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Improving durability and predictability of boron steel components

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This thesis work focuses on improving durability and predictability aspects of boron steel components used in the traction solution industry. The thesis starts with an introduction of the company Nordic Traction and its products. The key properties of boron steel, like high hardness and wear resistances are explained and introduced. Manufacturing processes and additional procedures in the industry have remained quite stagnant for a while, so more optimized and recent methods can be beneficial for the company. This thesis work is a literature review, where the research to enhance boron steels are found from scientific articles and studies globally. Key findings of the thesis can be divided mainly into two parts: heat treatment procedures, and surface treatments or coatings. Heat treatment procedures consist of cryogenic treatments, subcritical annealing and hardening, and quenching and partitioning. Coating portion focuses on the laser cladding principle which is compared to case hardening and protective paintings. All the previously mentioned processes showed significant increases to wear resistances and hardness values of boron steels, but the required additional machinery, knowledge, energy costs, and lack of research data specifically tailored on boron steels still offer some challenges in the industry.

Key words: boron steel, traction solution, wear resistance, heat treatment, laser cladding.

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Tämä diplomityö keskittyy booriteräksen kestävyyden ja ennustettavuuden parantamiseen erilaisissa pitoa parantavissa ketjuissa sekä oheiskomponenteissa. Työ alkaa Nordic Traction yrityksen sekä sen valmistamien tuotteiden esittelyllä. Booriterästen tärkeät ominaisuudet, kuten kovuus ja kulutuskestävyys selitetään myös tarkemmin. Valmistusprosessit ja lisätoimenpiteet tässä teollisuuden haarassa ovat säilyneet muuttumattomina suhteellisen kauan, joten yhä optimoidummat ja nykyisemmät metodit voivat olla yritykselle kannattavia. Tämä diplomityö on kirjallisuuskatsaus, jossa booriterästen tehostamiseen käytetty tutkimusmateriaali on kerätty tieteellisistä artikkeleista ja tutkimuksista ympäri maailman. Tärkeimmät löydökset voidaan jakaa pääasiallisesti kahteen osaan: lämpökäsittelymenetelmiin, sekä erilaisiin pintakäsittelymenetelmiin. Lämpökäsittelymenetelmät koostuvat muun muassa kryogeenisestä käsittelystä, subkriittisestä hehkutuksesta ja kovettamisesta, sekä osittaiskarkaisusta. Pintakäsittelymenetelmät keskittyvät puolestaan laserpäällysteisiin, joita verrataan pintakarkaisuun ja suojaaviin maaleihin. Kaikki edellä mainitut toimenpiteet onnistuivat tehostamaan booriterästen kulutuskestävyyttä sekä kovuutta merkittävästi, mutta niiden vaatima mahdollinen lisäkoneisto, osaaminen, energiakustannukset, tai erityisesti booriteräksillä tehdyn tutkimusdatan puute tarjoaa osansa teollisuushaaran haasteista.

Avainsanat: booriteräs, vetoratkaisu, kulutuskestävyys, lämpökäsittely, laserpäällyste.

Abbreviations

APT = atom probe tomography

BCC = body-centered cubic

CHT = conventional heat treatment

DCT = deep cryogenic treatment

FCC = face-centred cubic

HEA = high-entropy alloy

HV (0,5 – 10) = Vickers Hardness (with loads of 0,5 – 10 kg)

HRC = Rockwell hardness C-scale

HSS = high-speed steel

MMC = metal matrix composites

ppm = parts per million

PVD = physical vapor disposition

Q&P = quenching and partitioning

RA = retained austenite

SEM = scanning electron microscopy

TEM = transmission electron microscopy

WC = tungsten carbide

XRD = X-ray diffraction

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1 Introduction

This thesis is written with the cooperation of Nordic Traction Oy in Loimaa. The aim of the thesis is to discuss and find solutions for boron steel and its uses in the traction solution industry. Main reason for using these traction chains and solutions is to improve traction properties in high-demanding environments. Different traction chains and solutions can theoretically be used in any vehicles, which have tires. The thesis focuses on applications on heavier vehicles, for example forest machines, tractors, and heavy trucks, because those are the main target group for Nordic Traction Oy.

Boron steel has been a prevalent material choice in the tire chain industry for a long time due to its excellent mechanical properties, cost efficient manufacturing, and the engineering knowledge currently available. While boron steel is a good material choice for these kinds of tire chains, it is recommendable trying to find alternative methods or material combinations to improve efficiencies, costs, and durability aspects of boron steel components. Environmental aspects have become more and more important topic globally, and reducing CO_2 and other emissions is a good way for Nordic Traction Oy to be competitive and more responsible in the field.

1.1 Purpose of the thesis

Research part of the thesis can be divided into three different main problems and questions. **The first** question consists of how to increase the operational lifespans and overall durability of the products. **Secondly,** it is in the company's interest to improve predictability of the components. The chains produced by the company have different structures and parts in their components, so it is important to be able to predict what are the weaker links in the assembly and how often they must be maintenanced or changed before they break apart completely. **The third** aspect of the thesis is to increase the environmental side of the product. This can happen by reducing CO_2 gas emissions by lengthening lifespans of the components, or finding more efficient and sustainable manufacturing processes, which consume less energy during the creation of the parts.

The aim of the thesis is to improve durability, predictability and environmental aspects of the tire chain manufacturing and its components. Boron steel is the most widely used material in the traction chain industry, and it is used for a good reason. Finding different materials or material combinations, inventing unique coating solutions, or improving traditional heat treatment procedures are all good researchable solutions for getting more competition to boron steel components. After finding possible alternatives, they can be compared and measured against the boron steel performance in different areas. The comparison between currently used boron steel components and possible future variations can open interesting notions and improved results going forward. As Nordic Traction Oy is preparing to transfer from wholesale model to traction as a service model, it is specifically important to increase predictability of the products, so for example planning the maintenance schedule for the customers can be a lot easier and efficient.

Focus on the thesis is finding relatively new information: studies or articles about different materials and procedures to gain potential competition to boron steel. This thesis is practically a widely analysed literature review of current scientifical studies and articles regarding the topic. The most important aspects are that the research used for the thesis must be quite recent, at most 5-7 years old. Another important aspect is, that when comparing different alternatives to the original components, whole life cycle and different areas of the product needs to be analysed. This means, that the process starts from getting the raw materials, preparing them for manufacturing, the manufacturing itself, the complete product in use, and how to deal with the product after its lifecycle ends, are all important variables to be taken into consideration. Increasing product efficiency and durability, improving environmental aspects and sustainability, while also keeping the products and its parts easily predictable is the key for the next step in the traction chain industry.

2 Theoretical background

2.1 Boron steel components in tire chain industry

Nordic traction Group is among the largest traction solution manufacturing companies globally for forest machines and tractors. The company's product "NordChain" is a microalloyed boron steel chain, which size can vary up to 19 millimetres. Before these chains are manufactured, they go through pre-treatment procedures [1]. After pre-treatment is done, the boron steel material is bent in a large link machine before they are welded. This procedure happens by first heating up the link joints electrically and then pressing them together under high pressure, as can be seen in Figure 1. Using this process makes the weld extremely strong and sturdy. Afterwards, the components are cut, assembled, and welded together for getting a desirable type of chain. Finally, the chain is case hardened in a large oven at 900 °C for several hours, and carbon atoms are added to the steel to make it even harder and tougher.

Figure 1. Boron steel chains being heated and pressured together in high pressure. Image reproduced with permission from [1].

The Nordic Traction Group manufactures boron steel chains on top of the tires in many different sizes and types according to the needed application. Main point is to increase traction in tougher and more demanding environments, for example in uneven forests and in snowy and icy surroundings. There are lots of different sized vehicles in the forest machine industry and logically when the weight of the machines and size of tires grow bigger, also the chains need to be sturdier and thicker. While more traditional trucks or trailers use quite thin 5-millimetre diameter chains, the heavy forest machines or construction machines might need chain diameter up to 19 millimetres [2].

On top the chains links depicted in the Figure 1, Nordic Traction also provides many different traction components used with the chains to add functionality. The ends of manufactured chains can be connected with special **plug couplings**. These couplings can also be used for simple and easy tensioning of the chain. Another trademark characteristic of the company is **a butt - welded u-studs** [3]**,** which enables better grip properties and more efficient self-cleaning of the chains. When chains are placed on top the tire, the pattern of the chains resembles a diamond shape, which have special **rings** to offer more stability and linking the chains together. On top of these components, some chain types also use so called **tight sides** to offer even more protection for the tyre in hard stony environments. An example of these components can be seen in Figure 2 below.

Figure 2. The overall diamond shape, connecting rings, and u-studs better illustrated on a tire. Image reproduced with permission from [3]

2.2 Properties of Boron steel

2.2.1 Early history

Different steels are widely used materials in various applications and industries. Melting and heating iron ore in big furnaces and adding coal into the mix, enables iron and carbon atoms to get combined to steel. This procedure makes the final product (steel) have even more toughness and strength than its source materials. Steel itself is already a strong and sturdy material but adding boron can improve its properties such as hardenability or strength even further especially in the traction solution industry.

First mentions of boron steel are found as early as late 19th century studies, although the commercial applications occurred later around years 1925 – 1950. Between those years boron was incidentally found in some ferro-alloys, which also contained certain elements (aluminium, zinc, zirconium, tin), that protected boron from reaction with oxygen or nitrogen. It was found that even in very minor concentrations, boron had an improved effect on hardenability (a measure of the ability to harden a steel to a given depth) properties on steels [4]. After this relation with boron and steel was realized, it was named "the boron effect [5]."

When "the boron effect" was firstly introduced and used in different steels, the science behind the properties of boron was not very well known. Instead, the main drive to use boron with steels was to reduce the usage of more expensive metals or elements, for example nickel, chromium, manganese, molybdenum [6]. In comparison, adding only 10-30 wt ppm of boron to steel is relative to adding 6000 ppm of manganese or 15000 wt ppm of nickel, which is a drastic difference in concentrations, while simultaneously preserving similar hardenability properties [7]. While boron has been used with steel alloys for an almost hundred years, it has also certain issues. Some of these are related to distortions, tendencies to overheat, or even decreasing some mechanical properties [5].

2.2.2 Hardenability

As briefly described in earlier chapter, hardenability is one important property, which boron enhances in steel alloys. Very small amounts of soluble boron can lead to significant improvements in hardenability [8]. The mechanism behind the hardenability aspect of boron is well-known in the industry. Boron separates the austenite grain boundaries (GB), slows down the formation of ferrite and other diffusion products by contaminating the nucleation sites of prior austenite grain boundaries (PAGB) for non-martensitic products. This leads to a promoted martensite formation, which results in improved hardenability and strength values for the material [5]. The precipitates consisting of boron along austenite grain boundaries can slow down the formation of the ferrite. Using either solute boron or boron-containing precipitates are both good ways to increase the hardenability of the alloy.

If boron is added homogenously in the steel matrix, it is important to know that the hardenability properties do not change. If hardenability aspect needs to be improved, boron has to be segregated or precipitated to borocarbides at the austenite grain boundary. While boron can substitute other more expensive materials in improving hardenability (nickel or molybdenum), the surface hardness remains similar overall and is more dependent on the carbon content of the material. [5]

While boron steels have significant improvements in hardenability, they also tend to have some problems in alloyed steels. Boron makes steel quite sensitive to repeated heat-treatments due to high temperatures and long-soaking times. This sensitivity can lead to deboronization, where boron effuses in the surface, or boron fade [5], where the material loses its hardenability effect. In case of boro-carbides, it is also important to control their manufacturing efficiently, because if these compounds are coarser than intended, it is very likely that the effect on hardenability is the opposite.

Improvement of hardenability by boron addition in steel alloys is greatly dependent on the steel alloys composition and different metals and their concentrations in it. The hardenability effect diminishes as carbon content in the alloy increases [7]. After a certain limit, which is 0.8 wt% of carbon or more, the hardenability enhancing effect is close to zero. The principle behind this behavior results from the competition between boron and carbon in austenite grain boundaries. In high carbon contents, carbon atoms dominantly occupy the sites, and segregated boron is restrained, which leads to energy in ground boundaries staying the same [5]. Carbon is also harmful to solubility of boron, because it tends to make the combined boro-carbides too coarse.

Adding titanium in the steel and boron alloy enables boron to maintain its hardenability effect efficiently, and in many cases, titanium is added for this very reason. Addition of titanium into steel alloys with boron, makes titanium additions bind the free nitrogen, forming TiN and leaving boron free in the system. If titanium is not used in the alloy, it is important to control and minimize the amount of harmful nitrogen or use aluminium instead of titanium. This enables boron to not react with free nitrogen in the system preventing the harmful effect to alloys hardenability. Boron also has some interesting synergies with certain elements, for example using molybdenum and boron together improves hardenability greatly (2 times more) compared to using molybdenum without boron for getting better hardenability properties [5]. Tungsten is another element with similar synergy with boron, but it is required more concentration-wise in the mix compared to molybdenum [8].

On top of different materials, also different heat treatments play a part in boron hardenability effect. The optimum austenitization temperature varies between 800 and 1000 °C [5], which is partially affected by the composition of the material (the amounts of chromium, molybdenum, and manganese for example). The main factors affected with heat treatments like annealing, enables bigger boron concentrations at grain boundaries. After certain temperatures, the hardenability aspect starts to decline, because more boron distributes in the steel matrix without leaving enough at the grain boundaries, resulting in lower hardenability properties of the material.

2.2.3 Toughness

Toughness depicts a materials ability to receive energy and change its shape plastically without breaking. It is an important factor to consider, when manufacturing materials for high-demanding uses in harsh conditions. While boron has been added to steel for a long time, the mechanisms behind its effect on toughness are still not yet completely understood. Toughness tests vary quite a lot from Charpy tests to Brugger impact tests, which also makes comparison difficult. The amounts and the size of boron added to steel alloys is so miniscule, adding more complexity to measuring and estimating its effects. As earlier mentioned, some elements like titanium protect boron in alloys, so the additional elements used in the system and their effects need to be specified and taken into consideration. While toughness measurements have been challenging to be made efficiently, in research studies some of the characteristics have been interpreted with the help of recent characterization methods, like SEM, TEM, or APT [5].

Boron’s effect on toughness in different steel alloys depends a lot on the composition of the steel and the differences in processing conditions. There have been studies where boron has enhanced the toughness of an alloy due to its aspect of improving grain boundary cohesion [5,9]. Some elements like phosphorus and titanium for example, can decrease the need of competition for nucleation sites [5,9]. Increases in hardenability can also improve toughness values, because they generate a more uniform microstructure in the alloy.

In contrast, there are also many studies where toughness values can decrease due to boron addition. The coarser boron particles affect negatively to the hardenability and toughness values [5]. There is also the coarsening effect if the alloy does not consist of titanium or aluminium particles, that can bond with excess nitrogen. The absence of this interaction with nitrogen affects negatively to both hardenability and toughness values. While the boron additions to steel alloys might offer better hardenability and toughness attributes, it is important to know that those occur only in the proper conditions.

2.2.3 Feasibility and applicability

Mechanical properties like hardness and strength are vital factors when manufacturing materials for harsh conditions and high demand. Additional challenge is, that these requirements need to be met with feasibility in mind. Using boron steels, the metal alloys have high strength attributes, more complex moldability [7] while also remaining relatively lighter, than the alloys without boron. The lightness of the alloy also results in decrease of raw materials [5,9], which lead to diminished overall costs of manufacturing.

While using boron additions in steel make the materials less expensive compared to common alloy steels with similar hardenability, boron also provides additional effects on mechanical properties. Miniscule amounts of boron added in the alloy results in increases at hardness and strength values [8]. Only 20 ppm additions of boron [5] increase both the tensile strength and hardness due to carbide forming aspect of boron.

Using boron in steel alloys is beneficial economically due to using small concentrations of boron instead of more expensive metal alloys and still gain good mechanical properties [6]. Boron additive steels can be processed quite easily, and mechanical properties are easy to alter after the heat treatments [7]. Boron steel also offers better machinability and weldability capabilities compared to similar hardness non-boron steels [7]. Better machinability means, that boron additive steels are less probable to get quench cracks or distortions during different heat treatments. These mechanical properties enable boron steels to be used in wide variety of different applications [8], from automotive industry to different tools and constructional equipment.

Boron steels have overall good flexibility to be used in various industries. Its properties enable it to be suitable in environmentally friendly processes, for example water quenching [8]. It also provides good hardness results with oil and gas quenching [8]. On top of the hardness and strength properties, boron steels have also excellent wear and abrasion resistance [8], which means more durability and less material loss during long periods of time. Higher durability leads to low maintenance intervals, longer life cycles and therefore diminished costs. A uniform microstructure, excellent mechanical properties, and brilliant resistances to abrasive wear are key factors why boron steel is a great material to be used in the traction solution industry.

2.2.4 Weldability and predictability

Weldability and predictability are few key concerns which boron steel has in the traction solution industry. Reducing emissions and improving fuel economy is a key factor when choosing materials for these kinds of solutions [10,11]. Reducing overall weight while simultaneously keeping good mechanical properties in the components is a significant reason why boron steel has become relevant in the traction solution industry. Combining different materials and components together is needed, because product assemblies are currently such complex structures, that hard pressing them solely is not necessarily an efficient option. While welding is the most common and simple way to combine different materials and components together, it also has some downsides like creating areas with lesser durability and mechanical properties.

Due to high strength values of boron steel, its cold formability properties are not good compared to other steel alloys [10,11]. This means that hot forming processes are used to mold boron steel to required forms and shapes. With different material combinations or heat treatment procedures it might be possible to make more complex products without the necessary hot temperatures or welding operations.

Using spot welding for joining components together results in different mechanical properties in different areas of the component. Welding different regions together results in softer heat-affected zone between the two regions [10,11]. The softer zone leads to weaker strength of the weld, which fails more likely under load. Weaker mechanical properties also affect on the predictability of the product: it is harder to estimate, when the product would break or when the needed maintenance should be made. Furtherly studying different welding techniques and methods to join different components together could offer some direction how the negative effect of welds can be minimized. This could also offer solutions for better prediction of possible failures in the material.

2.2.5 Summary

The most important aspects of boron steel components, such as mechanical properties or advantages and disadvantages, have been compiled from previous chapters to a Table 1 below.

Table 1. Advantages and disadvantages of boron steel

Pros	Cons
Excellent wear and abrasion resistances	Boron addition requires precision
Good mechanical properties (hardenability, hardness, toughness, strength, deformability)	Reaction between boron and nitrogen/oxygen lead to diminished mechanical properties → Elements needed to bind gases
Provides benefits even in small concentrations → Preserves more expensive materials	Weldability issues (additional strains, heat-affected zones)
Environmentally friendly	Cold formability not great compared to other steels

Adding boron to a steel alloy leads to better mechanical properties: hardenability and hardness, toughness, strength, and deformability [7], while remaining even lighter than traditional steel alloys. Excellent wear and abrasion resistances [8] are key factors in traction chain industry, and boron steels excel in those attributes. Using boron in steel alloys could be a reliable way to improve mechanical attributes, preserve environment, and lower manufacturing costs of the material in the traction solution industry.

Using boron as an additive material in steel alloys has many benefits compared to boron-free steel alloys. Boron can be used in very small concentrations to have a great effect on steel alloys. This means that boron preserves the usage of other expensive and scarce metal alloys

[6]. On top of the economic aspects, the boron steels are also more environmentally friendly, because they are suitable for wider variety of different processes [8]. Previously mentioned benefits are the key factor why boron addition in steel has become a cornerstone in many different industries, where high durability, mechanical attributes, and cost efficiency are a key factor.

Some of the current issues with boron steels are excess boron, and its tendencies to lower toughness and hardenability while simultaneously making steel brittle if the boron addition is not properly controlled [5]. Controlling this is hard, because the range of boron concentration needed is very small. Boron is sensitive to nitrogen and oxygen, which can also lead to diminished effectiveness of mechanical properties, if other elements to bind the gases are not used [5]. Using high temperature treatments or welding for example, can cause additional strain to certain spots, which can result to weaker parts in the final product [10,11]. While welding procedures and usage of heat treatments have their uses, it should also be examined if different material combinations or procedures offer alternative ways for more efficient and predictable boron steel components.

3 Research and discussion

3.1 Heat treatment procedures

Heat treatment processes are a potential way to alter the mechanical properties of boron steels. More traditional heat treatments usually consist of annealing, quenching and tempering, which all are based on rising the temperature of the material and then cooling it down with different temperatures and time cycles. Opting for using additional heat treatments like cold aka cryogenic treatments or salt baths (Quenching and partitioning) on top of common methods can be a way to enhance mechanical properties. It is also possible to lower environmental impact and product costs with more compact heat treatment procedures like subcritical annealing and hardening.

3.1.1 Cryogenic treatment

Boron steels are economically more appealing option compared to, for example, molybdenum steels while stile having excellent mechanical properties like toughness, ductility, and wear resistance [11]. Besides examining different materials or their combinations, also heat treatments can be used to improve mechanical properties or feasibility [12,13]. One recently researched study subject is cryogenic treatments. With different cryogenic treatments it is possible to alter the important mechanical properties of the alloys to increase wear resistances, which are one of the most important factors in the traction solution industry. The cryogenic or cold/subzero treatments are not an alternative heat treatment, but they are meant to be used as an additional tool[11] to more traditional heat treatments.

Cryogenic treatment consists of few main factors: **temperature, cooling rate, heating rate** and **soaking period** [12]**. Temperature** factor divides cryogenic treatment to three different sub-categories: cold treatment (from 0 to -80 °C), shallow cryogenic treatment (from -80 to -160 °C), and deep cryogenic treatment (from -160 to -190 °C) [11]. **Cooling rate** and **heating rates** depicts the change in the temperature in different phases, and both rates are usually kept the same. Too rapid cooling or heating might result to cracks and failures of the material so it is important that the values don’t exceed 20-30 °C per hour [11]. Last factor in cold treatments is **soaking time**, which varies from half-day to three days[11] usually, and depends a lot of material compositions and used cryogenic temperature.

Like previously mentioned, cryogenic treatments are not meant to be used as an alternative heat treatment, but as a supplementary method to adjust steel alloys properties. This treatment is a permanent one-time process and is usually performed after quenching procedures, but before tempering treatments [11]. While cryogenic treatments have been studied to some degree with more traditional steels and irons, further studies with boron steel are still quite recent. Retained austenite conversion into martensite, precipitation of secondary carbides, and reductions in residual stresses [11] are the key mechanisms that cold treatment adjusts. Considering different cryogenic temperatures, there are cases, where deep cryogenic treatments offer better mechanical property improvements [13], than using warmer cold treatments or shallow cryogenic treatments in more conventional steel alloys.

A few recent studies made about boron steels and effect on their mechanical properties by using cryogenic treatments with 36CrB4 [11] and 30MnCrB4 [12] boron steels. In these studies, conventionally heat-treated boron steels were further processed with deep cryogenic or shallow cryogenic temperatures with different soaking times (Table 2). After manufacturing, their important mechanical properties like hardness and wear resistances were analysed with different analysis methods like XRD or Rietveld analysis [11].

Table 2. 36CrB4 specimen divided in 8 different groups with different heat treatments, temperatures and soaking times as described in [11].

Group number	Depiction of group materials
1	No heat treatments
2	Basic heat treatment (Austenizing at 850 °C for 1h, quenching at room temperature, and tempering at 250 °C for 2h)
3	Basic + 12h cryogenic at -145 °C
4	Basic + 24h cryogenic at -145 °C
5	Basic + 36h cryogenic at -145 °C
6	Basic + 12h cryogenic at -196 °C
7	Basic + 24h cryogenic at -196 °C
8	Basic + 36h cryogenic at -196 °C

Cold treatments have provided improved results in mechanical properties of boron steels, especially the wear resistances [12,13], which is one of the more important aspects of boron steel applications. Using these cryogenic treatments is an environmentally friendly[12] procedure and the mechanisms behind it affect the whole cross section of materials. In one study the boron steel used: 36CrB4 obtained highest hardness values (Figure 4) in very low cryogenic temperatures (-196 °C [11]) while soaking time was 36h. The overall process included traditional heat treatment before cold treatment, and tempering procedure after it in 250 °C. The increases in hardness values are explained with increased carbide ($Cr_{23}C_6$) ratios compared to boron steels with lower cryogenic temperatures and shorter soaking times. Overall, the hardness values increased about seven percents compared to only traditionally heat-treated samples. On top of hardness values, the vital adhesive (Figure 5) and abrasive wear tests (Figure 6) [11] also showed notable improvements when using deep cryogenic treatments.

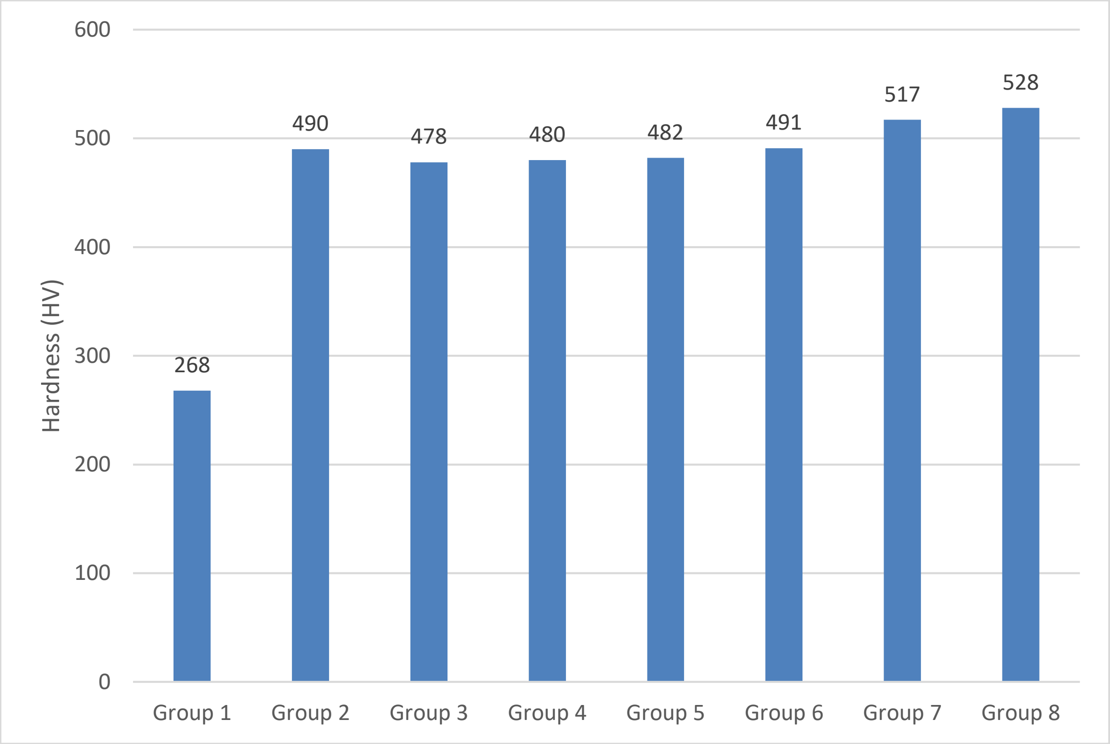

Figure 3. Hardness values of different 36CrB4 specimen with different heat treatments as presented in [11].

While longer soaking times increases the hardness values of boron steels, the cryogenic temperature used in the treatments also play a significant role. Using longer soaking times with colder temperatures (deep cryogenic) provides the best results (Figure 4)[11] in the specimen examined.

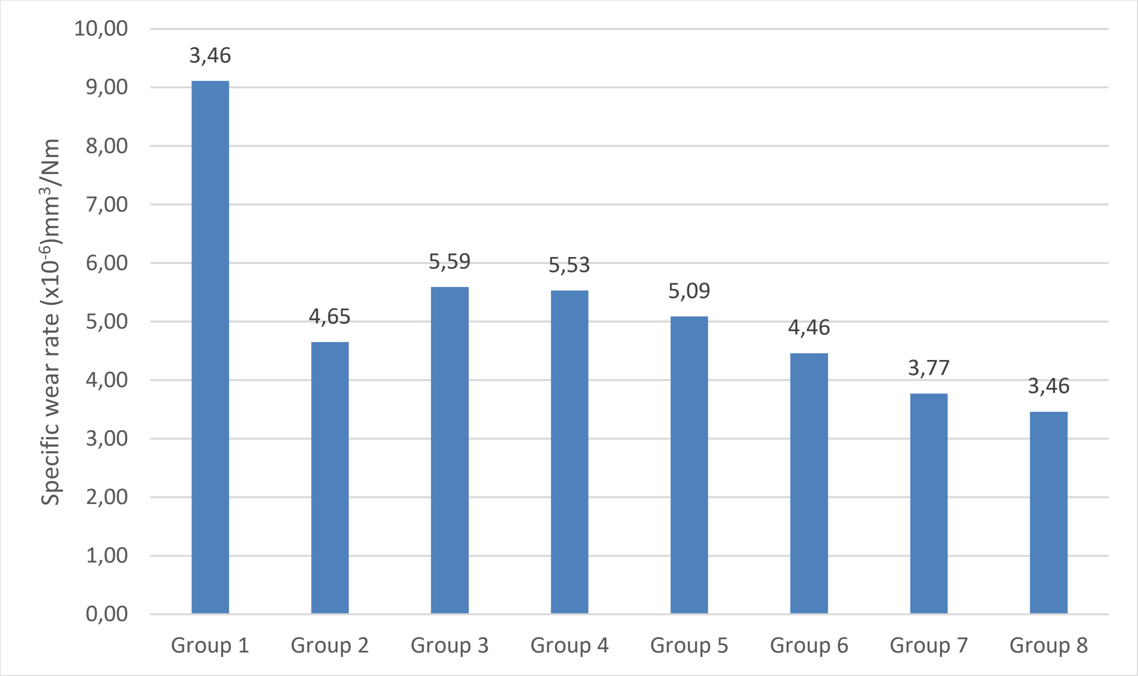

Figure 4. 36CrB4 specimen adhesive wear tests with different heat treatments as described in [11].

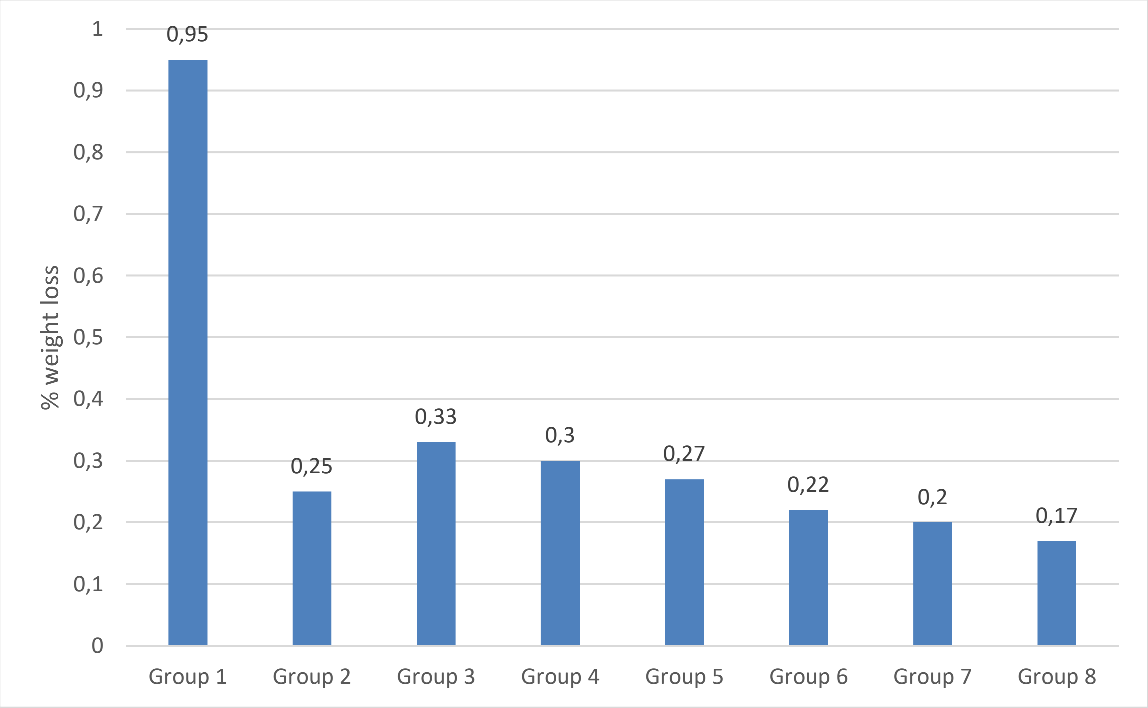

Figure 5. 36CrB4 specimen abrasive wear test with aluminium oxide abrasive paper categorized in different heat treatment groups as presented in [11].

Somewhat similar trends can be found with hardness values (Figure 4) than with adhesive and abrasive wear results (Figures 5 and 6). Using the coldest deep cryogenic treatments and longest soaking times offer the best wear resistances in the material. Differences with wear resistances come with the shallower cryogenic temperature treatments (Groups 3-5), where it seems that the basic conventional heat treatment (Group 2) offers better resistance values.

Another study examined 30MnCrB4 boron steel alloys properties with different heat treatments [12]. In this case that alloy was mainly used in agricultural implementations such as rotavators in machines. The main properties required like wear resistance are similar to a lot of the needs of the applications in the traction solution industry. While previously mentioned study focused more on the variations in the cryogenic temperatures and soaking times, this second one reviews similar cryogenic circumstances and the variations in tests come more from different tempering temperatures afterwards.

Group I of test specimen were non-heat treated 30MnCrB4. In **Group II** CHT was done with the material. This included water quenching in 900 °C with 40 min soaking period. **Group III** consisted of DCT on top of conventional heat treatments. Parameters for DCT were: temperature -185 °C, soaking period was 12 h, and heating and cooling rates were 0.5 °C per minute [12]. The groups 4 - 6 included CHT and DCT, and after these treatments 1h tempering period was done before the furnace cooling. **Group IV** was tempered in 200 **Group V** in 250, and **Group VI** in 300 °C. The main properties examined were hardness, impact strength, and abrasive wear of the material.

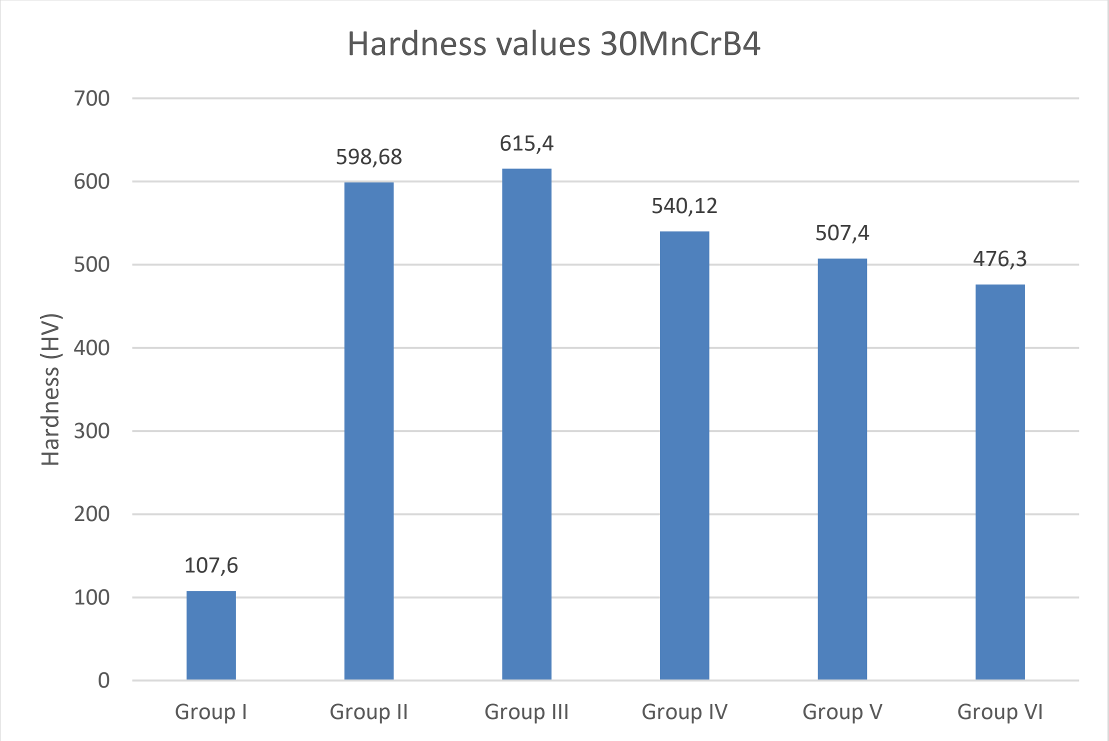

Figure 6. Hardness values for 30MnCrB4 alloy with different heat treatments as presented in [12].

As can be seen from Figure 7, just the conventional heat treatment with water quenching (Group II) offers massive increases in hardness values compared to untreated material (Group I). Adding cold treatment into equation (Group III) provides still some minor improvements in hardness, but the difference is much smaller than between the first two groups. Post cryogenic treatment tempering on other hand is not beneficial from the hardness perspective. Group IV, Group V, and Group VI all have decreased hardness values, and when the tempering temperature goes higher, the overall hardness diminishes.

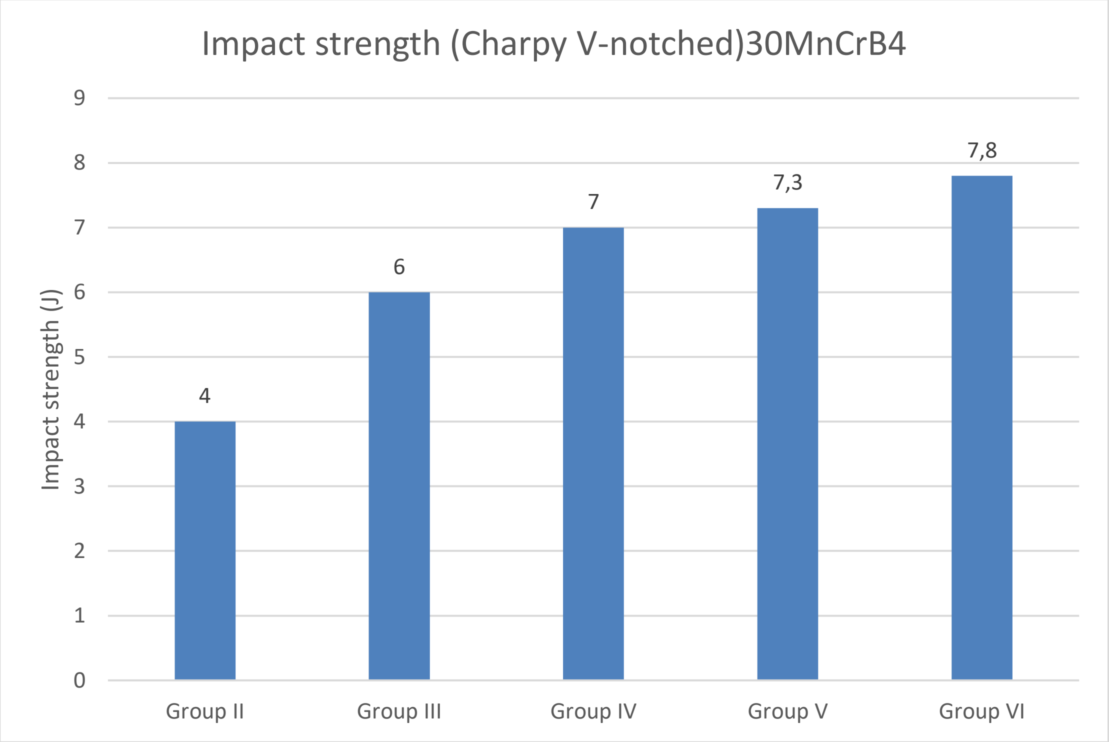

Figure 7. Impact strength in joules by using Charpy V-notch test as described in [12].

Figure 8 shows that the impact strength grows consistently with additive cryo treatments and tempering procedures. This means that before critical fractures, more plastic deformation is present in the specimen. There are notable increases between CHT specimen and the one with added cryogenic treatment (50% growth). After the cold treatment, tempering further increased the impact strength values, which can be seen with groups IV – VI [12]. The main factor behind the improvement of impact strength is the mechanism of specimens' transformation from martensite to tempered martensite, secondary carbide formation and the overall reductions of residual stresses with tempering after the cold treatment [12,13].

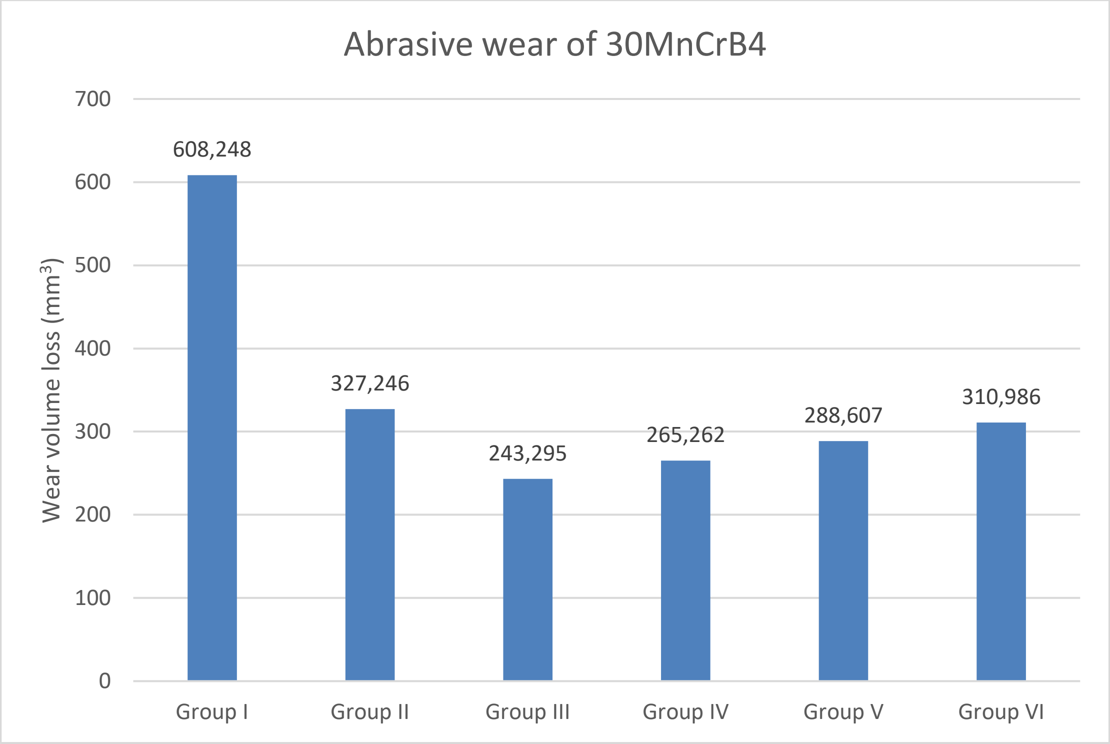

Figure 8. Abrasive wear loss of untreated and heat-treated materials as presented in [12].

Figure 9 above shows the differences of the abrasive wear in the material. The simple CHT treatments offer almost 50% increases in wear resistance compared to the untreated specimen. While cryogenic treatment offers further improvements on wear resistances, the higher tempering temperatures diminishes those improvements. This can be seen when group III has the best abrasive resistance values while tempering with high temperatures in procedure, abrasive wear starts to increase [12].

Supplementary heat treatment tests and studies done with the 33MnCrB5-2 alloys also suggest that using cryogenic treatments can offer significant mechanical improvements for boron steel alloys [14]. In these tests 33MnCrB5-2 boron steel specimen was divided into 4 different test groups. **Group A** consist of just forged material without any heat treatments. **Group B** materials were cold treated in -80 °C for 2 hours. **Group C** had the conventional heat treatment with 400 °C tempering temperature for 1.5 h. **Group D** had the conventional treatment of Group C, and after they received Group B cold treatment. Mechanical tests used for these groups resulted in hardness and wear resistance values.

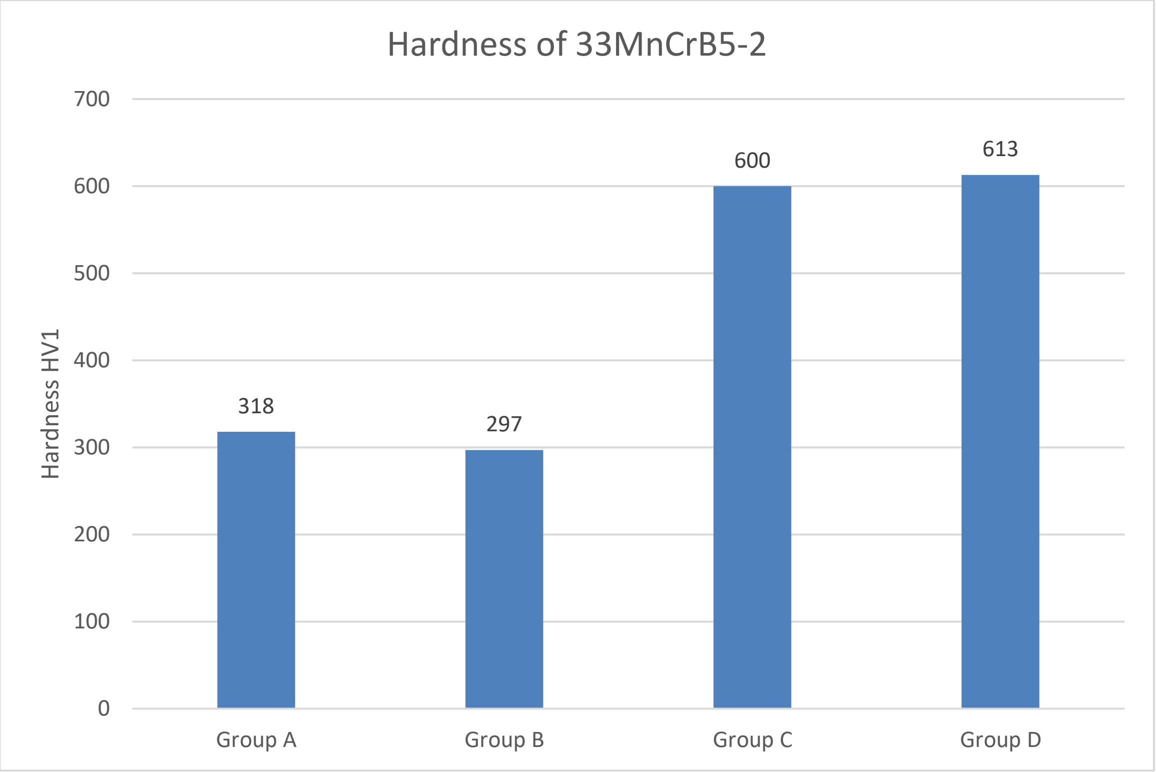

Figure 9. Hardness values (HV1 equals HV hardness with 1 kg load) of 33MnCrB5-2 with different heat treatments as described in [14].

Results of hardness tests (Figure 10) confirm that heat treatment plays a major role in increasing the mechanical properties of boron steel alloys. It is notable that when it comes to hardness values, tempering treatment offers the most substantial increases (almost doubled) compared to non-treated material. Cold treatment after the tempering procedure can provide small improvements on hardness but used as a sole heat treatment method the effects on mechanical properties can become even opposite than wanted [12,15]. Compared to other cryogenic boron steel alloy tests, it is notable that even done after the tempering, cold treatments still have positive results on the material.

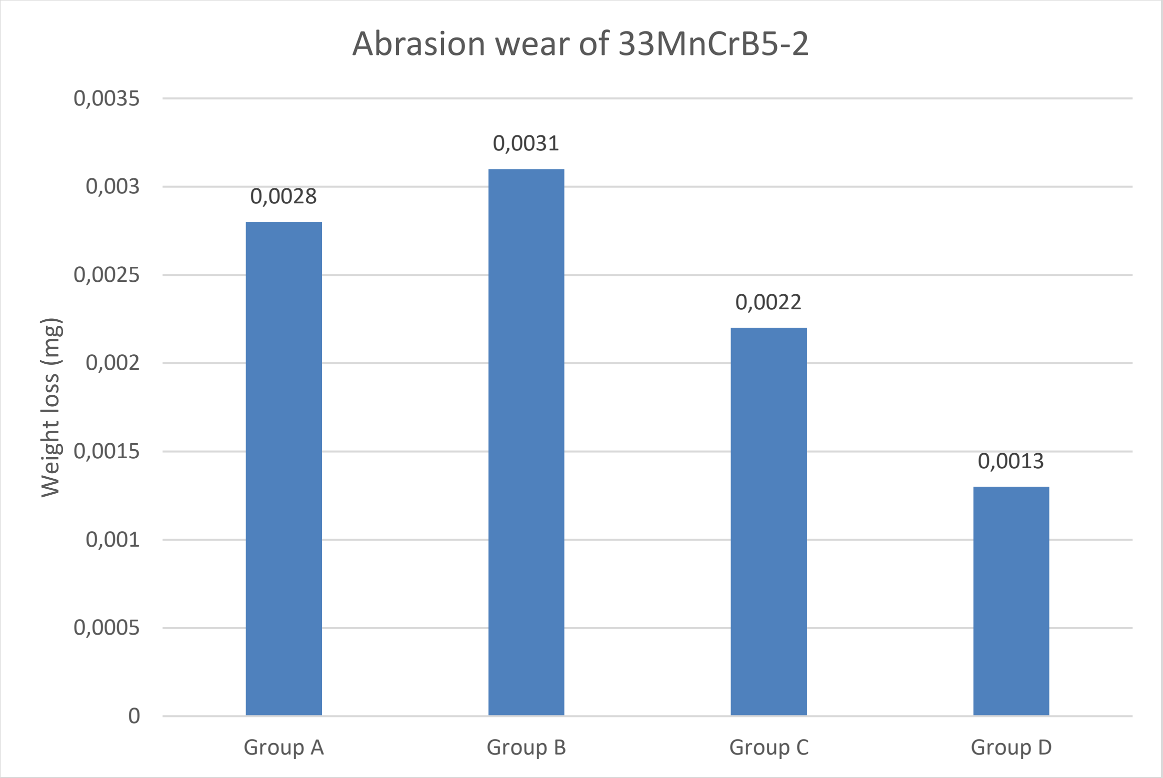

Figure 10. Abrasion wear results of 33MnCrB5-2 alloys. Abrasion tester was used in 1000m distance with a load of 25N as presented in [14].

Abrasive wear test results (Figure 11) show similar trends with different heat treatments as hardness values. Using just the cryogenic treatment has no positive effects on wear resistances, while tempering improves the material notably (20 %). The best results were again obtained with using the conventional heat treatments and adding cryogenic treatment as a supplementary procedure post tempering (53 % improvement). Like in the test results analyzed in other studies, it can be seen than combining traditional heat treatments with cold treatments offer potential to increase mechanical properties in an environmentally friendly and cost-effective way [13,15].

Using cryogenic treatments with more conventional heat procedures is a good way to alter and improve mechanical properties of boron steel components [13,15]. To study the most optimal heat treatment parameters and methods, boron steel materials need to be tested further with alternating parameters and treatment procedure combinations. Getting the most optimal boron steels for traction solution industry is not a simple task, but the potential of cryogenic treatments, especially the deep cryogenic ones, give a good alternative for improving current traction solutions even further [12,13,15].

3.1.2 Subcritical annealing and hardening

Boron steels and conventional heat treatments using water quenching lead to a good combination when high wear and abrasive resistances are required. On top of that, the combination results in lesser overall weights and higher fatigue resistances compared to other more traditional steel alloys [15]. While boron steels and conventional heat treatments (with water quenching/hardening) offer many applications where high wear resistances are mandatory, there are still ways to optimize these processes even further.

A study to decrease the production costs and lower the environmental impact of boron steels by optimizing heat treatments was done in the University of Madrid [15]. Two boron steels used in the study were 30MnB5 and RAEX450. From life cycle assessment (LCA) standpoint RAEX450 was used as a reference material, while 30MnB5 was more superior option cost-efficiently due to lacking more scarce and valuable metals (chromium, nickel, molybdenum). Mechanical performance of both candidates was pretty similar, and RAEX450 was mainly chosen due to its widely usage in different wear-resistant applications with traditional heat treatment (hardened from 900 °C and tempered at 500 °C). On the contrary, 30MnB5 was treated with the new subcritical annealing and hardening method at 770 °C with varying times and hardening in water, and the results were compared between these two different materials.

New heat treatment method used in the study was a newer type of water quenching procedure. Basic principle is, that the hardening process is performed at a lower temperature (770 °C) and with a short cycle heating, which was varied between 10 and 15 minutes [15]. This subcritical hardening leads to a binary ferrite and martensite structure, and its mechanical properties can be adjusted by changing the percentages of these two phases. The great variability provided by this method is one mentionable advantage, the other one being the simplicity in variables during the process: only temperature and time are the important factors in the process. The simplistic hardening phase also removes the requirement of the annealing stage, which results naturally in lesser annealing times while the stage is removed from the whole process. This diminishes the overall production costs and makes a big improvement on the environmental aspect of the heat treatment procedures [16,17]. From mechanical properties standpoint there are no disadvantages even with the removed treatment stage. Some mechanical properties (hardness or toughness) can be enhanced with subcritical hardening compared to more conventional heat treatment procedures [15]. While the factory heat treated RAEX450 had a tested Rockwell hardness of 43 HRC, the hardness values of 30MnB5 surpassed those values with all different subcritical annealing times. More exact values can be seen from the Table 3.

Table 3. Rockwell and converted indicative Vickers hardness values [17] of 30MnB5 annealed in 770 °C with different subcritical annealing times as described in [15].

Times (minutes)	**Hardness** (HRC)	**Hardness** (HV)
10	51	528
15	57	633
20	54	577
25	54	577
30	52	544

As can be seen from the Table 3 even very short annealing times provide superior hardness values for 30MnB5 boron steel specimen, compared to traditionally processed RAEX450 specimen (43 HRC). All these hardness values are appropriate for wear-resistant usage applications, and for further testing, the annealing time of 15 minutes with HRC value of 57 were chosen from the 30MnB5 specimen. The wear resistance tests being the most important properties in these applications, were tested with ASTM international standard G99-95a (2000)e1, using a tungsten carbide pin. The results gotten from tests were presented as values for the coefficient of friction [15]. These values were 0.54 for the subcritical 30MnB5 and 0.63 for the traditionally treated RAEX450. It can again be seen that the subcritical material had better wear resistance properties than the traditional reference material.

To summarize, 30MnB5 with subcritical annealing and hardening has a lot of advantages compared to more traditionally heat treated RAEX450. It’s chemical composition already makes it more feasible and attainable solution due to lacking more expensive additional metals (nickel, chromium, molybdenum) [16,17]. The new subcritical heat treatment was less time consuming and required lower temperatures for annealing (900 °C vs 770 °C) [15]. The extended tempering stage and tempering time is not required in the new procedure at all. This leads to lesser energy needs in the manufacturing process, and the benefits from the LCA standpoint are recommendable. On top of energy savings, the new heat treatment is also more environmentally friendly due to previously mentioned advantages [15]. Compared to conventional heat treatments, the subcritical method also maintains or even improves mechanical properties of the material. With no significant disadvantages, the newer subcritical annealing and hardening procedure seems to be effective alternative for manufacturing high-wear resistant boron steel components more energy efficiently and environmentally friendly than older, more traditional heat treatment processes.

3.1.3 Quenching and partitioning

Boron steels have many advantages compared to more traditional steel alloys, for example lower cost and better mechanical properties. There are also some disadvantages or issues what boron addition brings into the alloy. Boride (Fe_2B) which is used to strengthen boron steels tends to be distributed in such a way that it can damage the continuation of the matrix in the microstructure. This can lead to defects in the structure that lower toughness values in certain areas [18]. Fe_2B also causes some brittleness to boron steel due to weaker boron-boron bonds, which can lead to diminished wear resistances and limits the usage and application of boron steels on harsher conditions.

Traditional heat treatments or alloying can be good solutions for solving and addressing the two previously mentioned issues with boron steels. Newer heat treatment methods have also been tested for improving boron steel qualities regarding these issues. It is possible to insert an amount of RA in the stronger phase (martensite) by using Q&P heat treatment. The method is currently quite new but seems to show potential when it comes to improving boron steels microstructure or performance [18]. Next chapters are going to compare Q&P treated high boron steel properties and their performances against more traditionally treated materials.

A study by Wuhan University of Science and Technology studied this new heat treatment method with high boron steels with 1.6 wt.% of boron [18]. This amount of boron was required for the formation of Fe_2B, and adding carbon and manganese lead to improved toughness values during the Q&P process. The process was performed by using electric furnace and salt baths, and begins with austenitizing high boron steel at 1050 °C for 2 h in the furnace to get better microstructure for the borides. After the oven, the samples were moved into the salt bath (quench temperature 165 °C) with variable quenching times (0,30, 60, 90, and 120 s) [18]. After the quenching temperature was reached, samples were transferred to another salt bath, which had a temperature of 400 °C and time of 60 seconds. This stage was the partitioning step of the heat treatment process. The final step consisted of quenching the water to room temperature and then obtaining the final samples.

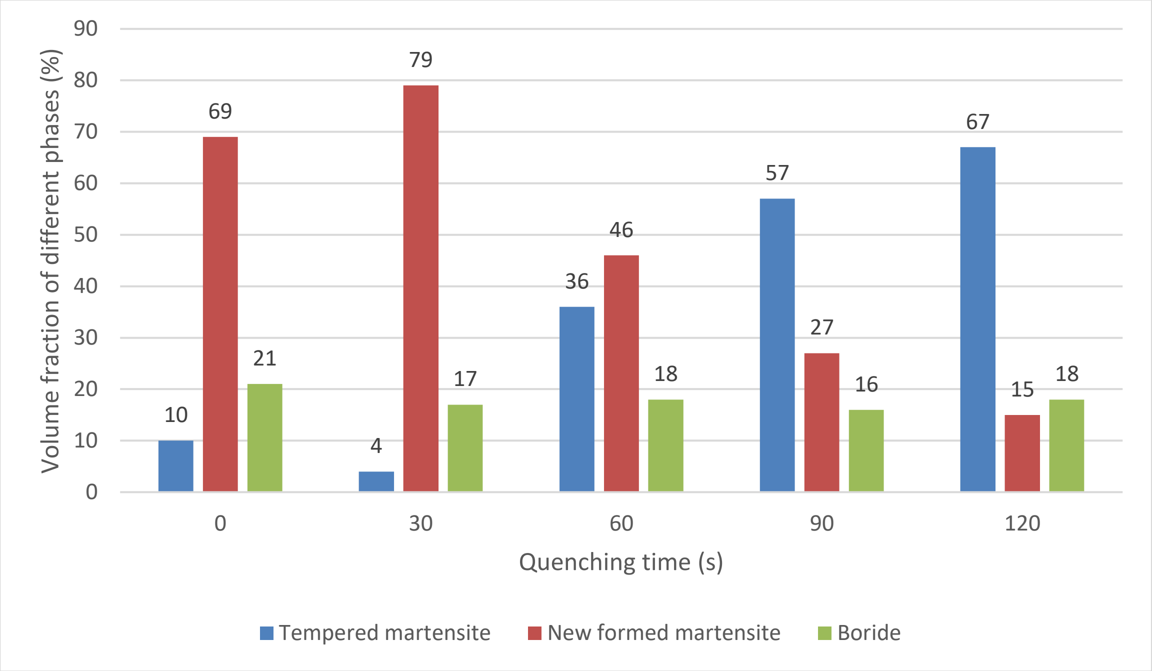

Figure 11. Volume fractions of samples with different phases and quenching times as described in [18] with new Q&P method.

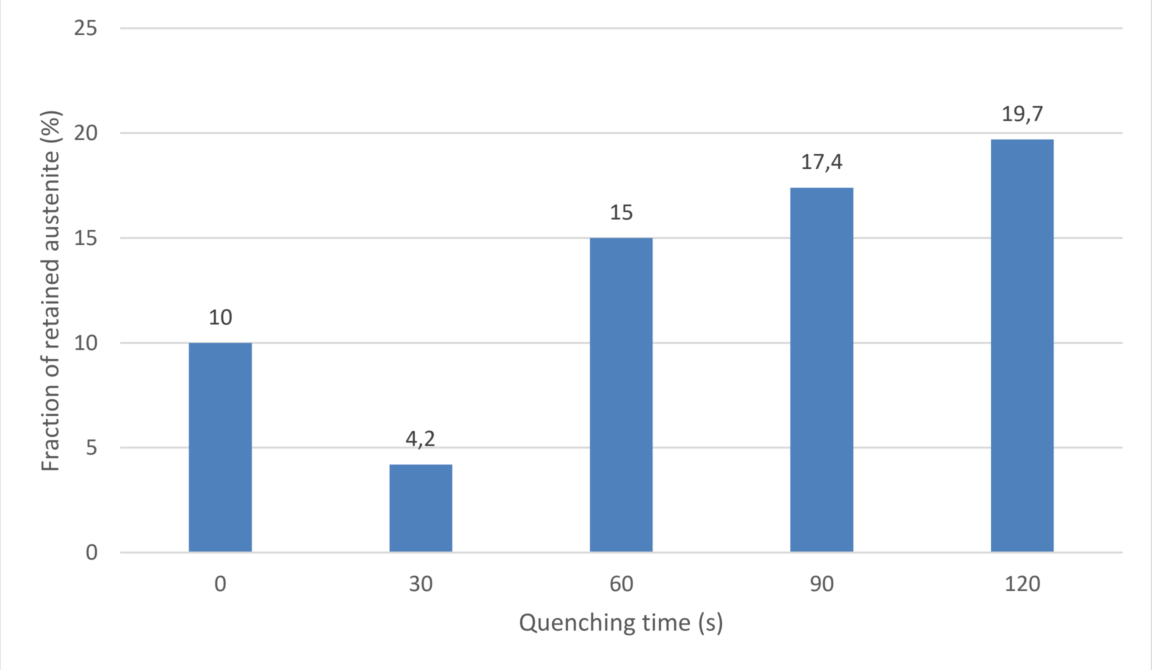

Figure 12. Fraction of retained austenite (RA) in the microstructure with different quenching times. As described in [18] with Q&P heat treatment.

As shown in Figure 12, the boride fraction remains similar throughout the different quenching times in the process. Tempered martensite grows its fraction gradually when quenching times get longer. While tempered martensite becomes more common, the amount of newly formed martensite decreases gradually. In this case, the new formed martensite means the product that occurs when the retained austenite turns into martensite.

Figure 13 shows the changes in the fraction of RA in the samples. While RA fraction grows hand in hand with longer quenching times, it is notable that before the heat treatment RA fraction decreases from around 10 % to 4.2 % in very short quenching time [18]. This happens, because in the very short quenching time only small amount of carbon can be diffused into RA during the next partitioning phase at 400 °C for 60 s and stabilized to room temperature. Meanwhile, when the quenching time increases more carbon can be diffused and better stability achieved with RA.

Table 4. Rockwell hardness, converted to indicative Vickers hardness values [17] and impact toughness values of Q&P samples with different quenching times as described in [18].

Quenching time (s)	Hardness (HRC)	Hardness (HV)	Impact toughness ($J*cm^{-2}$)
0	59.0	674	3.7
30	61.8	741	4.4
60	58.0	653	5.6
90	56.1	615	7.5
120	55.3	600	6.3

Changing the microstructure of high boron steels with Q&P heat treatment also has meaningful improvements to its mechanical properties. Hardness and impact toughness were two of the three measured mechanical properties of high boron steels after the special heat treatment. As Table 4 shows, hardness values of the samples decrease gradually with longer quenching times. Before the treatments the hardness value is 59.0, so even the short quenching improves the hardness before it starts to diminish below the initial hardness. The hardness improvements at the beginning of the treatment are results of the homogenization of the composition and removal of bulky RA. After longer quenching the softer phases of RA start to become more common, which leads to decreasing hardness values [18].

Impact toughness on the other hand is improved more significantly with the Q&P heat treatment. Before the treatment impact toughness is 3.7 $J*cm^{-2}$ and reaches its maximum value around 90 seconds of quenching at 7.5 $J*cm^{-2}$ [18]. This is the result of the microstructure and matrix toughness achieving stronger and more crack-resistant forms overall. However, with longer quenching, the matrix starts to lose its hardness due high fraction of RA. This leads to partial borides that escape from the structure and cause more brittle fractures in the microstructure [18].

The most important property of high boron steels is the wear properties, so it is important to find out how Q&P treatment affects them. Wear resistances were tested with a dry sliding wear tests for 3 hours, and the results were compared between heat treated samples with different quenching times, non-treated samples and reference specimen (NM500) [18].

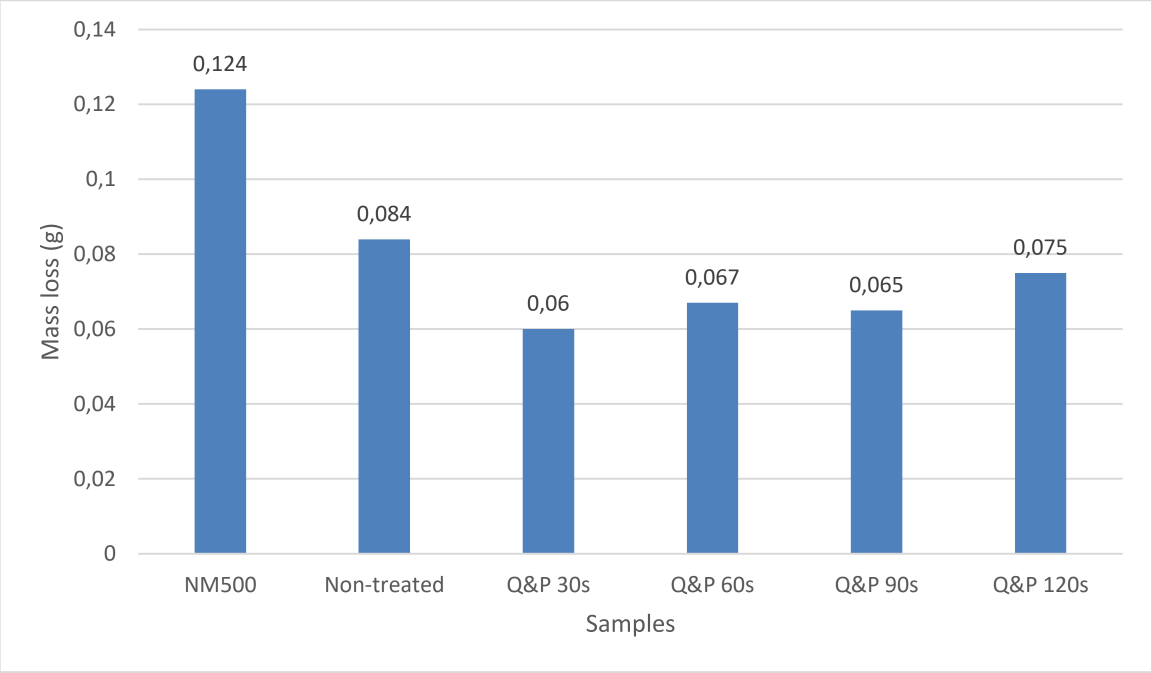

Figure 13. Wear test and mass losses of different high boron steel samples as described in [18].

It can be seen from Figure 14, that the wear resistance properties are affected by the matrix microstructure. Shorter quenching time (Q&P 30s) shows the best wear resistances, because of the harder matrix structure. When the quenching times increase, more and more of the RA occur, which leads to lower hardness of the matrix and therefore larger wear losses. It is however notable, that 90s sample has better wear loss than 60s sample. This is expected due to wear stresses at the surface that might cause RA to transform into martensite [18].

While alloying and traditional heat treatment methods offer improvements on the morphology of the borides, Q&P treatment focuses more on strengthening the matrix. Q&P procedure enables more RA in the matrix, leading to more optimized heat treatment process with boron steels resulting in potentially better mechanical properties, like wear resistance, hardness, and toughness. Although hardness values decreased when going into longer quenching times, toughness was significantly better (more than doubled compared to non-treated samples [18]). The vital property of wear resistances showed also significant increases between the non-treated and treated samples (up to 28 %).

The improvements caused by Q&P treatment are a result of changes in boride morphology and structures in the matrix. Retained austenite and its volume fraction is the important factor to control in this heat treatment. If the fraction gets too high, the mechanical properties like toughness and wear resistance start to diminish, and in the Wuhan study the fraction of RA was controlled at 16 % to get best results possible [18]. While the Q&P heat treatments show some potential at improving boron steel properties it also has some current disadvantages. Like previously mentioned, the process needs to be controlled quite precisely to get desired results, and it is harder to perform on a bigger scale. There are also not many studies done with boron steels, so further examination in the future is expected to lead to better results with various boron steels. Q&P method can also cause some added costs for production, which is not tempting aspect compared to conventional heat treatment equipment. To get significant benefits from the Q&P treatment currently, it probably still needs a few more years to get more optimized with boron steel components, although it already shows interesting potential in the field.

3.2 Coating solutions/Surface treatments

On top of different heat treatments to alter the structure of the whole boron steel components, surface treatments or different coating solutions are also a good option to be considered. These solutions focus more on the changes on the surface, while the core of the component remains quite unaffected. Case hardening has been traditionally used for getting higher outer surface properties while having more ductile core cost-efficiently. Physical Vapor Disposition and Laser cladding are examples of a newer coating procedures, which are currently becoming more used in the industry and have some advantages and disadvantages compared to traditional coatings. Protective paints on the other hand have been and are still used for fighting against corrosion, even though high wear and impact environments tend to wear these paints off more easily compared to other coating types.

3.2.1 Laser cladding

Laser cladding is currently widely used surface modification technology among different metals. The process of laser cladding consists of high-energy density laser, cladding materials (powders), and the surface of the substrate material (Figure 15). The thin layer of cladding material and substrate melts and solidifies simultaneously producing new metallurgic bonds. These new bonds lead to improvements in various mechanical properties, such as hardness or wear resistance [19,20,21]. While laser cladding as a procedure adds some additional costs to manufacturing, the benefits for improved mechanical properties can be worth it. The most notable advantage using laser cladding is that the needed mechanical improvements can be targeted precisely. Strengthening the most critical areas of different components can lead to lengthened life cycle of the product, and therefore also increase the predictability aspect of the component.

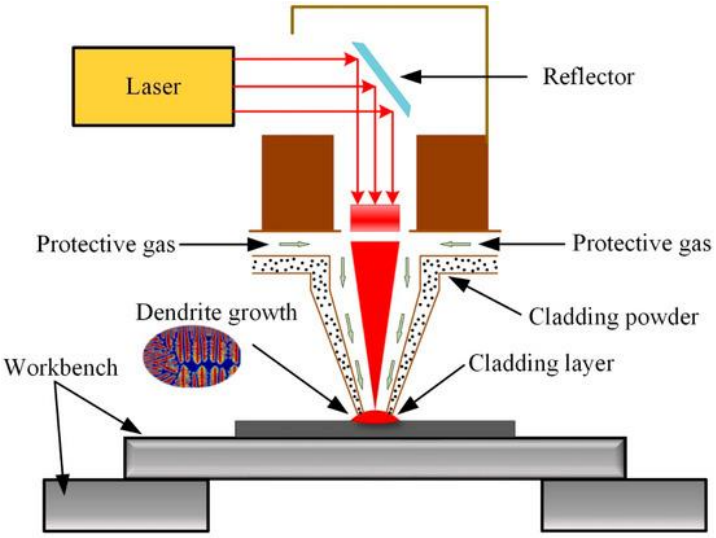

Figure 14. Schematic picture explaining the principles of laser cladding (from Li et al., 2024) [22] Reproduced under the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

Usage of different powders and laser parameters can be utilized to alter the surface material (cladding) or even modifying the bulk (alloying) [19]. Cladding produces an additional layer on the substrate, and it can be used with many materials. It is an efficient alternative when the surface properties of the component are required to be at a certain level, for example in a high-wear areas. Cladding materials that can be appropriate for the purposes of Nordic Traction, are WC, different borides and carbides, or stellites (cobalt alloys).

Laser cladding technology was originally used for producing hard coatings, which prevented the origin material such as different steels from a significant wear damage [23]. Main applications for these hard coatings are in mining, aircraft or automotive industries [19]. Laser cladding as a procedure has a lot of beneficial trademarks, such as refined microstructures, minimal dilute rates, great resistance properties (wear and corrosion), and strong metallurgical bonding with different substrate materials [23]. It also has high work efficiency, minimal pollution rate, and can be performed to manufacture even thicker coatings than with the more traditional surface treatments [21]. In the recent years, there have been many different studies about laser cladding and various materials, which can be utilized efficiently with the procedure. Examples of these materials are Co-based, Fe-based or Ni-based alloys with different mixtures of titanium, nitrogen, carbon or tantalum [23]. Besides these, WC is one of the most prominent for laser cladding coatings.

Main characteristics that make WC suitable for laser cladding procedures lie in its mechanical properties. WC has high fracture toughness (28 $MPa*m^{1/2}$), really high hardness values (from 16 to 22 GPa under 0.5 kg load Vickers), high melting point at 2850 °C, low friction coefficients and good wettability. Utilizing WC with other metal-based alloys has produced good results in the laser cladding field.

A study made in School of Mechanical and Electrical Engineering, China University of Mining and technology examined Fe-based laser cladding coatings, and how the different sizes of tungsten carbides affect the mechanical properties of material [23]. Mixtures of Fe60 alloy was combined with WC to produce reinforced composite coatings in the study. Different samples were divided into four different groups: Group without added WC in the coating (W-free), WC particles with diameter of 15-40 μm (WC-small), particles with a diameter of 80-120 μm (WC-large), and WC particles with both large and small particles (WC-both). After the WC was blended with the Fe60 in a vacuum ball milling equipment for 4h, the powders were dried at 60 °C for 10 h, and the substrate of 16Mn steel was prepared and cleaned [23]. Microhardness values and wear rates were measured with different group samples and results are compared in Table 5.

Table 5. Test results of different WC particle sizes in the coatings as described in [23].

	WC-free	WC-small	WC-both	WC-large
Average microhardness at 0,5 kg Vickers	580.3	931.4	613.5	613.5
Wear rates 10^{-6} mm^3 / mN	85.1	1.19	3.71	6.3
Average Friction coefficients	0.68	0.55	0.59	0.59

When the larger WC particles were added into the samples (WC-both and WC-large), irregularity in the specimen increased, and average microhardness and friction coefficients were harder to measure. While it affected the measurements, the trend can be clearly seen between the samples. Microhardness values remained similar comparing the WC-free samples to the both samples with larger particles (WC-large, WC-both). The most notable difference occurred with smaller particle sizes, which can be seen as a drastic increase in hardness values (around 60%). With friction coefficients the variation was less significant, but again sample with small particle size showed best results compared to the sample without WC. However, the most drastic increase occurred in the wear resistance tests. While all the different WC coatings showed over tenfold improvements compared to the non-WC sample, the small particle sample was enhanced 70-time fold [23]. These results show, that using properly adjusted and manufactured WC coatings can offer a significant boost to the surface properties of different steel components, for example in the traction solution industry.

Another study about the effects of adding WC to Fe-based alloy powders in laser cladding processes was made in China with the assistance of different technological universities [21]. In this study the main objective was to examine the changed morphology, microstructures and mechanical properties of a coated Q550 structural steel for improving its wear resistances and life cycles of the wind turbine gears [21]. WC powder used had a nickel content of 15.2 wt.%. The nickel content could potentially increase the wettability and the bonding strength between WC and Q550. The final composite Fe-based alloy powder had different variations of WC content (0, 4, 8, 12 or 16%), which were compared and analysed.

Microhardness values without WC were 763.1 HV and with 16 wt.% WC it increased to 826.2 HV growing gradually as the content of WC grew from 0 to 16 wt.% [21]. As the WC content increased, the proportion of hard phase of WC and chromium carbides increased as well. Additionally, some of the W atoms dissolved into the matrix, which resulted as a strengthened matrix and higher microhardness values. With additional WC, the grains were also more refined, which improved densities at the grain boundaries and stopped the occurred dislocations from moving more efficiently.

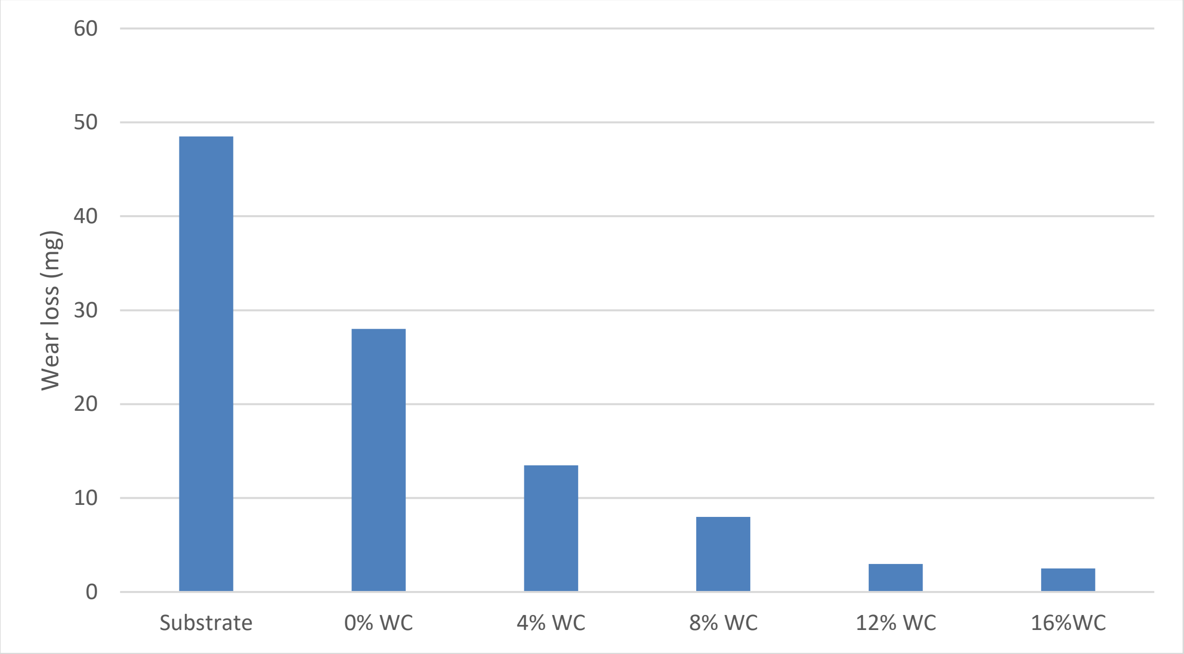

Figure 15. Adhesive wear loss results with the substrate and the coatings with different WC contents as shown in [21].

Wear loss properties showed again more drastic changes compared to microhardness values as seen in the Figure 16. Compared to the Q550 substrate, even more traditional Fe-based coating without WC improved the overall wear losses significantly (around 40%). When WC was added in the powder mix, the wear loss properties continued to improve greatly from the start (around 50% improvements with small amounts of WC) [21]. When WC content reached 12%, the effect on wear losses started to diminish proportionally while getting closer to maximum wear resistances. It can be seen, that increases in WC content improve gradually the wear properties of the substrate material.

The usage of WC in Fe-based coatings has shown beneficial impacts in several studies [21,22]. Even a few wt.% additions to a cladding mix offer significant increases especially on wear properties. Further optimization of laser cladding parameters or WC particle sizes can boost the coatings to be even more effective and applicable for a broader industry field. While the laser cladding as a procedure can add additional costs in the manufacturing process of the components, the major improvements against wear can lengthen the products life cycle remarkably while simultaneously making life span predictions easier. The additional process costs stay somewhat modest, because re-enforcing the materials with the coatings can be precisely targeted by area, so the structure of the bulk of the material stays similar and the needed resources remain regulated.

While Fe-based alloys are among the most popular ones amongst the laser cladding composites, other alternatives can also be utilized. A Brazilian study compared reinforcing nickel and cobalt alloys with WC for getting improvements in wear resistances and mechanical properties [24]. While most of the literature of laser cladded coatings suggest, that WC increases the properties of the coatings, there are also studies where excessive WC content, different particle sizes and shapes or matrix materials itself affect negatively on the performances of the coatings [24, 25].

The most common Ni alloy for MMC is Inconel 625. Various research studies support that using WC with Ni alloys increases hardness and wear resistances in laser cladded coatings [25,26]. One study examined that spherical WC particles offered even better wear performance values. While WC combined with Ni alloys can result to enhanced mechanical properties, excessive contents of WC may lead to reduced wear resistances and increased embrittlement of the material [24].

Co alloys have also shown good results in MMC tests, and one of the most used alloy is Stellite 6. It has shown improved wear resistances due to addition of WC, and again certain shapes and angles of WC particles offered better results than others [24]. A comparison study made in Brazil used AISI 304 substrates coated with either Inconel 625 or Stellite 6 with added WC contents. The percentages of WC content used in the coatings were: 10, 20, 30, and 40 %. There were also a group without WC for the reference. The particle sizes of Inconel and Stellite was around 50-150 µm, while WC consisted of 45-105 µm sized particles [24]. Before the tests the substrate was cleaned efficiently, and powders were heated in oven to remove possible moisture.

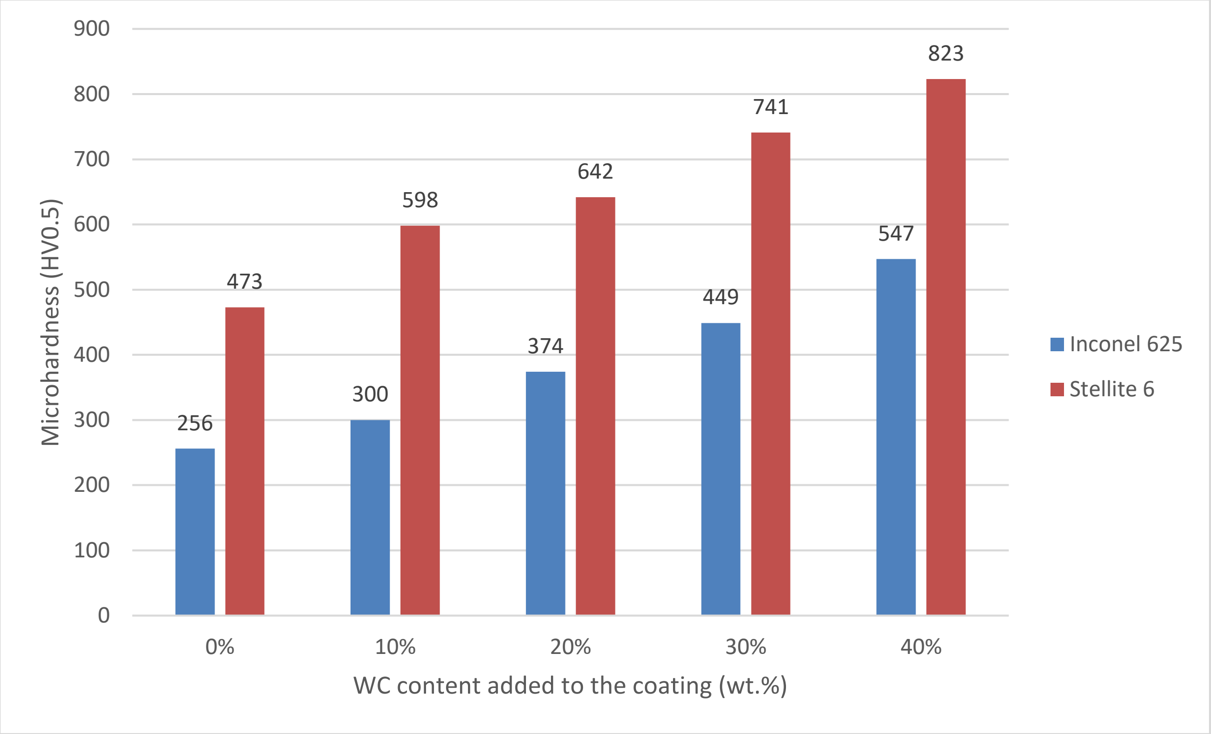

Figure 16. Effect of different WC content to average microhardness values (HV0.5) of the coatings as shown in [24].

As can be seen from Figure 17, both Inconel 625 and Stellite 6 coatings get enhanced microhardness properties when WC content is added in the mix. While more WC is added, the microhardness steadily increases with both coating types. The higher average hardness values of Stellite 6 compared to Inconel 625 can be explained with Stellite 6 having more carbides inherently in its composition without added WC [24].

Abrasive wear resistance test results shown in Figure 18 are not similar to microhardness results. Overall, Inconel 625 coatings showed better wear resistances and Stellite 6 counterpart on lower WC contents. The most drastic difference occurred when WC was not added at all in the mix (almost 50% more wear loss on Stellite). Wear resistance properties of Stellite 6 coating improved gradually, when WC content was increased and the best wear resistance value was produced with the highest proportion (40%) of WC. Inconel 625 was opposite to Stellite: It had best wear resistances with very low WC proportions (0-10% [24]) and increasing WC content lead to lower wear resistances.

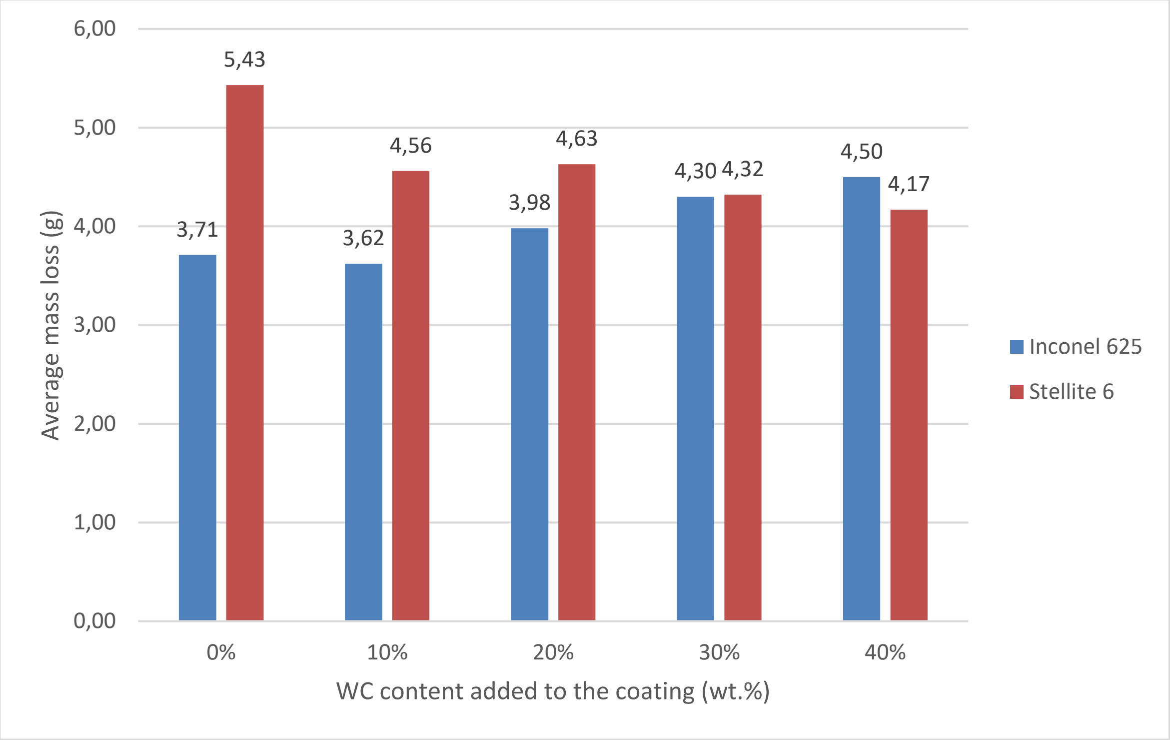

Figure 17. Effect of different WC content to abrasive wear resistances of the coatings as described in [24].

While microhardness results showed that Stellite 6 should be sturdier mechanically compared to its Inconel 625 counterpart, the wear resistance tests presented Inconel 625 being the superior alloy. The interesting contradiction can be explained when wear mechanisms are furtherly examined with SEM analysis. The analysis showed that Inconel 625 coatings had characteristics of rolling abrasive particles, while Stellite 6 showed sliding wear [24]. This suggests that Inconel 625 has ductility properties, which eases the mechanical stresses affecting the surface of the coatings and results to lower probabilities of localized fractures under wear stresses. Stellite 6 and its higher wear losses can be explained by its composition: Co and Cr are main parts of the alloy on top of dispersed carbides [24]. This can result to increased amount of carbide fractures and delaminations, which directly weaken the wear resistance properties of the material.

While WC reinforcement of metal composite coatings has commonly resulted in increased hardness and wear resistances [27,28], that is not always the case [29,30]. The microstructures and properties of different metal alloys and their matrixes can affect greatly to mechanical attributes. Material compositions and particle size or shape are all important factors, that need to be studied when optimizing laser cladded coatings in applications where harsh environmental factors are present. However, laser cladded coatings, especially with the added

WC content, can offer significant enhancements to hardness and wear resistance properties of the substrate material [31,32]. The procedure and its targeting precision can result in better predictability and longer life cycles, when the weaker or more vital parts can be reinforced with the method.

On top of WC reinforced coatings there is also other notable alternatives with good improvements on mechanical properties. One example is different HEAs. While normally alloys used in laser cladded coatings consist of one main-element alloys, HEAs consist of five or more element alloys with close to equal atomic fractions [35]. The composition of several primary elements in the alloys leads to different high-entropy, diffusion, and lattice distortion effects, which result in higher hardness values, improved wear resistance properties, and great corrosion resistances. Because there are lots of different suitable elements and content ranges for HEAs, also the mechanical properties can vary significantly depending on the compositions. Currently CoCrFeNi series of HEAs have gotten attention due to their simplistic phase compositions and reduced costs [34,35]. On the other hand, refractory HEAs seem to have better mechanical properties, but their processes are more expensive and complex [35].

Different elements in the alloy can offer significant changes in HEAs, for example changing its structure from FCC to BCC. A study made in China suggested that if Al was added to CoCrFeNi - HEAs, the previously mentioned structure change occurs, which results in increased hardness from 228 HV to 520 HV [38]. On top of that, the wear resistances increased massively (almost 6-fold). Another study furtherly showed that adding Si to AlCoCrFeNi – HEA increases already high hardness and wear resistances even more [39] due to increases in the BCC structure formation. While BCC structure shows improvements on mechanical properties like previously mentioned, it also promotes the entry of interstitial atoms, which leads to furtherly enhanced hardness and wear resistances [35].

Using boron additions in different HEAs can also enhance hardness and wear resistances of the material. The boriding process used in HEAs is a thermochemical surface treatment procedure, where borides are formed on the surface of the substrate due to diffusion of boron atoms. This diffusion requires high temperatures to move boron into the material from the source [40]. Using boronized layers resulted to 10 times higher hardness values in the study while wear resistance also improved [35]. Results also suggested that increasing the boron content in the surface layer (to 46.88 at. %) affects beneficially on the hardness and wear resistances. There are also other studies where boriding high entropy alloys by laser cladding can enhance mechanical properties of the material surfaces. A Study about $NiCrFeCoB_x$ high entropy alloys with boron addition showed significant improvements on hardness values (from 221 to 603 HV), friction coefficients (from 0.63 to 0.42), and wear rates (from 2.4 x 10^{-6} to 0.78 x 10^{-6} mm / Nm) [41]. This trend was not seen with just one HEA ($NiCrFeCoB_x$), but other studies published with different HEA compositions show similar trends [40,41,42]. One example alloy was FeCoCrNiCu coating, which showed also massive increases in wear rate performances and hardness values. Wear rates of those coatings decreased 55 % and friction coefficients 43 %, while hardness increased 37 % compared to the same HEA without boron additions [45]. Good results were also gotten with HEA $Al_{1.5}CoCr_2Fe_{1.5}NiSi_{0.5}B_2$ [35]: the average hardness value of the coating was 912 HV, while wear rate was calculated to be 4.78 x 10^{-6} mm / Nm, and friction coefficient 0.59. These values surpassed performance-wise many other HEAs used in the same environment [35]. The reason behind the higher performance values is stronger internal lattice distortions in the BCC structure of the coatings, which leads to formation of an interstitial solid solution enabling better movement of boron atoms.

While boron addition into HEAs has showed decent results to improve mechanical properties of the coatings, there are still not too many studies where boron contents added to the coatings are at high levels in laser cladding procedures [35]. Further studying different HEA compositions on laser cladded coatings might offer even more enhanced performances on surface coatings, and these applications can provide improvements on durability and predictability in the traction solution industry.

Different high entropy alloys, or WC reinforced composites can offer decent performance increases in laser cladded coatings. Various other coating types can also be suitable for increasing materials durability in harsher environments. For reference, some comparisons between HEAs, WC enforced composites, and more traditional coating types can be made. In this case, studies about boron and carbon/iron alloyed composites with different enhancing particles can be examined.

Laser cladded coatings have several different factors that can affect the properties of the surface. While coating materials and alloys or the substrates itself play a big role, parameters of the lasers effect also on the outcome. For example, different laser powers or scanning speeds can make a difference. There was a Polish/Slovakian study about the effects of laser parameters in composite coatings and how different reinforcing particles (B_4C and Si) can alter the mechanical properties of the laser cladded coatings [46]. The study examined results of laser cladding two different powder mixtures with C45 steel. First mixture consisted of Fe-B, and the second was Fe-B-B_4C-Si. Fe-B mixtures composition was 20 wt.% B, 70 wt.% Fe and 10 wt.% (Si + C + Al), while the second one had 75 wt.% Fe-B, and 25 wt.% reinforced particles (20 % B_4C and 5 % Si). Laser beam powers in the study were altered between 600 and 800 W, and scanning speeds varied (600, 800, 1000 mm/min). Difference between laser variables and powders were examined, and mechanical properties and microstructures compared. While iron-based alloy coatings are popular among the laser cladding processes due to their high hardness, wear resistances and corrosion resistances, using reinforcing particles can enhance the mechanical properties even further as can be shown in the study [46].

Adding the reinforcing particles of B_4C and Si to the Fe-B alloy increased almost tripled the average microhardness value (from 400 to 1100 HV). Increasing the laser beams power from 600 to 800 W seemed to decrease the microhardness values quite significantly: from 480 to 320 HV with Fe-B alloy, and from 1100 to 600 HV with the Fe-B-B_4C-Si. Using optimized laser parameters and reinforced powder mixture lead to two times lower mass losses after five hours, and corrosion resistances increased also in the process [46]. Alternating laser parameters showed that the best results were seen with the laser power of 600 W and scanning speed varying between 600 and 800 mm/min. Lesser power and scanning speeds promoted more consistent surface and uniform microstructures on the coatings. Boride and silicon phases formed due to additional reinforcing particles play a significant role enhancing the needed mechanical properties of the laser cladded coatings [46].

While wear resistance and microhardness values are few of the top priorities when making coatings to strengthen weaker parts of the materials to sustain in harsher conditions, also the environmental aspect is important. A one recently studied and environmentally prominent material group is iron aluminides, which can be alloyed with boron and carbon atoms to promote stronger boride and carbide phases in the microstructures, and enhance the mechanical properties [47].

Compared to commonly used wear resistant materials which consist of Cr, Co, or Ni for example, iron aluminides are more environmentally friendly. This is due to lesser expensive material costs, and simpler processing routes from casting to the final coatings [48]. While the environmental impact is lower than some other common wear resistant materials, the mechanical properties and resistances still show good results [49]. One advantage of using iron aluminide coatings is that the preparing method can vary from different sprayings (thermal, plasma, electric arc etc. [50]) to laser-based coatings [51]. One factor why laser cladding is a popular alternative, is its compatibility with different substrate materials [47].

Iron aluminides hardness values and wear properties can be enhanced further by different strengthening effects, like precipitation hardening, solid solution strengthening, and the formation of binary and ternary intermetallic compounds [52]. Adding more noble metals like Nb, Ti, or Mo can improve wear properties, like abrasion resistance significantly due to solid solution strengthening [53]. Examples of precipitation hardening can be achieved by alloying titanium with boron or carbon to iron aluminides, which also results to decreased wear rates on ambient and higher temperatures [54].

Recent Austrian study examined wear properties of iron aluminide (Fe_3Al) based laser claddings with only carbon (C), only boron (B), and both carbon and boron additions while remaining sustainable and having mechanically satisfactory properties [47]. Iron aluminides used in the study were divided into nine different groups by different atomic percents: Fe30Al5B, Fe30Al10B, Fe30Al20B, Fe30Al5C, Fe30Al10C, Fe30Al20C, Fe30Al2.5B2.5C, Fe30Al5B5C, and Fe30Al10B10C. The numbers in front of different elements represent the atomic fraction of element content in the coating alloy. For example, 30Al means that the aluminium content stays the same in all groups (30 at. %), while boron and carbon contents vary between the groups, as well as the amount of iron diminishes when contents of other elements increase in the mix. Hardness values with HV10 and abrasion wear tests were performed and comparisons made between different group samples [47].

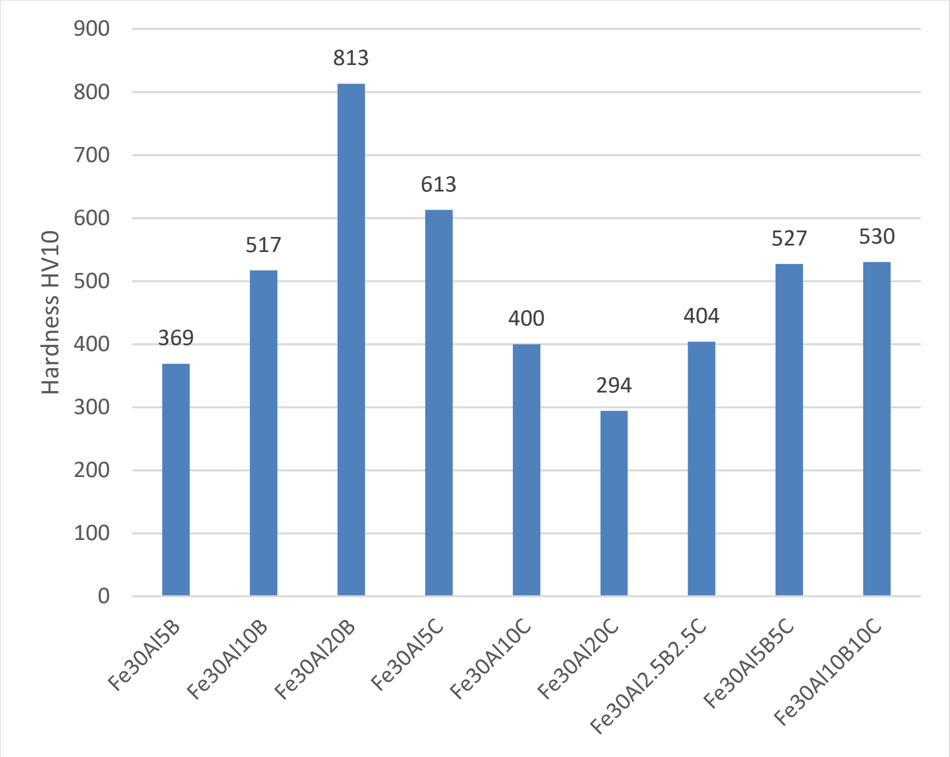

Figure 18. Hardness values (HV10) of different iron aluminide specimen with varying contents of boron and carbon elements (at. %) as depicted in [47].

As can be seen from Figures 19 and 20, the hardness values and wear rates follow somewhat similar trends depending on the atomic contents of coating. Adding boron content increases the mechanical properties (both hardness and wear rate) greatly due to boride microstructure. In contrast, higher carbon additions lead to the formation of graphite, which has a negative effect on the microstructure and mechanical wear properties. For example, Fe30Al5C has the second highest hardness values from any sample groups, but its wear rate is still only 7th best overall. The combination of both boron and carbon atoms seem to provide medium wear resistances and hardness values [47]. It is also notable that the starting hardness value of Fe30Al cladding without alloying had 260 HV10, so even the negative formation of graphite was still a mechanical improvement compared to non-alloyed iron aluminide.

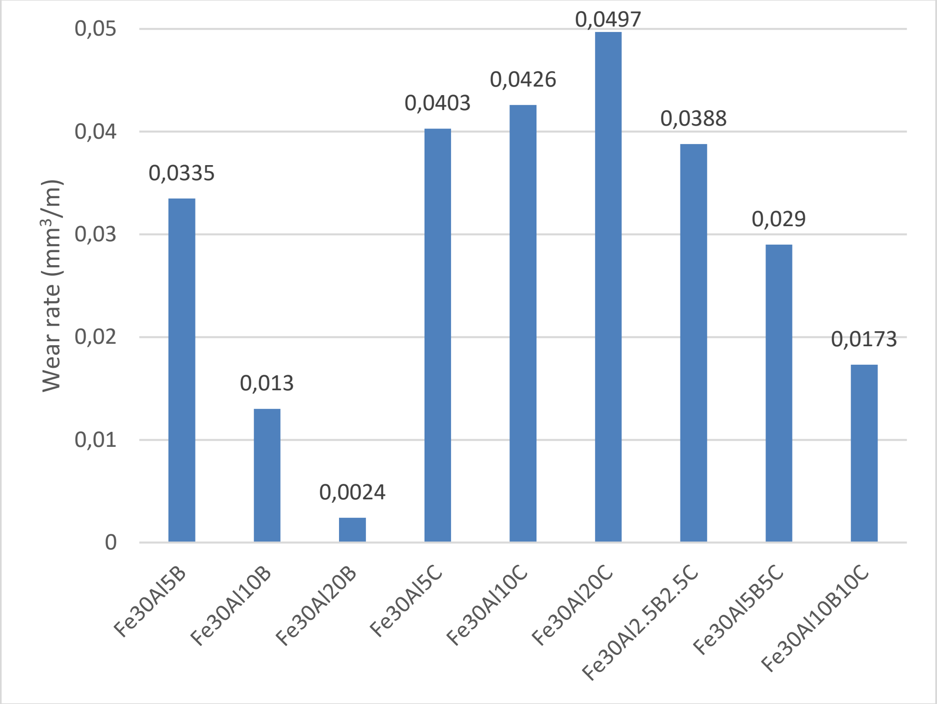

Figure 19. Abrasive wear rates (mm^3/m) of different iron aluminide specimen with varying contents of boron and carbon elements (at. %) as depicted in [47].

The best performance in the study was shown to be Fe30Al20B with clearly the highest hardness value 813 HV10 and lowest wear rate of 0,0024 mm^3/m, suggesting that especially higher boron contents offer best potential for sustainable wear applications.

The composition with carbon additions to iron aluminides contradicts the logical belief that higher hardnesses always lead to better wear rates, and the changes in the microstructure are as important for the overall mechanical performance. It is possible that even hard phases in the microstructure might have tendencies to fracture more easily or debond from the surroundings, for example. The best performing specimen in the study (Fe30Al20B) shows great potential in abrasive wear tests compared to other commonly used laser cladded coatings as can be seen from Figure 21 below [47].

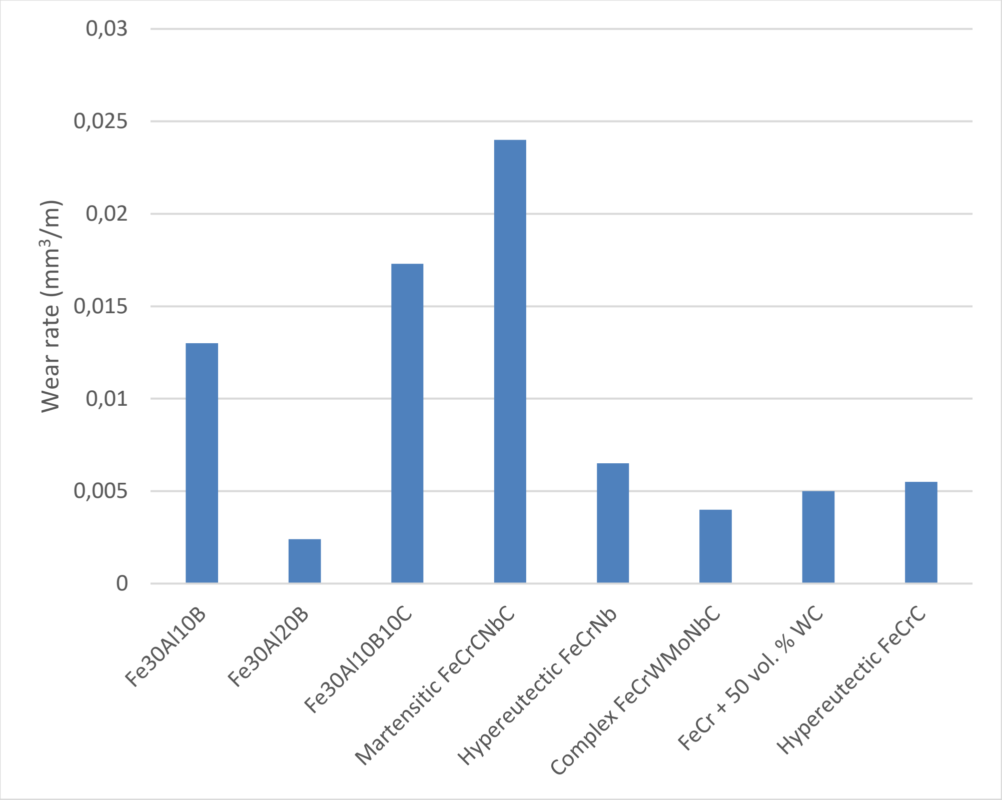

Figure 20. Wear rates of iron aluminide claddings [47] compared to commonly used FeCrC-based claddings [41, 42].

3.2.2 Physical Vapor Disposition

On top of laser cladding, another commonly used coating method is PVD. The method consists of using vaporization to add one material on top of another in a controlled environment [57]. PVD allows manufacturing multi-layered metallic structures on the surface of the material, which allows different functional properties in the coatings for different applications. PVDs can be used for example in solar panels, medical devices, or in different protective films, but one of the main uses is in different tool steels, which require higher wear resistances to increase the life cycle of the tools itself [57]. Due to the requirement of molecular bonding between the substrates in PVD, the suitable materials are more restricted than in laser cladding, for example.

Study made in India researched how using a PVD process (sputtering and thermal evaporation) with Al_2O_3, SiC, and B_4C multilayer-coatings on HSS rod can improve mechanical properties [57]. The different coating thicknesses examined were (0, 1.1, 1.7, and 1.9 µm) and results in wear rates and microhardness values were compared.

Table 6. Wear (adhesive) and microhardness test results of HSS rod with different layer thicknesses of Al_2O_3, SiC, and B_4C coating as depicted in [57].

Coating layer thickness (µm)	Wear (µm)	Hardness (Gpa)
0 (Uncoated)	441	7.56
1.1	24	34.8
1.7	21	35.6
1.9	20	37.2

As can be seen from Table 6, the decrease in wear rates is drastic (18 times better) when even thin coatings are applied to the material. Adding more thicker layer from 1.1 to 1.9 µm increases the wear performances around 17 %, which is quite marginal compared to the enhancements of the uncoated rod. The microhardness values followed similar trend with wear rates. The most significant increase occurred when the coating was added to the uncoated sample (around 4.5-times enhancement) while thickening the coating layer managed to improve the hardness values subtly (about 7 % increase) [57]. Further cost analysis could reveal if the additional layer thickness is worth utilizing in the long run.

On top of previous mechanical enhancements, also thermal stresses were managed to cut down when the coatings were applied into the material, and the coated samples were also the most corrosion resistant in the group. By using PVD coating methods the life cycle of HSS could be increased up to 7-time fold [57]. While using multi-layered coatings produced with PVD can show great increases in the mechanical properties of materials, comparisons can be made with other available coating methods, such as laser cladding. While PVD shows promise in adhesive wear and surface hardnesses, it also has quite large drawbacks in harsher environments. Abrasive wear and impacts, for example rocks and soil, can provide too much damage to thinner and more brittle layers of PVD [58]. This makes it not suitable for Nordic Tractions purposes currently. Another disadvantage compared to laser cladding is the manufacturing precision. While laser cladding can be localized into certain small areas of the components, PVD chambers target the whole surface of the material and the chamber size itself limits how large components can be processed. Overall, the PVD process gets more difficult and expensive when more complex and larger components are required [59].

3.2.3 Case hardening and protective paints

Case hardening is one of the most used surface hardening processes among many different industries, like automotive, mechanical or aviation [60]. Surface hardening processes include different procedures where materials surface layer is treated, creating changes the structure and mechanical properties of the material. Case hardening furtherly consists of saturation phase, where using certain elements (carbon, nitrogen, boron) creates interstitial hardening on the alloy's crystal lattice on the surface. Another part of the case hardening is the heat treatment (quenching) phase. Depending on the saturation element used in the process, quenching can be done before saturation with boron or nitrogen (boriding, nitriding), or more commonly after with carbon (carburising) [60]. The goal of case hardening is to harden the surface of the material for better wear resistances while simultaneously keeping the inner core more ductile to absorb impacts without getting fractured. While nitriding and boriding are used in some cases, their costs are higher than in carburising, and their abrasive (nitriding) or impact (boriding) resistances [60] are not high enough for general uses in traction solution industry.

A study made in Egypt researched how different case hardening parameters affected on mechanical properties of different steel alloys [61]. Wear resistances were the main factors tested, and for comparison three different steel alloys: 16MnCr5, 17CrNiMo6, and 18MnCrB5 were tested with different carburising time periods (6, 10, and 12 h). Heat treatment method started with liquid carburizing at 915 °C with various time periods and was followed with oil quenching at 860 °C for 1 h. Tempering phase occurred after quenching and was performed to get hardness values of 48, 52, and 56 HRC [61]. The wear rates, case hardened depth, and hardness values were obtained with all steel alloys.

Test results support that wear rates decrease with all three alloys when the case hardness values (48, 52, 56 HRC) and carburising times (6, 10, 12h) increase [61]. The study also showed that wear rate of 16MnCr5 was better than 18MnCrB5 and 17CrNiMo6 with all different carburising times and decreased more when case hardness increased. Best wear rates were obtained with 56 HRC and 10h carburising time. With the best performing parameters, 16MnCr5 had 45% better wear rate than 18MnCrB5, and 15% better than 17CrNiMo6, which is explained by smaller carbide content, higher martensite fractions, and less retained austenite on the material [61].

Overall, increasing carburising time leads to case depth and carbon content increases. Occurrence of retained austenite in the microstructure leads to decreases in hardness and wear resistances with all alloys. While the wear rates at optimal carburising time and hardness values suggest that 16MnCr5 performs best, comparing to similar alloys without the case hardening treatment, other two alloys perform even better. Case hardening results in 55% less wear rate with 16MnCr5, while 17CrNiMo6 obtains 67% less wear, and 18MnCrB5 83% less wear [61]. Carburising, quenching and tempering as a treatment offer significant mechanical property increases with low costs: the surface is hard and has high wear resistance, while simultaneously core remains ductile, tough, and can absorb impacts efficiently. Even with quite long processing times, case hardening procedures offer great enhancements to non-treated alloys, and by utilizing it with additional treatments (for example laser cladding or protective paints) can provide even greater results for the traction solution industry.

Protective paints are one way to further enhance the surface properties for traction solution components. Case hardening treatments do not add significant corrosion resistance, so the main purpose of using protective paintings is to avoid corroding [62]. Beside corrosion resistance, some paintings can improve wear and impact resistances without chipping immediately off. Surface properties of martensitic steels can also provide limitations for choosing suitable paints.

Two commonly used protective paints are polyurea [63] and different zinc-rich epoxy coatings [64]. Polyurea offers good wear resistances and provides good energy absorption properties without cracking [63]. New materials and research have improved the polyurea's properties in protective paints. It also has some disadvantages, like complex spraying process, which requires great precision to get good results. The reparation of already damaged coating is also difficult procedure and requires additional surface treatment of the original coating. The most notable disadvantage is the cost of polyurea: the material itself and the machinery it requires is quite expensive [63]. Even with disadvantages polyurea still offers excellent impact protections compared to epoxy resins and polyurethane for example.

Zinc-Rich epoxy coatings consist of metallic zinc and organic binders like epoxy, or inorganic binders like different silicates. Zinc- rich coatings have excellent corrosion resistance and their application is a lot simpler than with many other coatings. While alone these zinc- epoxy coatings don't offer significant wear resistances, they can be used with additional topcoats to get better mechanical protection [64]. Using topcoats lead to higher costs, and the maintenance must be regular to keep the beneficial properties. In high wear environments like forests, this epoxy + topcoat approach is not so feasible.

Choosing the best suitable paint for harsher environments is not a simple task. While paints with higher costs offer better overall protection, high wear still chips coatings off eventually. In traction solution industry it needs to be furtherly assessed if maintaining and spraying additional coatings is worth the cost or is it better to use paints as a sacrificial part. Prevention of corrosion is the main factor in using protective paints, and alternative methods (like laser cladding) can be used to enhance high wear areas in the components with better performance.

4 Results and conclusions

During the research process a lot of different heat treatments, surface treatments, and coatings offering great enhancements on the durability of boron steel components in the traction solution industry were found. While these improvements seem relevant in many cases, the cost aspect of the procedures needs to be taken into consideration to get the most optimised and attainable methods to improve boron steels. For more throughout comparisons, hardness conversion table is added into the appendix. Different treatments and structural changes on material however alter the properties of the material, so the conversion tables are only indicative. This also applies with different Vickers tests, where higher test loads (HV10 > HV1 > HV0.5) follow similar hardness trends within small error margins compared to lower loads.

The cryogenic heat treatment is a way to increase mechanical properties of the material additionally to the traditional heat treatments (annealing, quenching, tempering). **Deep cryogenic treatments** (-160 °C or lower temperature) showed better improvements in wear resistances and hardness values than lower temperature cryogenic treatments. It was also seen that using cryogenic treatments without conventional heat treatments alongside, the results were quite poor. When used **in combination with traditional treatments**, the **hardness** values increased only up to **5 %** while **wear resistances** improved around **25 - 40 %** between the studies. While cryogenic treatments are environmentally friendly, the machinery required on top of added operating costs makes the procedure not necessarily the most feasible option currently compared to gained performance increases.

Subcritical annealing and hardening procedure decrease overall production costs and lower environmental impact by optimizing heat treatment procedures, while acting as a new water quenching method. This process has good customization with alternating ferrite and martensite fractions in the structure easily and the method is also quite simple due to only two variables (time and temperature). Due to simplistic hardening phase, this heat treatment method removes the long, traditional annealing phase, leading to smaller operational costs and decreased processing times. Only 15 minutes of subcritical annealing increased **hardness** values by **30 %**, while **wear resistances** enhanced by **5-15 %** (estimations from coefficients of friction), compared **traditionally heat-treated** materials. Additional benefit is that the impact toughness is not lost in the process. Enhanced mechanical properties on top of smaller operational costs and better environmental impacts, make subcritical annealing and hardening a promising heat treatment method.

Another example of interesting heat treatments for boron steels was **Q&P.** Q&P method inserts retained austenite to a stronger martensite phase in the microstructure. This process consisted of usage of the electric furnace and different salt baths. While **hardness and wear resistance** values increased modestly (up to **5 % and 30 %**) compared to **non-treated material**, also impact toughness improved, and could be even doubled when diminishing the improvements on hardness and wear resistance values. Q&P improved the mechanical properties of the material, but it also increased the processing times and costs compared to traditional heat treatments. The process is also quite hard to control and complex to perform on a larger scale. Compared to subcritical annealing and hardening, Q&P seems to not offer better results to counterbalance additional disadvantages with higher processing costs and more complex process control.

Different surface treatments are also common techniques to enhance the wear properties of different materials. **PVD** enables using multi-layered structures with broad variety of different applications. Only 1.1 μm thin coatings showed improvements of **18-timefold** in **adhesive wear** and **5-timefold** in **hardness** values. Furtherly thickening the coating enhanced the properties more at the cost of material consumption. While previously mentioned mechanical improvements are great, PVD also has some disadvantages. Suitable materials for different coatings are very limited due to molecular bonding. Because the coatings are thin, substrates are quite weak against abrasive wear and impacts. Compared to other surface treatments like laser cladding, manufacturing cannot be focused on precise area, which causes difficulties and increases process costs. Corrosion resistances of the coating are also good, but overall, it is still not suitable for harsher environments with the risk of damaging abrasion and impacts.

Case hardening and protective paints are currently a combination, which offer great performances on many needed aspects in traction solution components. Case hardening is a process where atoms (C, N, or B) are induced into the surface of a material. After the diffusion, quenching is performed to achieve the hard and wear resistant surface, while the inner core remains ductile and impact absorbent. The wear rate improvements varied from **55 % to 83 %** between different examined alloys. This shows that case hardening process with carbon atoms offers significant increases in mechanical aspects with low costs. Disadvantages of the procedure are longer processing times, and limited compatibility with different alloys.

Using the surface treatment with protective paints like polyurea or zinc-rich epoxy coatings, enables adding required corrosion resistance to the components with minor additional costs. Some paints can also enhance the wear properties of the surfaces, but usually high wear environments will chip it off eventually. Overall, combining case hardening with protective paints offer a broad protective layer on top of the traction solution components while staying low cost.

Laser cladding as a surface treatment has become more commonly researched recently. Basic principle of the process consists of laser melting cladding powders on the surface of the material. While laser machinery can be quite expensive, the precision of enhancing critical and weaker areas is a great way to lengthen the life cycles and increase predictability of the components. Laser cladding works with a lot of different material and powder combinations, which also makes finding the most optimal combinations difficult. Most prominent materials seemed to be **WC reinforced Fe-powders**, with the hardness values increases of around **8 %**, and wear resistances around **90 %**. Wear losses were **19 times greater** on non-cladded materials. **Iron aluminides** also showed great results with good environmental aspects, cost-efficiency, and together with additional boron had **half of the wear rates** than the next best cladding material.

In Table 7, different treatments are compiled and compared in different categories. Comparing the three non-surface specific treatments (Cryogenic, Subcritical annealing and hardening, and Q&P) show that the mechanical enhancements are quite modest compared to the surface treatments. Cryogenic treatment and Q&P have additional costs in the form of additional cooling equipment and salt baths, added process complexity (cooling/temperature control) and therefore they are also worse environmentally without adding significant improvements to mechanical properties. **Subcritical annealing and hardening** on the other hand showed improvements on mechanical side, while also decreased costs and process complexity leading to improved environmental aspects also. This treatment type is a potential candidate for improving current heat treatment procedures.

Table 7. Comparison of different treatments and reviewing their various aspects with points from 1 to 6 (worst to best).

	Cryogenic treatment	Subcritical annealing and hardening	Quenching and partitioning	Physical Vapor Disposition	Case Hardening + Protective paints	Laser cladding
Mechanical performance	4	3	2	1	5	6
Cost	3	6	4	1	5	2
Environmental aspect	3	6	2	4	1	5
Process complexity	3	6	2	4	5	1
Overall score	**13 (4th)**	**21 (1st)**	**10 (6th)**	**10 (6th)**	**16 (2nd)**	**14 (3rd)**

PVD on the surface treatments does not offer suitable mechanical property improvements for harsher environments (impacts and heavy loads) and adds extra complexity and costs. Scalability also suffers from limitations on batch sizes while material waste is also an issue. Case hardening is currently the main surface treatment used in the company, and additional equipment is not required for the process leading to decreased costs. Mechanical improvements are good, and the process is quite simple, while the emissions of the process are not environmentally friendly. Laser claddings targeting precision and mechanical improvements on the surface are excellent, but the cost of energy and required machinery are disadvantages. While case hardening offers good value currently, **laser claddings** targeting potential and surface enhancements make the process tempting alternative for critical wear areas. Precise targeting and repairability can also be a key element for increasing predictability of the products and the compatibility with different substrates offer a lot of customization options for the future. While the process itself is energy-intensive, it generates minimal waste and does not have gas emissions. It can also be considered that the targeting on smaller critical areas reduces the overall energy costs compared to other surface treatments.

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Appendices

1. Hardness conversion table adapted from [17]

HRC	**HV**
62	746
60	697
58	653
56	613
54	577
52	544
50	513
48	484
46	458
44	434
42	412