Cobalt in High Speed Steels

Elsa Saikoff, Edvin Andersson, Monika Galstyan, Christoffer Olausen, Felix Bengtsson, David Vikström, Joseph Byström Lazraq
Abstract

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One of the most important additives in High Speed Steels (HSS) is cobalt, mainly for its effect on the hot properties. Based on statistic data about the increased price of cobalt and its negative effect on human health, an ethical and financial barrier in the steel industry have occurred. In order to solve the problem, it is of great importance to examine the future cobalt price and accessibility, as well as examine the possibility of finding alternative substitutes to cobalt. The purpose of this project was therefore to examine alternatives to cobalt as an alloying element in HSS. A qualitative literature study was performed by analyzing the economy of cobalt, studying the main reasons for cobalts tendency to improve the hot properties of the steel and finding alternative elements to replace, or at least reduce, cobalt in HSS without degrading the hot properties.

Cobalt is used both in the chemical and metallurgical business. But the demand of cobalt is largely driven by chemical purposes with the focus on its rechargeable battery applications. The analysis shows that there is nothing pointing at a significant decrease of the price of cobalt. Lithium ion batteries stands for about 50% of current cobalt supply, which is why the price has surged the recent years. The market for electric vehicles and rechargeable batteries has skyrocketed. To decrease the price of cobalt, a substitute for cobalt in rechargeable batteries would need to be found, which is not very likely for the time being.

The effect of cobalt in HSS is mainly on the red hardness and tempering resistance. Cobalt increases the bonding strength in the steel matrix and changes the microstructure of the finer secondary carbides. Also the growth rate and coalescence rate of the carbides decreases. This causes the red hardness and the tempering resistance to increase. To replace cobalt, several alternative alloying elements have been researched. Among the most promising are niobium, nitrogen and aluminium, where niobium were found to be of most interest, due to the broad support of relevant articles in the field of powder metallurgical processing. The positive effect of niobium could be regarded as three-fold. The first contribution is the refinement of grain size and homogeneity of the primary carbides, which increases the overall hardness. The second effect is that the addition of niobium shifts the phase equilibria in such a way that the precipitation of primary carbides mainly will be in the form of hard and stable NbC. The majority of the other alloying elements will hence be precipitated as secondary carbides during tempering. The final effect is an increase in secondary hardness, as a consequence of the large amounts of vanadium and smaller amounts of niobium that is being precipitated during tempering to the secondary carbides. This enables a high matrix hardening potential in the optimal state of tempering.
Cobalt in High Speed Steels

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Abstract

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1. Introduction

Cobalt is one of the important components in High Speed Steels (HSS) to affect the hot-properties, among other important qualities of the steel. Based on statistic data the price of cobalt has increased remarkably over the years for variable reasons. Besides that, cobalt has a negative effect on the human health. The fact that cobalt is unhealthy and that the price is rising higher and higher creates ethical as well as financial barriers in the steel-industry where cobalt is present. In order to solve this problem it is of great importance to both examine the future price for cobalt and accessibility, as well as to examine the possibility of finding a substitute to cobalt.

High speed steels are often used as the material in cutting tools. During machining, the shear stress developed in the interface between cutting edge and working surface along with high processing speed, causes the cutting tool’s temperature to rise above 500 °C. It is therefore of great importance that the HSS is able to maintain high hardness at high temperatures. Alloying elements are added to improve the properties of HSS and cobalt is one of them. Cobalt is known for its positive effects on the hot properties of steel. Hot properties are all physical properties at elevated temperatures, for example hardness, electrical conductivity and magnetic properties.

Erasteel kloster AB is a company specializing in HSS powder metallurgy, among other things. Erasteel is looking to replace cobalt in HSS, due to the high price, health risks and ethically problematic production. In order to find a solution to this problem, Erasteel has decided to engage a group of students that will examine the issue and find alternative solutions. The project will provide deeper knowledge of how alloying with cobalt affects the performance of the HSS. Specifically, the reasons behind its effect on the hot properties are to be researched. New possible alloying elements for replacing cobalt will be presented alongside the analysis of the availability and the price of cobalt.

Since Erasteel is a company specialized in powder metallurgical processing (PM), the focus will hence be on powder processing. PM processing is a generic term describing a wide range of techniques in which HSS is produced from metal powders. These techniques have several benefits in comparison to the conventional ingot casting technique. One great advantage is the allowance of increased cooling rates during solidification, which decreases the grain size, leading to an increase in hardness. Another advantage is that PM processing enables the use of elementary compositions that in some cases is impossible to achieve in conventional ingot casting. One final advantage is that the technique reduced the need for after-treatment, which in most cases results in lower manufacturing costs. [42].
1.1 Purpose

The purpose of the project is to examine alternatives to cobalt as an alloying element in high speed steels. Research of the effects of cobalt in high speed steels were made to conclude the main reasons for cobalt's tendency to improve hot properties of the steel. Also a deeper study is made to find alternative alloying elements to completely or partially substitute cobalt as an alloy in high speed steel without degrading the hot properties. A study of the historical price variation and an approximation of the price in the near future was conducted, in order to determine this.

2. Method

The qualitative literature study started with a review of articles given by Erasteel. The articles gave a basic knowledge of HSS and cobalt, which made it possible to specify keywords for the search for new literature. The search only included published articles and literature on material chemistry. The process was initiated by using the database Google scholar, Knovel and the university’s own digital library for a general search. The initial keywords used was for example “Red hardness”, “Powder metallurgic high speed steels” and “Aluminum microstructure high speed steel”. Exclusion criteria was not used for any of the searches, because when adding a criteria, for example “peer reviewed” or “material science”, either it did not help with the selection or excluded most of the articles in the search. The search path can be viewed in table 1 below.

Table 1: The search path for the new literature.

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Database</th>
<th>Exclusion criteria</th>
<th>Number of hits</th>
<th>Number of used articles</th>
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<tr>
<td>Zirconium alloying high speed steel</td>
<td>Uppsala bibliotek</td>
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<td>Powder metallurgic high speed steels</td>
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<td>Google Scholar, Knovel</td>
<td>None</td>
<td>365.000, 506</td>
<td>1</td>
</tr>
</tbody>
</table>
The reading process started with reading the abstract and then proceed to the conclusion, in order to exclude irrelevant articles. The conclusion was compared with the headlines in the articles. If the headlines were relevant, but the text in the articles were irrelevant, the articles was not used further in the study. If the article passed through the selection, then the experiment part of the article was read to conclude if the method was reliable. The method was compared to other studies to determine if it was reliable or not. The general research of HSS continued with selecting relevant articles. The articles included information about the effect of cobalt and alternatives for the replacement of cobalt. In consultation with Erasteel, aluminium was considered highly relevant as a replacement. Niobium, nitrogen and silicon was also chosen for further research. The next step was conducting a more thoroughly research of the elements. Based on their similar properties to cobalt and compatibility with HSS, the elements was chosen to be presented as alternatives.

2.1 Interviews

Urban Wiklund, professor in material science at the department of engineering at Uppsala university, provided information about dislocation movements and over-aging in steels. Wiklund was also interviewed by email to validate conclusions the student group has drawn about hardness at elevated temperatures.

3. Theory and Background

Steel is an alloy which consists of a combination of iron and carbon, and in most cases other alloying elements. The additives to the steel matrix, for example vanadium, tungsten and chromium, are added to improve the properties of the steel. Different elements give different characteristics. The alloying elements tungsten and molybdenum gives the HSS its special properties, in combination with other elements. The HSS with the abbreviation T1 is a tungsten based steel. But when adding molybdenum and chromium to the tungsten steel solution, the HSS becomes a molybdenum based steel with the abbreviation MX. X stands for a number and each steel combination has its own number [1].

The combination of iron and carbon can form allotropes of iron, also known as different phases. There are three stable allotropes at atmospheric pressure, α-Fe (Ferrite), γ-Fe (Austenite) and δ-Fe (Delta Ferrite). The austenite phase can only exist above a temperature of 727 °C, in plain-carbon steels, and is a non magnetic allotrope. When the austenite phase is being quickly cooled down, in other words quenched, a
martensite phase is formed. This consequently prohibits the grains to form bigger structures and remain small, which indicates that martensite is a metastable phase. Cementite, Fe₃C, is a stable phase but like martensite, a different phase of iron and carbon composition, or in other words, an intermediate transition of carbides in the metal [1].

3.1 The current market of cobalt

Cobalt applications can be split into two categories: chemical and metallurgical. The demand of cobalt is largely driven by chemical purposes with the focus on rechargeable battery applications. Batteries drive 50% of demand, where the majority comes from cobalt’s usage in lithium ion battery cathodes, while high-performance superalloys drive 17% of cobalt demand, as displayed in figure 1 [2]. The use of cobalt in batteries has grown by an average of 13% annually over the last ten years [3]. At the same time, the use of cobalt in metallurgical applications has only risen 3.4% per year [2]. Intuitively then, the main driver for cobalt demand will continue to be rechargeable lithium ion batteries.

![Cobalt Consumption Chart](http://www.co27.com/cobalt/about/)

Figure 1 - Chart of cobalt applications in 2016.

Cobalt's unique thermal properties and positive performance has been thrilling to the electric vehicle (EV) manufacturers. As cobalt is one of the key components in rechargeable lithium ion batteries that power these kind of cars, the demand of cobalt will continue to rise as the use of electric vehicles increases. Many forecasts have been made on how successful the market penetration will be for EVs, with rates ranging from 5% to 35% by year 2025. Even with differences between the predictions of how extensive the transition will be, they all agree that the current cobalt supply chain will be insufficient.

The total cobalt mine supply consists of approximately 100,000 tonnes/year [4]. This is, to put in perspective, 50% the size of the lithium market and 0.5% the size of the copper market. About 98% of the total cobalt extraction comes as by-product from nickel and copper mining. Only one mine in Morocco
has cobalt as its main resource [3]. In 2016, 63% of the global production of cobalt come from the Democratic Republic of Congo (DRC). In 2025 it may increase to 73% as major producers like Glencore expand their mines. The second largest producer has a production of less than a tenth of DRC’s and the total reserves are estimated to be significantly lower. The top three supplying countries 2016 were DRC with 64000 tonnes/year, Russia with 5600 tonnes/year and Australia with 5000 tonnes/year [5]. The DRC has been a dependable producer of cobalt since 2003, when it recovered from a civil war that cost millions of lives and crippled the mining industry. The vast business network, that reaches every corner of the economy, was built by president Joseph Kabila and his family in 2001 [6].

Artisanal mining is legal in DRC but there are major weaknesses in the regulations of it. Traders buy minerals no matter where they come from or how they have been mined. As much as 20% or 14'000 tonnes of congoles cobalt, with today's production rate, is currently coming from informal mines that Amnesty international alleges may rely on child labor [6]. Traders sell the ore to companies like Congo Dongfang Mining International (or CDM, a company owned by the Chinese mineral company Zhejiang Huayou Cobalt Company) who process and export it. Then Huayou Cobalt further melts it, and sells the processed cobalt to battery component manufacturers in China and South Korea. These companies then sell to battery manufacturers, who sell to well-known brands of smartphone and vehicle makers [7].

The increase of cobalt demand has led to a rise in awareness of the current situation in the DRC’s mining industry. A growing trend among companies is to use “clean” cobalt in their industries, which means to have cobalt from formal mines and in the best case locally produced [8]. In 2016 Apple Inc. and Samsung Electronics Co. came under public pressure to thoroughly examine their supply chains regarding the inhumane labour. Recently Apple Inc. went public with ambitions about buying cobalt directly from the miners [9]. This is partially to obtain better control over the mining conditions of which the cobalt that is being used is coming from but mostly to ensure a cobalt supply ahead of the possible upcoming period of cobalt deficiency.

3.2 General information about High Speed Steels

High-speed steel (HSS) is a category of steels with the ability to maintain hardness at high temperatures (≈500-600 °C) and is strongly wear resistant, making them favourable in cutting and milling applications where high friction temperatures are developed.

3.2.1 Heat treatment and Microstructure

Despite the large amounts of high-speed steels, the number of precipitation reactions and phase transformations that takes place are found to be remarkably similar. The carbides that are formed are MC, M₂C, M₆C and sometimes M₁₇C₆, where M is a carbide forming metal.

The heat treatment of powder metallurgic HSS begins by heating the powder to a temperature high above the austenite transition temperature (normally 1000 -1220 °C depending on the HSS), in order to achieve a considerable degree of dissolution of carbide-forming elements that can be reprecipitated in the matrix as refined secondary carbides. The austenization time is kept as short as possible to prevent grain growth,
that would otherwise reduce the hardening. The sample is then quenched down to room temperature, transforming the austenite to martensite and 25-30% retained austenite. It has been shown that proeutectoid carbides, MC and M\textsubscript{2}C, is formed in the austenite between 900-1000 °C which diminishes the supersolution of the martensite that forms during hardening and further decreases the amount of secondary hardening. Due to these carbides being larger than the ones formed during tempering, their hardening effect is significantly smaller. It is therefore crucial to cool rapidly during this temperature interval to prevent the increment of these proeutectoid carbides. [10]

The primary carbides that are formed during the solidification process are mainly MC and M\textsubscript{6}C which have a quite coarse microstructure, making the steel wear resistant. Further, the primary carbides improves the attachment of the austenite grain boundaries, which prevents grain coarsening during hardening. These carbides lie embedded in densely twinned martensite and retained austenite (~25-30%). The role of the martensitic matrix is to keep the wear resistant primary carbides in place despite the high temperatures and shear stresses developed at the interface between material and cutting edge. When room temperature is reached, the steel is then heat treated by repeated tempering. The tempering is repeated 2-3 times at a temperature of ~550-560 °C in order to convert the retained austenite to martensite and create secondary carbides. This contributes to a finer microstructure for the secondary carbides formed by strengthening the austenite matrix and thus increasing the hardness. During the air-cooling from the step-quenching temperature at ~500°C down to room temperature, cementite can also be precipitated in the martensite matrix at grain boundaries and at twin boundaries (auto tempering). The major drawback with M\textsubscript{6}C is that it can contribute to nucleation sites for secondary carbides during tempering. These secondary carbides are coarser than those formed from the retained austenite, which will decrease hardness. It has further been shown that a part of the M\textsubscript{6}C does not completely dissolve and transform to the secondary carbides, MC and M\textsubscript{2}C, which in turn will reduce the total volume fraction of MC and M\textsubscript{2}C and thereby decrease the hardening. [10]

3.2.2 Important properties

3.2.2.1 Red hardness

One of the most important characteristics of high speed steels is the red hardness, which stands for the temperature where the hardness decreases. Red hardness causes the hardened steel to have an ability to maintain hardness at approximately 600-700 °C. Red hardness is directly linked to the cutting qualities of the steel, since the maintained hardness is decisive for the cutting ability. Studies show that red hardness depends on the martensite-composition and the quantity of dissolved content of carbide-phase in the steel. Precipitates blocks the dislocation movements in the martensite structure and increases the strength of interatomic bonds, which inhibits the dislocation movements. When steel undergoes a heat treatment, a redistribution of the alloy elements in the solid solution occurs. The redistribution causes an increase of boundary areas and the precipitates binds to the solid solutions lattice coherently [11].

3.2.2.2 Tempering resistance

Another important property of a high speed steel is the ability to maintain a high hardness at high temperatures for an extended period of time, referred to in this report as tempering resistance. This means
that the rate of reactions such as over-aging, where precipitates become larger and coalesce, or the reaction where martensite turns into ferrite is sufficiently low [1]. These can be achieved through many different means, and some of these means will be discussed in more detail later.

3.2.3. Alloying elements
The reason behind the special properties of HSS is the presence and influence of the alloying elements such as vanadium, tungsten, molybdenum, chromium, aluminium and cobalt added to the steel matrix. The alloying elements affect the properties of the steel in various ways.

3.2.3.1 Carbon
Carbon is the most important element in high-speed steel. The main influence of carbon can be divided in two. The first part is for the formation of martensite, which is achieved through quenching. Secondly it contributes to the basic matrix hardness of HSS due to the formation of carbides with the alloying elements and thereby gives the steel an increased wear resistance. It is crucial to keep the carbon content within certain limits, since even small changes in the content is known to cause major changes in the mechanical- and cutting properties. It is well known that by increasing the carbon concentration the hardness, as well as the red hardness increases. However, since there is an upper concentration limit when the hardness will begin to decrease. The reason behind the decrease is believed to originate from the increased formation of cementite. As mentioned previously, the disadvantage with cementite is that it acts as a contributor to the increment in nucleation sites for the secondary carbides during tempering. These secondary carbides are coarser than those formed from the retained austenite, leading to a decrease in hardness. [12]

3.2.3.2 Molybdenum and Tungsten
Molybdenum and tungsten are two alloying elements that contributes to the retention of hardness and improvement of the red hardness, as well as improving the matrix high-temperature strength in high-speed steel. Molybdenum acts very similar to tungsten in the sense that it forms a double carbide with carbon. The difference on the other hand is that molybdenum only weighs half of tungsten. The fact that molybdenum has a lower melting temperature than tungsten implies that the hardening temperature can be lowered, but also entails a narrower hardening range. HSS with a high content of molybdenum have generally a higher toughness but at the expense of a lowered red hardness. One way to compensate for this drop in red hardness is by adding tungsten to the steel matrix, as well as lowering the addition of vanadium. [12]

3.2.3.3 Vanadium
The effect of vanadium is to increase the resistance of high-temperature wear and cause a less detainment of the matrix high-temperature strength as well as increasing the overall hardness. This by contributing to the formation of very hard and stable vanadium carbides which drastically increases the hardness. Different carefully adapted combinations and amounts of those alloying elements in high-speed steel generate specific characteristics and properties, but have a quite low impact on the overall improvement in toughness. [12]
3.2.3.4 Chromium

Chromium increases the hardenability of the HSS as well as reducing the oxidation and scaling during tempering. Moreover, it facilitates the formation of soluble carbides, thereby contributing to the increase in hardness. The chromium content is normally set between 3-5%, but a content of 4% is conventionally used due to its great balance in hardness and toughness [12].

3.2.3.5 Aluminium

The influence of aluminium in high speed steel involves improvement of red hardness and retention of hardness, like the impact of cobalt in high speed steel [12].

3.2.3.6 Silicon

The silicon content in HSS is for most part set to less than 1%. The effect silicon has on the steels mechanical properties is quite limited. It has been shown that an increase from 0,15-0,45% gives a minor improvement in red hardness and slightly influences the composition of the formed carbides. The major drawback is that the increased silicon composition is on the expense of toughness. [37]

4. Cobalt and Economy

The sharp change of cobalt applications and demand have put pressure on the cobalt supply chain. With the current supply and demand of cobalt the price is at around 40 USD/lb. In order to meet the predicted demand the production will have to increase from 100,000 tonnes/year to 300,000 tonnes/year, which is a tall ask for cobalt as a by-product. All signs points toward supply shortages and a price increase.

4.1 Past

The cobalt market has historically been extremely volatile because of concerns about the supply security due to war, unrest and political uncertainty in the DRC and the former Soviet Union. Figure 2 displays the fluctuation of the price during the years between 1973 and 1997 [13].
There were predictions in 1998 that demand would not keep up with the overwhelming development of production as a result of the upcoming projects of cobalt mining. The forecast for 2001 to 2010 was around 7 USD/lb “given the likelihood of producer curtailment due to falling prices resulting from market surplus”. What they did not know was that the advancing battery industry would turn out to be a very fast growing area of application. This resulted in a price development far beyond the predicted one in 1998 [13].

During the years between 2006 and 2009, as seen in figure 3, there were many factors that affected the price of cobalt. The DRC placed restrictions on export of ores and concentrates causing demand to increase higher than supply as the market for hybrid cars and EVs advanced fast. At the same time, the United States stopped selling of stockpiles and began to review the state of certain metals which would add to the price increase [14]. In 2008 the price reached over 50 USD/lb. Later that same year the global financial crisis occurred, decreasing the value of commodities, including cobalt, as seen in figure 3. The following years were relatively stable for the cobalt market and the average price was around 15 USD/lb. Recently the price has started to increase fast as the EV market skyrockets and as the awareness of the current cobalt situation increases.
4.2 Forecast

According to an entrepreneur and investor in the cobalt market, Mike Beck, the most likely penetration rate for EVs by 2025 will be 15%. Sales are expected to pass 14 million per year from less than one million per year in 2017, fuelling a surge in the consumption of battery materials [15]. The resulting cobalt demand is expected to be 3 times today’s total mine supply or around 300,000 tonnes/year. In the next few years only five new cobalt mines are due to open and they will add about 50,000 tonnes/year adding to the total of 150,000 tonnes/year, which is far from the predicted demand. Since cobalt currently is mined as a by-product of copper and nickel there will only be a material increase in cobalt supply if a major increase of copper or nickel production occurs [16]. But since nickel, just as cobalt, is a key ingredient in EV batteries, the demand for nickel will also increase significantly. A humble estimation of the cobalt price by 2025 is 100 USD/lb, not taking commercial electric vehicles or grit storage applications in account [17]. Another factor that has to be reckoned is that battery manufacturers and investors are stockpiling the metal in fear of shortages with the surging demand. This will probably be a growing issue and will drive the prices even further.

One event that would result in a major decrease of the cobalt price is if a substitute for cobalt, partially or completely, in lithium ion batteries would be discovered. If the substitute is shown to be an improvement in properties or that it is much cheaper or more sustainable than cobalt, there will probably be major investments from larger companies. However, new battery technology will not see the light of day in 10 years at best after discovery. First it needs to be proven, then it needs to be adopted by the industry and then the supply chain will need to re-tool.
In 2025 the share of the global cobalt production coming from the DRC may increase to 73% as major producers like Glencore expand mines even though the political uncertainty in the country shows no signs of improvement. There is a possibility of nationalization and that changes may happen in legislation that would ban raw material exports. The country could try to move up the value chain by requiring processing to happen within its borders, which would bring the cobalt supply chain to a temporary halt, causing additional surge [18].

Even if the DRC will continue to contribute with the majority of the world’s cobalt supply, the country’s instability will accelerate the exploration of other potential mining sites outside of Africa, especially in Canada and the western United States. The now abandoned Canadian silver mining town Cobalt has drawn the most attention from cobalt mining giants and newcomers. The town is poised to become a cobalt producing “mecca” as the mining areas has been expected to contain a cobalt concentration of 4% or as much as 7.64%. This is a very high number since cobalt is a metal that can be economical at concentrations far below 1% [14]. The opening of cobalt mines outside of Africa would lead the increase of the cobalt price to ease off but would probably not lead to a decrease.

The awareness of the cobalt situation and need of sources has led entrepreneurs to invest in recycling technologies. American Manganese Inc., one of the largest recycling companies, claims being able to supply cobalt for all the electric vehicles on the road in 2017, solely by recycling lithium ion batteries [19]. According to the upcoming battery manufacturer Northvolt, if cobalt is partially replaced, there is a lower limit of cobalt content in a battery in order for it to be profitable to recycle. This is because of how costly battery recycling processes are today [20]. However, recycling in big scale is not set to take of until the first wave of EVs is near the end of their life which probably is up to 10-12 years from now. Today there is not enough batteries to recycle to make the processes profitable [15]. Nonetheless, major recyclers stays confident that supply will come and it is evident that companies plans to take advantage of the growing battery market [19]. In 2017 about 7,110 tonnes of cobalt came from recycling. Commodity research group CRU expects 11,600 tonnes of cobalt by 2021 and 24,900 tonnes of cobalt by 2026 will come from recycling which is equal to 10% and 18% of the total supply respectively [15]. This would somewhat slow down the surge and help stabilize the price of cobalt in the future but would probably not be enough to result in a decrease.

5. The effect of Cobalt in High Speed Steels

The addition of cobalt to HSS has a couple of advantageous effects in the properties of the steel. It results in increased hardness and red hardness, as well as higher tempering resistance.

5.1 Hardness and Red hardness

The main effect of adding cobalt to HSS is the increase of the hardness and red hardness and thereby increasing the maintainability of hardness at elevated temperatures. This increase is due to several factors. Cobalt increases the bond strength between metal atoms in the steel matrix, which causes an increase of the recrystallization temperature. Another factor is a change in the microstructure. It is shown that when
adding cobalt, the amount of finer secondary carbides increases. This is due to a decrease in growth rate and an increase in nucleation rate [10]. The formed carbides also become less likely to coalesce, as the mobility of carbon, and also tungsten, decreases with the addition of cobalt. Further aiding in keeping the secondary carbides small and plentiful [11]. Lastly, cobalt inhibits the growth of cementite during quenching.

By adding cobalt in steel the properties of the solid solution changes, which is the main reason for the increase in red hardness and therefore the cutting properties. As mentioned earlier, carbon stands for the basic hardness of HSS and cobalt causes retention of the matrix hardness. Cobalt affects the softening of carbon during annealing. The bonding strength between the metal atoms is increased when adding cobalt, which causes an inhibitory effect to the softening. It is also shown when tungsten, vanadium and molybdenum is present, the effect of cobalt is more evident. This leads to the hardness of the basic matrix in HSS and improvement of red hardness [11].

5.2 Tempering resistance

Increased tempering resistance is achieved through similar mechanism as for red hardness. The main reason for the reduction of hardness in HSS is the growth and coalesce of secondary carbides and the transformation of martensite to ferrite and cementite. By adding cobalt, the growth rate and coalescence rate of the carbides decreases. Cobalt is a austenite former, which leads to an acceleration of the transformation of residual austenite. The acceleration is due to an elevated martensite start temperature, \( M_s \), causing the martensitic reaction to start at a higher temperature during the quenching of austenite. By making the martensitic phase more stable, cobalt inhibits the breakdown of martensite at higher temperatures [11]. These effects above are responsible for high tempering resistance in HSS containing cobalt [40].

5.3 Magnetic properties

A possible hypothesis of the improvement in hot properties when alloying a HSS with cobalt can be the change in the steels magnetic properties, which would lead to a slower diffusion rate. Slower diffusion would be the effect of a higher curie temperature, the temperature where a material loses its permanent magnetic property. If the curie temperature is exceeded, the magnetic properties changes. The increase of the curie temperature would cause the material to remain ferromagnetic, the ability to become permanent magnetic, at its operating temperature. Diffusion is slower in a ferromagnetic material as the the magnetic ordering must be changed for diffusion to occur, in addition to all the regular requirements for diffusion. While this seems plausible, it has been shown that, although cobalt does affect the Curie temperature and other magnetic properties of high speed steels in some cases, the hot properties are still improved when no noticeable change in Curie temperature is present [21]. The project has therefore elected not to focus on the magnetic properties in this study.
6. Alternatives to Cobalt in High Speed Steels

Since the cobalt prices are fastly increasing due to the growing battery industry where cobalt is also used, alternatives must be found in order to keep the HSS business going. Some of these alternatives are niobium, aluminum, silicon, molybdenum and tungsten, where aluminum and niobium are the most promising. The alternative additives have different effects on the HSS depending on which alloy and what amount is added.

In the 1970s, a new type of super HSS was developed by the Crucible Materials Corporation. The new steel type was cobalt-free HSS. Due to the lack of cobalt on the market at the time, M61 and M62 was produced without cobalt influenced by the characteristics of T15 and M42 with cobalt. M and T stands for molybdenum and tungsten, which can be seen as the base in that kind of the HSS. To accomplish cobalt free HSS, cobalt was replaced with molybdenum and/or tungsten which resulted in a higher amount of carbides in the steel. When heated, the carbides dissolved, and a harder material was achieved. The results showed that M61 without cobalt had a higher temperature resistance, a greater wear resistance and a higher heat treat response than T15 with 5% cobalt. The heat treat response stands for how a material reacts while undergoing a heat treatment. The greater wear resistance depends on a higher amount of carbides in the volume. M61, M62 without cobalt have a higher heat resistance and an increase in wear resistance in comparison with M42 with 8% cobalt [12].

6.1 Niobium in High Speed Steels

Niobium might be a possible candidate to increase the red hardness in HSS and could eventually replace, or at least reduce the amount of used cobalt needed to increase the red hardness. The main influence of niobium is to promote the formation of MC carbides during quenching. As previously mentioned it is more favourable to form MC carbides than $M_6C$ carbides, since they are considerably harder and thermodynamically more stable. Previous studies have been made on both conventional processing and powder metallurgical processing which clarifies that the only way to achieve satisfactory results would be to use powder metallurgical processing [22]; [23]. The reason for this is that the crystallisation begins at an earlier stage for NbC compared to ferrite at niobium contents of 3% or higher, which enables the NbC grains to grow very large in size [24]. Large grains are not of interest since they are destructive to the toughness as well as to the grindability and therefore poorly utilized for wear resistance. Furthermore, addition of Nb in conventional processing tends to shift the solidification path from $M_6C$ to the least favoured $M_6C$. In metallurgical processing on the other hand, these problems are avoided, due to the rapid cooling, enabling the use of niobium contents higher than 3%.

When incorporating niobium in HSS it is crucial to consider the role of vanadium. Vanadium and niobium are very much related due to their position in the periodic table and the fact that both are very strong carbide formers, with niobium being the strongest. But there is also a very distinct difference between the two elements. It is well known that steels totally absent from vanadium develop no useful red hardness even at high niobium concentrations [25]. This is due to the high stability of the niobium carbides, making
them almost insoluble in the austenite phase (~ 0.02% solubility) [26]. This is of great importance since the amount of dissolved carbides in the retained austenite present after quenching is what causes the secondary hardening. In comparison to niobium, vanadium carbides is not as stable and thereby to a larger degree more soluble in austenite. The higher solubility in austenite makes it possible to precipitate a higher amount of vanadium carbides during tempering and consequently contribute to a larger extent to the secondary hardness. Suggestions have been made that vanadium is vital for the nucleation of the MC carbides responsible for the secondary hardness.

The poor solubility in austenite is the biggest downside when incorporating niobium in HSS, but as will be shown from now on the effect of niobium has still a great potential and many benefits speaks in favour of its usability in order to increase the hot properties of HSS.

In powder metallurgical processing, niobium favors the formation of metastable eutectic $\text{M}_2\text{C}$ carbides during austenization. During tempering these $\text{M}_2\text{C}$ carbides decomposes into $\text{M}_6\text{C}$ and MC carbides, where the MC carbides are particularly rich in vanadium. Because of its fine precipitation structure, the $\text{M}_6\text{C}$ carbides will in turn dissolve very rapidly during austenitization and thereby contribute with a great supply of vanadium for the formation of secondary carbides, enabling a high matrix hardening potential in the optimal state of tempering [26]. Niobium alters the phase equilibria in such a way that the precipitation of primary carbides mainly will be in the form of hard and stable NbC. Large amounts of the other alloying elements will hence be precipitated as secondary carbides during tempering. Besides forming NbC carbides during quenching, niobium also has the ability to replace some of the vanadium in the $\text{M}_6\text{C}$-carbides formed during tempering, which further improves the secondary hardness [26].

With this in mind, it can be concluded, that in order for an eventual incorporation of niobium to become successful it is important to still have vanadium present and according to previous studies addition of at least 1% vanadium is relevant in order to obtain a satisfactory secondary hardness [27].

What also makes niobium so interesting as an additive is the fact that it is theoretically more temperature resistant compared to vanadium, which raises the hope of improving the steels cutting abilities at raised operating temperatures even further. In addition, it is also well known that niobium generates a much finer and more homogenous distribution of the carbide population in the steel matrix, increasing the overall hardness. Another advantage is the fact that the incorporation of Nb in the vanadium grains should thermodynamically be favourable once formed [24].

The eutectic temperature of the NbC-Fe is considerably higher than that of Fe-$\text{M}_2\text{C}$, which enables higher austenitization temperatures without grain coarsening or carbide precipitation at the grain boundaries. The presence of Nb should consequently lead to further grain refinement and thereby an increase to the secondary hardness, as well as contributing to an improvement in tempering resistance.

In a study performed by S. Karagöz and H.F Fischmeister in 1989 a niobium enriched steel sample was made and its mechanical performance was compared to the two commercial steels; AISI T1 and AISI M2. The abbreviation AISI stands for the American Iron and Steel Institute. T1 and M2 are tungsten steel molybdenum steel respectively. When designing the composition of the niobium enriched steel, guidance
was taken from previous studies in design of typical matrix compositions and from their own experience based on construction of HSS matrices. The following HSS composition were used:

Table 2- Composition data for the HSS used in the studied

<table>
<thead>
<tr>
<th>Element</th>
<th>W</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>2.0</td>
<td>3.0</td>
<td>1.6</td>
<td>3.5</td>
<td>1.38</td>
</tr>
<tr>
<td>Steel analysis</td>
<td>2.05</td>
<td>2.87</td>
<td>1.61</td>
<td>3.21</td>
<td>1.31</td>
</tr>
</tbody>
</table>

(Plus 4.25 Cr, 0.45 Si, 0.02 N₂ and 0.20 to 0.33 O₂)

The steel sample was made by metallurgical processing. The powder was heated to ~ 1050-1080 °C and thereafter extruded to further strengthen the material. It was then soft annealed for 6 hours at a temperature of 800 °C and finally heat treated by triple tempering. But at what temperature this was carried out was never described, it was only hinted that the optimal tempering temperature was found by testing a series of temperatures and thereby using the one that turned out to have the best characteristics in terms of hardness.

The composition of the sample was tested using STEM-EDX. STEM is a microscope with an electron beam that scans the micro surface and EDX shows the data obtained in a graph as an diffractogram. The results from the test showed good resemblance with the target composition. The MC carbide grains were also analyzed with STEM-EDX, revealing a majority of the grains to be rich in niobium as previously expected. As can be seen in figure 4 the secondary hardness was found to persist at higher temperatures compared to the A1S1 M2 steel confirming the previous prediction that addition of niobium increases the secondary hardness and the temperature resistance.

![Graph showing tempering response and effect on secondary hardness for Exp. Nb-steel and A1S1 M2.][1]

Figure 4- tempering response and effect on secondary hardness for Exp. Nb-steel and A1S1 M2. [23]

The mechanical properties of the niobium enriched HSS was tested in terms of cutting performance and the result was compared to the previously mentioned commercial grades; A1S1 T1 and A1S1 M2 both
prepared in their optimal state of tempering. As can be seen in figure 4, the niobium enriched sample exhibits clearly improved cutting ability compared to AISI T1 and even though its hardness is 0.8 HRC below that of AISI M2 it shows almost equal cutting performance. The cutting test was carried out at a relatively low speed and further testing at higher rates was not possible due to the lack of accessible material. But the promising performance at low speed for the Nb-steel leads one to expect better performance at elevated temperatures compared to the AISI M2-steel due to the increased persistence of secondary hardness [23].

Moreover, in this study the composition of the Nb-enriched steel was intentionally put on the lean side with respect to the matrix composition as well as in the amount of primary carbides. As can be seen in table 2, the Mo and Nb content turned out to be lower than target. Both of these elements are very important to the secondary hardening, so an obvious measure in order to improve the red hardness would be to increase the amount of Mo and Nb. One concern on the other hand, is that the cooling from the austenization temperature down to ~ 900 °C requires certain attention. This is due to the presence of a pre-eutectoid precipitation of NbC occurring at this temperature interval, which is thought to imply a loss of Nb that otherwise would be accessible for the secondary hardening of the steel matrix.

If this loss could be avoided, tentatively by rapid cooling in this temperature interval, the temper resistance of the niobium enriched HSS has the potential to become even more superior than the traditional HSS grades.

In another study performed by B. Hribernik, G. Hackl, S. Karagöz and H.F Fischmeister published May 1991, two years later than the study mentioned above, two experimental Nb enriched steel samples with
different composition were tested. The study seems to be an extension of the previous study, but this time with the purpose of examine the effect of altered carbon content in experimental Nb-HSS. For this experiment two Nb enriched HSS with different carbon contents were examined; one with a lower carbon content and the other with a higher carbon content. The following compositions were used:

Table 3- Composition data, LC: low carbon, HC: high carbon

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>W</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Cr</th>
<th>(N_2)</th>
<th>(O_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC-2-3-2-3 Nb</td>
<td>1,31</td>
<td>2,05</td>
<td>2,87</td>
<td>1,61</td>
<td>3,21</td>
<td>4,25</td>
<td>0,02</td>
<td>0,20-0,33</td>
</tr>
<tr>
<td>HC-2-3-2-3 Nb</td>
<td>1,39</td>
<td>1,77</td>
<td>2,93</td>
<td>1,49</td>
<td>2,95</td>
<td>4,43</td>
<td>0,03</td>
<td>0,03-0,04</td>
</tr>
</tbody>
</table>

As can be seen in table 3, the LC variant corresponds to the same sample tested in the previous study performed by S. Karagöz and H.F Fischmeister. With a vast majority of the carbide population consisting of stable NbC carbides the variation of the carbon levels will directly affect the carbon content of the steel matrix and thereof the morphology of the formed martensite [24]. After quenching the LC sample were studied with SEM, which showed that the LC variant consisted for the most part of lath type martensite, while the HC variant consisted primarily of plate type martensite. The blocky carbides were found to consist entirely of MC carbide in the LC variant, while in the HC variant the blocky carbides consisted almost exclusively of MC carbides with a small population of \(M_6C\) carbides.

An elemental analysis of the composition of the blocky MC primary carbides formed during quenching was also performed, revealing a vast majority of the carbides to be rich in Nb, where the remaining MC carbides was found to be rich in vanadium as previously expected. The chemical composition of the carbides is tabulated in table 4 below:

Table 4- Composition of blocky primary MC carbides

<table>
<thead>
<tr>
<th>Carbide type</th>
<th>W</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-rich MC</td>
<td>3,7</td>
<td>5,9</td>
<td>8,2</td>
<td>78,4</td>
<td>0,6</td>
<td>2,8</td>
</tr>
<tr>
<td>V-rich MC</td>
<td>17,2</td>
<td>24,3</td>
<td>29,7</td>
<td>21,5</td>
<td>3,8</td>
<td>3,5</td>
</tr>
</tbody>
</table>

Since the properties of the LC sample already been stated earlier in the report, the focus will hence be on the HC sample. The optimal tempering and austenization temperature was found by various testing. The optimal tempering temperature was determined to be 550 °C after autenization at 1300 °C, generating a hardness of 67 HRC which is approximately 2,0 HRC above the standard level of A1S1 M1 at optimal state of tempering. Because of the high carbon content in the HC sample, it was necessary to assist with a fourth temper treatment, due to the high amount of residual austenite formed after quenching. The tempering response is illustrated below:
The mechanical properties were then tested in terms of wear resistance and cutting performance. The wear resistance test revealed the HC Nb-steel to be superior in comparison to the AISI M1 grade. This improvement in wear resistance is due to the elevated austenization temperature that increases the matrix strengthening.

The cutting test revealed the HC Nb-steel to be superior to the AISI M1 grade at high cutting speeds and high operating temperatures. It has thus been shown that the addition of niobium is highly accountable for an increase in the secondary hardness, this is due to the improved temper resistance of the secondary carbides.
The exact parameters and results regarding the cutting test was not revealed in this study, instead the authors referred to another study performed by B. Hribernik that is yet to be published. The fact this study is from 1991 and still has not been published is quite strange. One possible reason could be that they wanted to apply for a patent of their research. But at the same time it seems quite far-fetched since they have already presented all the data needed in order to replicate the sample in the experiment, so it is more likely another unknown reason.

In another study performed by S. Karagöz and H.F Fischmeister in 1998, the cutting performance of 13 HSS alloys were investigated. The following alloy compositions were studied:

<table>
<thead>
<tr>
<th>Alloy Number</th>
<th>Alloy Type</th>
<th>Chemical Composition (Wt Pct)</th>
<th>Austenitization (°C/3 min)</th>
<th>Tempering (°C/1 h)</th>
<th>Hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1</td>
<td>S18-0-1</td>
<td>0.74</td>
<td>17.86</td>
<td>0.41</td>
</tr>
<tr>
<td>2</td>
<td>M2</td>
<td>S6-5-2</td>
<td>0.92</td>
<td>5.99</td>
<td>4.50</td>
</tr>
<tr>
<td>3</td>
<td>M7</td>
<td>S2-9-2</td>
<td>0.84</td>
<td>1.62</td>
<td>8.77</td>
</tr>
<tr>
<td>4</td>
<td>M42</td>
<td>S2-9-1-3</td>
<td>1.09</td>
<td>1.22</td>
<td>8.78</td>
</tr>
<tr>
<td>5</td>
<td>PM/M2mod.</td>
<td>S-6-5-4</td>
<td>1.30</td>
<td>5.55</td>
<td>4.26</td>
</tr>
<tr>
<td>6</td>
<td>PM/5mod.</td>
<td>S10-2-5-8</td>
<td>1.60</td>
<td>10.00</td>
<td>1.98</td>
</tr>
<tr>
<td>7</td>
<td>PM/exp Nb</td>
<td></td>
<td>1.31</td>
<td>2.00</td>
<td>3.04</td>
</tr>
<tr>
<td>8</td>
<td>PM/exp Nb + 3Co</td>
<td></td>
<td>1.28</td>
<td>2.22</td>
<td>3.00</td>
</tr>
<tr>
<td>9</td>
<td>PM/exp Nb + 5Co</td>
<td></td>
<td>1.28</td>
<td>2.24</td>
<td>3.12</td>
</tr>
<tr>
<td>10</td>
<td>PM/exp Nb + 8Co</td>
<td></td>
<td>1.26</td>
<td>2.12</td>
<td>2.96</td>
</tr>
<tr>
<td>11</td>
<td>T1-Mx</td>
<td></td>
<td>0.44</td>
<td>7.29</td>
<td>0.55</td>
</tr>
<tr>
<td>12</td>
<td>M2-Mx</td>
<td></td>
<td>0.55</td>
<td>3.93</td>
<td>3.57</td>
</tr>
<tr>
<td>13</td>
<td>M7-Mx</td>
<td></td>
<td>0.52</td>
<td>1.12</td>
<td>4.58</td>
</tr>
</tbody>
</table>

Figure 8- Alloy compositions with accompanied hardness, austenitization temperature and tempering [22]

Alloy number 1 through 6 consist all of traditional HSS grades, starting with the tungsten grade AISI T1 (number 1), via the tungsten-molybdenum grade AISI M1 (number 2) to the molybdenum-rich AISI M7. Grade no 4, AISI M42 is a high-carbon derivative of the AISI M7 grade with further addition of cobalt. Grade number 5 is a high-carbon as well as high-vanadium derivative of the AISI M2 steel with further addition of cobalt and number 6 is a cobalt alloyed tungsten grade. Alloy number 7 through 10 are all experimental Nb grades in which the vanadium has been partially replaced by niobium. In alloy 8 through 10, various amounts of cobalt has been added to the steel matrix. Alloy number 11 through 13 corresponds to the T1, M1 and M7 matrices but totally absent from primary blocky carbides.

Figure 9- Cutting performance for alloy 7-10; tool life at 25 m/min, 35 m/min and 45 m/min [22]
Figure 10- Cutting performance for alloy 6-10 at 45m/min and their corresponding microstructural contributions [22]

Figure 11- Cutting performance at 25m/min and 35m/min for all alloys with their corresponding micro structural contribution[22]

<table>
<thead>
<tr>
<th>Alloy Number</th>
<th>Alloy Type</th>
<th>$L_1$ (25 m/min)</th>
<th>$L_2$ (35 m/min)</th>
<th>$L_3$ (45 m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1</td>
<td>104.4</td>
<td>47.1</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>M2</td>
<td>99.4</td>
<td>50.9</td>
<td>1.24</td>
</tr>
<tr>
<td>3</td>
<td>M7</td>
<td>122.3</td>
<td>35.5</td>
<td>1.10</td>
</tr>
<tr>
<td>4</td>
<td>M42</td>
<td>97.2</td>
<td>50.9</td>
<td>1.18</td>
</tr>
<tr>
<td>5</td>
<td>PM/M2mod.</td>
<td>154.5</td>
<td>59.1</td>
<td>1.18</td>
</tr>
<tr>
<td>6</td>
<td>PM/T15mod.</td>
<td>201.7</td>
<td>57.5</td>
<td>27.27</td>
</tr>
<tr>
<td>7</td>
<td>PMexp Nb</td>
<td>150.7</td>
<td>40.4</td>
<td>1.84</td>
</tr>
<tr>
<td>8</td>
<td>PMexp Nb + 3Co</td>
<td>158.9</td>
<td>53.1</td>
<td>6.75</td>
</tr>
<tr>
<td>9</td>
<td>PMexp Nb + 5Co</td>
<td>178.3</td>
<td>61.6</td>
<td>7.91</td>
</tr>
<tr>
<td>10</td>
<td>PMexp Nb + 8Co</td>
<td>179.0</td>
<td>66.6</td>
<td>19.11</td>
</tr>
<tr>
<td>11</td>
<td>T1-Mt</td>
<td>93.4</td>
<td>0.5</td>
<td>0.16</td>
</tr>
<tr>
<td>12</td>
<td>M2-Mtx</td>
<td>95.6</td>
<td>16.6</td>
<td>0.73</td>
</tr>
<tr>
<td>13</td>
<td>M7-Mtx</td>
<td>104.8</td>
<td>7.4</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Figure 12- Cutting performance for all alloys at 25/min, 35m/min and 45m/min [22]

In this study, the main focus was to compare and investigate the tool life at various cutting speeds for the above mentioned alloys. A positive correlation of tool life with tempered hardness is generally observed and the intent of increasing the tempering resistance is of course also to prolong the operating time of the tool [28];[29];[30]. But the tool life is not only dependent on the tempering resistance, wear resistance is also a crucial factor that come into play, which is for most part affected by the population of blocky primary carbides in correlation with the surrounding martensitic matrix [22]. But regardless, the tool life could work as an indicator on how the tempering resistance is connected to the presence of different alloying elements.

The following exposition is for the most part speculative if no reference is assigned and should not be mistaken to be fully based on scientific truth, but rather act as a discussion in hope of comparing previous results and investigate whether niobium could be a possible candidate to reduce the amount of used cobalt.

As can be seen in figure 8, alloy number 7 which is an experimental Nb-enriched steel, has the exact same carbon content as the LC Nb-steel in the previous study performed by B. Hribernik, G. Hackl, S. Karagöz and H.F Fischmeister and with an elemental composition that is very similar. The hardness were found to be 64,5 HRC compared to 64,2 HRC in the previous study. In comparison to the M2 steel, the experimental niobium steel exhibits better performance at both low cutting speed (25m/min) as well as for high cutting speed (45m/min). At the lowest cutting speed of 25m/min, the strongest contribution comes from the matrix strength, in other words from the contribution of both primary carbides and the martensitic matrix, as previously mentioned. The reason for the superior performance at low speed for the Nb-steel is most likely due to the presence of harder and more homogeneously dispersed NbC. The better performance at 45m/min for the Nb-steel is due to the improved temper resistance of the secondary carbides [23]. At the highest cutting speed (45m/min) the impact of the matrix strength is diminished and due to the elevated operating temperatures, one can expect the predominant effect of the matrix stability to be highly dependent on the temper resistance.

In comparison to the M42 steel which contains almost 8% cobalt, the Nb-enriched steel is yet again revealed to be better at low as well as for high cutting speeds, this even though the hardness for the M42 steel is 3HRC higher than the experimental Nb-steel. The performance at 45m/min is scarcely improved for the Nb-steel but the fact that the hardness is 3HRC units below that of the M42 steel in addition to the high cobalt content, seems once again to be a convincing indication that the niobium addition is highly responsible for the improved hot properties.

As can be seen in figure 11, the alloy that shows of the best performance at the highest speed (45m/min) is alloy number 6 (PM/T15 mod.). In comparison to the experimental Nb-steel the tool life is approximately 15 times longer. The T15 steel is an alloy that combines both hot strength from a high content of cobalt (8,07%) and tungsten (10%) as well as a high matrix strength from a high content of formed carbides. One thing that should also be taken into account is the vast difference in the amount of alloying elements for the two HSS. In T15 the alloying content is almost twice that of the Nb-steel. With a
higher amount of alloying elements the hardenability of the steel will as a consequence also increase [31]. In this case, since the differences in matrix composition and matrix philosophy is so significant between the two steels, it becomes difficult to draw any conclusions. The only conclusion that can be made for certain is that due to the T15’s improved hot properties from the high amounts of cobalt and tungsten, accompanied by its high hardness, it becomes superior to the experimental Nb-steel in terms of tool life and most likely also in red hardness.

Since the cutting performance was proven to be very similar and even better for the Nb-steel in comparison to the M42 steel, it might be possible to construct a Nb-enriched steel with a high amount of tungsten similar to that of T15 that could have comparable effect on the tool life, if not better. No such proposals of steel matrices have been found during this literature study, but might be of interest for future research.

One thing that would also be very interesting to investigate and that was not demonstrated in this study, would be the cutting performance of the HC Nb-steel from the study performed by B. Hribernik, G. Hackl, S. Karagöz and H.F Fischmeister. The higher carbon content, improving the temper resistance as well as increasing the overall hardness, would most definitely result in a better cutting performance at high speed (45m/min) compared to the Nb-steel used for this study.

In this study the addition of three different cobalt contents ranging from 3-8% to Nb-enriched steels were also investigated. As could be expected, the tool life increases in step with the increased amount of added cobalt, this due to cobalts effect in decreasing the softening and improving the temper resistance. When comparing the M42 steel with the Nb-enriched steel with similar amount of added cobalt (~ 8%), it becomes evident that the tool life is vastly improved. The tool life becomes improved by almost 11 times. Even at only 3% addition of cobalt the effect on the tool life is more than three fold compared to the M42 steel. This seems to suggest that it is possible to reduce the amount of used cobalt by the replacement of approximately 3,5 % niobium used for the steels in this study.

6.1.2 Market and outlook for Niobium

A brief market analysis was made for niobium as it seemed to be a promising substitute for cobalt in high speed steel.

Approximately 90% of all niobium is currently consumed in the form of ferroniobium in high-strength steels and low-alloy steels for the construction, automotive and pipeline industries. The remaining 10% is used in a wide range of smaller volume but higher value applications such as high-performance alloys, carbides, superconductors, electric components and functional ceramics. [38]

The vast majority of ferroniobium supply comes from Brazil and Canada, and is extracted from the mineral pyrochlore. Last year there was a global production of 64000 tonnes, 89% of which came from Brazil followed by 10% that came from Canada. The global niobium reserves are estimated to be 4,300,000 tonnes. [39] Niobium that is used in non-steel applications are often derived from other minerals, such as columbite, that is mostly produced in Africa and South America.
The price of niobium have historically been very stable. It increased a little bit in 2006, when a producer-driven doubling in prices began, but have remained stable since, at around 18 US$/lb. [41] The outlook for the price is a gentle but steady increase where spikes are unlikely.

6.2 Increased Nitrogen in High Speed Steels

Another alloying alternative to increase the hot properties in HSS, might be by increasing the amount of nitrogen. In a study performed by H.Halfa, M. Eissa, K. El-Fawakhry, and T. Mattar in 2011, the effects of a HSS sample containing 0.145 wt% nitrogen based on the AISI M41 matrix, but with half of the amount of cobalt replaced by an increase in nitrogen was compared to the conventional super hard tool steel, AISI M41. The samples in the experiment were manufactured with ingot casting and for this reason the results may be different when using PM processing. But regardless, the result could give a good indication on how the nitrogen effects the hot properties in HSS. In most ingot casted HSS, the content of nitrogen is normally in the range of ~ 0.02-0.03 wt.%, which in comparison is about a factor 10 lower. In the study [26] the effect on secondary hardening temperature as well as the morphology of carbides in presence of nitrogen were investigated. The main effect of nitrogen as an alloying element in HSS is the formation of a more well distributed and fine-grained microstructure. It is well known that nitrogen has a greater impact on the secondary hardness than carbon. It is also known that higher carbon contents results in a more effective influence of nitrogen on the hardness growth. [26]

In this study three different compositions of niobium enriched steels were also tested, but since the study is based on casting and the fact that niobium’s effect in PM processing has already been discussed earlier in this project, the results for niobium in this study will be neglected.

In the sample where half the amount of cobalt had been replaced by nitrogen (0.145 wt% \(N_2\)) proved to be superior to the AISI M41 steel, in terms of hardness as well as in secondary hardness. When comparing the two steels in their optimal state of tempering the hardness for the nitrogen enriched sample is about 4 HRC units higher. The increase in hardness can be attributed to the increased transformation of the retained austenite. The nitrogen enriched sample turned out to have a higher precipitate content in comparison to the AISI M41 steel, leading to an increase in the secondary hardness. Moreover, the increased nitrogen content resulted in minimal softening. [26] But it should also be mentioned that a total replacement of cobalt by nitrogen would not lead to a sufficient secondary hardness, according to a previous study [43].

The AISI M41 steel in this study contained 5.02 wt% cobalt, in comparison to 2.78 wt% cobalt for the nitrogen enriched sample. The result is very promising, revealing that the replacement of approximately half the amount of cobalt with nitrogen (0.145 wt% \(N_2\)), is improving the hardness as well as the secondary hardness for the steel matrix. It can therefore be concluded that a vigorous increase in the amount of nitrogen could be a solution to decrease the amount of cobalt used in HSS. The only drawback, is the fact that the investigated steels were manufactured by ingot casting, which raises the question of whether the results are applicable in powder metallurgical processing.
As can be seen in figure 13, the presence of nitrogen as an alloying element in HSS shows the best impact on secondary hardening, minimises the softening, effects the hardness profile positively and reaches the highest hardness at 625 °C.

According to the results in the article, the best results were obtained with the following weight percentages of the different steel components in the steel, presented in the table down below:

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>6.5 wt.%</td>
</tr>
<tr>
<td>Mo</td>
<td>4.21 wt.%</td>
</tr>
<tr>
<td>Co</td>
<td>2.5 wt.%</td>
</tr>
<tr>
<td>Cr</td>
<td>4 wt.%</td>
</tr>
<tr>
<td>V</td>
<td>2 wt.%</td>
</tr>
<tr>
<td>N</td>
<td>0.145 wt.%</td>
</tr>
<tr>
<td>C</td>
<td>0.87 wt.%</td>
</tr>
</tbody>
</table>

As seen in table 5 above, the content of cobalt in this type of steel is considerably lower in comparison with the HSS, it approximately contains half the cobalt amount in standard HSS. The fact that half of the original cobalt content can be reduced to almost a third of its standard amount in HSS, of 8 wt.% to 10.5 wt.% cobalt, makes this solution the best fitting alloying alternative in this study. Even though Cobalt can not be eliminated entirely, this type of solution can significantly reduce the presence of cobalt in the HSS industry.

The study of High Nitrogen Steels suggest that a microstructure environment containing cobalt, but no nitrogen, has a lower secondary hardness and is not likely to be austenitized during increased
temperatures compared to a microstructure environment with both cobalt and nitrogen [32]. When HSS with a nitrogenous environment was compared to a HSS with niobium, results shows that the HSS with a nitrogenous environment have a higher hardness. Vanadium and cobalt together with nitrogen in HSS seems to have a positive effect on the secondary hardness.

In the research in the same article, the secondary hardness and microstructure were investigated when comparing modified cast AISI 41 HSS with a addition of niobium and nitrogen with regular HSS cast AISI 41. The results showed that M6C and M7C3 were the main carbides found in HSS with nitrogen content while the main eutectic carbides found in HSS with niobium content were M2C carbides. It can be concluded that niobium alloyed HSS has a tendency of shape-, distribution- and size-improvement of the produced carbides in the steel.

The measured temperature of the secondary hardness spike for nitrogen free HSS was at 600 °C and 625°C for a HSS with a nitrogenous environment. Contrarily, when the secondary hardness was reached for niobium alloyed HSS, the temperature for a low weight percentage of niobium (0.0847% and 0.213% niobium) was 575°C and for a high weight percentage of niobium (0.645% niobium), 550°C. As the results show, a nitrogenous HSS have good heat properties, high secondary hardness, and a high hardness at high temperatures. When comparing the nitrogenous HSS with the niobium alloyed HSS, the niobium alloyed HSS have a lower secondary hardness spike. The cause of the lower secondary hardness for the niobium alloyed HSS could be the absence of cobalt, which has better hardening properties.

6.3 Aluminium as an alloying element

In very small amounts, often 0.01%, aluminium is one of the most important deoxidizing agents in steel materials in general. The content of aluminium in fine-grained steel is often near 0.015%. Refined grain steel generates higher steel ductility and toughness. Low contents of aluminium increases the high temperature strength for high temperature steels.

6.3.1. Aluminium in High Speed Steels

A rather small amount of articles concerning aluminium in HSS could be found during this project. One of the articles focused on experimentally confirming the specific effect of aluminium on the microstructure and mechanical properties of as-cast M2 HSS, as well as the effects of heat treatment of the specific steels [33]. The compositions of M2 HSS in the experiment was, in wt.%, 0.87 C, 5.58 W, 4.51 MO, 3.90 Cr, and 1.73 V. According to the article, three relevant conclusions can be drawn about the effect of aluminium in HSS:

1. Aluminium decreases the solubility of carbon in austenite, and thereby increasing the volume fraction of carbides.

2. Aluminium forms and changes the structure of M_{2}C carbides in HSS, which decreases their stability. They can be transformed into MC and M_{0}C carbides by annealing at 900 °C for 3h.
3. Aluminium increases the solubility of carbon in martensite.

An increase in hardness is also observed, in accordance with other articles. The hardness of the M2 steel increased by 2 HRC with the addition of aluminium.

The conclusions would indeed result in a better tempering resistance, as carbides will not grow as fast in the martensite phase. Hardness and red hardness would also increase as the volume fraction of carbides would be higher. The noticeable difference compared to cobalt is that secondary hardening by way of carbide precipitation might be more difficult to achieve, due to the higher solubility of carbon in martensite.

Another problem with these conclusions regarding the effect of aluminium in HSS is that they are not universal. The experiments were only performed on one type of steel, making it quite unreliable in regards to other compositions. The effect of aluminium in HSS should not be completely disregarded however, as it is generally accepted that it increases red hardness and other hot properties [12]. The problem is finding reliable sources regarding these favourable properties. The mentioned article is the only source found during this study experimentally verifying the change in mechanical properties due to the addition of aluminium. It references other articles written about the same topic, but none of them were found online, possible due to them being quite old.

6.3.2 Aluminium in Boron High Speed Steel

Aluminium as an alloying element in Boron High Speed Steels (BHSS) has special effects on the steel properties in presence of boron. The purpose of analysing the presence of aluminium in BHSS is to examine the possible impact of aluminium in HSS. Due to the lack of scientific articles and relevant information basis about Aluminium in HSS, aluminium in BHSS is therefore being analysed.

According to the experimental results in article: "Effect of Heat Treatment on Microstructures and Mechanical Properties of Al-Modified Boron High Speed Steel" microstructure of BHSS mostly consists of dendrite martensites and M₇B borides. The presence of aluminium, as a alloying element, in the BHSS has a tendency to favorize the formation of ferrite and perlite. The bulk hardness of the steel tends to get improved significantly after proper addition of aluminium and heat treatment during destabilisation. Besides this effect, the presence of aluminium also promotes the following consequent precipitation-hardening efficacy [34].

One of the most common application of BHSS is roller materials, due to their toughness and higher wear resistance. In this study the obtained properties after the addition of aluminium in the steel was investigated at various tempering temperatures. The properties of interest was aging-hardening and the change of microstructure of tempered BHSS. Some of the investigation techniques behind this experiment were: X-ray diffraction (XRD), HR-150A Rockwell hardness-test machine and scanning electron microscopy (SEM). The experimental results in the article showed an increase of the bulk hardness when the destabilized temperature was enhanced.
The formed fine-grained microstructure from the low aluminium content, comes typically in combination with silicon in HSS. The obtained results in this study indicate that the $\delta$-Fe phase gets directly converted to $\alpha$-Fe and the austenitic phase gets reduced to a small region when the amount of aluminium in the steel attains 1.5 wt.% during quenching [35].

Higher contents than 1.5 wt.% aluminium results in decomposition of $\text{M}_7\text{B}$ borocarbides. High additional amounts of aluminium leads to decreased level of hardness by stabilizing the ferrite phase formation. In the article [36], it is claimed that the presence of aluminium in BHSS, as an alloying element, decreases the quenched toughness and increases the carbon solubility level in the steel matrix. Aluminium has the ability to dampen transformation of martensitic state in order to favour ferrite formation. A content of 0.6 wt.% Aluminium leads to a remarkable increase of fracture toughness. Furthermore, the presence of aluminium in BHSS enables formation of dislocations with high density [35].

The phase diagrams in the experiment referred to in the article were compiled by the software program Thermo-Calc with the following alloying element contents in the steel: 0 % - 1.0 % carbon, 6.0 % chromium, 2.0 % boron, 0.5 % manganese, 1.0 % vanadium, 1.0 % silicon, 4.0 % molybdenum and the concentration of aluminium was 0 %, 0.5 %, 1.0 %, 1.5 %, 2.0 %, 3.0 %, 4.0 %. Aluminium replaces some of the molybdenum and tungsten. The presence of aluminium in BHSS results in an increase of the red hardness. The most significant effect of aluminium in BHSS is the ability to improve the red hardness, tempering stability, and hardness [36]. According to the experimental results in the article it can be concluded that the austenitic area decreases to a smaller region in the phase diagram as the content of aluminium increases. During the quenching, even $\delta$-phase will be directly recomposed to ferrite. Besides the positive effects of BHSS, the main disadvantage with the steel is the high price of boron.

### 6.4 Silicon in High Speed Steels

Silicon is one of the alloying elements in today's HSS. Different kinds of HSS can be viewed in table 6. The composite numbers stands for wt.% contents.

<table>
<thead>
<tr>
<th></th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeMo$<em>{16}C</em>{0.9}$</td>
<td>$\text{W}_6\text{Mo}_3\text{Cr}_2\text{V}_4$</td>
<td>$\text{WMo}_3\text{Cr}_2\text{V}_4$</td>
<td>$\text{W}_6\text{Mo}_3\text{Cr}_4\text{V}_2$</td>
<td>$\text{WMo}_9\text{Cr}_3\text{V}_4$</td>
<td></td>
</tr>
</tbody>
</table>

The HSS in the table above do not have silicon as an alloying element. As an experiment, silicon was added to the steels in different amounts. Results show that an amount of maximum 3.5 wt.% silicon increases the red hardness for the steels 1, 2 and 3 in the table above. The silicon in the HSS 5 had an opposite effect with a decreased hardness. The reason to this differences is due to the amount of silicon added. This shows that the amount of silicon have a big impact on the secondary hardness, for example, the smaller amount of silicon added to HSS 5 in table 6, the higher secondary hardness.
Silicon is sensitive to high temperatures, which gives alloys with silicon an upper limit of the red hardness. After exceeding the limit of 600 °C, the hardness of the steel will decrease. However, an exception of this is for HSS 4 in table 5, as the red hardness increases after 600 °C. The major improvement is an increased formation of secondary carbides, like cementite. This is due to the silicon-containing environment in the HSS, which contributes to an increased red hardness. The articles suggested the reason behind the increased hardness is the changing amount and size of the carbides caused by the content of silicon in the HSS. With a higher amount of tungsten in the steel, more carbides are formed. But silicon contributes to a better martensite formation [37].

6.5 Molybdenum and Tungsten in High Speed Steels

High temperature resistance is an important characteristic of cutting tools, which is obtained by adding molybdenum and/or tungsten. The two metals combined with carbon increase the wear resistance by forming carbides, which decomposes and makes the steel harder during high temperatures [37]. According to a study about the effect of cobalt in HSS, the appearance of molybdenum and tungsten, both with and without cobalt, shows an increase in hardness [10]. Even though there are positive results on the secondary hardness of HSS without any content of cobalt such as M61 and M62 mentioned above, it is not as easy to find new compositions without cobalt. The reason for this is that cobalt have good hot properties and characteristics which can not be obtained from tungsten and/or molybdenum.

7. Result

7.1 Economy of cobalt

The cobalt price does not seem to be heading anywhere else but upwards in the near future. The battery industry seems to be relying on cobalt for many years to come. The market for electrical vehicles, as well as phones, computers and more, relies on rechargeable batteries containing cobalt. The market will continue to expand and demand will rise with it. At the same time, there are no signs of improvement of the stability of the largest cobalt producing country, the Democratic Republic of Congo, which also contributes to the market being volatile and unpredictable. The new mining sites planned to come online and the increasing interest in recycling will most likely not be enough to decrease the price of cobalt but may help to impede the current surge.

7.2 Alternative alloying elements

Regarding the replacement of cobalt in HSS, niobium was chosen as the most suitable candidate. Whilst not achieving as good hot properties as the best cobalt HSS, it has still shown significant improvements.
7.2.1 Niobium

Niobium is an alloying element that has shown to be very promising in order to improve the hot properties of HSS. Due to niobiums improved effect on the secondary hardness as well as its contribution on the refinement of the grain size and homogeneity of the steel matrix, the hardness has shown to persist to higher temperatures.

7.2.2 Increased Nitrogen

A higher amount of nitrogen present in HSS can improve the hot properties of the steel and at the same time reduce the amount of used cobalt alloying significantly in the steel. This alternative alloying method allows the cobalt concentration to reduce by a factor 2 (5.02 wt.% to 2.78 wt.%), which seems to be a very promising solution to partially replace a high amount of cobalt in HSS.

7.2.3 Aluminium

Aluminium as an alloying alternative has shown more promising improvements, however, the main reason why aluminium cannot be considered as a possible alloying substitute to cobalt is because the access to relevant articles about the aluminium effect in HSS was limited. This limitation mainly depends on the search difficulty within the preferred subject area. Despite the lack of articles and studies with full relevance, different studies with partial relevance were analysed in the report. From the obtained information till this day in this study, it can be concluded that aluminium may be a good alternative substitute to cobalt in HSS.

7.2.3.1 Aluminium in BHSS

As mentioned before, the microstructure of BHSS mainly contains dendrite M₇B borides and martensites. When aluminium is added as an alloying element in BHSS, the formation of ferrite and perlite becomes more favored. Another effect in presence of a proper amount of aluminium during heat treatment is the remarkable improvement of the bulk hardness of BHSS. In addition aluminium also tends to promote the consequent precipitation-hardening efficacy. However, the results and positive effects of aluminium are solely based on BHSS and not regular HSS, creating barriers and limitations to give an accurate analysis of the alloying impacts.

7.2.3.2 Aluminium in HSS

Aluminium has tendency to decreases the solubility of carbon in the austenite phase and consequently improve the carbide volume fraction. The main effects of aluminium in HSS are; the modification in structure of the M₇C carbides - decreasing the steel stability, increasing the steel hardness, improving the carbon solubility in the martensite phase. Another positive effect of aluminium in HSS is the increases of the tempering resistance, which occurs due to the fact that the growth of the carbies in the martensite phase gets reduced. However, besides the multiple positive effects of aluminium in HSS there were no other experimental credible articles found to support the conclusions in this particular research.
7.2.4 Non-promising alternatives

Other alloying alternatives were analysed, which lead to less promising conclusions related to the hot properties of HSS. Those alternative alloying elements were Silicon and a combination of Molybdenum and Tungsten.

7.2.4.1 Silicon

According to the research study, the smaller amount of silicon added to HSS, the higher secondary hardness becomes. Silicon is very sensitive to higher temperatures. Silicon alloyed steels have therefore an upper limit to the red hardness due to the dependence of the temperature level. The hardness of the steel with a silicon content decreases after exceeding a temperature limit of 600 °C. This quality makes silicon an improper candidate and alloying element in HSS due to the fact that high speed steels undergo high temperatures above 600 °C.

7.2.4.2 Molybdenum and Tungsten

An extra addition of molybdenum and tungsten in HSS improves the secondary hardness without the presence of cobalt. However, it is hard to maintain the good hot properties caused by cobalt solely by increasing the content of molybdenum and tungsten and eliminating cobalt entirely. Thus, this solution is not suitable either in order to replace or decrease the amount of cobalt.

8. Discussion

From the results it becomes evident that three alloying alternatives is of particular interest, when it comes to improving the hot properties of the HSS, namely niobium, nitrogen and aluminium. Niobium was found to be of most interest. The broad support of relevant articles in the field of powder metallurgical processing, in correlation with the low and stable price of niobium in comparison to cobalt is the motivation to why it is considered most interesting.

Increasing the nitrogen content was also found to be a promising alternative to cobalt. The only drawback is that the study was based on ingot casting, which raises the question of whether the results are applicable in powder metallurgical processing.

There are various reasons why the other alloying alternatives, such as aluminium, silicon, molybdenum and tungsten, are not suitable as substitutes to cobalt. Aluminium may be a promising alloying alternative according to various information sources. However, due to the lack of relevant articles containing scientific in-depth information it cannot be stated that aluminium is suitable to replace or reduce the amount of cobalt and at the same time maintain the properties of HSS. The reason why silicon is a improper candidate is due to the fact that the hardness of the steel containing silicon decreases after peaking at 600 °C. Due to this property it can be concluded that silicon is a not a appropriate alloying alternative, thus HSS undergo high temperature processes above 600 °C. When it comes to molybdenum
and tungsten as alloying alternatives it is not possible to maintain the steel properties by only increasing the amount of molybdenum and tungsten while cobalt is being eliminated.

9. Conclusion

From an economical point of view cobalt will not be a sustainable alloying element in High Speed Steels due to its major competitor application in the battery market causing a significant increase of the price, as well as the situation in the DRC making the largest supplier of cobalt uncertain and unpredictable. The effect of cobalt in HSS is mainly on the red hardness and tempering resistance. To replace cobalt, several alternative alloying elements have been researched. Among the most promising are niobium, nitrogen and aluminium. Niobium were found to be most interesting. The positive effect of niobium could be regarded as three-fold. The first contribution is the refinement of grain size and homogeneity of the primary carbides, which increases the overall hardness. The second effect is that the addition of niobium shifts the phase equilibria in such a way that the precipitation of primary carbides mainly will be in the form of hard and stable NbC. The majority of the other alloying elements will hence be precipitated as secondary carbides during tempering. The final effect is an increase in secondary hardness, as a consequence of the large amounts of vanadium and smaller amounts of niobium that is being precipitated during tempering to the secondary carbides. This enables a high matrix hardening potential in the optimal state of tempering. Niobium as an alternative have a great support of relevant articles in the field of powder metallurgical processing.

References


http://www.visualcapitalist.com/cobalt-precarious-supply-chain/
(read 2018-04-16)

(read 2018-04-16)

https://www.cobaltinstitute.org/statistics.html
(read 2018-04-19)

(read 2018-04-16)
[6] T. Wilson, We’ll All Be Relying on Congo to Power Our Electric Cars, 2017-10-27
(read 2018-04-12)

https://www.supplychain247.com/article/a_big_supply_chain_issue_-_cobalt_minning
(read 2018-04-23)

https://www.ft.com/content/dbf18e0e-416a-11e8-803a-295c97e6fd0b
(read 2018-04-19)

(read 2018-04-23)


https://link-springer-com.ezproxy.its.uu.se/content/pdf/10.1007%2FBF00654791.pdf

https://www.asminternational.org/documents/10192/1849770/06022g_sample.pdf

https://link.springer.com/content/pdf/10.1007%2Fs11837-998-0352-0.pdf
(read 2018-04-19)

http://www.visualcapitalist.com/top-10-reasons-investors-cobalt/
(read 2018-04-19)

[15] J. Harvey, Metal recyclers prepare for electric car revolution, 2017-11-17
https://www.reuters.com/article/us-batteries-recycling-analysis/metal-recyclers-prepare-for-electric-car-revolution-idUSKBN1DH1DS
[16] Investing News. Cobalt market forecast and cobalt stocks to buy, 2018

http://palisaderadio.com/mike-beck-the-most-supply-constrained-commodity-on-earth-by-far/
(read 2018-04-19)

https://worldview.stratfor.com/article/cobalt-metal-poised-peak
(read 2018-04-16)

(read 2018-05-09)

(read 2018-05-14)


https://link.springer.com/article/10.1007/BF02674013


[31] ScienceDirect. *Alloying element*, 2018
https://www.sciencedirect.com/topics/chemical-engineering/alloying-elements

https://link.springer.com/content/pdf/10.3103%2FS0967091217010132.pdf


[34] S. Ma, W. Pan, J. Xing, S. Guo, H. Fu, P. Lyu. *Materials Characterization 132, Microstructure and hardening behavior of Al-modified Fe-1.5 wt.% B-0.4 wt.% C high-speed steel during heat treatment*, 2017, p.1-9
https://reader.elsevier.com/reader/sd/0DA634FDE6B8E1B38E997D8AB217A91435A501A56873E7E87DCF02AA131DEF650DBCC49C1E10E7A3EBBD6BCF6788C023


https://ac.els-cdn.com/S1359645497001213/1-s2.0-S1359645497001213-main.pdf?_tid=5b0cfab7-3fd7-4bd0-acec-57b54a8ba965&acdnat=1526896214_8bd94b7d1ec25da18fa1939e5700800

[38] Roskill. *Niobium: Global Industry, Markets & Outlook 2018*
https://roskill.com/market-report/niobium/


https://ac.els-cdn.com/00433164889900811/1-s2.0-00433164889900811-main.pdf?_tid=b481da93-1b95-4949-a328-6001684f2e&acdnat=1526893698_700f84af34d302bb1c3c80fc87e763e

[41] Metalary. *Niobium Price*
https://www.metalary.com/niobium-price/

http://www.bucorp.com/media/pm_tool_steels_metallformingmagazine03.pdf


Articles

The following chapter is an exposition of articles that were investigated during the literature study but were not found to be of sufficient interest to be a part of the report. A relevance ranking has been assigned to the end of each article in the list below, ranging from 1-3, with the following descriptions:

(1): Somewhat of interest but still not relevant for this study
(2): Not relevant
(3): Not translatable with given means or linguistic abilities of the group

To each article a short motivation will be made, explaining the reason behind the individual ranking.

Motivation: The article contains information about phase equilibria of various niobium enriched HSS. However, the steel were made with conventional processing which makes it irrelevant in this study.


Motivation: The article was containing some interesting information about cobalt and its effect on HSS, however the information was insufficient for this article.


Motivation: The article was containing some interesting information about cobalt and its effect on HSS, however the information was insufficient for this article.


Motivation: A master thesis about additive manufacturing and 3D printing materials. The article has no relevant information for this article.


Motivation: The article probably contains useful information regarding cobalts effect in high speed steel, but it was written entirely in german, and no useful translation was achieved.


Motivation: Article was written in Japanese and since no person in the group knows Japanese, we could not translate.


Motivation: The article was containing some interesting information about cobalt and its effect, however the information was insufficient for this article and did not handle HSS.