Air hardening Steels – Ovako 677 and Ovako 477

Technical Report Archive

THE OVAKO STEEL, AIR HARDENING STEELS – OVAKO 677 AND OVAKO 477

Ovako has an extensive R&D since many years, an area that now is in an even higher intensity. Some of the R&D work is published in our technical reports.

Due to that Ovako of today has had a number of different company names and used various trade marks we have until now chosen to not have these reports publicly available. However, many of these technical reports contain valid data about material and steel grades that we still promote, but with other names etc.

The following Technical Report from 2001 is about the properties of the at that time new family of Air-hardening steel that Ovako developed, and specifically the two first grades Ovako 677 and Ovako 477.

Data and processes in this report represent state of art at time of publishing, that still in most cases are used and valid.

Ovako 477 and Ovako 677 are grades that is part of our current offer. In the Ovako Steel Navigator these materials are described under the version names Ovako 477L , Ovako 677L and Ovako 677Q.

In this Technical Report there is used the following Company names and trade marks that no longer is used by Ovako AB.

Ovako Steel; This company name is no longer used. The organization is now part of Ovako AB.

OVAKO STEEL

Technical Report 2/2001

The Ovako Steel Air-hardening Steels Ovako 677 and Ovako 477

Thore Lund and
Patrik Ölund,
Ovako Steel AB

ISSN 0284-3366

OVAKO STEEL

Ovako Steel is the world's leading manufacturer of bearing steel and a major producer of other special engineering steels. We are a fully owned subsidiary in the SKF group.

Our main strength is in the field of special engineering steel long products – seamless tube, bar, and surface removed wire. Rolled rings are also a specialty. A large part of the production is further processed by machining. This share is increasing and illustrates our intention to progress towards further processing and higher specialization.

The most important customer segments are the rolling bearing industry, the automotive industry together with their subcontractors as well as the rock drilling, and general engineering industries.

We have manufacturing units in Sweden, France, and the United States. Steel production is confined to Hofors, in Sweden. The production capacity is approx. 500,000 ton of special engineering steel per year.

Research & Development

Our R&D mission is to pursue an efficient product and process development, adapted to existing and new technology, and within our product are be recognized as the world leader in metallurgy, materials technology, machinability, and metal cutting technology as well as heat treatment. The ultimate target is to offer our customers the best total economy in their production.

Abstract

The quenching step in the hardening process is used to provide engineering components with adequate strength and fatigue properties. Unfortunately, it also causes significant problems in the further processing and is a potential health and safety hazard.

The large efforts that have been, and are being, spent to reduce the environmental problems caused by the quenching media and the uncontrollable distortion generated in the quench are only partially successful. This mainly due to the difficulties of combining steels with low hardenability and with a mild quench.

The Ovako Steel air-hardening steel family addresses these problems with a steel design that makes it possible to martensitically harden engineering components by slow air-cooling.

This largely eliminates distortion problems and totally eradicates quenching media generated health, safety and washing problems.

The Ovako Steel air-hardening family encompasses variants that effectively can substitute today's through-hardening, harden-and-tempering and carburising steels.

This also offers the potential of reducing the number of steel grades used in component production.

The alloy design used for the air-hardening family ensures that product properties are not only maintained compared to the standard variants used today but actually provides improved product performance in many respects.

The main product performance features are slightly different for the different variants in the air-hardening steel family, but common to them all are: high thermal stability and tempering resistance, very robust austenitisation, the possibility to combine high hardness and very high dimensional stability, high strength and in particular good toughness for the medium- and low carbon variants. Perhaps most importantly, air-hardening steels offer the potential to reduce the number of processing steps required in component production by utilising the steels potential to air-harden directly from the processing heat.

Background

The standard steels used for through-hardening, hardening-and-tempering and carburising today are conceptually about one hundred years old. The technological developments in steel making, de-oxidation which provides a clean and fatigue resistant steel, alloy design technology and know-ledge of how alloy design interacts with heat treatment have taken many leaps forward since the time when the base composition of traditional steels used for today's component production were first conceived.

Surprisingly, very little has happened as regards steel composition development in the recent times. Bearing steels for instance have the same base composition as the bearing steels produced at Ovako Steel when SKF bought the steel making plant in 1916. The same holds true for the majority of steels used for carbursised or hardened-and-tempered component manufacturing.

Certainly, the cleanliness of the steels produced today have improved immensely, and minor composition adjustments have generated better machining properties just as better process control capabilities have assured far better repeatability in all processing steps and in product properties.

When more sophisticated laboratory techniques, such as dilatometry and mathematical modeling program tools like Dictra and Thermocalc are used in combination with finite element calculation developments to predict transformational behavior, the potential to develop steels better suited for today's processing and application requirements vastly improve.

The Ovako Steel development work on the air-hardening steel family has tried to encompass all the technological tools available today. We wanted to generate a set of steel variants designed to meet the product requirements of today but with an objective to ensure that our customers component production could be made at lowest possible cost, with a minimum of impact on environment, while ensuring that safety and health hazards in the processing are minimised.

The air-hardening concept

Fundamental to all members in the Ovako Steel air-hardening steel family is the ability to provide a component with a fully martensitic structure throughout the component by simply allowing the component to cool in still air after austenitisation.

This provides the two primary advantages of the air-hardening family:

- the slow cooling ensures that the surface to core temperature gradient is very small at the point in time when the martensite transformation occurs. This has as consequence that the trans-formation occurs homogeneously and that unpredictable distortion generated in the quenching can be significantly reduced. The distortion generated in quenching has been a major concern for a long time due to the very negative impact it has on post heat-treatment operations. As the distortion generated in the quenching generates significant dimensional changes, large efforts have to be spent to rectify the component geometry. This is very costly and time consuming and is one of the main drawbacks in today's heat-treating operations. This is to be seen in the substantial costs and efforts spent in recent times to develop gas quenching facilities to reduce quenching distortion. These efforts have had some success: The distortion can be significantly reduced, but at the same time the component thickness that can be hardened is reduced, even if gas pressures are increased dramatically.
- the fact that the martensitic transformation in the air-hardening steels occurs even after a still air-quench of course makes the quenching baths used today redundant. Quenching media used today are either oil or salt baths and these are costly, difficult to maintain, health and safety hazards and the parts require washing operations to clean them prior to tempering.

In addition to the basic processing advantages of the air-hardening steels, each variant of the air-hardening family provides the potential to be air-hardened directly from a hot forming operation.

This can significantly reduce the processing costs by reducing the number of steps needed in component production.

The Ovako Steel Air-hardening Family

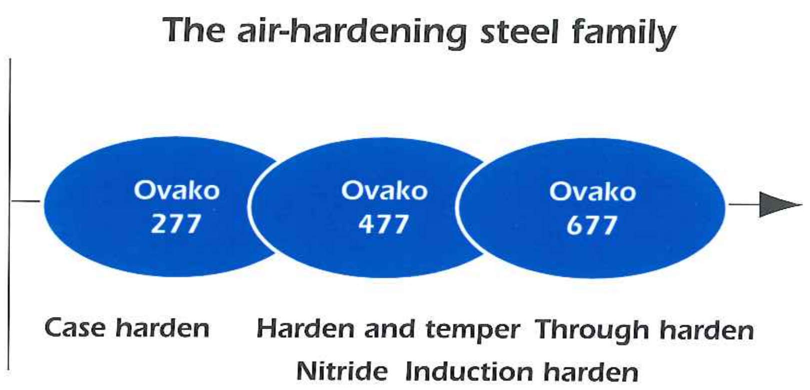
The starting point in the alloying design was to generate direct replacements for the most common steels used for component manufacturing today.

Simplifying somewhat, there are three basic steel types used to produce engineering components. The choice of steel is largely determined by the heat treatment process that is selected in order to find a workable combination between the processing steps required to give the component its final shape and the heat treatment operation selected in order to give the component its desired performance in the final application.

From a steel design point of view, the steel variants can be classified into three main groups:

- through hardening, high-carbon steels (typically rolling bearing components, distance rings, cold forming tools)
- medium carbon, harden-and-temper steels (typically mining equipment, gears, shafts, nitrided tools) used in the hardened-and-tempered condition or combined with a surface induction hardening or nitriding
- low carbon, carburizing steels (typically gears, shafts, rolling bearing and general engineering components) which also may be nitrided.

The Ovako Air Hardening steels have been designed as direct replacements to existing steel grade variants and they share one fundamental property with them: The maximum dimension to which they will through harden. While the basic similarity is that the Ovako Steel air-hardening variants will through harden at least the same dimensions as the standard oil quenched variants the parts are quenched in still air. When very large dimensions are used, heavily alloyed variants are needed for standard oil or salt bath quenching. In a similar way – more hardenable – variants will ultimately be made available using our air-hardening concept.



Design details, properties and potential processing routes

To further discuss the merits and product characteristics, it is necessary to separate between the air-hardening variants that have been developed and which are available today.

- Ovako 677 has been designed as an air-hardening alternative to today's high-carbon, low alloy, through hardening steels. The typical example is the rolling bearing steel SAE 52100.
- Ovako 477 is a harden-and-temper steel, and is the air-hardening alternative to the standard steels used in such applications today, typically SAE 4140.
- Ovako 277 will be described in detail in a later publication, and is the air-hardening alternative for the steels used for case hardening today such as SAE 8620.

Fundamentally, the major difference between the three air-hardening base variants is the carbon content.

In steel, after heat treatment, carbon has one main effect – it decides the maximum hardness level that can be achieved. The maximum hardness's attainable for the three base members of the air-hardening family today, when compared to the standard grades normally chosen for the same applications, are very similar.

Steel making

At Ovako Steel all production is based on scrap and EAF melting in an oval bottom tap vessel. Deoxidation, alloying, refining, and vacuum degassing is in an ASEA-SKF ladle furnace with inductive and argon stirring and followed by uphill teeming into 4.2 tonne ingots.

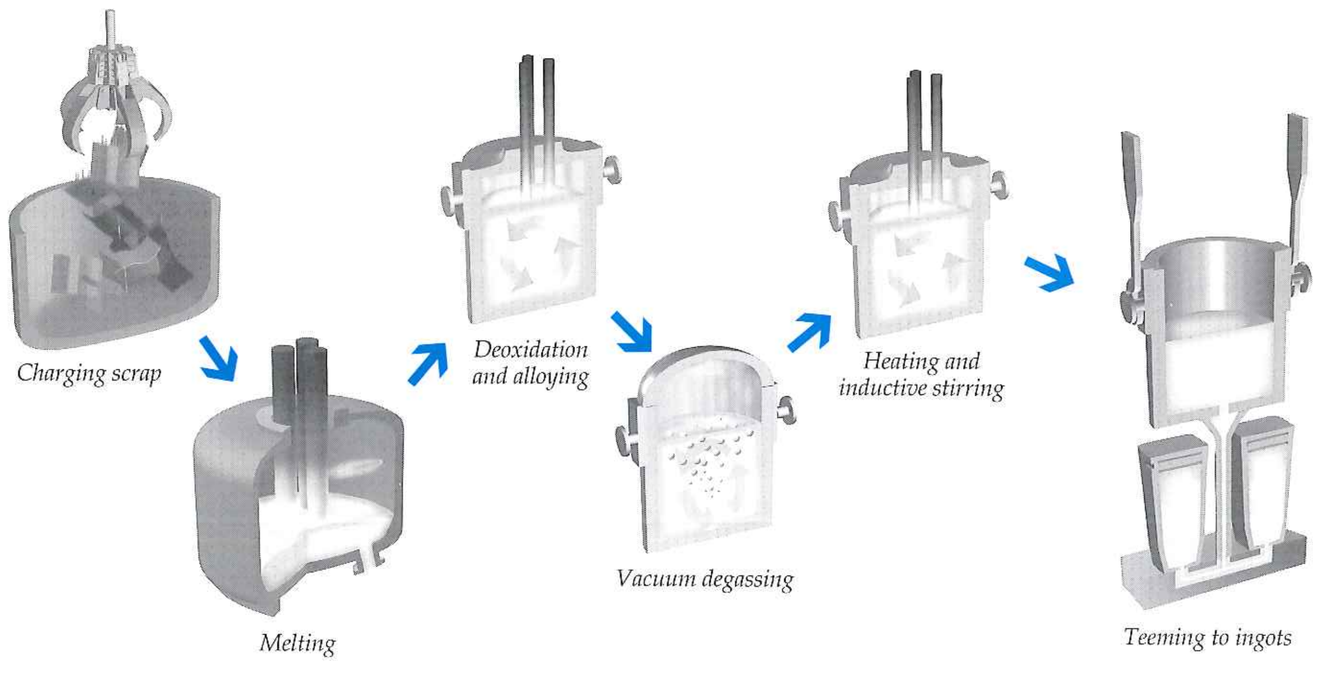
Cleanliness

The same processing route is used for our air-hardening steels which means that these modern steel grades will achieve the same cleanliness requirements as all other Ovako Steel high-quality products.

As cleanliness is an important factor in many aspects of product applications, it has been decided to produce the air-hardening steels with, as a minimum, Bearing Quality cleanliness levels. This means that the demands made regarding oxygen and titanium contents, and macro and micro inclusions in the Ovako Steel Cleanliness Specifications are met.

The air-hardening steels can also be obtained in a PBQ which is a cleanliness level normally used for replacing remelted (ESR / VAR) steels.

Steel making at Ovako Steel



Properties of Ovako 677

Average chemical composition

C	Si	Mn	Cr	Mo
0.67	1.50	1.45	1.10	0.25

Maximum oxygen content 9 ppm
Maximum titanium content 30 ppm

Soft annealing

The high-carbon air-hardening variant, Ovako 677, can be soft annealed using the cycle below. *(Fig 1)*

This will result in a well spheriodised structure with a slightly higher hardness to that normally achieved with a standard SAE 52100 steel. The reason for this is the different alloy design, which puts a significant amount of alloys in solid solution in the ferrite phase, strengthens the structure.

This is also reflected in the soft annealed properties.

	Yield strength (MPa)	Tensile strength (MPa)	Hardness (HB)
SAE 52100	410	700	190
Ovako 677	450	750	220

Even with the somewhat higher hardness, the machinability of Ovako 677 is the same as for SAE 52100. In standard ISO longitudinal turning test, as well as in an intermittent machining test – designed to more closely correlate with in-practice tool contact conditions used in CNC machining the figures are impressive. *(Fig 2 and 3)*

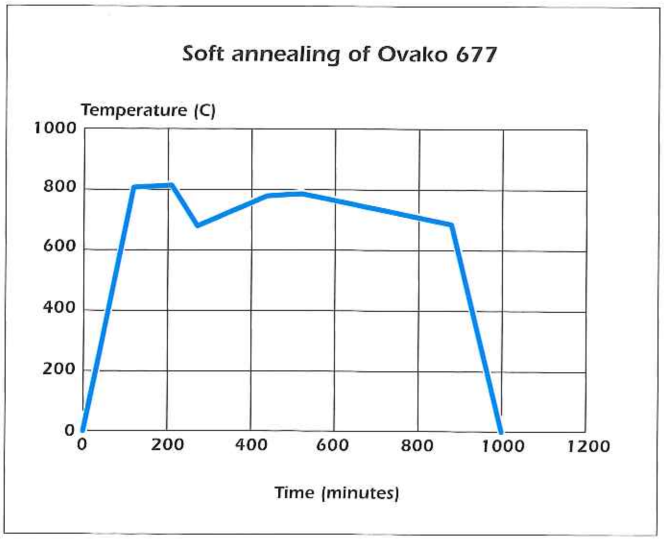


Fig 1. The high-carbon air-hardening variant, Ovako 677, can be soft annealed using this cycle.

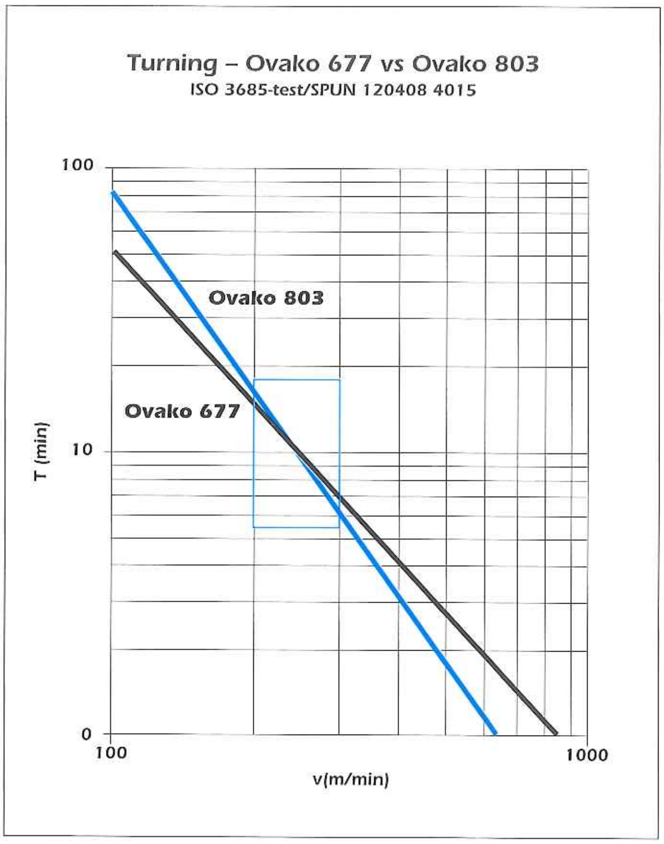


Fig 2.

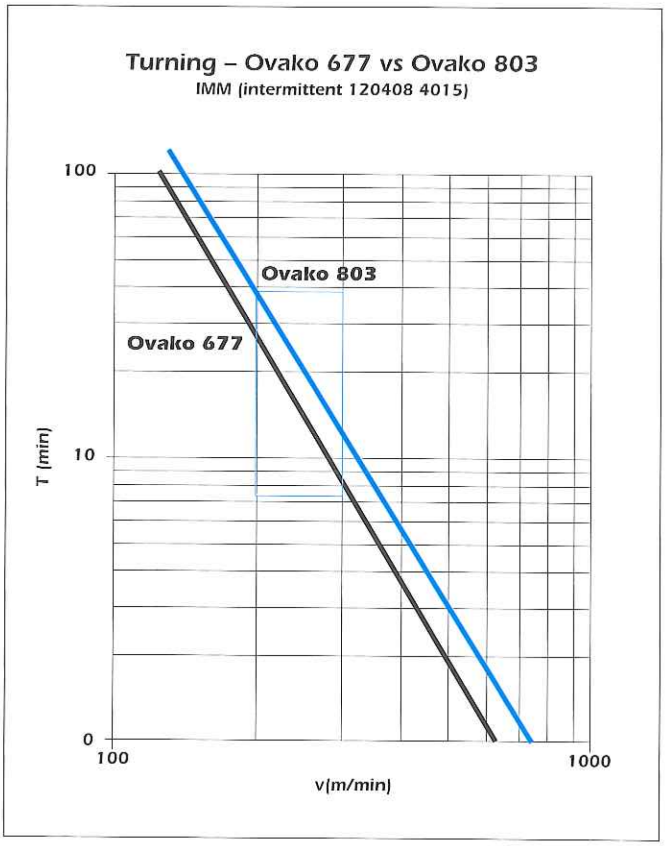


Fig 3.

As an alternative, Ovako 677 can also be supplied as tough tempered. *(Fig 4 to 7)*

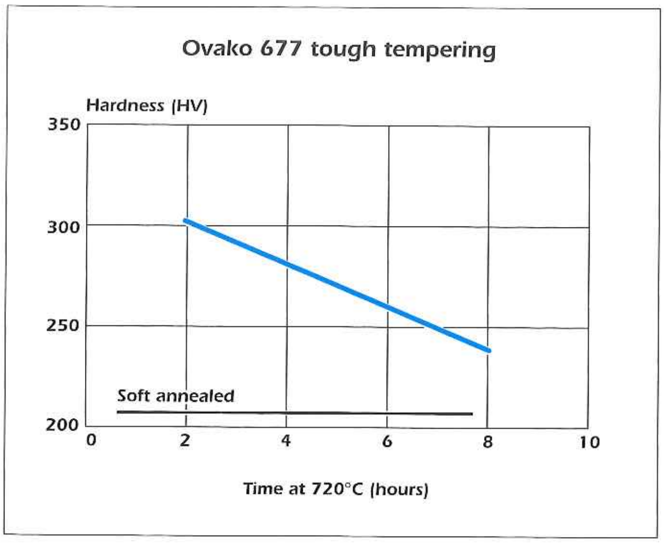


Fig 4.

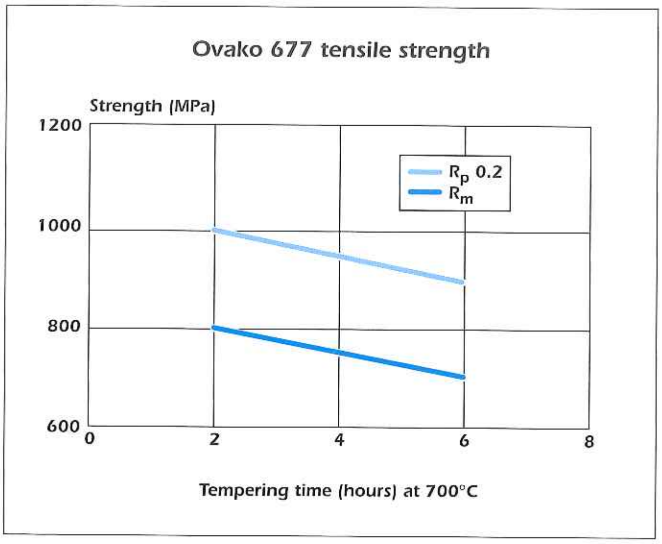


Fig 5.

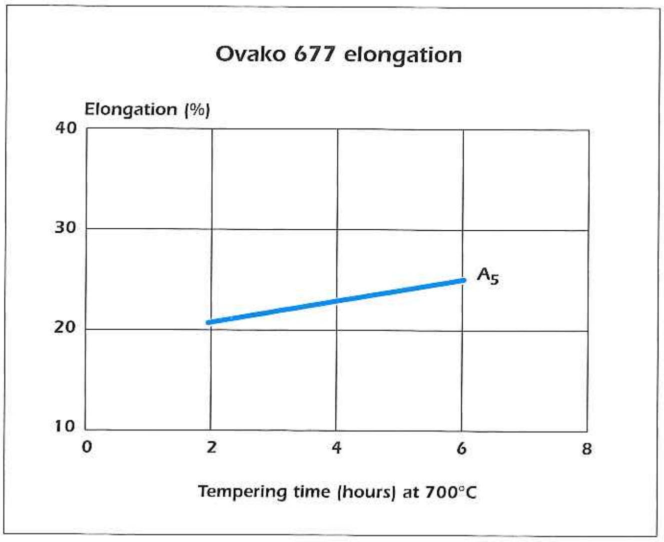


Fig 6.

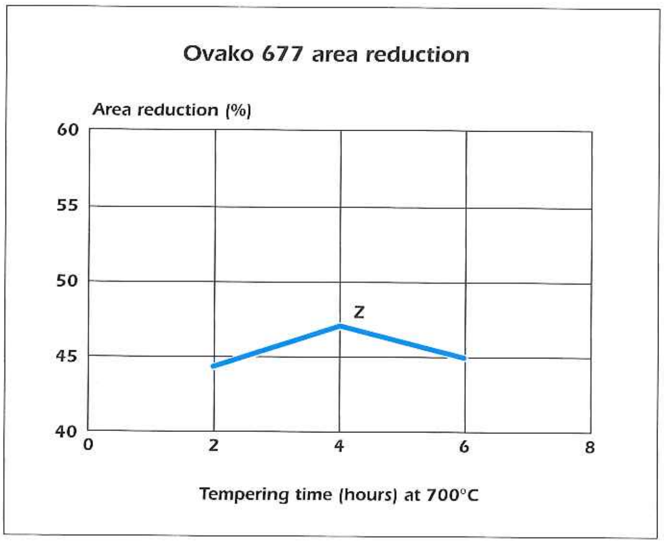


Fig 7.

Austenitisation

Ovako 677 can be austenitised in a way that is not as critical when compared with a normal through-hardening bearing steel.

The austenitisation of SAE 52100 type steels is quite critical since over-austenitisation causes severe deterioration of component properties.

This is not the case for the Ovako 677 steel. The carbon content and the alloying content have been designed to provide an austenite which is 'just right' for the martensitic transformation.

In steels with high carbon contents, such as SAE 52100, the carbon must only be partially dissolved in the austenite to attain maximum hardness and the desired structure. *(Fig 8)*

For Ovako 677 however, even at very high austenitisation temperature a well functioning martensite structure is achieved. This is a fundamental difference. One of the reasons why the air hardening steels can be effectively used to eliminate process steps is because it is now possible, under certain circumstances, to utilise the material forming heat rather than a separate additional heat treatment operation.

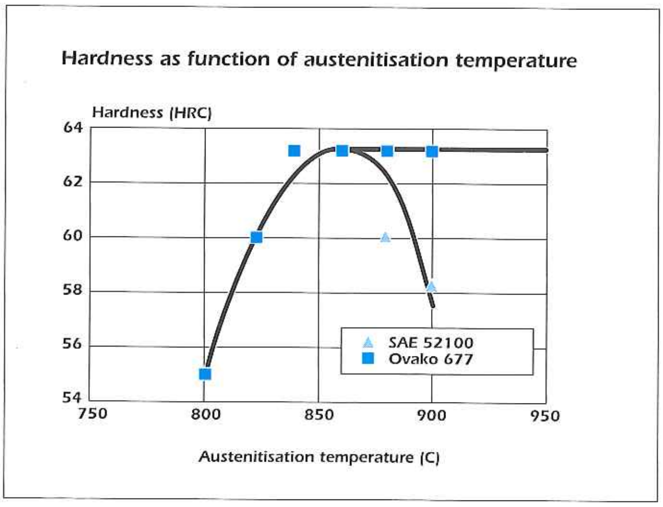


Fig 8.

Through hardenability

The air-hardening steels have been designed to provide a high-hardness martensite in a slow air-cooling and they perform as well as, or better than, the martensite structures achieved today in oil- or salt bath quenching. *(Fig 9 and 10)*

To enable this, a modern steel design is required. To achieve the desired properties a combination of silicon, manganese and molybdenum have been used in combination with chromium and different carbon content levels to give the air-hardening variants.

What limits the hardenability of steel components is the critical cooling rate. This critical cooling rate is the slowest cooling that any part of a component, for a given steel composition, can have while still providing a martensitic structure.

Possible achievements can be predicted from the steel's transformation characteristics, which can be displayed in a CCT (Continuous Cooling Transformation) diagram.

Ovako 677 has been designed to have at least the same through hardening capability, in slow open air cooling, as a standard SAE 52100 steel has in a fast oil quench.

Maximum diameter or wall	SAE 52100 oil quenched	Ovako 677 air-cooled
Bar	25 mm	30 mm
Ring or tube cut	15 mm	17 mm

SAE 52100 has a through hardenability in air-cooling which is certainly less than one mm and, conversely, Ovako 677 will through harden sections well in excess of 100 mm in an oil quench.

The structures obtained after hardening are somewhat different in composition and appearance.

	Retained austenite %	Retained carbides %	Martensite %
SAE 52100	10–15	4–6	79–86
Ovako 677	10–15	0–2	83–90

It should be noted, though, that the stability of the retained austenite in Ovako 677 is far higher than is found in SAE 52100. *(Photos on the following page, fig 11 and 12.)*

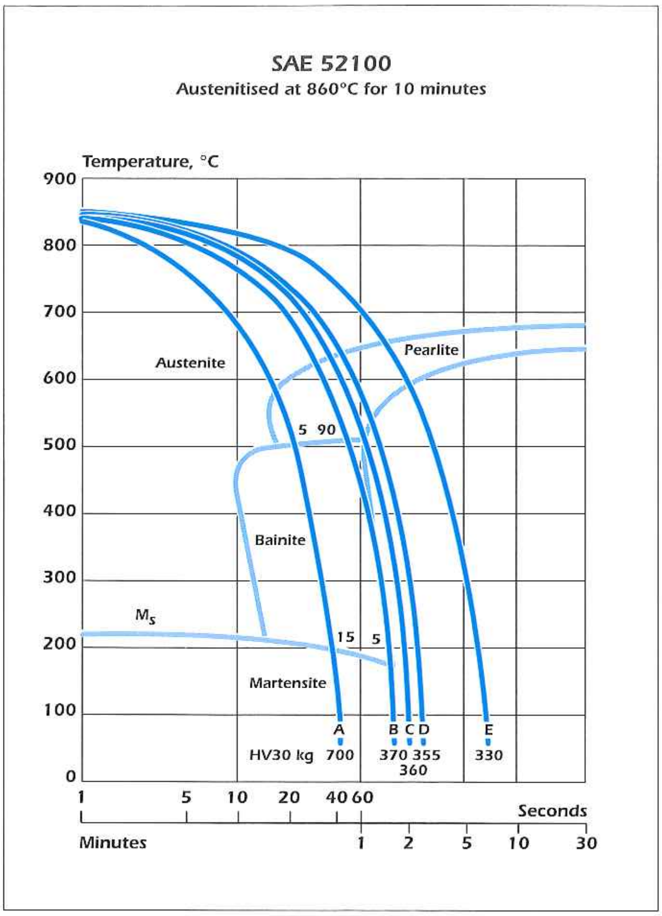


Fig 9.

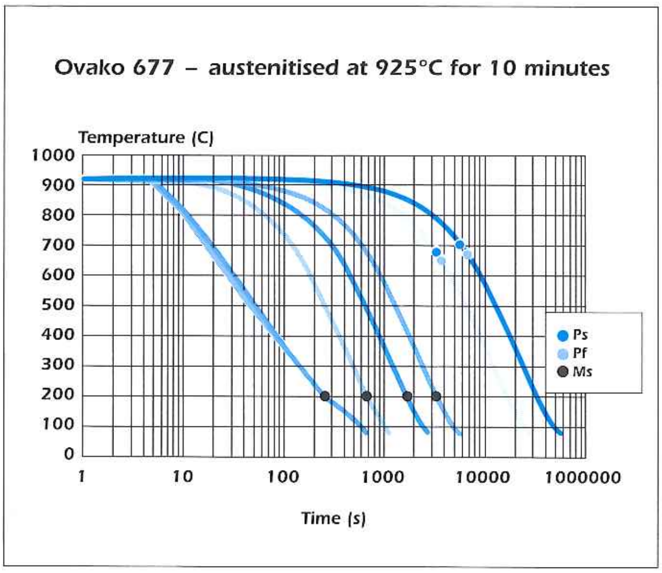


Fig 10.

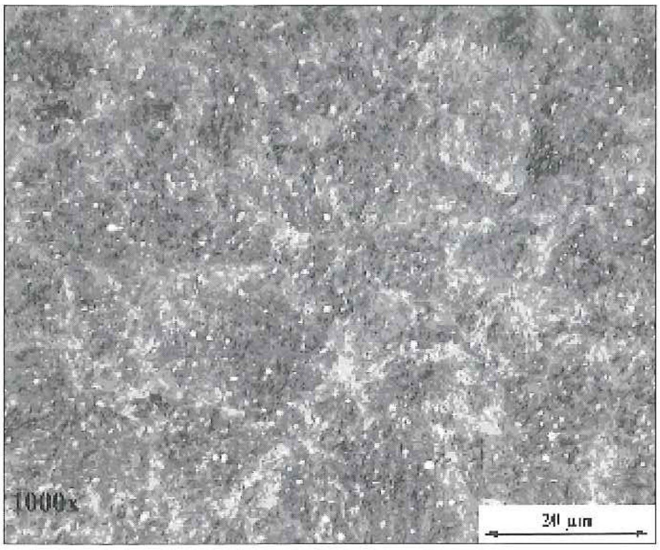


Fig 11. SAE 52100 oil quenched from 860°C, tempered 160°C, 1 hour.

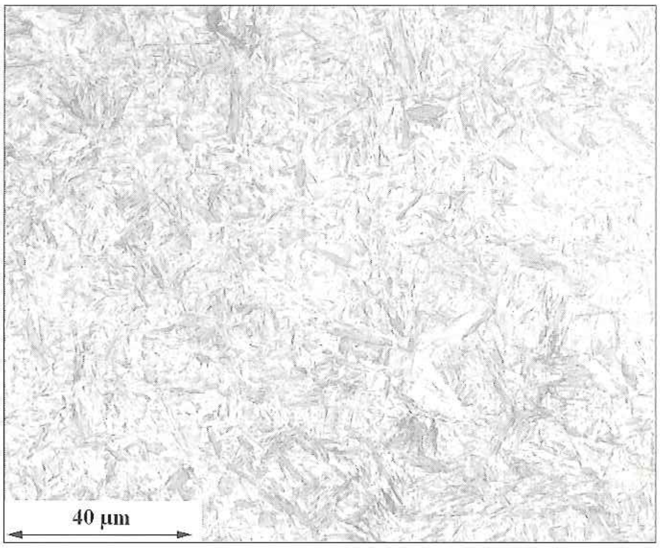


Fig 12. Ovako 677, air-hardened from 860°C, tempered 160°C, 1 hour.

Distortion

Distortion is a major processing problem for most hardened engineering components as the distortion is unpredictable and the effect is costly to rectify.

Much of the distortion generated in heat treatment is associated with the thermal gradients generated in the components during quenching. When using a fast quenchant, such as oil or salt, the surface temperature drops very rapidly while the core of the component must loose heat through conduction to the surface. This means that the martensite transformation will start in a situation where the component has significant temperature transients.

In a much slower air cooling situation the surface to core temperature differences will be much smaller at the point in time when the martensite transformation initiates. In addition it will progress much more homogeneously through the component.

This leads to significantly reduced hardening distortion. In a direct comparison on cylindrical roller bearing rings, a set of standard rings were produced in Ovako 677 steel, and after a standard austenitisation were simply allowed to cool in open air at room temperature.

For the standard ring after oil quenching, the average ovality caused by the quenching is 0.1 mm with considerable variation.

For the air hardened rings the ovality caused by the hardening is of the same order of magnitude as the ovality recorded after NC machining of the rings, and gives a figure about one tenth of what normally is experienced. *(Fig 13).*

In recent times significant efforts have, and are, being spent on developing gas quenching for engineering components. The object is to reduce the heat treatment distortion, and large benefits have been noted when gas quenching can be applied successfully. However, the very limited hardenability (or rather the very short critical cooling times) of standard steels makes it very difficult to replace conventional oil/salt quenching with gaseous media even when very powerful gas quenching plants are built.

The Ovako Steel air hardening steels provide a very effective solution for this dilemma as the quenching rates can be reduced and full through-hardenability can be achieved at very low cooling rates.

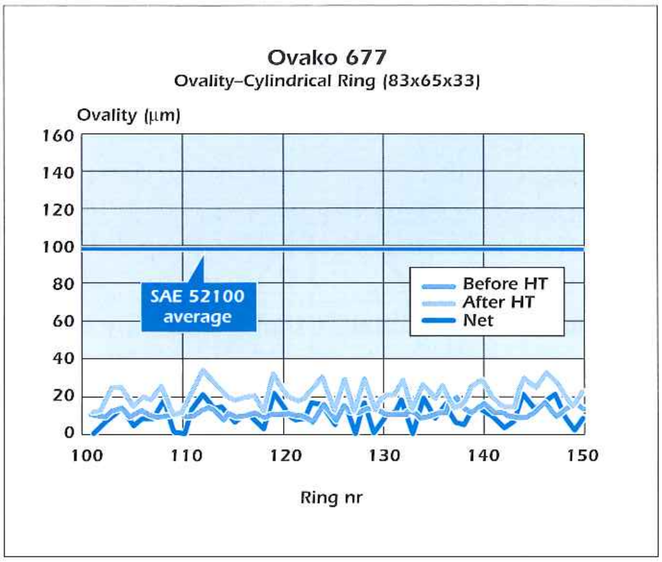


Fig 13.

Hardness and strength

The maximum hardness attainable for Ovako 677 after a standard 160°C tempering is the same as for SAE 52100 type steels and is about 62-64 HRC. *(Fig14 and 15).* The tensile properties and the toughness are also very similar.

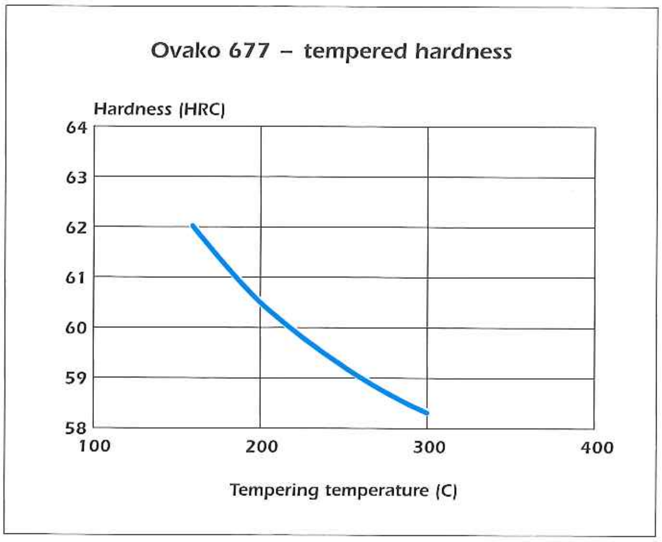


Fig 14.

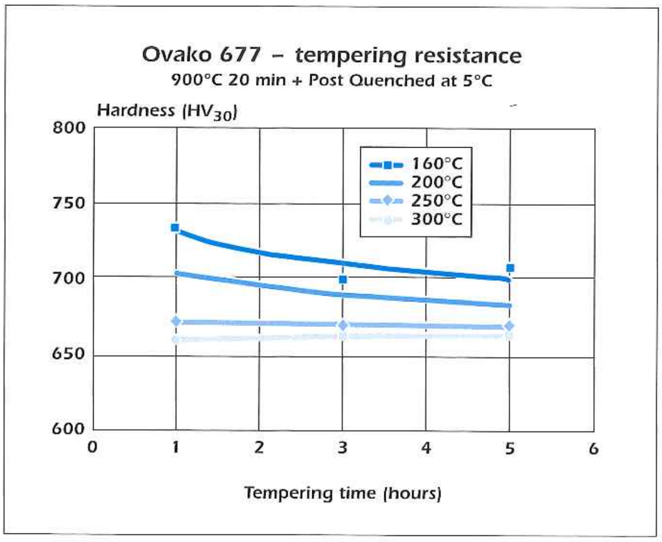


Fig 15.

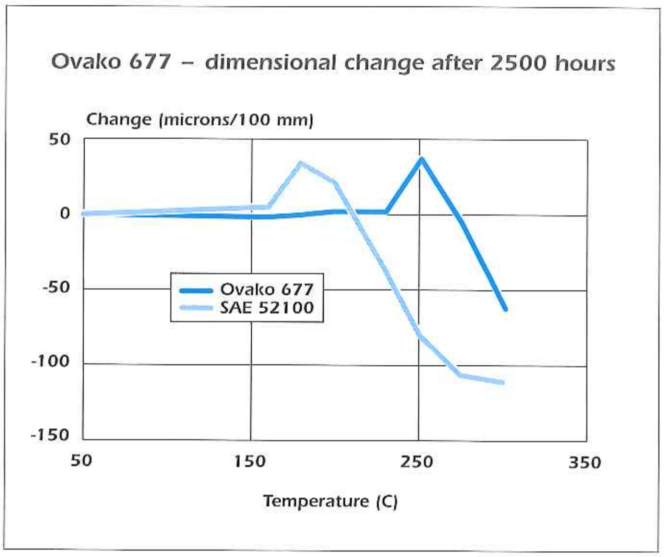


Fig 16.

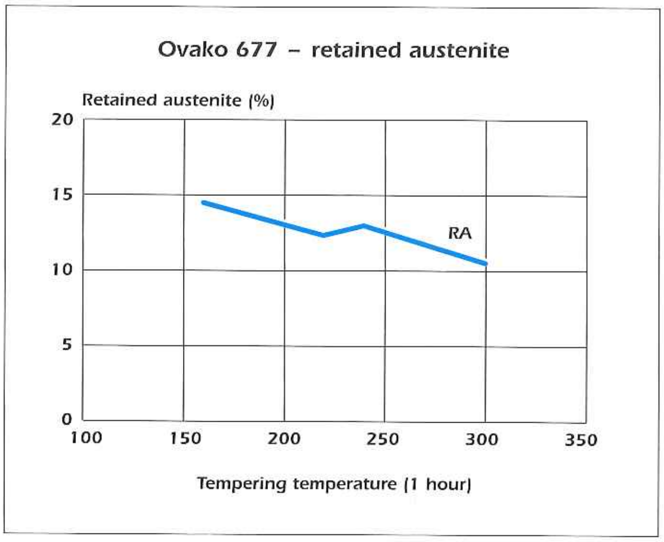


Fig 17.

This means that the combination of very high dimensional stability and high hardness, which is not possible to achieve in standard high-carbon bearing steels, is easily attained with Ovako 677.

Dimensional stability

The dimensional stability of Ovako 677 and SAE 52100 have been compared in an accelerated dilatometer test and for both variants the starting condition is a 160°C/1 hour tempering. *(Fig 16)*

The dimensional stability of Ovako 677 is far better.

This is due to the significantly more stable retained austenite. *(Fig 17)*

To reach the same stability with SAE 52100, an initial tempering is required which will reduce the hardness to about 59 HRC.

Fatigue

Fatigue of hard steel is largely defect initiated. As shown earlier Ovako Air Hardening Steels have excellent cleanliness.

Rotating beam tests performed on Ovako 677 have given high fatigue lives. *(Fig 18)*

For high-quality SAE 52100, median (50 %) lives of 3 to 6 million cycles are normally obtained.

Life tests performed on bearings produced from an early experimental air-hardening steel melt gave results which were at least as good as those obtained for standard SAE 52100 steel.

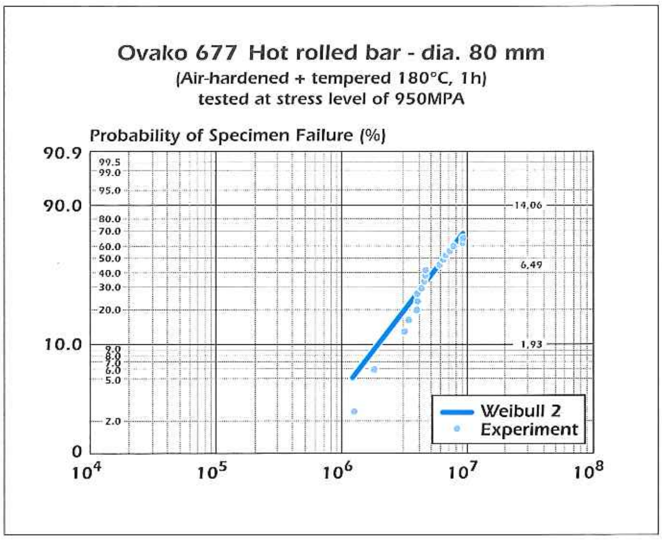


Fig 18.

Surface hardening

Ovako 677 is very well suited for surface hardening. After the inductive or laser heating the parts can be simply cooled in still air, and with the excellent hardenability of Ovako 677 the hardening depth can be adjusted to any desired level. The maximum attainable hardness is about 63 HRC.

A very significant advantage for Ovako 677 over other high-carbon steels is that the austenitisation does not need to be regulated so precisely. With Ovako 677 an overheating does not give the significantly negative influence on properties which occur with SAE 52100 type steels. Rather, Ovako 677 will react as the standard induction-hardening steels that tolerate significant overheating without any negative effect on the product properties.

In one example, quenched-and-tempered Ovako 677 was heated to different surface temperatures in one laser heating unit wher after the material was allowed to air cool. Evidently, a large range of

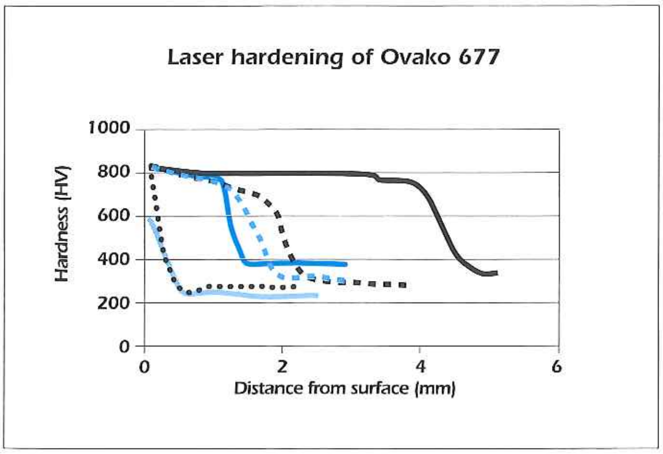


Fig 19.

hardening depths can be attained, with maintained surface characteristics, simply by changing the temperature to which the surface is heated.

This obviously is not possible with steels such as SAE 52100 as enhanced surface temperatures (other conditions being the same) would lead to rapid over-austenitisation of the surface.

Surface enrichment

The alloying design makes Ovako 677 well suited for carbonitriding and any other surface enrichment process.

Properties of Ovako 477

Average chemical composition

C	Si	Mn	Cr	Mo
0.40	1.70	1.45	1.55	0.45

Maximum oxygen content 11 ppm

Soft annealing

The medium carbon air hardening variant, Ovako 477, can be soft annealed or tempered to the desired hardness / strength level.

In the soft annealed condition a hardness of 200 HB is attained *(Fig 20)*

The machinability of the soft annealed variant is equivalent to a standard, softened harden-and-temper steel. *(Fig 21)*

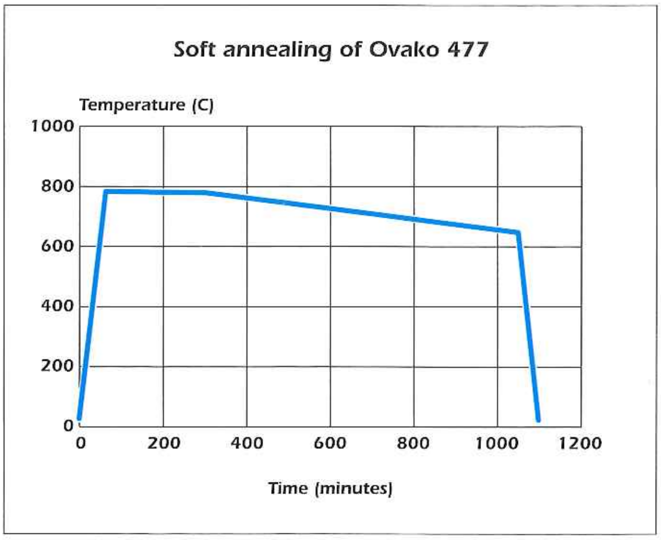


Fig 20.

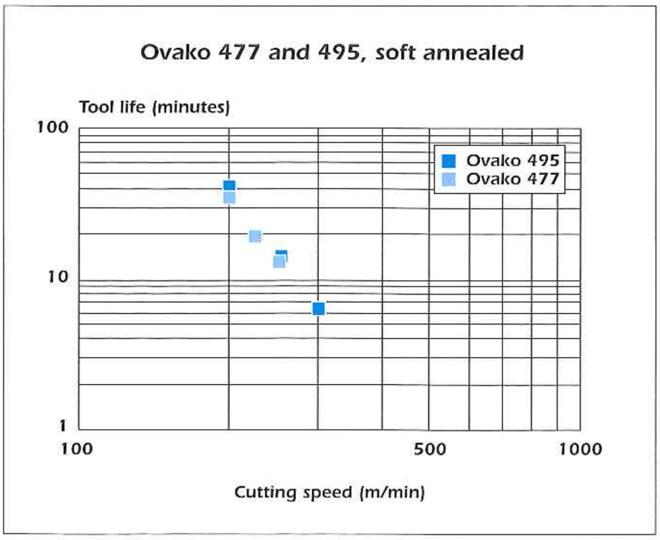


Fig 21.

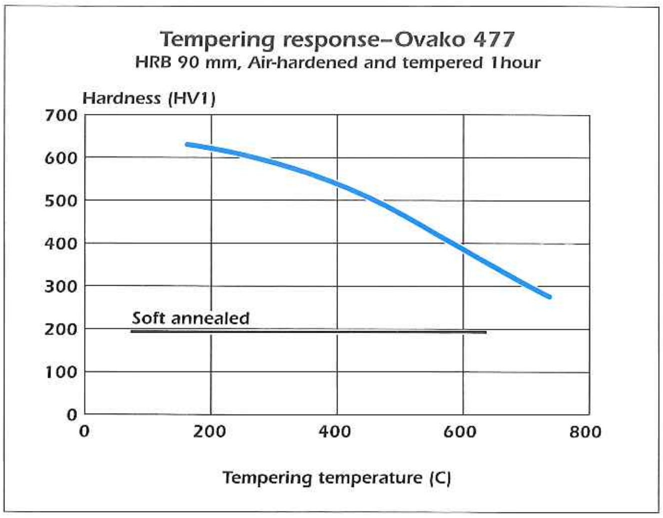


Fig 22.

Tough tempering

The standard delivery condition for Ovako 477 is tough tempered, and it can be supplied at yield strength levels between about 500–1600 MPa. *(Fig 22)*

Austenitisation

The Ovako 477 steel can be austenitised as any other harden-and-temper steel without any alterations.

The through hardenability in still air cooling is significant.

Maximum diameter or wall Ovako 477 air cooled	
Bar	60 mm
Ring or tube cut	35 mm

Through hardenability

The air-hardening steels have been designed to provide a high-hardness martensite in a slow air-cooling and they perform as well as, or better than, the martensite structures achieved today in oil- or salt bath quenching.

To enable this, a modern steel design is required. To achieve the desired properties a combination of silicon, manganese and molybdenum have been used in combination with chromium and different carbon content levels to give the air-hardening variants.

What limits the hardenability of steel components is the critical cooling rate. This critical cooling rate is the slowest cooling that any part of a component, for a given steel composition, can have while still providing a martensitic structure.

Possible achievements can be predicted from the steel's transformation characteristics that can be displayed in a CCT (Continuous Cooling Transformation) diagram. *(Fig 23 and 24)*

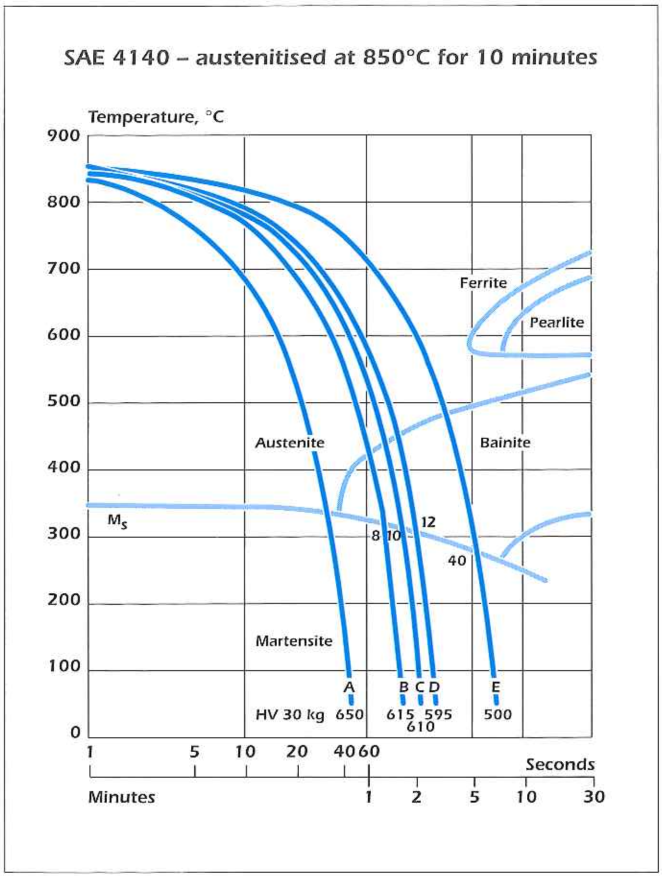


Fig 23.

Fig 25. SAE 4140 oil quenched from 860°C, tempered 160°C, 1 hour.

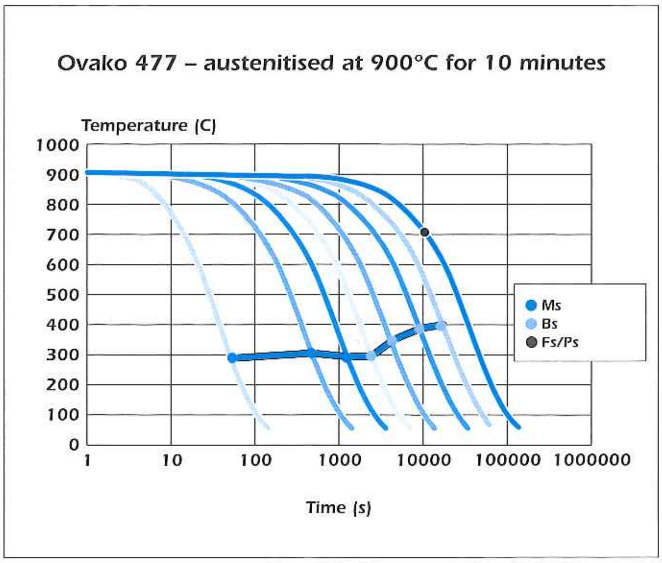


Fig 24.

Fig 26. Ovako 477, air-hardened from 860°C, tempered 160°C, 1 hour.

Distortion

As for Ovako 677, and for the same reasons, Ovako 477 will give little hardening distortion. Additionally, the Ovako 477 has the advantage that a fully martensitic structure will be achieved throughout the component assuming the critical cooling rate is not violated. One frequent cause of uncontrollable distortion is the fact that the steel does not have high enough hardenability to give a homogeneous structure through the entire section.

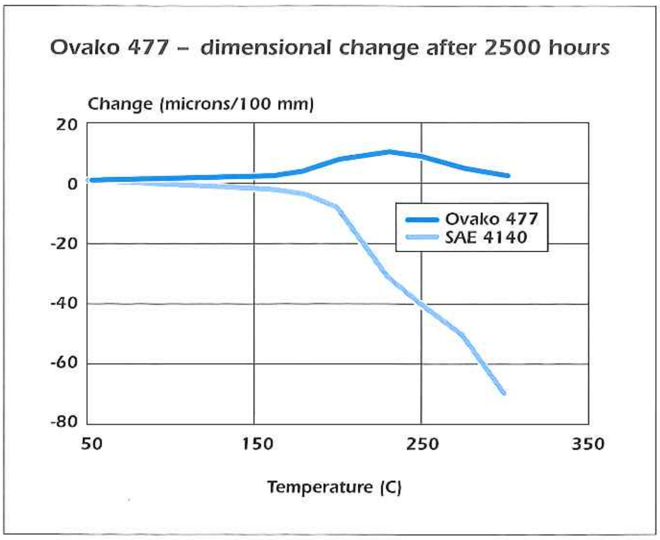


Fig 27.

This leads to formation of pearlite and/or bainite and as these structural components have volumes that differ from martensite, the size will change in an undesired manner.

Dimensional stability

Ovako 477 remains dimensional stable at significantly higher temperatures than SAE 4140. (*Fig 27*)

Hardness and strength

The maximum hardness attainable with Ovako 477 is slightly above 600 HV (about 55 HRC) after tempering 160°C for 1 hour. This is about the same level as can be reached with today's harden-and-temper steels.

The alloying strategy used provides good tempering resistance, and Ovako 477 loses hardness and strength somewhat slower than most conventional harden-and-temper steels. (*Fig 28*)

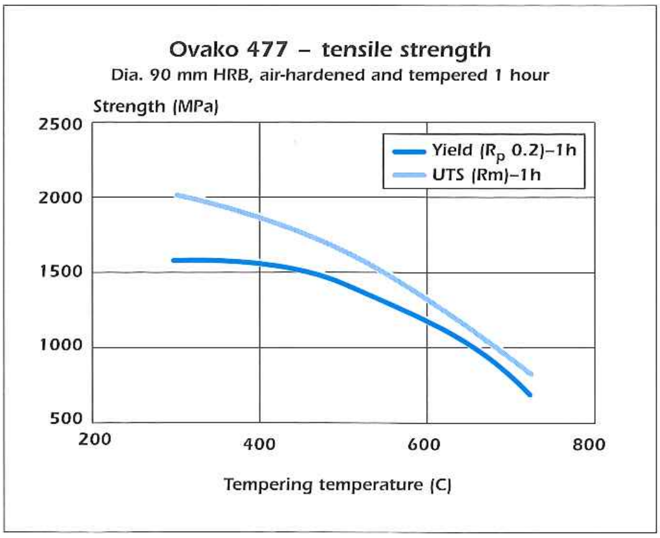


Fig 28.

Figures for yield and tensile strengths as function of tempering temperature are also available: (*Fig 29 to 31*)

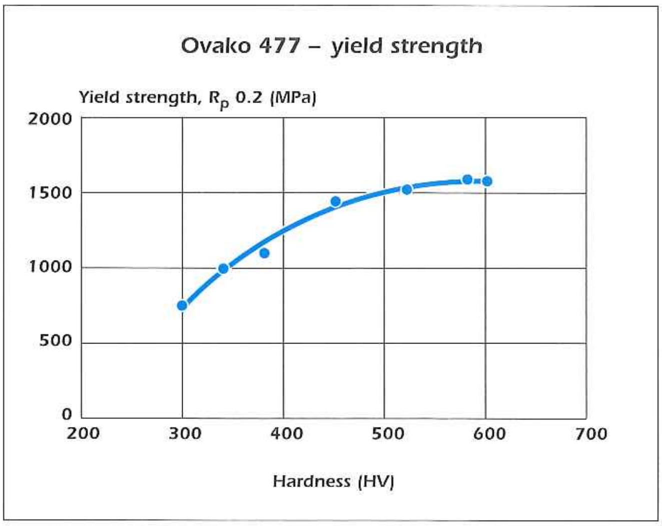


Fig 29.

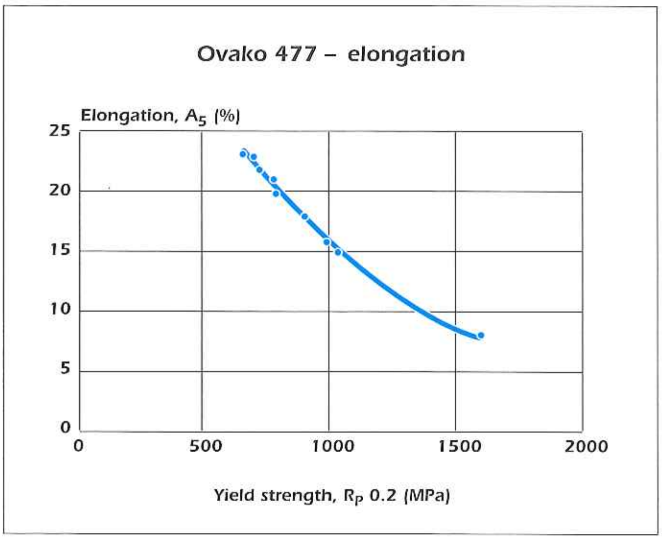


Fig 30.

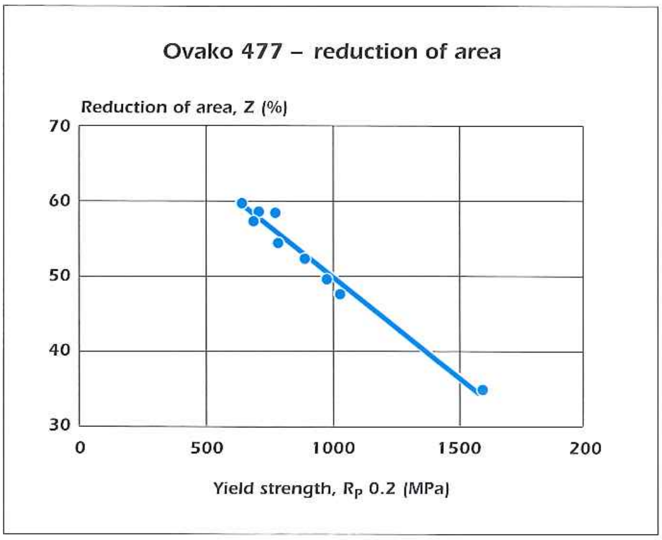


Fig 31.

The impact strength of Ovako 477 is well on par with what is achieved with the normal high-quality harden-and-temper steels available today.

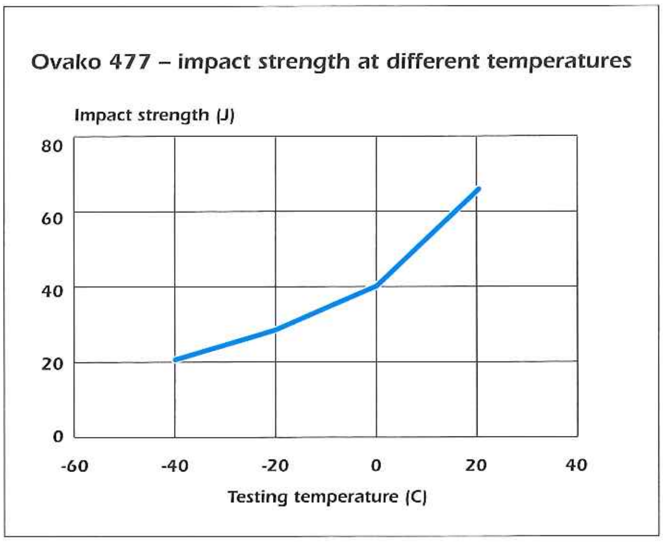


Fig 32.

Ovako 477 retains significant toughness also at low temperatures.

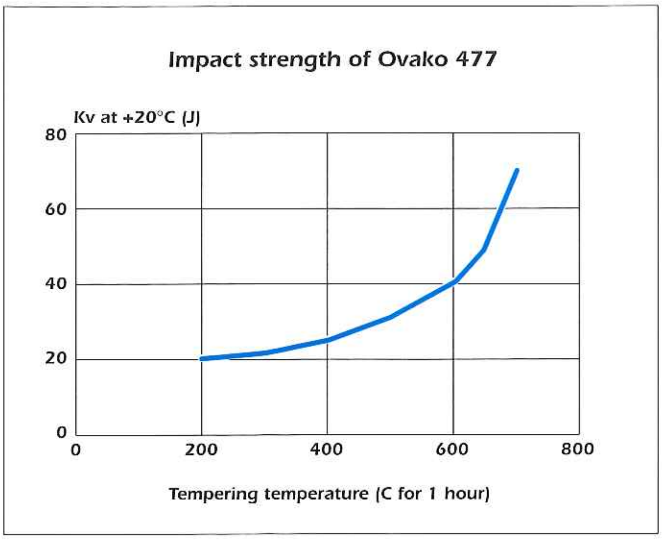


Fig 33.

Induction hardening

Ovako 477 is very well suited for induction hardening. The cooling after the inductive heating can be simply achieved through cooling in air, and with the excellent hardenability of Ovako 477 the hardening depth can be adjusted to any desired level. The maximum attainable surface hardness is about 57 HRC.

Surface enrichment

Ovako 477 is well suited for nitriding and nitrocarburising and can also be used for carburising.

In nitriding / nitrocarburising the tempering resistance of Ovako 477 provides a high strength after processing due to its tempering resistance, and the chemical composition of Ovako 477 makes nitriding simple.

For carburising, Ovako 477 can be an effective, reduced cost alternative to conventional carburising steels, however, the high silicon contents makes it necessary to reduce the carbon potential. One major advantage of using 477 is that the components can be directly hardened by air-cooling from the carburising process. This can provide large environmental advantages (quenching baths are avoided), and at the same time the slow cooling for air-hardening will significantly reduce hardening distortion which is one of the main processing problems in today's case hardening.

Continued work

Several different application areas are currently under evaluation to detail the advantages it is possible to obtain using the Ovako Steel air-hardening steel concept and product properties under varying usage conditions.

The carburising steel air-hardening variant is under development, and very shortly detailed information on its composition and properties will be released.

In some cases, variants may be needed which can through harden larger dimensions than are possible with the presently available grades. Such variants of 477 and 677 have been designed but not yet produced. Making such steel grades available based on the same concept is not a technical problem.

Conclusions

- The Ovako Steel air hardening steel grades combine their air hardenability with very high metallurgical cleanliness, good machinability and high finished product performance.
- The fundamental merits of air hardening steels are founded on the fact that today's quenching baths, which not only are often polluting health and safety risks but are also expensive to run and maintain, can be totally avoided and replaced by cooling in air.
- In addition one of the main problems associated with modern heat treatment, unpredictable hardening distortion, can largely be avoided. This, in turn, provides large potentials to save time and cost in the process steps needed to rectify the hardening distortion.
- The fact that the air hardening steels can be hardened even from very high austenitisation temperatures makes it potentially possible to reduce the number of processing steps required to produce a given component and thus significantly decrease total manufacturing cost.

OVAKO STEEL

Technology & Quality

S-813 82 Hofors, Sweden

RD-111US 04.01 5,000 Hällefors Tryckeri

Disclaimer

The information in this document is for illustrative purposes only. The data and examples are only general recommendations and not a warranty or a guarantee. The suitability of a product for a specific application can be confirmed only by Ovako once given the actual conditions. The purchaser of an Ovako product has the responsibility to ascertain and control the applicability of the products before using them.

Continuous development may necessitate changes in technical data without notice. This document is only valid for Ovako material. Other material, covering the same international specifications, does not necessarily comply with the properties presented in this document.

Ovako AB
SE-111 87 Stockholm, Sweden
Phone: +46 (0)8 622 13 00