High Performance Steel for Percussive Drilling

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Abstract

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Atlas Copco Secoroc AB are searching after new bulk materials for drill heads that are used in percussive drilling in order to improve their strength and durability. The aim of this project is to assist Atlas Copco in this search and provide them with further information regarding material properties, alloying elements, suppliers, etc.

A literary study was carried out in order to identify materials that had UTS and KIC more than or equal to 1700 MPa and 70 MPa*m^1/2, respectively. Materials that fulfilled these criteria were T250 grade maraging steel, Cobalt free maraging steel, High cobalt maraging steel, 300 grade maraging steel, AerMet 100, AF1410, SS3, M54, 300M, 4340M and PremoMet. These were categorized into maraging steels, high alloy secondary hardened steels, and low alloy steels, and were then further researched.

The material with the highest combination of UTS and KIC was M54 followed by AerMet 100; while AF1410 had the highest KIC but a low UTS, and PremoMet had the highest UTS but a low KIC. Maraging steels and HASH steels have a similar price range, while low alloy steels are much cheaper.
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1. Concepts

A summarized list of material concepts is presented in order for the reader to obtain a better understanding of the report.

**Corrosion fatigue**
Corrosion fatigue refers to cyclic stress in corrosive environments. Strength is usually lower in corrosive environments than in air; partly because corrosion pits on the surface act as crack propagation sites, but also because the crack propagation threshold value is lowered [1]. In other words, failure occurs after fewer cycles and at lower loads in a corrosive environment [2].

**Fracture toughness** ($K_C$)
Fracture toughness ($K_C$) is the resistance to crack propagation. $K_C$ is dependent of thickness for relatively thin specimens. However, it is independent when the thickness is much greater than the crack, which allows the condition of plane strain. Therefore, plane strain fracture toughness ($K_{IC}$) is usually measured for thick specimens. This property is quantitative and specific for a certain material and depends on microstructure, temperature, strain rate, etc. [3]. Moreover, toughness depends on the ease of cross slipping during plastic deformation in the material [4]. Henceforth, $K_{IC}$ will be referred to as fracture toughness.

**Impact energy**
Impact energy (also called notch impact) is measured by Charpy or Izod impact tests. They measure the required energy to break a bar with a V-notch by comparing the height of a pendulum before and after an impact blow. Hence, it is used to determine fracture properties. Impact energy is mostly used for comparison since it is more qualitative than for example $K_{IC}$ [3].

**Impact toughness**
Impact toughness is defined as the energy required to break a standardized shaped bar with a cross section of 1 cm$^2$ and can be measured with Charpy V-notch (CVN) [5].

**Impact strength**
Impact strength is the energy required to break a grooved machined test piece and can be measured with Charpy tests at controlled temperatures or Izod tests at ambient temperatures [6].

**Precipitation hardening**
Precipitation hardening involves solution treatment, quenching or cooling, and age hardening or precipitation. Solution treatment at high temperatures dissolves precipitates, and other potential alloying elements, or allows them to form a supersaturated solution before the material is rapidly cooled. Precipitates are formed during aging and increase the hardness and tensile strength of the material. Aging often involves heating, but also occurs at room temperature over time. Although, too high aging temperatures result in over-aging, which in turn results in larger grains, longer elongation, and lower hardness [7].
**Solid solution strengthening**
Solid solution strengthening is a strengthening mechanism where alloying elements solute in the matrix and act as substitution defects. This makes the structure heterogeneous and hinders dislocation movement, which strengthens the material [8].

**Stress corrosion cracking (SCC)**
Stress corrosion cracking (SCC) is caused by static loadings (external or residual). The cracks are intergranular and/or transgranular, and have a slow propagation rate before the stress is high enough for final failure. SCC is specific to a certain environment and therefore, an environment that causes SCC in one alloy may not cause it in another. It occurs in alloy/environment combinations where a film is formed on the metal surface, which makes SCC an important property for corrosion resistant alloys [9]. This property is sometimes described with its threshold stress intensity, $K_{SCC}$ [10].

**Tempering**
Tempering is a process that can make brittle martensitic steels more ductile and tough. It involves heating steel below the eutectoid temperature for a certain amount of time [3].

**Ultimate tensile strength (UTS)**
Ultimate tensile strength (UTS) is the maximum stress a material can withstand before elongating to fracture. Before this point, the deformation is uniform in the narrow region of the tensile specimen, but afterwards it is contained in the neck formed [3].

**Ultra high strength (UHS) steel**
Ultra high strength (UHS) steel is a category of steels with a minimum yield strength of 1380 MPa [11].

**Wear resistance**
Generally, wear resistance is a tribological property that is surface related. As a result wear resistance is related to properties such as hardness, structure, surface roughness and impurities. It can therefore be enhanced by surface treatment. Since wear resistance is dependent on the material system and is not a material property, it is rarely expressed in numbers [1].

**Yield strength**
Yield strength is the amount of stress a material can withstand before entering the plastic region. For materials with a linear elastic region, an offset method can be used to determine yield strength by locating where the stress-strain curve deviates from elasticity with 0.2%. For materials with nonlinear elastic regions, it is determined with the stress that produces an arbitrary defined amount of strain [3].
2. Introduction

2.1 Background

The art of rock drilling has been a cornerstone in heavy industry for centuries, with numerous applications such as tunneling, mining, and construction. It is of immense importance to continuously develop smarter and more effective tools in order to maintain a leading role in the world market. Therefore, Atlas Copco Secoroc AB - a world leading developer and manufacturer in this field - wants to produce and deliver tools with improved performance and life expectancy to their customers. The company is funding this project with the aim to identify new materials for rock drilling tools and more specifically, new bulk materials for the drill heads (Figure 1) [12].

Today’s drill heads are made out of a bulk of common rock drilling steel 6418. Small bits of cemented carbide are attached to the top of the drill head, where they function as the primary cutting material. The drill heads have a life expectancy of approximately 4 hours if they run about 3 m/min. The drill heads can drill about 100 m before they have to be regrinded, and they can be regrinded about eight times before they have to be replaced. This gives about 800 m of drilling, but in some cases they do not last as long. The drill heads most often drill in granite, but also in limestone [13]. On the Mohs hardness scale, limestone and granite obtains a hardness of 3-4 and 6-7, respectively. Converted to Rockwell hardness, these values are around 0 HRC for limestone and between 45-60 HRC for granite [14-15].

Two of the more important material properties for rock drilling are ultimate tensile strength (UTS) and fracture toughness (K\text{IC}). UTS is the maximum stress a material can withstand before elongating to fracture, while K\text{IC} is the resistance to propagation of cracks. Increased strength usually leads to decreased toughness [3]. However, there are exceptions [16], which make materials with high values in both UTS and K\text{IC} of great interest. For this project, a minimum requirement of these properties was set to 1700 MPa in UTS and 70 MPa*m\text{1/2} in K\text{IC} by the project group in agreement with Göran Stenberg at Atlas Copco Secoroc AB. Materials that fulfill these requirements, illustrated by the large blue area in Figure 2, are to be further investigated [13]. Materials that do not are either discarded or put in Appendix.
According to Atlas Copco Secoroc AB other properties are also of importance and should be taken into consideration for this application. Rock drilling often takes place in a corrosive (for example moist and salty) environment, which makes corrosion fatigue a contributing factor to the wear of the drill head. Resistance to corrosion is therefore an important property. High working temperature of the drill head is another factor to take into account. The drill tip can reach up to 700°C locally during drilling, but the temperature quickly decreases afterwards. However, it is harmful for the thread (which attach the drill head to a tube or a rod) to reach temperatures above 200°C. The strength of many metals decreases significantly at higher temperatures, which makes them unsuitable for high temperature drilling. In addition, bending toughness, hardness, fatigue strength, wear resistance, alloying elements, manufacturing processes, applications, suppliers, prices, and more are also of interest for Atlas Copco Secoroc AB [13].

2.1.1 Maraging steel history

A material group that might be suitable for percussive drilling is maraging steels. These were developed in the USA in the 1940s when it became known that magnetic alloys, such as Fe–Ni–Ti–Al alloys, could undergo heat treatments in order to be hardened. Improvements of
these steels were made in a period of time, which resulted in addition of cobalt and molybdenum. Maraging steels were originally developed for specialized aerospace and military applications, and were introduced to submarine hulls in the 1960s. However, the first grades of maraging steels proved unsuitable for that application, but more suitable for tools and dies [17].

In the 1970s, the availability of cobalt sharply decreased, resulting in a rise of material cost [17]. In addition, cobalt powder is harmful for workers [18]. This demanded a development of cobalt free maraging steels with similar mechanical properties. Hence, a variety of steels with different alloying elements were developed. As a result, steels with lower amount of nickel and precipitates containing aluminum, titanium and copper were found. In general, these cobalt free maraging steels did not have as good properties as the ones containing cobalt, but they seemed to be good enough for their area of use [17].

In the beginning, maraging steels contained 20 wt% or 25 wt% nickel, but the amount of nickel was later reduced to 18 wt%. This development was founded on the appearance of brittleness at high-temperature strength levels for steels with higher amounts of nickel. But also because they demanded complicated annealing and aging treatments. A lower amount of nickel improved fracture toughness and fatigue, yield and tensile strength, which made these steels achieve the demanding requirements for the aerospace industry [19].

2.2 Aim

Atlas Copco Secoroc AB are searching for new materials for drill heads, in order to develop stronger and more durable drill heads. The aim of this project is to assist Atlas Copco Secoroc AB’s search while also providing further insight on effects of different alloying elements, manufacturing processes, and how they affect the properties of the final product.

2.3 Goal

The goal of this project is to identify new materials with longer life expectancy and hence a better performance than common rock drilling steel 6418.

3. Method

This project was a literature study to identify appropriate materials for drill heads with a focus on ferrous alloys, since they tend to be suitable for percussive drilling regarding UTS and $K_{IC}$ while being cost efficient. A study visit was made at Atlas Copco Secoroc AB in order to learn
how the final stages of the production works, but also to get a better insight of the challenges the materials have to face. To assure that the project progressed in a desired direction, weekly meetings were held via Webex with the project owner Göran Stenberg.

First, a scanning of ferrous alloys was conducted in order to identify existing and under development materials that met or exceeded the set UTS and $K_{IC}$ threshold. The identified materials were then researched in depth and an overview concerning material properties and applications were compiled. These materials were included in a halftime report and presentation. For the final report, further research on properties, alloying elements, prices, applications, and suppliers was carried out and a few new materials were added. A table with all of the materials was made in order to obtain a better overview. Materials with properties that almost fulfilled the UTS and $K_{IC}$ requirements, or materials with unknown UTS or $K_{IC}$, were placed in an appendix. Some of these materials exhibited properties somewhat similar to those in the actual report, which could provide Atlas Copco Secoroc AB with enough information to determine whether the material is worthy of further investigation.

The literature studies mainly involved reading articles about existing and available materials. Primarily, scientific articles and books were used to collect general data, but company datasheets and websites were used when necessary. Other ways to get information was contacting people with knowledge of the industry. A negative aspect of retrieving information from companies is that they can be less trustworthy. Since we did not necessarily confirm the collected data, it was important to be aware of the source and its intentions. However, these sources can also provide specific data for the actual material Atlas Copco Secoroc AB may purchase.

The Vancouver system was used for references in the report. This referencing system was chosen because it frequently occurred in articles while conducting our research and was deemed suitable for this report.

Our project group consisted of four chemical engineering students with materials focus and one materials engineering student. The project time frame was ten weeks and our work was iterative. We worked together almost everyday, and we had follow-up meetings to check the progression of each individual and the project as a whole. In addition, regular contact was held with project manager Ibrahim Alaff and technical supervisor Mats Boman.

One of our challenges in this project was to write a coherent report since our sources do not have the same main focus, which made it difficult to collect the same kind of information. Another challenge was that we were five authors with different ways of phrasing and expressing information in text, which also affected the coherency.
4. Theory

4.1 Maraging steels

Maraging steels are a category of UHS steels where martensite is formed after quenching and thereafter aged at around 500°C. Precipitates such as copper clusters, Ni$_3$Ti and NiAl (intermetallic phases) are formed during the aging process which results in a stronger material due to precipitation hardening. Not only toughness and tensile strength are enhanced, but also hardenability, ductility, and weldability. In addition, only a simple heat treatment is necessary [17]. Maraging steels are precipitation hardened steels often based on 18 wt% nickel, but other amounts of nickel also occur [20].

Maraging steels are named after their nominal UTS in ksi, for example M250, M300 and M350. The 'M' represents maraging steel and is commonly exchanged for C or T$^1$ which implies high concentration of cobalt or titanium, respectively [20]. A higher alloy number indicates higher amounts of cobalt and titanium [22].

Intermetallic phases are often preferable to carbides that can also be formed during the aging process [17, 23]. Intermetallic phases are formed by primary crystallization without eutectic transformation that provides a refined dispersion even before heat treatment. This dispersion is maintained after deformation (e.g. forging or rolling), better than for networked, eutectic carbides. In addition, intermetallic phases have diameters up to 2-3 μm and are therefore smaller than carbides. As a result, the damaging effect of the precipitates on strength and ductility is lower for intermetallic phases. But these properties are also less affected by the degree of deformation [17].

Maximum hardness for metals with intermetallic phases is achieved when the precipitates are smaller than 5-20 nm with distances of approximately 100 nm, both of which are lower than for carbides [17].

A lower embrittlement effect is achieved for intermetallic compounds formed in low carbon or carbon free martensite (or austenite) than that of carbides. This due to their fine dispersion in these phases, especially in the presence of nickel, despite their small dimensions. A higher volume fraction of intermetallic phases increases the embrittlement effect, but they maintain a higher level of dispersion than carbides [17].

Another difference between intermetallic phases and carbides is the temperature and time necessary for precipitation hardening. The temperature used to achieve maximum hardness depends on the matrix and what intermetallic phase is precipitated. Lower temperatures are used for steels with intermetallic phases than for austenitic steels with precipitated carbides. But a longer hold time is necessary to obtain maximum hardness of nickel steels. For nickel steels, the hardness increases rapidly during the first 10-15 minutes of precipitation hardening and reach maximum hardness after 5-10 hours. This while carbide strengthening reaches maximum hardness after 30-40 minutes. Reduced hardness occurs when clusters

$^1$ Does not contain cobalt.
are present. These are formed at higher aging temperatures for intermetallic phases than for carbides [17].

Maraging steels are useful in areas where resistance against crack formation and the ability to withstand high loads are of importance. However, most maraging steels are not stainless. Hence, some applications demand coating or plating in order to obtain corrosion protection. It would be preferable to use stainless steel with equivalent mechanical properties that does not need coating with regard to manufacturing, environmental and reliability factors [17].

Maraging steels are produced with double vacuum melting by Vacuum Induction Melt (VIM) followed by Vacuum Arc Remelt (VAR) in order to obtain annealed and descaled steel, at least for the C-type. This provides a rather soft material (30-35 HRC) that is later hardened by aging [24-25]. No protective atmosphere is required for annealing and aging of maraging steels due to their low carbon content. This type of steels is purchased in the solution annealed condition [24].

Machining can be performed on both solution treated and precipitation hardened maraging steels by conventional techniques. Furthermore, the machinability is as good or slightly better than that of conventional steels of the same hardness [26]. It is important to use rigid equipment and firm tool support, but also very sharp tools and an abundance of cutting fluids [24, 26]. These cutting fluids must be free of low-melting components, such as lead and sulfur, because their residues can cause embrittlement during subsequent heat treatment [26].

Maraging steels exhibits approximately two times slower corrosion rates than that of conventional steels in industrial and marine environments. They also show slightly better corrosion resistance in saline and acidic solutions. 18Ni maraging steels have uniform corrosion in atmospheric environments, which results in the surface getting covered by rust. A study shows that their corrosion behavior at the corrosion potential is dependent of pH, but also of intermediates remaining on the surface in the active region since these favor passivity [27].

Dilatometry of a cobalt free maraging steel with the chemical composition Fe-18.9Ni-4.1Mo-1.9Ti (wt%) (see Figure 3) shows expansion up to 510°C where precipitation starts. As the temperature rises, the material expands linearly before it contracts when austenite starts to form at 602°C (Aₜ). This contraction slows down at 660°C and linear expansion is resumed at the austinite finish temperature (Aₜ) of 720°C. Complete solution is reached after holding 900°C for 30 min. During cooling, there is a drastic expansion due to the rapid formation of martensite at 135°C (Mₜ) until the martensite finish temperature of 25°C (Mₘ) is reached [28]. Martensite formation results in expansion because the structure is changed from FCC to BCT through polymorphic transformation [3]. The dilatometric curves for T300 (Fe-18Ni-2.4Mo-2.2Ti, wt%) and C350 (Fe-18.77Ni-10.8Co-4.2Mo-1Ti, wt%) do normally not return to zero, but below the original point. This residual strain might be a result of the martensite phase transformation and its thermal and transition changes [28].
Figure 3 shows the dilation of a 2000 MPa grade cobalt free maraging steel specimen during heat treatment [28].

It may happen that not all austenite is transformed to martensite during quenching. This is called retained austenite and is obtained when steel is not quenched to or below $M_f$ [29]. As a result the tensile strength is decreased [30]. In some cases, a cryogenic treatment (CT) or refrigeration is used to reduce the amount of retained austenite. These use temperatures below -70°C to further transform austenite to martensite. Consequently, the hardness is increased [31-32]. In addition, a study shows that CT increases hardness and UTS, but reduces fracture toughness [30].

4.2 High alloy secondary hardened steels

High alloy secondary hardened (HASH) steels are a type of quenched and tempered (QT) steels. After an initial solution tempering the steel is quenched, followed by tempering to initiate a precipitation reaction. A high tempering temperature is required to optimize precipitation, at which many simpler steels would soften. In addition, HASH steels precipitate a fine dispersion of carbides that leads to hardening, hence the name secondary hardened [11, 33].

The conditions required for the hereafter called “secondary hardening” to occur, differ depending on the chemical composition of the material. The general principle for secondary hardening is that martensite is initially formed in the material through either a certain degree of cold work or quenching. Thereafter the material is tempered in order for metal carbides to precipitate, unlike the case with maraging steels where the purpose is to precipitate intermetallic phases [11, 17].
During tempering, coarse cementite particles are formed when martensite decomposes, which are later replaced by a dispersion of fine alloying carbides [11]. This raises material hardness and temperature resistance. These two properties depend on the precipitate concentration (depicted in Figure 4), which in turn depends on the amount of alloying elements in the material [34]. As illustrated in Figure 4, the martensite decomposition increases with increasing temperature. Meanwhile, carbide precipitates form continuously up to a certain temperature, after which they start to decompose. These two factors affect the material hardness and can be combined into a tempering curve, which shows how hardness is related to temperature [34].

At room temperature, HASH steels have BCC structure. BCC structure is harder to form than that of metals with a FCC structure, but easier than that of those with HCP. Forming these materials using various methods are therefore possible at room temperature [35].

Due to the general high strength and hardness of HASH steels, machining is difficult compared to softer steels [36-37]. This difficulty is increased for materials that have been heat treated to achieve higher strength and hardness. Still, the method is feasible when conducted under appropriate conditions (regarding cutting tools, work temperatures, etc.) [35]. Additional secondary hardening may occur due to the heat that emerges from friction during the process. This may cause further difficulties [38].

4.3 Low alloy steels

Low alloy steels are a category of UHS steels that are recognized by their low content of alloying elements, often less than 8 wt% [8]. Their hardenability is primarily a result of precipitated iron carbides, but their alloying elements also strengthen the steel through solid solution strengthening [11].

To preserve strength while increasing $K_{IC}$ of low alloy steels there are three main factors to consider: retained austenite, mixed microstructures, and control of non-metallic inclusions [11].

Retained austenite can be achieved in two different ways: high temperature austenitizing (HTA) treatment, or by adding austenite stabilizers. It has been documented that HTA treated low alloy steels can obtain a 90% increase in $K_{IC}$ without any decrease in strength, while the Charpy impact energy decreases. Furthermore, alloy additions that act as austenite stabilizers will improve $K_{IC}$ significantly (e.g. a 65% improvement for Fe-O.3C-4Cr steel with a yield strength of 1300 MPa) without lowering other properties [11].
Mixed microstructures (e.g. bainite with martensite) leads to increased $K_{IC}$. As an example, 4340 steel went from 54 MPa$m^{1/2}$ to 78 MPa$m^{1/2}$. The only way to mix microstructures in a controlled manner is through isothermal heat treatment, which is uncommon in the industry \[11\].

Control of non-metallic inclusion is mostly seen as control of sulfur inclusions that affect the toughness in a negative way. The sulfur levels are best controlled in the early stages of the manufacturing process. However, this adds costs in the manufacturing process \[11\].

When making low alloy UHS steel, the austenitizing is usually performed at 870°C, but can also be conducted at 1200°C. Thereafter, the steel is quenched. This is followed by tempering, where it is recommended for low alloy UHS steels to use temperatures up to 250°C. However, even higher temperatures are used for some steels (e.g. 300M). Lath martensite crystals will remain unchanged under 250°C and therefore, strength is maintained. In addition, transition carbides are formed during tempering, which help the steel maintain high strength. If higher tempering temperatures are used, the retained austenite turns into more carbides, or ferrite and cementite, which cause embrittlement. This means that the material will become brittle at higher temperatures than 250°C \[11\].

This type of quench and tempering formed two types of carbides: ε-carbide and η-carbide. The former has a hexagonal close-packed crystal structure with the composition Fe$_{2.4}$C, while the latter has an orthorhombic crystal structure with the composition Fe$_2$C \[11\].

### 4.4 Alloying elements

#### 4.4.1 Maraging steels

Hardening alloying elements of maraging steel are titanium, vanadium, aluminum, beryllium, manganese, molybdenum, tungsten, niobium, tantalum, silicon and copper \[28\]. Several other alloying elements can also have an impact on the material properties. Elements treated in this section are cobalt, molybdenum, titanium, nickel, chromium, carbon and silicon.

**Cobalt** does not have an immediate effect on the material strength since it is solved in the martensitic matrix. However, maximum effect of cobalt in maraging steels is achieved when co-alloyed with molybdenum due to a special Co-Mo interaction that strengthens the material. Cobalt suppresses the solid solubility of molybdenum and therefore simplifies the formation of Mo-precipitates during aging, which results in a stronger material. This Co-Mo relationship is proved by the fact that 18Ni(350) has more than 300 MPa higher strength than a maraging steel named 2000 MPa grade steel. A higher strength is obtained despite a 0.93 wt% lower titanium content; this without loss in toughness. In summary, a higher amount of molybdenum results in higher strength for similar nickel and titanium contents for cobalt containing maraging steels \[28\].
Strength of **cobalt free** maraging steels is increased by higher **titanium** contents if the remaining alloying elements are of similar amounts because it leads to more titanium precipitates. Moreover, the solid solution state for **low molybdenum** steel gains 100 MPa extra yield strength and 180 MPa UTS when compared to a 2000 MPa grade steel, where the former has an extra 0.7 wt% titanium. Furthermore, the low molybdenum steel gains 400 MPa extra yield strength after aging. However, this increase in matrix hardness decreases the toughness of the material. In addition, there is no significant difference in strength and no difference in ductility between high and low molybdenum maraging steels. This since there is no cobalt present, which results in molybdenum not fully contributing to the precipitation during the aging process [28].

**Cobalt** can suppress the recovery of dislocation sub-structures in many UHS steels. As a result, their M₃C carbides are smaller and more densely distributed. After normal aging, the distribution of precipitates is even and fine regardless of the amount of cobalt. Furthermore, the precipitate size and dislocation density do not seem to be related to the presence of cobalt due to different precipitates formed in cobalt containing and cobalt free grades [28].

Nucleation rates are different depending on the material and its precipitates. For instance, the nucleation rate of the **cobalt** containing maraging steels increases along dislocation lines due to the Co-Mo relationship with **molybdenum** based precipitates. The cobalt free ones also have a high nucleation rate, but with **titanium** based precipitates [28].

Another important alloying element with impact on mechanical properties is **nickel**. Nickel facilitates cross slipping during plastic deformation in maraging steel that results in higher fracture toughness. In addition, nickel in itself does not contribute to hardening (during aging). Other alloying elements can lower the toughness, which seems to occur because of inhibition of the nickel contribution. However, if nickel is precipitated for some reason, its concentration is reduced in the iron matrix and inhibition could occur because of formation of intermetallic compounds. For example, Ni₃Mo is precipitated for 18Ni maraging steels, but also Ni₃Ti if **titanium** is added [4].

Maraging steels aged at low temperatures obtain **nickel** or **molybdenum** rich zones, while higher temperatures (above 460°C) only get molybdenum rich zones. Thus, these precipitates affect the nickel concentration in the matrix and thereby the toughness, as described above [4].

**Chromium** is added in order to lower $M_s$ below 350°C. Too high $M_s$ can result in formation of precipitates during quenching that impairs the material properties. However, too low $M_s$ (e.g. below 100°C) can result in failure of precipitate formation during the aging process [4].

**Carbon** is also an alloying element worth considering. A carbon content lower than 0.03 wt% is unnecessary since the toughness is not as negatively affected by carbon as previously believed. Although, too high carbon contents increase the strength as solution treated and lowers the workability and machinability [4].

In general, **silicon** deoxidizes steel since it facilitates the removing of oxygen bubbles in molten steel. It occurs in low amounts, normally below 0.4 wt%, and can strengthen steel
because it dissolves in iron [39]. Note that this information is general, and not specific for maraging steels.

4.4.2 High alloy secondary hardening steel

Alloying elements that form carbides are needed to achieve secondary hardening. Molybdenum, chromium, tungsten, and vanadium are commonly used as good carbide formers. Elevated temperatures (450-600°C) are required to enable the otherwise slow diffusion of these alloying elements. Chromium does not by itself provide sufficient strengthening, which is why almost all HASH steels contain some amount of molybdenum, tungsten and/or vanadium [40]. Titanium is another carbide former that can enhance precipitation [33].

A combination of high strength and $K_{IC}$ can be achieved through the addition of cobalt. AerMet 100 is one example of this with 13.4 wt% cobalt [40]. Studies have shown that cobalt promotes a finer precipitate size, while making the precipitates cluster, which could lead to a stronger material at elevated temperatures [11]. Alloying with aluminum, silicon, nickel and/or cobalt can lead to increased hardness [40].

Nickel is also known for improving the hardenability of the material by forming a lath martensite microstructure. In addition, alloying with nickel lowers the ductile-brittle transition temperature, resulting in a more ductile (and thus a tougher) material at room temperature. Finally, nickel can lead to an increase of retained austenite by lowering the $M_s$ temperature. Co-alloying with cobalt could prevent this increase [41].

4.4.3 Low alloy steels

Carbon is the main alloying element in low alloy steels [11, 39]. Among all UHS steels, low alloy steels have the highest carbon amounts which lead to a higher $M_s$. Therefore, martensite is formed earlier in the cooling process, and less retained austenite is formed. Higher amounts of carbon also help the steel attain higher strength, hardenability, and brittleness since it forms carbides during the heat treatment [11].

Nickel is an important austenite stabilizer that is added to obtain higher $K_{IC}$ [11]. Austenite stabilizers increase the stability of the austenite phase over a wider temperature range, since the eutectoid temperature is lowered [42]. As a result, the steel is less likely to contain any ferrite phase that makes the steel brittle [1].

Chromium forms carbides that help prevent the occurrence of cementite if steel with 0.2 wt% carbon contains 1 wt% chromium [1, 39, 42]. Vanadium helps restricting grain growth [39, 42].
5. Results

5.1 Materials

5.1.1 T250 grade maraging steel

Maraging steel

<table>
<thead>
<tr>
<th>UTS:</th>
<th>1760 MPa [44]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K&lt;sub&gt;IC&lt;/sub&gt;:</td>
<td>105 MPa*m&lt;sup&gt;1/2&lt;/sup&gt; [44]</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of T250 grade maraging steel in wt% [44].

<table>
<thead>
<tr>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>C</th>
<th>P</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>H</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.1</td>
<td>2.25</td>
<td>1.39</td>
<td>0.01</td>
<td>0.008</td>
<td>0.008</td>
<td>0.004</td>
<td>0.003</td>
<td>0.001</td>
<td>0.0002</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

A T250 grade maraging steel (cobalt free) was examined in a study from 1998 and has its chemical composition presented in Table 1. The steel obtained a maximum tensile strength of 1830 MPa when aged at 480°C for 25 hours. The most optimal UTS and K<sub>IC</sub> values were determined to be 1760 MPa and 105 MPa*m<sup>1/2</sup>, respectively. This optimal combination, having both high UTS and K<sub>IC</sub>, was obtained after the steel had been aged at 500°C for 3-5 hours. A maximum hardness of 52 HRC was achieved after 3 hours of aging at this temperature [44].

The steel used in this study was supplied as forged and annealed bars with a diameter of 100 mm. Thereafter, it was forged and finished rolled at 850°C to plates with a thickness of 20 mm. Further on it was solution treated at 825°C for 1 hour, air-cooled, surface machined, and at last cut to pieces. K<sub>IC</sub> tests were made on 12.5 mm thick specimens in agreement with ASTM Standard E-399. Tensile tests (uniaxial) were made on flat specimens with a thickness of 4 mm and a gauge length of 25 mm in agreement with ASTM Standard A-370 [44].

A lath martensitic matrix with fine precipitates were observed in the steel that had been aged at 500°C for 3 hours with a transmission electron micrograph (TEM). After 5 hours of aging the precipitates were fairly coarsened, but they could not be identified before the steel had been over-aged for 100 hours. They were then identified to be rod shaped hexagonal η-Ni<sub>3</sub>−Ti and two variants of (2240)η-Ni<sub>3</sub>−Ti out of 12 possible [44].

It was also observed that the tensile strength still increased after the steel had been aged at 450°C for 100 hours. The same increasing trend, at the same temperature, was obtained for the fracture toughness when aged for 50 hours. No further investigation was made at this temperature; therefore, no peak values were determined [44].

The mechanical properties aggravated in an early stage when aged at 550°C and 600°C. The obtained strengths for these two temperatures were lower than the highest attainable for the steel, but also lower than the most optimal strength obtained by aging at 500°C. An
increase in aging temperature also influenced the precipitate size and amount of reverted austenite [44].

Suppliers, sectors and applications for this specific T250 grade maraging steel have not been identified. However, there is another maraging steel of the same T-grade available at Metalmen. This steel is used in aerospace, the military, and for tools; as jet engine shafts, missile components, tooling, and other applications requiring high toughness and high strength [45]. Therefore, it is possible that this T250 grade maraging steel can be used in a similar fashion.

| Price:       | N/A |
| Suppliers:   | N/A |
| Sectors:     | N/A |
| Applications:| N/A |

5.1.2 Cobalt free maraging steel

**Maraging steel**

- **UTS:** 1705 MPa [23]
- **K$_{IC}$:** 82.3 MPa*m$^{1/2}$ [23]

*Table 2: Chemical composition of cobalt free maraging steel in wt% [23].*

<table>
<thead>
<tr>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

A cobalt free maraging steel, with chemical composition presented in Table 2, obtained an UTS of 1705 MPa and a K$_{IC}$ of 82.3 MPa*m$^{1/2}$ after a heat treatment consisting of annealing and then ageing at 480°C for 3 hours. The heat treatment was made on a bar with a diameter of 32 mm in forged condition. A Charpy value of 15 J was also documented [23].

The microstructure consisted of lath martensite with high dislocation density. Precipitates such as Fe$_2$Mo were observed in the martensitic matrix at high magnifications. Other phases such as NiTi, Ni$_3$Ti and TiC were also found with transmission electron microscopy (TEM) [23].

Suppliers, sectors and applications for this specific material have not been identified.

| Price:       | N/A |
| Suppliers:   | N/A |
| Sectors:     | N/A |
| Applications:| N/A |
5.1.3 High cobalt maraging steel

Maraging steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>1912 MPa</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>70.1 MPa m$^{1/2}$</td>
</tr>
</tbody>
</table>

Table 3: Chemical composition of high cobalt maraging steel in wt% [23].

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>13.4</td>
</tr>
<tr>
<td>Ni</td>
<td>11.5</td>
</tr>
<tr>
<td>Mo</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>0.23</td>
</tr>
</tbody>
</table>

A high cobalt maraging steel, with the chemical composition presented in Table 3, obtained an UTS of 1912 MPa and a $K_{IC}$ of 70.1 MPa m$^{1/2}$. This after being subjected to annealing, refrigeration treatment at -80°C due to retained austenite, and thereafter ageing at 480°C for 3 hours. The heat treatment was made on a bar with a diameter of 32 mm in forged condition. Cracks that were developed in this steel showed to be more ductile and flat than cracks in the cobalt free maraging steel (mentioned in 5.1.2). This steel also obtained a Charpy value of 39 J [23].

The microstructure consists of lath martensite with high dislocation density. Precipitates were also observed in the martensitic matrix at high magnifications. They were identified to be hexagonal Mo$_2$C and hexagonal MoC with an X-ray diffraction pattern of the steel [23].

Suppliers, sectors and applications for this specific material have not been identified.

<table>
<thead>
<tr>
<th>Price</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suppliers</td>
<td>N/A</td>
</tr>
<tr>
<td>Sectors</td>
<td>N/A</td>
</tr>
<tr>
<td>Applications</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5.1.4 300 grade maraging steel

Maraging steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>1931 MPa</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>77 MPa m$^{1/2}$</td>
</tr>
</tbody>
</table>

Table 4: Chemical composition of 300 grade maraging steel in wt% [30].

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>18.8</td>
</tr>
<tr>
<td>Co</td>
<td>9.07</td>
</tr>
<tr>
<td>Mo</td>
<td>4.94</td>
</tr>
<tr>
<td>Ti</td>
<td>0.69</td>
</tr>
<tr>
<td>Al</td>
<td>0.11</td>
</tr>
<tr>
<td>Si</td>
<td>0.07</td>
</tr>
<tr>
<td>Mn</td>
<td>0.05</td>
</tr>
<tr>
<td>Zr</td>
<td>0.016</td>
</tr>
<tr>
<td>C</td>
<td>0.006</td>
</tr>
<tr>
<td>S</td>
<td>0.003</td>
</tr>
<tr>
<td>B</td>
<td>0.0027</td>
</tr>
<tr>
<td>P</td>
<td>0.002</td>
</tr>
<tr>
<td>Ca</td>
<td>0.0003</td>
</tr>
<tr>
<td>Fe</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

A 300 grade maraging steel with chemical composition presented in Table 4, achieved a $K_{IC}$ of about 77 MPa m$^{1/2}$ at an UTS of 1931 MPa. This strength-toughness combination was
obtained after the steel had been solution annealed and aged. The annealing process was performed by heating the steel at a rate of 0.33°C/s to 825°C and then maintaining this temperature for 2 hours followed by cooling to room temperature in the furnace. $A_s$ and $A_f$ for the steel were determined to be 615°C and 781°C, respectively. Furthermore, $M_s$ and $M_f$ were 156°C and 60°C, respectively. Thereafter the steel was aged at 490°C for 3.5 hours. In addition, a hardness of 53.5 HRC was obtained [30].

The billet that was used for the tests had an original diameter of 7.6 cm and was supplied in solution annealed and centerless ground condition. Furthermore, the billet was homogenized at 1150°C for 6 hours in a slightly oxidizing atmosphere. Later on it was hot rolled to a flat plate with a thickness of 3.8 cm. 13 mm thick compact tension specimens were machined with the rolling direction parallel to the loading direction. These specimens were then used for the $K_{IC}$ tests [30].

An increase in $K_{IC}$ to 116 MPa·m$^{1/2}$ was also measured while the UTS decreased to 1655 MPa. This as a result of one thermal cycle in addition to solution annealing and ageing. When the steel was exposed to thermal cycling the temperature was increased to 825°C at a rate of 0.33°C/s, followed by a hold period of 2 minutes at 825°C, and then cooled to room temperature in the furnace. The decrease in UTS depended on the appearance of a lamellar phase in the matrix, also identified as retained austenite, which in this case is a result of thermal cycling. Repeated thermal cycling leads to additional forming of retained austenite and consequently to decrease in UTS. This also resulted in a decrease in hardness to 47 HRC [30].

Suppliers, sectors and applications for this material have not been identified. However, there is another maraging steel with the same M-grade and almost the same heat treatment. This steel is used in aerospace, vehicles, tools, and in the military as bearings, springs, bolts, rocket motor and missiles cases, shafts, transmission shafts, aircraft wing components and forgings, couplings, and pins. Therefore, it is possible to believe that this 300 grade maraging steel can be used in a similar fashion. Metal Suppliers Online and Online Metals are two companies that supply the aforementioned commercial maraging steel [46].

Price: Approximately 294-312 SEK/kg [47]
Suppliers: N/A
Sectors: N/A
Applications: N/A
5.1.5 AerMet 100

High Alloy Secondary Hardened Steel

UTS: 1965 MPa [48]
$K_{IC}$: 126 MPa$\cdot$m$^{1/2}$ [48]

Table 5: Chemical composition of AerMet 100 in wt% [48].

<table>
<thead>
<tr>
<th></th>
<th>Co</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.3-13.5</td>
<td>11-12</td>
<td>3.1</td>
<td>1.0-1.3</td>
<td>0.21-0.27</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

AerMet 100 is a HASH steel, a type of martensitic UHS steel alloy. Its main alloying elements are cobalt and nickel, but it also contains small amounts of molybdenum, chromium and carbon, see Table 5. AerMet 100 showcases a fairly high UTS of around 1965 MPa and a $K_{IC}$ around 126 MPa$\cdot$m$^{1/2}$. These values are reached by ageing at 480°C followed by air-cooling [48]. It is also unaffected by temperatures well up to 425°C, but is not considered to have a particularly high corrosion resistance, although it has excellent corrosion cracking resistance [49]. AerMet 100 has a $K_{ISC}$ of 33 MPa$\cdot$m$^{1/2}$ obtained after 1000 hours in 3.5% NaCl [50]. The hardness of AerMet 100 is around 53-54 HRC [51].

Due to its mechanical abilities AerMet 100 is considered one of the most difficult steels to machine [52]. When forging AerMet 100, a maximum temperature of 1232°C should be reached and the forging process must finish below a temperature of 899°C. The material should then be air-cooled to room temperature, annealed at 677°C followed by 16 hours of air-cooling, then get normalized at 899°C, and air cooled for 1 hour. Heat treatment of AerMet 100 is crucial since the $K_{IC}$ is very dependent of the purity and homogeneity of the material. Therefore, AerMet 100 is usually only supplied in the VIM/VAR melted condition. This method ensures sufficient purity and homogeneity [48].

Price: 287-298 SEK/kg [47]
Suppliers: Carpenter Technology Corporation, Michlin Metals incorporation, Rickard Specialty Metals & Engineering, NeoNickel, Haihong International Trade (HK) CO.
Sectors: Aerospace [48]
Applications: Armor, landing gear, driving shafts, etc. [48]
5.1.6 AF1410

High Alloy Secondary Hardened Steel

**UTS:** 1750 MPa  [48]

**K\text{IC}:** 154 MPa*\text{m}^{1/2}  [48]

<table>
<thead>
<tr>
<th>Co</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5-14.5</td>
<td>0.5-9.5</td>
<td>1.8-2.2</td>
<td>0.90-1.1</td>
<td>0.13-0.17</td>
<td>0.10 max.</td>
<td>0.10 min.</td>
<td>0.0080</td>
<td>0.0050</td>
</tr>
</tbody>
</table>

**Table 6:** Chemical composition of AF1410 in wt% [50].

AF1410 with chemical composition presented in Table 6, is a HASH steel developed in the Air-Force and is the predecessor of Aermet [50]. Due to its uses in military applications, projects using AF1410 must be approved by the Department of Defense [53]. Its strength and toughness come from the martensitic transformation in the quenching step, and the precipitation of chromium and molybdenum carbides during tempering [54]. AF1410 have a microstructure consisting of Fe-Ni lath martensite. Differences in aging parameters and composition of AF1410 can result in a UTS of 1725 MPa and a K\text{IC} of 118 MPa*\text{m}^{1/2}, or an UTS of 1758 MPa and a K\text{IC} of 87 MPa*\text{m}^{1/2} [50]. The high K\text{IC} value of AF1410 correlates to K\text{ISCC} of 45 MPa*\text{m}^{1/2}, which is obtained after 1000 hours in 3.5% NaCl [50].

To forge AF1410, a maximum starting temperature of 1120°C should be used for the initial breakdown. Forgings should then be air-cooled down to room temperature and then further normalized and annealed. Normalization occurs at 880-900°C and afterwards, the material is air-cooled. Annealing is carried out at around 675°C for a minimum time of 5 hours before air-cooling [48]. After aging the resulting hardness is around 35 HRC [55].

**Price:** 286-296 SEK/kg [47]

**Suppliers:** Carpenter Technology Corporation, Aircraft Materials, Tech Steel & Materials, Haihong International Trade (HK) CO

**Sectors:** Aerospace, marine [48]

**Application:** Aircraft components, submarine hulls, etc. [48]
5.1.7 Ferrium S53

High alloy secondary hardened steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>1990 MPa [56]</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>71.4 MPa$\cdot$m$^{1/2}$ [56]</td>
</tr>
</tbody>
</table>

Table 7: Chemical composition of Ferrium S53 in wt% [56].

<table>
<thead>
<tr>
<th>Element</th>
<th>Co</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>W</th>
<th>V</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>14</td>
<td>10</td>
<td>5.5</td>
<td>2.0</td>
<td>1.0</td>
<td>0.30</td>
<td>0.21</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Ferrium S53 is an UHS steel with the chemical composition presented in Table 7. It was computationally designed by QuesTek Innovations LLC in order to develop a material with superior mechanical properties to high-strength materials such as 300M. S53 also provides an improved corrosion resistance and resistance to SCC compared to 300M and 4340 [57].

S53 receives its superior properties due to precipitation of $M_2C$ carbides while avoiding carbides of other stoichiometries [56]. The $M_2C$ carbides have a high modulus misfit compared to the BCC iron, which provides the strengthening effect. Alloying with chromium provides a passive layer that protects against general corrosion. S53 is also designed to maximize grain boundary cohesion, which leads to high SCC resistance [58]. S53 is solution treated at 1085°C for 1 hour, then quenched and tempered at 501°C for 3 hours, thereafter quenched again, and finally a second tempering occurs at 482°C for 12 hours. The steel can obtain a hardness of 54 HRC [56].

S53 is usually supplied in round bar form and responds to processing similarly to that of other secondary hardened steels and has been successfully forged at several occasions. Recommended forging temperatures range from 982°C to 1121°C. Elevated temperatures improve the forgeability but can lead to an undesired grain growth. Machining S53 is in general more difficult than that of 300M and 4340. Typical cutting tools are those used for 4000 series stainless steel. It has also been demonstrated that S53 is readily weldable [36].

Price: 385-485 SEK/kg [59]
Suppliers: Carpenter Technology Corporation
Sectors: Aerospace, military [57]
Applications: Landing gears, flak traps, actuators, structural applications, etc. [56]
5.1.8 Ferrium M54

**High alloy secondary hardened steel**

- **UTS:** 2020 MPa [16]
- **K<sub>IC</sub>:** 130 MPa·m<sup>1/2</sup> [16]

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>W</th>
<th>Cr</th>
<th>C</th>
<th>V</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.0</td>
<td>2.0</td>
<td>1.3</td>
<td>1.0</td>
<td>0.30</td>
<td>0.10</td>
<td>Bal.</td>
<td></td>
</tr>
</tbody>
</table>

*Table 8: Chemical composition of M54 in wt% [16].*

Ferrium M54 has its chemical composition presented in Table 8, and belongs to the group of HASH steels. It is another material computationally designed by QuesTek Innovations LLC, with a goal to be a cost effective alternative to AerMet 100 while achieving improved values in UTS and K<sub>IC</sub>. This resulted in a material with slightly lower alloying content than that of the other HASH steels mentioned above. M54 does also have excellent resistance to SCC, approximately 400% better than that of AerMet 100 [60].

M54 is currently one of the strongest and toughest steels in the world [60]. Similarly to S53, M54 uses a precipitation of M<sub>23</sub>C carbides to achieve high strength and toughness. It is solution treated at 1060°C for 1-1.5 hours, then quenched, and finally tempered at 524°C for 6 hours. The steel has a measured hardness of 54 HRC [16].

It is usually supplied in round bar form and responds to processing similarly to that of other secondary hardened steels and has been successfully forged at several occasions. Machining M54 is in general more difficult than 300M and 4340 but easier than AerMet 100. There are currently no studies available regarding the weldability of M54 [37].

- **Price:** 385-485 SEK/kg [59]
- **Suppliers:** Carpenter Technology Corporation
- **Sectors:** Aerospace, military [16]
- **Applications:** Landing gear, arresting tailhooks, armor, etc. [16]
5.1.9 4340

**Low alloy steel**

<table>
<thead>
<tr>
<th>UTS:</th>
<th>1965 MPa</th>
<th>[50]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{IC}$</td>
<td>71 MPa*m$^{1/2}$</td>
<td>[50]</td>
</tr>
</tbody>
</table>

**Table 9: Chemical composition of 4340 in wt% [50].**

<table>
<thead>
<tr>
<th>Ni</th>
<th>Cr</th>
<th>Mn</th>
<th>C</th>
<th>Mo</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>0.85</td>
<td>0.70</td>
<td>0.40</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>

4340 is a low alloy steel with its chemical composition presented in Table 9 [50]. 4340 is the predecessor of 300M and they are almost identical except that 4340 has a lower amount of added silicon. It has an UTS value of 1900-2070 MPa and a fracture toughness around 70 MPa*m$^{1/2}$ depending on the heat treatment [49]. Because of the low alloying content of 4340 it can only be used in temperatures up to around 200°C [50]. 4340 has a $K_{ISC}$ around 11-16 MPa*m$^{1/2}$, that is obtained after 1000 hours in 3.5% NaCl, as a result of its low $K_{IC}$ [50]. Depending on slight variations in composition and tempering, hardness values of 17-62 HRC can be obtained [61].

4340 is usually forged at temperatures of 1065-1230°C. Thereafter, the material is air-cooled or rather furnace-cooled, and then tempered at 260°C. This specific process would give an UTS of 1724 MPa and a $K_{IC}$ of 53 MPa*m$^{1/2}$ [48]. The process to obtain the higher UTS and $K_{IC}$ values mentioned above could not be found but are assumed to be of similar character.

**Price:** 8.07-8.76 SEK/kg [47]

**Suppliers:** Carpenter Technology Corporations

**Sectors:** Aerospace [50]

**Applications:** Landing gears [50]

5.1.10 300M

**Low alloy Steel**

<table>
<thead>
<tr>
<th>UTS:</th>
<th>1965 MPa</th>
<th>[50]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{IC}$</td>
<td>71 MPa*m$^{1/2}$</td>
<td>[50]</td>
</tr>
</tbody>
</table>

**Table 10: Chemical composition of 300M in wt% [50].**

<table>
<thead>
<tr>
<th>Ni</th>
<th>Si</th>
<th>Cr</th>
<th>Mn</th>
<th>C</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>1.6</td>
<td>0.85</td>
<td>0.70</td>
<td>0.40</td>
<td>0.40</td>
<td>0.10</td>
</tr>
</tbody>
</table>

300M is a low alloy steel (see chemical composition in Table 10) with high hardenability and strength, but also good ductility and toughness; particularly in heavy sections. In addition, 300M
can obtain an UTS value of 1862-2068 MPa and a $K_{IC}$ around 70 MPa$m^{1/2}$ depending on the tempering process [50, 62]. A hardness value of 55 HRC has been recorded [63].

When producing 300M, VIM/VAR is usually the method employed, although argon-oxygen decarburization melting is an alternative. 300M is then tempered at around 316°C in order to precipitate carbides [48]. Addition of silicon enables higher yield strength and therefore, the steel requires higher tempering temperatures than 4340 [62]. 300M has a $K_{ISCC}$ of around 11-16 MPa$m^{1/2}$, which is obtained after 1000 hours in 3.5% NaCl, as a result of its low $K_{IC}$ [50].

Price: 9-10 SEK/kg [47]
Suppliers: Carpenter Technology Corporation
Sectors: Aerospace [50]
Applications: Landing gear, aircraft parts, etc. [50]

5.1.11 PremoMet

Low Alloy Steel

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UTS:</strong></td>
<td>2034 MPa</td>
</tr>
<tr>
<td><strong>$K_{IC}$:</strong></td>
<td>80.8 MPa$m^{1/2}$</td>
</tr>
</tbody>
</table>

Table 11: Chemical composition of PremoMet in wt% [64].

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Si</th>
<th>Cr</th>
<th>Mn</th>
<th>Mo</th>
<th>Cu</th>
<th>C</th>
<th>V</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.81</td>
<td>1.5</td>
<td>1.3</td>
<td>0.75</td>
<td>0.52</td>
<td>0.51</td>
<td>0.40</td>
<td>0.30</td>
<td>0.005 max.</td>
<td>0.0011</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

PremoMet is considered to be a low alloy steel and was developed to be an improvement of 300M. Therefore, it has the same alloying elements as 300M, except for an addition of copper. PremoMet also has increased nickel, chromium, and vanadium levels (see its chemical composition in Table 11). In addition, copper has been theorized to affect the carbon diffusivity, which could lead to control of carbide clustering [8].

In one study, three samples were prepared by VIM/VAR, then hot rolled to a diameter of 19 mm, normalized at 927°C for 1 hour, and thereafter annealed at 677°C for 8 hours. The best strength/toughness relation was obtained when austenitization was conducted for 1.5 hours at 918°C, followed by quenching, and then refrigeration for 1 hour at -73°C. Afterwards, it was tempered for 2 hours at 260°C, which resulted in an UTS of 2034 MPa and a $K_{IC}$ of 80.8 MPa$m^{1/2}$. MC carbides are most common after tempering and seem to have the most impact on toughness [64]. In addition, a hardness of 54 HRC has been recorded [65].

Price: N/A
Suppliers: Carpenter Technology Corporation
Sectors: Train engine [65]
Applications: Gears, connecting rods, crankshafts, springs, drive shafts [65]
5.2 Summary of the materials

Table 12 and Figure 4 are presented in order provide a better overview of the mentioned steels.

Table 12: Summary of the mentioned steels regarding UTS, KIC, price, hardness and alloying content.

<table>
<thead>
<tr>
<th>Steel</th>
<th>UTS (MPa)</th>
<th>KIC (MPa*m$^{1/2}$)</th>
<th>Price (SEK/kg)</th>
<th>Hardness (HRC)</th>
<th>Alloying content (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Rock drilling Steel 6418 (Reference)</td>
<td>1600</td>
<td>125</td>
<td>10-15 [13]</td>
<td>46</td>
<td>~6</td>
</tr>
<tr>
<td>T250 grade maraging steel</td>
<td>1760</td>
<td>105</td>
<td>N/A</td>
<td>52</td>
<td>~21</td>
</tr>
<tr>
<td>High cobalt maraging steel</td>
<td>1912</td>
<td>70.1</td>
<td>N/A</td>
<td>N/A</td>
<td>~27</td>
</tr>
<tr>
<td>Cobalt free maraging steel</td>
<td>1705</td>
<td>82.3</td>
<td>N/A</td>
<td>N/A</td>
<td>~22</td>
</tr>
<tr>
<td>300 grade maraging steel</td>
<td>1931</td>
<td>77</td>
<td>N/A</td>
<td>53.5</td>
<td>~34</td>
</tr>
<tr>
<td>AerMet 100</td>
<td>1965</td>
<td>126</td>
<td>287-298*</td>
<td>53-54</td>
<td>~29</td>
</tr>
<tr>
<td>AF1410</td>
<td>1750</td>
<td>154</td>
<td>286-296*</td>
<td>35</td>
<td>~26-28</td>
</tr>
<tr>
<td>S53</td>
<td>1990</td>
<td>71.4</td>
<td>385-485</td>
<td>54</td>
<td>~33</td>
</tr>
<tr>
<td>M54</td>
<td>2020</td>
<td>130</td>
<td>385-485</td>
<td>54</td>
<td>~22</td>
</tr>
<tr>
<td>4340</td>
<td>1965</td>
<td>71</td>
<td>8.07-8.76*</td>
<td>17-62</td>
<td>~4</td>
</tr>
<tr>
<td>300M</td>
<td>1965</td>
<td>71</td>
<td>9-10*</td>
<td>55</td>
<td>~6</td>
</tr>
<tr>
<td>PremoMet</td>
<td>2034</td>
<td>80.8</td>
<td>N/A</td>
<td>54</td>
<td>~9</td>
</tr>
</tbody>
</table>

* These prices are approximations taken from CES Edupack 2016 [47].
6. Discussion

In general, the increase of UTS most often results in lower $K_{IC}$, or the other way around. Therefore, the material choice depends on which property is to be prioritized. Other properties may be of varying importance, and are therefore discussed separately.

6.1 Maraging steels

Considering maraging steels, 300 grade maraging steel has the highest UTS (1931 MPa), while T250 grade maraging steel has the highest $K_{IC}$ (105 MPa·m$^{1/2}$) [30, 44].

None of the maraging steels presented in the result section have identified suppliers. However, these steels might be available as special orders at some companies that produce other maraging steels. Another alternative is to further investigate the commercially available maraging steels (see Appendix). Most of these have no recorded $K_{IC}$ values, but different impact tests have been conducted [24, 66-69].

In an environmental perspective, the cobalt free grade maraging steels is preferable since cobalt is harmful as a powder, but also expensive [18]. However, no prices have been found for these steels.
Both of the cobalt free maraging steels have a microstructure of lath martensite with Ni$_3$Ti precipitates in a martensitic matrix. However, the precipitates may be of different variants according to their orientation in the slip planes. The material named cobalt free maraging steel also contains phases such as Fe$_2$Mo, NiTi, and TiC, while T250 grade maraging steel only has different variants of Ni$_3$Ti precipitates. This can be one of the reasons why their UTS and $K_{IC}$ differ [23, 44]. The high cobalt maraging steel has a microstructure consisting of lath martensite. But in contrast, this steel has precipitated carbides in the martensitic matrix instead of intermetallic phases [44]. However, intermetallic phases are the main reason for hardening of maraging steels, not carbides [17]. Therefore, the impact on UTS and $K_{IC}$ of the carbides is not clear. 300 grade maraging steel has a different microstructure than the previously mentioned maraging steels. Instead, the matrix contains a lamellar phase. This lamellar phase is identified as retained austenite, and has no identified precipitates [30].

No prices for these particular steels were found. However, closely related maraging steels (containing cobalt) in the Appendix costs about 250-305 SEK/kg [70] and 400 SEK/kg [71]. It is reasonable to believe that these steels have similar prices since they have similar heat treatments and alloying contents.

6.2 High alloy secondary hardened steels

When comparing the HASH steels regarding UTS and $K_{IC}$, Ferrium M54 has the highest values of both UTS (2020 MPa) and $K_{IC}$ (130 MPa*m$^{1/2}$), followed by AerMet 100 [16]. If instead $K_{IC}$ is to be prioritized, AF1410 is regarded as the best alternative although it does not have an UTS value as high as the materials mentioned earlier.

All of the HASH steels have cobalt as a main alloying element with an amount around 13-14 wt%, except for M54 where the amount is slightly lower (7 wt%). One of the effects from cobalt is a finer dispersion of the precipitates. The lower amount of cobalt in M54 is therefore sufficient since the overall alloying content in M54 is lower than that of the other steels. In addition, this material group contains larger amounts of nickel along with smaller amounts of chromium, except for Ferrium S53 where the amount of chromium is higher for an improved corrosion resistance [16, 49-50, 56].

Typical applications for HASH steels are in the aerospace industry, commonly as landing gears or other applications requiring high hardness and strength combined with ductility and toughness. This application requires excellent mechanical properties, which may in many ways overlap with those needed for high performance drilling materials. Worth taking into account is that the pricing of these high performance materials might be considered high, since they are mainly used in specialized parts and not as bulk material. The pricing of Ferrium S53 and M54 are roughly estimated to 385-485 SEK/kg [59]. According to CES Edupack, AerMet 100 and AF1410 are almost 100 SEK/kg cheaper than S53 and M54 [47].
6.3 Low alloy steels

4340 and 300M are very similar despite the fact that 300M contains more silicon that improves the steel. 300M has a higher tempering temperature than 4340 by approximately 60°C [48], which implies that 300M has the better service temperature. To be added, PremoMet has the same tempering temperature as 4340.

4340 and 300M both have a relatively low $K_{IC}$ compared to other materials in this report and these values can only be reached under optimal conditions. Thus, it is uncertain whether 4340 and 300M are suitable for percussive drilling. In addition, their service temperature might be considered too low, which may lead to unwanted changes in material properties at higher temperatures.

PremoMet can be considered to be a low alloy steel because of its low tempering temperature and its close relation to 300M. This despite a alloying content higher than 8 wt% [8] and a occurrence of non-ferrous carbides. PremoMet has the highest chromium content (1.1%) of the low alloy steels, which suggests that it has some corrosion resistance. This gives an advantage compared to other low alloy steels that have poor corrosion resistance due to their low alloying content [64].

It can be assumed that 4340 and 300M have approximately the same cost since they both rely on vacuum techniques to purify the material and are heat treated in similar ways. PremoMet is newer and has a higher alloying content, which might lead to a higher price. In addition, PremoMet seems to be the best low alloy alternative since all of its mentioned properties are superior to the other steels of this category. Prices for low alloy steels are, in general, 8-10 SEK/kg according to CES Edupack [47].

6.4 General discussion

There are some similarities between these different groups of steels. For example, they all contain martensite phase with precipitated particles and their manufacturing processes are similar to each other. In general, heat treatment is essential for generating the material properties, but also small variations in chemical composition. Both maraging steels and HASH steels have high alloying contents, which also leads to more freedom of choice regarding amounts of alloying elements compared to low alloy steels. This leads to a higher potential to discover new optimal compositions with improved properties in the future. However, this could involve years of research including multiple prototype testings, which could also be necessary for some commercial steels.

These different groups of steels have different carbon contents. For steels mentioned in the report, maraging steels have the lowest carbon content of 0.005-0.008 wt% (with the exception of the high cobalt maraging steel with 0.23 wt%), while HASH steels contains 0.15-0.3 wt% carbon, and low alloy steels 0.40 wt%.
It is possible that maraging steels and HASH steels have similar service temperatures (around 450°C, see Appendix) since their aging and tempering temperatures are both around 480°C. Low alloy steels seem to have a lower service temperature (300M has approximately 300°C).

All mentioned steels, but AF1410 and 4340, have hardness around 50 HRC [55]. Therefore, they are harder than limestone (0 HRC), but not necessarily harder than granite (45-60 HRC) [14]. Although, the cemented carbide parts of the drill head suffer the greatest impact with the rock, the bulk material would probably be exposed to abrasion.

Maraging steels have slightly better machinability than HASH steels with the same hardness [26]. HASH steels have difficulties in machinability partly because of their higher strength in general [36-37], and must therefore be machined under special conditions [35].

The low alloying content in low alloy steels should result in lower environmental impacts compared to steels with high alloying content. In addition, HASH steels and cobalt containing maraging steels have rather high cobalt content that is considered negative in this aspect.

Low alloy steels are available at much lower prices than HASH and maraging steels, most likely because of their low alloying content. It is more difficult to compare HASH and maraging steels since they both have wide price ranges, but both the upper and lower price limits are lower for maraging steels. Another reason behind the comparison difficulties is that some of these approximate prices are taken from the database CES Edupack and some directly from companies. Furthermore, it is unknown what manufacturing processes are taken into consideration for the CES Edupack estimates.

7. Conclusion

The material with highest combination of UTS and $K_{IC}$ is Ferrium M54 closely followed by AerMet 100. Both of these steels also have good resistance to SCC and their hardness values are very similar.

If one of these properties (UTS and $K_{IC}$) were to be of greater importance than the other, PremoMet has the highest documented UTS and AF1410 has the highest documented $K_{IC}$. However, these are not considered to be suitable due to other factors.

Maraging steels have slightly better machinability than HASH steels with the same hardness.

Low alloy steels have by far the lowest price, while HASH and maraging steels both have wide price ranges, where maraging steels seem to be cheaper in general.

If Atlas Copco Secoroc AB were to find any of the identified materials interesting, we would recommend them to contact the suppliers directly for more exact values on properties and prices, but also to perform further testing.
8. References


[51] Service Steel Aerospace Corp. AerMet® 100 ALLOY DATA SHEET [Internet]. Service Steel Aerospace Corp; 2016. [cited 2017-05-12]. Available from: https://www.google.se/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiX8aaw6vHTAhVJiCwKHYGMCaUQFggjMAAA&url=http%3A%2F%2Fwww.ssa-corp.com%2Fdocuments%2FData%2520Sheet%2520AerMet100.pdf&usg=AFQjCNE6qFmRxNlpbKNt5QJr8UmEVZzFFw&sig2=ap4oCxzL3hJbN0ltlwU69Q&cad=rja


[56] MatWeb. QuesTek® Innovations Ferrium® S53® Corrosion Resistant High Strength Steel for Aerospace Structural Applications [Internet]. MatWeb; [cited 2017 May 12], Available from: http://www.matweb.com/search/DataSheet.aspx?MatGUID=09c2c0807740426787318635107a0b5&ckck=1


[59] Email, Kerem Taskin, QuesTek Innovations LLC, 2017 May 5.

[60] QuesTek. Ferrium® M54® [Internet]. QuesTek; [cited 2017 May 12], Available from: http://www.questek.com/ferrium-m54.html


[70] Email, Juha Hatunen, REC Indovent AB, 2017 May 18.

[71] Email, Johan Norlander, Livallco stål AB, 2017 May 19.


[91] Email, Cesar Pay Gomez, Uppsala University, 2017 Apr 11.

[92] Email, Magnus Tidesten, Uddeholm, 2017 Apr 5.

[93] Email, Ulrik Beste, VBN Components, 2017 Apr 19.

[94] Email, Per Olof Larsson, Höganäs, 2017 Apr 4.
9. Appendix

In the following appendix a number of materials are presented that does not fulfill the required values of UTS and $K_{IC}$. However, these materials are still considered to be somewhat relevant to this report. In some cases, the UTS and $K_{IC}$ values are just below the requirements and in other cases data for $K_{IC}$ is missing, but similar tests (e.g. impact toughness) have been conducted.

Lastly, there is one section on future materials that are currently under development. Some of these are promising, but sufficient values of UTS and $K_{IC}$ are yet to be documented.

9.1 Present materials

9.1.1 C250, C300 and C350

Maraging steel

<table>
<thead>
<tr>
<th>Steel</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>C</th>
<th>Al</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>C250</td>
<td>18.50</td>
<td>7.50</td>
<td>4.80</td>
<td>0.40</td>
<td>0.03 max.</td>
<td>0.10</td>
<td>0.10 max.</td>
<td>0.10 max.</td>
<td>Bal.</td>
</tr>
<tr>
<td>C300</td>
<td>18.50</td>
<td>9.0</td>
<td>4.80</td>
<td>0.60</td>
<td>0.03 max.</td>
<td>0.10</td>
<td>0.10 max.</td>
<td>0.03 max.</td>
<td>Bal.</td>
</tr>
<tr>
<td>C350</td>
<td>18.50</td>
<td>12.0</td>
<td>4.80</td>
<td>1.40</td>
<td>0.03 max.</td>
<td>0.10</td>
<td>0.10 max.</td>
<td>0.03 max.</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 13: Chemical composition of C250, C300 and C350 in wt% [24].

C250, C300 and C350 are maraging steels with the chemical compositions found in Table 13. These maraging steels have UTS values of 1751-2358 MPa and impact toughness values of 68-77 J, where C350 has the highest values of both properties, see Table 14 [24].
Table 14: Mechanical properties of maraging steels C250, C300 and C350 [24].

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Tensile strength (MPa)</th>
<th>Impact toughness (J)</th>
<th>0.02% Yield strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C250</td>
<td>1751</td>
<td>68</td>
<td>1710</td>
</tr>
<tr>
<td>C300</td>
<td>2020</td>
<td>73</td>
<td>1972</td>
</tr>
<tr>
<td>C350</td>
<td>2358</td>
<td>77</td>
<td>2317</td>
</tr>
</tbody>
</table>

The aging process is very similar for all grades, but results in different hardness, tensile strength, impact toughness, etc. The hardness ranges from 48 to 60 HRC, see Table 15. Longer aging is required for steels with larger cross sections [24].

Table 15: Aging temperature, aging time and resulting hardness for maraging steels 250, 300 and 350 [24].

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Aging temperature (°C)</th>
<th>Aging time (hrs)</th>
<th>Resulting hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maraging 250</td>
<td>482-496</td>
<td>6</td>
<td>48-52</td>
</tr>
<tr>
<td>Maraging 300</td>
<td>482-496</td>
<td>6</td>
<td>50-55</td>
</tr>
<tr>
<td>Maraging 350</td>
<td>482-496 or 510</td>
<td>6 or 3</td>
<td>55-60 or 55-60</td>
</tr>
</tbody>
</table>

These maraging steels should not be used at service temperatures higher than 425°C [71]. In addition, they are said to have better resistance to pitting and corrosion than common tool steel, but are also easily reworked and retreated [24]. The steels are available as billet, bar, rod and customized forgings [24].

Sectors and applications for these specific materials have not been identified. However, there are other maraging steels of the same C-grades that might be used in a similar fashion. C250 is used in vehicles and the military as missile and ejector systems, slat tracks and drive shafts [72]. C300 is used for tools, in vehicles and aerospace as transmission shafts, autosport components, and light aircraft landing gear [73]. C350 is used in aerospace, vehicles, and in the military as missile and rocket motor cases, landing and takeoff gear components, high performance shafting, gears and fasteners [74].

Price: 400 SEK/kg. However, the price can be reduced if large amounts are purchased [71].

Suppliers: Livallco stål AB, Carpenter Technology Corporation

Sectors: N/A

Applications: N/A
9.1.2 MARVAL18

Maraging steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>1850 MPa</td>
<td>[66]</td>
</tr>
<tr>
<td>Impact strength KCU</td>
<td>40 J/cm²</td>
<td>[66]</td>
</tr>
</tbody>
</table>

Table 16: Chemical composition of MARVAL18 in wt% [66].

<table>
<thead>
<tr>
<th>Element</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>18.00</td>
<td>8.00</td>
<td>5.00</td>
<td>0.50</td>
<td>0.03</td>
</tr>
</tbody>
</table>

MARVAL18 is a maraging steel similar to C250 and its chemical composition is found in Table 16. After solution treatment at 825°C, air cooling, and aging at 480°C for 4 hours the following properties were measured at 20°C: UTS of 1850 MPa, 0.2% yield strength of 1780 MPa, and impact strength KCU of 40 J/cm². In addition, an elongation (5d) of 9% was obtained after aging, and nitriding for additional surface hardness is possible. Furthermore, a contraction of approximately 0.05% occurs during the aging process with a hold time of 4 hours. Forging occurs at 1250/800°C [66].

Price: N/A
Suppliers: Aubert & Duval
Sectors: Aerospace [66]
Applications: Structural components, welded assemblies, deck landing hooks, rocket motor bodies, defense components, fasteners, etc. [66]

9.1.3 MY19

Maraging steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS</td>
<td>2050 MPa</td>
<td>[67]</td>
</tr>
<tr>
<td>$K_{IC}$</td>
<td>65 MPa·m$^{1/2}$</td>
<td>[67]</td>
</tr>
</tbody>
</table>

Table 17: Chemical composition of MY19 in wt% [67].

<table>
<thead>
<tr>
<th>Element</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>18.00</td>
<td>8.75</td>
<td>4.90</td>
<td>0.70</td>
<td>0.10</td>
<td>≤ 0.010</td>
</tr>
</tbody>
</table>

MY19 is a maraging steel similar to C300, with its chemical composition found in Table 17. It is subjected to the following heat treatment: solution treatment at 820°C, air-cooling, and then aging at 480°C for 4 hours. At 20°C an UTS of 2050 MPa, 0.2% yield strength of 1980 MPa, $K_{IC}$ of 65 MPa·m$^{1/2}$, impact strength KV of 25 J, hardness of 53 HRC, and an elongation (5d) of 8.5% were measured. In addition, a contraction of approximately 0.07% occurs during the aging process. Forging occurs at 1280/830°C [67].
9.1.4 BÖHLER V725

Maraging steel

UTS: 2300-2500 MPa [68]
Impact strength DVM 10 J [68]

<table>
<thead>
<tr>
<th>Ni</th>
<th>Co</th>
<th>Ti</th>
<th>Mo</th>
<th>Al</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.00</td>
<td>12.30</td>
<td>1.70</td>
<td>4.20</td>
<td>0.15</td>
<td>0.05</td>
<td>0.005 max.</td>
<td>0.005 max.</td>
</tr>
</tbody>
</table>

V725 is a 350 grade maraging steel with the average chemical composition found in Table 18 [68].

This steel reaches an UTS of 2300-2500 MPa when solution annealed at 820°C for 1 hour and aged for 3 hours at 510°C, both in air. However, a lower tensile strength can be achieved if a higher temperature is used during the aging process. Moreover, impact strength (DVM) of 10 J (minimum) was obtained after the mentioned aging process [68].

In addition, an average bending fatigue strength of 750 N/mm² (N=10⁷), an average hardness of 59 HRC, and a minimum elongation A₅ of 5% are documented [68]. Elongation A₅ represents elongation for specimens with an original length of 5 x diameter [75]. The minimum 0.2% proof stress was measured at different temperatures and ranged from 2200 MPa at room temperature to 1400 MPa at 500°C, see Table 19. Furthermore, BÖHLER V725 has a long-time service temperature reaching 450°C, and can be used for hot and cold work [68].

Table 19: Minimum 0.2% proof stress of V725 at different temperatures [68].

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Min. yield strength, 0.2% (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>2200</td>
</tr>
<tr>
<td>100</td>
<td>2050</td>
</tr>
<tr>
<td>200</td>
<td>1950</td>
</tr>
<tr>
<td>300</td>
<td>1850</td>
</tr>
<tr>
<td>400</td>
<td>1700</td>
</tr>
<tr>
<td>500</td>
<td>1400</td>
</tr>
</tbody>
</table>
Note that all mechanical property values are measured on longitudinal specimens with a maximum diameter of 100 mm [68].

This maraging steel is most commonly machined with BOEHLERIT® sintered carbide (main groups P and K), both in annealed and precipitation hardened condition. Although, high speed tool steels are a suitable alternative [68].

Nitriding gives a harder surface and can therefore exchange the aging process. A gas nitration for 45 hours at 500°C results in harnesses over 800 HV with an approximate depth of 0.2 mm. However, the core material will only be solution annealed, which leads to an UTS of 1100-1250 MPa and a minimum impact strength (DVM) of 40 J [68].

Price: 200-255 SEK/kg plus an additional delivery day alloying cost, currently on 50 SEK/kg [70]

Suppliers: REC Indovent AB, BÖHLER Edelstahl

Sectors: Aerospace, tools, etc. [68]

Applications: Heavy stress components, pressure vessels, hot pressing tools, die casting tools (for zinc and aluminum alloys), screws and bolts, etc. [68]

9.1.5 BÖHLER V720

Maraging steel
UTS: 1720-1870 MPa [69]
Impact strength DVM: 24 J [69]

Table 20: Chemical composition of BÖHLER V720 in wt% [69].

<table>
<thead>
<tr>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.50</td>
<td>8.80</td>
<td>5.00</td>
<td>0.70</td>
<td>0.11</td>
<td>0.05 max.</td>
<td>0.05 max.</td>
<td>0.005 max.</td>
</tr>
</tbody>
</table>

BÖHLER V720, is a 300 grade maraging steel with the chemical composition in Table 20 [69].

The solution annealing is the same as for V725, but it is aged at 430°C or 480°C for 3 hours and is then quenched in air. UTS of 1720-1870 MPa or 1860-2260 MPa is obtained, respectively. In addition the impact strength is minimum 24 J when aged at 430°C and 21 J when aged at 480°C. Also, the 0.2% proof strength remains over 1325 MPa at 300°C. See these, and more, mechanical properties for longitudinal specimens with diameter up to 100 mm in Table 21 [69].
Table 21: Impact strength, bendig fatigue stress, yield strength, elongation A5 and hardness for BÖHLER V720 at different aging temperatures [69].

<table>
<thead>
<tr>
<th>Condition</th>
<th>Aged at 430°C</th>
<th>Aged at 480°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact strength (DVM) min. (J)</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Bendig fatigue stress (N=10^7)</td>
<td>634</td>
<td>735</td>
</tr>
<tr>
<td>average (N/mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength, 0.2% (MPa) at:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT</td>
<td>1620</td>
<td>1815</td>
</tr>
<tr>
<td>100°C</td>
<td>1520</td>
<td>1765</td>
</tr>
<tr>
<td>200°C</td>
<td>1420</td>
<td>1670</td>
</tr>
<tr>
<td>300°C</td>
<td>1325</td>
<td>1570</td>
</tr>
<tr>
<td>400°C</td>
<td>1180</td>
<td>1275</td>
</tr>
<tr>
<td>500°C</td>
<td>930</td>
<td>980</td>
</tr>
<tr>
<td>Elongation A5 (%)</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Hardness HRC (average)</td>
<td>51</td>
<td>55</td>
</tr>
</tbody>
</table>

This maraging steel is most commonly machined with BOEHLERIT® sintered carbide (main groups P and K), both in annealed and precipitation hardened condition. Although, high speed tool steels are a suitable alternative [69].

A long-time service temperature of approximately 450°C is achieved, and it is possible to use the same nitriding process for nitration as for V725. Because the nitriding process in this case replaces aging, the core material will only be solution annealed with UTS of 980-1130 MPa and have minimum impact strength (DVM) of 48 J [69].

**Price:** 200-255 SEK/kg plus an additional delivery day alloying cost, currently on 50 SEK/kg [70]

**Suppliers:** REC Indovent AB, BÖHLER Edelstahl

**Sectors:** Aerospace, tools, etc. [69]

**Applications:** Heavy stress components, pressure vessels, hot pressing tools, die casting tools (for zinc and aluminum alloys), screws, etc. [69]
9.1.6 2800-MPa grade maraging steel

Maraging steel

UTS: 2700 MPa [31]

\( K_Ic: \) Around 30 MPa\( \cdot m^{1/2} \) [31]

Table 22: Chemical composition of a 2800-MPa grade maraging steel in wt% [31].

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>C</th>
<th>O</th>
<th>S</th>
<th>N</th>
<th>P</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17.88</td>
<td>14.75</td>
<td>6.69</td>
<td>1.10</td>
<td>0.08</td>
<td>0.02</td>
<td>0.007</td>
<td>0.0037</td>
<td>0.0025</td>
<td>0.002</td>
<td>0.0015</td>
<td>0.001</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

There have been many attempts to invent a 2800 MPa grade maraging steel, a steel with higher tensile strength than the already existing 18Ni types such as 18Ni(350), 13Ni(400), 15Ni–25Co–7Mo, 16Ni–15Co–(5–7)Mo–2.5Ti and 17Ni–15Co–6Mo–1Ti are some high strength steels that more or less have been developed with the desired strength. Unfortunately, they have difficulty reaching a good toughness and ductility with such a high strength because of undissolved Fe\(_2\)Mo laves phases in the matrix. The \( K_Ic \) values got some improvements after a thermomechanical treatment, but they were still around 30 MPa\( \cdot m^{1/2} \) [31].

Another attempt to improve the \( K_Ic \) and ductility without decreasing the strength has been made for a 2800 MPa grade maraging steel, its chemical composition is found in Table 22. The obtained \( K_Ic \) values were improved to around 40 MPa\( \cdot m^{1/2} \), but the strength then decreased to around 2200 MPa because of retained austenite in the microstructure. Despite this, an increase in strength to 2700 MPa could be obtained by removing the retained austenite by CT at -73°C before aging at 500°C for 4 hours. But the \( K_Ic \) then decreased to just over 30 MPa\( \cdot m^{1/2} \). The maximum hardness is obtained when aged at 500°C for about 3 hours [31].

The microstructure of the steel consists of lath martensite with high dislocation density. Precipitates in needle-like shapes are also found in the lath martensite matrix and are identified to be Ni\(_3\)(Mo,Ti) type phases [31].

Suppliers, sectors and applications for this material have not been identified.

| Price: | N/A |
| Suppliers: | N/A |
| Sectors: | N/A |
| Applications: | N/A |
9.1.7 PH13-8Mo

**Maraging steel (stainless)**

**UTS:** 1551 MPa [50]

**K<sub>IC</sub>:** 81 MPa*<sup>1/2</sup> [50]

*Table 23: Alloying elements of PH13-8Mo, in wt%, corresponding to the UTS and KIC mentioned above [50].*

<table>
<thead>
<tr>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>8</td>
<td>2.2</td>
<td>1.1</td>
<td>0.04</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

PH13-8Mo is a precipitation hardened martensitic stainless (maraging) steel with nanosized NiAl precipitates [28, 76]. These increase the material hardness without changing the matrix even when over-aged at 620°C. In addition, it has good resistance against corrosion and stress-corrosion cracking, but also good toughness and ductility [76].

A previous study has shown a yield strength of 1434 MPa, UTS of 1551 MPa and a K<sub>IC</sub> of 81 MPa*<sup>1/2</sup> for PH13-8Mo, with chemical composition found in Table 23. But also a K<sub>ISCC</sub> over 69 MPa*<sup>1/2</sup> obtained after 1000 hours in 3.5% NaCl in water [50]. However, it is possible for an improved type of PH13-8Mo to obtain a yield strength up to 1500 MPa and K<sub>IC</sub> up to 90 MPa*<sup>1/2</sup> [77]. An article indicates that UTS values are rather stable up to 400°C (maximum UTS) and then decreases significantly. But also the longer hold time, the lower UTS [78].

The highest values encountered for PH13-8 are an UTS of 1620 MPa and a Charpy impact of 27 J [79]. However, the production process is unknown since the company, AZoMaterials, does not share it.

Note that the chemical composition corresponding to property values from different sources differ slightly from the one mentioned in Table 23.

**Price:** N/A

**Suppliers:** AZoMaterials

**Sectors:** Aerospace, nuclear, petrochemical, machinery etc. [76, 64]

**Applications:** Structural sections, landing gears, shafts, valves, etc. [64]
9.1.8 Vibenite® 150

**High-speed steel**

**Yield strength:** 2300-3100 MPa \[80\]

$K_{IC}$: N/A

<table>
<thead>
<tr>
<th>Table 24: Chemical composition of Vibenite® 150 in wt% [80].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
</tr>
<tr>
<td>4.0</td>
</tr>
</tbody>
</table>

Vibenite® 150 is a powder metallurgy steel (see chemical composition in Table 24) that is 3D-printed, and available as heat treated or untreated. The steel has an iron matrix with finely dispersed carbides. In addition, its yield strength varies with hardness, for example 3100 MPa at 64 HRC or 2300 MPa at 58 HRC \[80\].

**Price:** N/A

**Suppliers:** VBN Components AB

**Sectors:** Tools \[80\]

**Applications:** Functional prototypes, tool holders, applications demanding both wear resistance and toughness, wear parts, etc. \[80\]

9.1.9 NanoFlex

**Precipitation hardened austenitic stainless steel**

**UTS:** 1850 MPa \[81\]

$K_{IC}$: N/A

<table>
<thead>
<tr>
<th>Table 25: Chemical composition of NanoFlex in wt% [81].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

NanoFlex is a precipitation hardened austenitic stainless steel with its chemical composition presented in Table 25. It is specifically designed for applications requiring high strength and good ductility. NanoFlex is one of the very few commercially available steels containing quasicrystals. Possible ranges for the mechanical properties, in both cold rolled and aged conditions are presented below. The strength level after ageing depends on the degree of cold deformation and therefore, also on the material dimension \[81\].

**Cold rolled:** UTS of 950-1850 MPa \[81\]

**Cold rolled + aged:** UTS of 1400-2600 MPa \[81\]
The material is highly suitable for products requiring good corrosion resistance, high strength, and good ductility in the final product, combined with high formability in the delivered condition. It is especially suitable for complicated designs that have high strength requirements. NanoFlex also provides an opportunity for reaching high strength levels in relatively heavy gauge components [81].

Price: N/A  
Suppliers: Sandvik AB  
Sectors: Medical [81]  
Applications: Surgical needles [81]

9.1.10 ASP2005 and ASP2012

Powder metallurgy high-speed steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>Cr</th>
<th>V</th>
<th>W</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASP2005</td>
<td>4.0</td>
<td>4.0</td>
<td>2.5</td>
<td>2.5</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>Bal.</td>
</tr>
<tr>
<td>ASP2012</td>
<td>4.0</td>
<td>1.5</td>
<td>2.1</td>
<td>2.0</td>
<td>0.6</td>
<td>1.0</td>
<td>0.3</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 26: Chemical composition of ASP2005 and ASP2012 in wt% [82].

ASP2005 and ASP2012 are two powder metallurgy high-speed steels with chemical compositions found in Table 26 and material properties in Table 27. These steels have the following key benefits: homogeneous and fine microstructures; high hardness and wear resistance because of higher contents of tungsten (carbide-forming element). In addition, they have higher toughness than similar non-powder steels because they are free from carbide segregation [82]. ASP2005 has good qualities against abrasion, but if a material with better toughness is required Erasteel recommend ASP2012 [83].

Table 27: Material properties for ASP2005 and ASP2012 [82].

<table>
<thead>
<tr>
<th>Steel</th>
<th>Impact energy (J) unnotched</th>
<th>Hardness (HV/HRC)</th>
<th>UTS (MPa)</th>
<th>Ultimate bend strength (MPa)</th>
<th>Compression yield stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASP2005</td>
<td>50-140</td>
<td>610-830/55-65</td>
<td>N/A</td>
<td>4500-5500</td>
<td>1900-3100</td>
</tr>
<tr>
<td>ASP2012</td>
<td>280</td>
<td>680/58</td>
<td>2000-2500</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
9.2 Future materials

9.2.1 High entropy alloys

High entropy alloys (HEAs) are a relatively new field, which has been subjected to extensive research since the first publications in 2004 [84]. HEAs with super high $K_{IC}$ values (over 200 MPa*m$^{1/2}$) [85], and high UTS at elevated temperatures have been reported [86]. The vastness of this field combined with reported findings of excellent mechanical and functional properties makes HEAs of interest for drilling applications.

There are several different definitions of a HEA. Largely, these can be summarized into either a substance with five or more principal elements, or a substance where the entropy exceeds a lower limit. These definitions are closely related as a high number of principal elements contribute to high entropy. Some definitions also require the substance to be a single-phase solid solution, which is thermodynamically favorable due to the high entropy [84].

HEAs are categorized into two major groups; 3d-transition HEAs and refractory HEAs. Currently, 3d-transition HEAs cannot compete with high nickel super alloys and precipitation hardened stainless steels regarding strength [84]. However, the $K_{IC}$ relative to the strength is in some cases excellent [85-86].

Refractory HEAs are showing promise with high compressive strength, but so far there are very few reports regarding tensile properties. This HEA group was developed to compete with superalloys and stainless steels since they have a tendency to retain high strength at high temperatures [84, 87]. In addition, some refractory HEAs are brittle at room temperature [88].

AB Sandvik Coromant has recently received funding from Vinnova for a study concerning HEAs as a binder in cemented carbides. HEAs will replace cobalt with intention to improve mechanical properties. The cemented carbides are used in cutting tools [89], an application that might have similar material requirements as percussive drilling.

9.2.2 Quasicrystals

Quasicrystals have essentially sharp diffraction patterns and aperiodic crystals, which means that a three dimensional lattice is absent. Quasicrystals have symmetry in higher dimensions, so they are not amorphous [90]. The use of quasicrystals in metallic alloys is a relatively new
area of work. The crystals must be allowed to grow and bind effectively to the surrounding matrix, which only works for certain metallic alloys today [91].

Quasicrystals have different characteristics and are formed in different ways. Stable quasicrystals are formed by a very slow cooling rate and must also contain the right elements in the right proportions for them to be formed. This should also be done under the appropriate conditions for production on a large scale, at a low cost, etc. Therefore, quasicrystals are very limited in number [91].

The reason for wanting quasicrystals is that they are almost free from defects and disorder, making them although brittle, very strong, with low friction and high tensile strength. They also have thermal resistance, corrosion resistance and low friction properties [91].

9.2.3 Uddeholm’s upcoming boride steel
The Swedish company Uddeholm is currently working on a steel that contains borides. However, they believe that it will not have high $K_{IC}$ or UTS, but high wear resistance and hardness. They also commented that they have no greater knowledge about this application and that they do not produce any steel they consider to be optimal [92].

9.2.4 VBN’s upcoming steel
According to Ulrik Beste at VBN components, they have made ferrous alloys with high hardness and high strength. They are also in progress of developing a new product profiled towards drill heads. Thus, their future product that they say will launch next year is going to have higher toughness than their current products [93].

9.2.5 Höganäs’ powder metallurgy
According to the Swedish company Höganäs that works with metal powders, their kind of powder metallurgy cannot be used for this application [94].