OVAKO

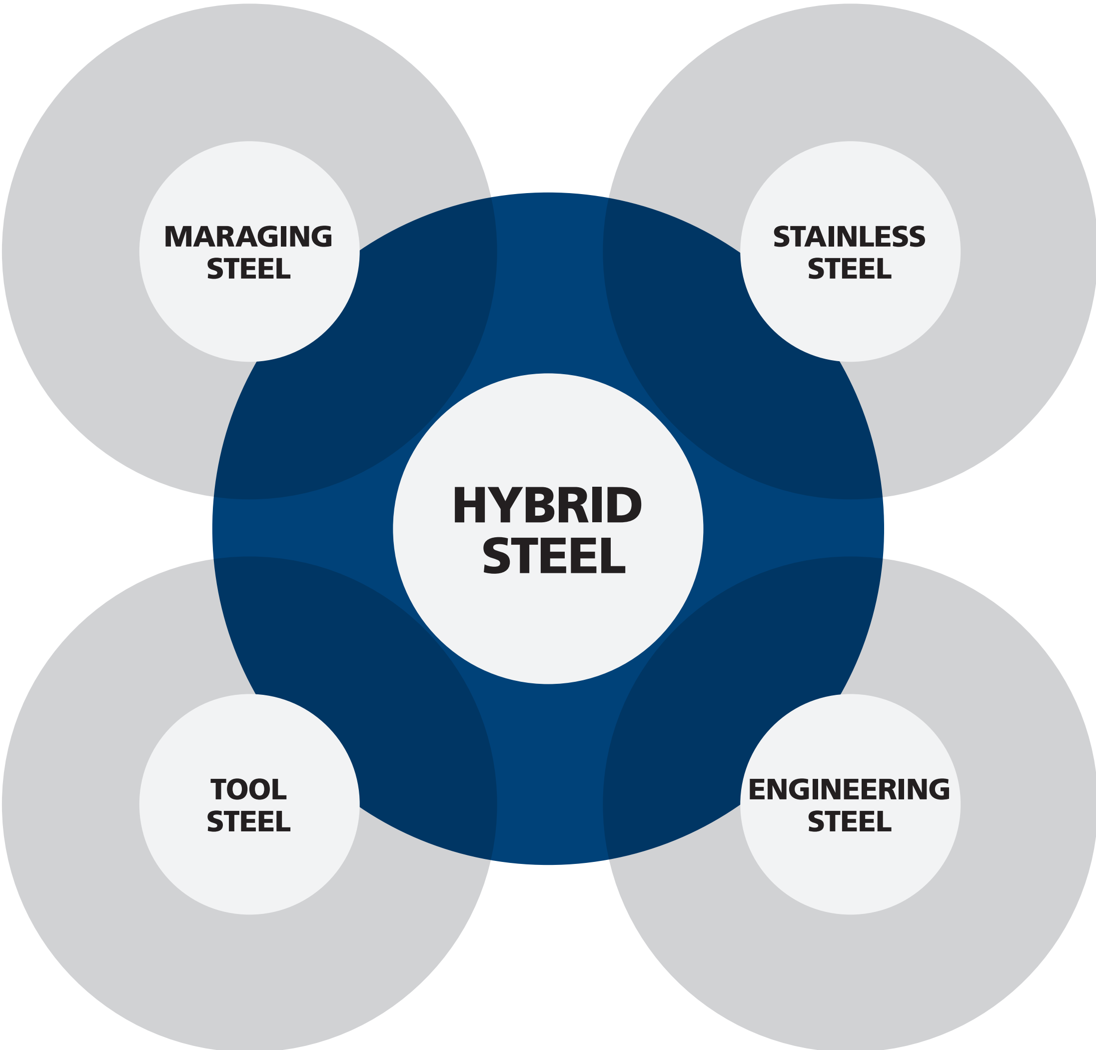
HYBRID STEEL®
NO COMPROMISES

What is Hybrid Steel?

Hybrid Steel has up to three times the yield and tensile strength of conventional steel at temperatures up to 500°C. With properties normally found in other specialty steels, it bridges performance gaps to create a whole new steel category.

"This steel combines two strengthening mechanisms... and the properties are very good. In particular, the material maintains these properties at elevated temperatures. ... it has very good corrosion properties, and it contains fewer expensive alloying elements."

John Ågren, Professor in Physical Metallurgy, KTH



Creating a new steel category
A few years ago, we set out on a mission to find and test alternative steel hardening mechanisms. Our aim? To meet the demands of high-stress, elevated-temperature applications where mechanical and fatigue strength are critical – without the need for expensive small-batch processes.

Hybrid Steel is here
This development work resulted in a new steel category. We named it Hybrid Steel® – a new range of steel grades that combines the properties of maraging steel, stainless steel, tool steel and lower alloy engineering steel. By bridging long-standing performance gaps in ways few thought possible, Hybrid Steel opens up completely new opportunities in performance gains, cost savings and the elimination of processing steps. It's a remarkable breakthrough, enabled by the first successful combination of secondary carbide hardening and precipitation hardening.

Groundbreaking steel grades
Hybrid Steel 50, Hybrid Steel 55 and Hybrid Steel 60 are the first three commercially available grades in the growing Hybrid Steel range. The former is designed to 50 HRC hardness and the second to 55 HRC, which provides an array of engineering steel capabilities. The third is designated to 60 HRC hardness and is an equally unique grade of bearing steel for applications where added strength is needed. All are produced with the help of large-scale, automated ingot cast processes. And all are already in the hands of customers, testing teams and research institutes worldwide.

What can Hybrid Steel do for you?
True to its name, Hybrid Steel can mean many things to many applications. By combining high strength at elevated temperatures with good weldability, high hardenability, low segregation and excellent surface treatment possibilities, it offers the best of many worlds. Which is why we've compiled this guide to Hybrid Steel to highlight eight key properties, as verified by the outcomes of our most recent validated tests.

MATERIAL BENEFITS AND PROCESSING ADVANTAGES

HYBRID STEEL®

1.
Ultra-high strength especially at elevated temperatures

2.
High-volume, cost-efficient production

3.
High hardenability enabling low distortion

4.
High fatigue strength at elevated temperatures and in corrosive enviroments

5.
Uniform properties with low microstructural segregation

6.
Weldable corrosion resistant ultra-high strength steel

7.
Excellent surface treatment possibilities

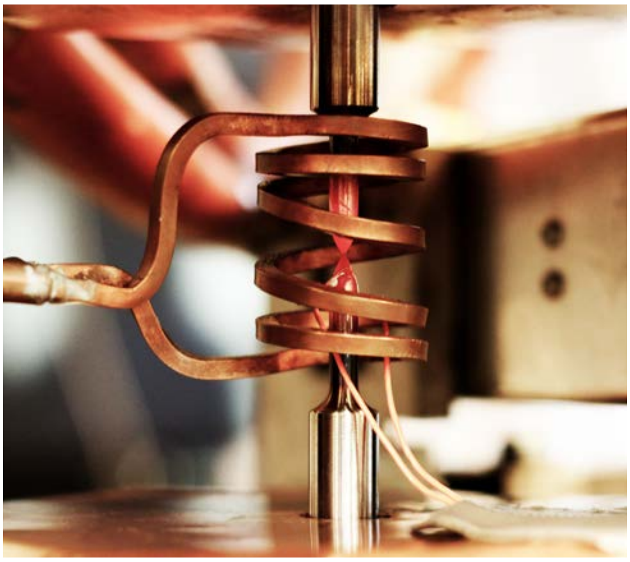
8.
Good corrosion and hydrogen resistance

Discover an unprecedented combination of steel properties

Imagine a steel that develops its full hardness at tempering temperatures. One that can be machined in a soft condition and then hardened with minimal distortion. A steel that enhances its strength following post-welding heat treatment. Hybrid Steel combines all these possibilities and more in a single innovative material.

The advantages of Hybrid Steel go far beyond its strength. Because the steel develops its hardness at tempering temperatures, it's now possible to machine components in a softer condition closer to their finished form. Similarly, it is well suited for welding, since a post-welding heat treatment will actually enhance strength. It also offers a range of advantages for nitriding, polishing, and more.

Even at a glance, it's clear that no material property is sufficient to define the expanded possibilities of Hybrid Steel. So we've defined the eight key properties that our tests have proven to be the major performance breakthroughs so far. This research is ongoing, and we expect to identify many more material benefits and processing advantages.



Hot tensile testing of Hybrid Steel 55.

Eight amazing properties of Hybrid Steel

1. **Ultra-high strength especially at elevated temperatures**
2. **High-volume, cost-efficient production**
3. **High hardenability enabling low distortion**
4. **High fatigue strength at elevated temperatures and in corrosive enviroments**
5. **Uniform properties with low microstructural segregation**
6. **Weldable corrosion resistant ultra-high strength steel**
7. **Excellent surface treatment possibilities**
8. **Good corrosion and hydrogen resistance**

1. Ultra-high strength especially at elevated temperatures

Of all the benefits of Hybrid Steel, its excellent strength at high temperatures is where it truly excels. This breakthrough creates new opportunities for manufacturers in need of a high-strength steel at elevated temperatures.

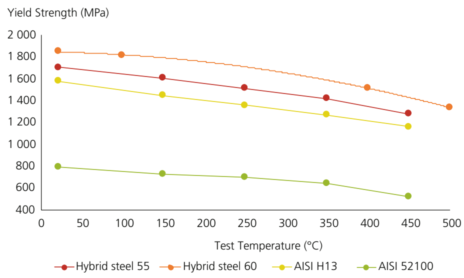
The original goal behind the development of Hybrid Steel was to create a steel grade that could successfully maintain its strength at elevated temperatures.

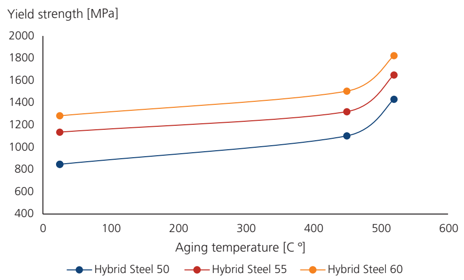
As seen in the first figure to the right, tests show that Hybrid Steel maintains remarkable strength levels even when subjected to elevated-temperature conditions.

The second figure shows the effect of aging temperature for the three Hybrid Steel grades.

Each grade has three different strength levels. The as-rolled (solution treated) condition possesses the lowest strength, representing the lower graph's left results. Half aged condition is achieved when the steel is aged at 450°C. The peak aged condition can be reached when the steel is aged above 520°C.

YIELD STRENGTH AND HARDNESS COMPARISONS





The yield strength of Hybrid steels is superior to other commonly used high-strength steels at elevated temperatures. All steel grades were tempered at 550°C before tensile testing.

Each Hybrid Steel grade can be heat treated to 3 different strength level conditions depending on the final application demands. As-rolled (solution treated), half-aged and peak-aged heat treatment.

2. High-volume, cost-efficient production

The large-batch ingot casting process behind Hybrid Steel creates attractive economies of scale for steel component manufacturers who are accustomed to small-batch, expensive tool steels and maraging steels. This makes it an excellent alternative to electroslag remelting (ESR), vacuum induction melting (VIM) + vacuum arc remelting (VAR) and other high-cost, high-strength steel processing routes.

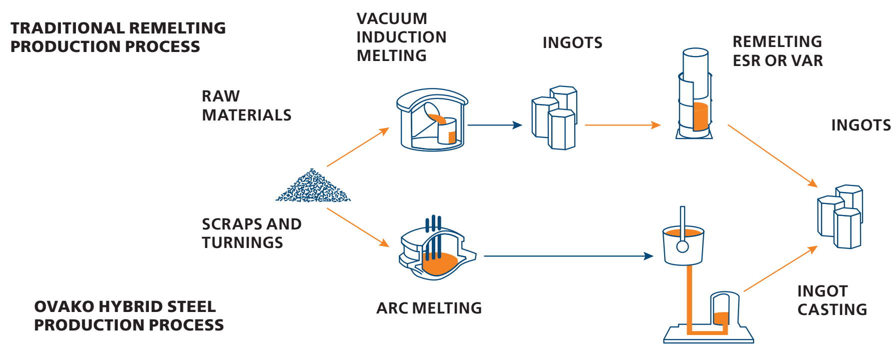
To achieve their beneficial properties, remelted steels must undergo a lengthy small-batch process. Each of these processing steps adds significantly to the final material cost.

By contrast, one ingot-cast melt produces one hundred tonnes of Hybrid Steel. This is a batch size ranging from ten to one hundred times larger than a typical batch of remelted tool steel, produced with just half the processing steps.

The result is a top-performance steel with low production costs, making it ideally suited to cost-effective manufacturing of advanced components in highly demanding applications.

SIMPLIFIED PRODUCTION PROCESS

When compared with other high-performing steels, the steelmaking process for Hybrid Steel is radically simplified due to large-scale ingot casting. Hybrid Steel also makes it possible to limit costly downstream production processes such as heat treatment, forced cooling, machining and grinding, and enables welded high-strength components and repair-welding.



3. High hardenability enabling low distortion

Laboratory tests show that Hybrid Steel experiences minimal distortion during hardening, aging, nitriding and other processes at elevated temperatures. Depending on the manufactured components, you can significantly reduce later processing steps and grinding allowances.

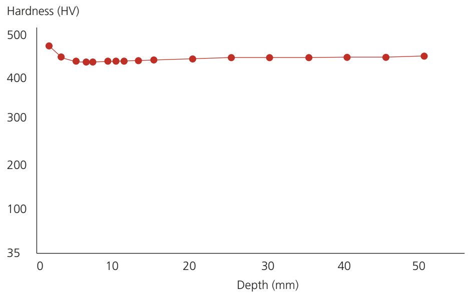
Hybrid Steel's high hardenability and robust microstructure contribute to low distortion in various heat treatment processes. Low distortion after aging enables soft machining close to final product dimensions.

As a result, component manufacturers can significantly reduce or eliminate variables such as grinding allowances, leading to substantial reductions in overall manufacturing costs.

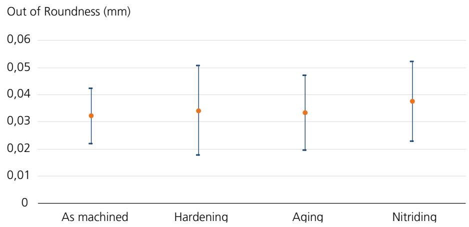
In the manufacturing chain, Hybrid Steel makes it possible to limit or eliminate a range of costly production processes.

Grinding alone represents some 30% of total production costs in bearing production. The cost can be vastly reduced thanks to Hybrid Steel's low distortion after heat treatment.

LOW DISTORTION DURING HEAT TREATMENT



Jominy curve of Hybrid 55 shows a very high hardenability, allowing slow cooling after heat treatment, resulting in low distortion.



Minimal distortion is detected after various processing steps for Hybrid Steel rings of dimension 140 x 120 x 20 mm. (OD x ID x height)".

4. High fatigue strength at elevated temperatures and in corrosive enviroments

Because Hybrid Steel has low levels of unwanted inclusion elements, it is considered a clean steel with a fatigue strength similar to conventional bearing steels. However, it has a higher fatigue strength at moderately elevated temperatures than the other benchmark steels tested.

At ambient temperatures, Hybrid Steel offers superior mechanical fatigue strength compared to conventional steels. However, it is at elevated temperatures that the steel truly excels. At temperatures of 250°C, the fatigue strength of Hybrid Steel decreases by just 8% vs room temperature, compared to 22% for conventional bearing steels.

The cleanness of Hybrid Steel can be seen in the low levels of inclusion elements such as oxygen (0), sulfur (S) and nitrogen (N). At just 14 ppm for Hybrid Steel 50, it is in fact the lowest value for these elements ever produced in a steel at our mill in Hofors.

Rotating bending fatigue tests show that one direct result is a high level of fatigue strength – up to 730 MPa – at temperatures of 250°C.

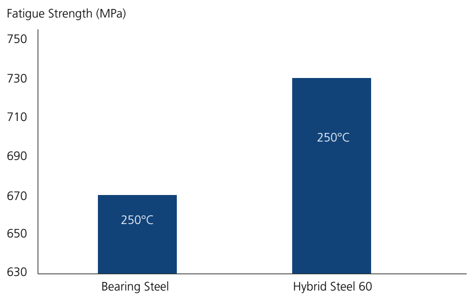
Hybrid Steels have shown substantially better fatigue resistance in corrosive environments than other steels. This is important since corrosion is often a "hidden" factor behind service life limitations in many types of end usage.

CHEMICAL COMPOSITION OF HYBRID STEEL, % BY WEIGHT

	C	Si	Mn	Cr	Ni	Mo	V	Al	S*	O*	N*	(S+O+N)*
Hybrid steel® 50	0.1	0.1	0.3	4.9	4.9	0.7	0.1	2.0	1	5	8	14
Hybrid steel® 55	0.2	0.1	0.3	5.1	6.1	0.7	0.5	2.4	3	3	28	34
Hybrid steel® 60	0.3	0.1	0.3	5.6	5.9	0.7	0.5	2.4	3	3	13	19

○ = Lowest value ever produced in our steel plant in Hofors

* ppm



Hybrid Steel maintains its fatigue strength even at 250°C

5. Uniform properties with low microstructural segregation

Our effort to create a ultra-strong elevated temperature steel started with achieving the lowest possible segregation of elements. An extremely close look at the microstructure of Hybrid Steel reveals the secret behind its success.

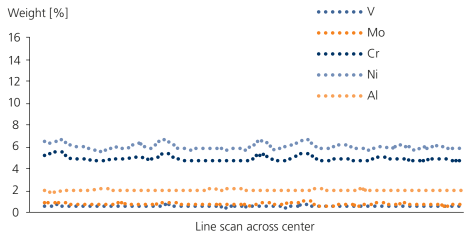
The strength of Hybrid Steel depends on a uniform distribution of very small precipitated compounds. These intermetallic particles and secondary carbides are so small, that a volume of just 1 µm³ of Hybrid Steel contains more than 500,000 particles.

In terms of performance, this means that Hybrid Steel provides all the same high-strength benefits as tool steel and maraging steel, but without the costly compromises.

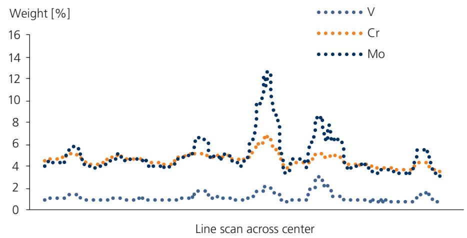
Hybrid steel requires no expensive remelt process to achieve low segregation. It also contains fewer expensive alloying elements, e.g. titanium (Ti) and cobalt (Co), compared to levels found commonly in maraging steels.

SEGREGATION IN HYBRID STEEL VS. TOOL STEEL

Hybrid Steel 55



Re-melted tool steel



Chemical variation in the center of a 147mm square section taken from a 100-ton Hybrid Steel melt production shows very little segregation.

6. Weldable corrosion resistant ultra-high strength steel

Until now, ultra high-strength steels have been nearly impossible to weld due to their high carbon content, which makes them sensitive to cracking. Hybrid Steel makes it possible for the first time. This opens up new degrees of design freedom for component designers and also enables additive manufacturing.

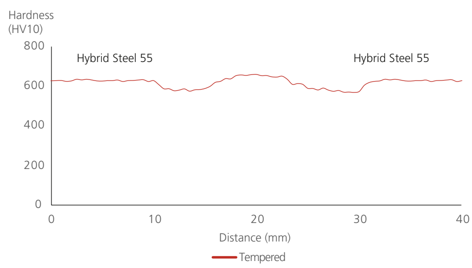
The low carbon content of Hybrid Steel provides yet another promising advantage for manufacturers: A truly weldable ultra-high-strength steel.

With welding tests still in their early stages, Ovako has been able to confirm that welded joints maintain the same high-strength properties as raw, untreated Hybrid Steel.

Ongoing tests are now being performed to expand on our initial findings, which suggest a wide range of breakthrough applications that were previously impossible with traditional high-strength steels.

STRONG WELDING PROPERTIES

Initial tests show that welded joints maintain high strength without cracking.



Results from practical tests shows good weldability.

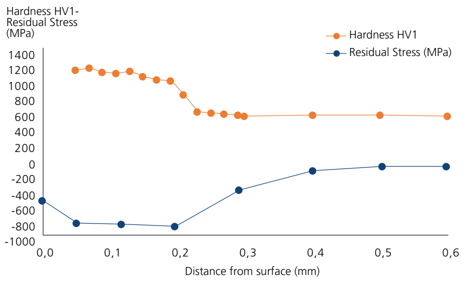
7. Excellent surface treatment possibilities

Hybrid Steel makes it possible to eliminate today's compromises between surface and core hardness. The material's hybrid hardening and alloying composition allow for treatments at elevated temperatures with maintained core hardness. This makes the steel highly suitable for processes such as nitriding.

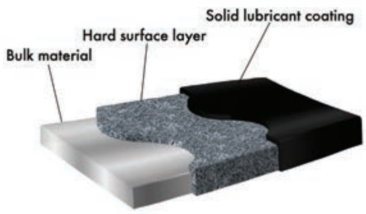
Thanks to its high content of aluminum (Al) and chromium (Cr), which are strong nitride-forming elements, Hybrid Steel is particularly well suited for nitriding. The ability to achieve high surface hardness and beneficial residual compressive stresses, with maintained or even strengthened core hardness, makes it possible to reduce both case depth and nitriding process time.

Additional coating treatments can also be applied with maintained strength. In collaboration with Applied Nano Surfaces, a company specializing in wear and friction reduction, testing has been made on an innovative Tribonite coating, which is applied on a nitrided surface to reduce friction and wear. Hybrid Steel is ideally suited to such applications due to its ability to maintain or even increase strength at the elevated temperatures typically used in these processes.

HIGH SURFACE AND CORE HARDNESS AFTER NITRIDING



Nitriding generates high surface hardness. With Hybrid Steel 55, the core strength is maintained.



Hybrid Steel is ideally suited to innovative surface treatments.

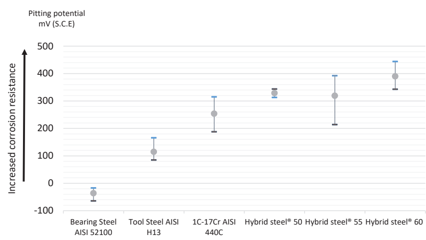
8. Good corrosion and hydrogen resistance

Compared to typical engineering steels, Hybrid Steel shows much higher levels of corrosion resistance. Preliminary rankings reveal a corrosion resistance far higher than bearing steel, and even slightly higher than AISI 440C stainless steel.

Hybrid Steel offers a favorable alternative to common engineering steel in applications that encounter corrosion. As seen to the right, Hybrid steel outperforms bearing steels, tool steels, and martensitic stainless steels in a corrosion test. Minimum surface rust is observed even it was left outdoors for more than a year.

Future developments of the Hybrid Steel family should allow for even better corrosion resistance. Thanks to a higher chromium (Cr) content than engineering steel, in combination with its aluminum content, Hybrid Steel's excellent corrosion resistance challenges the commonly held notions behind today's corrosion rating systems. The aluminum content also provides strong resistance to oxidation at elevated temperatures.

PROVEN CORROSION RESISTANCE



Higher corrosion resistance compared to engineering steels.

Minimum surface rust observed in Hybrid Steel vs. conventional steel after one year of environmental exposure.

The strength of dual hardening mechanisms

Hybrid Steel is relatively low in carbon and contains a number of carefully controlled alloying elements, most importantly chromium (Cr), molybdenum (Mo), vanadium (V), nickel (Ni) and aluminum (Al). This enables simultaneous hardening by secondary carbides and intermetallic precipitates at tempering temperatures, resulting in a steel with an ideal distribution of extremely small strengthening particles.

The chemistry behind the breakthrough

Our initial aim in developing Hybrid Steel was to create a steel with superior mechanical and fatigue strength at high temperatures, compared to conventional steels. This required a systematic study of small ingots to identify various segregation levels, and to ensure the most stable microstructure possible after tempering at 500-600°C.

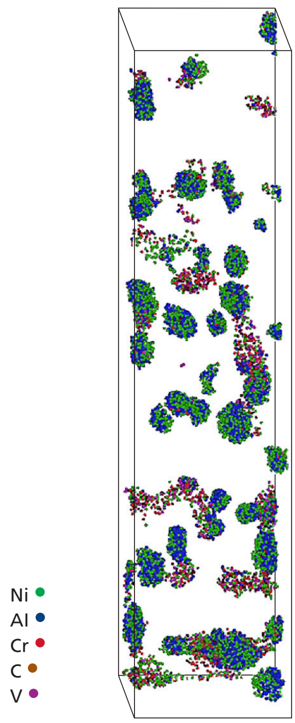
The base composition chosen for Hybrid Steel was a low-carbon, low-vanadium, low-molybdenum alloy. In order to boost strength, nickel and aluminum were added in order to form an intermetallic precipitation strengthening mechanism.

Microstructural strength

An atomic probe reconstruction of Hybrid Steel 55, shown right, clearly demonstrates how successfully our initial objectives were achieved. The microstructure of Hybrid Steel consists of tempered martensite and fine carbides, with an intermetallic phase of NiAl. By removing the iron content in this atomic probe tomography, it is possible to see the extremely small, evenly dispersed strengthening particles of the tempered Hybrid Steel.

Unlocking new possibilities

Hybrid Steel's unique chemical composition, in addition to ensuring high strength at temperatures up to 500°C, opens up a range of other possibilities. The aluminum and nickel content contributes to very good oxidation resistance, even after 500 hours at 700°C. The composition is uniquely suited to performing nitriding and tempering in a single process step. And low distortion during heat treatment enables substantial reductions in component manufacturing costs.



An atomic probe reconstruction of Hybrid Steel 55 aged at 520°C for 3 hours. Iron (Fe) atoms have been removed, and a homogenous fine distribution of very small NiAl intermetallic precipitates and secondary carbides can be seen. Sample volume: $20*20*90\ nm^3$. $1\mu m^3$ steel contains 500,000 NiAl particles.

CHEMICAL COMPOSTION, % BY WEIGHT

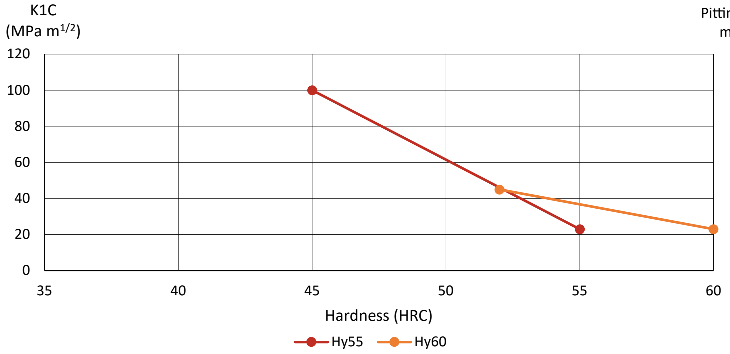
	C	Si	Mn	Cr	Ni	Mo	V	Al
Hybrid steel® 50	0.04	0.1	0.3	5	5	0.7	0.1	2
Hybrid steel® 55	0.18	0.1	0.3	5	6	0.7	0.5	2
Hybrid steel® 60	0.28							

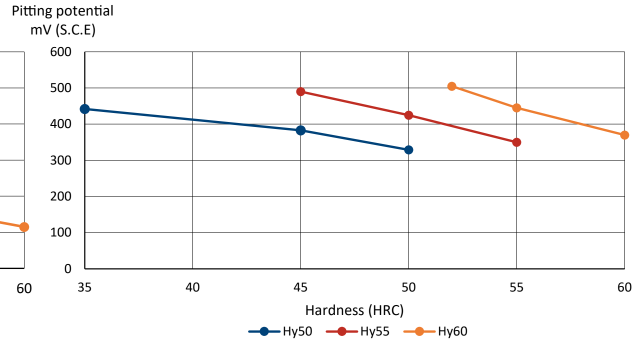
Two simultaneous strengthening mechanisms Secondary carbides NiAl intermetallic phase

Wide range of possibilities for different heat treatment conditions
The standard condition for Hybrid Steel is in its maximum aged condition 50, 55 and 60 HRC respectively for Hybrid Steel 50, Hybrid Steel 55 and Hybrid Steel 60. But with its unique combination of alloying elements it opens up a wide range of possibilities for different heat treatment conditions for each Hybrid Steel grade.

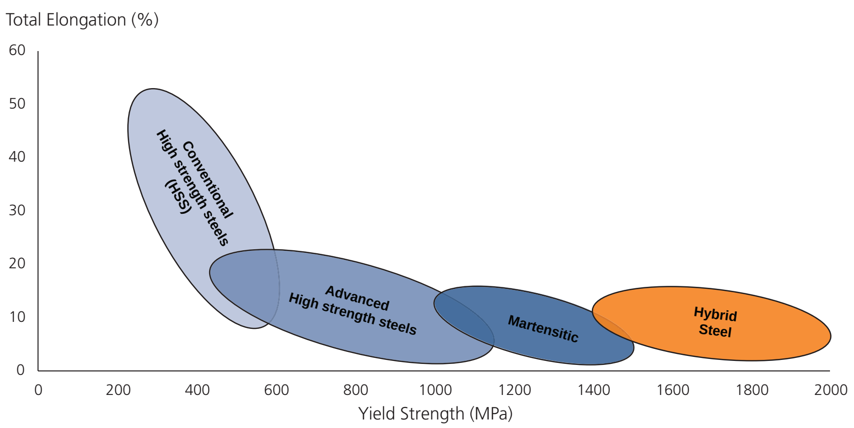
For solution treated or 450°C aged conditioned steel, modified properties are possible. Both toughness (K1C) and corrosion resistance are increased with lower hardness for all grades in the Hybrid Steel family.

Condition	Heat treatment	Hy50	Hy55	Hy60
As-Rolled	Solution treated	35 HRC	45 HRC	53 HRC
Half-aged	Aged 450C	45 HRC	50 HRC	55 HRC
Max-aged	Aged 520C	50 HRC	55 HRC	60 HRC





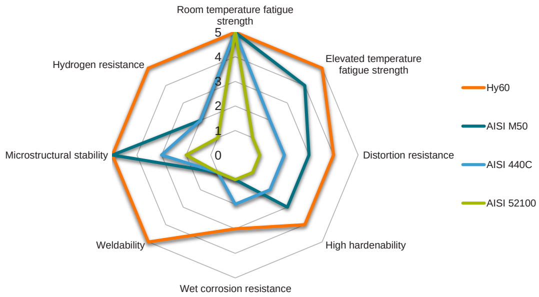
Fewer compromises needed between strength and ductility
Normally the ductility is reduced with increased strength for high strength steels (HSS). Therefore more advanced high strength steels have been developed along with the martensitic steels for moderate ductility at higher strength levels. With the development of Hybrid Steel both the ductility and the strength are improved compared to conventional martensitic steels. Hybrid Steel allows fewer compromises between critical properties for highly stressed applications.



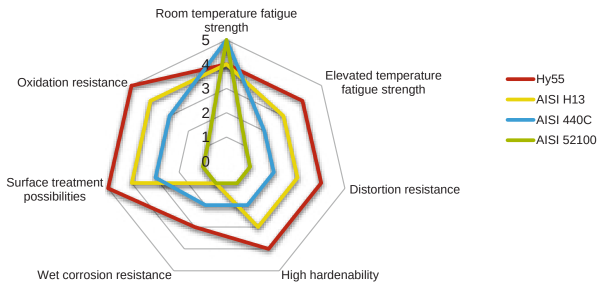
Bearings
High-performance bearings at lower cost

High hardness and fatigue strength are fundamental for bearing performance. Hybrid Steel meets these requirements while also offering:

- Significantly reduced grinding allowances in the costly late-stage of manufacturing steps, due to very low distortion.
- High fatigue strength, especially at elevated temperatures. Due to the high aging temperature and stable microstructure, Hybrid Steel has better resistance to material decay compared to conventional bearing steel.
- Good corrosion resistance is one of the vital properties of bearing steels due to water-containing lubricants. Hybrid Steel has a higher resistance to corrosion than conventional bearing steel and martensitic stainless steel.
- Resistance to hydrogen embrittlement is essential and will become more critical over the next few years due to the future hydrogen economy. The Hybrid Steel's passive oxide layer prevents hydrogen from getting into the material, and with the deep hydrogen traps due to the chromium-rich and vanadium-rich carbides, the hydrogen atoms can be trapped if they get into the material.



Fuel injection components
Reduce emissions by handling high pressure at elevated temperatures



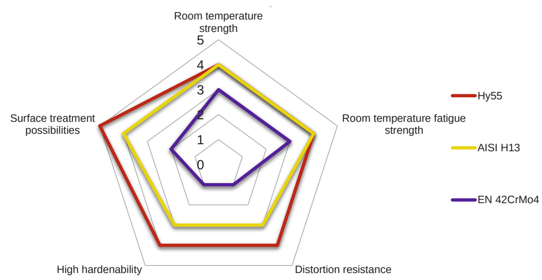
To improve fuel combustion, a steel that handles high pressure at elevated temperatures is essential. Hybrid Steel offers a wide range of benefits for gasoline and diesel injection components including:

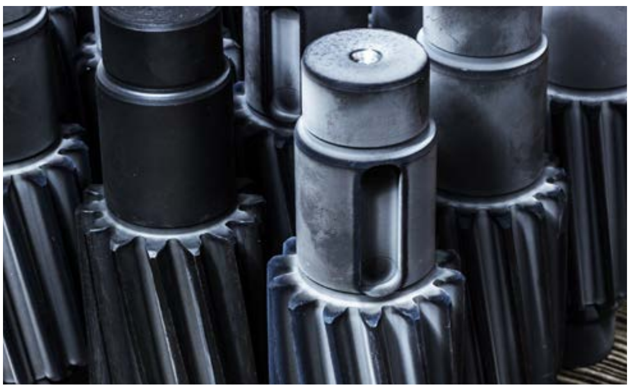
- Improved corrosion resistance in fuel combustion and stagnant conditions, especially in ethanol and water-containing environment. Hybrid Steel has good protection against corrosion in many environments compared to other engineering steels.
- Combusted fuel and high injection cycles place high demands on the steel for increased fatigue strength, especially at elevated temperatures. When engineering steel is working at the edge, then Hybrid Steel steps up.
- Surface treatments like nitriding are commonly used in demanding applications. With nitrided Hybrid Steel, the wear resistance can be further improved.

Nitrided components
Improved performance due to high surface and core hardness

Nitrided Hybrid Steel is ideal for strengthening and extending the lifetime of hydraulic and transmission components. In addition to eliminating process steps, other beneficial features include:

- The Hybrid Steel is normally aged between 500-600°C, which is also the typical nitriding temperature. Hence, both aging and nitriding processes can be performed simultaneously.
- The high core hardness allows shorter processing times and reduces costs. The low distortion of the Hybrid Steel after long processing times such as used for nitriding of around 20 hours or more shows low dimensional changes and enable no or minimum grinding after nitriding.
- Final properties after nitriding of the Hybrid Steel result in relatively high compressive stresses and high wear resistance due to the high surface hardness.

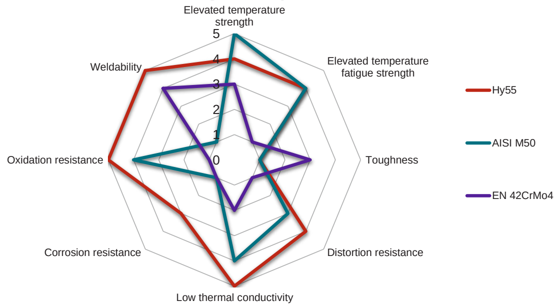




Engine components

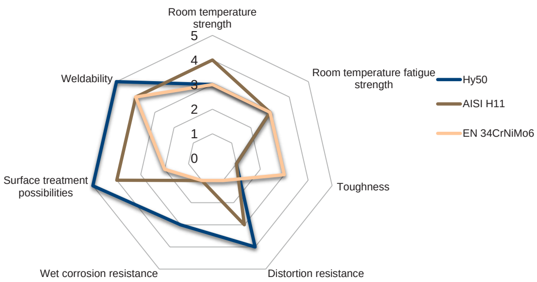
Managing the heat with a unique combination of properties

- Hybrid Steel has some very interesting properties in terms of high-temperature oxidation and thermal physical properties. Designed with this in mind, a new engine platform can achieve higher efficiency and reduce CO_2 emissions.
- Lower thermal conductivity reduces heat losses through the piston and increases the thermal efficiency of the combustion process. The high strength of Hybrid Steel permits the increase of thermal load on the pistons.
- Lower thermal expansion of the piston gives opportunities to run smaller piston clearance and reduce blow-by of gases to the crankcase, improve efficiency further, and reduce oil degradation.
- Oxidation resistance, called scaling resistance, is important for engine components that encounter high temperatures. Hybrid Steel has a very high oxidation resistance compared to conventional engineering steel.
- High-strength steels are usually not weldable, but Hybrid Steel can, a necessary production process for many engine components.



Percussive tools

High-performance with a steel that can take a beating

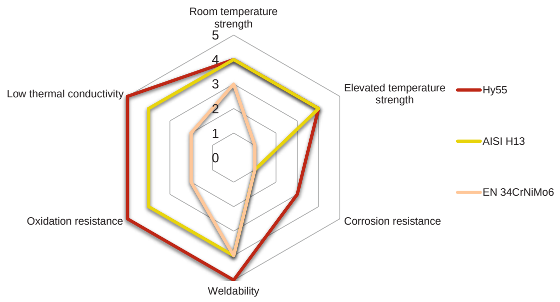


A steel with high fatigue strength is vital for any producer of different types of percussive tools. Depending on the application, more or less impact toughness is needed. Hybrid Steel can reduce total production costs and improve product lifetime in high-fatigue and corrosive applications, such as for mining tools, by combining:

- High fatigue strength, an essential property in percussive applications. This needs to be combined with sufficiently high toughness and other properties of interest. Hybrid Steel provides the opportunity for many such combinations.
- Many production tools are often welded with nickel-based material to withstand elevated temperatures. The weldability of Hybrid Steel also allows for innovative product designs.
- Corrosion resistance is important for many applications, often more than is actually realized. The onset of corrosion can affect other properties such as fatigue strength. Normally a compromise between these properties has to be made. Hybrid Steel can be the ideal solution, where compromises can be minimized.
- Different surface treatments such as coating or nitriding are often used on production tools. Normally the compromise between core and surface hardness has to be made, but with the Hybrid Steel no such compromises are needed.

Forming tools

Cost-efficient high strength and corrosion resistance in forming operations



A steel with high strength at elevated temperatures and a fine surface finish is key to many forming tool applications. Hybrid Steel can be a cost-efficient alternative to the types of steels normally used today thanks to its many helpful features:

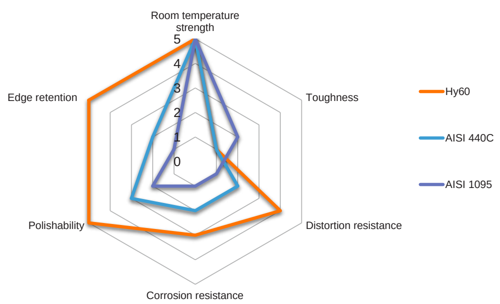
- Surface roughness is important for various production tools for good quality. The lack of coarse primary carbide in hybrid steel enables a smooth surface to be produced.
- A steel with high elevated temperature strength is vital for any producer of forming tools. This property in combination with high oxidation resistance and lower thermal conductivity makes Hybrid Steel an attractive choice.
- For forming operations at lower temperatures, corrosion can be a concern and this is again an area where Hybrid Steel excels at the strength levels required.
- The weldability of Hybrid Steel allows for innovative product designs. Tools can also be repair welded and then post-weld heat treated to full strength again.

Sharp edge applications

Staying sharp and rust free in knives and other cutting edge applications

The cutting surfaces of tools are subjected to extreme conditions. The applied stresses and wear, together with sometimes corrosive conditions, make frequent sharpening of knives a necessity. Better options could be possible thanks to a clever combination of properties:

- Hybrid Steel offers the strength of other knife materials but with an additional corrosion performance that would prolong sharpness in a corrosive environment.
- Thanks to nano-sized hardening particles, and smooth surfaces, Hybrid Steel also keeps its edge sharpness longer than high-carbon steels.
- In production, Hybrid Steel offers cost-saving opportunities thanks to its low distortion and also thanks to its high polishability with smooth surfaces.
- Lack of primary coarse carbides and/or carbide bands reduce the susceptibility of chipping due to carbide pullout on the knife edge during sharpening.



Ovako develops high-tech steel solutions for, and in cooperation with, its customers in the bearing, transport and manufacturing industries. Our steel makes our customers' end products more resilient and extends their useful life, ultimately resulting in smarter, more energy-efficient and more environmentally-friendly products.

Our production is based on recycled scrap and includes steel in the form of bar, tube, rings and pre-components. Ovako has around 2,700 employees in more than 30 countries. Ovako is a subsidiary of Sanyo Special Steel and a member of Nippon Steel Corporation group, one of the largest steel producers in the world with more than 100,000 employees globally.

For more information, please visit us at www.ovako.com, www.sanyo-steel.co.jp and www.nipponsteel.com.

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