Hybrid Steel® – the next step in steel evolution

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EXECUTIVE OVERVIEW

In 2017, Ovako introduced a step-change in the evolution of steel metallurgy with the launch of Hybrid Steel. The aim was to challenge the long-established divisions between the specific steel categories of tool steel, maraging steel, and stainless steel. Instead, the ambition was to merge the unique properties in each steel category into one high-performance steel grade with the production economy of conventional engineering steel.

This invention was enabled by a successful combination of alloy carbide and intermetallic precipitation hardening. Hybrid Steel offers superior strength over conventional steels, especially for high temperature applications. It has particular appeal for use in engine components, bearings and tools that operate in extreme environments and in demanding conditions. Due to its high hardenability, Hybrid Steel does not need to be quenched to achieve a fully martensitic structure for the subsequence tempering process. This results in minimum component distortion and enables a reduction in final machining processes.

Furthermore, Hybrid Steel has surprisingly good corrosion and oxidation resistance. Even with a much lower chromium content, it still has similar corrosion resistance levels as the lower end of stainless steels. This comes as the result of its aluminum content, which has a strong effect on the passive layer formation. In addition, it is suitable for welded high-strength components. Its final high strength is achieved by a simple aging treatment in the temperature range 500–600°C. During this process the steel exhibits extremely good dimensional stability.

Optimization of the alloying elements was made during the alloy design stage to minimize the segregation of alloying elements across a large (<150mm) steel section. This ensured a very high uniformity of properties, even when used for large components.

The key features of Hybrid Steel include:
1. High strength, especially at elevated temperatures
2. High-volume, cost-efficient production
3. High hardenability enabling low distortion
4. High cleanness and fatigue strength at elevated temperatures
5. Uniform properties with low micro-structural segregation
6. High strength with good weldability
7. Excellent surface treatment possibilities
8. Good corrosion resistance

Hybrid Steel 50, 55 and 60 are the first three commercially available grades in the growing Hybrid Steel family. The former two are designed to 50 and 55 HRC hardness, which provides an array of engineering steel capabilities. The latter is designed to 60 HRC hardness and is a unique grade of bearing steel for applications where added performance is needed. All three are produced with large-scale automated ingot cast processes.

In this white paper, we outline the background to the development of Hybrid Steel and its potential advantages when used for the manufacture of highly stressed components.

1 – INTRODUCTION

Modern steels are divided into separate categories of tool steel, stainless steel, and lower alloy engineering steel, as well as more sophisticated maraging steels. Ovako's latest invention is to challenge these long-established divisions and to merge the unique properties in each category into one high-performance steel. (Figure 1).

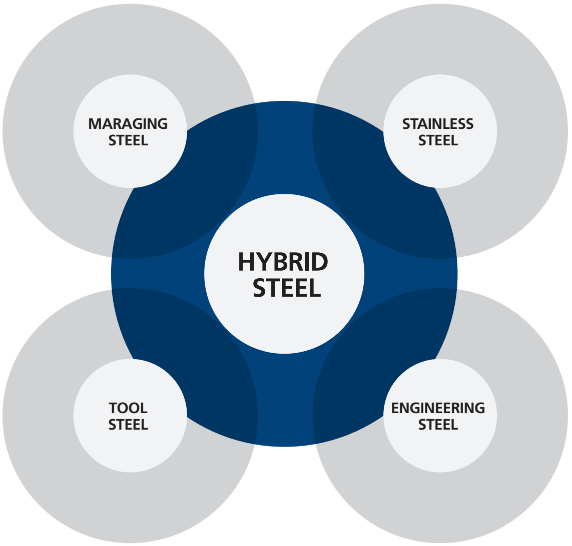

Figure 1 – The properties possesed by Hybrid Steel cover all the categories of modern steel.

The new steel family is called 'Hybrid Steel'. The reason is that a combination of two well-established precipitate phases is used to strengthen this steel: alloy carbide and intermetallic. Furthermore, Hybrid Steel is made possible by a creative alloying philosophy that minimizes segregation. The result is a steel with more than twice the yield and tensile strength of conventional bearing steel (52100) when tempered for use at elevated temperatures. We believe this new steel family will help our customers and end-users to grow, improve efficiency and save costs.

Advanced engineering components need high-performance steels that not only sustain high loads but are also reliable. One method to increase reliability is to improve fatigue life. For ultra-high-strength steels, fatigue is an essential life-limiting factor for any well-designed component. There are two critical factors in optimizing the fatigue resistance of steel. Both of these were considered in the development and production of Hybrid Steel.

First, it is vital to control the size and population of defects (inclusions) in steel that act as stress concentrators and crack initiators. Ovako is a leader in the production of 'clean' steel with over a century of experience in supplying it to the bearing industry. Second, perhaps the most important criteria for fatigue resistance is that the microstructure should not be weakened when exposed to the operating temperature and load. Operating under high load and at elevated temperature effectively provides an energy input that causes the steel microstructure to degrade. This degradation can occur at moderate temperatures with long exposure times or at elevated temperature applications over a much shorter time. Hybrid Steel achieves its strength after high-temperature tempering, and the resulting microstructure is extremely stable. The steel, therefore, offers a much higher fatigue resistance. Highly alloyed tool steels can also be tempered at 500–600°C and exhibit a low tendency for microstructural degradation. However, these steels have issues in large scale production.

In addition to the long fatigue life, Hybrid Steel has several other advantages, for example, it has good corrosion resistance and it is suitable for nitriding. Furthermore, it has a very high hardenability; hence, it does not require any quenching, resulting in a very low distortion of the heat-treated component. There is also potential to simplify the manufacturing process with the use of Hybrid Steel, enabling further cost reduction for customers. We are only starting to explore the potential of Hybrid Steel across many diverse applications.

2 – THE CHALLENGE OF ELEVATED TEMPERATURE APPLICATIONS

Advanced engineering components need to operate at high temperatures so that the efficiency can be improved. However the metallurgical instabilities of conventional steel reduce the operating life of high-temperature components. Failure by creep or fatigue is enhanced at high operating temperatures.

Any metal is expected to experience microstructure changes at elevated temperatures. In conventional bearing steel (52100), the iron carbide (cementite, Fe_3C) that is present tends to coarsen quickly with increasing temperatures and this results in the reduction of strength, as shown in Figure 2.

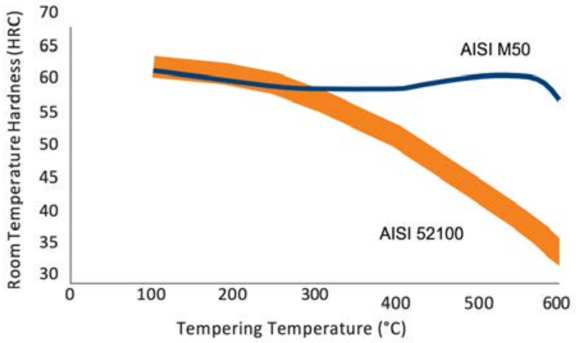

Figure 2 – Conventional bearing steels (52100) experience a reduction in strength corresponding with increased tempering temperatures.

Tool steels , such as AISI M50 do not start to soften until the tempering temperature is raised above 550°C, see figure 2. The drawback with this steel is that the addition of carbide forming elements will typically generate large primary carbides during solidification due to their partitioning during dendrite formation. These large carbides can act as fatigue initiation points and effectively off-set the beneficial effect of the stable microstructure.

Tool steels without the large primary carbides can be produced, but require an expensive secondary remelting process.

Another aspect of this temperature sensitivity of high strength steels relates to various processes to modify surfaces. Such processes can be applied to improve hardness, compressive stresses, low-friction properties, corrosion resistance and more. In many cases the processes are applied at an elevated temperature, which means that the underlying steel stands the risk of losing some of its properties. Similarly, press-fitting of carbide inserts in rock drilling tools is often carried out at an elevated temperature. A steel that reaches its full strength at elevated temperatures can therefore offer benefits when such processes are applied.

3 – THE HYBRID STEEL CONCEPT AND DEVELOPMENT STORY

In 2015, Ovako embarked on the development of a new alloy that would fulfill three main criteria:

- The steel must be tempered/aged at 500–600°C to obtain high strength and a stable microstructure.
- A target hardness above 60 HRC and 55 HRC after tempering, so that it is suitable for bearings and other highly stressed engineering components.
- Achieve both aims without any harmful segregation of elements as well as being suitable for large-scale production.

Minimizing segregation during the solidification and formation of sizeable primary carbides during ingot casting was identified as the most critical stage in the alloy development. Systematic studies and creative alloying were performed on experimental small ingots to understand the segregation levels that could be achieved for various alloying systems. At the top (20 mm from the top surface) of the ingots, the variation of the chemical composition was analyzed, and the max/min ratio of composition was established. If this ratio is one, no segregation occurs, while a high value indicates severe segregation of the elements.

Figure 3 shows the variation in composition ratio at the top of the test ingot. It shows that the segregation level of Cr, Mo, and V increase considerably with the increase of carbon content. Therefore, low carbon steel must be produced to avoid significant segregation. However, low carbon steel does not offer the required strength after tempering, as indicated by the blue line in Figure 4. The segregation of both nickel (Ni) and aluminum (Al) is not influenced by the carbon concentration (Figure 3). Therefore. Al and Ni can be added to boost the strength by forming intermetallic precipitates, and this made it possible to reach the high strength level required.

The composition of the two newly developed Hybrid Steel grades is shown in Table 1. The numerical designation of the steel indicates the maximum hardness in HRC, which is mainly due to the difference in the carbon content.

The aging behavior of both Hybrid 55 and 60 are shown in figure 4. The figure indicates that a large tempering window can be applied to achieve peak strength. The hardening and softening trend are similar for the two steel grades with Hybrid 60 showing a higher hardness level.

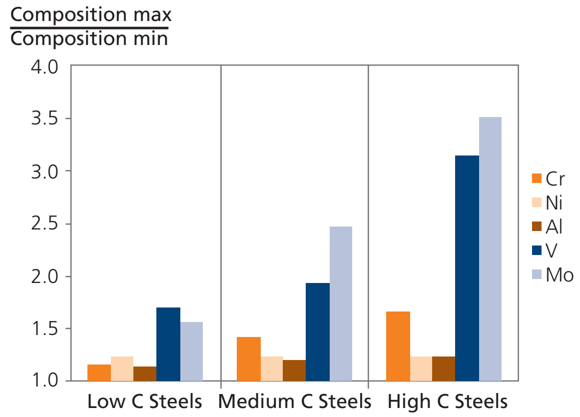

Figure 3 – The variation in the composition ratio at the top of the test ingots was measured.

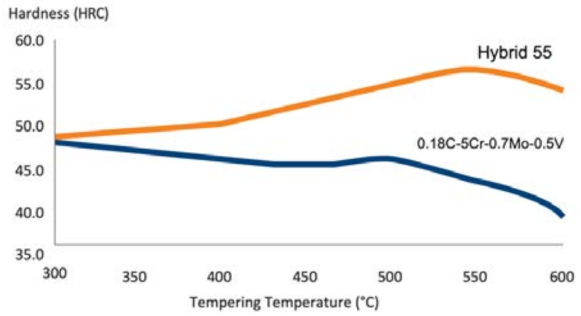

Figure 4 – The orange line shows the improved tempering resistance of the Hybrid Steel 55.

	C	Si	Mn	Cr	Ni	Mo	V	Al
Hybrid Steel® 50	0.04	0.1	0.3	5	5	0.7	-	2
Hybrid Steel® 55	0.18	0.1	0.3	5	6	0.7	0.5	2
Hybrid Steel® 60	0.28	0.1	0.3	5	6	0.7	0.5	2

Table 1 – Composition of the first three Hybrid Steel grades.

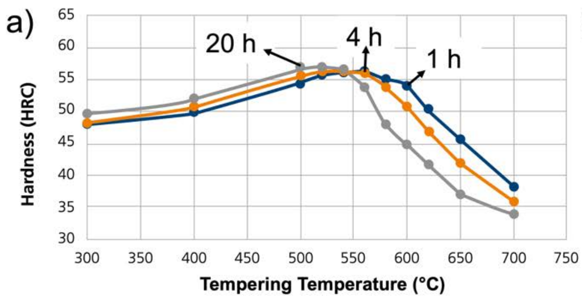

Figure 5a – Aging behavior of Hybrid 55.

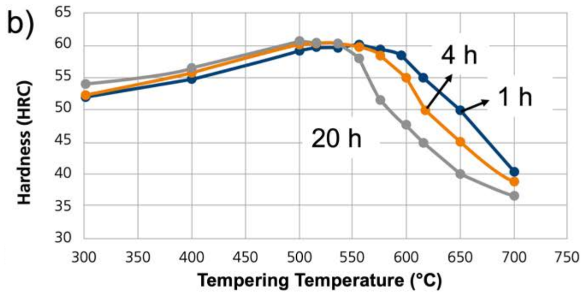

Figure 5b) Aging behavior of Hybrid 60.

4 – MICROSTRUCTURE AND PRECIPITATE SPECIES

The martensite formed after solution treatment in Hybrid Steel is predominantly lath type. This is due to the low carbon (<0.3wt%) content and relatively high martensite transformation temperature (350°C). The formation of lath type martensite creates a high density of dislocations (as high as 10^{16} m^{-2}), which is comparable with the dislocation density of a cold-worked metal (5 x 10^{15} m^{-2}). The high dislocation density in the martensite is beneficial to increase the number density and promoting the formation of precipitates during tempering since the dislocation can act as a nucleation site for the precipitates.

Due to the high-temperature stability of the carbide formed after soft annealing, the carbides did not fully dissolve after solution treatment. Figure 6 shows the residual carbides of M_6C and MC within the martensitic matrix in the as- solution treated Hybrid 55. The detected carbide size is less than 500 nm and is not expected to have any detrimental effect on the mechanical properties.

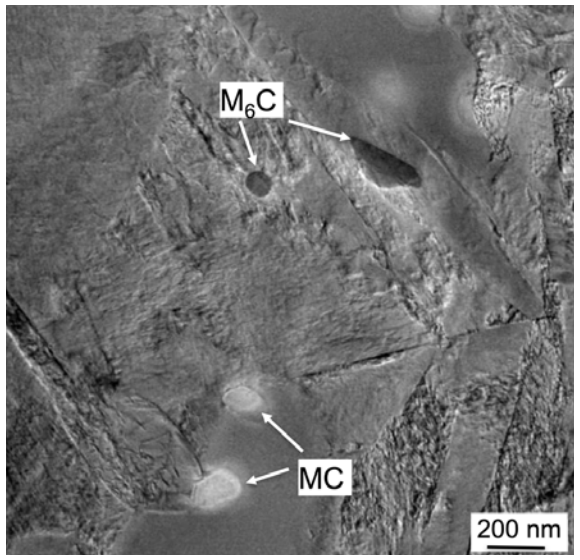

Figure 6 – Residual carbide of M_6C. and MC observed within the martensitic matrix in the as- solution treated Hybrid 55.

The final strength of Hybrid Steel is derived from a martensitic microstructure containing a combination of alloy carbide and intermetallic precipitation hardening. The intermetallic precipitate has a BCC_B2 crystal structure and composition of (Fe, Ni)Al. The carbides present are plate-shaped MC and spherical M_7C_3 precipitates, where 'M' is the carbide forming elements, such as iron (Fe), vanadium, chromium, and molybdenum.

Computer simulation and high energy X-ray synchrotron experiments prove that the formation of MC carbide is promoted during high-temperature tempering (above 540°C). Since MC carbide is known to trap hydrogen and improve hydrogen resistance, work is in progress to verify the beneficial effect of a high tempering temperature.

Figure 7 shows an atom probe tomography (APT) reconstruction of Hybrid 55 tempered at low temperature (520°C for 3 h) where MC carbides did not form. The measured composition of the M_7C_3 carbide precipitates was 16C-3Mo-3V-25Cr-50Fe (at.%) with minor additions of other elements. The measured composition of the NiAl precipitates was 31Al-30Ni-31Fe (at.%), with small enrichments of manganese (Mn) and copper (Cu).

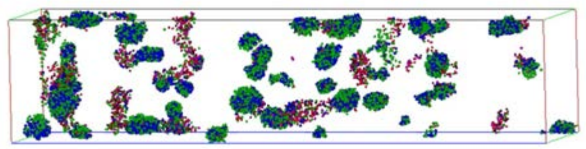

Figure 7 – An atom probe reconstruction of Hybrid Steel 55 aged at 520°C for 3 hours. The Fe atoms have been removed and clusters of NiAl atoms as well as Cr;V-C can be seen.

5 – RESISTANCE TO HYDROGEN EMBRITTLEMENT

The absorption of atomic hydrogen into bearing steels from the decomposition of lubricants, corrosion, electrical stray current or contaminants such as water promotes premature bearing failure. Such premature failure is typically detected with the formation of white etching crack (WEC) underneath the raceway. Bearings used in wind turbine gearboxes, automotive, paper mill and marine applications are reported to encounter this type of failure.

Figure 8 shows the effect of hydrogen on the rotating bending fatigue life as measured in the number of cycles before failure for 52100 and Hybrid 60 bearing steels. It is shown that the fatigue life of Hybrid 60 is less sensitive to hydrogen compared to the popular 52100 bearing steel.

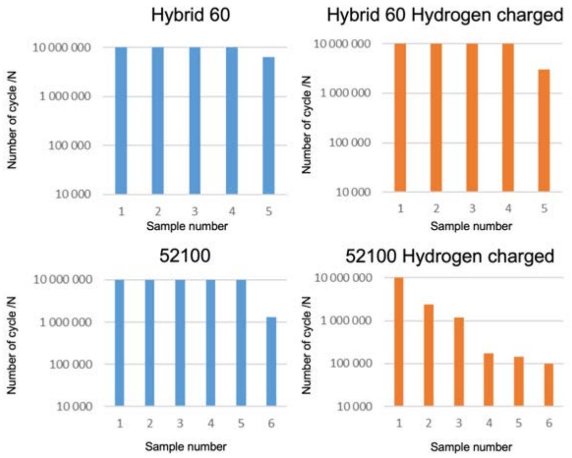

Figure 8 – Effect of hydrogen on the rotating bending fatigue life of 52100 and Hybrid 60 bearing steels. The rotating bending fatigue stress is 725 MPa. Hydrogen charging was performed on 0.5M Na_2SO_4 electrolyte, with a current density of 5 mA/cm^2, for 20 hours)

Figure 9 shows the hydrogen trapping capacity of Hybrid 60 compared to the 52100 bearing steel. An alloy that is capable of trapping infused hydrogen and rendering it harmless is one of the methods in preventing hydrogen embrittlement in high strength steel. Hybrid 60 can trap more hydrogen (~5 times). Due to the high hydrogen trapping capacity and high alloy element addition, the diffusivity of hydrogen in Hybrid 60 is also expected to be slower compared to 52100 steel. Both increases in hydrogen trapping capacity and slow hydrogen diffusivity improve the hydrogen resistance during service.

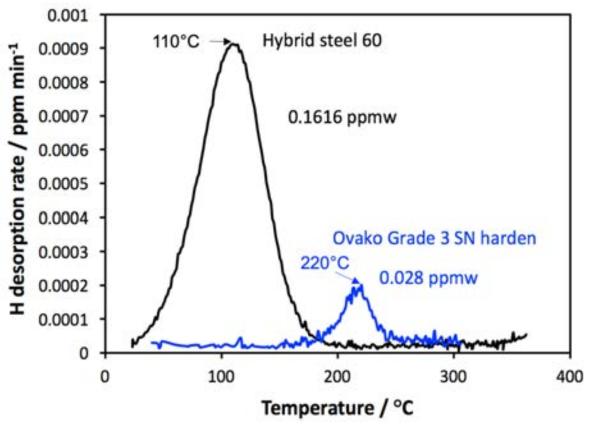

Figure 9 – Thermal desorption spectra of Hybrid 60 and 52100 bearing steel after hydrogen charging (same condition as in figure 6) and aged at room temperature until the diffusible hydrogen is fully desorbed. The detected hydrogen is a measurement of the hydrogen trapping capacity of the steel.

6 – NITRIDING

Surface nitriding is one of the most popular methods to prolong the life of treated parts. It is mainly used to increase the surface hardness and improve wear, fatigue, and tribological performance.

The composition of Hybrid Steel with the addition of 5 % Cr and 2 % Al makes it very suitable for nitriding. Since the steel is highly thermal resistant, a high core hardness can be maintained after nitriding. This means that a shallower case depth can be accepted, compared to nitriding of standard engineering steel. Nitriding of Hybrid Steel can be performed at the same temperature as the tempering (500°C–600°C), which means that this can be done in a single step.

Figure 10 shows the microstructure of plasma nitrided Hybrid 55, where the compound layer is suppressed; nevertheless, the measured surface hardness is above 1300 HV1. Figure 11 shows the hardness and residual stress after the plasma-nitriding of Hybrid 55 at 520°C for 20 hours. Both ε-$Fe_{2.4}N$ and γ'-Fe_4N nitride compounds were detected to form at the plasma nitriding surface (Figure 12). If the corrosion resistance is important after nitriding, the nitriding process can be performed at low nitriding potential and at a lower temperature (below 400°C) to avoid the formation of mixed compound layers and chromium and aluminum nitride (Cr, Al)N, which would deteriorate the corrosion resistance. Besides, the removal of the passive layer during nitriding is vital before and during nitriding to ensure effective nitrogen uptake.

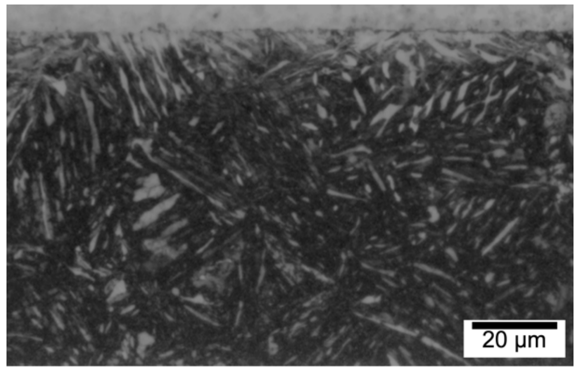

Figure 10 – The microstructure of plasma nitrided Hybrid 55, where the compound layer is suppressed. The measured surface hardness is above 1300 HV1.

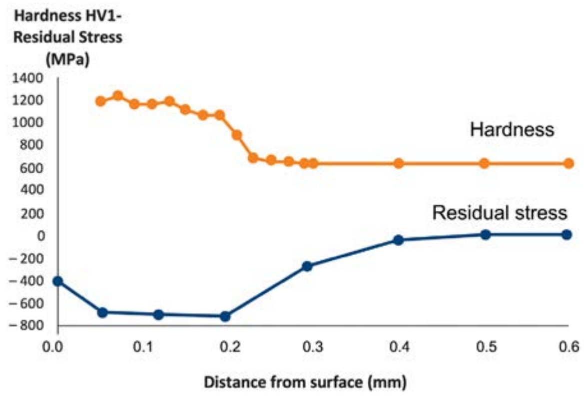

Figure 11 – The hardness and residual stress profile resulting from the plasma-nitriding of Hybrid 55.

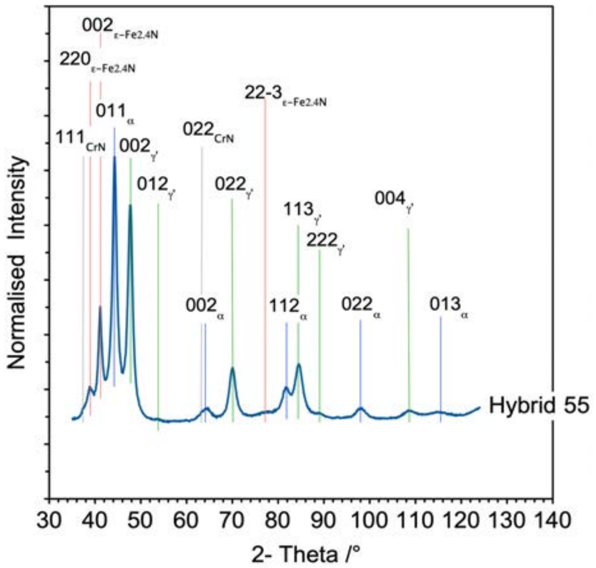

Figure 12 – X-ray diffraction spectra from the nitrided surface. Both ε-$Fe_{2.4}N$ and γ'-Fe_4N nitride compounds were detected. The formation of (Cr, Al)N is not conclusive due to the peak overlaps. The plasma nitriding was performed at 520°C for 20 hours in the atmosphere of N_2 75% - H_2 25%.

7 – OXIDATION AND CORROSION RESISTANCE

Oxidation is an essential form of material degradation that often has severe implications for component reliability during high-temperature service. Hybrid Steel contains 2wt% of aluminum and hence shows excellent oxidation resistance. Figure 13 shows the mass increase due to the oxide layer formation for various steels after exposure to the specified thermal condition. Hybrid 55 shows a minimal oxide formation even after 500 hours at 700°C. It is indicated that the oxide layer that forms on Hybrid steel is a chemically and mechanically stable oxide that also prevents diffusion of oxygen.

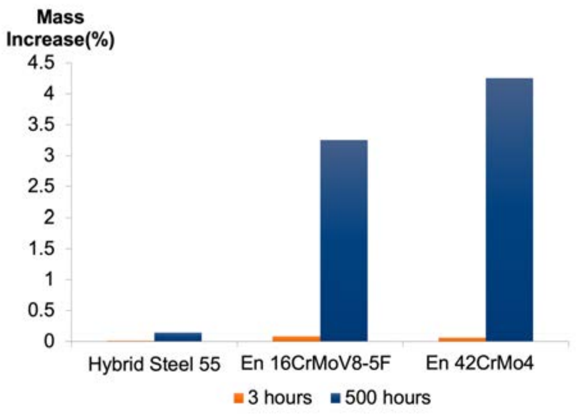

Figure 13 – Oxidation resistance tested at 700°C for 3 hours and 500 hours.

The wet corrosion resistance of stainless steels in chloride containing solutions is often ranked by using the so-called PREN formula, typically described as PREN = wt-%Cr + 3.3*wt-%Mo + 16*wt-%N. While aluminum is a well recognized passivating agent in oxidizing environments, it has so far not been included in the PREN formula. This is a natural consequence of the difficulties of creating such alloy combinations. With the new advances by Ovako, large scale production of the novel alloying family of Hybrid Steels is a reality. In the future the PREN formula will need to be adapted, since we can already establish a very strong effect by the aluminum additions on wet corrosion resistance.

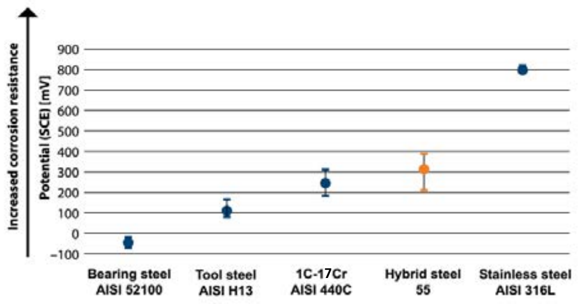

Figure 14 – Preliminary ranking of corrosion resistance.

Figure 14 shows the preliminary ranking of various steels on the corrosion resistance test according to ISO15158. On this test, the test pieces are immersed in 0.01M NaCl, and with increasing voltage until the current of 100 uA/cm2 is reached. The higher the voltage, the better the corrosion resistance. Compared to standard engineering steel (Bearing steel), Hybrid Steel shows much better corrosion resistance and even slightly better than AISI 440C. On the same test, as shown in figure 15, it is also established that the passive layer has formed on Hybrid Steel, while no noticeable passive region was observed on bearing steel (52100), H13, and 440C steel.

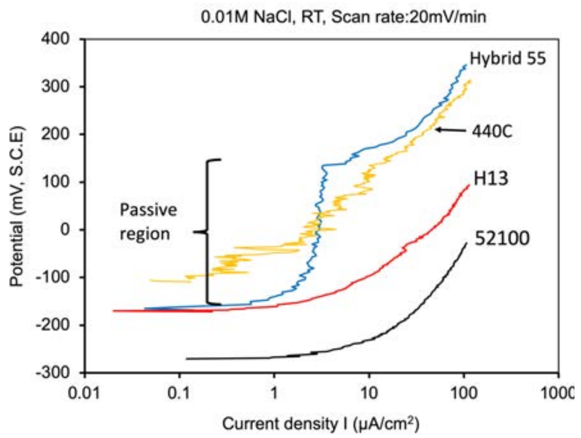

Figure 15 – The beneficial effect of 2wt%Al addition to Hybrid 55 is shown. The improvement in the corrosion resistance in Hybrid 55 can be attributed to the formation of the passive film, whereas the stable passive layer is not observed on 440C, H13, and 52100 steel.

8 – ELEVATED-TEMPERATURE APPLICATIONS

Hybrid Steel achieved higher strength compared to the standard engineering and tool steel after tempering at high temperature. Elevated temperature tensile properties for conventional steels and Hybrid Steels are shown in Figure 16.

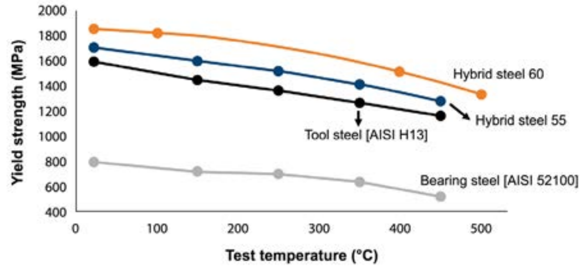

Figure 16 – Tensile test results at elevated temperatures. The tests were performed according to SS-EN ISO 6892-2:2011. All steels were tempered at 550°C for three hours before testing.

As can be seen, a high strength level is retained by both Hybrid 60 and 55. This is the essential characteristic of this new steel, which is expected to outperform many conventional steels when used at elevated temperatures. For a component that experiences elevated temperatures, the first property considered is the strength during short-term exposure, such as in figure 16. The short-time tensile properties are usually sufficient in the mechanical design of steel components for applications that involve short-term exposure to temperatures below 480 °C.

The microstructure after tempering at high temperatures is exceptionally stable under normal operating temperatures. Intermetallic nickel aluminide ((Fe, Ni)Al) precipitate is one of the major strengthening components in Hybrid steel. It has an ordered BCC_B2 crystal structure phase and a well-matched lattice parameter to the martensitic matrix phase, which results in the low coarsening rate at high temperatures. Furthermore, the concentration of chromium is relatively low (5 wt.%), compared to standard stainless steel, low chromium concentrations also reduce the tendency for chromium carbide (M_7C_3 and $M_{23}C_6$) to coarsen. For the reasons mentioned, Hybrid Steel can maintain high strength at elevated temperatures compared to other engineering steels.

In addition to the microstructural stability at high temperature, the crystal structure of the matrix of the Hybrid Steel is body-centered cubic (BCC), which results in a low coefficient of thermal expansion and high thermal conductivity when compared to austenitic steels. These properties permit Hybrid Steel to resist thermal fatigue when used in thick section components.

There is a constant need for new creep resistant ferritic steels that permit the use of higher steam temperatures in the energy and petrochemical industries, which allow greater operational efficiency. Stable microstructure at high temperature, high solid solution strengthening, and stable precipitates that resist the motion of dislocations in Hybrid steel present and opportunity for this steel in applications where long term creep deformation is the life-limiting factor. Other requirements in such applications, such as weldability, corrosion, and oxidation resistance, can be potentially fulfilled by the Hybrid Steel.

9 – MANUFACTURING PROCESSES

Hybrid Steel is suitable for near net shape forging. Due to its high hardenability, the Hybrid Steel does not need to be quenched to achieve a martensitic structure for the subsequent heat-treatment process. This avoids the need for an environmentally harmful quenchant and also minimizes component distortion, enabling a reduction in the need for final machining processes. The decrease in scrap and less handling increase productivity and save machining tool costs. The suitability of Hybrid Steel for heat-treated large components such as for off-highway equipment, wind turbines, and steel mills is especially important. Due to the low distortion during heat treatment, there is potential for significant cost savings in the subsequent finish machining/grinding step. Figure 17 shows the measured out of roundness of an outer diameter of a ring after undergoing machining, thermal treatments and nitriding.

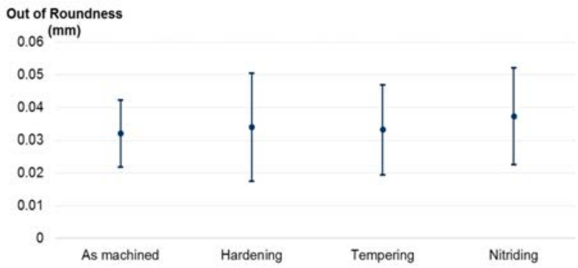

Figure 17 – Measured out of roundness (distortion) after machining, hardening, tempering and nitriding of an outer diameter of a ring (140 mm outside diameter, 120 mm inside diameter and 20mm thick).

Like most tool steels, Hybrid Steel is easiest to machine by cutting tools after it has been soft annealed. New machining technologies such as hard machining, electrical discharge machining, laser, and water jet cutting can be considered to machine Hybrid Steel in the as-rolled and hardened condition. Due to the need for access to specialized equipment and set-up, a high initial production cost can be expected for machining of as-rolled or hardened Hybrid Steel. However, cost-savings can be found in the simplified hardening step since the component can be hardened to achieve final strength at low tempering temperatures (500-600°C). Full hardening across the section can be expected even in very thick sections.

We understand that the total manufacturing cost of the finished part is the primary consideration for our customers. Ovako therefore has a team of engineers, metallurgists and production specialists that are keen to work with customers to find the optimized manufacturing process for the application of Hybrid Steel.

Until now, welding of ultra-high-strength steels has been near impossible due to the high carbon content, which promotes cracking sensitivity in as-welded conditions. The low carbon content in Hybrid Steel makes the welding of ultra-high-strength tubes and bars possible for the first time. Due to the high strength and high carbon equivalent (CE) of Hybrid Steel, both pre-heat and post-heats may be necessary for fusion welding.

Due to its high-temperature capability, Hybrid Steel is suitable for friction welding. Figure 18 shows the macrostructure, and the corresponding hardness of friction welded Hybrid 55, where there is no significant hardness change across the fusion zone. Furthermore, new opportunities for additive manufacturing and other advanced applications have now been explored. This also opens up new degrees of design freedom for component designers.

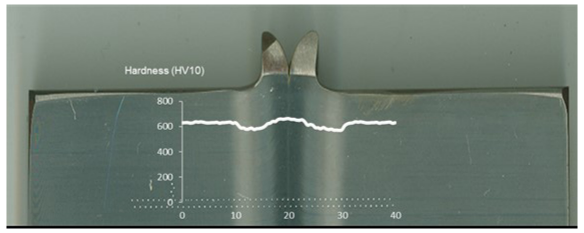

Figure 18 – Macrostructure and the corresponding hardness measurement across friction welded Hybrid 55.

10 – SUMMARY

We believe that Hybrid Steel will prove to be one of the most significant developments in the steel industry for many decades. It is anticipated that it will find a wide variety of uses in highly demanding applications such as engine components, bearings, fuel injection components, mining tools and machining tools. Hybrid Steel could be a key part of the solution in future weight and energy-saving initiatives across the engineering sector.

The full scope of its potential is only just starting to be explored as we work with customers to explore the opportunities for Hybrid Steel. It has been shown that Hybrid Steel possesses a superior combination of mechanical properties. It has high-strength at elevated temperatures, high fatigue life and weldability and also offers enhanced corrosion resistance. Furthermore, the ease of manufacturing and the potential for the reduction of the processing steps that enable cost reductions in a manufactured component are the key advantages of Hybrid Steel compared to conventional engineering steel.

It must be emphasized that Hybrid Steel is much more than a new type of steel. It is a new concept representing a family of steels from which different grades will emerge over time to suit specific customer needs.

It is the combination of properties that make Hybrid steel so interesting and also continues to cause a great deal of excitement both within Ovako and our customers. The critical properties of Hybrid Steel are:

1. High strength, especially at elevated temperatures
2. High-volume, cost-efficient production
3. High hardenability enabling low distortion
4. High cleanness and fatigue strength at elevated temperatures
5. Uniform properties with low micro-structural segregation
6. High strength with good weldability
7. Excellent surface treatment possibilities
8. Good corrosion resistance

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12 – ABOUT THE AUTHORS

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Jan-Erik Andersson graduated from KTH (Royal Institute of Technology) in 1986. He worked for five years at the Swedish Institute for Metals Research. Since 1990 he has worked at Ovako's R&D organization in Hofors, apart from 1997-2001, when he worked at the SKF European Research Centre.

Steve Ooi
Steve Ooi is a Group Technical Specialist of Ovako Steel, joining the company in 2019 after working at the University of Cambridge for nine years. He obtained his BEng, MPhil, and Ph.D. from Swansea University. His work specializes in alloy and process design in the context of steels for complex engineering applications where component failure can lead to significant consequences. Much of his research has, therefore, been focused on critical components in aeroengines, automobiles, deep-ocean structures and bearings.

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