too much and the surface is left uneven, which then means that the trolley will have to drive uphill in this position, this increases the likelihood of wheel slip.

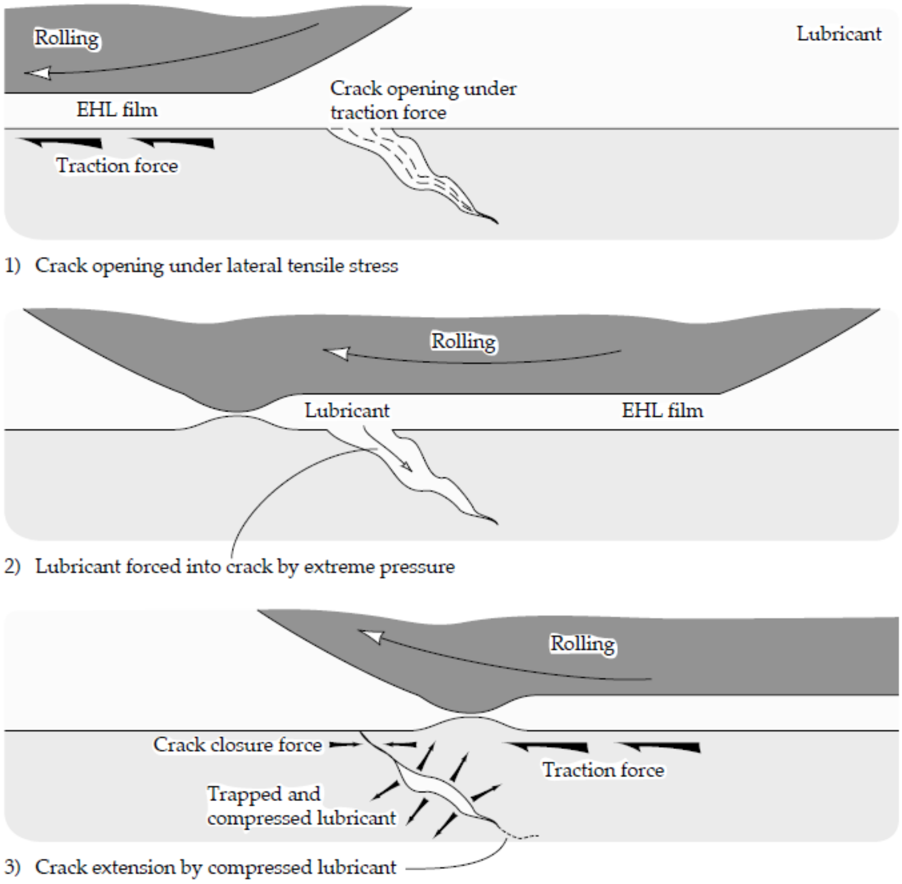


Figure 12 Hydraulic pressure crack propagation *(Stachowiak & Batchelor, 2014, p. 637)*

Figure 12 shows how lubricant seeps into a previously opened crack and once the crack is closed by pressure from the rolling the lubricant is left trapped in the crack and as it is compressed it build up pressure. After enough repeats the crack will extend and cause a part of the material to break off. On crane rails there is no lubricant in use, but the operative environment of the crane can be very humid, and some water will condense on the rails with potential to cause this to occur also on the cranes. (Stachowiak & Batchelor, 2014, pp. 636-637)

A combined effect of all the causes introduced in this chapter can have an impact and cause the corrugation of the rail, but it seems likely that the repeated plastic deformation introduced in figure 2 fits this situation the best and the wheel is too hard when compared to the rail. Therefore, the selected remedy of replacing the rail to a harder one can be consider as the correct way to go.

## 2.3 Wheel Rail Contact

In trains the wheels are connected with a single axel and they thus have the same rotating speed, which then causes additional slip during curves as the other side needs to cover more ground during the same amount of time. As mentioned earlier these types of cranes do not have any curves in them, and the driving wheels are connected with an axel and they have only one traversing machinery, so this should not be an issue in the cranes. Nevertheless, it is possible that occasional wheel slip happens more on the other wheel, especially as the other rail can be cleaner than the other one, causing variance in friction coefficient between the two sides.

From previous studies conducted it has been discovered that the used high alloy steel material has a friction coefficient between 0,4 – 0,5 when running on a standard rail. These tests have been conducted under laboratory conditions so they may not be totally accurate with the real-world situation of a very dirty environment. In comparison also another type of wheel material has been considered as a replacement for the current wheel. The material would be austempered ductile iron, in its base condition it is slightly softer than the current material in use, but after work hardening it actually becomes harder than the current wheel, hardness increases from 400 to 600HB. When running on an S355 rail it has a slightly lower coefficient of friction, around 0,35 – 0,45, and as it is a graphite it has self-lubricating properties that increase the lifetime of the wheel and rail. But whether the lower friction coefficient combined with the self-lubrication can overcome the increased hardness would require additional testing. (VTT, 2013)

This chapter gave insight to the theory of the wear and suggested probable root causes, the next chapter will introduce the materials selected for comparison.

# 3 RAIL MATERIALS

This chapter will introduce several different steel materials that have been identified to have potential to help in removing the corrugation problem from the current rail material. Increasing rail hardness has been identified in previous studies to remove the corrugation problem, so hardness of the rail will be a key factor in this study as well. Also, availability and price will be considered and as weldability tends to decrease when hardness increases it needs to be considered as well. (Grassle, 2009, pp. 581-596)

## 3.1 Price and availability

Rail material selection for further testing was done with co-operation between engineering and long-term suppliers. Following materials were chosen, Imacro EL700 and SB500 manufactured by Ovako, S690Q manufactured by Thyssenkrupp and Hardox 400 manufactured by SSAB.

Typical crane span is between 20 and 60 meters and it consist of several pieces of rail. Currently rails are supplied with varying lengths depending on the supplier, but typical lengths vary between 6 and 10 meters, which means 3 – 10 rails per each main girder. Rails are butt welded together and fillet welded to the flange of the main girder, so the shorter rails, the more connective butt welds are required.

*Table 2 Rail materials 80x60*

| Material | Strenght [Mpa] | Hardness [HRC] | CEV | Price €/m | Delivery Length | Delivery State |
|---|---|---|---|---|---|---|
| **S355** | 355 | >10 | 0,44 | 40,2 | 9,1m | As Rolled |
| **Imacro EL700** | 600 | 20-35 | 1,03 | 106,96 | 6m | As Rolled |
| **S690Q** | 650 | ~28 | 0,81 | 105,29 | 6m | Quenched and tempered |
| **Hardox 400** | 1100 | 39-44 | 0,82 | 102,96 | 6m | Quenched and tempered |
| **SB500** | 470 | 18-22 | 0,56 | 48,2 | 6m | As Rolled |

Table 2 shows some basic technical features of the rail materials selected. Strength, hardness, price per meter, the delivery length, which has an impact on number of welds required and carbon equivalent value (CEV) and delivery state which are important for weldability. Prices for EL700, S690Q and Hardox 400 are based on prices from a smaller batch so it is likely that the prices would decrease if order quantities would increase. Prices for S355 and SB500 are more reliable. Prices and delivery lengths are correct when ordering inside Finland, global price and delivery length differences are not considered in this thesis.

Availability needs to be considered carefully for all materials since shorter delivery times and smaller minimum order quantities have a direct impact on stock values. A material that is available quickly and in smaller batches can be purchased later and with more precise quantity for a particular crane, which results in less money being tied up for the materials for a shorter time. The rails are also required to have rounded corners, which has an added impact on the cost and delivery time and this impact varies slightly depending on the material. Of course, all of these are depended on demand and supply and if demand would increase it would also have an impact on the supply of the materials, but this impact is neglected from this thesis and focus in only on the as is situation for all materials.

## 3.2 Delivery state

Steels are available in different delivery states:

- Quenched and tempered, QT
- Thermo-mechanical controlled process, TMCP
- Direct quenched, DQ
- As rolled, AR

All the above manufacturing processes are capable of reaching similar mechanical properties for steels, but the microstructures inside the materials will be different. This difference in the microstructure has an impact on the weldability of the materials. Therefore it is not possible to only use strength, hardness or any other mechanical property as a definition for weldability, but also the delivery state and chemical composition of the material must be known. Out of the selected materials Hardox 400 and S690Q are quenched and tempered and the SB500 and EL700 are in an as rolled state. The quenched and tempered materials run the risk of losing their properties during welding as the heat input from the welding can in a way reset the improved microstructure of the material.

### 3.2.1 Quenched and tempered

Quenching and tempering involves heating the steel first to about 900 °C and then quickly cooling and then increasing the temperature back to about 600 °C. The temperature will be kept at a tempering temperature of 600 °C for a longer time if the plates are thick. After the tempering the steel is allowed to cool down. If the temperature of the steel rises above the tempering temperature during the lifetime of the steel the steel will start to lose its strength. This poses a problem for welding since temperatures during welding can quite easily exceed these temperatures. The microstructure for quenched and tempered steels is bainitic and martensitic. (Niemi, 2010) (Pirinen, 2013, p. 15)

### 3.2.2 Thermo-mechanically controlled process

In thermo-mechanically controlled process the steel is first heated to about 1200 °C and then it is rolled, same as in regular as rolled steels, but in thermo-mechanically controlled process the final rolling happens at a lower temperature of 750 °C. (TWI, 2019)

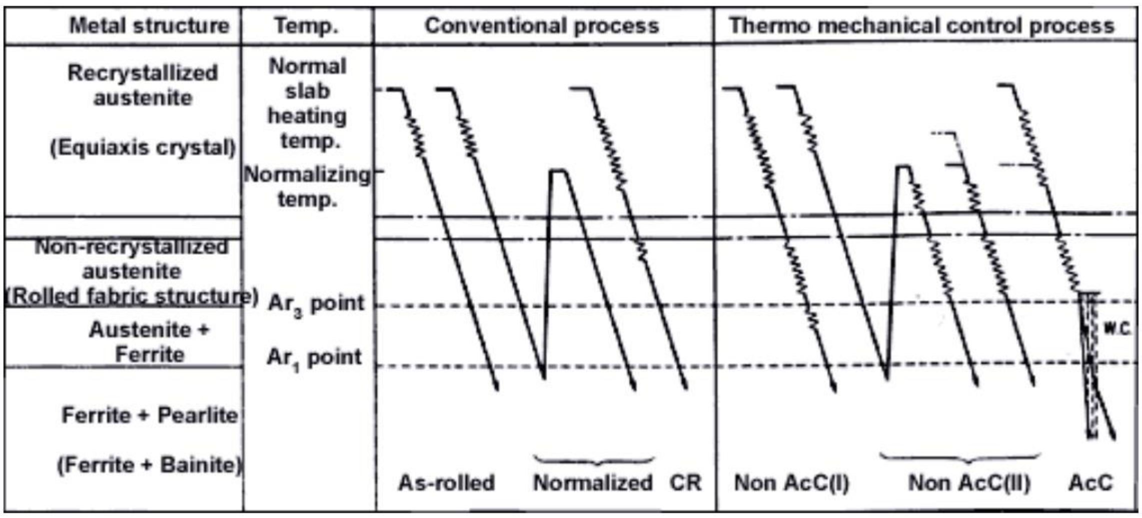


Figure 13 Thermo-mechanical controlled process

Thermo-mechanical controlled process can be done in several ways, three different ways are shown in the right-hand side of Figure 13, the left- hand side shows three similar ways of rolling, but only conventionally rolled. By rolling with varying temperatures the final microstructure of the steel can be manipulated. All TMCP steels are not necessarily bainitic and martensitic, they can also be ferritic and bainitic. The benefit of TMCP steels is a lesser need for alloying elements, which results in a lower CEV value and a better weldability. (Pirinen, 2013, p. 16) (TWI, 2019)

### 3.2.3 Direct quenching

In direct quenching the steel is first heated to about 1200 °C and kept there for a while, after that the steel is rolled and immediately quenched into water. After the quenching the steel can be heated up again and then left to air cool, the process is shown in Figure 14. The microstructure after direct quenching is bainitic and martensitic. (Guizhi Xiao, 2010, pp. 868-872)

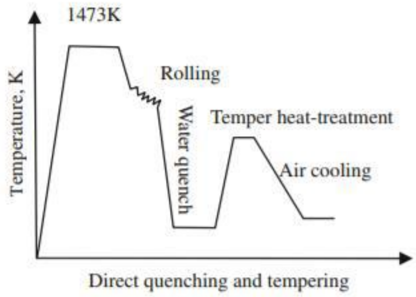


Figure 14 Direct quenching *(Guizhi Xiao, 2010, p. 870)*

### 3.2.4 As rolled

The mechanical properties of as rolled steels are purely based on their chemical composition. From a welding point of view as rolled steels are typically the easiest to weld, but if high strengths are required then as rolled steels typically require a high alloying content which tends to be bad for welding. (Ruukki, 2011)

## 3.3 Alloying

Dozens of different alloying elements are used in steels to enhance its mechanical properties, this chapter will introduce some of the most important ones and how they impact weldability.

Weldability is measured using carbon equivalent value CEV, which measures the degree of hardenability in the steel, meaning how easily the steel becomes martensitic after cooling. Biggest influence on hardenability is the amount of carbon in the steel, it would be good to keep carbon content below 0,25% as after that weldability tends to decrease and special procedures, such as preheating are required. Most alloying elements also increase hardenability, which as mentioned decreases the weldability. The ratio of hardenability varies from one alloying element to another and this is calculated by formula 1. (Ovako, Ovakon Terästen Hitsaus, 2012)

$$CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} \tag{1}$$

As we can see from the formula 1 alloying elements affecting hardenability are Carbon (C), Manganese (Mn), Molybdenum (Mo), Vanadium (V), Nickel (Ni) and Copper (Cu). Outside these ones, also other alloying elements have an impact on hardenability and there is more than one formula for calculating weldability but those will be introduced later in this thesis.

### 3.3.1 Carbon

Carbon content is the biggest influencer to steel’s mechanical properties and weldability. When carbon content is below 0,8% it increases the strength and hardness of the steel while decreasing plasticity and toughness. If carbon content is above 1% it will begin to decrease the strength of the steel. Increasing carbon content decreases weldability and if carbon content is above 0,3% the weldability of the steel has been significantly decreased. (MachineMfg, 2019)

### 3.3.2 Manganese

Manganese is used often in steels, but in very small quantities. Adding manganese increases the strength of the steel without losing any toughness, if manganese content is above 1,5% the steel will become brittle. Increased manganese content also increases the hardenability of the steel making it less weldable. (Pirinen, 2013, p. 28)

### 3.3.3 Chromium

Chromium is mainly used in steels to improve its ability to withstand corrosion and it is the main alloying element when making stainless steels. Chromium is the most used alloying element in steels. Chromium also slightly increases steel's strength and gives improved heat resistance. Adding chromium increases the hardenability of the steel making it less weldable. (Sarna, Chromium in Steels, 2014)

### 3.3.4 Molybdenum

Molybdenum is added into steels for increased corrosion and heat resistance. Molybdenum increases hardenability of steels, but it also prevents hydrogen cracking while welding so the effect on welding is not straightforwardly negative or positive. Typically, molybdenum contents are under 1%, but in tool steels contents maybe as high as 9%. (IMOA, 2019)

### 3.3.5 Vanadium

Vanadium is added into steels for increased strength and toughness, typical content is under 0,1% as higher quantities will decrease toughness. Adding vanadium will also increase the hardenability of the steel making welding more difficult. (Kou, 2003, p. 405)

### 3.3.6 Nickel

Nickel is added into steels to improve toughness and give more corrosion resistance, but it also increases hardness and heat resistance. About 65% of all the nickel production in the world goes towards making stainless steels. Nickel quantities in steels vary greatly, starting from under 1% and going up to 30%. Adding nickel into steels increases the hardenability of the steel making welding more difficult. (Sarna, Nickel in Steels, 2014)

### 3.3.7 Copper

Copper is added into steels for increased corrosion resistance, but if the copper content is above 0,75% it will also increase the strength of the steel. Adding copper is also done to make it easier to harden the steel but adding copper will also decrease the weldability of the steel. (Sarna, Copper in Steels, 2014)

### 3.3.8 Boron

Boron is added into steel to increase the hardness that is achieved through hardening, and it also increases the heat resistance of the steel. Typical amounts of boron are minimal, 0,0003 -0,0005%, but it still has a huge impact on the hardenability of the steel, which will make welding more difficult. But using boron often means that less carbon and other alloying elements are used, so the impact is not always purely negative for welding. (Pirinen, 2013, p. 27) (Materia, 2007)

### 3.3.9 Silicon

Silicon is found in virtually all steels, weather as an added alloying element or a leftover from the manufacturing process. The leftover quantities are typically insignificant, under 0,002%, when added on purpose quantities are usually between 0,15% and 1%, but special cases where increased magnetism is wished on the steel quantities maybe up to 5%. Silicon is typically used to decrease the amount of oxygen, but it also provides increased strength and hardness and gives some acid resistance. Adding silicon also increases the hardenability of the steel, making welding more difficult, but only very slightly. (Sarna, Silicon in Steel, 2014)

Table 3 shows the chemical composition of the steel materials selected for this thesis. Looking at the chemical composition of the materials, they are on a similar level of alloying, except for Imacro EL700, which has considerably less carbon and a very high chromium content when compared to the other materials.

*Table 3 Chemical composition of rail steels*

| **Material** | C | Si | Mn | P | S | N | Al | Cu | Cr | Ni | Mo | V | Ti | Nb | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S355** | 0,16 | 0,29 | 1,53 | 0,017 | 0,006 | 0,005 | 0,026 | 0,02 | 0,05 | 0,04 | 0,01 | 0,01 | 0,01 | 0,002 | |
| **Imacro EL700** | 0,05 | 0,31 | 0,95 | 0,009 | 0,009 | | 0,028 | | 3,79 | | | | | 0,045 | |
| **S690Q** | 0,14 | 0,22 | 1,23 | 0,011 | 0,0007 | | 0,089 | | 0,343 | 0,041 | 0,417 | 0,003 | 0,003 | 0,027 | 0,0026 |
| **Hardox 400** | 0,24 | 0,24 | 0,84 | 0,008 | 0,001 | | | | | 0,48 | 0,354 | | | | 0,001 |
| **SB500** | 0,16 | 0,34 | 1,46 | 0,016 | 0,021 | | | | | | | | | | |

## 3.4 Literature review of the selected rail materials

A literature review of the selected rail materials was done to determine what has already been studied about the materials, especially in relation to welding. As it was not possible to find studies conducted on all the materials, the search was expanded to materials with similar mechanical properties.

Cheng and others did a study how welding two butt joints affected properties of S690Q. They discovered that the material softens in the heat affected zone of the weld, HAZ, and the size of the softer zone would increase with a higher heat input. Tensile strength would also decrease 3 – 8% with the increased heat input. They also noted that minimum hardness in the HAZ was 36% less than in the base material, regardless of different heat inputs, meaning the increased heat only had an impact on the size of the softer area, not the minimum hardness value. It was discovered that the microstructure of the steel had changed from martensite to ferrite and cementite and this caused the weaker area in the HAZ (Cheng Chen, 2018, pp. 153-168)

Cabrilo and others studied how welding affects the mechanical properties of Protac 500, a high hardness armour steel with similar mechanical properties as Hardox 400 selected for this thesis. They used several different welding procedures for both manual and automated welding and compared the results. They noted a decrease in hardness of the material by 23 - 40% in manual welding and 27 – 38% with automatic welding. Ultimate tensile strength was 129 MPa lower after manual welding when compared to automatic welding, yield strength however was on a similar level between all samples. They also conducted Charpy impact tests on the samples at varying temperatures -40, -20, 0 and 20 °C, and noted that the absorbed energy was 39, 46, 62 and 75 J respectively. Microstructure in the HAZ changed from quenched and tempered martensite to bainitic martensite in all welded samples. (Aleksandar Cabrilo, 2018, pp. 1281-1295)

Mazur and others studied how welding affects the mechanical properties of Hardox 450, which is only a slightly stronger version of the Hardox 400 selected for this thesis. They conducted tests for tensile strength, hardness and impact toughness. As they were using a wire with lower strength than the base material, so naturally all the samples failed the tensile strength test at the weld material. They carried out Charpy tests at -40 °C and were able to achieve very good results, ranging from 70 to 140 J. Hardness testing revealed a minimum hardness of 200 HV, when compared to the 400 HV of the base material, the minimum hardness value was found in HAZ. (M. Mazur, 2014, pp. 122-128)

Cerjak and Letofsky studied the effects of welding in a low carbon, high chromium steel with similar hardness as EL700 selected for this thesis. The material used in their studies has 9% chromium compared to 3,8 % in EL700, so a direct comparison should not be made. They discovered a decrease in hardness compared to base material from 250 HV to 210 HV in HAZ. (Cerjak, 2004, pp. 31-36)

Willms and Schröter studied several high-performance steels, including S460 and S690Q selected for this thesis. They noticed a decrease in hardness in the HAZ of both materials. In S460 hardness decreased by 40% when compared to the base material and in S690Q the decrease was 50%. (Willms, 2016, pp. 49-56)

This chapter introduced the rail materials selected for comparison and provided information about the effect of delivery state and alloying elements used in steels. The next chapter will focus on the weldability of the materials.

# 4 WELDABILITY OF RAIL STEELS

Weldability is a measure of how easy the material is to weld successfully. Basically, it means the amount of special procedures that are required for an acceptable end result. In case the material would require special procedures, and these are ignored, it usually leads into problems. Typical welding problems are hot cracking, cold cracking, lamellar tearing and a decrease in impact toughness. A lot of welding problems can be avoided during engineering through material and geometry selection.

Weldability can be separated into three different categories, material, manufacturing and design. Table 4 shows several factors that define each category. Based on the names these are quite self-explanatory, material is all about the material properties and metallurgy, manufacture is about the welding procedure and preparation, whereas design is about the geometry of the part. So, when defining the weldability of a part or a construction all of these should be considered in order to achieve successful and safe welds.

*Table 4 Weldability categorization (Bodea, 2017, p. 55)*

| **MATERIAL**<br><br>WELDING SUITABILITY | **MANUFACTURE**<br><br>WELDING POSSIBILITY | **DESIGN**<br><br>WELDING SAFETY |
|---|---|---|
| • Chemical composition<br>• Metallurgical properties<br>• Physical properties | • Welding preparation<br>• Welding execution<br>• Heat treatments | • Design<br>• Stress condition |
| • Tendency to hardening<br>• Tendency to ageing<br>• Tendency to hot cracking<br>• Weld pool behaviour<br>• Segregations<br>• Inclusions<br>• Grain size<br>• Anisotropy<br>• Expansion coefficient<br>• Thermal conductivity<br>• Melting point<br>• Mechanical properties | • Welding technology<br>• Groove shape<br>• Preheating<br>• Susceptibility to cracking<br>• Heat input control<br>• Welding position<br>• Welding sequence<br>• Weld penetration<br>• Pool shape<br>• Post weld heat treatment<br>• Grinding<br>• Pickling | • Material thickness<br>• Notch effect<br>• Stiffness differences<br>• Joint geometry and displacement<br>• Type and level of strains<br>• Temperature<br>• Corrosion<br>• Loads and stress distribution<br>• Weld bead shape |

## 4.1 Calculating weldability

Weldability is calculated by estimating the equivalent carbon content, by using a formula that takes into account the chemical composition of the material. There are several different formulas available, but the most used ones are CEV, CET, (Carbon equivalent value SEW088) and Pcm (Critical metal parameter, Ito & Bessyo)

CEV was already introduced earlier in chapter 3.3, formula 1. CET is introduced in formula 2 and it is quick to notice that the formulas are very similar to one another. Only difference is the absence of vanadium and the factors are slightly different for the elements. If the carbon content of the steel is high, it is recommended to calculate weldability using CET. (Ovako, Ovakon Terästen Hitsaus, 2012)

$$CET = C + \frac{Mn}{10} + \frac{Mo}{10} + \frac{Cr}{20} + \frac{Cu}{20} + \frac{Ni}{40} \qquad (2)$$

The third common way of evaluating weldability is a formula developed by Japanese Ito and Bessyo, called Pcm. Introduced below in formula 3.

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \qquad (3)$$

It too is very similar to CEV and CET, the factors are again slightly different, and silicon and boron have been considered. Notable difference is the large factor on boron.

| Variant | Cast | Weldability | | C % | Si % | Mn % | P % | S % | Cr % | Ni % | Mo % | Cu % | Al % | Nb % | N % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imacro EL700 | CC | CEV $1.03_{max}$ | Min | 0.04 | 0.10 | 0.85 | - | - | 3.75 | - | - | - | 0.020 | 0.040 | - |
| | | Pcm $0.27_{max}$ | Max | 0.06 | 0.40 | 1.15 | 0.025 | 0.020 | 4.25 | 0.40 | 0.12 | 0.30 | 0.035 | 0.080 | 0.0150 |

Figure 15 Chemical composition of Ovako Imacro EL700 *(Ovako, IMACRO EL700, 2017)*

Figure 15 shows the chemical composition of Ovako Imacro EL700 steel, which is a high strength structural steel, with a yield strength of 600 – 650 MPa, depending on the thickness. If carbon equivalent content is calculated on this for this particular material using all three formulas described above it is easy to see that the values change based on the formula. Formula 1 CEV, gives a value of 1,172, formula 2 CET gives a value of 0,425 and formula 3 Pcm gives a value of 0,373. The results above are a good indication why the CEV formula is the most used as it gives the biggest value and is therefore the worst-case scenario, so basing engineering on this value will be the safest one to use.

When the carbon equivalent value is below 0,41 the steel is considered easily weldable, when the value is below 0,6 the steel is typically weldable using special procedures, after that welding becomes increasingly difficult. But it should be noted that these values should only be used as guidelines and not the only indication of weldability as other factors such as plate thickness also affect weldability. (Ovako, 2012)

## 4.2 Welding zones and microstructures

During welding part of the materials melts and part of the material heats up to extreme temperatures, this has an influence on the microstructure of the joint. The weld is distributed into several zones depending on the amount of heat that is affecting that zone and the microstructure it ends up in. Figure 16 illustrates the different zones inside the fusion zone of the weld, zones are labelled with number from 1 to 6 depending on how far from the weld the zone is, also the amount of heat and microstructure are shown. The example below is from a steel with a carbon content of below 0,15%. Visually it is possible to see two zones, zone 1 and zones 2-6 the heat affected zone, HAZ. A third zone can also be seen, which would be zone 7, the base material, an area that has not been impacted by the welding at all. When speaking of welds in a more general way, these three zones are used the weld, the heat affected zone and base material.

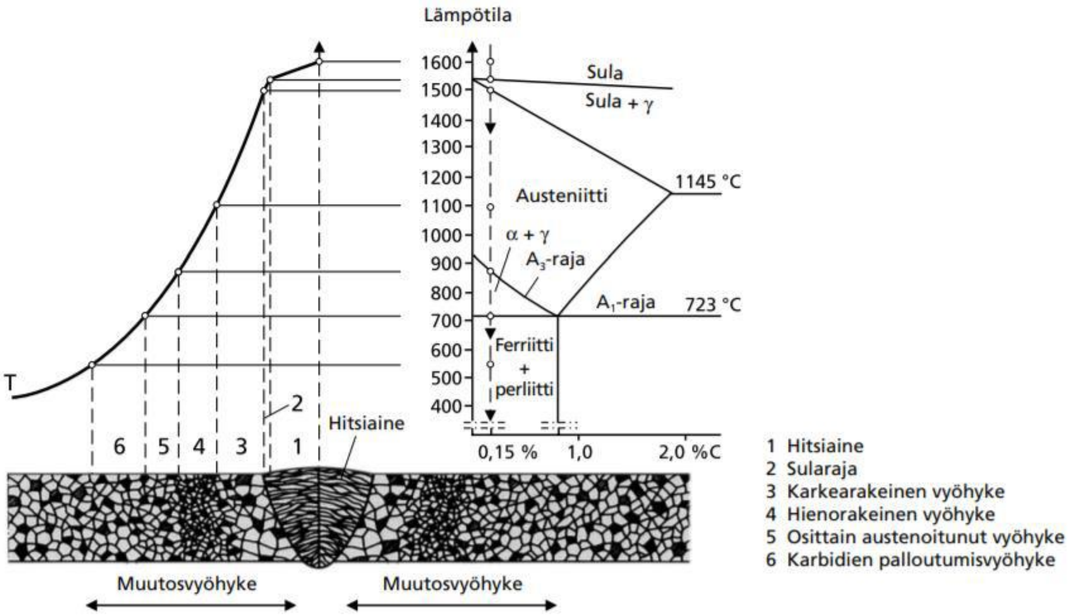


Figure 16 Fusion zone of a weld *(Ovako, 2012)*

In zone 3, which is the grain growth zone, the temperature has exceeded 1100 °C and austenite grain growth has happened. In zone 4, which is the recrystallized zone, temperature has exceeded the A3 boundary and microstructure has been changed. Steels with low carbon content typically have a normalized microstructure in the recrystallized zone. Zone 5, which is the partially transformed zone, has its temperatures between A3 and A1 boundaries and has a partially austenitic microstructure. In zone 6 the temperature has exceeded 500 °C and no major microstructure changes are occurring, some spherization of carbides and recrystallization can happen. Welding can be compared to heat treatment of a small area, first the steel is heated to an extreme temperature and then allowed to cool, this causes changes in the microstructure of the material which have an effect on the weldability of the material and the likelihood of cold cracking. (Ovako, 2012)

The most important changes in the microstructure of the steel happen during the cooling and especially between the period 800 °C to 500 °C. The time it takes to cool from 800 °C to 500 °C is called $t_{8/5}$. To calculate this time, two formulas are used, depending on the thickness of the material, if one is not sure which formula to use, both can be calculated, and the higher value can be chosen. The two formulas are introduced below in formula 4 and 5.

$$t_{8/5} = (4300 - 4{,}3\,T_0) * 10^5 * \frac{Q^2}{d^2} * \left[\left(\frac{1}{500-T_0}\right)^2 - \left(\frac{1}{800-T_0}\right)^2\right] * F_2 \tag{4}$$

$$t_{8/5} = (6700 - 5\,T_0) * Q * \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right) * F_3 \qquad (5)$$

Formula 4 is used when the weldable material is thin plates and formula 5 is used when it is thick.

$T_0$ = Preheating temperature (°C)

Q = Heat input (KJ/mm)

d = Material thickness

$F_2/F_3$ = Welding geometry factor

The welding geometry factors depend on the geometry of the weld and the values range between 0,45 and 1. They are introduced in Figure 17.

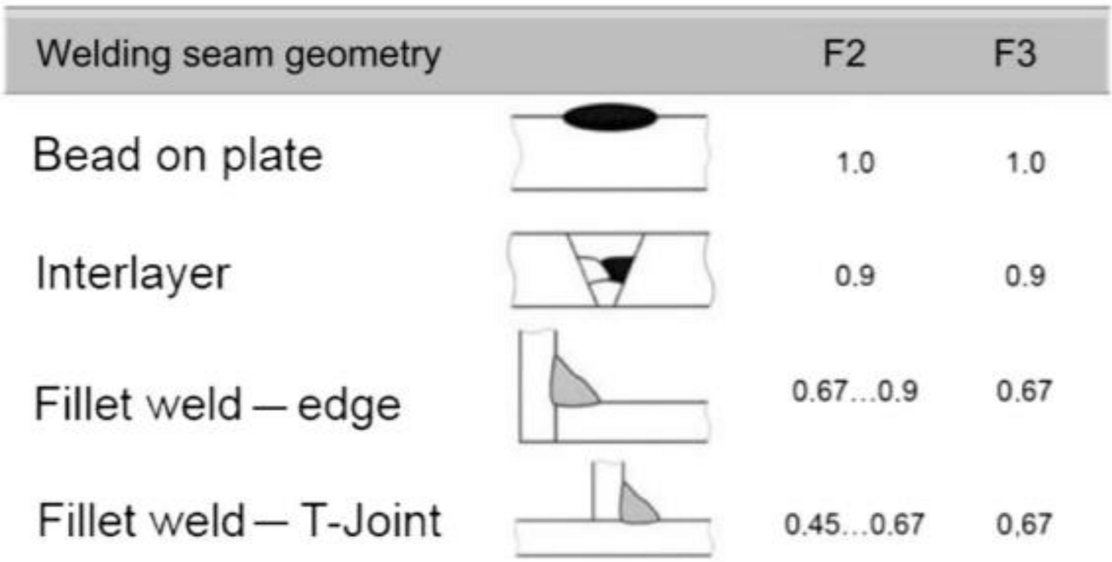


Figure 17 Welding Geometry factors *(A. Hälsig, 2017, pp. 745-754)*

Heat input Q is calculated using formula 6.

$$Q = \eta \times E \qquad (6)$$

$\eta$ = efficiency factor

E = Welding energy (KJ/mm)

Welding energy E is calculated using formula 7.

$$E = \frac{I \times U \times 60}{v \times 1000} \text{ (kJ/mm)} \tag{7}$$

I = Welding current (A)

U = Electric Tension (V)

v = Welding speed (m/min)

Efficiency factor η depends on the welding process and the values possible are introduced in Table 5.

*Table 5 Efficency factor η*

| **Welding process** | **Efficiency factor η** |
|---|---|
| Manual Metal Arc | 0.8 |
| Submerged Arc | 1.0 |
| Metal Active Gas (MAG) | 0.8 |
| Metal Inert Gas (MIG) | 0.7 |
| Flux Cored Arc (FCAW) | 0.9 |
| Tungsten Inert Gas (TIG) | 0.7 |

The formulas above make it possible to calculate heat input and cooling time, the higher the heat input, the longer the cooling time. If the hardenability of the steel is not high, a high heat input can prevent hardening in the fusion zone, but too much heat input will decrease the toughness of the material. The faster the steel cools the more martensite is built up, which will make the steel harder but more brittle, and will increase cracking probability. A longer cooling time will give the austenite time to disperse and create more ductile ferrite-pearlitic microstructures. High strength steels often do not have fully ferrite-pearlitic microstructures. Cooling time can be influenced by preheating or by welding with multiple passes. (Ovako, 2012)

## 4.3 Welding high strength steels

As it was mentioned already earlier, no one attribute of a material, such as strength, can be used to assess its weldability. In addition, the chemical composition and delivery state should be known and taken into account. But as a general guideline it is possible to say that the stronger or harder the material is, the harder it usually is to weld. This chapter will introduce some of the most common welding defects and how to avoid them, especially when it comes to high strength steels.

### 4.3.1 Cold Cracking

Cold cracking is the most common welding defect, especially with high strength steels. Cold cracking can happen due to three different reasons, either there is too much martensite built up, there is too much hydrogen in the weld or due to residual stresses. As it was mentioned in the previous chapter too much martensite can build up in the weld due to the high hardenability of the material and too fast cooling. This can be avoided by selecting a material with a low equivalent carbon value or by controlling heat input and cooling time or by preheating the piece before welding.

Hydrogen can find its way to the weld through multiple sources. For example, from surrounding snow, ice or rust, or through the welding procedure from the welding electrode, welding wire or from the welding powder. Out of these the welding wire is the most common one to introduce hydrogen into a weld. Easiest way to avoid hydrogen is to clean the welding area properly and use a welding wire with a low hydrogen content. The welding process also has an impact on hydrogen content, MIG/MAG and TIG are the best ones for avoiding hydrogen. It also possible to perform dehydrogenation annealing for the weld, which means upholding the temperature in the weld above 150 °C until the hydrogen has disappeared from the weld, this can take several hours.

Residual stresses build up to the weld as the material expands due to the heat, but when it hits a part of cold metal the expansion of forced to stop. Once the weld then starts to cool down it can leave residual stresses behind. Residual stresses can be diminished by using a welding wire that is softer than the base material or by welding in an elevated temperature.

Stress relieving procedure can also be done after the welding, keeping the temperature high and controlling the cooling so it does not happen too quickly. (Ovako, 2012)

### 4.3.2 Tension Cracking

Tension crack is caused by weld material shrinking as it cools down and concentration of impurities along the centre line of the weld. Tension cracking probability can be estimated based on the chemical composition of the material. USC, Units of Cracking Susceptibility is used to evaluate the probability and it calculated with formula 8.

$$UCS = 230\ C + 190\ S + 75\ P + 45\ Nb - 12{,}3\ Si - 5{,}4\ Mn - 1 \qquad (8)$$

The end result can be divided into three categories.

USC < 10, no risk for tension cracking
USC 10 – 30 the risk for tension cracking is increased as the ratio between the depth and width of the weld increases, or when welding speed is high, or air gap is large.
USC > 30 high risk for tension cracking

Looking at the formula 8, it can be seen that the amount of coal, sulphur, phosphorus and niobium increases the risk for tensile cracking, whereas silicon and manganese reduce the risk. The risk of tension cracking is higher when the gap being welded is deep and narrow, so the risk can be reduced by widening or shallowing the gap. Other methods for reducing the risk are using a welding wire with a high manganese content or by reducing the welding energy or welding speed. Tension cracking is a relatively common problem with high strength steels, but the probability varies based on the chemical composition and especially in steels with low carbon content the risk is often not very high. But certain steels the risk can be very high, for example the EL700 steel introduced in Figure 15 has an USC of 32,4, meaning it has a high risk for tension cracking. (Ovako, 2012)

### 4.3.3 Lamellar tearing

Lamellar tearing happens in rolled materials, into the direction of the rolling, if the weld is such that tensile stresses appear in the direction perpendicular to the rolling. Lamellar tearing can be prevented by using high welding energy, increasing the area of the grooves, making the weld with several passes, making a buffer weld with a welding wire that is tough and low strength, also preheating can prevent lamellar tearing. (Ovako, 2012) (Kou, 2003, p. 423)

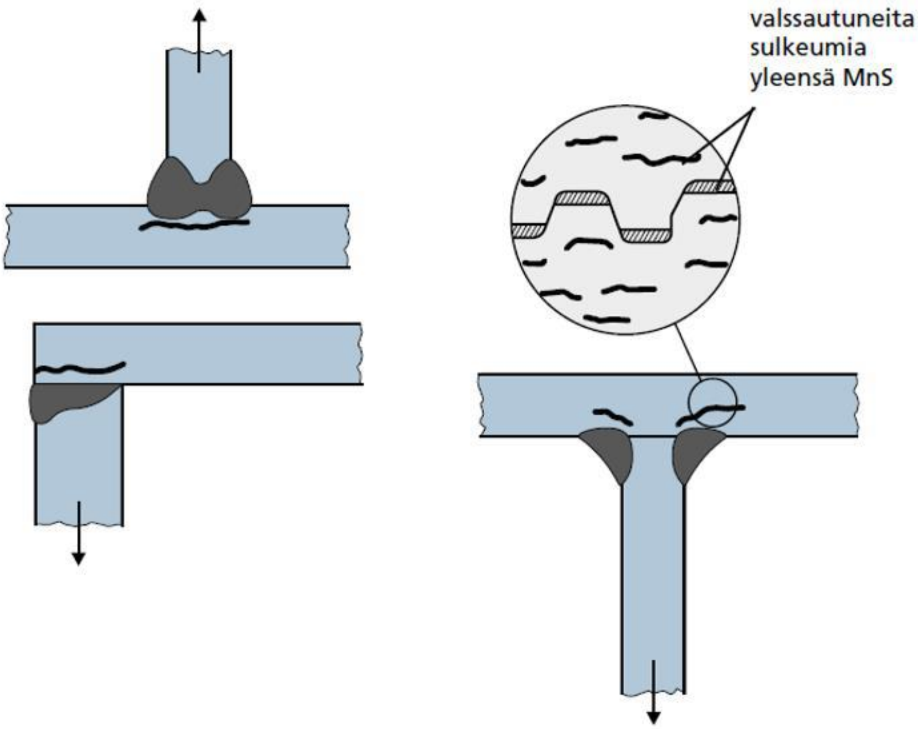


Figure 18 Most common locations for lamellar tearing *(Ovako, 2012)*

Figure 18 shows the most common locations for lamellar tearing. Lamellar tearing is no more common in high strength steels than it is in other steels, but high welding energy should be avoided when welding high strength steels to reduce the potential for lamellar tearing.

### 4.3.4 Welding wires

Selection of welding wires has a huge impact on welding result in general and especially with high strength steels. Welding wires are categorized in three different ways, depending on their relative yield strength when compared with the base material. If the yield strengths are close to equal in the base material and weld wire, it is called a matching wire, in case it is lower or higher the wires are called under matched or over matched. Low strength steels are often welded with an over matched wire, since the weld is often a place for stress concentration and by using an over matched wire that area can be given some extra strength to better cope with the stresses. High strength steels are often welded with an under matched wire. It has been noticed that the strength of the under matched wire increases slightly during welding, but using it causes fewer residual stresses in the welds and it decreases the risk for cracking. Using an under matched welding wire often decreases or eliminates the need for preheating. (Pirinen, 2013, pp. 37-41) (Ovako, 2012)

### 4.3.5 Heat input and cooling time

Heat input and cooling time can be calculated with formulas 4 to 7 as introduced earlier and these are the most important welding parameters. These are also something that can be changed during manufacturing. As mentioned earlier a low heat input is preferable when welding high strength steels, often a value below 1 KJ/min. If the heat input is too high it reduces the toughness of the material and makes the weld prone to hot cracking. Several researches indicate that the ideal cooling time for high strength steels would be between 10 and 20 seconds, but this is of course highly depending on the weld. If the cooling is too quick the final microstructure will be martensitic and brittle and thus prone to cold cracking. (Pirinen, 2013, pp. 42-46)

## 4.4 Steel Classification for welding

Metals are classified into different groups according standard CEN ISO/TR 15608:2017, all together for metals there are more than a hundred groups and subgroups, but for steels there are eleven main groups and each of the groups has between two and four subgroups. The purpose of the groups is to give the welder an idea of the material's properties and how it is expected to behave when welded. Knowing the classification is also necessary when making welding procedure specifications, as it has direct impact on approval limits according SFS-EN ISO 15614-1:2017 + A1:2019. The classification and approval limit for maximum hardness for steels considered in this thesis are shown in Table 6.

*Table 6 Steel Classification*

| **Material** | **Classification** | **Max. Hardness[HV 10]** |
|---|---|---|
| **S355** | 1.2 | 380 |
| **Imacro EL700** | 9.1 | 350 |
| **S690Q** | 3.1 | 380 |
| **Hardox 400** | 3.2 | 380 |
| **SB500** | 1 | 380 |

This chapter introduced weldability of rail steels and typical problems that can happen during and after welding. The next chapter will explain about the weld tests.

# 5 WELD TESTS

In order to determine which of the selected rail materials could be used to replace the current rail, it was necessary to conduct weld tests and analyse the results in a laboratory. This chapter will explain about the testing procedures and introduce some of the key results and compare them against similar studies conducted earlier.

## 5.1 Testing practicalities

As already introduced earlier, four different materials were selected to be tested, based on their mechanical properties and discussion between engineering and suppliers. The four materials being Imacro EL700 and SB500 manufactured by Ovako, S690Q manufactured by Thyssenkrupp and Hardox 400 manufactured by SSAB. Each of the materials were welded with three different setups.

1. Weld with one pass until almost full, surface pass with harder wire
2. Weld with multiple passes, surface pass with harder wire
3. Weld with one pass, same wire all throughout

The third setup was also fillet welded into a plate of S355 for fillet weld analysis.

The welding was done using a Kemppi FastMig MSF55, two different welding wires were used, Lincoln SupraMig HD 1,2mm for most of the welding and for the harder surface passes Esab OK Autrodur 38 G M wire was used. Shielding gas was SK18%, with 82% argon and 18% carbon dioxide and it had a flow of 15 l/min. All the rails were prepped with a V-groove with 20° bevel angle on both sides, resulting in a 40° groove angle, groove was achieved by sawing and the surface was cleaned before welding. All welds had a ceramic backing in use. Temperatures were checked with a Fluke thermometer 62 max+. All rails were preheated with a torch to varying temperatures, based on the manufacturer’s recommendations, EL700 was heated to 120 °C, Thyssen SQ690Q was heated to 130 °C, Hardox 400 was heated to 175 °C and SB500 was heated to 75 °C. Interpass temperatures were kept at 250 °C throughout all the tests. After each pass, the weld was cleaned with a chipping hammer. Voltage and amperage were recorded from the welds as well as arc time, these can be used to calculate welding speed and heat input. Also, total phase time for each test piece was recorded to evaluate productivity of each material and welding procedure. After welding the surface was grinded flat. Table 7 shows the different setups used during the tests.

*Table 7 Welding setups*

| No | Material | Fillet | Pre heat °C | Interpass temperature °C | Passes | Esab Wire |
|---|---|---|---|---|---|---|
| 1 | Ovako Imarco EL700 | | 120 | 250 | Two | Yes |
| 2 | Ovako Imarco EL700 | | 120 | 250 | Multiple | Yes |
| 3 | Ovako Imarco EL700 | Yes | 120 | 250 | One | |
| 4 | Thyssen S690Q | | 130 | 250 | Two | Yes |
| 5 | Thyssen S690Q | | 130 | 250 | Multiple | Yes |
| 6 | Thyssen S690Q | Yes | 130 | 250 | One | |
| 7 | Hardox 400 | | 175 | 250 | Two | Yes |
| 8 | Hardox 400 | | 175 | 250 | Multiple | Yes |
| 9 | Hardox 400 | Yes | 175 | 250 | One | |
| 10 | SB500 | | 75 | 250 | Two | Yes |
| 11 | SB500 | | 75 | 250 | Multiple | Yes |
| 12 | SB500 | Yes | 75 | 250 | One | |

Figure 19 Welding setup

Figure 19 shows the setup before welding was started, both ends are clamped to minimize angular distortions and two copper plates are used on both sides of the weld to help with smoother sides and minimize grinding need after the welding, also a ceramic backing is used under the weld.

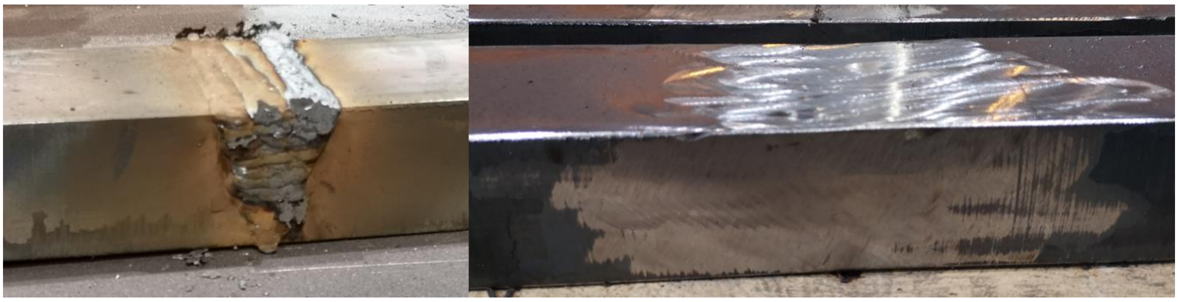

Figure 20 Weld before and after grinding

Figure 20 shows on the left the state of the weld after the welding has been completed and, on the right, after it has been grinded for a smooth finish.


Figure 21 Finished test pieces

Figure 21 shows a finished set of S690Q test materials, all test pieces were labelled with a sequential number and material type to keep track which test piece is which. From figure 21 we can also see the fillet weld for the test piece 6. Similar fillet weld into a plate of S355 was done for test pieces 3, 9 and 12.

## 5.2 Results

The key properties that were selected for analysis were hardness and impact toughness, at the same time keeping in mind the productivity of the welding procedure and cost of the material itself. Acceptable results should have surface hardness minimum 200 HB and average impact toughness 27J at -20 °C to be approved for J2 class, maximum hardness should also stay below the value specified for each material class. Surface hardness measurement was done using a calibrated, portable hardness tester Hartip 2000. Impact tests were conducted according to standard SFS-EN ISO 148-1.

Productivity for the three different procedures varied a lot, the fastest one taking only ten minutes from start to finish, and the slowest one took two and half hours. Material selection only had a slight impact on the productivity of the welding, heating and cooling rates remained very similar between all the materials. The SB500 test pieces were smaller in size than the other materials, 60x40 compared to the others being 80x60 so one to one comparison is not possible. But with these test pieces naturally the productivity was higher for the smaller rails.

All the test pieces where the surface layer weld was done with the softer wire were at an unacceptable level, so using the harder wire is a must for acceptable results. Out of the test pieces where the harder ESAB wire was used all pieces had an acceptable surface hardness at the weld point, only SB500 base material had a few values around 180 HB and S690Q had one value in HAZ at 150HB.

Impact toughness stayed at an acceptable level in all materials except the Hardox 400, but only when doing the welding with several passes. The SB500 was the only material where the impact toughness was on an acceptable level even when the weld was done with only one pass.

After the first round of testing it seems that SB500, S690Q and EL700 might all be probable candidates to replace the current rail, SB500 has some uncertainty as the supplier only promises hardness between 180 – 220 HB, but at least the pieces used in this test were on a higher level than what the supplier promises. EL700 has a lot worse availability than the other materials and a high price too, so it was decided to be left out of further testing. Second round of testing was planned to increase the reliability for the testing using only two materials SB500 and S690Q.

*Table 8 Weld test results*

| No | Material | Fillet | Total phase time [MIN] | Esab wire | Surface hardness >200 HB | Impact >27 J |
|---|---|---|---|---|---|---|
| 1 | Ovako Imarco EL700 | | 30 | x | OK | Not OK |
| 2 | Ovako Imarco EL700 | | 150 | N/A | Not OK | OK |
| 3 | Ovako Imarco EL700 | x | 15 | N/A | OK | N/A |
| 4 | Thyssen S690Q | | 30 | x | OK | Not OK |
| 5 | Thyssen S690Q | | 150 | x | OK | OK |
| 6 | Thyssen S690Q | x | 30 | | Not OK | N/A |
| 7 | Hardox 400 | | 70 | x | OK | Not OK |
| 8 | Hardox 400 | | 125 | x | OK | Not OK |
| 9 | Hardox 400 | x | 15 | | Not OK | N/A |
| 10 | SB500 | | 30 | x | ~OK | OK |
| 11 | SB500 | | 60 | x | ~OK | OK |
| 12 | SB500 | x | 10 | | Not OK | N/A |

Table 8 shows the conclusions of the tests. The surface hardness for test pieces two and three indicate that there has been a human error made during the testing and the harder wire was used in test piece three, but not in test piece two. Generally, the slow welding with multiple passes gives the best end result for all materials as can be expected, but the total phase times are bit too excessive for that kind of welding to be considered economical. Only the SB500 would be usable with an economical welding procedure, and even that had a couple of surface hardness values around 180HB in the HAZ and also in the base material, so using it carries a bit of uncertainty.

When looking at the root side hardness for test pieces 3, 6, 9 and 12 and comparing it to the maximum allowed hardness shown earlier in Table 6 it can be seen that none of the material pass the criteria. All the materials fail in HAZ which is on the side of the S355 flange. The maximum allowed hardness would have been 380 HV for all the materials, except for Imacro EL700 the maximum allowed hardness is slightly lower at 350 HV. The highest measured value in all cases is between 395 – 424 HV. Hardox 400 also fails the test on the Hardox 400 HAZ with a hardness of 490 HV. The results are summed up in Table 9.

*Table 9 Root Side Hardness*

| No | Material | Max allowed hardness [HB] | Measured Hardness | Location |
|---|---|---|---|---|
| 3 | Ovako Imarco EL700 | 350 | 406 | S355 HAZ |
| 6 | Thyssen S690Q | 380 | 395 | S355 HAZ |
| 9 | Hardox 400 | 380 | 490<br>421 | Hardox HAZ<br>S355 HAZ |
| 12 | SB500 | 380 | 424 | S355 HAZ |

5.3 Second round of testing

To increase the reliability of the results a second round of testing was conducted for the two materials that showed the most promise based on the first tests. Imarco EL700 was left out due to availability issues and Hardox 400 lost its heat treatment benefits during welding and did not pass on the acceptance criteria. Due to these reasons the second testing was conducted only on S690Q and SB500. And based on the first testing it was noted that the harder wire for the surface was required and that the multiple pass welding simply took too much time to be considered economical, so the second test only followed the procedure number one, where the gap was filled with a single pass until almost full and then after a cool down period the surface layer was done with the harder wire.

For the second round of testing three test pieces of SB500 and two test pieces of S609Q were welded.

*Table 10 Second weld test procedures*

| No | Material | Fillet | Pre heat °C | Interpass temperature °C | Passes | Esab Wire |
|---|---|---|---|---|---|---|
| 13 | SB500 | | 75 | 350 | Two | Yes |
| 14 | SB500 | | 75 | 200 | Two | Yes |
| 15 | SB500 | | Room temp | 400 | Two | Yes |
| 16 | Thyssen S690Q | | 150 | 200 | Two | Yes |
| 17 | Thyssen S690Q | | 150 | 550 | Two | Yes |

Table 10 shows the different procedures that were tried during the second testing. One of the SB500 pieces was tested without pre-heating and for all the other tests different interpass temperatures were tried. As the cooling time to the suggested 200 °C was around 20 minutes it would make the welding a lot more economical if an approved result could be achieved if the surface layer could be welded directly after the first weld or with only a five-minute cool down period to 350 °C.

Similar as for the first round of testing hardness and impact toughness were analysed in a laboratory. Table 11 sums up the results for the second round of testing.

*Table 11 Second weld test results*

| No | Material | Fillet | Total phase time[min] | Esab wire | Surface hardness >200 HB | Impact >27 J |
|---|---|---|---|---|---|---|
| 13 | SB500 | | 12 | x | ~OK | Not OK |
| 14 | SB500 | | 25 | x | ~OK | Not OK |
| 15 | SB500 | | 6 | x | ~OK | Not OK |
| 16 | Thyssen S690Q | | N/A | x | OK | Not OK |
| 17 | Thyssen S690Q | | 13 | x | OK | Not OK |

As can be seen from the table not a single test piece was fully on an acceptable level. For the SB500 test pieces the surface hardness values below 200HB are in the base material or in the HAZ, hardness in the weld area are all well above the acceptable level. For the S690Q test pieces all the hardness measures in all measurement points are above 200HB. But all five test pieces in both SB500 and S690Q the impact test results are all well below the acceptable level, average results ranging between 7 – 17 J. It is notable that the difference in impact test values varied between 7 – 171 J for SB500 throughout all the tests, and average values also varied between 8 – 34 J for all the single pass welds. With the variance being this high it causes reliability issues for the testing and further testing would be recommended.

Based on the results received from the testing it was decided to use SB500 material and weld it with one pass until almost full and then weld the surface layer with the harder wire in case the requirement for impact is in J0 class and weld with multiple passes in case the customer or the crane's environment requires J2. As J0 class cannot be directly assumed from results achieved by J2 one additional round of testing will be conducted and tested for J0, but as the J2 results were acceptable in the first round of testing the assumption is that for J0 they will be on an acceptable level, but this testing will not be a part of this thesis. Additionally, the S690Q can be used for special cases where additional hardness is required, but it will require welding with multiple passes.

## 5.4 Comparing results against literature

Since the amount of test pieces is quite low a comparison of the results against similar tests done earlier is required to increase the reliability of the results. No exactly matching studies were discovered, but plenty of research made with materials with similar properties does exists. This chapter is split into studies about hardness and impact toughness.

### 5.4.1 Hardness

This chapter will review several sources about welding high strength steels and how the welding affects the hardness of the material.

L.A. Efimenko and others did a study about controlling the softening of the HAZ of high strength steels using varying cooling rates and reported similar amounts of softening when the steels were heated to a region between 850 – 950 °C. The cooling rates had the biggest impact on hardness in materials with the highest strengths. As the heat measurement tool used in weld tests for this thesis had a maximum on 650 °C, which was reached on all our test pieces, it is difficult to say just how high the temperatures were, but the materials did cool down to measurable amounts rather quickly so the 850 – 950 °C region would seem plausible. (L. A. Efimenko, 2016, pp. 435-441)

Ahiale and Oh did a study about microstructure and fatigue performance of butt welds in high strength steels and as a part of that study they measured the hardness of the material after the welding and discovered similar amount of softening in the HAZ as reported in our weld testing. They also used one martensitic material which had its hardness dropped by nearly 50%, which would match the results received for Hardox 400 in our testing. (G.K. Ahiale, 2013, pp. 581-596)

M. Pirinen and others did a study of microstructure and mechanical properties in HAZ of QT and TMCP steels of strength similar to S690Q and the results out of the QT match quite closely to the results measured from the S690Q. It is notable that the TMCP steel of similar strength did slightly better than the QT one and did not lose as much hardness. (M. Pirinen, 2014, p. 301)

### 5.4.2 Impact Toughness

This chapter will review several sources about welding high strength steels and how the welding affects the impact toughness of the material.

Hun and others did a study about the effect of heat input on microstructure and toughness for high strength steels with a similar hardness as in the materials selected for this thesis. Their research shows that controlling the heat input has a major influence both to impact toughness and hardness, and that the ideal solution for their material was between low and high heat input. But the results they had received match the tests performed for this thesis, both on the high and low heat inputs. (Jun Hun, 2013, pp. 161-168)

Lan and others studied the microstructure and impact toughness of welding low carbon bainitic steels. They had selected a TMCP steel with yield strength of 760 MPa, so it is slightly different than any material selected for this thesis, but the impact toughness and hardness decrease by similar amounts as the materials selected for this thesis. (Liangyun Lan, 2011, pp. 192-200)

Arsic and others did a study to discover the optimal welding procedure for S690QL and they were able to find a three-phase welding procedure that would fulfil the technical requirements of this thesis, this was however done on a thinner plate and it might not work the same on the thick rail. Also, the three-phase process would not be economical enough to be consider useful. They also did the welding using multiple passes and the results they received are quite close to the ones achieved in this thesis on S690Q using multiple passes. (Dušan Arsić, 2015, p. 33)

This chapter described the two rounds of weld tests and a rail material with an acceptable welding procedure was selected. The results were also compared against literature and were found to be on a similar level. The next chapter will discuss the key findings of the thesis and analyse reliability of the thesis.

# 6 DISCUSSION

This chapter will discuss the results and findings of this thesis and assess the reliability and value of the thesis.

## 6.1 Comparison of thesis results against other results

As described earlier the results of this thesis seem to match with results found from literature quite well, which also increases the reliability of the thesis.

## 6.2 Reliability

This thesis has been written with an open mind and trying to stay as objective as possible, but some ideas could have possibly been studied further instead of neglecting them on face value based on initial estimates.

The reliability of the thesis is on a level where the results can be trusted as they are similar to the results of other studies conducted on similar materials, but due to the low volume of test pieces and low amount of initial data on the failed cranes the thesis does carry some uncertainty. High variance of the impact toughness tests is the biggest cause of concern for reliability, values varying between 8 and 137 J inside a single test piece in the worst case and seven other test pieces having variance more than 45 J inside the test piece. Validity of the thesis is on a high level as it was very clear what was required to measure, and all the measurements were done according to standards.

## 6.3 Error analysis

With the low amount of testing done for this thesis conducting the mathematical error analyses will not provide usable results. But through triangulation between the laboratory results, literature review and previous experience of Konecranes professionals it can be said that they all match for results, which indicates low error probability.

## 6.4 Key findings

Key findings of this thesis are related to welding data out of these new materials and their behavior during and after welding. The data is now available on how the selected materials behave with the selected welding procedures, and what kind of surface hardness and impact toughness they have. This data will be used in selecting the new rail material but can also be referenced later for any further research. One additional key finding is the lack of material data available on the rails and wheels, and in addition the poor discipline in storing the data in an organized fashion that it would be easy to find later on.

## 6.5 Novelty value of the results

Novelty value of the results is limited to weld test results of materials not welded at Konecranes earlier, so there is some novelty value.

## 6.6 Usability of the results

The results of this thesis will be used as a basis for rail material selection, so the results can be considered very useful.

## 6.7 Further research

Further research could be made by considering other materials for rail replacement or wheel material replacement. A preliminary assessment was already made about using tribological coatings, but that could be also studied further. Further optimizing of the welding procedure should also be studied especially in cases where J2 is required. The root cause for the corrugation could not be determined as a part of this thesis, so further study to determine that could still be done.

## 7 CONCLUSION

The goal of this thesis was to discover a welding procedure for a suitable steel material that could be used to replace the current flat rail used in cranes with a high duty class. Heavy duty class meaning that the cranes are used non-stop all year and mostly carrying loads near the specified maximum. The current combination of wheel and rail has on a few cases worn out much too quickly and caused corrugation on the rails. Current rail in use is standard structural steel and wheel materials is hardened high alloyed steel. Initial review was done on the topic and it was decided to replace the rail material with a steel having a higher hardness. Materials with a high hardness are known to be more difficult to weld successfully, thus it was necessary to conduct welding testing and do laboratory tests to prove that the selected process is usable for the selected material.

As the root cause for the corrugation is unknown, theory of tribology and rolling contact failure was studied and probable root causes were suggested, though not confirmed. Most likely root cause however is repeated plastic deformation caused by the wheel being too hard when compared to the rail.

Rail materials selected for comparison were Imacro EL700, S690Q, Hardox 400 and SB500. These materials were evaluated for cost, availability, weldability and mechanical properties. The materials have varying delivery states, Hardox 400 and S690Q and quenched and tempered, and EL700 and SB500 are as rolled. The quenched and tempered materials are somewhat harder than the as rolled ones, but they lost more hardness during welding than the as rolled ones. It was also found that price and availability of EL700 was not an acceptable level.

Theory of weldability was studied to better understand the results and to be more prepared for the weld tests. First round of testing was conducted for three samples of all the selected materials, with varying welding procedures. After the first round it was noticed that welding the surface layer with a harder wire was a must for acceptable results and that welding with multiple passes is not economical as a standard process. A second round of testing was conducted on the best performing materials for the first tests, SB500 and S690Q. After two rounds of testing it was discovered that the best solution for J0 class would be to weld SB500 with a single pass until almost full and surface layer would be welded with a harder wire Esab OK Autrodur 38 G M with an interpass temperature of 250 °C. If impact value J2 is required, the procedure would be kept the same except the initial filling would be done with multiple passes. During the time of writing this thesis the J0 procedure has not yet been tested, but it is expected to be acceptable.

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