Heat treatment and mechanical properties of Ovatec™ 277 – an update and progress report

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HEAT TREATMENT AND MECHANICAL PROPERTIES OF OVATEC™ 277 – AN UPDATE AND PROGRESS REPORT

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 2004 is about heat treatment and mechanical properties of a grade developed within, Ovako 277.

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

Ovako 277 is a grade that is part of our current offer. In the Ovako Steel Navigator this material is described under the version names Ovako 277L and Ovako 277Q.

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

Ovatec; this trade mark is owned but no longer used by Ovako Sweden AB.

Technical Report 2/2004

Heat treatment and mechanical properties of Ovatec™ 277 – an update and progress report

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OVAKO STEEL
Excellence in engineering steels

OVAKO STEEL

Ovako Steel is the world's leading manufacturer of steels for rolling bearings and a major producer of other special engineering steels. The company is a fully owned subsidiary of AB SKF.

The production programme includes hot and cold worked products in the forms of bars, surface removed wire and seamless tubes. In addition the programme also includes rolled and forged rings. A large part of the production is further processed into precomponents for direct applications in the customers' production.

The most important customer groups are rolling bearing manufacturers, the automotive industry together with their subcontractors, suppliers of rock drilling equipment, the hydraulic industry, and the general engineering industry.

Ovako Steel has own production units in Sweden and France. The marketing is carried out by own sales companies or independent distributors on the most important markets in Europe and North America.

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 areas 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.

Background

The objective of this report is twofold:

- To provide guidelines on how the processing of Ovatec 277 products should be handled in different application environments in order to provide maximum benefits from its potentials.

- To serve as a technical guide to the properties which are attained when applying different processing routes and heat treatment to Ovatec 277 products.

Abstract

Since the introduction and presentation of Ovatec 277 (Technical Report 1/2002) a significant number of laboratory and application tests have been performed, and the Ovatec 277 steel has found industrial use in a number of different fields.

Ovatec 277 has proven to be a very versatile steel, and today is used in applications where normally micro-alloyed, harden-and-temper or case hardening steels are used.

To meet the requirements of very demanding applications, a special metallurgical variant has been developed. While the standard variant (designated Ovatec 277L) is a high cleanliness variant produced to Bearing Quality requirements, the newly developed high performance variant (designated Ovatec 277Q) is given very high metallurgical cleanliness and is primarily intended for use in demanding applications where often remelted steels are specified, or where highly isotropic properties are required.

Introduction

The Ovatec family of steels has been designed to provide a robust, easy to heat treat, high performance alternative to all the low-alloy steel variants used for component manufacturing today, *Fig 1.*

Common to the Ovatec steels are that they have very high hardenability, *Fig 2*, providing the potential of being martensite hardened even on very slow cooling after austenitisation which sometimes offers a potential of simplifying component production significantly.

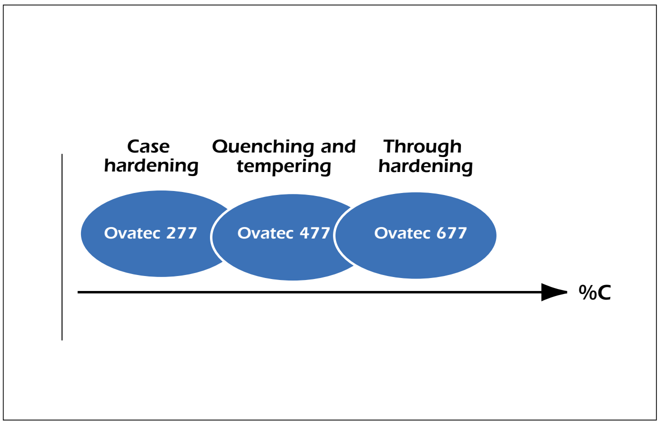


Figure 1 – The family of Ovatec steels.

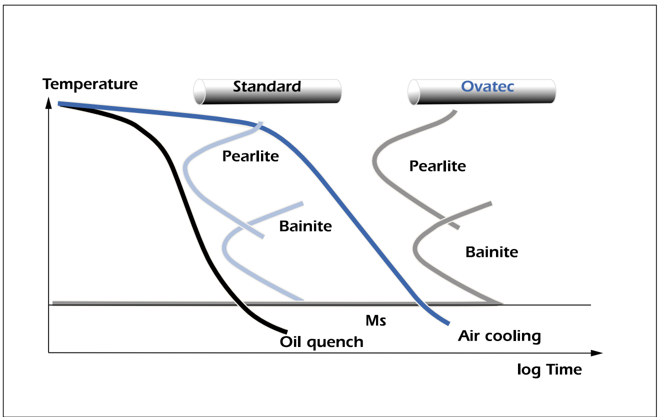


Figure 2 – Available cooling times for martensite formation (principle) in comparison between Ovatec steels and standard steels.

Contents

In this report, a number of aspects of processing and heat-treating of Ovatec 277 are covered, as well as results from various heat treatment- and mechanical properties tests conducted.

Wherever possible, practical application examples have been quoted to the extent possible considering company-privileged information.

Chemical composition

The chemical composition of steel largely determines the heat treatment routes, which can be selected, and the properties, which a component can attain in application.

The Ovatec 277 steel is a low carbon, alloyed steel, which normally would be classified as a case hardening steel. However, due to the combination of alloying elements selected, Ovatec 277 gives the potential to replace a number of steels in a range of applications.

Ovatec has a basic composition, which utilises manganese, chromium and molybdenum as main alloying elements to provide its unique ability to generate a fully martensitic structure even in very heavy components also at very low cooling rates. It is also alloyed with vanadium to promote precipitation of sub-microscopic particles to promote strength and ductility, and with a minor amount of nickel to further enhance toughness. The steel has low carbon contents, and in order to facilitate carbon pick-up and diffusion also has low silicon content.

The base variant, which is denoted Ovatec 277L has the composition given in *Table 1.*

In a variation utilising prolonged ladle furnace treatment processing with special features, the steel is given even further enhanced properties.

This variant, which is denoted Ovatec 277Q, has the composition shown in *Table 2.*

		C	Si	Mn	P	S	Cr	Ni	Mo	V
Ovatec 277L	Min Max	0.14 0.17	 0.15	1.20 1.40	 0.020	0.020 0.030	2.10 2.30	0.45 0.55	0.45 0.55	0.15 0.25

Table 1 – Chemical composition limits for Ovatec 277L.

		C	Si	Mn	P	S	Cr	Ni	Mo	V
Ovatec 277Q	Min Max	0.14 0.17	 0.30	1.20 1.40	 0.020	 0.002	2.10 2.30	0.45 0.55	0.45 0.55	0.15 0.25

Table 2 – Chemical composition limits for Ovatec 277Q.

Metallurgical cleanliness

Metallurgical cleanliness is often defined by the content of non-metallic inclusions, and the content of elements forming such inclusions.

Non-metallic inclusions are traditionally divided into macro-inclusions (large inclusions deriving from auxiliary elements used in the steel making process as sands, teeming powder, etc.) and micro-inclusions (small oxide rich inclusions deriving from residues of the deoxidation process and sulphides). At Ovako Steel, we also control the contents of inclusions in the size range in between these two; meso-inclusions. Meso-inclusions are oxides, and to a high extent derive from re-oxidation occurring during teeming of the steel. The definition of the groups of inclusions is outlined in *Fig 3*, and the different inclusion types need different inspection methods for their assessment. The content of micro-inclusions in steel is closely related to the total content of the two main elements forming them, oxygen and sulphur. The oxygen content of metallurgically well process steel can be kept to a low level, but there is a clear difference in between low and high carbon steels in this context, *Fig 4*.

For Ovatec 277, however, we manage to keep the oxygen content at the same low level as for high-carbon rolling bearing steels. For sulphides, however, the situation is different as sulphur content is directly processing dependent and can be regulated down to extremely low levels in any type of low alloy steel regardless the carbon content, *Fig 5*. The meso-inclusions contents, just as the oxygen content is clearly higher in low carbon steels than in corresponding high carbon variants, *Fig 6*. This relates to the positive effect of a high carbon content in the melt, which aids the teeming shroud in protecting the stream from re-oxidation. Ovatec 277Q deviates here, and in spite of its low carbon content evidences meso-inclusion contents of the same order as high-carbon steels.

The Ovatec 277 steel variants are produced against the cleanliness limits given in the most recent issue of the Ovako Steel Cleanliness Specifications.

Transformation characteristics

With the composition that the steel has been given, it will provide a very wide range of cooling rates

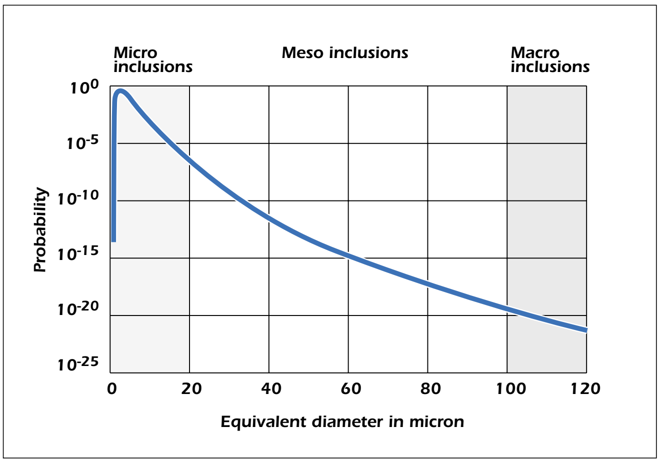


Figure 3 – Non-metallic inclusion size distribution in steel.

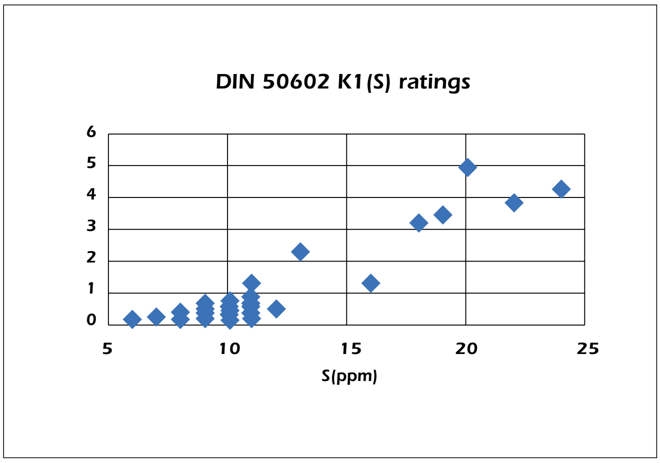


Figure 5 – Sulphide distribution at different sulphur contents.

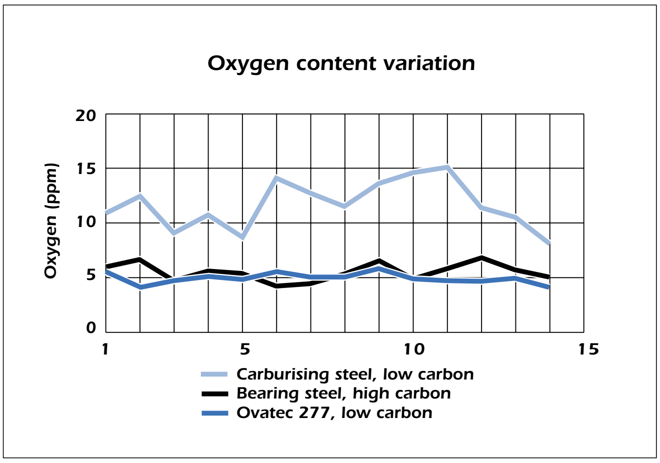


Figure 4 – Oxygen content distribution in different steel grades.

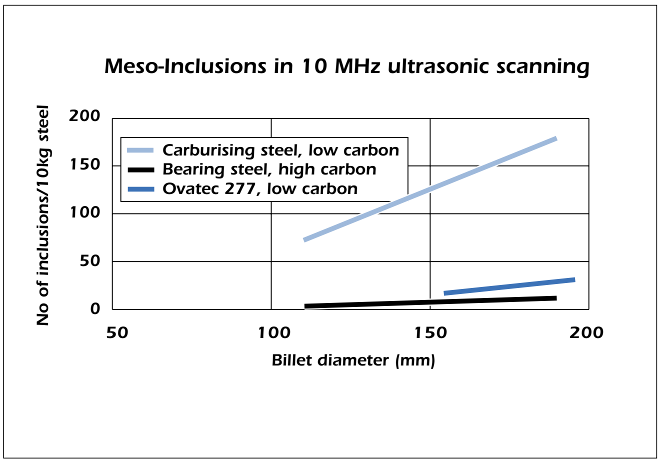


Figure 6 – Number of meso inclusions at different bar dimensions in different steel types.

where the end transformation product will be fully martensitic. As evident from the continuous-cooling-transformation (CCT-) diagram, *Fig 7*, even very slow cooling rates, as in still air cooling, will provide full martensitic hardness to the base material of an Ovatec 277 product.

Ovatec 277 will not produce the two-phase pearlite-ferrite structure normally obtained on slow cooling of case hardening or harden and temper steels. On very slow (furnace) cooling the structure will instead spheroidise and the result will be a structure with spheroidised carbides in a ferrite matrix.

Hardenability

Ideal critical diameter

The base composition of Ovatec 277 gives the steel very high through hardenability even if given a slow cooling. The calculated ideal critical diameter (DI-value) in accordance with the ASTM A-255 standard for the composition achieved in standard production is 300 mm. The calculated DI-values for Ovatec 277 is compared to some often used case hardening and harden-and-temper steels in *Fig 8*.

End-quench hardenability

Of course, the hardenabilty attained in an end-quench Jominy test also is high. In *Fig 9*, Ovatec 277 is compared to some standard case hardening steels.

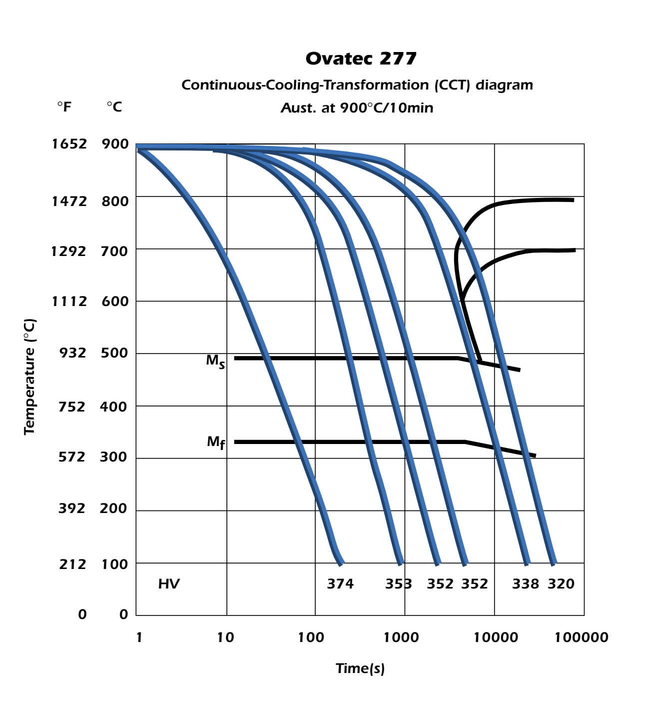


Figure 7 – Continuous Cooling Transformation diagram of Ovatec 277Q.

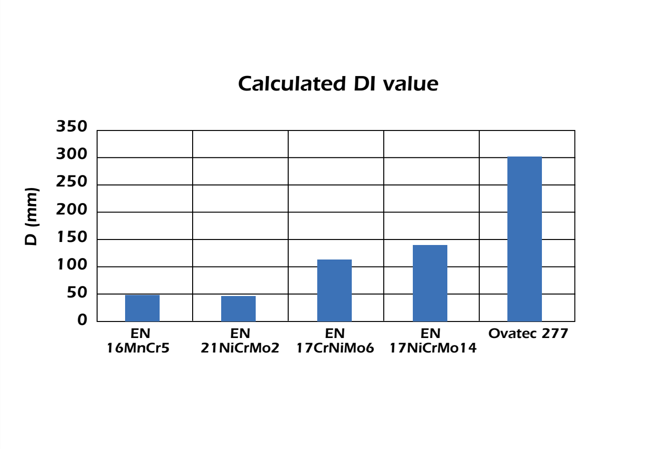


Figure 8 – The calculated ideal diameter for some steel grades.

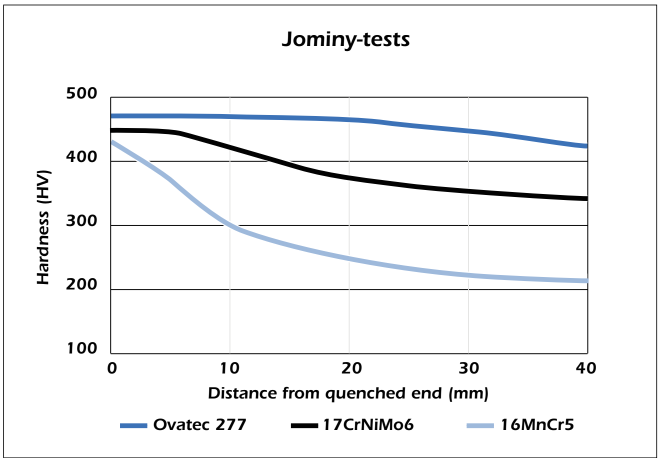


Figure 9 – Jominy end quench test of Ovatec 277 in comparison with two other carburizing steels.

Comparison of different steel grades

Ovako designation	Nearest equivalent		Nominal chemical composition					
	EN/DIN	SAE	C	Si	Mn	Cr	Ni	Mo
146	(16NiCr4)	3120	0.2	0.3	0.9	0,8	1.0	
159	17CrNiMo6		0.2	0.3	0.5	1.7	1.6	0.3
234	16MnCr		0.2	0.2	1.2	1.0		
327	42CrMo4	4140	0.4	0.3	0.8	1.0		0.2

Table 3 – Comparison of different steel grades mentioned in this report.

Practical example
In the production of tubes and bars in Ovatec 277, the hot rolling takes place at a temperature of about 1000° C. The material then cools in open air on cooling beds. In *Fig 10*, the hardnesses achieved for tubes are compared to the hardnesses measured on bars with varied diameters.

Grain size

The grain size of Ovatec 277 of course increases with enhanced temperatures, but fairly slowly, *Fig 11*. Even when hardened directly from a hot forming operation as rolling or forging, Ovatec 277 will provide a fine martensitic structure with good mechanical properties, *Fig 12*.

Manufacturing into semi-finished products (rolling/forging)

In hot forming operations, no special precautions need to be taken – hot rolling or forging can be made using standard settings and temperatures.

Case hardened components
Today, the standard processing route for the pre-components that are to be case hardened is one of the following alternatives:

- Production of tube or bars ⇨ soft annealing ⇨ (and then soft machining and case hardening)
- Production of bar ⇨ forging ⇨ controlled cooling (and then soft machining and case hardening).

The first alternative route is directly applicable for Ovatec 277 even if it will generate another type of microstructure, but the second route – involving controlled cooling – needs some consideration when Ovatec 277 is used.

The controlled cooling is used to obtain a well-defined and soft dual-phase structure of pearlite and ferrite, *Fig 13*. As discussed above, Ovatec 277 will not form pearlite under virtually any circumstances. If brought to the temperature normally employed in controlled cooling and held there, nothing will happen in a very long time, and when the parts are air cooled to room temperature after

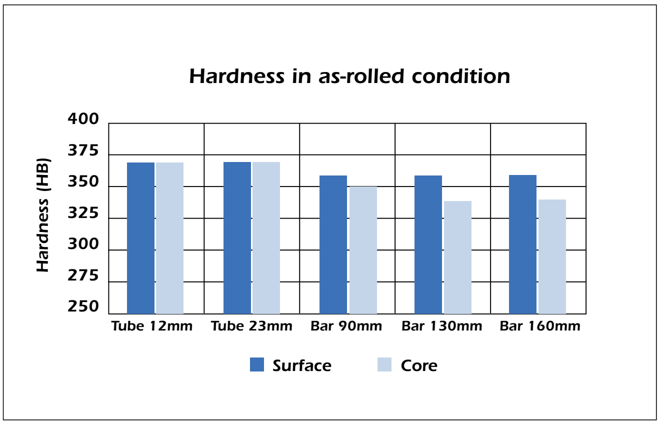


Figure 10 – Hardnesses after slow cooling in air, measured on tubes, and at the surface and centre of bars of different dimensions of Ovatec 277.

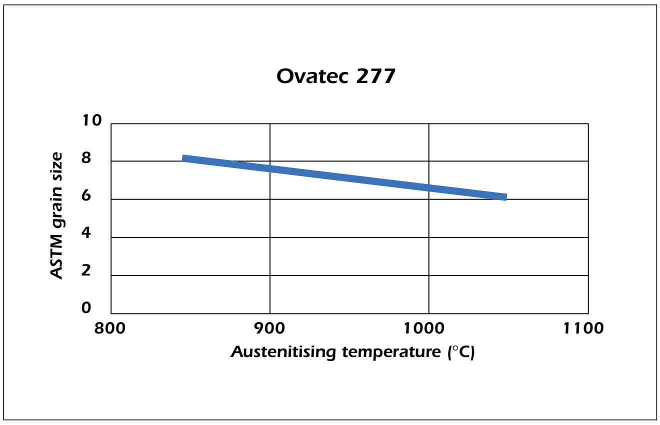


Figure 11 – Grain size of Ovatec 277 at varied austenitisation temperatures.

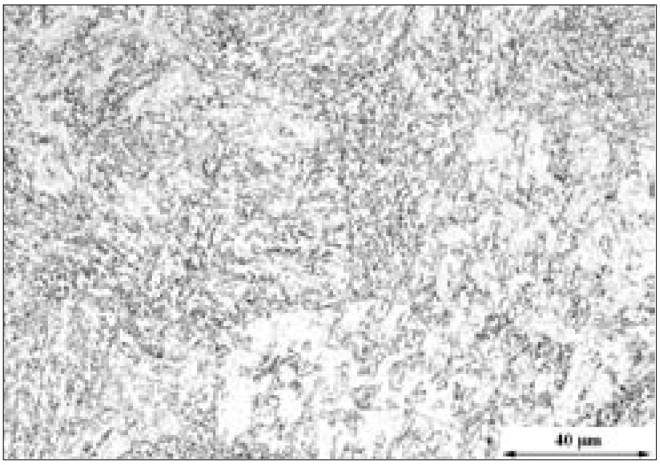


Figure 12 – Martensitic structure after slow cooling from hot rolling temperature.

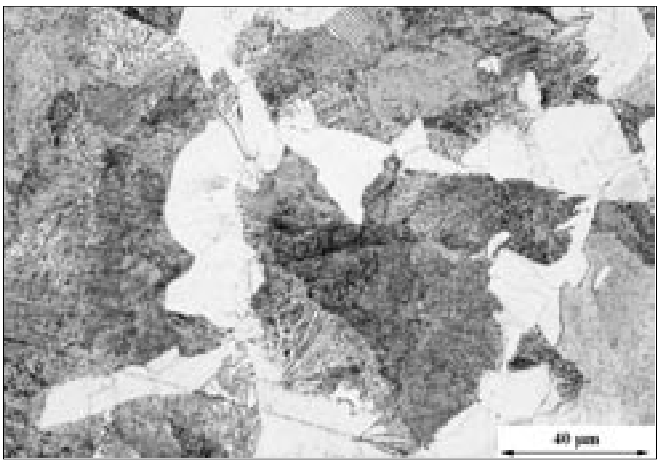


Figure 13 – Pearlitic/ferritic structure after a controlled cooled standard carburising steel.

the controlled cooling holding time, Ovatec 277 will transform into martensite, *Fig 14.* This means that another controlled cooling cycle is needed, or the parts should be air cooled directly from the forging temperature and then high temperature tempered or annealed.

Hardened-and-tempered components

In processing pre-components designated for harden-and-temper steel applications the processing route today is:

- Hot form (rolling or forging) ⇨ air-cooling ⇨ hardening ⇨ high temperature tempering (and then soft machining and sometimes surface induction hardening).

The initial structure after hot forming and air-cooling is dual phase ferrite and pearlite, *Fig 15,* and after the hardening and tempering a highly tempered martensite with precipitated spheroidical carbides, *Fig 16.*

With Ovatec 277 steel, the processing route can be simplified into:

- Hot form (rolling or forging) ⇨ air-cooling ⇨ high temperature tempering.

The hardening step in the hardening-and-tempering thus can be avoided, and the resulting structure is very similar to what is seen in standard processed conventional steels, *Fig 17.*

Softening heat treatments for Ovatec 277

Ovatec 277 always will provide a starting structure, which is martensitic and has a hardness of about 35 HRC after hot forming and air-cooling. And this is repeatable and valid for almost any practically used component size.

This means that regardless whether a small component or a very heavy walled product is the starting product, the initial hardness and the initial structure will remain the same, a fully martensitic structure, *Fig 18,* with a hardness of approximately 35 HRC.

This, thus is the starting structure obtained on air cooling after a hot forming operation as tube rolling, bar rolling, ring rolling or forging when the hot formed parts are left to cool to room temperature in air.

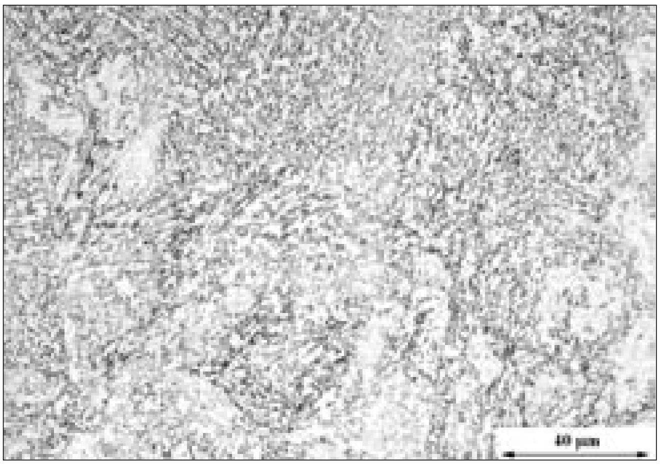


Figure 14 – A martensitic structure after controlled cooling from a forging operation.

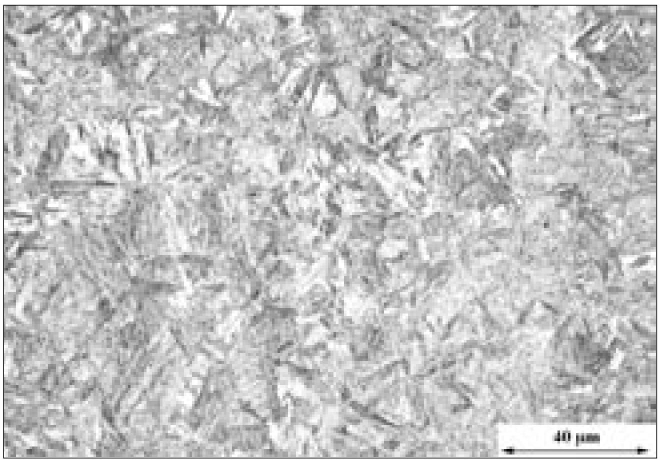


Figure 16 – Tough tempered conventional harden-and-temper steel.

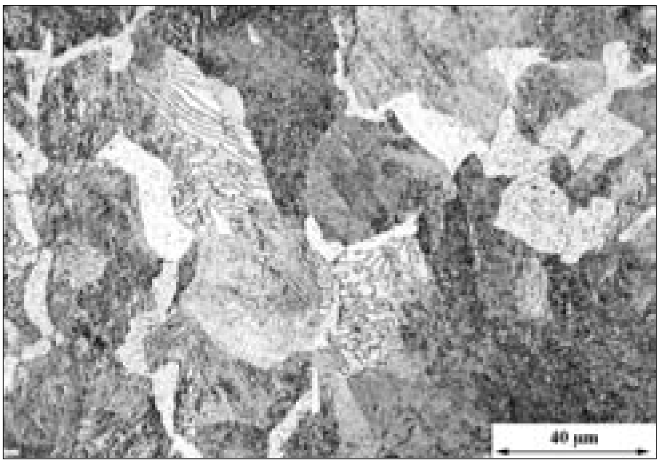


Figure 15 – A dual phase resulting from slow cooling a conventional harden-and-temper steel, the structure is pearlite and ferrite.

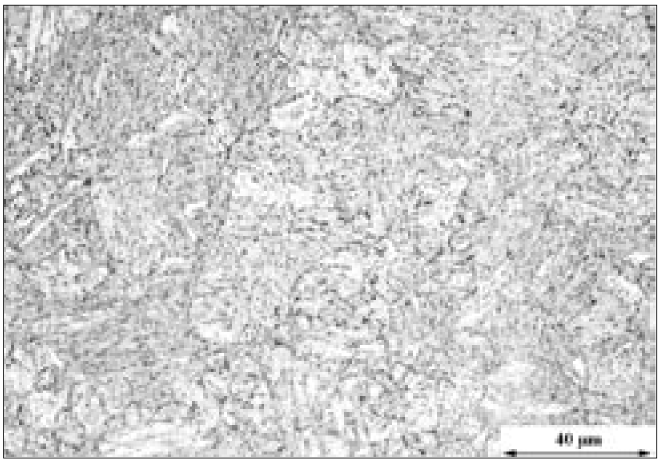


Figure 17 – Tough tempered Ovatec 277.

Auto-tempering

The steel has already been tempered. The reason for this is to be found in the CCT-diagram, which shows that the martensite transformation for Ovatec 277 steel starts at a temperature just above 500° C. Once the martensite has formed, an automatic tempering starts to take place, and this means that Ovatec 277, on slow cooling, always will have the structure and the hardness of a product tempered at 500° C, *Fig 19*.

This, in consequence, of course means that if a final hardness level about 35 HRC is required in a specific application (and machining can be performed at this hardness level which with modern machine tools is not a problem), Ovatec 277 steel can be used directly in the condition which is achieved after hot forming and air cooling. Thus, if a forged hardened-and-tempered product is used today requiring a final hardness about 35 HRC, and can be machined in this condition, Ovatec 277 products can be used directly in this condition. No hardening and no high temperature tempering is required.

Softening by tempering

With application of tempering temperatures higher than 500° C, hardness will be reduced and strength will drop while toughness increases.

The general relationship between tempering temperature, hardness and mechanical properties for Ovatec 277 is shown in *Fig 20*. This relationship is valid for both Ovatec 277 variants, the response to tempering as regards impact strength properties, however, is different.

This is due to the high metallurgical cleanliness given to the Ovatec 277Q, high performance, variant where in particular the transverse impact properties are significantly enhanced – even at very low temperatures, *Fig 21 (on the following page).*

Softening by annealing

If a very low hardness needs to be attained, this is accomplished by soft annealing. The soft annealing cycle best suited for Ovatec 277 is shown in *Fig 22*, and the resulting structure is shown in *Fig 23* while the corresponding strength data are given in *Table 4*. *(figures and table on the following page)*

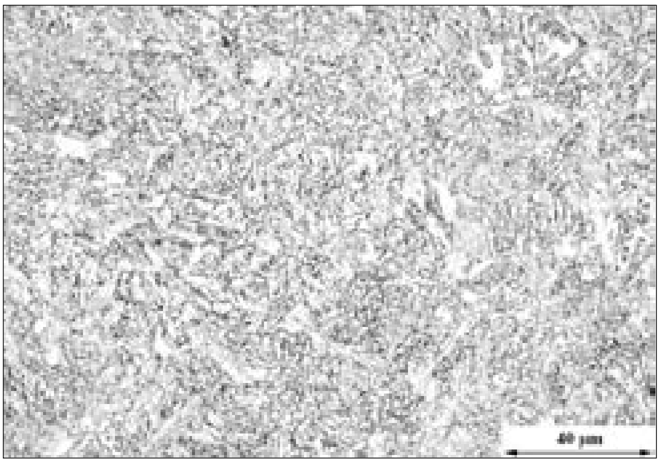


Figure 18 – A fully hardened, martensitic Ovatec 277 slow cooled, which is about 35 HRC.

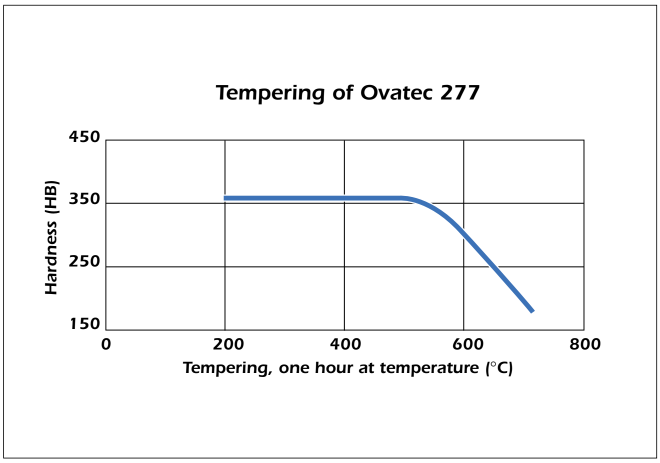


Figure 19 – Tempering response Ovatec 277.

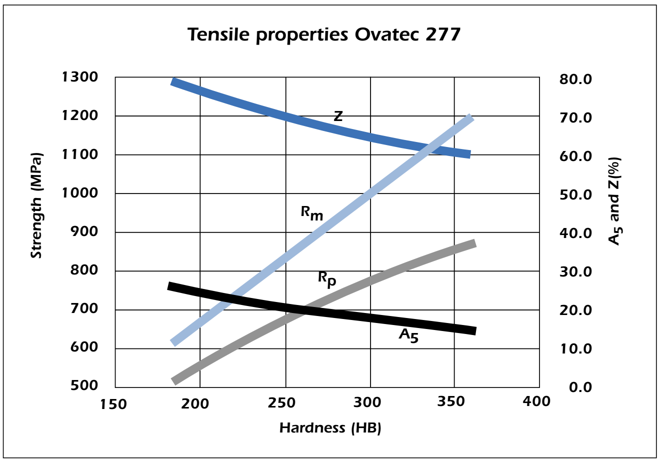


Figure 20 a – Tensile properties as function of hardness.

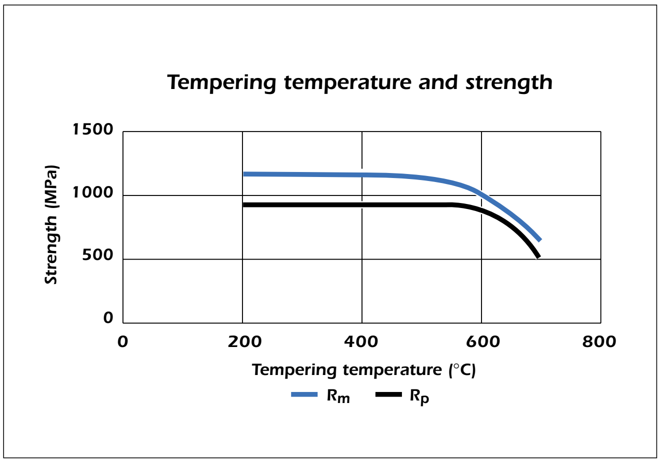


Figure 20 b – Tensile strength as function of tempering temperatures.

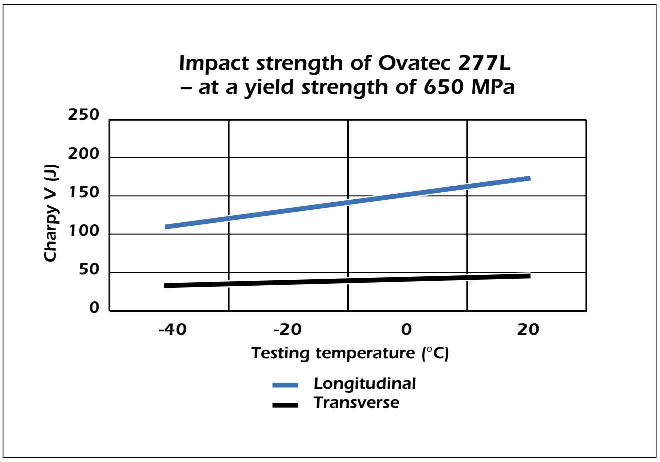


Figure 21 a – Impact strength at varied testing temperatures for Ovatec 277L.

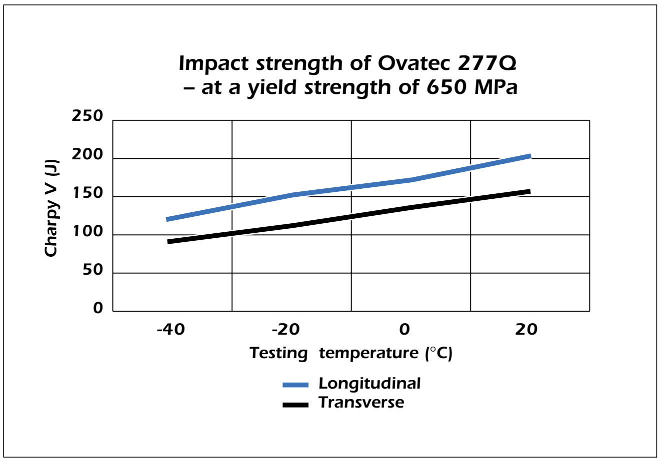


Figure 21 b – Impact strength at varied testing temperatures for Ovatec 277Q.

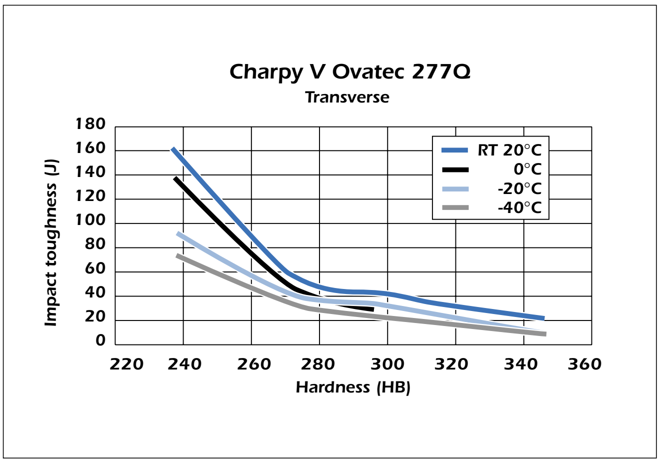


Figure 21 c – Transverse impact strength at varied hardness testing of Ovatec 277Q at various temperatures.

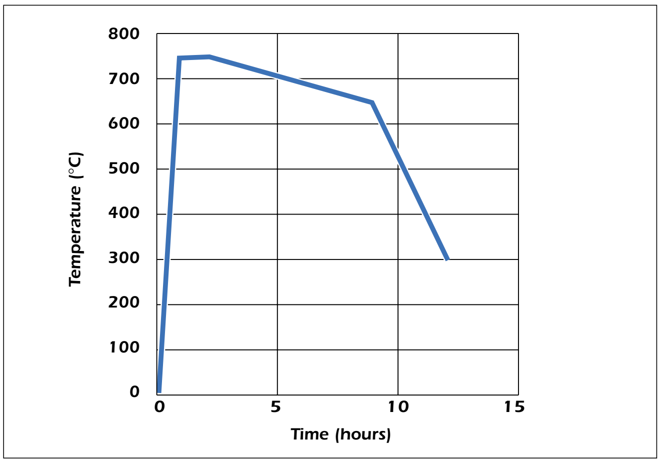


Figure 22 – Soft annealing cycle for Ovatec 277.

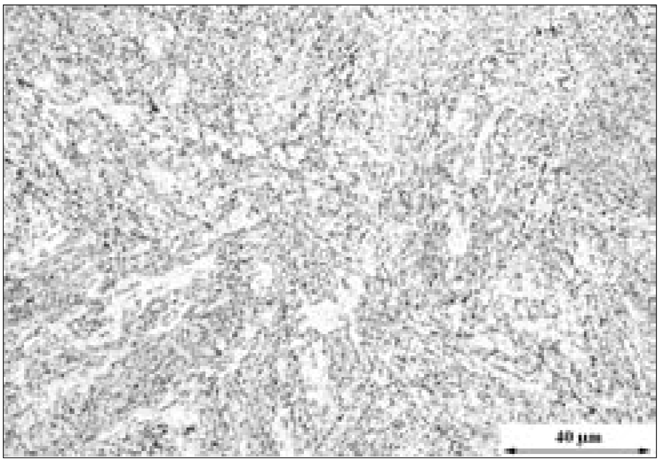


Figure 23 a – Soft annealed microstructure of Ovatec 277, spheroidised carbides, from a former martensitic structure.

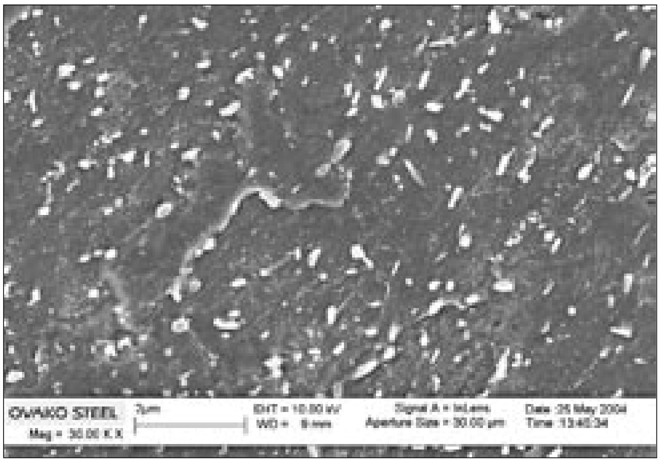


Figure 23 b – Soft annealed micro structure of Ovatec 277, spheroidised carbides, from a former martensitic structure, SEM.

Hardness	≈ 160-190 HB
R_m	≈ 550 MPa
$R_{p\,0.2}$	≈ 500 MPa
A_5	≈ 30%
Z	≈ 80%
K_v (20° C)	≈ 300 J

Table 4 – Strength properties of a soft annealed Ovatec 277.

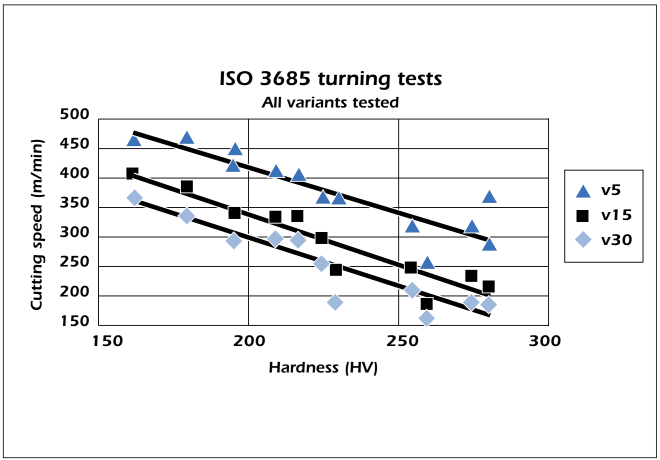


Figure 24 – Cutting speed at different tool lifes versus hardness for some conventional steels and Ovatec 277.

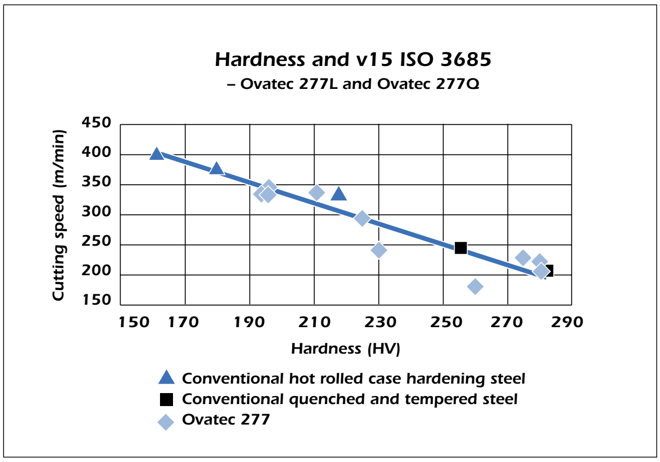


Figure 25 – Cutting speed versus hardness for some conventional steels and Ovatec 277L and Ovatec 277Q.

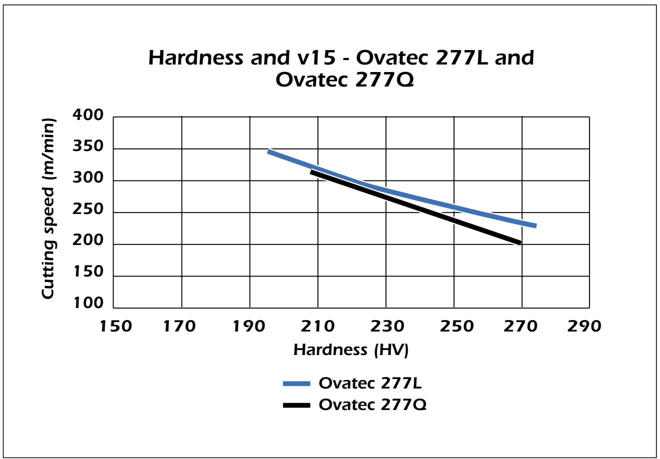


Figure 26 – Cutting speed versus hardness when soft machining Ovatec 277L and 277Q at a tool life of 15 minutes.

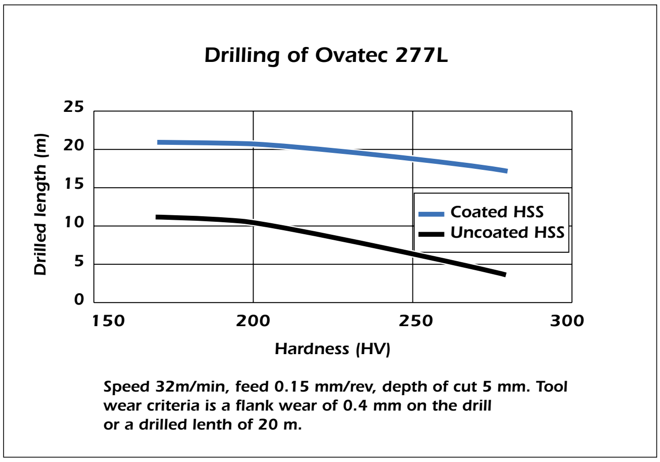


Figure 27 – Drilling with coated or uncoated high speed steels in Ovatec 277L, drilled length versus hardness of the steel.

Soft machining

As Ovatec 277 products in the two metallurgical variants today in production are used in widely varying application environments, a number of soft machining tests have been carried out in different heat treatment conditions, *Figs 24-27* and compared to more conventional products.

Low hardness is often considered the determining requirement for attaining good machinability, but this is not necessarily the entire truth.

The two-phase nature of the ferrite-pearlite structure of standard low-to-medium carbon steels leads to a situation where the cutting tool moves between a very soft ferrite phase and a hard brittle pearlite phase. In Ovatec 277, the structure is homogeneous, and has the same hardness through the entire section, *Fig 28*. This leads to a more even material removal that can be utilized to improve the surface quality of the machined products. It also seems that an spheroidised structure can be successfully machined at somewhat higher hardness levels than what is considered desirable for the two-phase structures normally used.

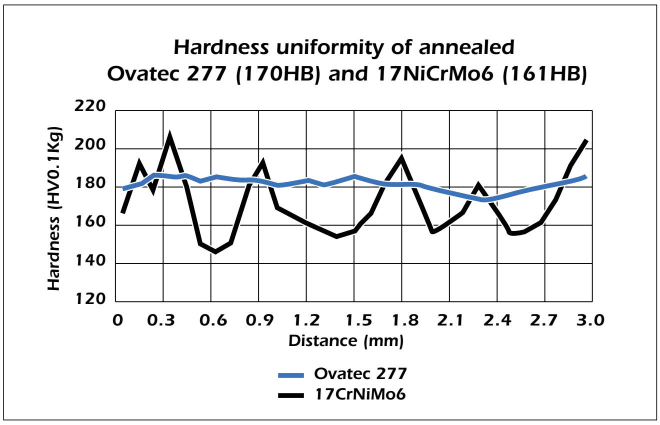


Figure 28 – Hardness measurement in spheroidised Ovatec 277 in comparison to the step annealed structure of a conventional steel.

Cold forming

Practical experience shows that Ovatec 277 can be cold formed as other case hardening steel variants. To reduce the hardness increase during cold deformation, it is recommendable to use soft annealed Ovatec 277 for cold forming operations.

The isotropic properties of the Ovatec 277Q variant makes it an attractive choice for heavily cold-formed parts.

Heat treating procedures

Carburising

Carburising is a process where a carbon rich atmosphere dissociates at the surface of a steel part and carbon diffuses into the steel. The carburising temperature is usually between 880 – 950° C, which is in the austenitic temperature range. The high hardenability of Ovatec 277 will make it possible to harden it using a slow cooling rate, and Ovatec 277 is ideally suited for gas quenching. The alloying design of Ovatec 277 makes it very simple to carburise, and the carbon potential used should be reduced in comparison to what conventionally is used in order to avoid over-carburisation. *Fig 29* shows the content of carbon in the case of Ovatec 277 attained at different carbon potentials, Cp.

It is recommended to use a carbon potential of maximum 0.7 % to avoid excessive retained austenite and grain boundary carbide formation.

Fig 30 shows the resulting hardness profile, case depth and core hardness of an Ovatec 277 component that was conventionally gas carburised and air-hardened and the corresponding profile measured on a conventionally oil quenched standard carburising steel.

Fig 31 shows the microstructure of the case of Ovatec 277.

Fig 32 shows the surface appearance after a slow cooling of a gear in a protective atmosphere in comparison to a direct air-cooling without any protective atmosphere. Internal oxidation originates from the carburising process due the oxygen that is always present in the atmosphere. The depth of internal oxidation is dependent on the carburising time, the amount of oxygen in the atmosphere, and the chemical composition of the steel. The internal oxidation in Ovatec 277 is very slight. During cooling in a protective atmosphere the only oxidation of the steel is the internal oxidation. But when cooling in still air without any protective atmosphere a light surface oxidation will occur. The amount of oxide formed is cooling rate dependent and a faster cooling gives little or no oxidation at all.

Residual stresses

Comparison between a conventionally case hardened standard steel and air hardened Ovatec 277 show that the residual stress distributions for parts with the same case depth are very similar, *Fig 33.* In this example, the components tested were given a carburising, which resulted in a 0.6 mm deep case. Thus, a slow cooling, even in still air, results in the same compressive surface stress situation as when a violent oil quench is used as is required for traditional case hardening steels.

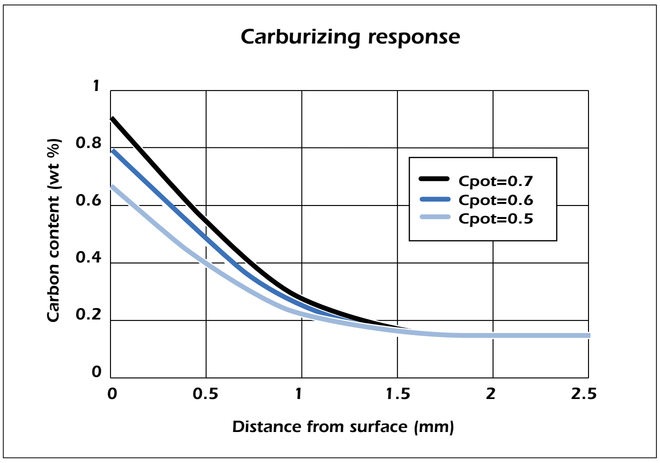


Figure 29 – Carbon content profiles in the case of Ovatec 277 due to different carbon potentials in the furnace atmosphere.

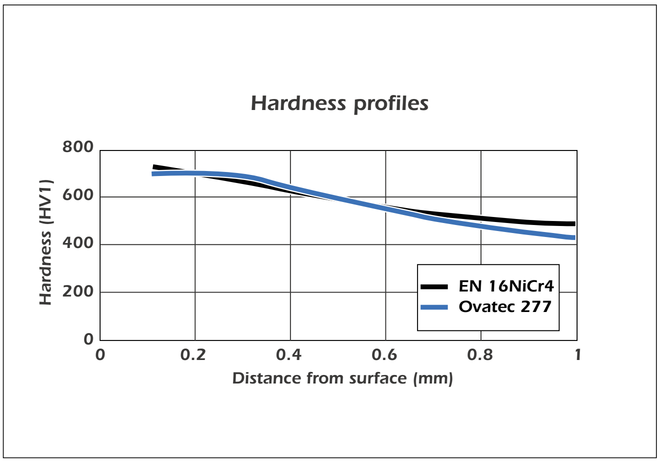


Figure 30 – The hardness profiles after carburising and air-cooling Ovatec 277 and an oil quenched conventional carburising steel grade.

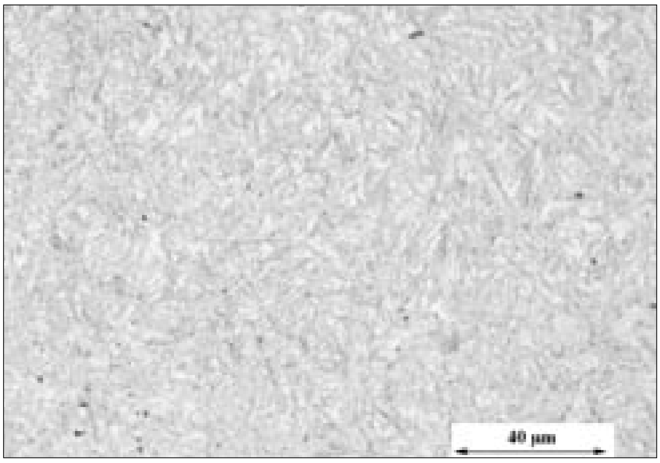


Figure 31 – Microstructure in the case of the carburised Ovatec 277. The structure is martensite with some retained austenite.

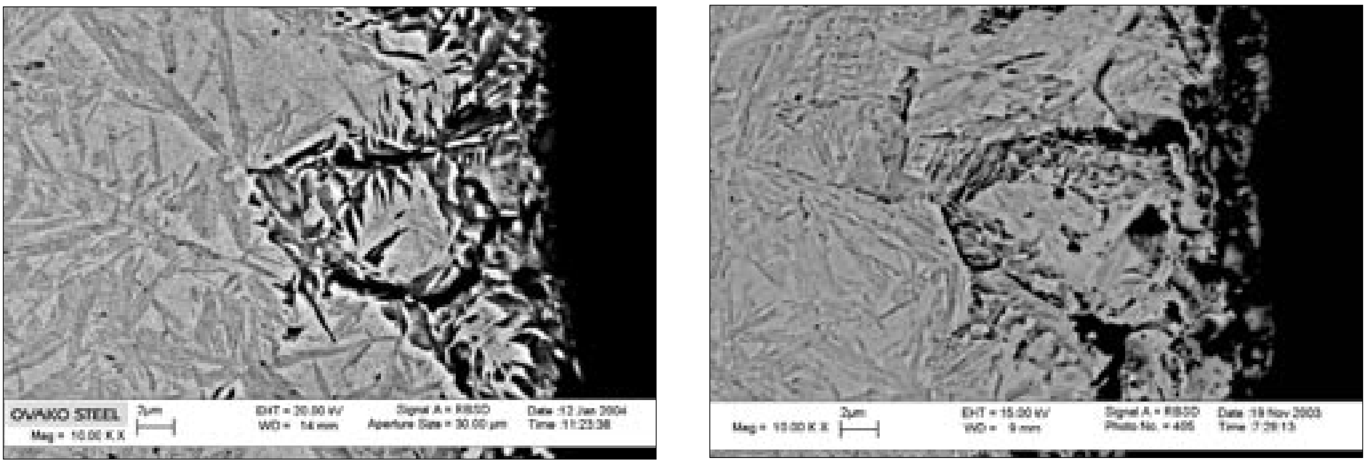


Figure 32 – Internal oxidation due to carburising of Ovatec 277. A slow cooling without a protective atmosphere gives a slight surface oxidation.

Distortion in case hardening

To show what is possible to achieve when using Ovatec 277, some examples have been selected in order to demonstrate the reductions in distortion that can be achieved.

A case hardened slim gear which gives significant distortion in conventional case hardening was used to see the influence of Ovatec 277 on hardening distortion. A direct comparison was made where a set of gear wheels was produced on the same machine in the standard carburising steel normally used and in Ovatec 277.

The gears were carburised in the same furnace using the same carburising cycle, with the difference that the carbon potential was reduced to 0.7 % for the Ovatec wheels.

The standard steel products were oil quenched while the Ovatec gears were allowed to cool in air directly after the carburisation. Results are shown in *Fig 34-35.*

A similar comparison was made on a thin-walled sleeve. The same procedure as above was followed, and the geometry of the sleeve was checked before and after the case hardening, where again the same carburisation parameters were used, but the Ovatec sleeves were air-cooled after carburising while the standard steel sleeves were oil quenched. *Fig 36-37 (on the following page).*

Fatigue properties

The life of many high performance components is limited by fatigue, especially so perhaps bearings and heavily loaded gears. The pitting occurring on ground gear flanks and the flaking occurring in

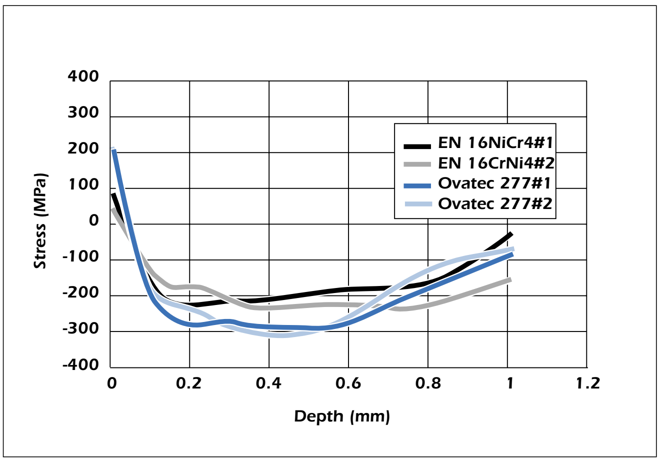


Figure 33 – Residual stress distribution in slow cooled Ovatec 277 and an oil quenched conventional steel.

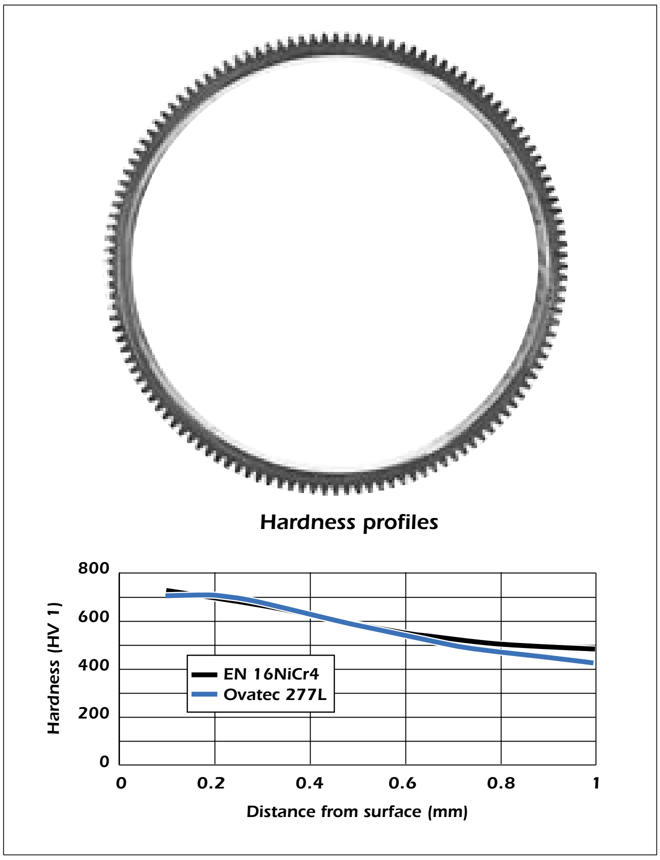
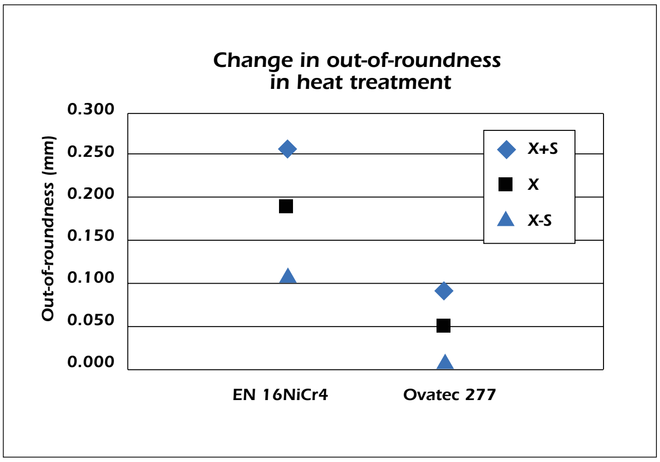


Figure 34 – A slim gear that was manufactured in Ovatec 277 and a conventional carburising steel.



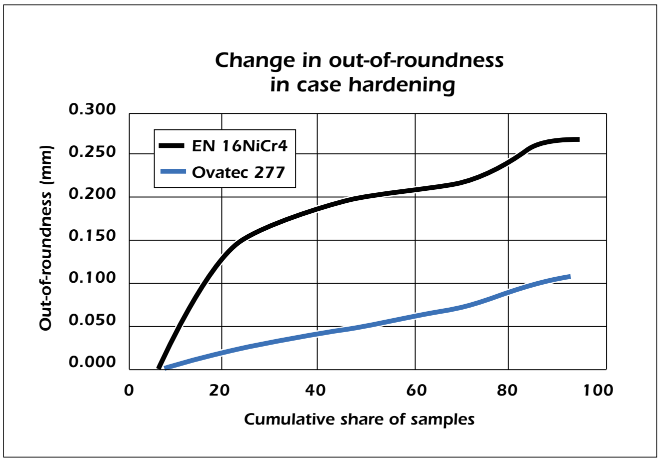


Figure 35 – Distortion results from the case hardening of Ovatec 277 and a conventionally case hardened gear.

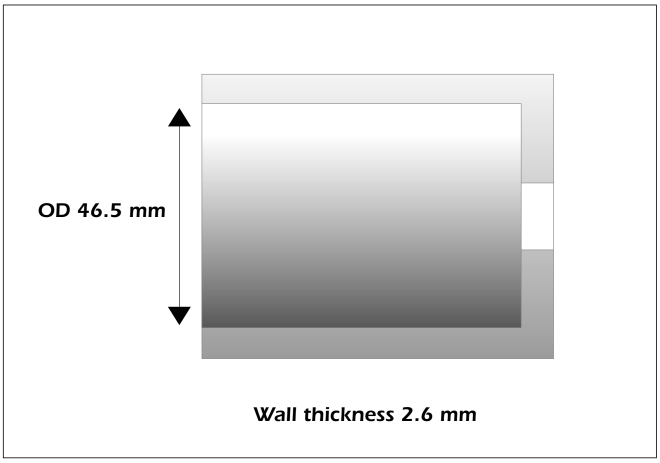


Figure 36 – Thin walled sleeve.

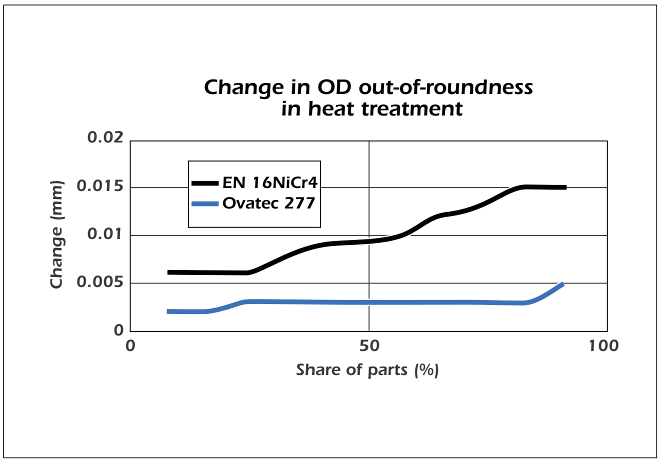


Figure 37 – Dimensional changes in case hardening for air-cooled Ovatec 277 and an oil quenched conventional carburising steel.

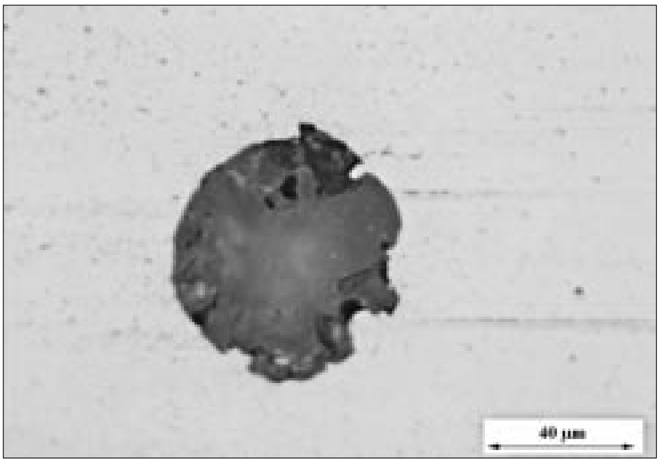


Figure 38 a – Calcium aluminates are potent potential fatigue initiators.

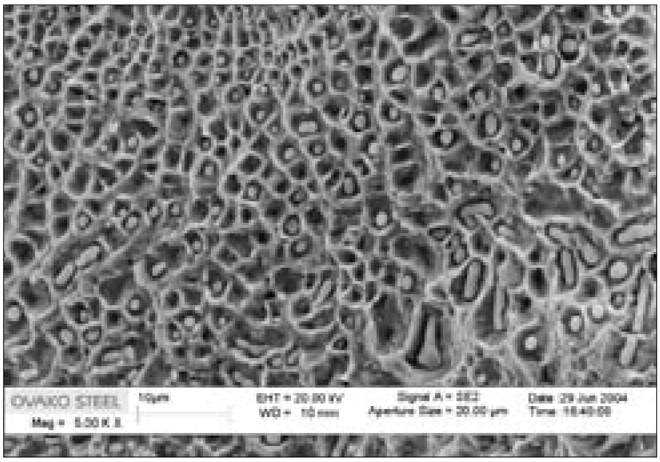


Figure 38 b – Manganese sulphide inclusions on a fatigue fracture surface.

bearing races are very similar and very often emanate from hard, oxidic, non-metallic inclusions, *Fig 38a*. Sulphide inclusions seldom initiate fatigue on their own, but sulphide stringers aid fatigue crack propagation, and in high resolution SEM analysis it can be clearly seen that the fracture front uses even very small sulphides in the propagation process, *Fig 38b*.

Gears have teeth roots which are difficult to finish properly and this leads to a situation where it often is the gear roots that initiate bending fatigue failures starting from surface defects as remaining scratches from the tooth milling, or from grain boundary oxidation generated in the carburising process. To maximize the fatigue resistance of gears it thus is of high importance to ensure that the teeth roots do not initiate the fatigue failures. To address this problem one needs to minimize the amount of internal oxidation and to ensure that the root

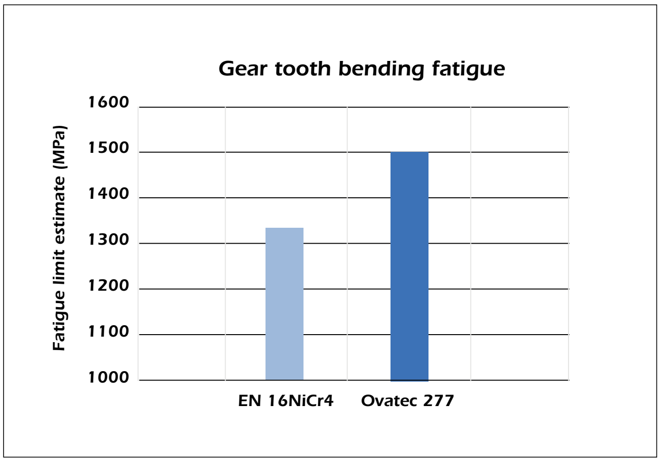


Figure 39 – Gear tooth bending fatigue of Ovatec 277 and a conventional carburising steel grade.

surface region has a compressive stress situation, which enhances the surface resistance to fatigue initiation. The internal oxidation can be combated by selecting an alloy composition, which is robust and resists the oxidation process, and by selecting a carburising environment, which provides a very low oxygen activity, as in low-pressure carburising.

If root teeth bending fatigue life can be extended, internal cleanliness of the steel becomes a significant issue. Once the fatigue initiation and fatigue crack growth has been moved sub-surface, the freedom from inclusions becomes the main issue.

Tooth bending fatigue

To try to understand the mechanisms of the fatigue initiation and fatigue life affecting parameters a direct comparison was made between three different steel and heat treatment variants in pulsating tooth bending fatigue of the same slim gear wheel discussed above as regards distortion.

The standard case hardening steel and Ovatec 277, both carburised in the same way, were tested in pulsating bending fatigue at the Institute for Metals Research in Stockholm (SIMR) in the as case hardened condition. To try to evaluate the influence of a standard carburatisation on gear root teeth performance, two variants of Ovatec 677 steel were also produced, and in this case the gears were through hardened utilizing a fast, magnetic through heating process. This means that no internal oxidation is obtained. After the air-hardening of the Ovatec 677 gears, half of the lot was subjected to shot peening while the second half was left in as-hardened condition.

Fig 39 shows the fatigue lives of the standard case hardened steel and the open-air hardened Ovatec 277 steel. Evidently, the Ovatec 277 steel, also when allowed to cool without any protective atmosphere provides a higher life expectancy than the conventionally quenched product.

Fig 40 shows the results obtained on these two variants together with the results attained with the through-hardened Ovatec 677 gears produced. Evidently, totally avoiding internal oxidation, as in the not shot peened Ovatec 677 variant does not enhance fatigue life, the life expectancy of the not-shot peened Ovatec 677 clearly is lower than for any case hardened variant.

However, when combining a short cycle through hardening (giving virtually no internal oxidation) with a shot peening providing the same level of surface compressive residual stresses as normally is achieved in case hardening, the through hardened variant outperforms the case hardened variants.

To ensure that no change occurred in the failure mode of through hardened gears occurs when moving from case hardened to through hardened gears occurs, back-to-back gear fatigue tests were performed at the Design Unit at Newcastle University.

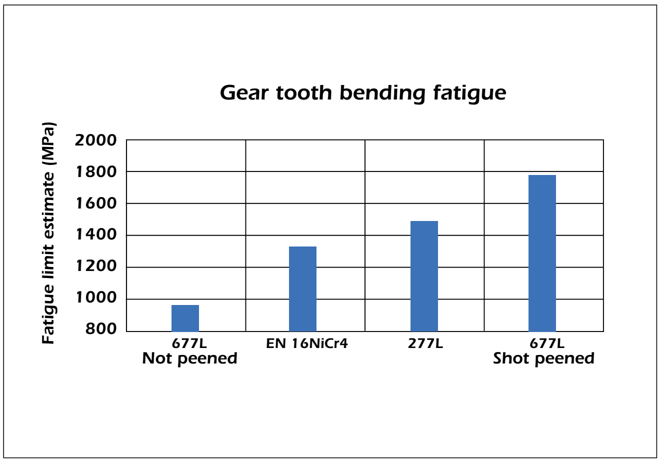


Figure 40 – A comparison of the fatigue lifes of a slow cooled Ovatec 677 through hardened steel, and air-hardened Ovatec 277, and an oil quenched conventional carburising steel.

The back-to-back tests showed that the lives of through hardened Ovatec 677 gears were at least on par with what is achieved with corresponding gears made out of case hardening steels, *Fig 41*, and that the likelihood of tooth breakage did not increase.

In another test, Ovatec 277 was compared to a standard case hardening steel in a direct performance test. The pinion gears used for the test were manufactured on the same machines (giving a very noticeable advantage in surface characteristics to the Ovatec gears produced) and run against each other in a test bench.

The load was sequentially increased until failure occurred, and on the end of testing, the gears were examined. The standard steel gear was totally broken; all the teeth had broken off, while the Ovatec 277 gear had the appearance shown in the section in *Fig 42*. Very evidently, the Ovatec products can take a very severe beating without suffering really substantial damages.

Nitridning and related processes

Nitriding is normally carried out in the temperature range 500-570° C, which is below the austenitising temperature of steel, nitriding is carried out in the ferritic condition. Owing to the low temperature, distortion is minimised as no structural transformations occur. Nitriding is time consuming, and often nitriding is carried out for 20-60 hours. Prior to the nitriding standard steels are hardened-and-tempered. The nitrided parts develop a compound layer and immediately below it a diffusion zone. The compound layer is a thin, non-etching, white layer that consists mainly of nitrides. The diffusion zone is deeper and consists of the base material and diffused nitrides.

Tests made and experience from production show that Ovatec 277 performs very well in all nitriding operations. As regards attainable hardness it even exceeds steels specially developed for nitriding applications, and compared to standard carburising and quench-and-temper steels signifi-

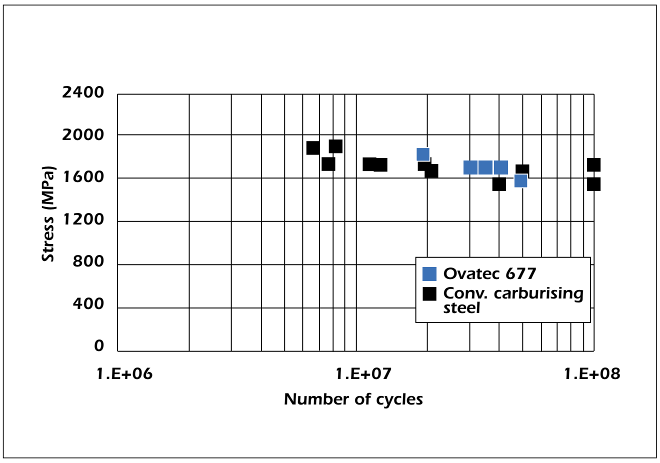


Figure 41 – Stress against number of cycles to failure for Ovatec 677 and a conventional carburising steel.

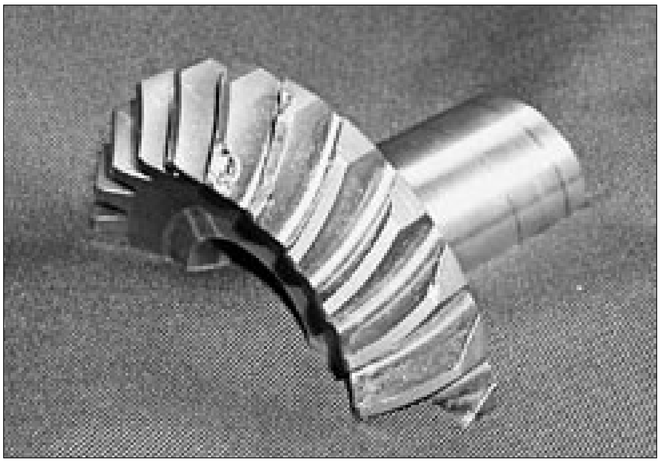


Figure 42 – The gear manufactured of Ovatec 277, which did not break when all the teeth of the opposite gear fractured.

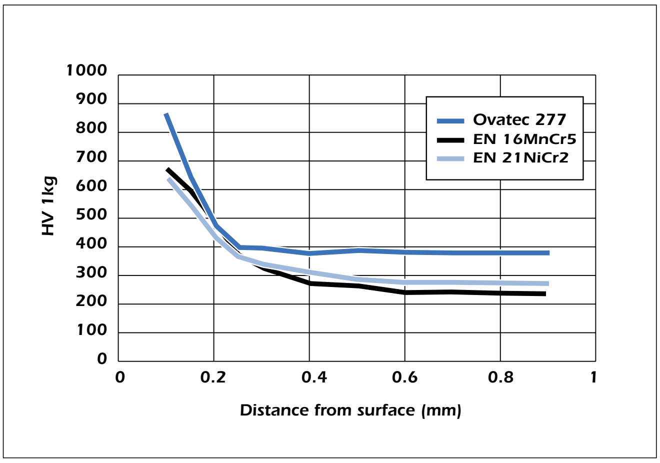


Figure 43 – Hardness profiles after gas nitriding of Ovatec 277 and two conventional carburising steels.

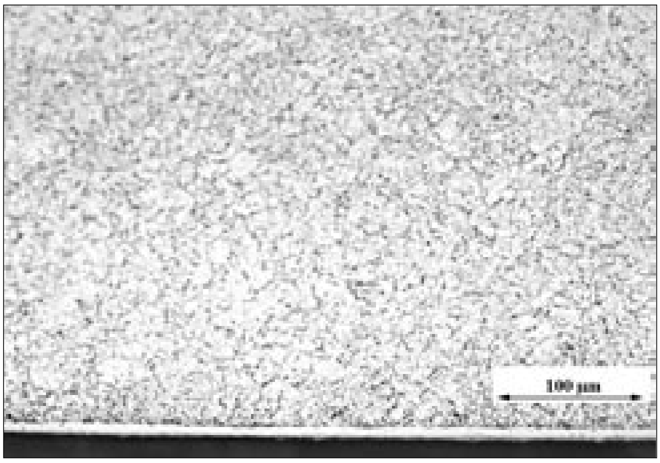


Figure 44 – The microstructure of gas nitrided Ovatec 277. The core is tempered martensite and then a diffusion zone and closest to the surface is the compound layer.

cantly higher surface hardnesses and depths can be achieved.

Gas nitriding

During gas nitriding the nitrogen is introduced to the steel surface by a gaseous atmosphere, usually ammonia. In one test, gas nitriding was performed on Ovatec 277 and standard carburising steels at 510° C for 50 hours; *Fig 43* shows the surface hardness profile obtained.

Fig 44 shows the microstructure of the gas nitrided Ovatec 277 with the compound layer and the diffusion zone.

Plasma nitridning

Plasma nitriding uses a glow discharge technology, where high-voltages are used in a vacuum to form a plasma wherein nitrogen ions are accelerated to impinge the steel surface.

Plasma nitriding has been tested on Ovatec 277 in comparison to a harden-and-temper steel, Ovako 327 and two carburising steels, Ovako 146 and Ovako 234. The plasma nitriding was performed for 15 hours at 490° C. *Fig 45* shows the hardness profiles for the steels after the plasma nitriding. *Fig 46* shows the microstructure of the plasma nitrided Ovatec 277.

Nitrocarburising

Nitrocarburising is a modified process of nitriding where carbon is added to the atmosphere. The steel is processed in the ferritic state. A compound layer is developed at the surface, which consists of iron carbonitrides and nitrides, and beneath it a diffusion zone and then the core. Nitrocarburising is usually performed at a temperature somewhat higher than nitriding temperatures, about 570° C.

A comparison has been done between Ovatec 277 and a harden and temper steel, Ovako 327 and two carburising steel grades, Ovako 146 and 234. The nitrocarburising was performed at 565° C for four hours. *Fig 47* shows the hardness profiles.

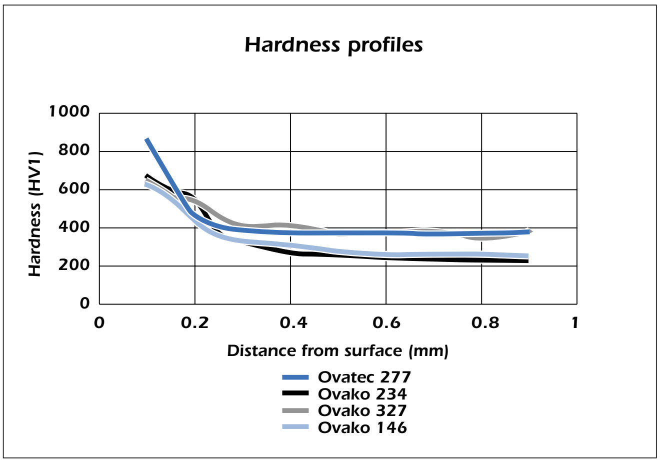


Figure 45 – The hardness profile after plasma nitriding of Ovatec 277 and some conventional steels.

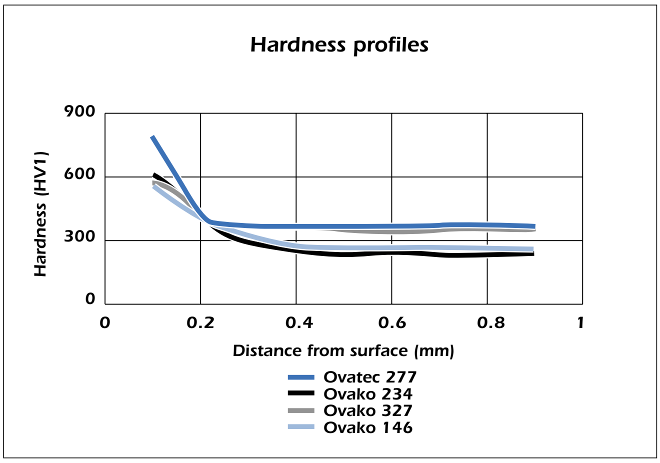


Figure 47 – The hardness profiles after nitrocarburising of Ovatec 277 and some conventional steels.

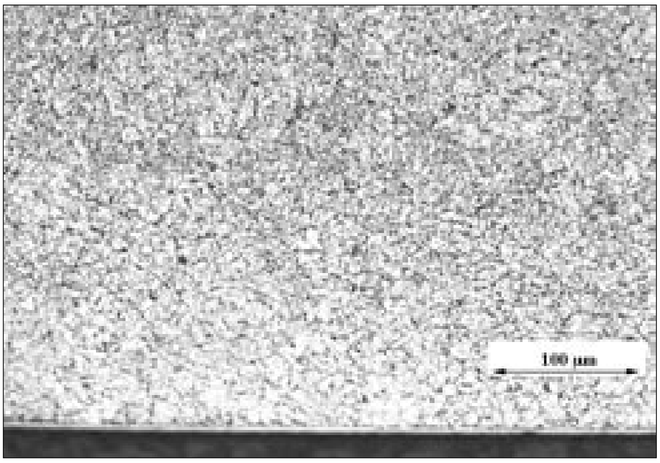


Figure 46 – The plasma nitrided microstructure of Ovatec 277.

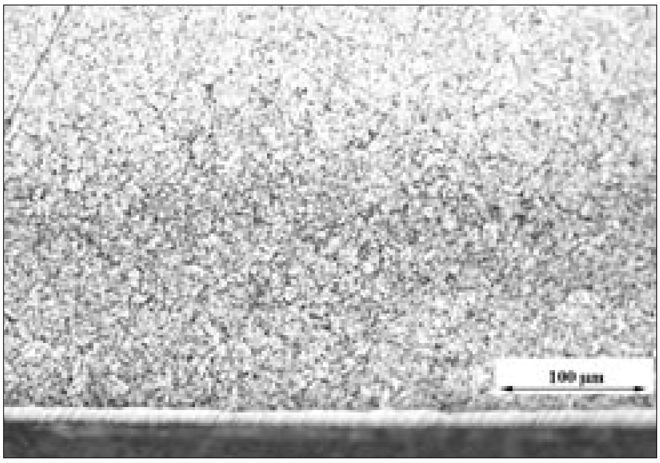


Figure 48 – The nitrocarburised microstructure of Ovatec 277.

Fig 48 (on the previous page), shows the microstructure after nitrocarburising of Ovatec 277.

<u>*Carbonitriding*</u>
Carbonitriding is a form of carburising process where nitrogen is added. The process temperature is in the austenite range as in carburising. Due to the hardenability of Ovatec 277 it is possible to cool slowly and thus reduce distortion in quenching. Nitrogen is an austenite stabiliser just as carbon and due to the increased hardenability of Ovatec 277 it is recommended to keep the carbon and the nitrogen activities lower than for conventional steels during carbonitriding to avoid excessive retained austenite contents.

Summary

Ovatec 277 has proven to be a very versitile steel providing benefits in a number of applications.

By combining strength and metallurgical cleanliness, high performance can be attained, often at reduced total costs due to its unique processing capabilities.

Today, it is a standard product in the Ovako Steel product range in both variants – Ovatec 277L and Ovatec 277Q.

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