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THE EFFECTS OF TEMPERING TEMPERATURE AND DIRECT HARDENING ON MECHANICAL PROPERTIES OF 35M13B AND 30M12CB

MASTER THESIS
REMI KLEIVEN FJELLDAL

Preface

The work on this thesis has been performed at the University of Stavanger, spring 2016. The thesis is a result of a cooperation between Kverneland Group and the University of Stavanger. I would like to thank my supervisors Professor Ajit Srividya (UiS) and Erlend Sølvberg (Kverneland), for their help and knowledge during my work.

Abstract

In this work the mechanical properties of the wear parts with respect to the different heat treatments applied have been investigated. Two different alloys and a total of nine different heat treatment procedures were tested. Alloy 35M13B have been tested with respect to tempering temperature and represents one wear part. The other wear part 30M12CB have been tested with respect to both tempering temperatures and effect of direct hardening.

The main goal of this work has been to improve the understanding of how the steel alloys used for the wear parts responds to different tempering temperatures and heat treatments.

During this work both alloys were tested using the following test methods; charpy impact testing, tensile testing and Vickers hardness testing. From production, wear part 30M12CB as currently produced and when directly hardened was to be investigated for its mechanical properties, thus alloy 30M12CB was heat treated at different temperatures with the aim to find two heat treatments that would match the wear parts pulled from production. The two chosen temperatures for 30M12CB were 850*C representing the current production and 1100*C representing direct hardening. Then, wear parts 30M12CB and 35M13B was heat treated accordingly and tempered. The current tempering temperature of 220*C was compared with 180*C and no tempering.

Charpy test specimens and tensile test specimens for 35M13B and 30M12CB were then tested with three parallels. The results recorded was then compared with respect to mechanical properties for the different tempering temperatures and heat treatments.

For all parts the strength increased slightly by lowering tempering temperature from 220*C to 180*C.

No tempering did not affect the ductility of 35M13B and improved the strength and hardness for this alloy, in contrast no tempering left 30M12CB-850 very brittle.

Directly hardening wear part 30M12CB will result in a slight reduction in quality, however the difference in quality will likely be slightly greater than the results from this work indicates.

It is reasonable to say that reducing the temperature of tempering for 35M13B may be preferable as it saves space, reduces production time and cost, while maintaining or increasing the hardness and strength of the material. Further, the slight reduction in ductility should not lead to brittle fractures and thus may not affect the end product negatively.

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1. INTRODUCTION

1.1 General

Steel alloys are used in manufacture of wear parts of agricultural machines. Production of the wear parts needs a good understanding of heat treatment of the steel alloys and the tempering temperatures to be used in production. The focus of the thesis is to improve the understanding of how the steel alloys used for the wear parts responds to different tempering temperatures and heat treatments. Furthermore, based on the findings this also has the potential to make the production more effective, save space and reduce cost. Two different wear parts of a plough being manufactured by Kverneland Group are taken for study in the present work. Specifically how the wear parts are heat treated and tempered, and thus what effects the different tempering temperatures and heat treatments have on the mechanical properties of the wear parts which is interesting for Kverneland in many ways,

Kverneland Group is a leading international company in development production and distribution of agricultural machines. Their agricultural machines mainly consist of different steel parts. Kverneland Group are strongly focused on innovation in order to deliver high quality products. Production of agricultural machines is a highly competitive industry, and thus research in all areas from development to production is key to staying competitive and delivering high quality products.

Kverneland Group now has multiple departments around the world. The department responsible for agricultural ploughs has collaborated with the University of Stavanger for this study, is located in Kverneland, 25 km outside of Stavanger. This is also where the company was founded in 1879, and is today the oldest production facility in the company (Kverneland Group, 2016).

1.2 Objectives

The goal of this thesis is thus to investigate and document the mechanical properties of the wear parts with respect to the different heat treatments applied.

The steel alloys investigated for this thesis are 30M12CB and 35M13B. They represent one wear part each. Common for both wear parts today, is that they are tempered at 220*C after hardening. The mechanical properties when tempering the wear parts at a lower temperature of 180*C is compared with the current temperature of 220*C, furthermore leaving out tempering completely is also looked at and compared with the two others. The aim of this is to see if there are any noticeable differences in the three approaches. If no tempering is necessary for the desired mechanical properties of a wear part, it would mean that the efficiency of production would improve by removing that step in the production. This would save space and reduce cost for Kverneland. Lowering the tempering temperature to 180*C would also lead to reduced cost due to the lower energy requirements.

The wear part from alloy 30M12CB is currently being produced by hot-forging, air cooling and reheating before hardening. Hardening the wear part directly after forging (i.e. direct hardening), is a different production method that could be applied. However the mechanical properties of the wear part when hardened directly is currently unknown, and will therefore be investigated during this thesis. If the mechanical properties of the wear part are sufficient when hardening the part directly, it would mean that the production time for the wear part could be reduced and hence improve the efficiency of production. This would also save space and energy of reheating, thus lowering production cost. Here too, the effect of tempering is investigated.

1.3 Scope

The work will consist of performing 27 charpy tests and 27 tensile test with the intent to improve the understanding of how the steel alloys used for the wear parts responds to different tempering temperatures and heat treatments.

2. LITTERATURE STUDY

2.1 Iron-Carbon phase diagram

Carbon is one of the most important alloying elements of steel. It is important for the properties and the possibilities for heat treatment (Holm, Pelle, & Toell, 2012). This is because carbon has an effect on the stability of the different phases of iron. Carbon and iron can form new phases that are compounds of iron and carbon. Most relevant of these is cementite (Fe3C). Figure 1 shows the Iron-Carbon phase diagram.
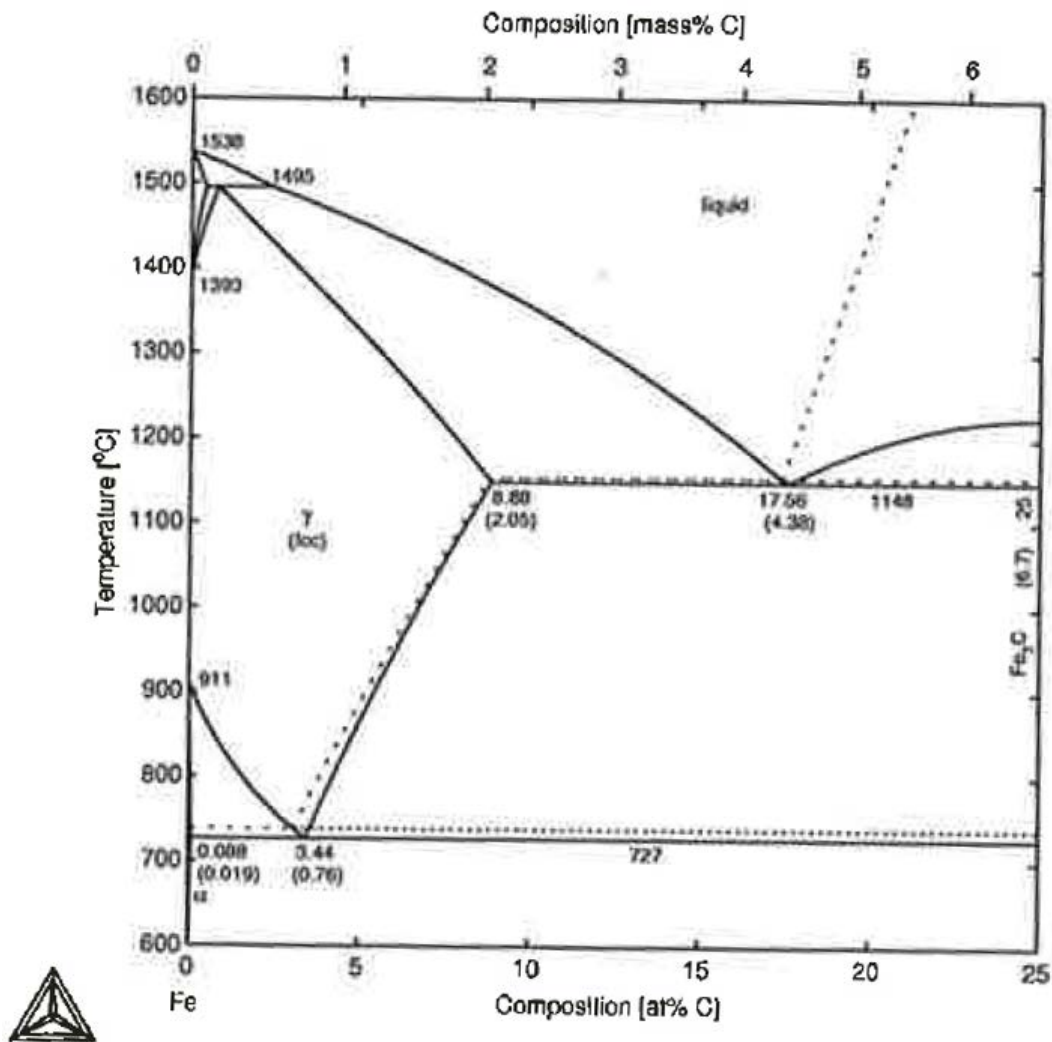
Figure 1: Iron-Carbon phase diagram. (Holm et al., 2012)

The Iron-Carbon phase diagram is important because it gives a fundamental understanding of heat treatment, as it helps us understand the different phase transformations of steel during heat treatment.

Different phases will be thermodynamically stable depending on the chemical composition and temperature. Ferrite α and cementite Fe3C are the equilibrium phases. In the temperature range of 727-911*C three phases can occur depending on the carbon content. Austenite γ+ ferrite α, austenite γ, and austenite γ + cementite Fe3C. It should however be pointed out that the Iron-Carbon phase diagram only describes the state of equilibrium. It does not take other factors into account such as time, or effects of other alloying elements.

At low temperature ferrite has a body-centered cubic (BCC) crystal structure. Austenite have a face-centered cubic (FCC) structure.

2.2 Time- temperature transformation

Time is one of the most important components in heat treatment. It is the combination of time and temperature that decides the different phases and components that can have, and thus what properties the steel can obtain. When water quenching austenized steel, martensite is formed. How much martensite and what other transformations take place is described by the CCT-diagram (Continuous-Cooling-Transformation). More on this is "2.5 Hardenability and hardening".

2.3 Diffusion

In solid materials, the atoms are not fully fixed to their positions. Due to thermal disorder, there is a tendency for the different atoms in a crystal to move in a more or less random way. In other words diffusion is the tendency for composition differences to level out at higher temperatures. Diffusion plays an important role in the transformation from austenite to ferrite and cementite.

Diffusion is a slower process than grain growth and the transformation rate is limited by how quickly the diffusion can take place. The formation of ferrite, pearlite and bainite is an example of diffusion-controlled phase transformation (Holm et al., 2012).

The diffusion is temperature dependent, and according to the Arrhenius equation (eq 1), the coefficient of diffusion increases with increasing temperature.

$$D = D_o \, exp(-Q/RT) \text{ (Eq. 1)}$$

Where D_o is the frequency factor and Q is the activation energy. R is a gas constant and T is the temperature (Holm et al., 2012).

2.4 Martensite

Martensite is a diffusionless transformation. The martensite transformation takes place when austenized steel is cooled rapidly, this process is often called quenching. When the cooling is rapid enough the precipitation of austenite to a mixture of ferrite and carbide is suppressed. The carbon concentration in the martensite will correspond to what is found in the austenite.

The transformation of austenite to martensite starts from the start temperature of martensite M_s and finishes at the temperature M_f. A simplified way one could describe the transformation from austenite to martensite, is that the transformation takes place through the crystal structure being deformed from FCC to BCC.

Retained austenite, is austenite that is not transformed to martensite or bainite during martensite transformation. A reason why retained austenite is stable has to do with the fact that it is rich in carbon. And thus lowering M_f below room temperature.

2.5 Hardenability and hardening

Hardenability refers to how easy it is to make a steel hard, in other words how easy it is to avoid diffusion-dependent transformations i.e. ferrite and pearlite. A steel with high hardenability would easily harden to 100% martensite by quenching. See figure 2.
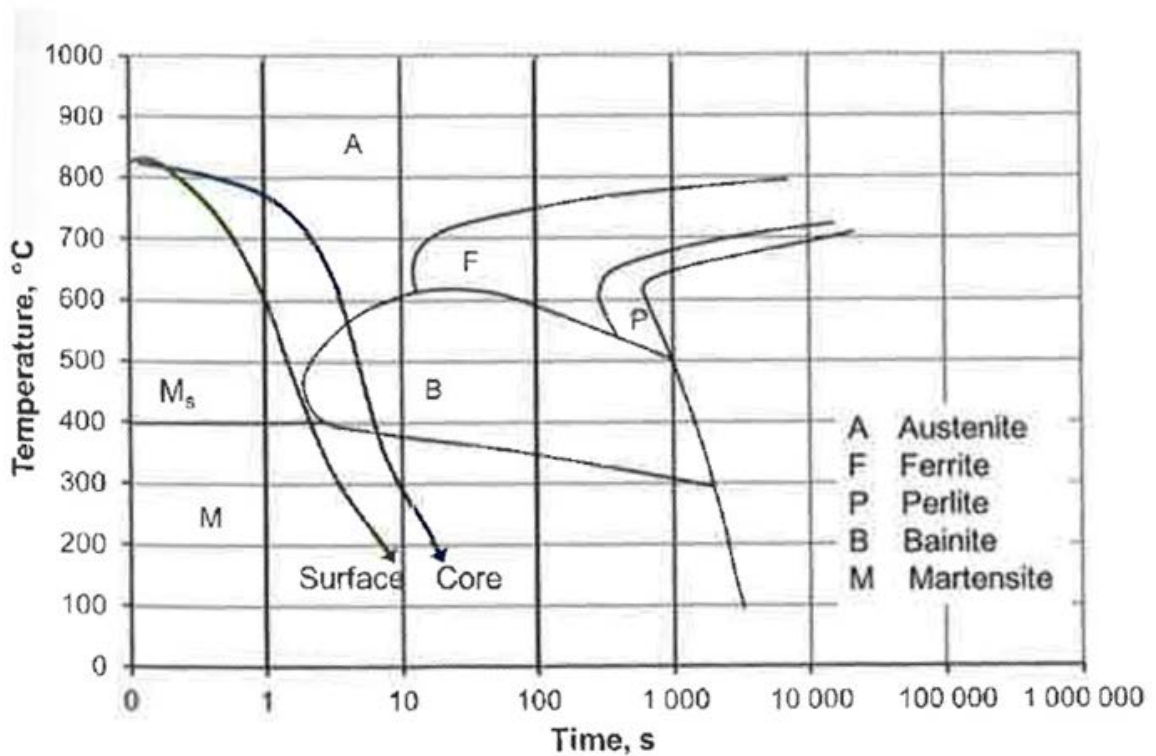
Figure 2: CCT-diagram with an example of a cooling curve (Holm et al., 2012).

Form the example in figure 2, it is seen that the surface transforms mostly to martensite because the temperature decreases fast enough with time. The core in the example does not have time to cool fast enough and thus some bainite is formed in the core. If cooling would have been slower, i.e the cooling curves would have been further to the right, the austenite would transform into ferrite and perlite if the curves crossed into their areas.

In order to reach maximum hardness the cooling curve must not interfere with the lines crossing over to Ferrite, Pearlite and Bainite. The further to the right the Ferrite, Pearlite and bainite areas are, the better the hardenability becomes.

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The most important factors of hardenability is the chemical composition of the steel and the austenite grain size. (Totten, 2007). The majority of alloying elements displaces the diffusion-dependent transformations towards longer times, thus increasing hardenability. Because nucleation centers are formed primarily along the austenite grain boundaries, a greater austenite grain size results in the formation of ferrite and pearlite takes longer time.

The alloying component boron is added to steel in order to improve the hardenability. Very small amounts of boron has great effect on the hardenability, it also improves the hardenability of other alloying elements, and is thus a very economical substitute for some of the more expensive elements. The benefits of boron is only apparent in steels with less than 0.6% carbon, and with boron content in amounts of thousandths of a percent, more boron does not further improve hardenability (Totten, 2007).

The cooling curve is essential for hardening. Cooling the austenized steel with intent to harden it is called quenching. The cooling sequence has a great effect on the properties of the steel, such as its microstructure, hardness, residual stresses, strength and also the distortion caused by hardening (Holm et al., 2012). The cooling capacity of quenchants is important to the hardening process, air for example has a low cooling capacity and therefore steel cooled in air rarely develops a great hardness. Water on the other hand has a greater cooling capacity, however pure water is not ideal because it's highest cooling rate is around 300*C/s. By adding 5-10% soda (NaOH) to water the cooling capacity improves greatly, and the cooling rate then lies around 500*C. The effects of soda water is best at around 20-40*C water temperature (Holm et al., 2012).

The rapid cooling of steel from quenching creates thermal stresses in the quenched part. The risk of of hardening cracks increases with cooling intensity, due to thermal stresses. With a higher hardenability of the steel, a milder quenchant should be used to avoid hardening cracks, in other words the cooling intensity should match the hardenability of the steel so that it is just enough to create the desired hardness.

Thermal residual stresses happens when quenching steel. At the start of quenching, the surface temperature decreases faster than the core temperature and as a result longitudinal tensile stresses develop at the surface and compressive stresses develop at the core. The core and surface cannot withstand these stresses and as a result they plastically deform. The surface extends and the core compresses. After a while the temperature of the core will decrease faster than the surface. Ultimately the core will reach the same temperature as the surface. And residual stresses that remain are compressive at the surface and tensile in the core as seen in figure 3 (Totten, 2007).
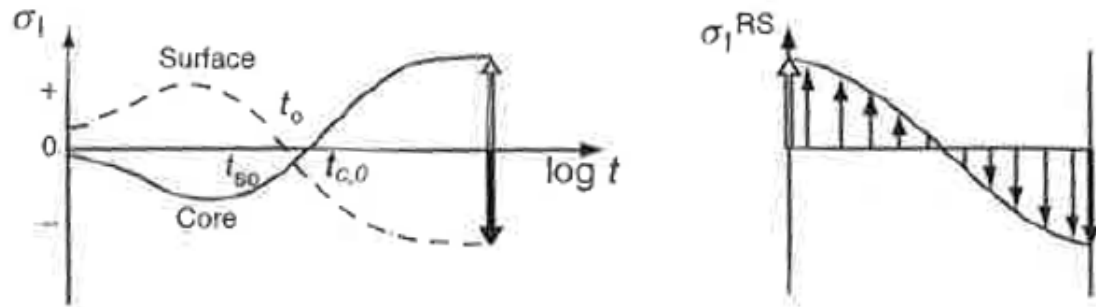
Figure 3: Thermal residual stresses when quenching a cylinder (Totten, 2007).

2.6 Direct hardening

Direct hardening refers to quenching forged steel right after the completion of forging, the quenching should happen quickly enough so that martensite is formed.

An advantage of direct hardening is clearly illustrated in figure 4. Direct hardening reduces the time and processes needed to complete the heat treatment and therefore reduce cost and energy. Normally after forging steel is cooled and then reheated again for hardening.
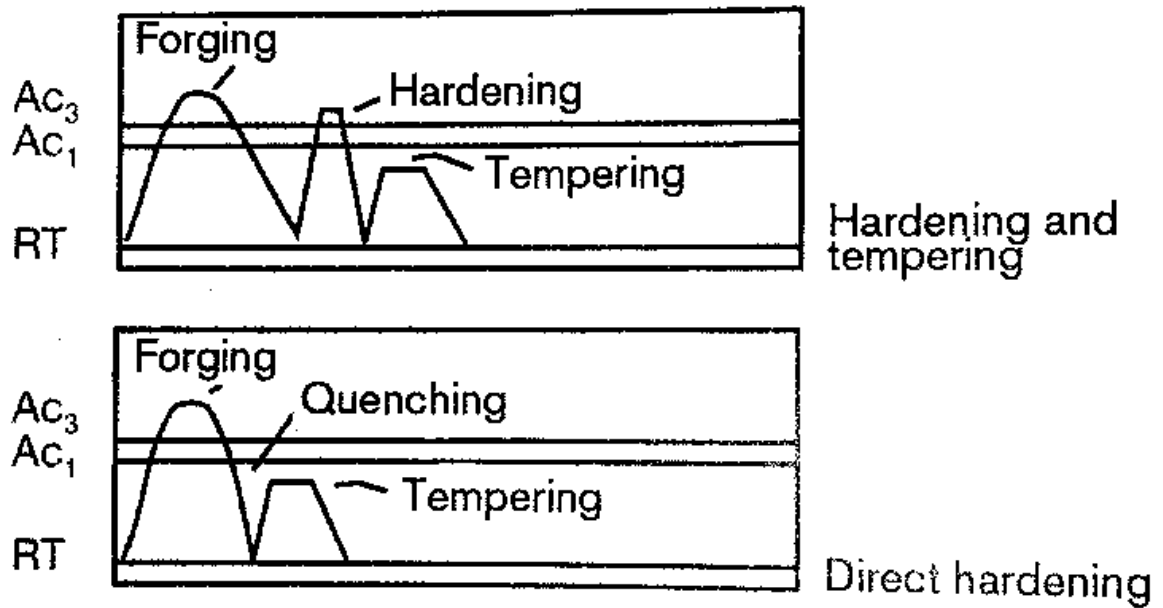
Figure 4: Process sequence for direct hardening compared with hardening and tempering (Holm et al., 2012).

However, direct hardening poses a risk of increased grain size, which negatively affects the mechanical properties of the steel. In order to inhibit grain growth at high temperature for boron steels, they sometimes contain a small amount of titanium (Holm et al., 2012).

2.7 Tempering

Tempering refers to heating hardened steel at a temperature below the A1 temperature, i.e. below the temperature needed to form austenite. Tempering is usually done in the range between 160-650*C (Holm et al., 2012). Tempering is a thermal martensitic treatment, at which the basic process that takes place is martensite precipitation. The first structural change that takes place is that the carbon in martensite segregates at dislocations, which will reduce the hardness but increases the ductility. Hardened steel has some untransformed austenite which if transforms later may lead to cracking or distortion (Totten, 2007). This is because of the tensile residual stresses that can form during quenching, the residual stress is a combination of the thermal gradients, phase transformation, difference in cross-section dimensions, decarburization and other chemical deviations (Holm et al., 2012). To overcome this problem tempering is done.

A transformation of retained austenite to a heterogeneous mixture composed of cementite and a supersaturated ferrite-solution, happens when the steel is heated over 200*C. This means that the retained austenite transforms to tempered martensite (Totten, 2007).

Structural changes takes place during tempering, the effect on the mechanical properties of steel depends on the particular tempering conditions. Generally, the effects on mechanical properties is corresponding with the tempering temperature, when temperatures increase the strength parameters decrease (yield strength and ultimate strength). Likewise the ductile parameters improve when temperatures increase.

2.8 Mechanical properties

The ability to resist plastic deformation upon exposure of external forces is related to a material's hardness. Hardness relates to several material properties, such as static strength, fatigue strength, and wear resistance (Holm et al., 2012).

Plastic deformation and ductile fractures can occur when high loads are subjected to materials that are ductile. If the stress exceeds the material's yield strength, the material becomes permanently distorted, furthermore if stress increases above and beyond the material's ultimate tensile strength a ductile fracture will occur. However for

materials with little ductile characteristics i.e. little capacity for plastic deformation, the fracture that happens when overloaded is a brittle fracture. In other words, the material's ability to be exposed to plastic deformation without cracking is materials ductility. When impact testing an unnotched test piece the energy required to fracture the piece is a measure of the materials ductility, other measures of ductility is the material's elongation at break and reduction of area when tensile testing is done.

2.9 Grain size
The grain size is important when it comes to the mechanical properties of steel. Large grains usually have a negative effect on the mechanical properties. One reason for this is the segregation of impurities such as phosphorus to grain boundaries (Holm et al., 2012). Large grains leads to fewer grain boundaries, which leads to higher degree of segregation, thus a higher local concentration of impurities which results in weaker boundaries. This may cause fractures to happen at old austenite grain boundaries. Larger grains reduce toughness, ductility and ultimate tensile strength. Grain boundaries make a serious obstacle to dislocation movements, and thus increases the yield strength of the material. This is because dislocation movements gets transferred from grain to grain, and is thus impeded by grain boundaries. The number of dislocations is proportional to the size of the grain, bigger grains can contain more dislocations than smaller grains, and as a result it is easier to transform plastic deformations in bigger grains.

This can be expressed by the Hall-Petch equation:

$$\sigma_y = \sigma_o + \frac{k_d}{\sqrt{d}}$$
  (eq. 2)

The d is the grain size, the k_d is a characteristic parameter for the material a constant. σ_y is the yield stress, and σ_o is the yield stress for a monocrystalline material.

2.10 Tensile testing

Tensile testing determines the relationship between the stresses imposed on a material and the level of deformation of the material. Tensile testing is done clamping a test piece in both ends and then by gradually increasing the load of a test piece until a fracture occurs.

Some of the material characteristics can be evaluated as a result of tensile testing are.

- Yield strength (0.2% offset)
- Ultimate tensile strength
- Elongation at fracture
- Area reduction

Yield strength is the stress needed to produce a small specified amount of plastic deformation in steel, if the yield strength is not exceeded the steel will go back to its original size. However, if a material is subjected to a load so heavy that the yield strength is exceeded then the material is plastically deformed.

Ultimate tensile strength is maximum tensile stress the specimen can take. When the ultimate strength is reached necking appears which decreases the cross-sectional area. Because stress is calculated based on the original cross sectional area, the stress falls in the diagram, but in reality the stress further increases until fracture.

Elongation at fracture provides a measure of the material's ductility. Together with the reduction of area at fracture it tells us how much plastic deformation the material can tolerate before fracture.The elongation at fracture how much the gauge length has elongated after fracture. And the area reduction is the reduction in the cross sectional area from the original cross section to the cross section at fracture.

2.11 Charpy testing

Charpy testing is performed by striking a test specimen with an edge mounted in a hammer that is mounted to a pendulum arm. A standard test specimen has the dimensions of 10mm x 10mm x 55mm, and include a 2mm deep notch with 45* angles between the sides. The notch is in the center of 55mm length of the specimen. The specimen is placed inside the test machine with both ends of the length facing a counterpart which holds the specimen in the right position and allow the hammer to bend/fracture the center of the specimen. The notch is placed on the opposite side of

where the strike edge impacts. The notch also serves as a guide to center the test piece horizontally.

The energy that is needed to fracture the test specimen is given in joule, tells us if the material is brittle or ductile, and how though it is. A brittle material will not be able to absorb much energy before fracturing because of its inability to plastically deform. The more impact that can be absorbed the higher the toughness of the material.

2.12 Vickers testing

Testing for hardness using Vickers testing is done by pressing a pyramid shaped diamond indenter with 136* apex angle into a material using a specific testing load. The determined hardness using Vickers test is designated HV. The load used for testing is indicated by the weight used to determine the hardness. HV10 refers to 10kg load for 10 seconds.

To determine the hardness the diagonals of the indentation is measured. The following equation is then used to calculate the HV value.

$$HV = 0.1891 * P/d^2 \qquad\qquad \text{(eq. 3)} \quad \text{(NS-EN ISO 6507-1)}$$

Where P is the force used on the material and d is the average of the diagonals on the indentation.

2.13 Grain size investigation

Microscopy can be used to determine grain size of the material. This is done by placing the material under a microscope in order to look at the grain size of the material. In order for the grain size to be visible in the microscope the surface must first and foremost be very fine. When a very fine surface roughness is achieved, acid is used to etch the material in order to highlight the grain boundaries.

The grain size can then be determined using different methods according to the ASTM E112 - Standard test methods for determining average grain size. One of these methods is line interception. The intercept method counts the number of grains which are overlapped or intersected along the measurement section. And then the number of grains which is divided by the length of the measure, resulting in a grain size.

3. Experimental Investigations

The experimental investigations carried out are split up in 4 parts. First the heat treatment, tempering, and test piece machining process will be covered as a similar process was used for each part investigated. After this, each alloy will be covered separately, as they represent different wear parts and require different investigations prior to testing. 30M12CB will be covered first, followed by 35M13B. Finally the material testing is covered, the same tests are done to each wear part.

A total of two steel alloys were investigated for this thesis, 30M12CB and 35M13B. Each are representing one wear part. From this point on, the wear parts investigated will be referred to by their respective names "30M12CB and 35M13B", for 30M12CB two different heat treatments were investigated. In order to identify each process the austenization temperature will be included at the end of the name for 30M12CB. The goal of the experimental investigations is to find out the effect tempering has on the mechanical properties of the wear parts, and thus if it is possible to register differences in the mechanical properties for the following tempering;

- No tempering
- 180 degrees C
- 220 degrees C (currently used at the production)

Furthermore an alternative production method for 30M12CB was investigated and compared to the current method, here too the effect of tempering was looked at.

The motivation for investigating alternative production methods and tempering temperatures is to see if the production can be made more effective in terms of time and cost. Cutting out tempering or lowering tempering temperature would reduce the cost and energy spent to produce the wear part. If tempering can be cut completely the cost and time to produce each part would be even further reduced. In addition to tempering, for 30M12CB the alternative production method investigated is direct hardening of the wear part, this would reduce the time and thus cost to produce the part significantly.

The chemical composition for each material is in the table below.

Table 1: chemical composition of each wear part in %.

% →	C	Si	Mn	P	S	Cr	Ti	Al	B	N
30M12CB	0,28	0,22	1,36	0,03	0,014	0,43	0,043	0,006	0,0029	-
35M13B	0,341	0,266	1,23	0,01	0,0006	0,139	0,034	0,034	0,0023	0,0032

The following tests are performed to determine the mechanical properties:

- Grain size determination
- Charpy impact testing
- Tensile testing
- Vickers hardness testing

Grain size determination was only investigated for wear part 30M12CB.

3.1 Heat Treatment, Quenching and Tempering

All the heat treatment, quenching and tempering were done at Kverneland. To austenitize the steel, i.e. heating the steel to a temperature at which the ferrite transforms into austinite, a "C.H.Evensen industrial oven, temperature controlled with a FLUKE 54IIB thermometer" to heat the steel to a range of temperatures from 850 degrees C to 1100 degrees C.

All the subsequent quenching was done by submerging the austenized steel vertically in NaOH+H2O(Lut) at room temperature.

All the tempering was done using a salt bath, the temperature of the salt was monitored using a FLUKE 54IIB thermometer. All the tempered steel was cooled in water at room temperature.

3.2 Machining of test piece
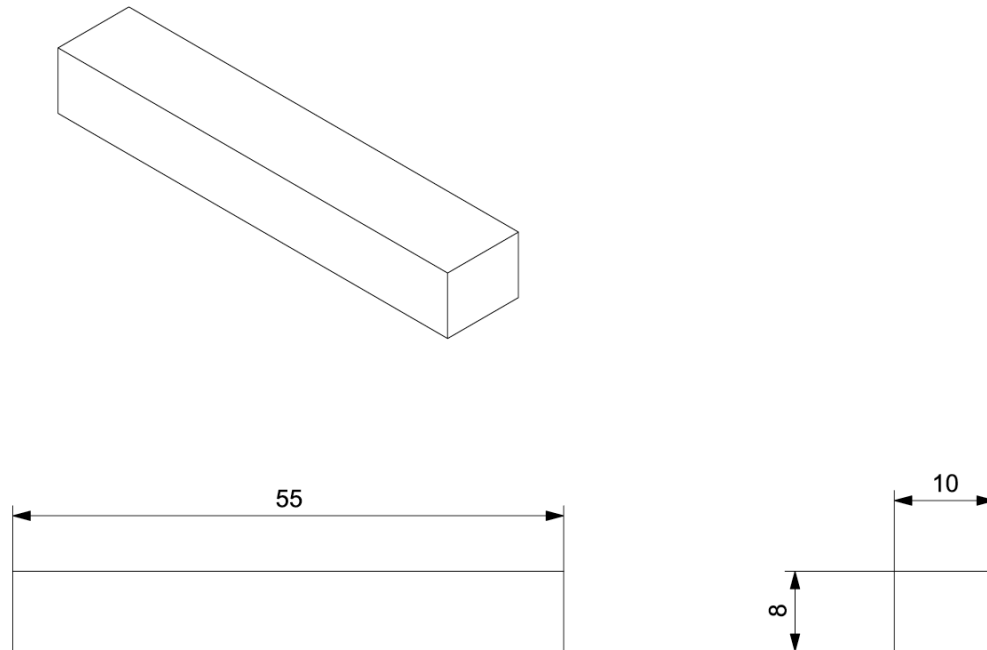
Figure 5: Technical drawing of Charpy Test piece

The charpy test pieces was cut across the rolling direction. For 30M12CB, the cross section is 22mm x 56mm, and thus the width of the material is the length of the Charpy piece. With a height of 8mm for the test piece, and a height of the cross section of 22mm, it was possible to extract two pieces of 8mm per cut of; 10 mm x 22mm x 56mm. I bandsaw was used to make these cuts. After the 10mm x 22mm x 56mm piece was cut, a milling cutter was used to machine the material to the right size, and finally a Stuers Discotom-10 was used to cut the 16,5mm x 10mm x 55mm pieces into two, 8mm x 10mm x 55mm pieces. The milling cutter cut equal amount of material from each side, hence the charpy tests came from the center of the 22mm x 55 mm cross section.

For 35M13B the height of the cross section was 12,5mm. A band saw was used to create the general shapes with 8,2 mm x 12,5 mm x 55mm before a milling cutter was used to achieve the final size.
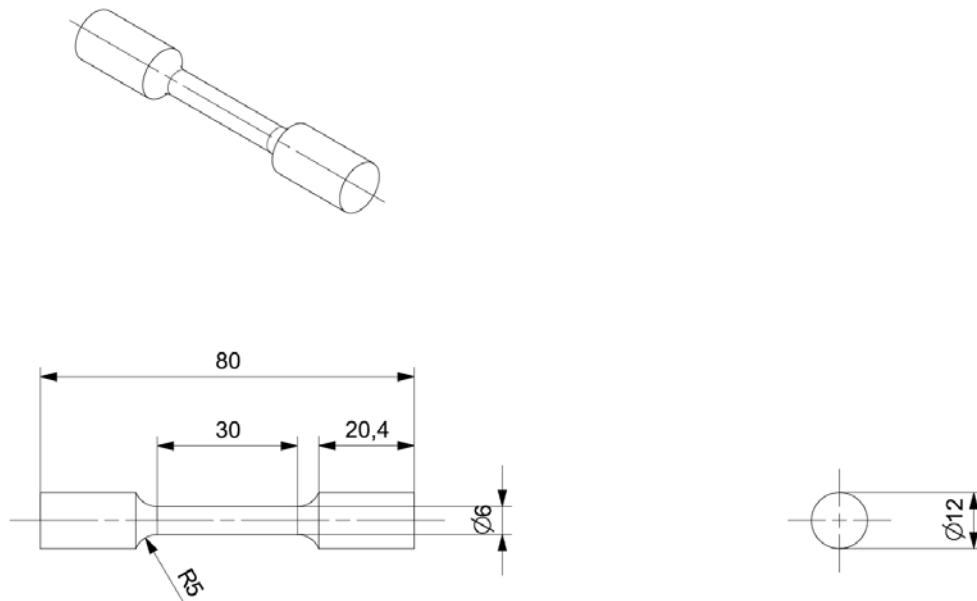
Figure 6: Tensile test technical drawing.

The tensile test pieces were machined using a combination of a manual lathe and a programmable CNC lathe. A general shape was achieved cutting the raw material into rectangular shapes using a bandsaw. From the 30M12CB material, the cross section was 55 mm x 22mm. The tensile test were cut along the rolling direction, and thus 3 pieces was taken from the cross section of 30M12CB, the three square pieces made cylindrical using lathe to a rough diameter of 16-14mm. For 35M13B the cross section thickness of the coil was 12 mm, the pieces was thus cut to a 12mm x 12mm cross section and then made cylindrical to a rough diameter of 11,5 mm. Once the cylindrical shapes were obtained the now 80-90mm long cylindrical pieces were placed in a CNC lathe with a program to precisely cut the test pieces to their final shapes. For 30M12CB the large diameter was 12mm, and for 35M13B the large diameter was 10mm. The technical drawing of the tensile test pieces are shown in figure X. What the drawing fails to mention is that pieces were also threaded, with M12x1,25 and M10x1,0 respectively. The reason for threading was better prevent the piece from breaking outside the reduced area.

3.3 WEAR PART 30M12CB

The current production process for the wear part 30M12CB is forging the steel at 1200 degrees C, once the intended shape is achieved, the piece gets air cool down to room temperature. The cooled steel is then austenized to approx. 900 degrees C, with a subsequent quenching in NaOH + H2O at room temperature finalizing the hardening process. Tempering is done at 220*C for 20 minute in a salt bath.

3.3.1 Deciding heat treatment temperature for 30M12CB

In order to decide what heat treatment temperatures to apply to the test pieces of 30M12CB, the average grain size of the production part was investigated. The information regarding the average grain size of 30M12CB was used as reference to find the temperature needed to match the grain size of the production part.

Since the test pieces won't be subjected to forging, air cooling and reheating to a new austenite temperature. The production process can't simply be reproduced for the test pieces. Hence the use of average grain size as a point of reference when deciding the temperatures. This is because the grain size is correlated with the mechanical properties of the steel. In order to get an accurate representation of test piece's mechanical properties relative to the piece from production, their grain sizes should try to be as similar as possible.

Furthermore, Kverneland is interested in investigating the possibility of changing the heat treatment process for 30M12CB. Instead of the current method of air cooling the piece after forging and then reheating it to an austenization temperature of 900 degrees C before quenching, the possibility of quenching the part directly after forging will be investigated (i.e. direct hardening). The motivation for using this method would be because it will reduce time and hence cost of producing the part.

3.3.2 Grain size investigation of 30M12CB

A wear part is taken from regular production to investigate the grain size. From production the wear part is also directly hardened instead of being air cooled. A small piece of each part is cut out using a Struers Discotom-6 with 0,3 mm/s feed rate, the cross section investigated is across the rolling direction of the material.

Along with investigating actual wear parts from production, 6 small pieces of 30M12CB cut out of the raw material using the same cutter. These pieces were heated to different temperatures to with the intent to find the grain size that would match the production part and directly hardened part. The pieces from the raw material was approximately 5mm x 22 mm x 57 mm and taken directly from untreated piece of 30M12CB. They were heated at the different temperatures for 10 minutes, followed by quenching them in NaOH+H20 at room temperature.

Before looking at the grain size each piece were tempered at 420*C for 20 minutes. The temperatures investigated were:

Table 2: Austenitization temperatures for grain size investigation of 30M12CB

Wear part	Austenitization temperature [°C]	Time	Tempering [°C]	Time
30M12CB	850	10 minutes	420	20 minutes
30M12CB	900	10 minutes	420	20 minutes
30M12CB	950	10 minutes	420	20 minutes
30M12CB	1000	10 minutes	420	20 minutes
30M12CB	1050	10 minutes	420	20 minutes
30M12CB	1100	10 minutes	420	20 minutes

The pieces from production had also been tempered at 420* C for 20 minutes.

To get a better look at the grains, all parts investigated for grain size were tempered to 420*C. Since we are not interested in the mechanical properties in this case, the difference in tempering temperature is negligible, because it does not affect the size of the grains.

3.3.3 PREPARING OF MICROSCOPY TESTS

Once all parts were tempered at 420 degrees C for 20 minutes. A small cross section across rolling directed was casted in a mixture of Struers DuroFast and ClaroFast hot mounting resins. DuroFast was used to cover the steel while ClaroFast was used to fill it up to a usable size. The machine used to mold was a Hot Mounting Press OPAL 410. The reason for molding the pieces is because the mount itself is very hard which helps reduce rounding of edges from polishing and because the top and bottom of the mount completely parallel. After mounting, all pieces was polished following the following method:

Table 3: Polishing steps for preparation of microscopy

Step #	Polish disc	Force	Time	Cooling liquid
1	MD Piano 220	90N	3 minutes	Water
2	MD Allegro	90N	3 minutes	DiaPro 9µm
3	MD Dac	90N	3 minutes	DiaPro 3µm
4	MP Nap	90N	3 minutes	DiaPro 1µm

In order to get a good look at the grain size the pieces must be acid treated. This is done by submerging them in a mixture of:

- 80 ml Water (H20)
- 28 ml Oxalic acid (10%)
- 4 ml Hydrogen peroxide (H202)

The surface of pieces was submerged for approximately 20 seconds before being rinsed with ethanol and dried using a hot air gun. Ethanol is preferred over water because it evaporates more rapidly.

3.3.4 Grain sizes for 30M12CB

To determine average grain size, the Hayn (4) lineal intercept procedure from "ASTM E112 - Standard test methods for determining average grain size" was used. Here are the results of the grain sizes:

Table 4: Average grain sizes using Hayn (4) lineal intercept procedure.

Specimen	Temperature [°C]	Average Grain Size (μm)	Number of lines investigated
Regular Production	$1200 \rightarrow 900$	**11,6**	**4**
Directly Hardened	*1200*	*17,54*	*6*
P1	*1100*	*15,46*	*6*
P2	1050	15,54	4
P3	1000	14,16	4
P4	950	13,91	4
P5	900	13,66	4
P6	**850**	**13,0**	**4**

The temperatures 1100 degrees and 850 degrees were chosen to represent the production part and directly hardened part respectively. As they are closest to the grain size of the production parts and thus will better represent the mechanical properties of the parts they represent. Ideal the grain sizes should be matched to the identical grain size of the production part. Below in figure 7, the grain size of directly hardened will be compared with P1, the lens used is 20x, and it shows the Hayn (4) lineal intercept

procedure. Figure 8 shows the grain size of Regular production compared with P6, the lens used for these picture are 50x and does not show the procedure.
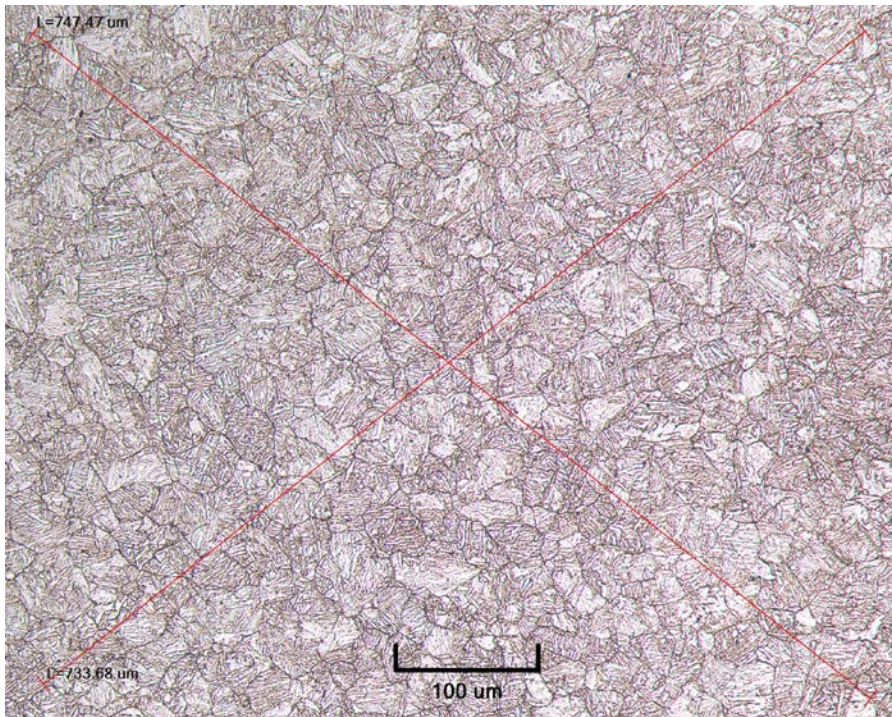
(a): Directly hardened part in 20x lens
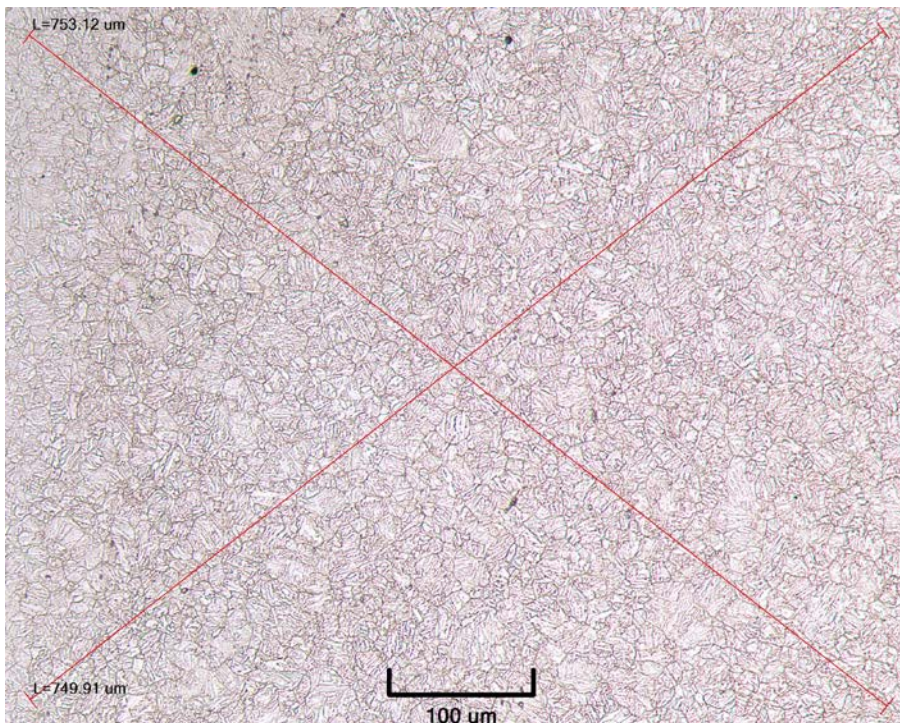
(b): P1 in 20x lens
Figure 7: Grain size comparison between directly hardened part and P1.

Figure 8 below shows Regular production compared with specimen P6.

(a) Regular Production in 50x lens
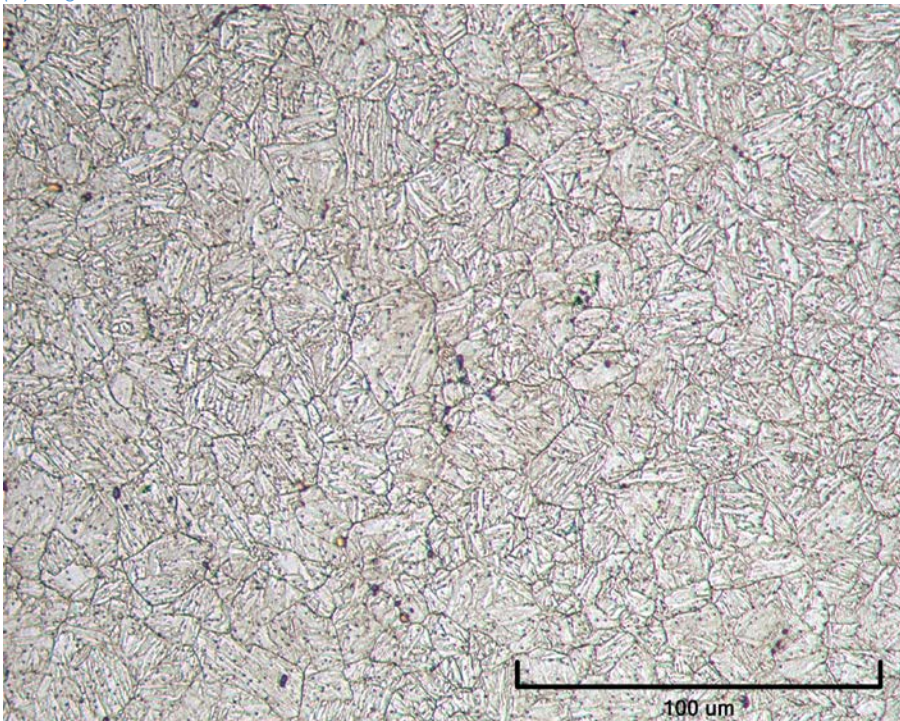
(b) P6 in 50x lens
Figure 8: Grain size comparison between regular production part and P6.

3.3.5 Heat treatment of 30M12CB

Below is a table of the heat treatment process applied all the test pieces. The heat treatment process is the same of both the charpy and tensile test pieces. To get more reliable results 3 pieces will be heat treated for each process. The quenching was done by hand one piece at the time, by submerging the test piece vertically in the circulating water mixture at room temperature. To get more reliable results, 3 parallels of both charpy and tensile test were used. Therefore a total of 18 pieces (9 charpy and 9 tensile) was heat treated for each of these two processes (total of 36 pieces).

The pieces were heated for 10 minutes until glowing red. Tempering was done in a salt bath for 20 minutes. Due to poor control of the tempering temperature all pieces tempered at 220°C kept rising during tempering and at the end of the 20 minutes the salt bath had reached 230°C.
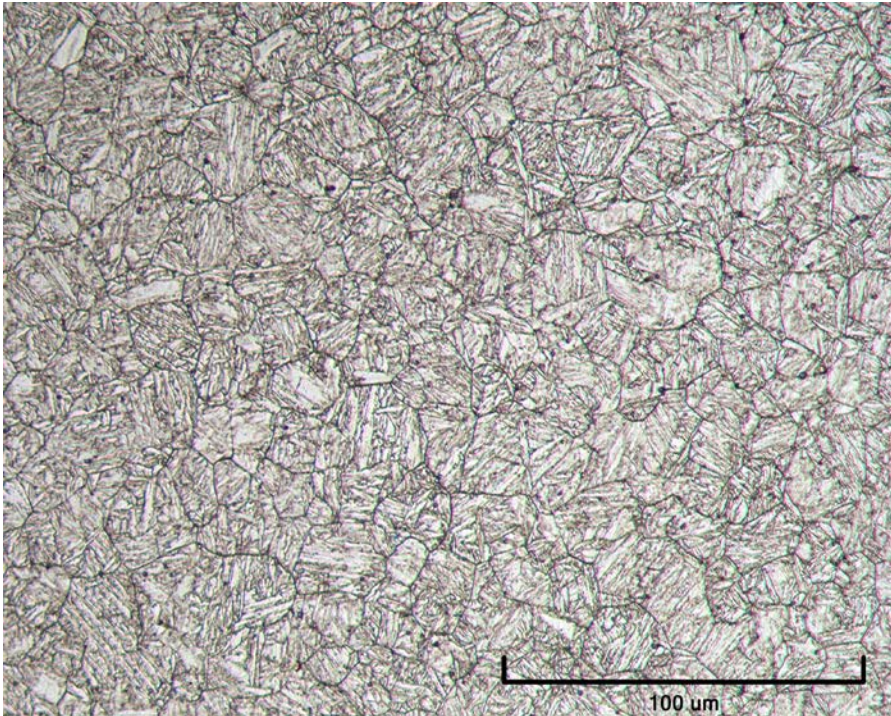
Table 5: Heat treatment of 30M13CB

Nr.	Material name	Representing production	Austenitization temperature [°C]	Quenching	Tempering [°C]
1	30M12CB-850	Current Production	850	(NaOH+H20)	220
2	30M12CB-850	CP: Different tempering	850	(NaOH+H20)	180
3	30M12CB-850	CP: Different tempering	850	(NaOH+H20)	ingen
Nr.	Material	Representing production process	Austenitization temperature [°C]	Quenching	Tempering [°C]
4	30M12CB-1100	Directly hardened	1100	(NaOH+H20)	220
5	30M12CB-1100	Directly hardened	1100	(NaOH+H20)	180
6	30M12CB-1100	Directly hardened	1100	(NaOH+H20)	ingen

3.4 Wear part 35M13B

The current production process for 35M13B is more straightforward than the wear part above. The wear part is formed at 950°C and then directly hardened in room temperature NaOH+H20. Now that the steel is hardened it is then taken to a new location for tempering at 220°C.

3.4.1 Heat treatment of 35M13B

Below is a table of the heat treatment process applied to 35M13B. Because the wear part is formed and not forged, the same temperature used in production was used on the test pieces. Same heat treatment was applied to both the tensile test and charpy tests. The same procedure described in 3.3.4 applies here too.

Table 6: Heat Treatment of 35M13B

Nr.	Material	Representing production	Austenitization temperature [°C]	Quenching	Tempering [°C]
7	35M13B	Current Production	950	(NaOH+H20)	220
8	35M13B	CP: Different tempering	950	(NaOH+H20)	180
9	35M13B	CP: Different tempering	950	(NaOH+H20)	ingen

3.5 MATERIAL TESTING

After all test pieces were heat treated to their corresponding temperatures the next step was the material testing. Each test method will be covered separately. The focus will be on what was done in preparation of the pieces, how the tests were carried out, what data were collected and which machines were used.

3.5.1 Charpy V Impact Tests

After the heat treatment, each charpy piece was marked and logged in separate containers to identify their heat treatment and tempering temperature. The charpy tests were given small notches at the corners using a angle grinder about 0,2 mm deep. Each tempering temperature and process was given a unique code to keep track of the pieces. This assured that the pieces would not get mixed up with each other, avoiding the trouble of not knowing which part represented what process.

After this, each piece was checked for distortions. Unfortunately distortions was found in many of the test pieces. To deal with this, the pieces straightened by applying small forces in order to counteract the distortion, thus making the piece straight again. The pieces which needed straightening was not further marked and mixed with the pieces which were already fine. Once all pieces looked fine to the naked eye no further action was taken.

The oxidation layer was removed by sandblasting, using a bench mounted dry blast cleaning cabinet. Once the oxidation layer was removed the pieces were sanded by hand using P80 sandpaper to remove residual oxidation and to meet the tolerances for charpy testing according to NS-EN ISO 148--1-2010.

The pieces were machined to the dimensions 8x10x55(mm) and no notch as requested by Kverneland. The pieces were placed in the charpy test machine with the 10mm surface horizontal and 8mm vertical. As shown in figure X below. Since there were no notch in center the piece, two reference points were used in order to place the piece as close as possible to the center using the naked eye.
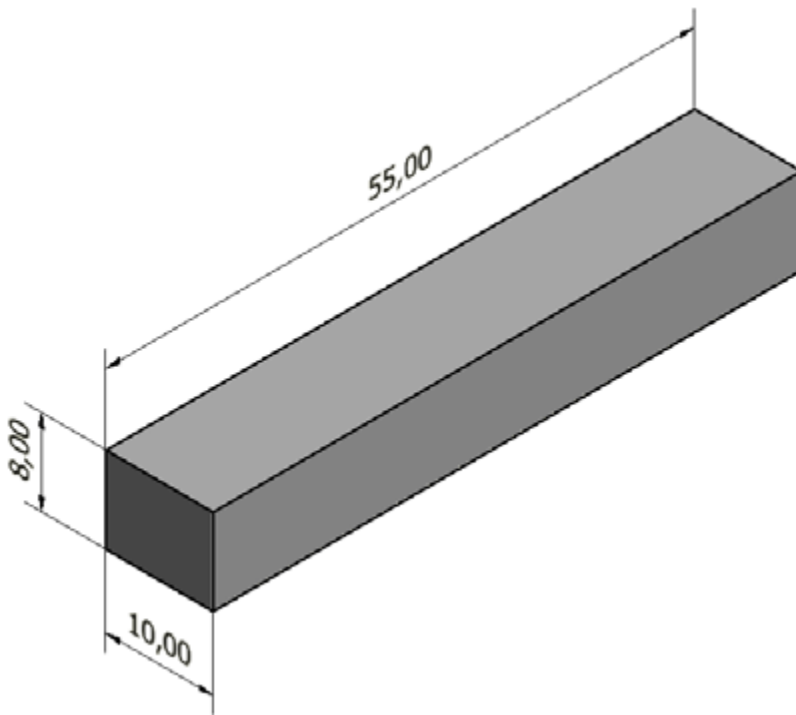
Figure 9: Charpy test piece without notch as place in the test machine.

Before each piece were tested, precise dimensions was obtained with a micrometer and noted down. The tests were carried out using a Zwick450 machine with digital results reading corrected for friction. The absorbed energy was noted down manually and logged in table X. Sample from 30M12CB 850 and 1100, along with 35M13B were taken from the charpy test and tested for hardness and grain size.

3.5.2 Tensile Tests

The tensile test were heat treated and subsequently handled in the same manner as the charpy test, with a few exception. Each type of tensile test were logged and marked to keep track of their heat treatment process, before being logged and bagged into their respective containers marked with type, heat treatment and tempering temperature.

After heat treatment each tensile test piece was investigated for distortion. Much like the charpy test here too, some of the pieces showed sign of distortion from quenching. Each piece was then inspected manually by rotating the piece and looking for distortion in the reduced section. To compensate for the distortion found, straightening was carried out. Once the straightened the piece was inspected again, and the same procedure was carried out until a desired result was achieved. The pieces that needed straightening was not further marked to later be identified.

When satisfied, the oxidation layer was removed by sandblasting, using a bench mounted dry blast cleaning cabinet.

The test were carried out using an Instron 5985 Floor Model Testing Systems for tensile testing. The data was collected by the corresponding software; Bluehill 3. Default calculated results included Yield strength offset 0.2%, Ultimate tensile strength, Area reduction and Elongation at fracture. The test pieces were treated into holders in order to avoid the specimen from breaking at the wrong place.

The results are based on the cross-section of the reduced area, to measure the diameter for for the reduced area a micrometer was used. All diameters were 6mm +/- 0,6mm. All results are based on the true diameter of the tested specimen.

3.5.3 Vickers hardness HV10

Once the charpy tests were carried out, one piece from each of the nine different temperature and tempering combination was tested for hardness using "Vickers hardness HV10". The tested charpy piece were cut using a "Struers Discotom-10 with feed rate 0,3mm/s) to a length less than 25mm, it was then mounted using a Cito-Press 30 hot mounting machine filled with 10ml SpeciFast acrylic hot mounting resin. The surface tested for hardness was the impact surface with 8mm width and a length less than 25mm in order to fit into the mount. The reason for mounting the pieces is that the top and bottom of the mount becomes completely parallel. The mount itself is very hard which helps reduce rounding of edges from sanding. Because the mount is completely parallel and very hard, the hardness test accuracy increases.

After mounting, each pieces were sanded to get a better surface to test for hardness.

The sanding was done using a Struers TegraPol-35 and a Struers TegraForce-5, and for lubrication water was used. Each step of the sanding process is given below.

Table 7: Sanding procedure in preparation of hardness testing

Step #	Sandpaper	Force	Time	Cooling liquid
1	P120	90N	1 minute	Water
2	P220	90N	1 minute	Water
3	P500	90N	2 minute	Water
4	P1000	90N	2 minute	Water
5	P2000	90N	2 minute	Water

A Struers DuraScan-20 was used to test the hardness. The method used was HV10, which is 10 kg pressure with duration of 10 seconds. At least 10 measures per piece was taken, the distance between each measure was 0,60 mm. Here is the list of charpy pieces selected for Hardness testing:

Material	ID	Number of test
30M12CB	A-2	12
30M12CB	A-4	19
30M12CB	A-9	36
30M12CB	B-2	11
30M12CB	B-4	15
30M12CB	B-7	15
35M13B	C-1	15
35M13B	C-5	47
35M13B	C-7	14

A temporary software error made some results unavailable at the time of testing, therefore a greater number of test were done on some pieces. Upon view the results, all test results were again available, and as a greater number tests increases the accuracy they were included.

4. RESULTS AND DISCUSSION

The results from each test will be covered in its own section, starting with Charpy test results, followed by the results from the tensile test and then the Vickers Hardness HV10 test. Each of the investigated parts will be covered under each test method. The two alternative production methods for 30M12CB will be looked at first, 35M13B will be looked at last. For each test method the results will be discussed, the results 30M12CB will be compared, and the effects of tempering temperature will be discussed for all parts. After each test method and their results is looked at and discussed individually, a summary of the mechanical properties will be given and discussed further.

4.1 Charpy Tests

The Charpy impact test were all carried out in room temperature and in accordance with standards (ISO 148-1:2009), the impact tip was 2 mm wide. Three parallels from each tempering were tested. The results were read of digitally and noted down in appendix X. The average absorbed energy was calculated from the results and will be shown for each wear part below. Side by side comparison of the different tempering methods.
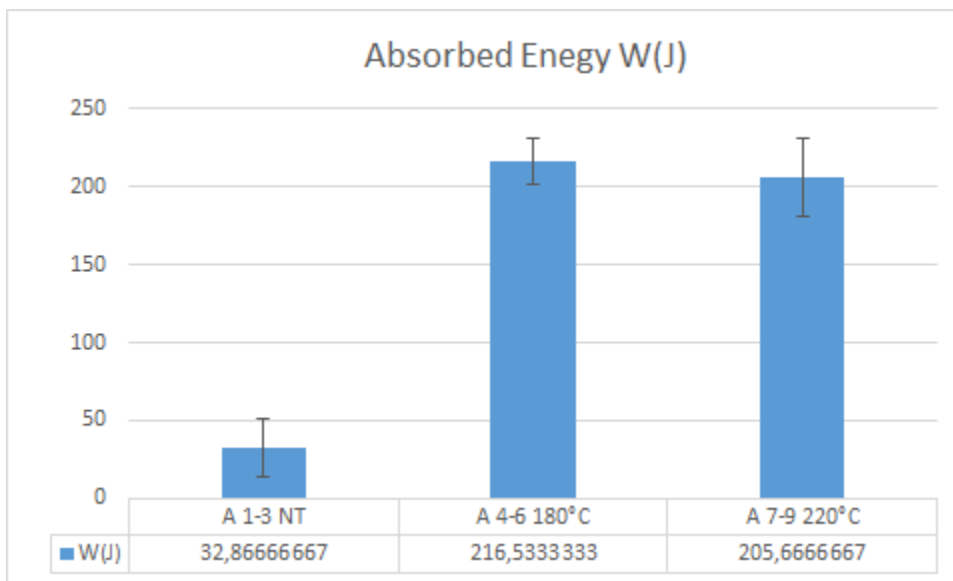
4.1.1 30M12CB-850

Figure 10: 30M12CB-850 average absorbed energy from Charpy Impact test, standard deviation is shown on the top of the bars.

The average impact results for 30M12CB-850, the current production method for wear part 30M12CB. It can be seen from figure 10 that the charpy piece A1-3 were very brittle, which can be expected when no tempering is applied. There results were widely spread for 180 degrees C and 220 degrees C tempering. The impact resistance was fairly similar for 180*C and 220*C. With 180*C being able to absorb a little more energy. However, with only three parallels it is hard to draw a significant conclusion based on the average numbers alone, as each piece varied a lot. The highest absorbed energy from 220*C was 234,6 J while the highest from 180*C was 232,9 J. No significant difference between 220 and 180 degrees was registered, however skipping tempering resulted in the steel being brittle, an undesirable property.

4.1.2 30M12CB-1100

Figure 11: 30M12CB-1100 average absorbed energy from Charpy Impact test, standard deviation is shown on the top of the bars.

For the test representing direct hardening of wear part 30M12CB leaving out tempering did not seem to make the part brittle. However, the material's ability to absorb energy increased with tempering to 180*C. Tempering the material to 220*C gave similar results to leaving out tempering. Large variance in results recorded from 220 degrees C could play a part in the average recorded.

4.1.3 35M13B

Absorbed energW(J)

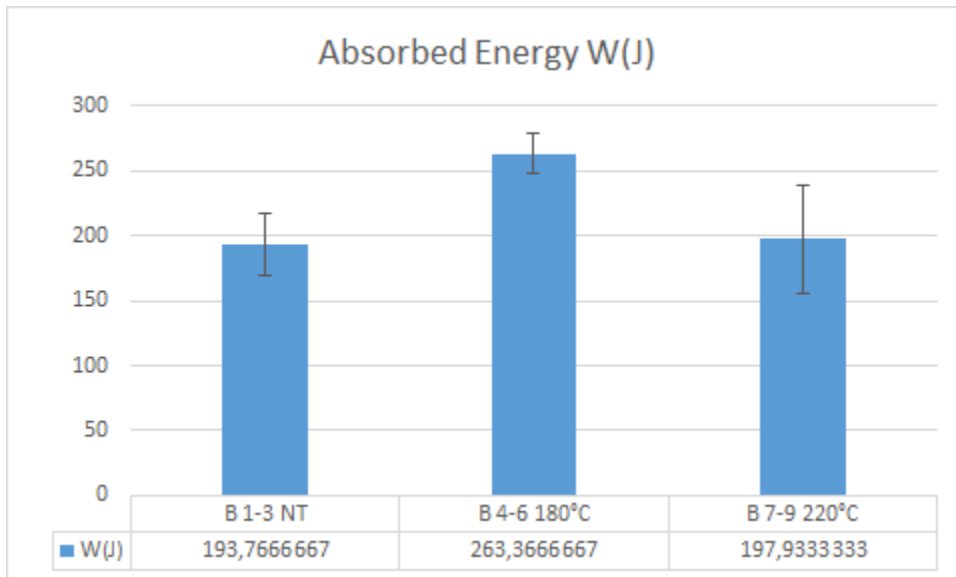|	C 1-3 NT	C 4-6 180°C	C 7-9 220°C
■ W(J)	423,1333333	449,1	449,1
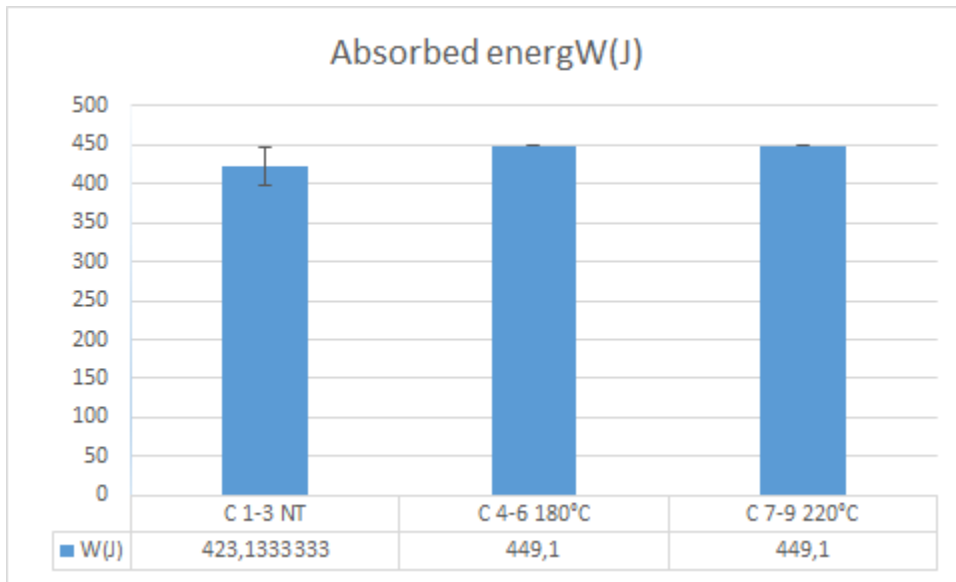
Figure 12: 35M13B average absorbed energy from Charpy Impact test, standard deviation is shown on the top of the bars. For C4-9 the test piece did not facture and maximum energy was absorbed.

For wear part 30M13B 7 out of the 9 tested pieces did not fracture (i.e absorbed maximum energy). However both fractured pieces C-1 and C-2 was not tempered. That could suggest that tempering would increase the ability to absorb impact. All piece including C 1-3 performed very well in the Charpy Impact test.

4.1.4 Summary of Charpy Impact tests

A visual comparison of all charpy results is given in figure 13. 35M13B performed very well across each tempering method. The difference between the two wear parts is not of concern as they serve a different purpose. Both production methods for 30M12CB seemed to deliver similar results, except for 30M12CB-850 NT and 30M12CB-1100_180*C, in a negative and positive way respectively.
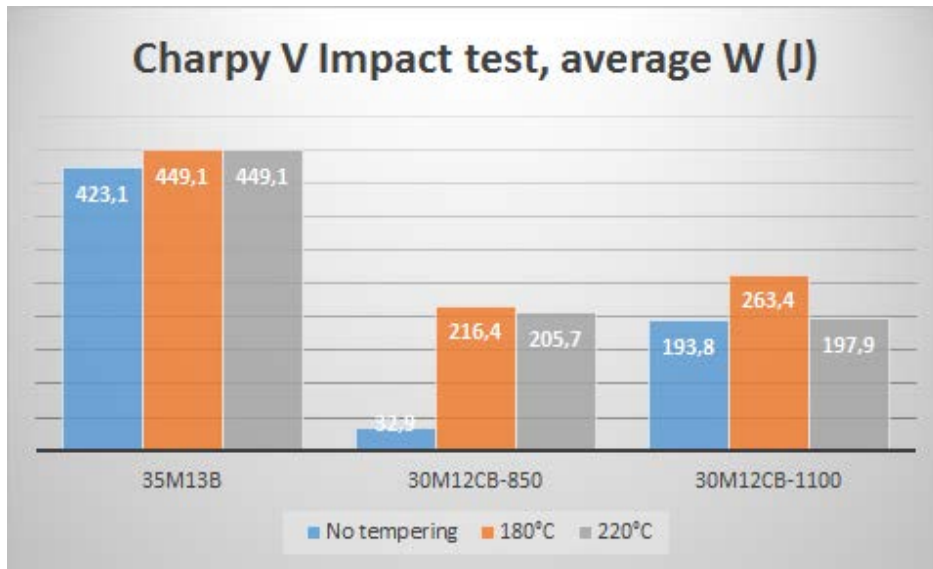
Figure 13: Comparison of results from Charpy impact testing for 30M13B, 30M12CB-850 and 30M12CB-1100.

For both 30M12CB wear parts, the charpy results varied considerably, and with only 3 parallels the accuracy of the results may vary. Though in both cases 180*C tempering showed slightly better impact results than 220*C.

A reason for the varied spread of results may be because some pieces were straightened after the heat treatment. Each charpy piece were sanded by hand to a varying degree, not having the exact same surface could also play a part in the variation of recorded impact absorption.

The tempering done at 220*C kept rising to 230*C during tempering, Results may therefore also vary from what could be recorded a part taken directly from production. Neither 30M12CB-850 or 30M12CB-11000 managed to match the grain size found in the parts taken from production, thus they could vary from the wear part taken from production. The grain size in 30M12CB-1100 is larger than for 850, yet it recorded the highest average absorbed energy from 30M12CB-1100_180*C.

4.2 TENSILE TEST

The tensile tests were carried out in room temperature using a Instron 5985 Floor Model Testing Systems, the data was recorded with Bluehill 3, and the among following measurements were taken:

Yield strength offset 0.2%, Ultimate tensile strength, Area reduction and Elongation at fracture.

The test were carried out in accordance with ISO 6892-1: 2009. Three parallels from each method was tested.

4.2.1 30M12CB-850
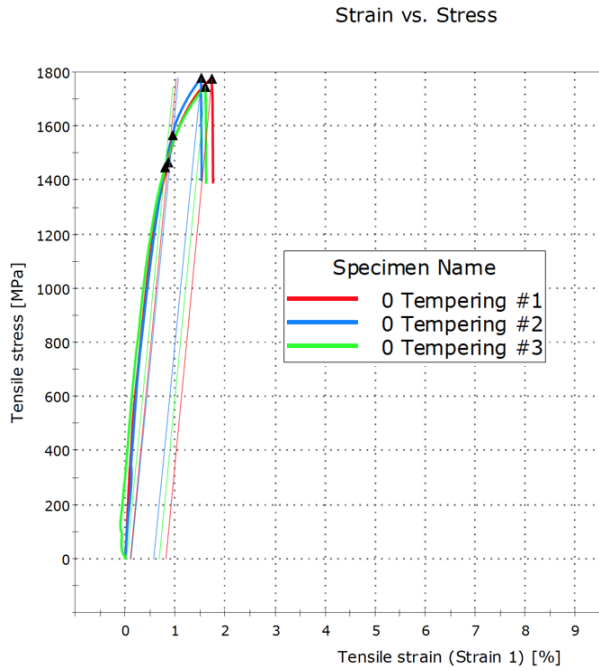
(a) 30M12CB-850_NT
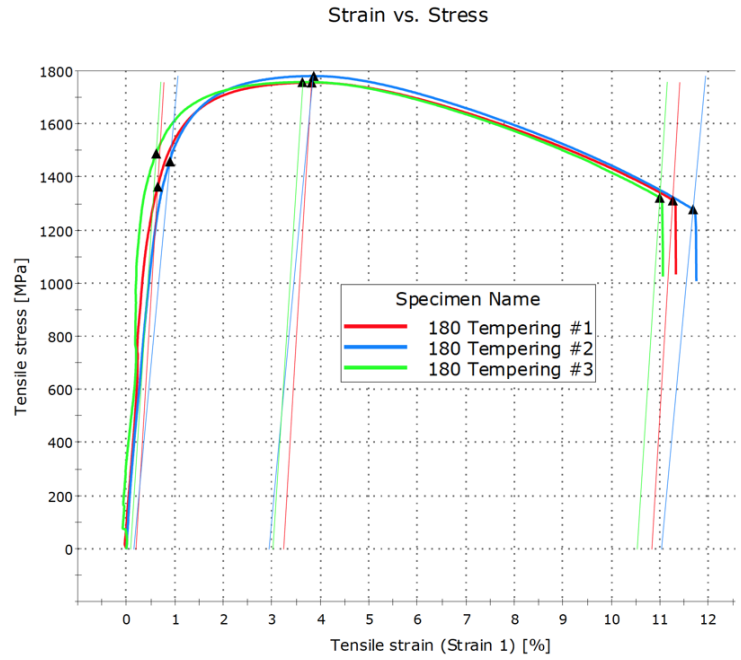
(b) 30M12CB-850_180*C
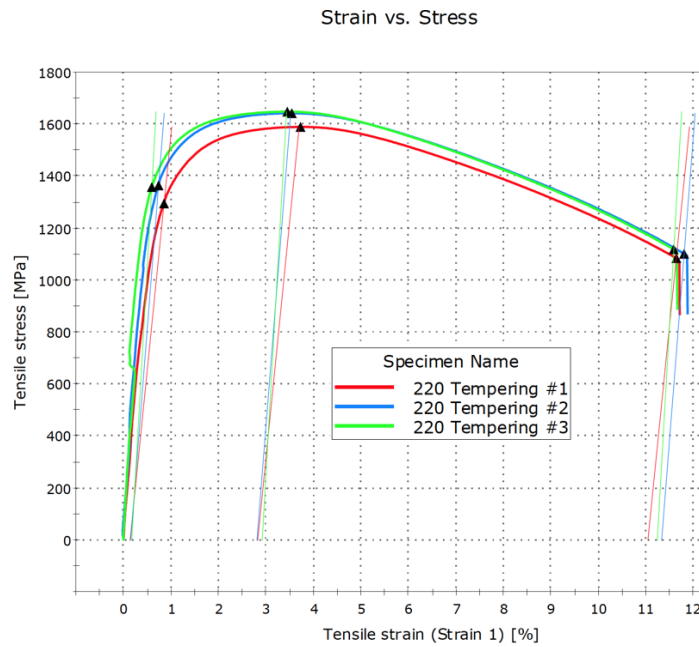
(c) 30M12CB-850_220*C

Figure 14: Tensile strength for 30M12CB -850, There were three parallels for each tempering method. 0 tempering refers to no tempering.

Figure 14 looks at the relationship between Stress and Strain for 30M12CB-850. Figure 14 (a), shows the results for no tempering. Like for the charpy tests for the same heat treatment, the material showed a brittle characteristic breaking at less than 1% elongation. 0,2% offset Yield strength was recorded as 1493,5 MPa, while ultimate stress recorded to 1766,3 MPa.

Figure 14 (b) shows the result for tempering at 180*C. 0,2% offset yield strength and ultimate stress was similar to that of (a), but elongation at break point were around 11%. For (c), 220*C a slight reduction in strength was recorded but elongation to break remained around 11%

In table 9 below some selected data recorded from the tensile test are given.

Table 9: 30M12CB-850 selected results from tensile testing

MATERIAL	30M12CB	-850		
Tempering temperature [°C]	Yield strength Offset 0.2% [MPa]	Ultimate tensile strenght [MPa]	Reduction of area at Area reduction [%]	% elongation (30 mm gauge length)
220	1339,05	1626,04	51,92	11,20%
180	1436,13	1764,50	50,70	10,80%
-	1493,46	1766,29	3,91	0,7%

Figure 15: Comparison of tensile strength, yield strength and % elongation for 30M12CB-850, based on average of the 3 parallels.

Figure 15 shows the yield and tensile strength for 30M12CB-850 along with the % elongation at fracture.

4.2.2 30M12CB-1100
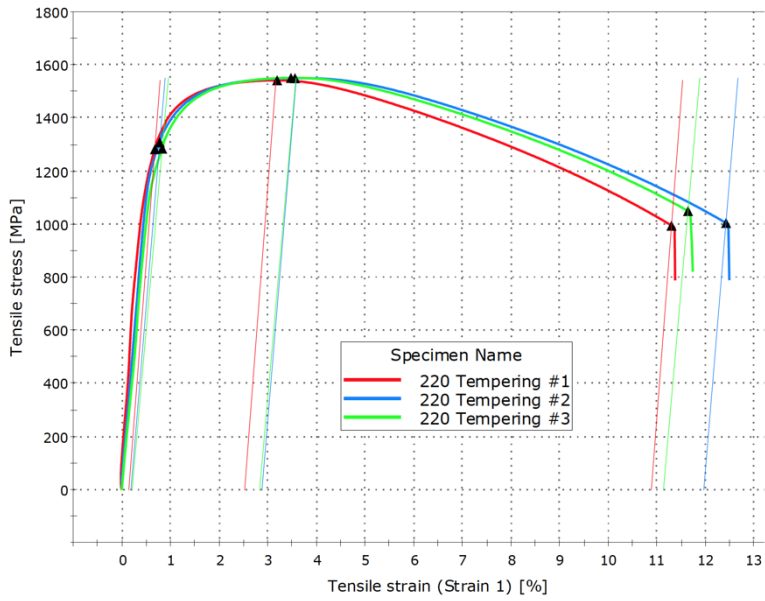
(a) 30M12CB-1100_220*C
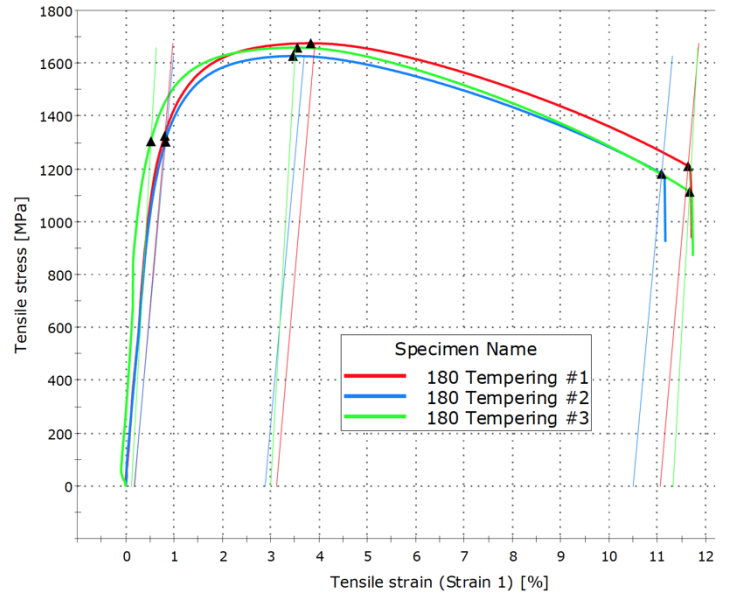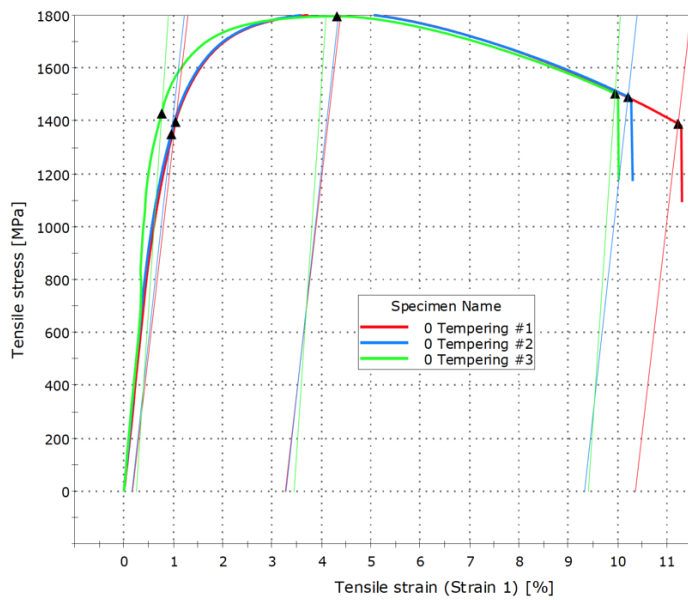
(b) 30M12CB-1100_180*C

(c) 30M12CB-1100_NT

Figure 16: Three parallels for each tempering method for 30M12CB-1100. 0 Tempering refers to no tempering.

Figure 16 shows that similar results were recorded for both tempered pieces, with a slightly higher score for 180*C compared to 220*C. The 0,2% offset yield was around 1300 MPa in both cases, the ultimate strength increasing slightly at 180*C (b) compared to 220*C (a) at 1650 MPa and 1550 MPa respectively. Both recorded an elongation at break of around 11%, with exception of (a) "220 Tempering #2" which was 12%. No tempering resulted in a slight reduction in elongation to around 9,5%. The offset yield increased slightly to around 1400 MPa, while a more significant increase in ultimate strength was recorded, from about 1600 MPa recorder from the tempered pieces to 1800 MPa for the untempered.

Table 10: 30M12CB-1100 selected results from tensile testing

Material	30M12CB	-1100		
Tempering temperature [°C]	Yield strength Offset 0.2% [MPa]	Ultimate tensile strenght [MPa]	Reduction of area at Area reduction [%]	% elongation (30 mm gauge length)
220	1292,12	1547,67	56,46	11,30%
180	1311,61	1651.94	50,43	10,90%
-	1392,16	1803,36	40,44	9,70%
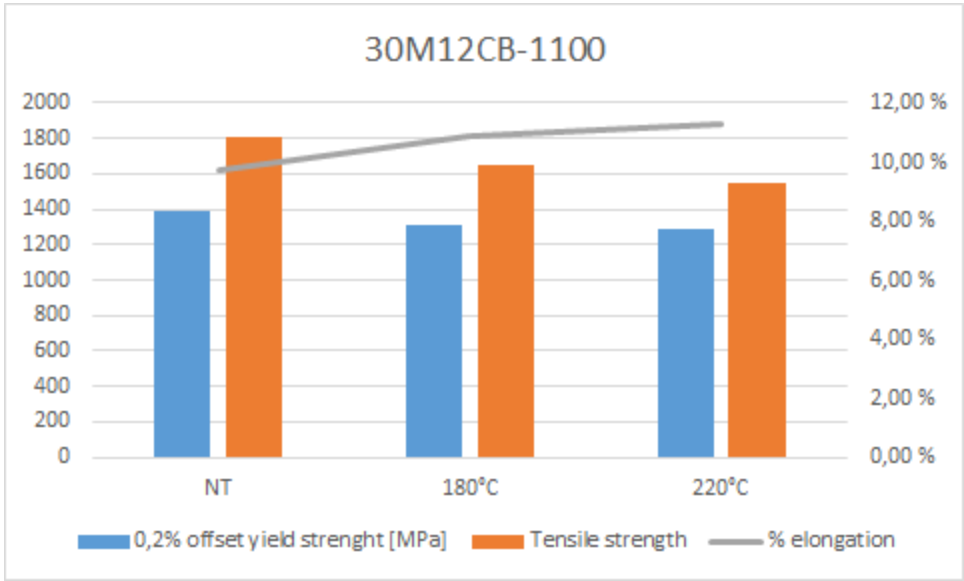
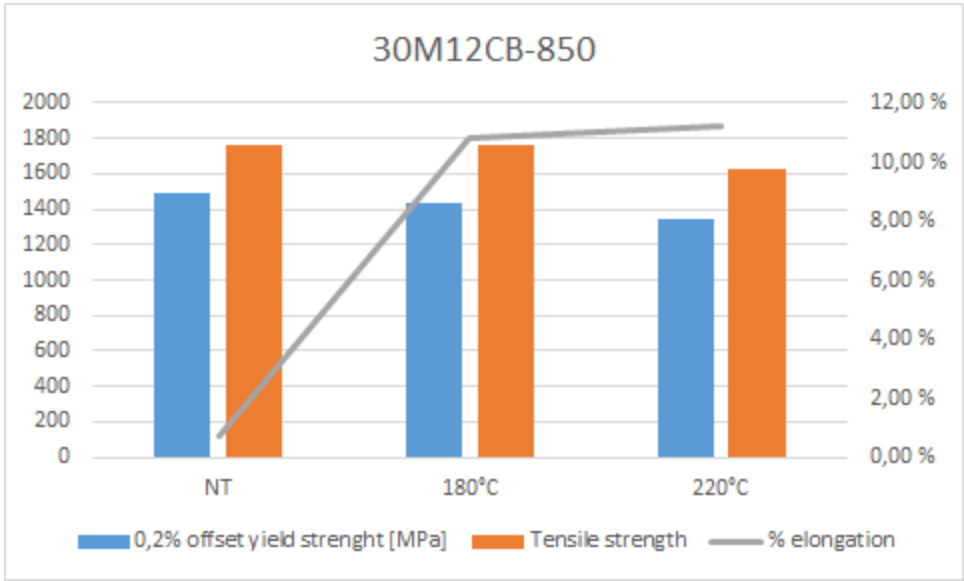*Figure 17: Comparison of tensile strength, yield strength and % elongation, for 30M12CB-1100, based on average of the 3 parallels.*

4.2.3 35M13B
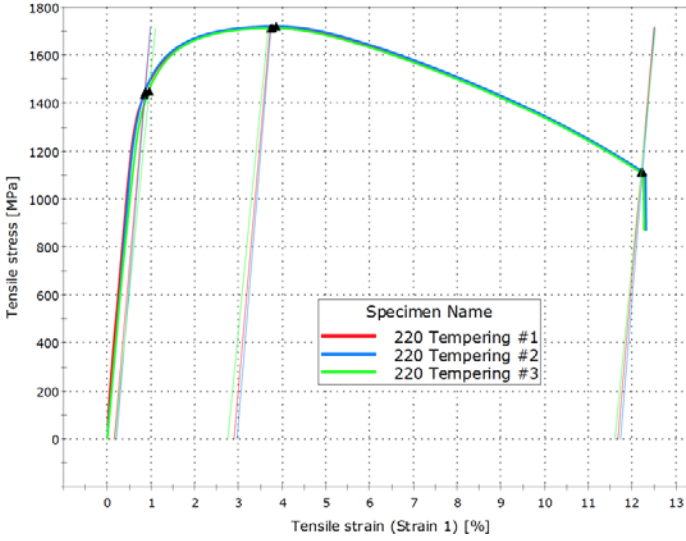
(a) 35M13B_220*C
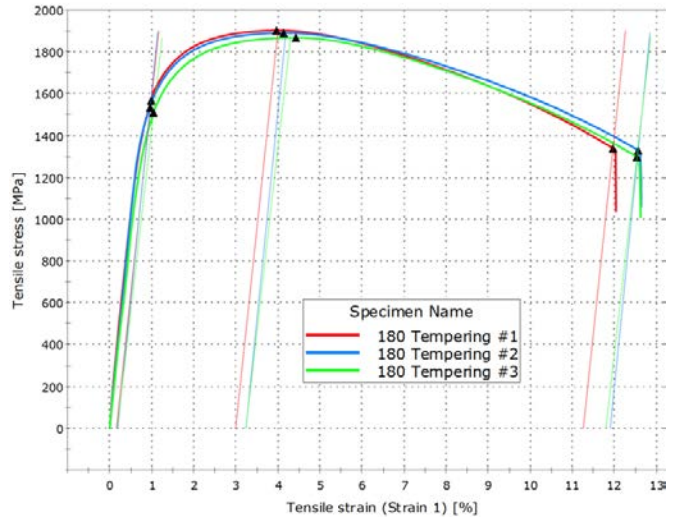
(b) 35M13B_180*C
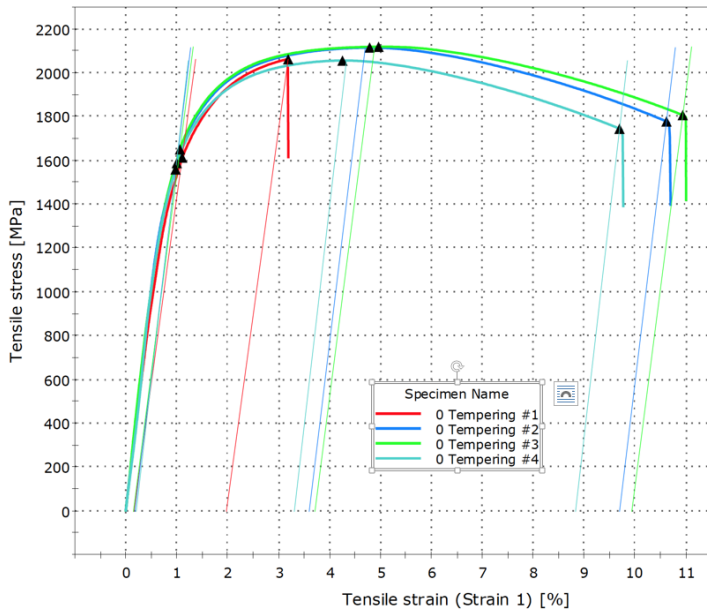
(c) 35M13B NT

Figure 18: Three parallels for each tempering method for 35M13B. 0 Tempering refers to no tempering and had 4 parallels.

Figure 18 shows the results from wear part 35M13B. The results reflect better results with less tempering. No tempering gave the highest results. Elongation at break for 220*C and 180*C were both around 11,5%, and slightly less for no tempering. From (c) "0 tempering #1" the results were a little different, it elongation at break came after just round 2% a quite brittle fracture, yield and ultimate strength remained closely the same.

A probable reason for the (c) 0 tempering #1 breaking could be due to the benching/ straightening of the piece which could have created more stress in the material. The fact that the rest of the pieces showed a different behavior could suggest that (c) 0 tempering #1 showed an unusual behavior, although yield and ultimate strength were similar for all 4 parallels with around 1600 MPa and 2100 MPa respectively. In table X below, the results from (c) #1 is not included in the average.

The results suggests that not tempering 35M13B gave the best results in terms of strength compared to tempering.

Table 11: 35M13B selected results from tensile testing

| Tempering temperature [°C]	Yield strength Offset 0.2% [MPa]	Ultimate tensile strenght [MPa]	Reduction of area at Area reduction [%]	% elongation (30 mm gauge length)
220	1445,85	1716,22	58,50	11,70%
180	1538,02	1887,49	55,90	11,50%
-*	1599,51	2096.15	38,76	9,50%
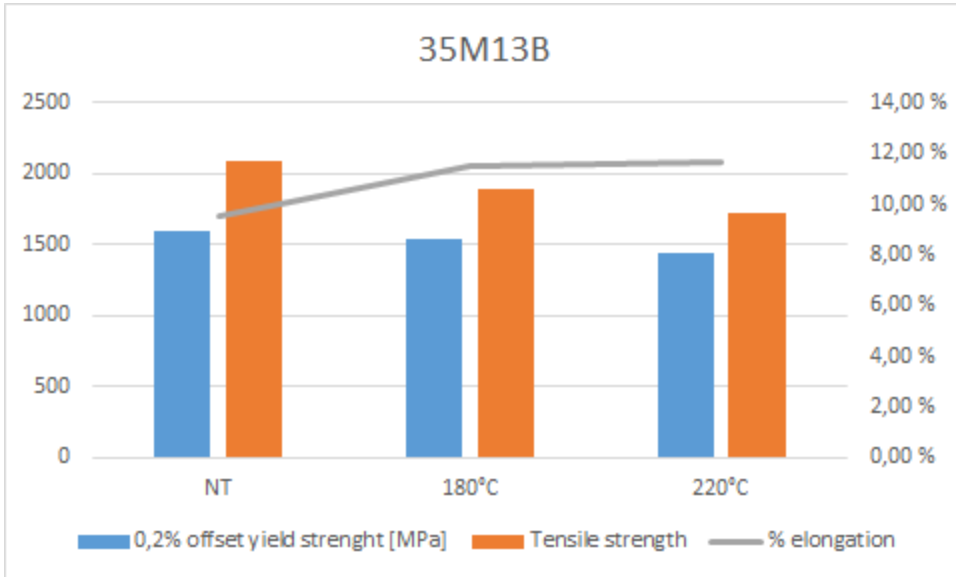
Figure 19: Comparison of tensile strength, yield strength and % elongation for 35M13B, based on average of the 3 parallels.

### 4.2.4 SUMMARY OF TENSILE TEST

For 30M12CB, the current production method (30M12CB-850) seemed to perform better than direct hardening (30M12CB-1100). Although yield strength and ultimate strength showed the highest numbers for no tempering of 30M12CB-850 the material were very brittle with an elongation at break of less than 1%. Interestingly 180*C tempering seemed to perform better across all results compared to 220*C. This is somewhat expected, as a higher tempering temperature decreases the strength of the material, if heated over a certain point. It may seem like 220*C, which during tempering increased to 230*C, was tempered to a high enough temperature to decrease the strength compared to 180*C. This might however not be the case if the tempering was at a true temperature of 220*C. And thus the results appear only slightly different for each temperature.

Interestingly no tempering of 30M12CB-1100 did not cause brittle fractures as opposed to 30M12CB-850. The reason or this might be: (more later).

The grain size should effect on the yield strength of the material is mathematically expressed with the Hall-Petch-equation (eq. 2).

$$\sigma_y = \sigma_o + k\frac{1}{\sqrt{D}} \text{ (eq. 2)}$$

Meaning a lower grain size would produce an increase in the materials yield strength. And thus from figure X, 30M12CB-1100 yield strength is lower than its counterpart.
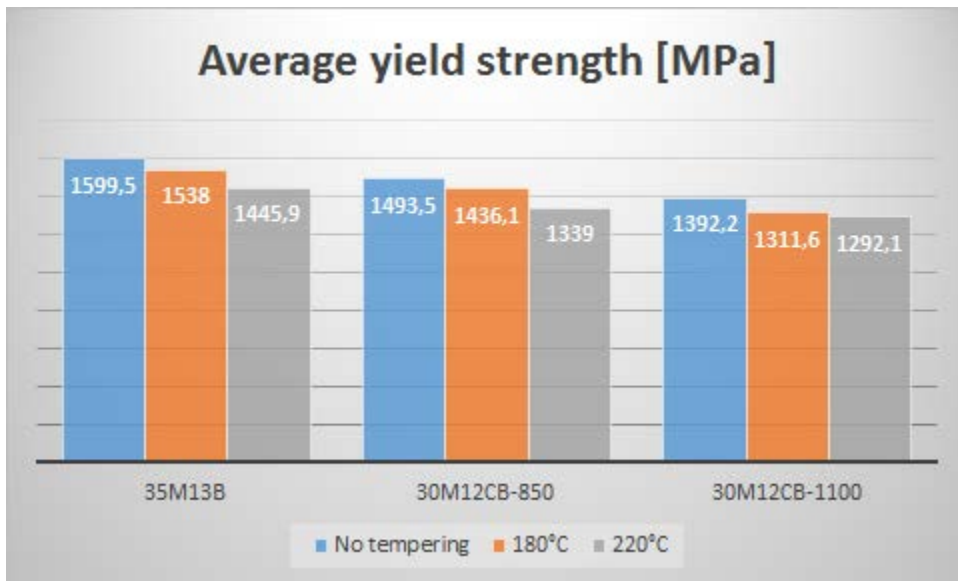
Figure 20: Average "0.2% offset yield strength" for all wear parts.

For wear part 35M13B no tempering did not cause the material to have undesirable properties. Both yield, ultimate strength and elongation at break showed that the material with no tampering was very strong yet retained some ductile properties.

Table 12: below shows the average key figures from all heat treatments.

Material	Tempering	Yield strenght	Ultimate tensile strenght	Area reduction	% elongation at break
30M12CB-850	220*C	1339,05	1626,04	51,92	11,20%
30M12CB-850	180*C	1436,13	1764,50	50,70	10,80%
30M12CB-850	-	1493,46	1766,29	3,91	0,7%
30M12CB-1100	220*C	1292,12	1547,67	56,46 %	11,30%
30M12CB-1100	180*C	1311,61	1651.94	50,43 %	10,90%
30M12CB-1100	-	1392,16	1803,36	40,44 %	9,70%
35M13B	220*	1445,85	1716,22	58,50 %	11,70%
35M13B	180*C	1538,02	1887,49	55,90 %	11,50%
35M13B	-	1599,51	2096.15	38,76 %	9,50%

4.3 HARDNESS TESTS

The hardness test is taken from the charpy pieces. A piece of the tested charpy test was cut using a Struers Discotom-10 with automatic feed rate of 0,3 mm/s. It was mounted using 10ml SpeciFast in a CitoPress-30 hot mounting machine. This was done to make the top and the bottom completely parallel for more accurate results. The tests were taken on the 8 mm surface of the piece.

4.3.1 30M12CB-850

Table 13: Vickers Hardness results for 30M12CB-850

Material	ID	Tempering	Average Hardness	Standard Deviation	Nr of tests
30M12CB 850	A-9	220	501,5	5,6	36
30M12CB 850	A-4	180	540,26	6,25	19
30M12CB 850	A-2	-	539,25	5,4	12
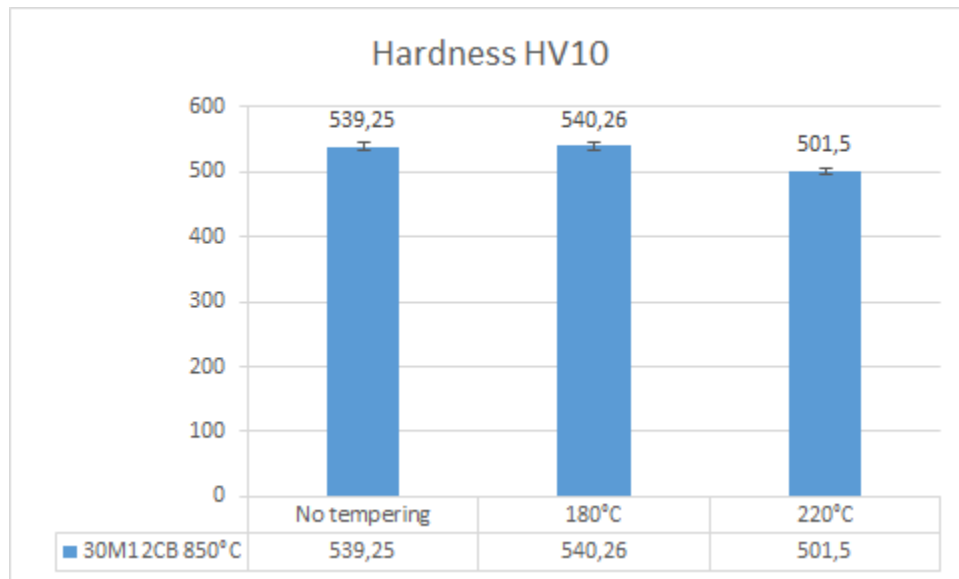
Figure 21: HV10 Vickers Hardness results for 30M12CB-850

Figure 21 shows the results of hardness tested on the surface of the charpy piece. A more accurate measure would be to test that hardness in the center of material as it is not subjected to possible work hardening form machining/sanding. However each tempering method was tested the same way and the results are therefore comparable to some extent. No significant difference was found between no tempering and 180*C tempering. However the hardness slightly decreased at 220*C tempering.

4.3.2 30M12CB-1100

Table 14:Vickers Hardness results for 30M12CB-1100

Material	ID	Tempering	Average Hardness	Standard Deviation	Nr of tests
30M12CB 1100	B-7	220	499,5	3,66	15
30M12CB 1100	B-4	180	524,6	4,9	15
30M12CB 1100	B-2	-	526,6	5,97	11

Hardness HV10

	No tempering	180°C	220°C
■30M12CB 1100°C	526,6	524,6	499,5
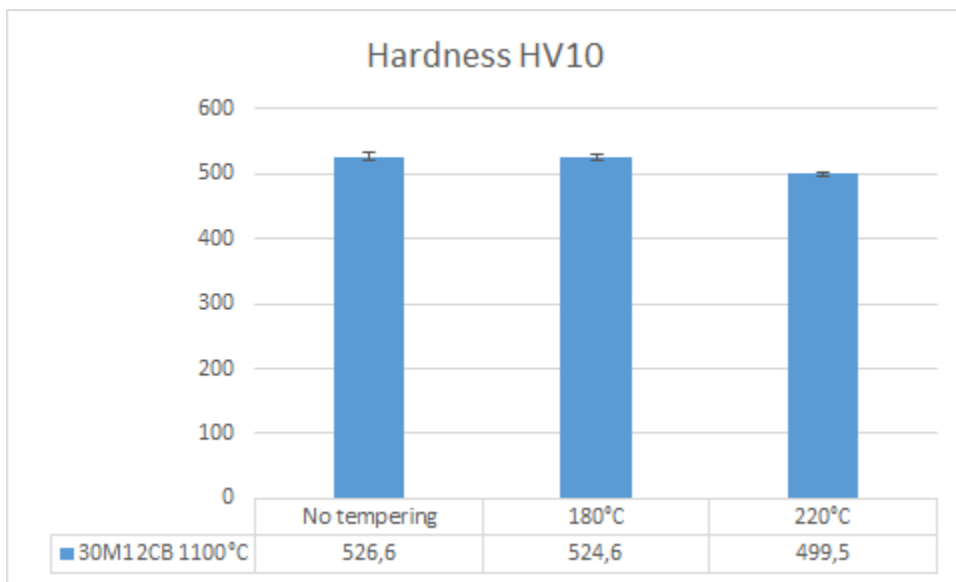
Figure 22: HV10 Vickers Hardness results for 30M12CB-1100

Figure 22 shows the results from 30M12CB-1100, the hardness was slightly lower for 220*C tempering compared to 180*C and no tempering.

4.3.3 35M13B

Table 15: Vickers Hardness results for 35M13B

Material	ID	Tempering	Average Hardness	Standard Deviation	Nr of tests
35M13B	C-7	220	543,0	3,77	14
35M13B	C-5	180	587,0	7,41	47
35M13B	C-1	-	589,6	6.14	15

	No tempering	180°C	220°C
■ 35M13B 950°C	589,6	587	543
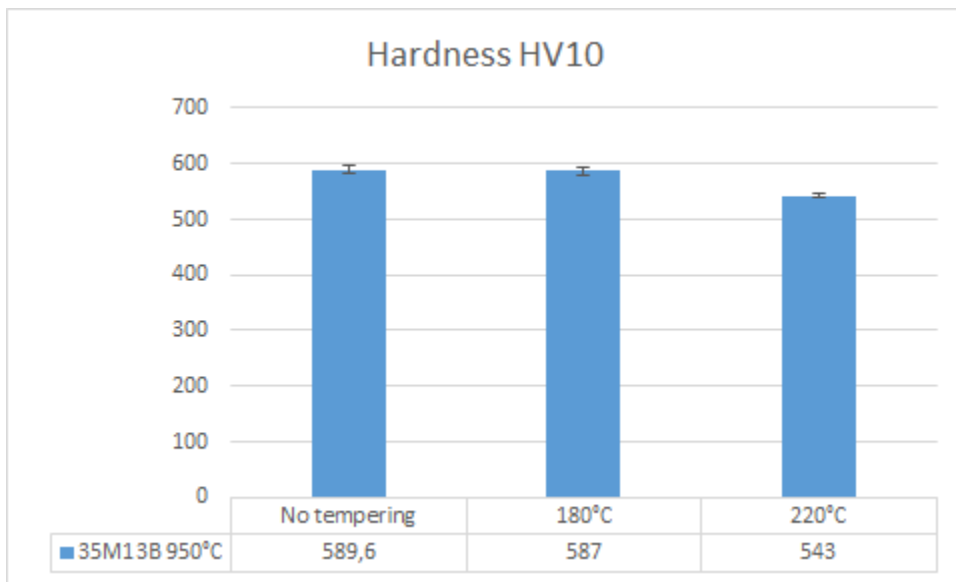
Figure 23: HV10 Vickers Hardness results for 35M13B

Figure 23 shows the VIckers Hardness results for 35M13B. No significant difference between no tempering and 180*C tempering. Both were just around 590. A slight reduction in hardness was measured for 220*C tempering.

4.3.4 Summary of Hardness results

Figure X below shows all the results measured from the vickers hardness tests. For all parts 220*C decreased the hardness of the material. When tempering steel the carbon precipitate as particles, this in turn reduces the hardness of the material while increasing the ductility. For carbon to precipitate as particles the tempering temperature has to be at a certain heat, no real difference were observed from no tempering and 180*C tempering. This suggests that more carbon precipitated as particles when tempering to 220*C. It is however important to note, that during the tempering for all test pieces tested for this thesis, the true tempering temperature for 220*C, was infact a bit higher and during the tempering increased to 230*C. A true tempering of 220*C could therefore show more similar results to those of 180*C and no tempering.

The tested area for hardness was at the surface of the charpy piece. The tested surface is across the rolling direction for all parts.

30M12CB-850 showed slightly higher hardness than that of 30M12CB-1100, this is to be expected as the grain size for 850 were smaller than 1100, (Hall–Petch relationship).

Figure 24: Comparison of Hardness for all three investigated materials.

4.4 Discussion

4.4.1 Tempering

The main goal of this thesis is to figure out what effect the different tempering temperatures have on the mechanical properties of the investigated wear parts. Currently Kverneland tempers the wear parts in a salt bath at 220*C. Reducing this temperature, or ideally cutting out tempering completely would have positive effects on the cost and potentially reducing time for production of the parts. Cutting tempering out completely would reduce the production process with a whole step, 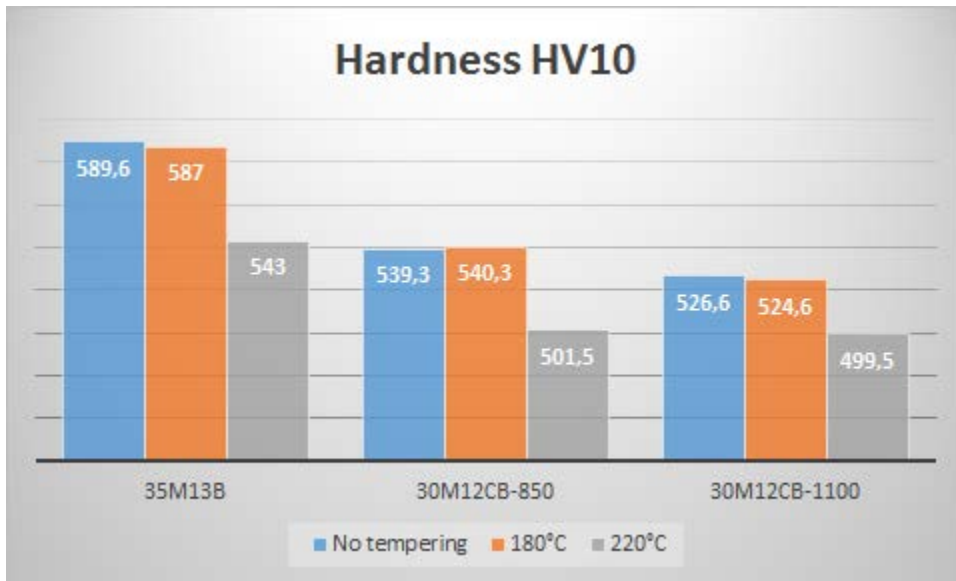saving space, time and cost of production. It is also interesting to compare it to a lower tempering temperature both from a cost perspective but also from a performance of wear part perspective. Lowering the tempering temperature has the potential to increase the strength of the material as further explained below.

Tempering length was 20 minutes in salt bath, this time was chosen to ensure that the whole piece remained at the tempering temperature for at last 15 minutes. Salt bath is a preferred method of tempering since salt is better at transporting heat than air, furthermore it is what is used in production at Kverneland and thus more reliable as a comparison.

The reduction in hardness if tempering temperature is lowered from 220*C to 180*C can be explained as follows. To reduce the hardness of steel, it is required that the tempering temperature is over a certain level for the hardness to be noticeably reduced/affected. The reduction in hardness from tempering happens through diffusion, the diffusion rate increased with the temperature, thus increasing the tempering temperature from 180*C to 220*C was enough to cause a noticeable reduction in hardness for both 30M12CB and 35M13B. It was noted that the true tempering temperature increased to 230*C during the tempering for both alloys. It might be that 230*C caused the reduction and a lower change would happen for a true 220*C, however retained austenite often gets diffused to tempered martensite above 200*C. However it is safe to say that lowering the tempering temperature to 180*C is in fact not a problem when tempering both alloys.

For 35M13B, tempering reduced the strength of the material. Hence, no tempering did not leave the material brittle and as result no real benefits were achieved through tempering. It should be noted that the ability to absorb impact slightly reduced for no tempering, 2 of the 3 tested charpy species fractured, while none of the tempered species did. However 1 of the charpy species (C-3) that were not tempered also absorbed maximum energy and did not fracture. The results vary high throughout the material. However, both yield and tensile strength increased.

4.4.2 Heat treatment and quenching

All quenching was done manually by submerging the heated test piece into room temperature circulating water mixed with NaOH. The addition of NaOH to the quenching water helps because it removes some of the oxidative layer, allowing the piece to cool down quicker. As each piece was removed one by one, some pieces got slightly more time at glowing temperature, which could slightly give some variances for between the samples.

For the tensile test, a manual quenching left many of the pieces distorted, a preferred method of quenching would be to make a special holder to quench all pieces simultaneously, and at the same time hold them in place to make sure that no distortion took place during quenching.

4.4.3 Hardness

All hardness tests were hot mounted in a Struers Citopress-30, a process which took a total of 9 minutes. During hot mounting the temperature increases to around 100*C. A possible tempering effect from hot mounting could have affected the results. However all pieces were hot mounted and thus treated in the same way.

All hardness tests were taken on the 8mm surface of a tested charpy piece for each heat treatment method. The charpy pieces were not equally sanded before the charpy test, and thus a small variation on how much sanding was done could have affected the case. However, the results generally suggested that the pieces were of equal conditions as nothing unexpected was reported in relation to the other pieces they were compared with. Further, the fact that the surface was tested for hardness as opposed to the center of the piece could also affect the results. Quenching could lead to decarburization of the material at the surface, i.e. a lower carbon content at the surface of the material. The hardness values could thus indeed be different if the core of the material were tested as opposed to the surface.

The method used was HV10, as it was the biggest load the testing machine could offer, it is possible that using HV30 would give slightly more accurate results.

4.4.4 Charpy

The charpy pieces showed large variations in results with only 3 parallels from each method. Ideally more tests should be done to get a better understanding of their behavior. Some of the charpy pieces showed signs of distortion after quenching, due to large thermal stress from quenching. The pieces that showed distortion were straightend which is done by applying a relatively large amount of pressure to bend the piece back into a straight shape. This could cause further stress in the material by introducing residual stress. Only 30M12CB NT showed a brittle behavior in all three parallels. The average absorbed energy was round 32 J, however two parallels gave results in the low

20s while one result was over 50 J. Compared to tempering 30M12CB, it showed undesirable a qualities. The same was observed for tensile testing of 30M12CB NT.

4.4.5 Tensile test

Like the test specimens for charpy testing, the tensile test specimens showed signs of distortion. Like the charpy pieces they were straightened after tempering. However it was not possible to get them completely straight. As a result when inserting them in the test machine, the specimens were subjected to some forces holding them straight during testing. This should not affect the results too much however, it is a likely the reason for some small variations within a given heat treatment.

4.4.6 Production method for 30M12CB

Figure 7 and 8 shows the pictures of the average grain sizes of the specimens used in this thesis, compared with the grain sizes of the parts from production. The scale of figure 7 and 8 are not the same, figure 7 is taken using a 20x lens, while figure 8 is using a 50x lens. The reason why figure 7 is compared in 20x lens and the figure 8 in 50x lens are because 50x lens pictures did not exist for the directly hardened part in figure 7. However, it should still be easy to compare (a) and (b) in figure 7, and (a) and (b) in figure 8. Comparing figure 7 to figure 8 is however difficult, but the grain sizes are listed in table 4. Figure 7 illustrates the procedure used to estimate the average grain size.

From table 4, it can be seen that the difference between Regular Production and Direct hardening is 11,6μm to 17,54μm respectively, which is a difference of 5,94μm. The difference between the average grain sizes used in this thesis are smaller, from 15,46μm for P1 to 13,0μm for P6, that is a difference of only 2,46μm. What this suggests is that there is less difference in mechanical properties of the tested pieces in this thesis. The difference is likely greater for the parts produced in the factory. For clarity in can be noted that P1 is 30M12CB-1100, while P6 is 30M12CB-850.

When trying to find grain sizes that matched the pieces pulled from production the temperatures 850-1100*C was used. It was expected that there would be a greater difference in size than it actually was. The glowing time in the oven was only 15 minutes, which is enough to heat the small sample thoroughly, however longer heating could have shown different results and likely produce larger grains.

Any real effects from forging is not represented, however that is true for both tested methods, and thus their comparison is fair, however not truly representative for the end product produced in the factory.

As for tempering temperature 180*C seemed to perform just as well, and generally better than 220*C, it is however important to keep in mind that the actual tempering temperature ended up at 230*C. It is reasonable to say that a reduction in tempering temperature from 220*C to 180*C did not cause any negative effects. 30M12CB remained the same level of ductility for both tempering temperatures, but the strength seemed to increase slightly for 180*C. That is true for both production methods. More interestingly is that 30M12CB-1100 was more ductile than 30M12CB-850 when no tempering was performed. A possible explanation for this might be that the large grain size allowed the material to deform more plastically even without tempering.
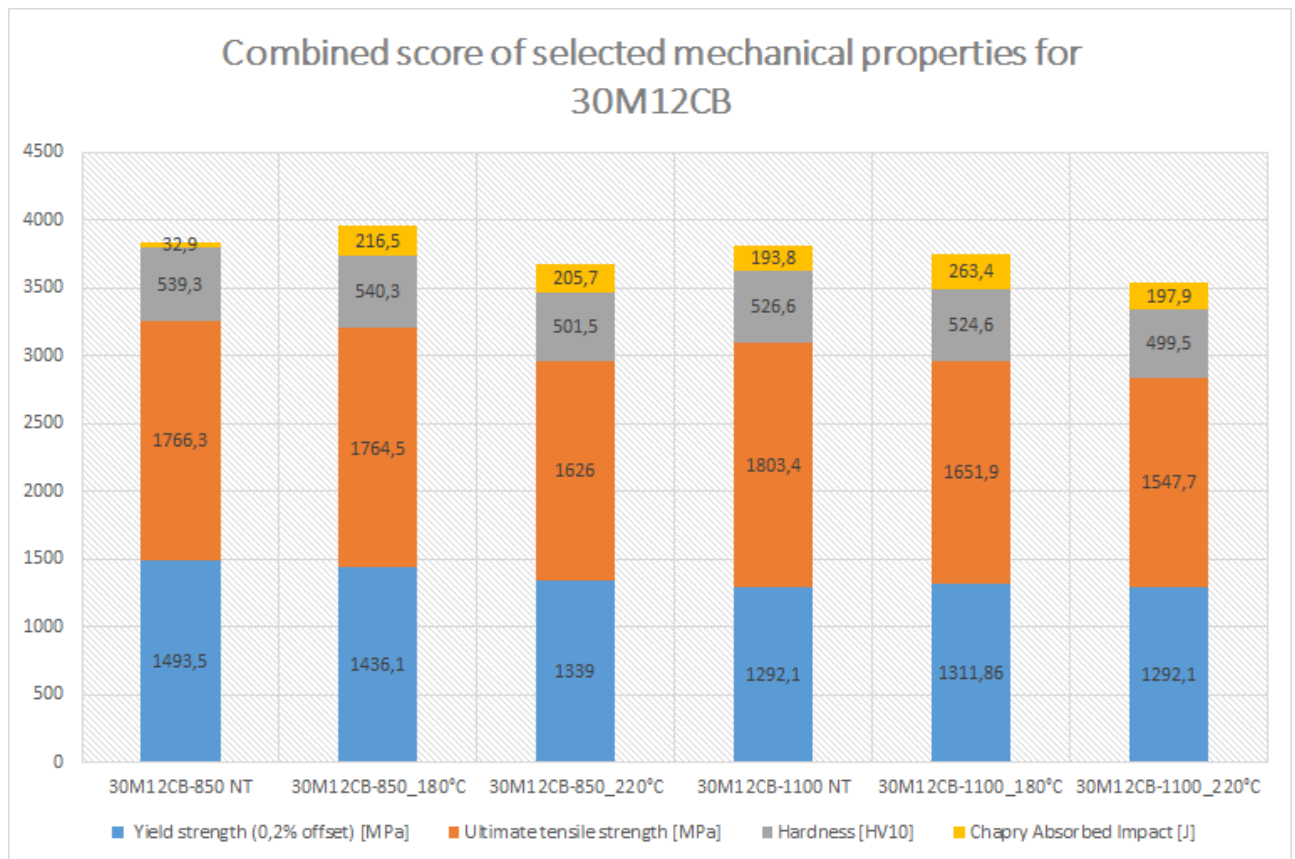
Figure 25: Combined score of selected criteria for all 30M12CB.

Figure 25 shows a combined score of selected criteria for 30M12CB. These scores should not serve a numerical decision tool when deciding the production method for 30M12CB, but are there to illustrate how each production method and tempering temperature performed in the test done in this thesis. The only indicator for the ductile behavior for each tested material shown in figure 25 is the charpy testing. Chapter 4.2 shows more results related to the ductile nature of the tested specimens. However, 30M12CB-850_NT was the only heat treatment process that showed a very brittle behavior. When comparing the rest of the results in figure 25, both production method seemed to

perform quite similarly, and 180*C tempering seemed to generally perform better than 220*C.

4.4.7 35M13B

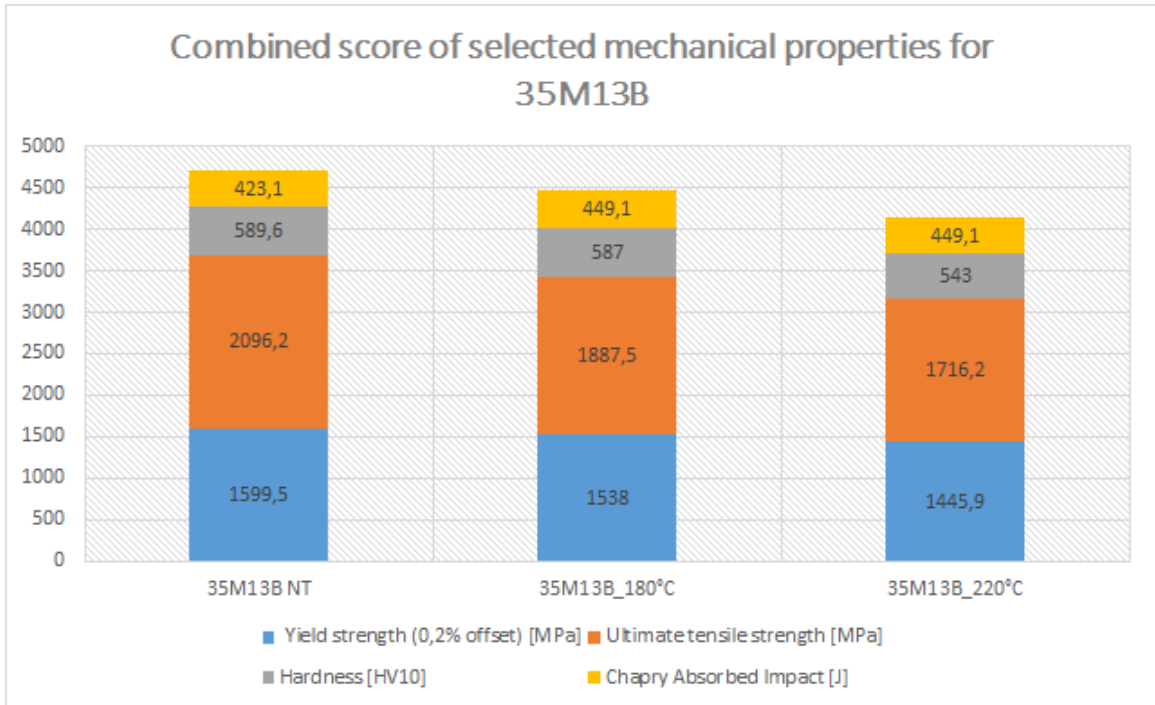*Figure 26: Combined score of selected criteria for all 35M13B.*

Figure 26 shows the combined results for wear part 35M13B. No tempering performed best in all criteria except Charpy impact testing. However the ability to absorb impact was still very high without tempering.

5. Conclusions and Recommendation

5.1 Conclusions

During this thesis two wear parts were investigated with respect to their mechanical properties. The main goal of this work was to find the effect that different tempering temperatures had on the mechanical properties of the wear parts. Another goal was to find the effect of directly hardening wear part 30M12CB. The average grain size of wear part 30M12CB from the production factory was investigated to serve as a reference for the two methods. The following conclusions can be drawn from the work performed in this study.

Effects of tempering temperature for 35M13B:

- The strength increased slightly by lowering tempering temperature from 220*C to 180*C
- No tempering did not affect the ductility of the material and improved the strength and hardness for this alloy
- It is reasonable to say that reducing the temperature of tempering for 35M13B may be preferable as it saves space, reduces production time and cost, while maintaining or increasing the hardness and strength of the material. Further, the slight reduction in ductility should not lead to brittle fractures and thus may not affect the end product negatively.

Effects of tempering temperature for 30M12CB:

- Tempering temperature of 180*C has the best effect on mechanical properties of 30M12CB. This was true for both 30M12CB-850 and 30M12CB-1100.
- For the current production method for 30M12CB, no tempering results in a brittle wear part. Tempering is therefore important in order to avoid brittleness.

Production method for 30M12CB:

- Both 30M12CB-850 and 30M12-1100 performed similar during the work done in this thesis, but 30M12CB-850 was slightly better when tempered.
- Directly hardening wear part 30M12CB will result in a slight reduction in quality, the difference in quality will likely be slightly greater than the results from this work indicates.
- The heat treatment method representing direct hardening 30M12CB-1100 did however perform reasonably well throughout this work, enough so to not rule out the possibility of direct hardening completely.

5.2 Recommendations for future work.

In order to get a more precise indication of the mechanical properties of the directly hardened wear part 30M12CB, the average grain size of the test specimens should match the wear part, through applying different austenization temperatures and different holding times the average grain size should eventually be found. More testing should then be done applying those heat treatments.

The cost of production of a directly hardened wear part should then be compared and evaluated against the slight reduction in quality. A final decision regarding what production method should be used, will be a question of price vs quality.

REFERENCES

Holm, T., Olsson, P., & Troell, E. (2012). *Steel And Its Heat Treatment – a handbook.* Mølndal, Sweeden: Swerea IVF.

Kverneland Group. (2016, June 24). Retrieved from http://ien.kvernelandgroup.com/About-us/Kverneland-Group-in-Brief/About-us

Totten, G. E. (2007). *Steel Heat Treatment: Metallurgy and Technologies.* Portland, Oregon: Taylor & Francis Group.

APPENDIX

Appendix A

Charpy results:

(*No Fracture)

Nr.	Material	HT (*C)	Height (mm)	Width (mm)	Length (mm)	Tempering (*C)	W (J)
C-1	35M13B	950	8,0	10,10	55,60	-	418,4
C-2	35M13B	950	8,07	10,09	55,57	-	401,9
C-3	35M13B	950	8,06	10,09	55,66	-	449,1* (NF)
C-4	35M13B	950	8,05	10,10	55,59	180	449,1* (NF)
C-5	35M13B	950	8,07	10,10	55,58	180	449,1* (NF)
C-6	35M13B	950	8,06	10,06	55,50	180	449,1* (NF)
C-7	35M13B	950	8,07	10,11	55,60	220	449,1* (NF)
C-8	35M13B	950	8,07	10,09	55,59	220	449,1* (NF)
C-9	35M13B	950	8,08	10,05	55,60	220	449,1* (NF)

Nr.	Material	HT (*C)	Height (mm)	Width (mm)	Length (mm)	Tempering (*C)	W (J)
A-1	30M12CB	850	8,07	10,09	55,57	-	20,3
A-2	30M12CB	850	8,07	10,10	55,60	-	24,1
A-3	30M12CB	850	8,06	10,07	55,57	-	54,2
A-4	30M12CB	850	8,05	10,11	55,57	180	213,9
A-5	30M12CB	850	8,03	10,09	55,56	180	232,9
A-6	30M12CB	850	8,06	10,10	55,59	180	202,8
A-7	30M12CB	850	8,07	10,09	55,58	220	192,6
A-8	30M12CB	850	8,07	10,10	55,56	220	189,8
A-9	30M12CB	850	8,08	10,07	55,59	220	234,6

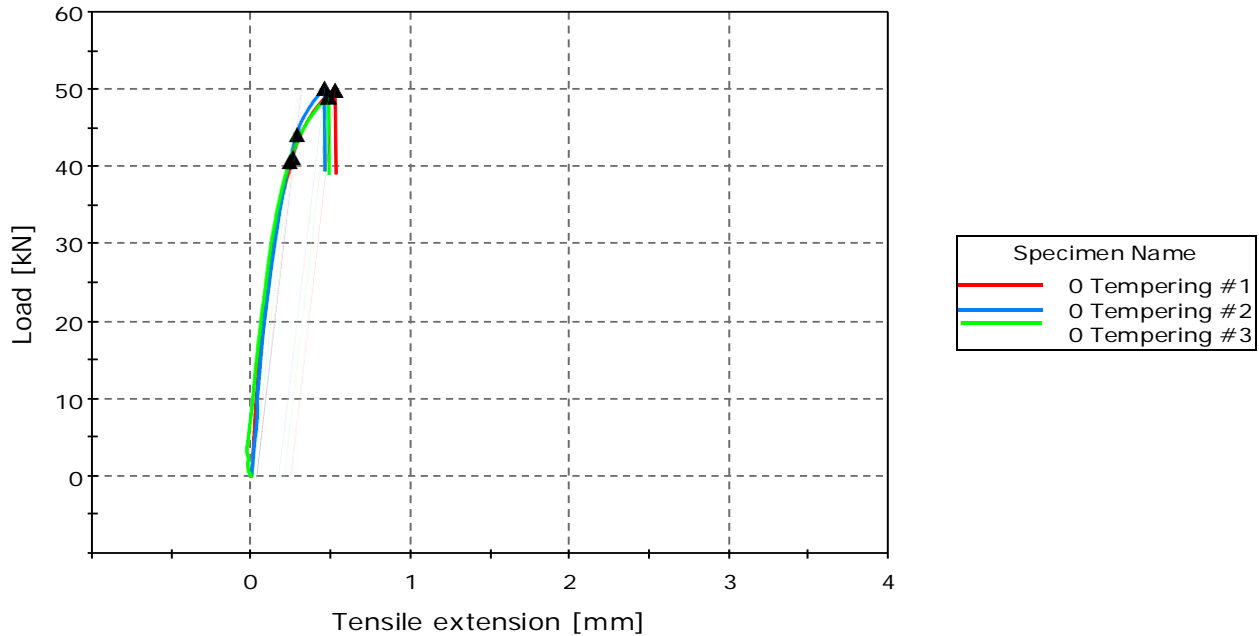| Nr.	Material	HT (*C)	Height (mm)	Width (mm)	Length (mm)	Tempering (*C)	W (J)
B-1	30M12CB	1100	8,05	10,05	55,43	-	215,2
B-2	30M12CB	1100	8,06	10,04	55,48	-	168,2
B-3	30M12CB	1100	8,95	9,99	55,50	-	197,9
B-4	30M12CB	1100	7,98	10,07	55,42	180	269,4
B-5	30M12CB	1100	8,04	10,03	55,44	180	246,3
B-6	30M12CB	1100	8,04	10,08	55,27	180	274,4
B-7	30M12CB	1100	8,07	10,0	55,24	220	237,4
B-8	30M12CB	1100	7,97	10,04	55,32	220	202,2
B-9	30M12CB	1100	7,95	10,04	55,49	220	154,2

Appendix B Tensile test reports

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Instron Applications Laboratory
30M12CB

This template is suitable for creating test procedures that comply with ISO 6892-1: 2009. Test rates and control are set according to "Method A" recommended ranges. Template is intended for specimens that produce a clearly-defined linear elastic region and homogeneous deformation. Default calculated results include Rp 0.2, Fm, Rm and A.

Load vs. Extension

Specimen Name
- 0 Tempering #1
- 0 Tempering #2
- 0 Tempering #3

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.98702	193.3	1466.02	50.2	1775.35	0.008	0.246
2	29.89364	187.1	1566.27	50.4	1778.34	0.006	0.172
3	29.85965	189.1	1448.09	49.3	1745.19	0.007	0.204

Graph 2

Strain vs. Stress

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	1775.35	0.017	0.521	0.008	0.246	4.93750
2	1778.34	0.015	0.456	0.006	0.172	3.30010
3	1745.19	0.016	0.480	0.007	0.204	3.30556

Instron Applications Laboratory
30M12CB

This template is suitable for creating test procedures that comply with ISO 6892-1: 2009. Test rates and control are set according to "Method A" recommended ranges. Template is intended for specimens that produce a clearly-defined linear elastic region and homogeneous deformation. Default calculated results include Rp 0.2, Fm, Rm and A.
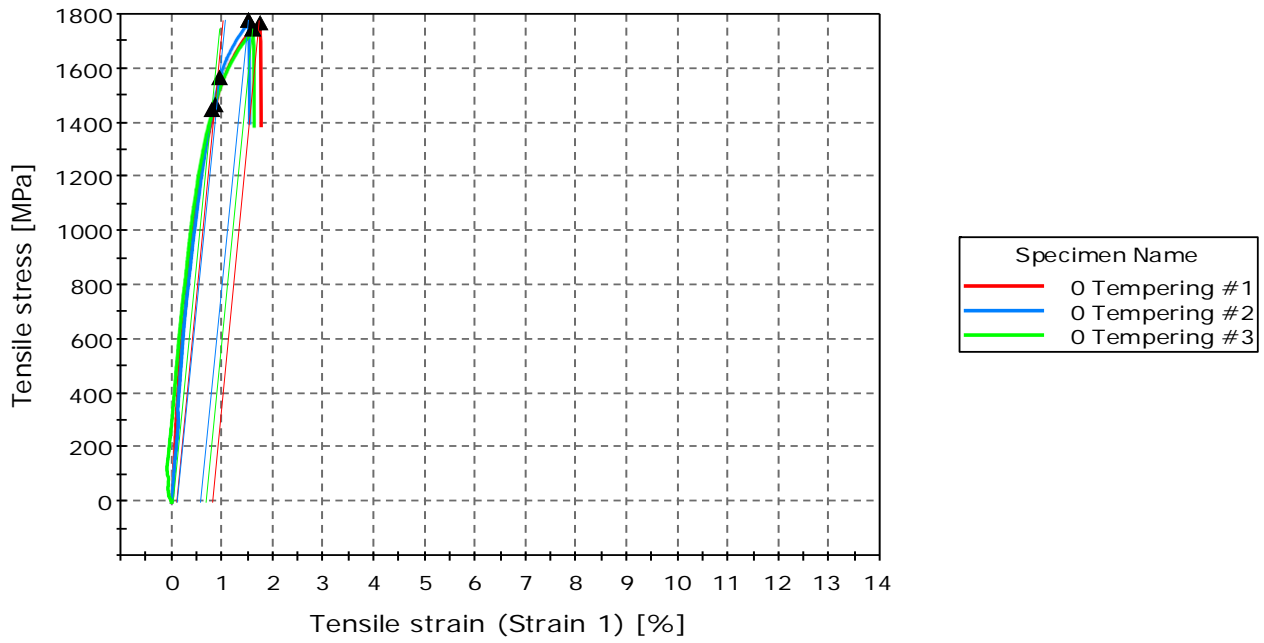
Load vs. Extension

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.93950	305.0	1364.39	49.5	1755.65	0.032	0.970
2	29.98907	196.4	1458.66	50.3	1780.31	0.029	0.882
3	30.05999	283.3	1488.33	50.2	1757.55	0.030	0.907

INSTRON®

Graph 2

Strain vs. Stress

Specimen Name
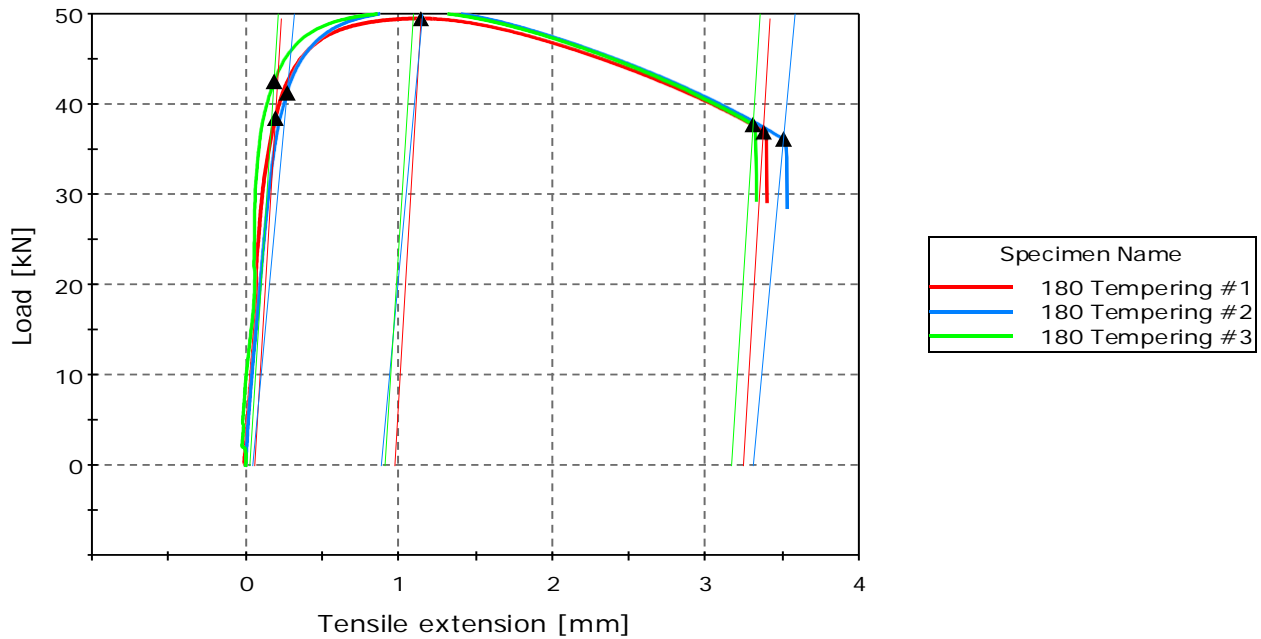— 180 Tempering #1
— 180 Tempering #2
— 180 Tempering #3

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	1312.46	0.112	3.368
2	1279.06	0.117	3.499
3	1322.30	0.110	3.301

	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.108	3.239	49.65872
2	0.110	3.303	53.30556
3	0.105	3.161	49.14867

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30M12CB

This template is suitable for creating test procedures that comply with ISO 6892-1: 2009. Test rates and control are set according to "Method A" recommended ranges. Template is intended for specimens that produce a clearly-defined linear elastic region and homogeneous deformation. Default calculated results include Rp 0.2, Fm, Rm and A.
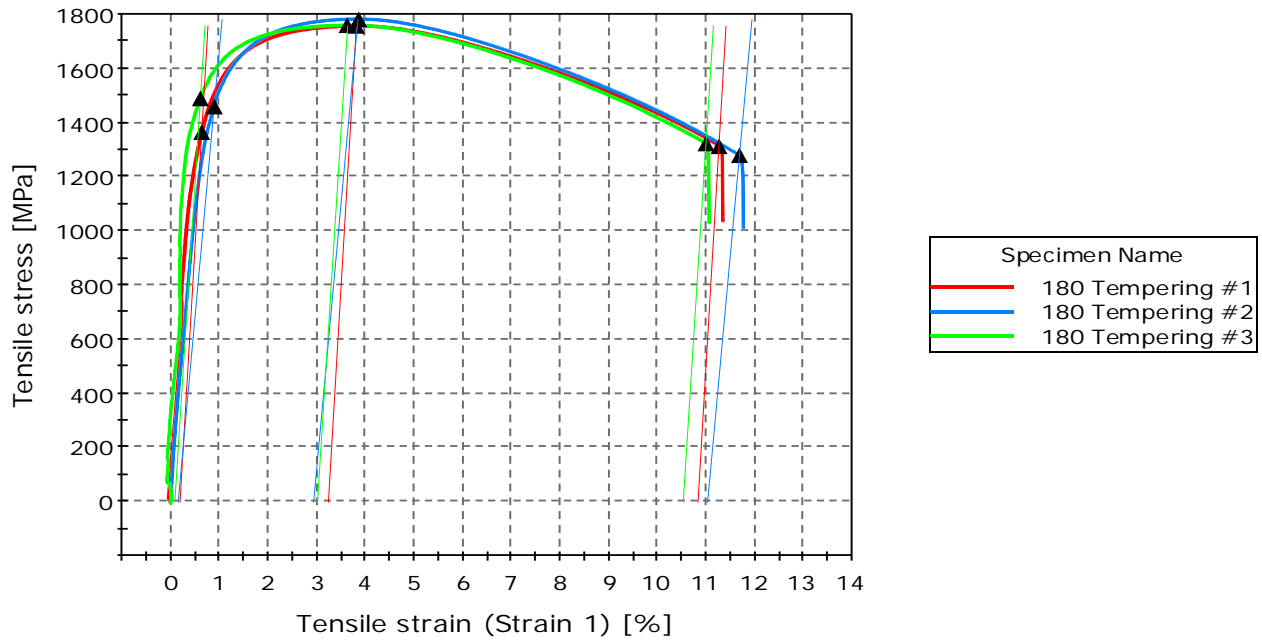
Load vs. Extension

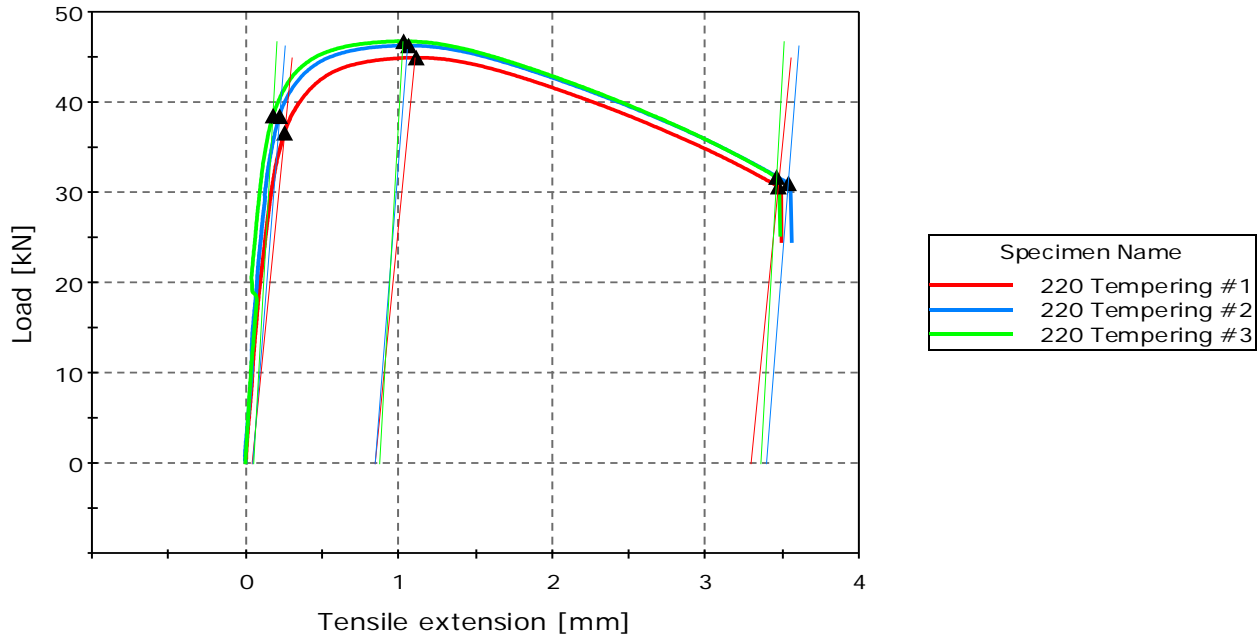|	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.81147	182.0	1295.25	44.9	1589.02	0.028	0.842
2	29.94716	232.2	1364.31	46.3	1641.66	0.028	0.841
3	29.85288	322.1	1357.60	46.7	1647.45	0.029	0.872

Graph 2

Strain vs. Stress
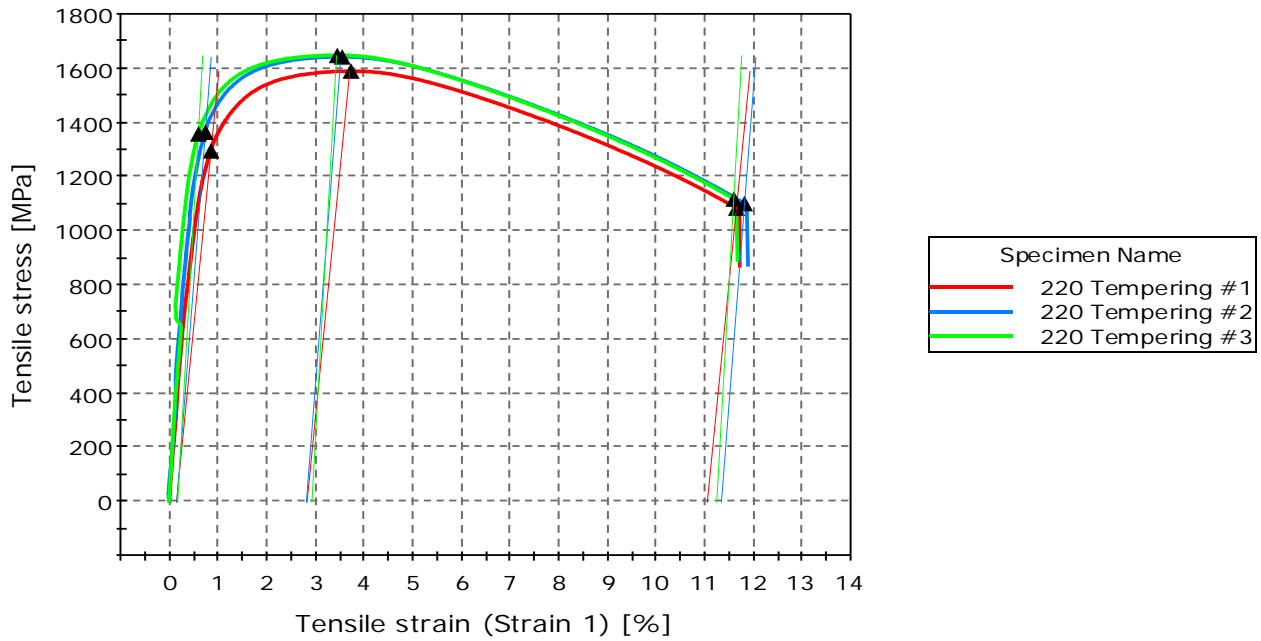
Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	1084.84	0.116	3.466
2	1101.23	0.118	3.531
3	1118.30	0.116	3.454

	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.110	3.288	46.22222
2	0.113	3.389	54.51072
3	0.112	3.351	55.03639

![INSTRON]

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30M12CB-1100

This template is suitable for creating test procedures that comply with ISO 6892-1: 2009. Test rates and control are set according to "Method A" recommended ranges. Template is intended for specimens that produce a clearly-defined linear elastic region and homogeneous deformation. Default calculated results include Rp 0.2, Fm, Rm and A.
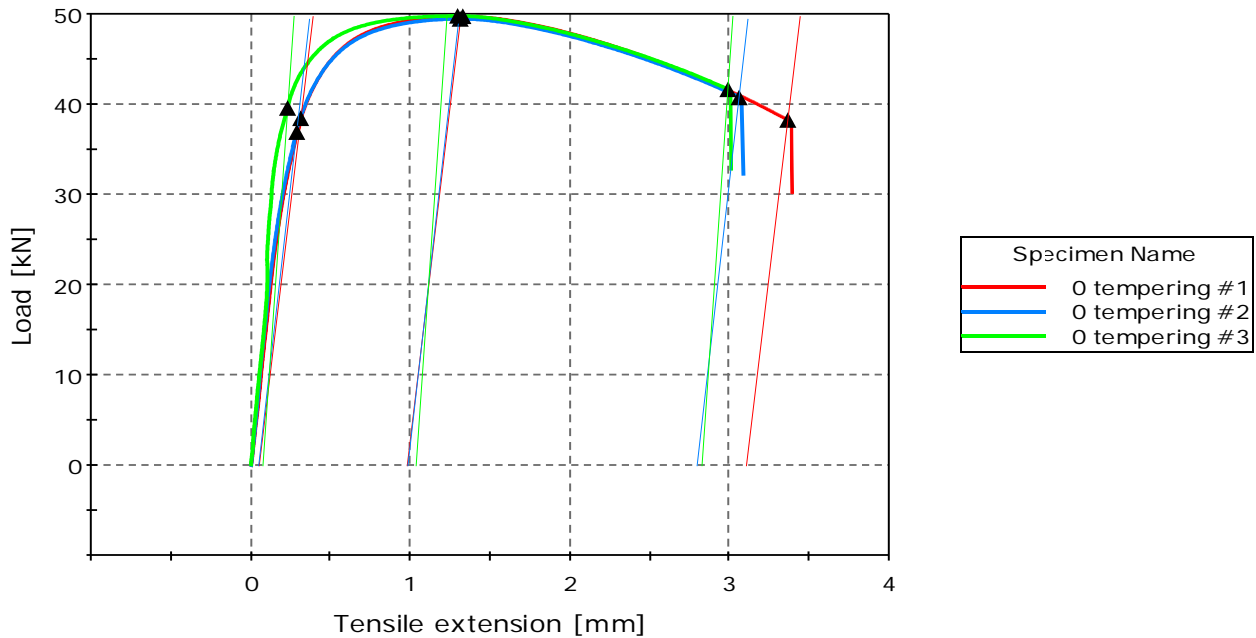
Load vs. Extension

Specimen Name
— 0 tempering #1
— 0 tempering #2
— 0 tempering #3

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.95706	160.6	1396.83	49.7	1806.31	0.033	0.978
2	29.94445	169.6	1350.76	49.4	1808.26	0.033	0.982
3	30.02769	278.1	1428.89	49.8	1795.51	0.034	1.034

Graph 2

Strain vs. Stress
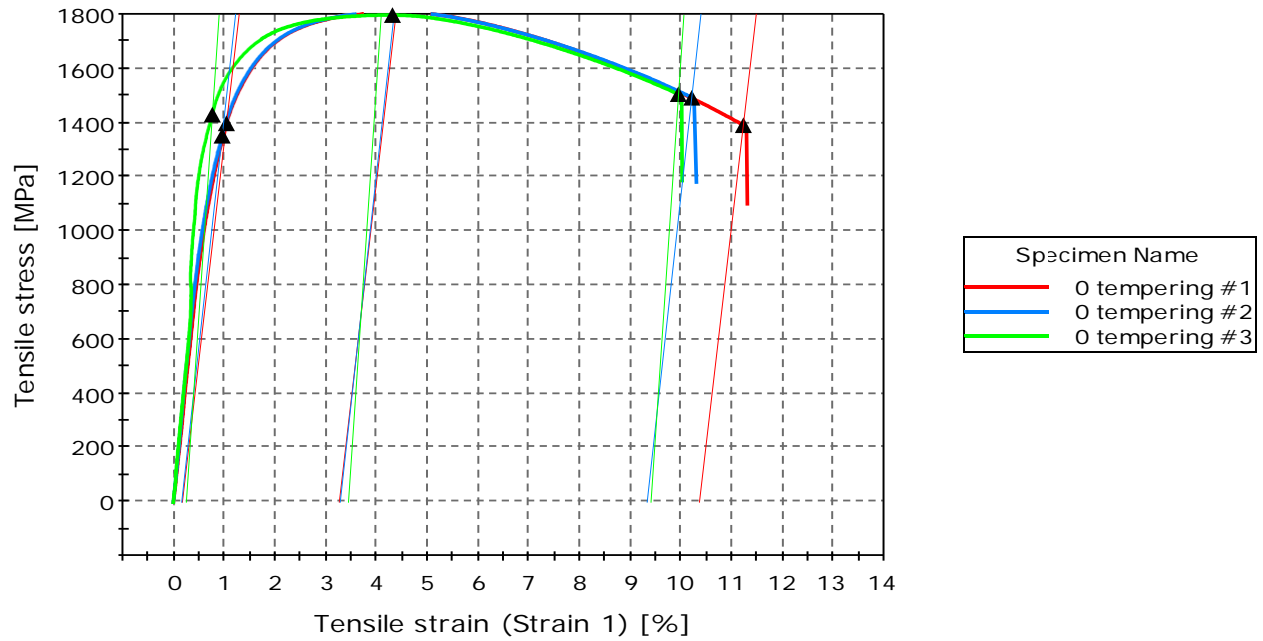
Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	1389.78	0.112	3.359
2	1490.86	0.102	3.054
3	1503.58	0.099	2.983

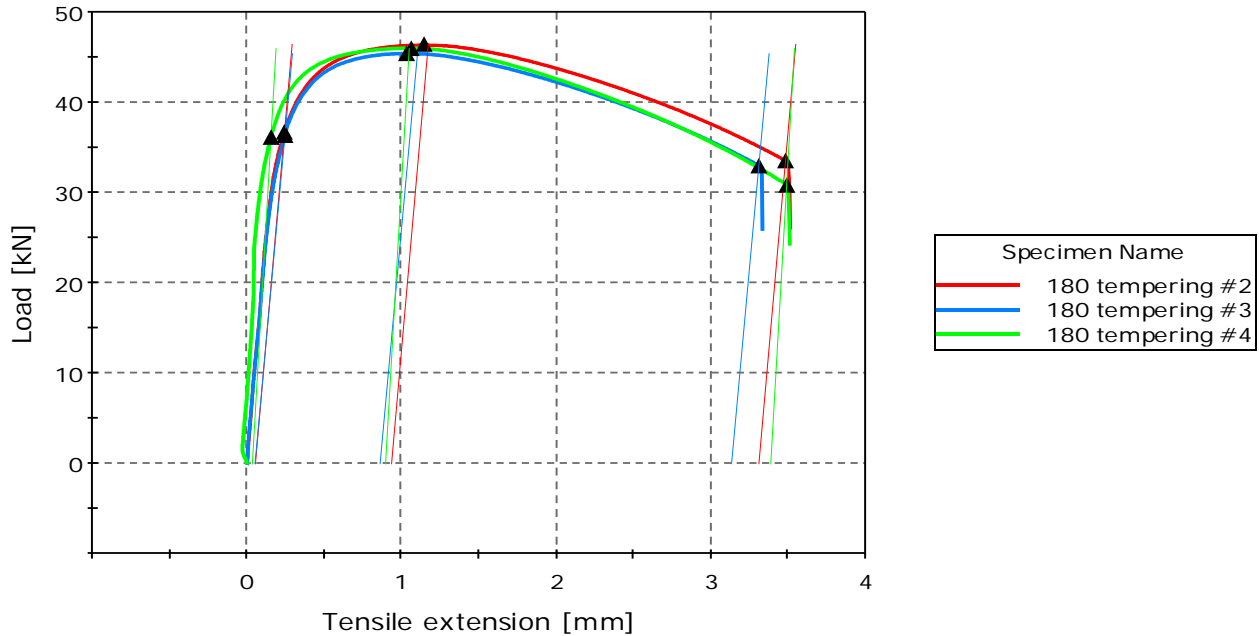|	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.103	3.099	45.50967
2	0.093	2.790	37.61678
3	0.094	2.821	38.18970

Instron Applications Laboratory
30M12CB-1100

This template is suitable for creating test procedures that comply with ISO 6892-1: 2009. Test rates and control are set according to "Method A" recommended ranges. Template is intended for specimens that produce a clearly-defined linear elastic region and homogeneous deformation. Default calculated results include Rp 0.2, Fm, Rm and A.
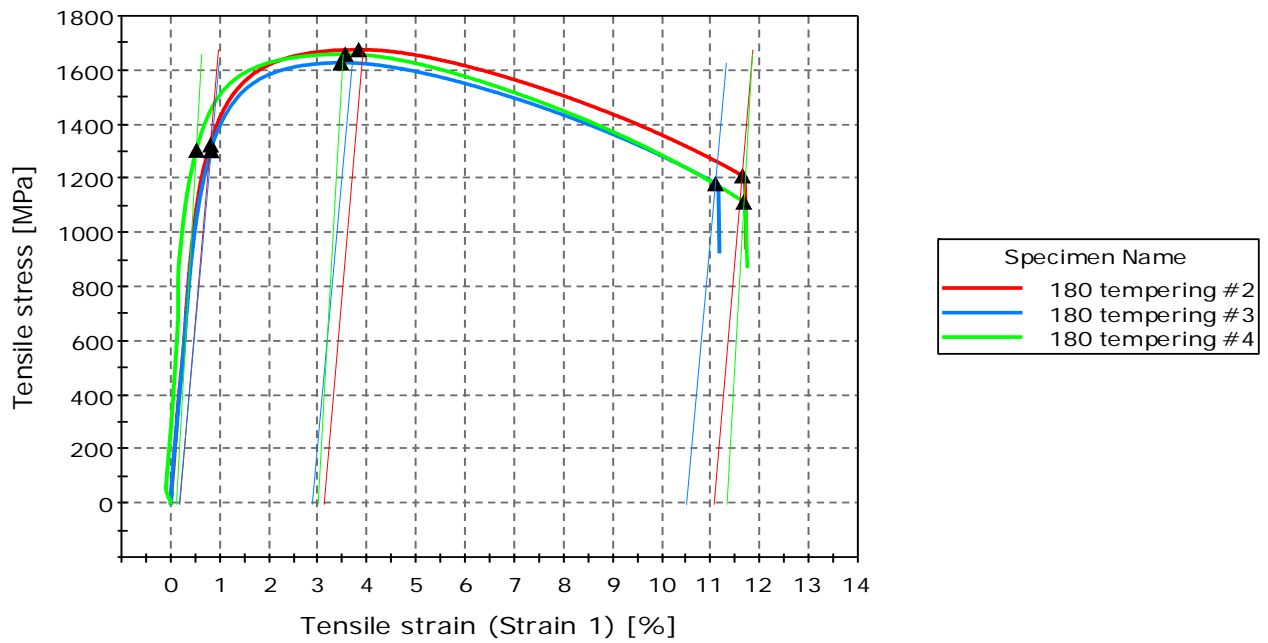
Load vs. Extension

Specimen Name
- 180 tempering #2
- 180 tempering #3
- 180 tempering #4

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
2	29.92659	211.1	1325.90	46.4	1675.53	0.031	0.933
3	29.83688	200.8	1303.92	45.4	1627.25	0.029	0.859
4	29.89973	324.2	1305.00	46.0	1659.03	0.030	0.896

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Graph 2
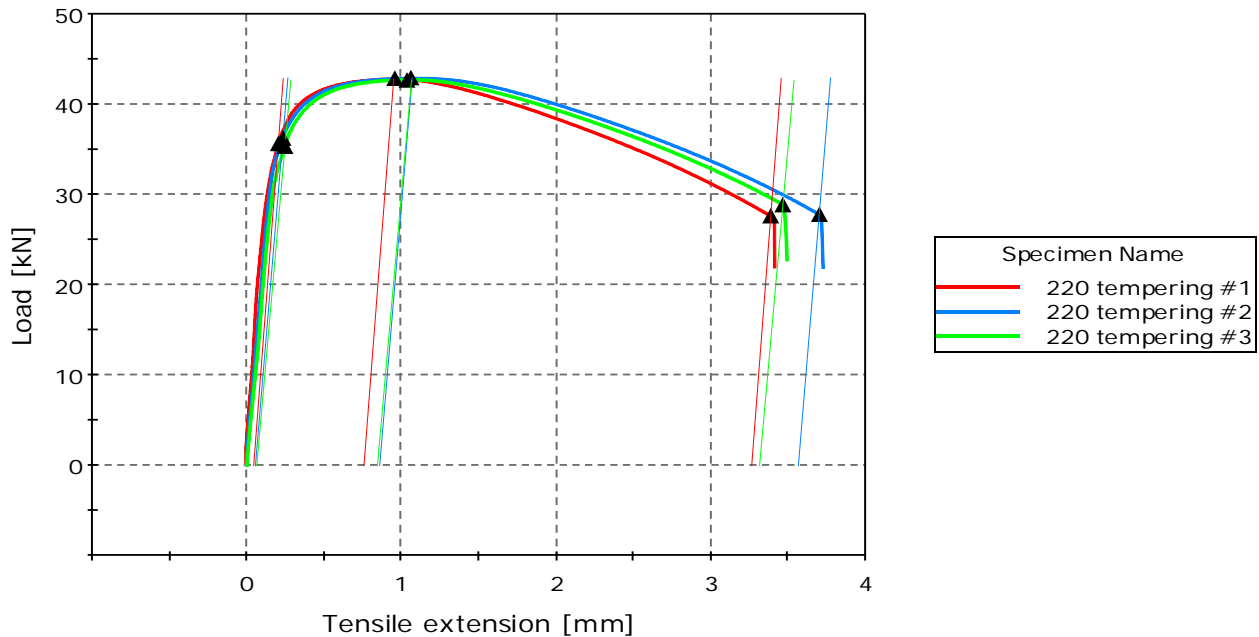
Strain vs. Stress

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
2	1211.44	0.116	3.477	0.110	3.305	49.52782
3	1182.54	0.111	3.303	0.105	3.128	51.28147
4	1114.50	0.116	3.483	0.113	3.380	50.48011

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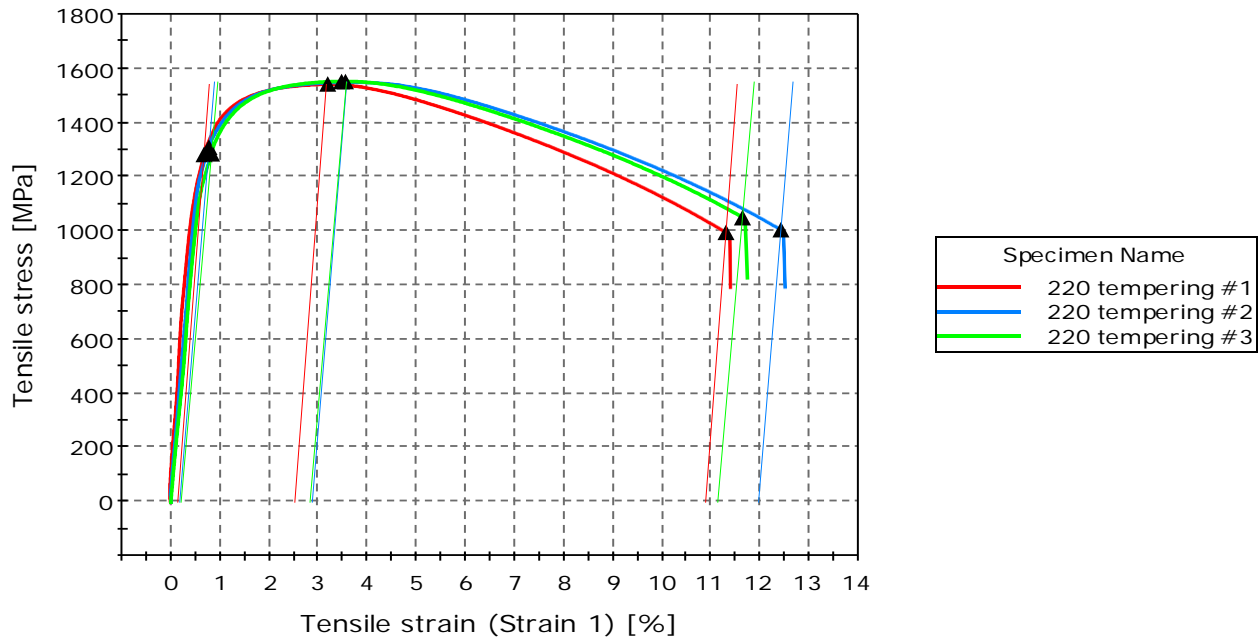
Load vs. Extension

Specimen Name
- 220 tempering #1
- 220 tempering #2
- 220 tempering #3

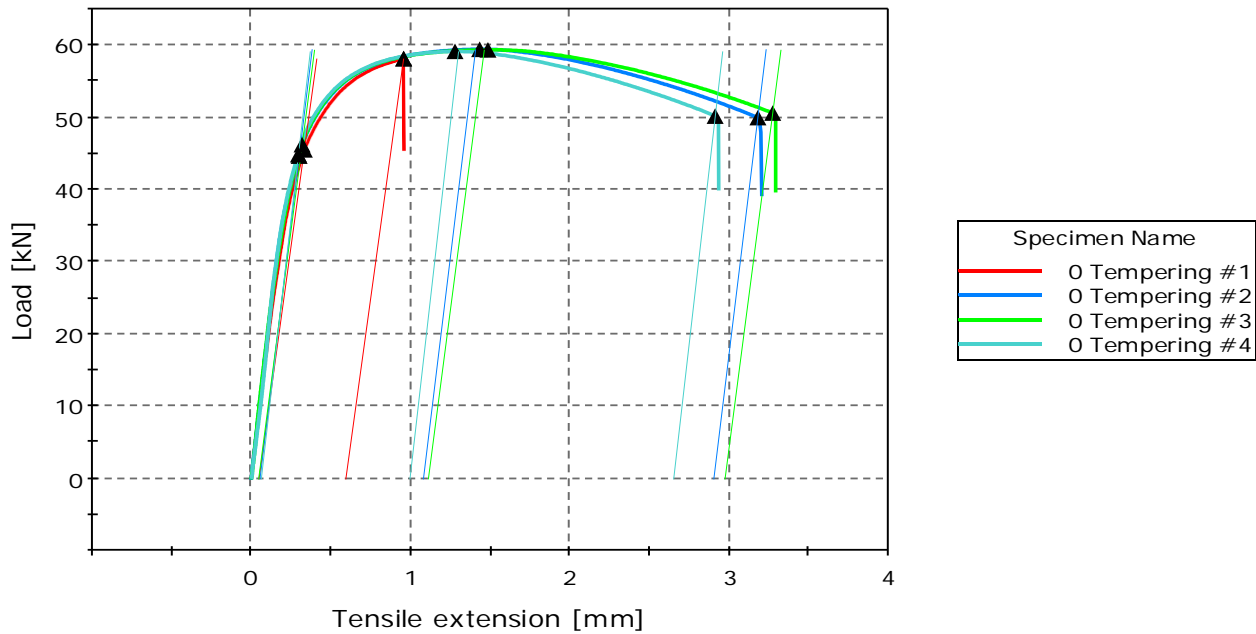|	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.95679	239.9	1282.56	42.9	1541.78	0.025	0.755
2	29.78359	220.2	1308.88	43.0	1550.12	0.029	0.857
3	29.75416	207.5	1284.93	42.7	1551.02	0.028	0.841

Graph 2

Strain vs. Stress

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	995.05	0.113	3.381	0.109	3.256	57.69536
2	1005.17	0.124	3.694	0.119	3.558	57.33315
3	1049.85	0.116	3.458	0.111	3.308	54.34624

Instron Applications Laboratory 35M13B

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Load vs. Extension

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.94250	170.0	1614.03	58.1	2061.56	0.020	0.591
2	29.93782	192.9	1588.66	59.4	2114.41	0.036	1.077
3	29.91364	180.8	1650.30	59.3	2118.40	0.037	1.109
4	30.03323	201.7	1559.63	59.1	2055.64	0.033	0.993

Graph 2

Strain vs. Stress
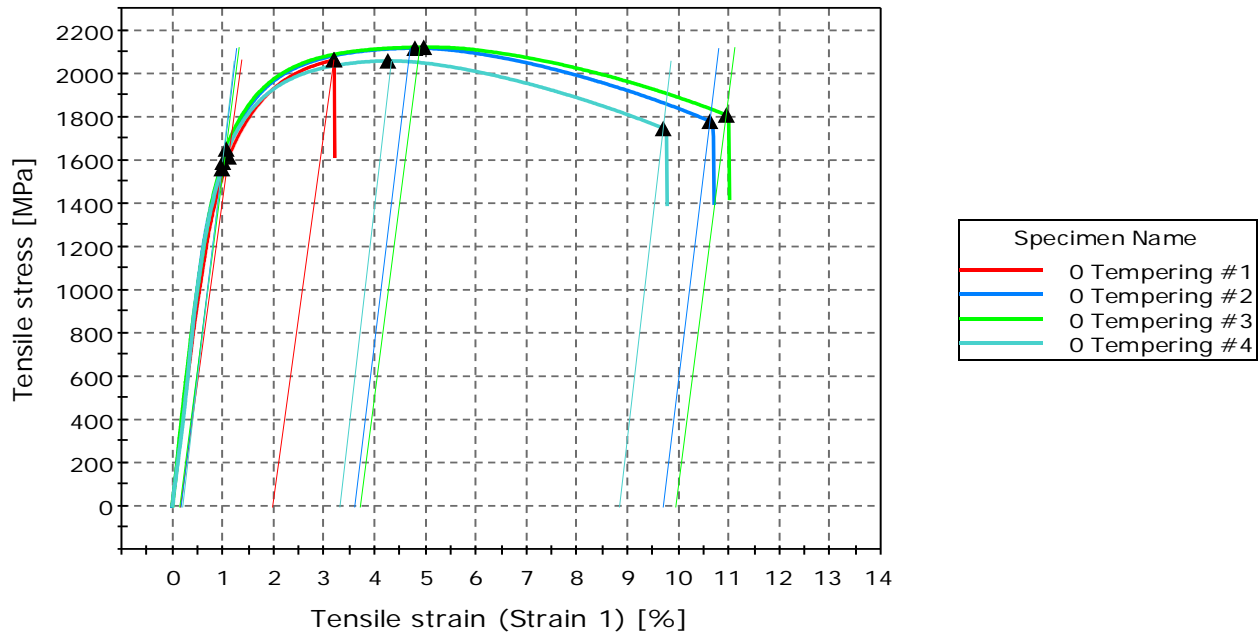
Results table 2

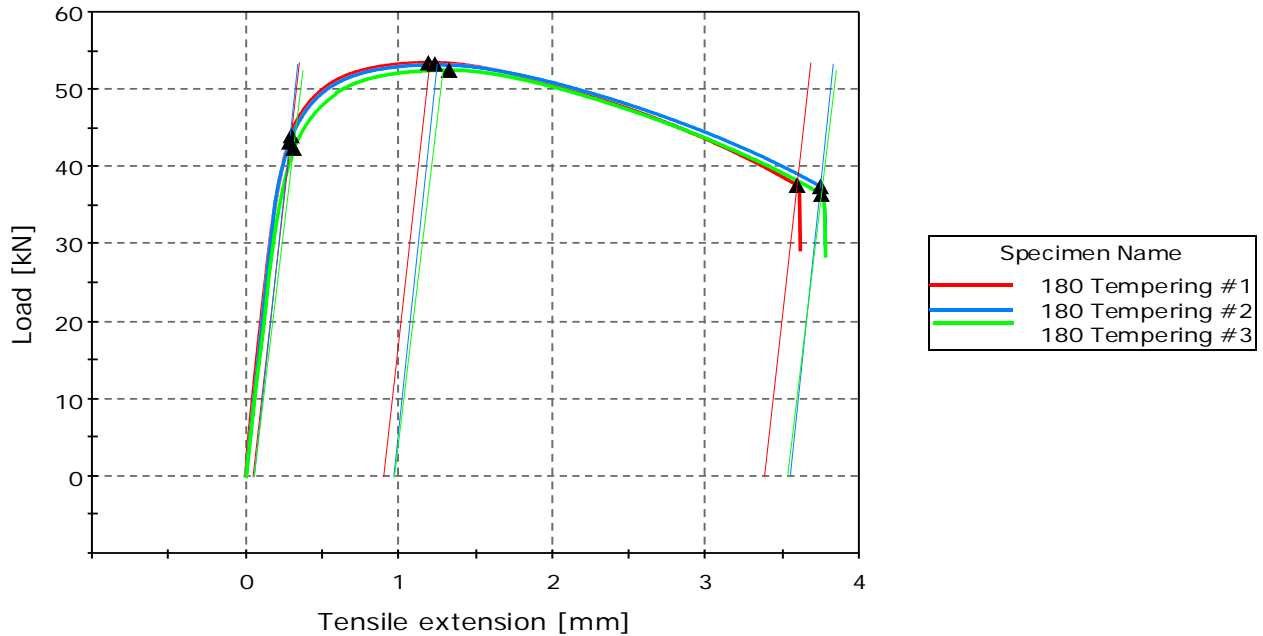|	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	2061.56	0.032	0.954
2	1777.89	0.106	3.175
3	1806.59	0.109	3.268
4	1744.57	0.097	2.908

	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.020	0.591	4.61983
2	0.097	2.899	36.90647
3	0.099	2.969	37.49204
4	0.088	2.648	38.87603

Instron Applications Laboratory
35M13B

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Load vs. Extension

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	30.01602	189.4	1569.12	53.4	1903.06	0.030	0.898
2	29.80123	200.0	1533.93	53.3	1890.99	0.032	0.965
3	29.92686	175.8	1511.00	52.5	1868.41	0.032	0.967

Graph 2

Strain vs. Stress
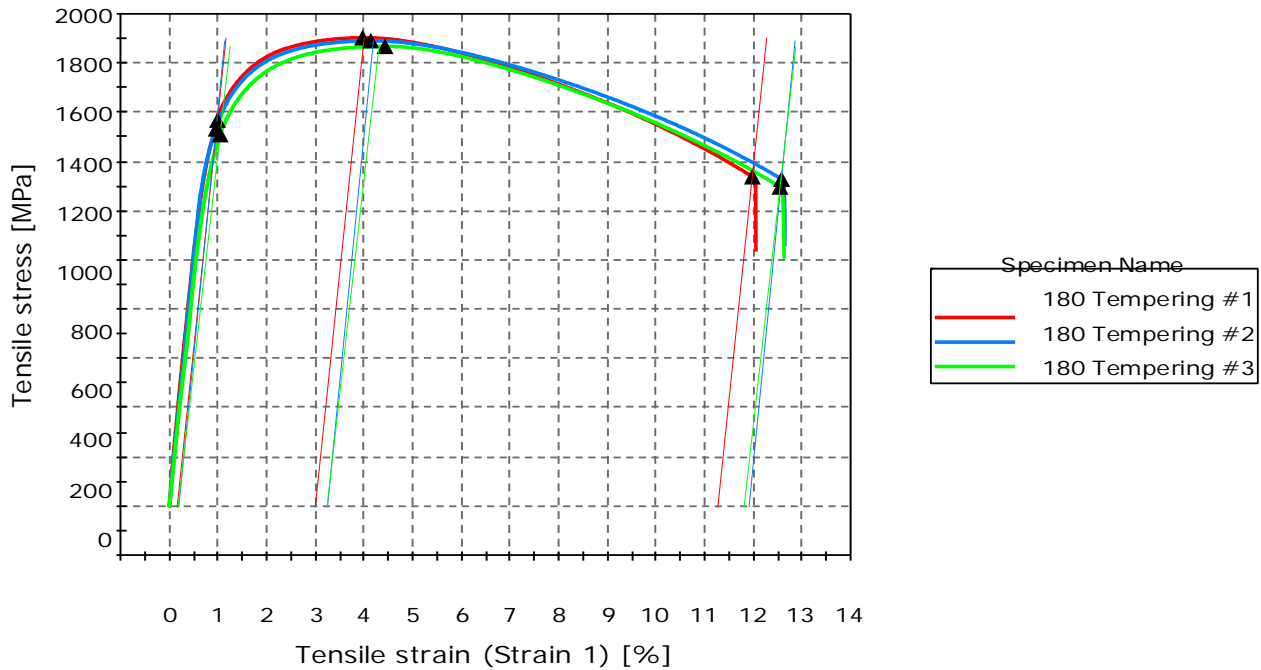
Specimen Name
- 180 Tempering #1
- 180 Tempering #2
- 180 Tempering #3

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	1339.85	0.120	3.588
2	1330.19	0.125	3.740
3	1298.90	0.125	3.746

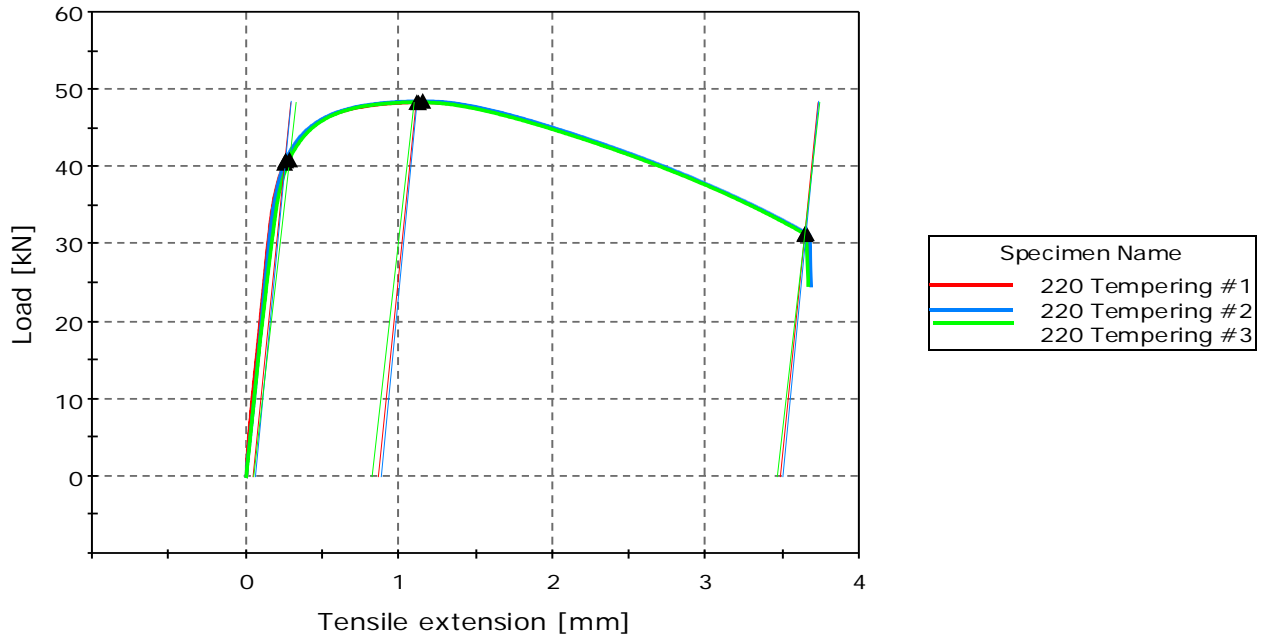|	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.112	3.375	55.25777
2	0.119	3.541	55.85185
3	0.118	3.525	56.58997

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35M13B

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Load vs. Extension

	Strain 1 gauge length [mm]	Modulus (E-Modulus) [GPa]	Tensile stress at Offset yield 0.2% [MPa]	Fm [kN]	Tensile stress at Max load [MPa]	% Elongation at tensile strength at Non-proportional elongation (Standard) [mm/mm]	Elongation at tensile strength at Non-proportional elongation (Standard) [mm]
1	29.83217	208.5	1437.35	48.3	1715.01	0.029	0.864
2	29.82962	220.1	1448.89	48.5	1720.94	0.030	0.884
3	29.84697	185.4	1451.30	48.3	1712.72	0.028	0.822

Graph 2

Strain vs. Stress
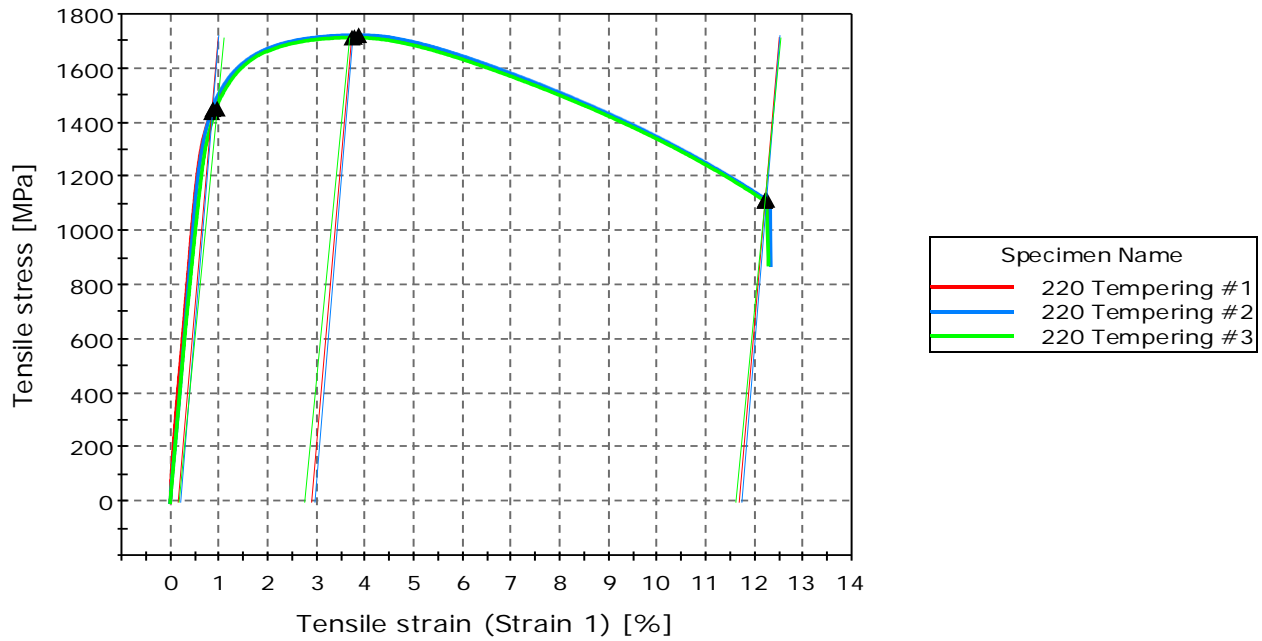
Specimen Name
220 Tempering #1
220 Tempering #2
220 Tempering #3

Results table 2

	Tensile stress at Break (Standard) [MPa]	Tensile strain (Strain 1) at Break (Standard) [mm/mm]	Tensile extension at Break (Standard) [mm]
1	1114.84	0.122	3.638
2	1115.12	0.122	3.646
3	1109.95	0.122	3.638

	% Elongation at break at Non-proportional elongation (Standard) [mm/mm]	Elongation at break at Non-proportional elongation (Standard) [mm]	Reduction of area at Area reduction [%]
1	0.117	3.478	58.47392
2	0.117	3.495	58.47392
3	0.116	3.459	58.54316