

Fundamentals of:



Heat Treatment of Steel

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1 – INTRODUCTION

Heat treatment is a process that has been used for thousands of years to increase the hardness and strength of steel. Over time, several different heat-treatment operations have emerged with very different characteristics and aims.

In general, it is possible to differentiate between heat treatments intended to make the steel "softer" (reducing hardness and eliminating stresses) and those that make steel "harder" (increasing the hardness at the surface or over the whole cross-section).

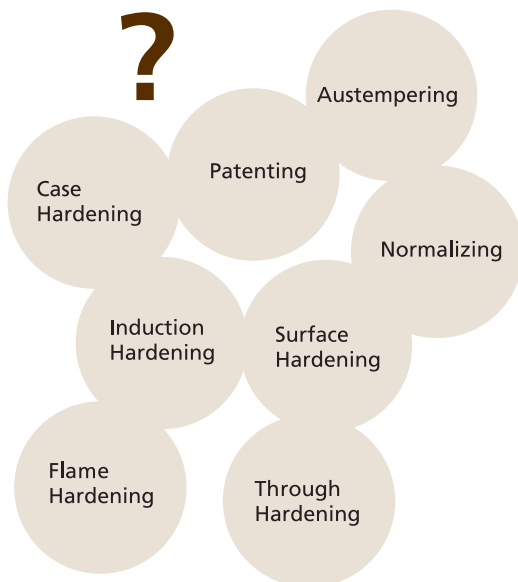


Figure 1 – Furthermore, some terms appear to lack any basis in reality: Case-hardening (which case?), patenting (which patent?), normalising (what's normal?), tempering (tempering what?).

In the same way as with steel grades, the classification of heat treatment methods is very inconsistent in the general technical terminology used. One classification system for heat treatment methods is based on the method used (induction-hardening, flame-hardening), another is based on how much of the cross-section is changed (surface-hardening, through-hardening), a third system is based on the resulting product (martensite-hardening, austempering).

The basis for describing what happens during most forms of heat treatment is found in the changes which occur in iron (Fe) when its temperature or carbon content are changed.



Figure 2 – A description of the heat treatment methods often applied to our products.

There is a strong relationship between the steel grade and the heat treatment, but often the same type of heat treatment can be used on many different steel grades. It is not possible to case-harden ball-bearing steel but both ball-bearing steel and hardened and tempered steel can be tough hardened. However, it is easy to case-harden structural steel and hardened and tempered steel as well as carburizing- steel. Therefore, the choice of steel grade, combined with heat treatment, provides a very large degree of freedom.

There is only one important consideration that applies: to achieve the minimum cost for the sum of the material and its heat treatment while ensuring that the finished product meets all its requirements.

To do this we must know:

- The demands on the product
- How the steel grade and heat treatment can be combined to meet these demands
- The combined costs of the steel and heat treatment

The important limiting factor is often the type of heat treatment equipment used by customers. Ovako's ability to supply the steel material is almost always greater than a customer's capability to combine machining and heat treatment.

It is vital never to forget the basic rule:

All forms of heat treatment are expensive, logistically difficult to handle and require stringent inspection.

Heat treatment is a necessary evil which should be avoided at all costs whenever possible. This can be done by:

- Always substituting high strength micro-alloyed steel for hardening and tempering.
- Always substituting through hardening or surface hardening (induction) for case hardening.
- Always substituting martensite hardening for austempering.
- Always substituting normalizing for soft annealing.

Naturally, in this context "always" means whenever the requirements demanded of the material can be met. Customers using our steels are often very conservative. It is never wrong to question a particular combination of heat treatment and steel grade. In fact, customers will often do this themselves at regular intervals.

2 – THEORY, PART 1

If a prepared sample of iron is magnified several hundred times under a microscope you will see that the metal is made up of irregular grains. Within each grain, the iron atoms line up in a specific pattern, called atomic lattices. This pattern is rectilinear and three dimensional, making it appear cubical. The corners of these cubes are made up of atoms and every corner atom is a part of eight separate cubes (elementary cells). In addition to the corner atoms, there are other atoms, whose quantity and position are determined by temperature.

At room temperature, for example, there is an atom in the center of each cube in addition to the corner atoms. That is why it is known as a body-centered-cubic (BCC) crystal structure). Iron with this type of BCC structure is called [ferrite](#).

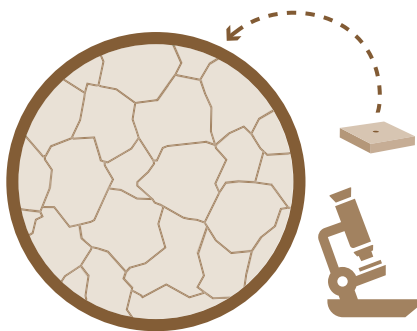


Figure 3 – Ferrite. Magnification x 200.

Ferrite is relatively soft. To reach a required hardness, an additive, usually carbon (C), is needed. Carbon atoms form a structural compound with iron called [cementite](#). In an unprocessed material, cementite forms thin flakes lying parallel and mixed with ferrite flakes.

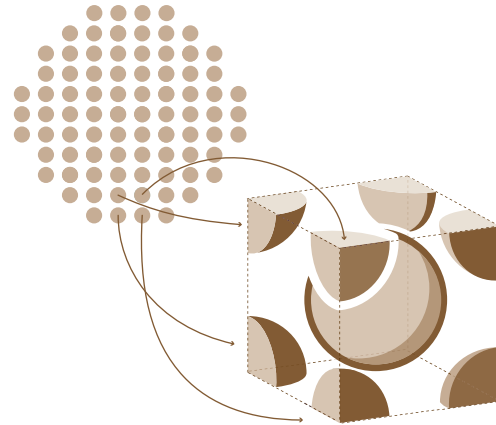


Figure 4 – Ferrite. Magnification x 100 million.

Cementite is hard and acts as a reinforcement that makes ferrite more rigid so that the hardness and strength are increased. The more carbon added, the more cementite is formed and the greater the hardness and strength. [Pearlite](#) is the aggregate of ferrite and cementite flakes.

Iron, with up to 2% carbon added, is defined as [steel](#). Silicon (Si) and manganese (Mn) are always found in ordinary carbon steel.

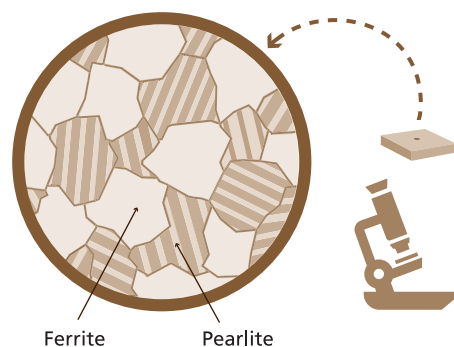


Figure 5 – Ferrite and Pearlite. Magnification x 500.

HEAT TREATMENT

The properties of steel can be changed in many ways by heat treatment. They include hardness, formability, machinability and strength.

Treatment for:

Improved toughness

The [toughness](#) of a non-alloy steel can be increased by heating the material to a temperature of 800-900°C followed by cooling in still air. At this point the grains are transformed and a smoother and more uniform structure is obtained. This process is called [normalization](#).

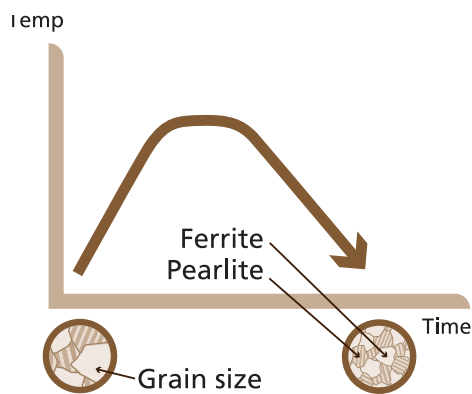


Figure 6 – Grain size transformation through normalization.

The cooling can also occur in stages, which affects the size of the ferrite and cementite flakes.

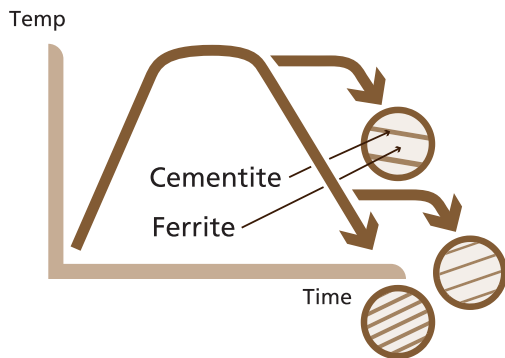


Figure 7 – Cementite depending on formation temperature.

Softer steel

If a softer steel is desired, heating is conducted at 700-800°C followed by gradual cooling. The cementite flakes contract at the high temperature and form nodules. This reduces the reinforcement effect and the hardness is lowered.

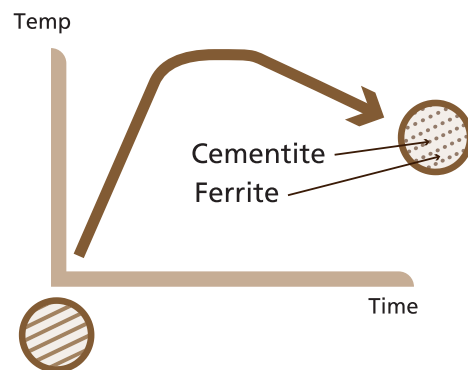


Figure 8 – Cementite globularization.

Process for greater hardness

Greater hardness and strength are obtained by heating the material above its “critical” range to temperatures between 800-1,000°C followed by rapid cooling. At the high temperature, a portion, if not all, of the cementite is dissolved and the carbon from the cementite is spread out in the ferrite lattice.

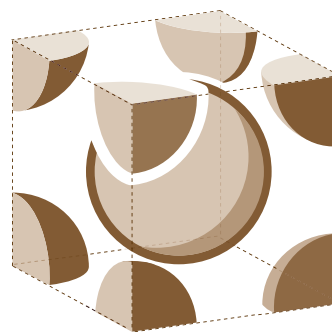


Figure 9 – Ferrite.

The iron atom lattice (the ferrite) is transformed in such a way that the iron atom previously located in the center of each cube in the lattice disappears. Instead, an atom is now located in the center of each side of the cube, resulting in a face-centered cubic (FCC) crystal structure. This FCC crystal structure is called [austenite](#).

The distance between the corner atoms is greater in austenite than in ferrite. The carbon atoms which previously could not fit between the corner atoms, now find room in the larger space.

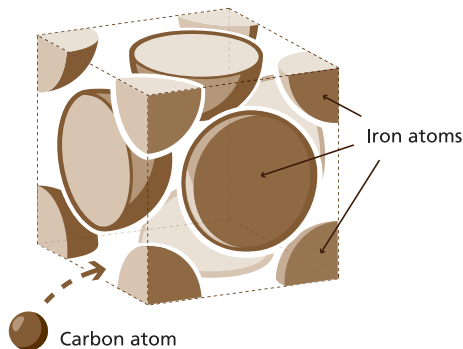


Figure 10 – Austenite.

When cooled, the iron atom lattice returns to the same pattern as it had before being heated. If the cooling occurs rapidly enough, the carbon atoms become firmly locked between the iron atoms in spaces which again become too small for them.

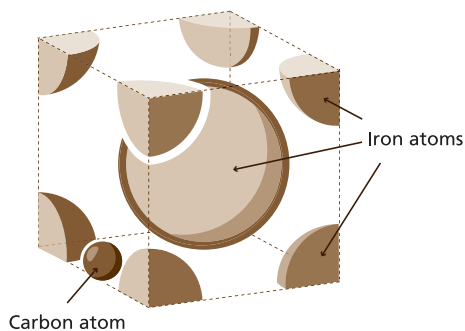


Figure 11 – Martensite.

At this point, the carbon atoms push the iron atoms apart so that the previously rectilinear pattern is disarranged. This causes pressure within the material resulting in significant increases in hardness and strength.

The toughness in the [martensite](#) (the transformation product of austenite) is low, so low in fact that reheating to 150-650°C must be carried out so that the carbon atoms become more easily movable and a portion of them can leave their firmly held positions and re-form the harder compound of cementite. This heat treatment process is called [hardening and tempering](#). As with unprocessed steel, a higher carbon content causes an increase in hardness.

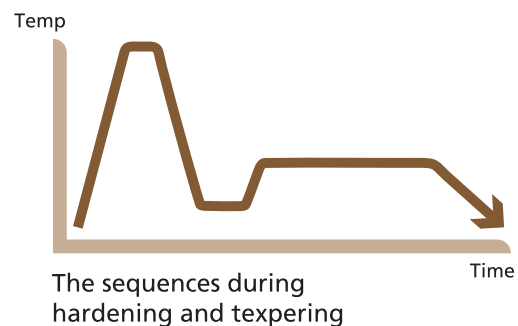


Figure 12 – Heat treatment sequence.

If steel is alloyed with a material other than carbon, then approximately the same hardness values are obtained as with a single carbon alloy steel - if the cooling process in both cases occurs in water. This is because the usual alloying atoms cannot space themselves between the iron atoms, but instead must replace the iron atoms in their places in the corners of the cubes. There is therefore less disorder arising in the lattices. The usual alloying elements, such as chromium (Cr), nickel (Ni) and molybdenum (Mo) however, affect the ability of the carbon atoms to leave the spaces between the iron atoms. The more alloyed the steel is, the slower it can be cooled to prevent the iron atoms from roaming out of the ferrite lattice and allowing the ferrite to re-establish its natural low hardness. Certain alloying materials, such as chromium and molybdenum are included in the matrix (the ferrite or the martensite) and in the cementite and form carbides. These carbides contribute to the steel's durability. Other alloying materials, such as nickel and manganese, are only included in the matrix.

3 – ANNEALING

STRESS RELIEVING ANNEALING

A steel which is subjected to cold forming or which is rapidly and unevenly cooled from a high temperature contains "internal stresses". This means that there are tensile stresses in certain areas of the material and compressive stress in other areas. These stresses can be removed by stress relieving annealing at 500-600°C for a few hours with subsequent cooling in the furnace or in the air.

The larger the size of the material, the longer the time required. No structural changes occur, neither are there other changes in respect of strength properties. The surface is oxidized only to an insignificant extent.

Stress relieving annealing is used in cases such as long axles, which must not buckle, especially if the basic material is cold drawn or cold straightened. Also, after normalizing of intricately designed steel ingots and, sometimes, after rough turning, which can also introduce stresses into the material. Welding also often requires stress relieving annealing,

When stress relieving annealing is combined with normalizing, the material is allowed to cool to about 600-700°C in air. Afterwards, the material is placed in a furnace at 500-600°C and is allowed to cool to room temperature within the furnace.

RECRYSTALLISATION ANNEALING

Material subjected to cold forming, such as cold rolling, deep drawing or other similar working operations, hardens because of the deformation of the structure. Recrystallisation annealing is used to make hardened material soft again. As indicated by the term, the annealing process is adapted in such a way that the material is subjected to recrystallisation. During this recrystallisation, new non-deformed grains develop and replace the old ones. The temperature is generally about 650°C – which is around 50°C above the recrystallisation temperature. The soaking time does not need to be longer than that required to thoroughly through-heat the entire material. In cases in which a certain amount of spheroidization of the carbide phase is required (which for example is common in the case of cold-rolled strip), a higher temperature and longer soaking time are required.

In general, alloyed steel has a somewhat higher recrystallisation temperature than unalloyed steel. The annealing temperature is therefore correspondingly higher.

Apart from being affected by the earlier grain size, the grain size resulting from recrystallisation annealing also depends on the degree of cold working and the annealing temperature. In cases in which very strict demands are made to achieve a certain grain size, the cold-forming process prior to annealing must be carefully adapted. In general, however, it is sufficient if the degree of cold forming is so great that no larger grain size is obtained. In special cases in which a larger grain size is desired, the degree of reduction before annealing is selected to be as close as possible above the critical level. After the completion of recrystallisation, the material undergoes grain-size increase during further heat treatment. Normally, the growth in grain size is so slow that it is of little importance. The soaking time at full heat should not, however, be unnecessarily long.

ISOTHERMAL ANNEALING

Isothermal annealing is a process that heats the steel above its upper critical temperature so that its structure is converted rapidly into austenite. It is then cooled to a temperature below the lower critical temperature (A_1), about 650°C , and held at this temperature for a considerable time.

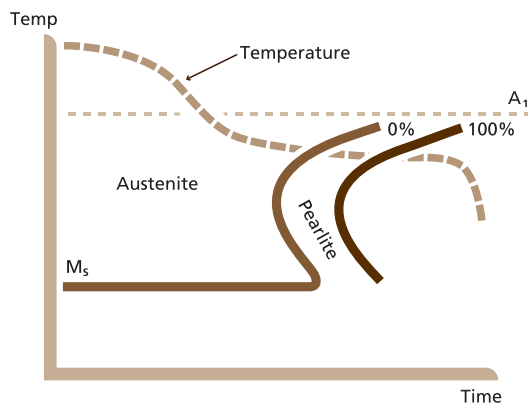


Figure 13 – Isothermal annealing.

After isothermal annealing, the structure consists of ferrite and pearlite. For practical reasons, isothermal annealing cannot be performed in a conventional muffle furnace since its tremendous heat content does not permit a rapid temperature reduction. Instead, two muffle furnaces or a continuous furnace with varying temperature zones are used.

Isothermal annealing is usually performed on an alloyed carburizing steel. The reason for performing isothermal annealing is to obtain a more uniform structure for mechanical machining (a mixture of ferrite and pearlite with a blocky structure – scharz weiss fuge). In addition, any deformations are reduced during subsequent carburizing.

SOFT ANNEALING

Lamellar pearlite is hard and brittle. A steel with a high degree of lamellar pearlite is therefore difficult to machine with cutting tools, such as in turning or milling. Furthermore, it cracks easily during cold forming operations such as pressing. These drawbacks can be counteracted by soft annealing.

Hypoeutectoid steel is heated to a temperature just below A_1 and is held at this temperature for a long time. The carbon in the pearlite can then diffuse through the ferrite and the cementite is transformed from the lamellar form to a more or less globular form, called spheroidized cementite. The cooling rate is unimportant.

Hypereutectoid steel is heated to a temperature just above A_1 , usually for 2 to 4 hours. The pearlite is then transformed into austenite, although the transformation is not complete. Extremely small residues of the pearlite's cementite are left. The grain boundary cementite is transformed into globular cementite grains in the same way as the pearlite cementite during soft annealing of hypoeutectoid steel. The steel is then allowed to cool down slowly (usually at a rate of 5 to $30^{\circ}\text{C}/\text{hour}$) to about 600°C , and the austenite is transformed into ferrite and cementite. The cementite crystallizes on the remains of the existing carbides.

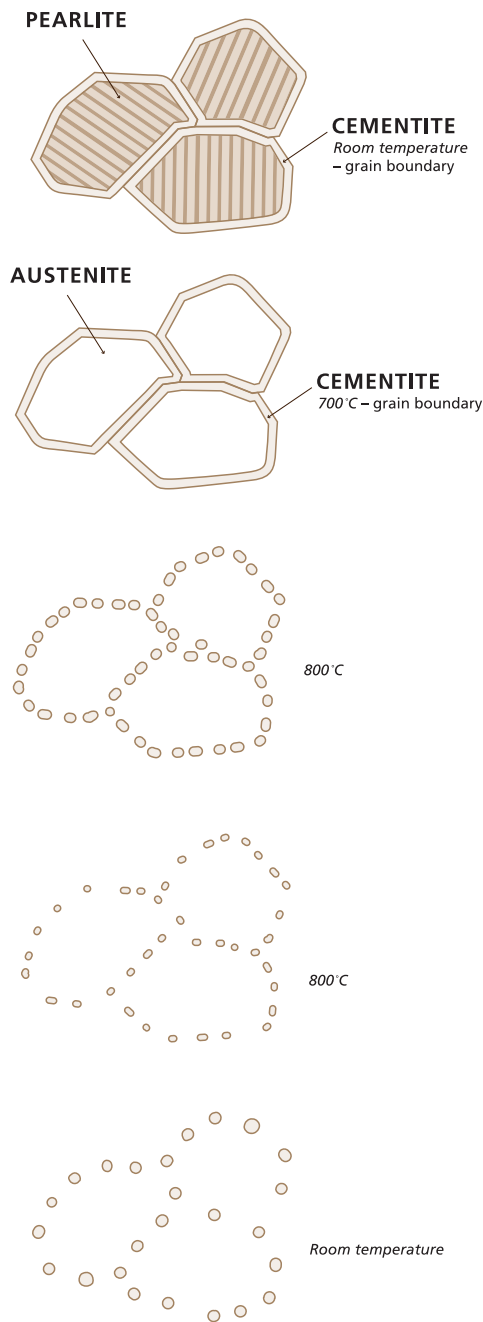


Figure 14 – Soft annealing of 1 % Carbon steel.

During soft annealing the hardness, yield stress limit and tensile stress limit are reduced while elongation and contraction increase.

Soft annealing is used primarily for steel with higher carbon contents, intended to be machined with cutting tools and then hardened. Almost all carbon steels with carbon contents above 0.6% are supplied soft annealed from the mill.

Carbon steel with less than 0.55% carbon is soft annealed only in exceptional circumstances, since these are, in any case, quite easily machined in a hot rolled condition.

At a carbon content less than 0.4% soft annealing is undesirable in most cases. The difference between soft annealing and normalizing is shown schematically in the figure which shows the ultimate strength and the yield stress limit as functions of the carbon content for carbon steel.

Ovako soft anneals all high carbon content steels (for example ball bearing steel) in continuous furnaces prior to delivery.

The development of annealing cycles for a particular material requires great care to ensure optimum results.

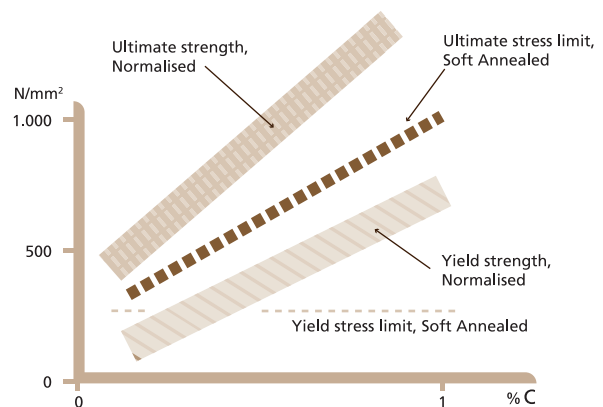


Figure 15 – Mechanical properties in soft annealed steel depending on carbon content.

4 – NORMALIZING

Normalizing a steel means heating it to the austenite range followed by uncontrolled cooling in air. Normalizing involves a double crystal transformation in the structure. During heating the structure is transformed into austenite and during cooling, ferrite and carbide are reformed. The structure becomes pearlitic with excess ferrite in hypoeutectoid steel and excess carbide in hypereutectoid steel.

The double transformation eliminates unsuitable structures, such as large grain size and/or streakiness as the material is given a "normal" structure corresponding to its composition.

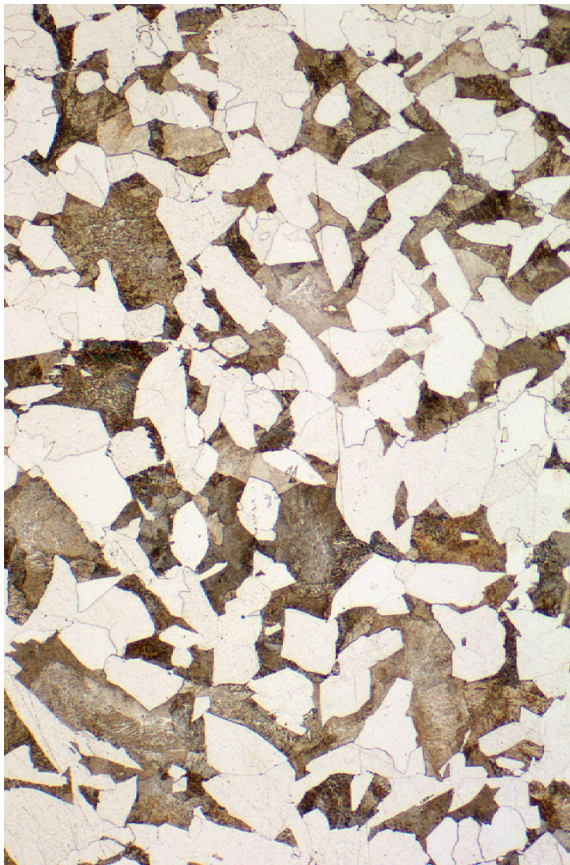


Figure 16 – Hot rolled 20MnV6.

High carbon steels are not often normalized. In order to achieve good formability and a suitable structure for heat treatment, soft annealing is used instead.

In normalizing, the material is heated to the austenitizing temperature and is kept at that temperature for about 10 to 20 minutes and afterwards allowed to cool freely in air. For conventional steel (20MnV6) the normalizing temperature is 980°C.

Following normalization, a conventional structural steel receives a fine grain size and high toughness. This enables the impact strength of S355 and 20MnV6 steel to be better than 27J at temperatures down to -60°C.

Normalizing is sometimes used to break down the carbide network in carburized surface layers in connection with case hardening.

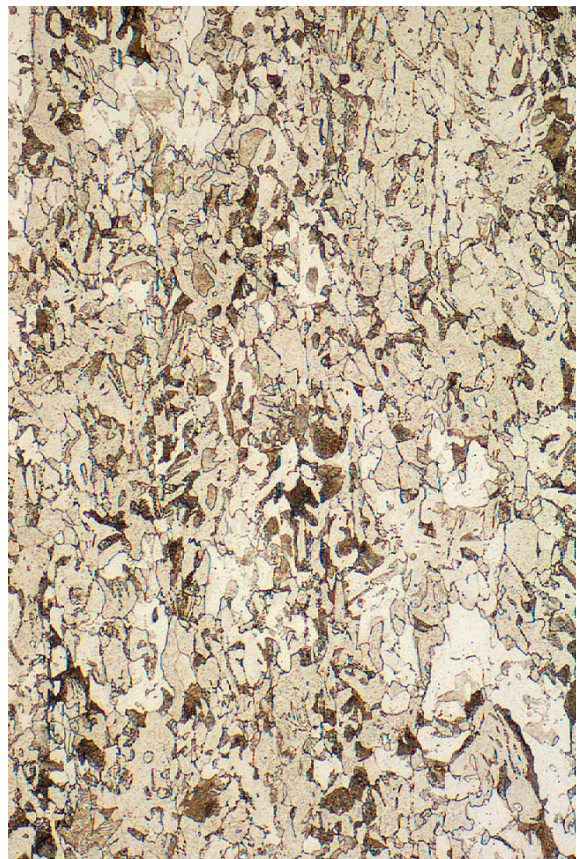


Figure 17 – 20MnV6 Normalized.

5 – PATENTING

Patenting is a form of heat treatment designed to attain a structure of very fine pearlite in the steel.

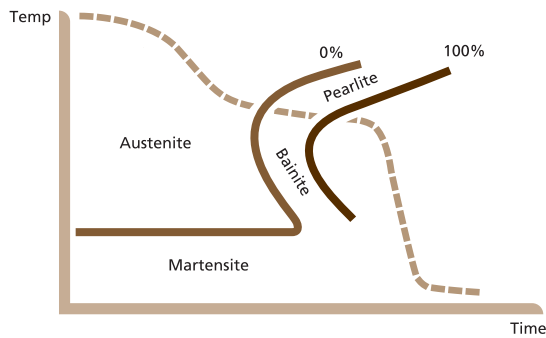


Figure 18 – Patenting.

After austenitizing the material is cooled in a lead bath to about 500°C and is kept at that temperature until the transformation is complete. Unalloyed or low-alloyed steel with carbon contents of about 0.6 to 1.1% are the principal types used in patenting.

Despite a relatively high ultimate strength, patenting results in a good degree of toughness and machinability for drawing. Patenting is used primarily for wire which after the process can be cold drawn with large reductions.

In patenting, it has been shown to be appropriate to perform austenitizing at comparatively high temperatures, so that a somewhat coarse austenite structure is attained. In this way a smaller grain boundary area is obtained and fewer starting points for pearlite formation since the process proceeds more slowly. Pearlite formation is shifted towards lower temperatures which result in finer structures.

The treatment used in EDC cooling of wire produces a result which corresponds well to "conventional" patenting.

6 – HARDENING

CASE HARDENING

Case hardening produces a hard, highly resistant surface layer and a tough core. After case hardening the surface layer contains substantial compressive stresses. Case hardening is often used for applications in which the loading produces high surface pressure in combination with fatigue stresses.

Case hardening consists of two separate treatment stages. Sometimes they are performed in direct succession. In the first stage some form of carbon is added to the surface layer of the material. In the second stage hardening is performed.

Background

In case hardening low-alloyed steel is often used, the carbon content is usually 0.15 to 0.25%. In principle, all steels with carbon contents less than about 0.8% can be case hardened, but many of the advantages of case hardening then disappear.

Carburizing involves the addition of carbon to the surface layer of the material. The thickness of the carburized surface layer is controlled by the diffusion of the carbon in the austenite, which is the structure the material has during carburizing (850 to 950°C).

The diffusion speed is roughly dependent on temperature and time. The carburizing depth attained can be calculated approximately as:

$$X = k \cdot \sqrt{t}$$

in which

X = case-hardening depth (mm)

t = time in hours

k = is determined by the temperature

Temp. °C	k
875	0,34
900	0,41
925	0,52

After carburizing, the carbon content varies as shown in the figure, and after hardening the hardness achieved is therefore a function of the distance from the surface.

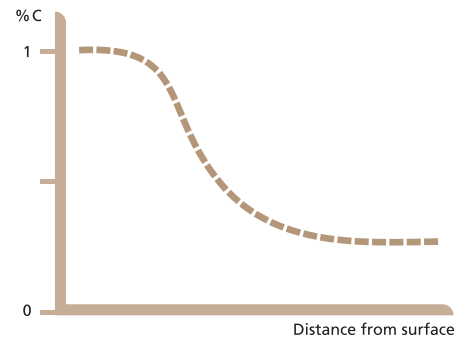


Figure 19 – Carbon content – Surface distance.

The load which the component will be subjected to determines how large the in-carbonization depth (depth of hardness after hardening) needs to be. The tooth face of a cog, for example, which transfers a certain load undergoes a strain which varies with the depth under the surface, as shown in the figure. The case-hardened layer must then be provided with a strength profile which at every point, from the surface to the core, corresponds to the load applied.

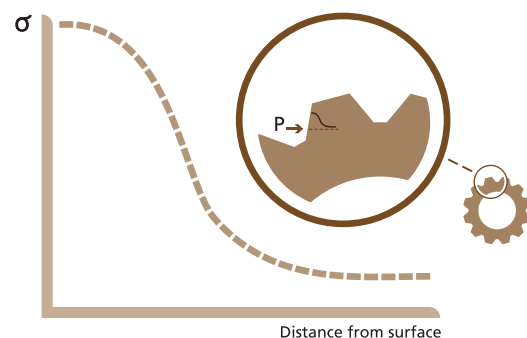


Figure 20 – Stress – Surface distance.

Carburizing

The processing stage in which carbon is added to the surface of the material is called carburizing or in-carbonization. In-carbonization occurs at high temperatures which can result in substantial grain growth. This grain growth can be effectively counteracted by using fine-grain treated material.

Occasionally, the material is normalized after carburizing. At present, three different methods are used to add carbon. Common to all methods is that the material used to envelope the material has a relatively high carbon content - to simplify matters it can be said that the surrounding material has a carbon content of about 1%.

The carbon in the surrounding atmosphere is absorbed relatively fast by the surface at the carburizing temperature, and the carbon then diffuses from the surface towards the core. Gas carburizing is not really the correct term to use as carburizing is always performed via a gas phase. What is meant by gas carburizing is that the carbon discharging agent is supplied to the furnace in the form of a gas. There are several methods of doing this, either a gas with a high CO content is generated by complete combustion of some hydrocarbon material, or some hydrocarbon (which evaporates) is cropped into the furnace.

[Gas carburizing](#) is the most common method used on an industrial scale and it offers major advantages from the standpoint of productivity and control.

[Salt bath carburizing](#) is performed in a cyanide salt and is most often used when a relatively small in-carbonization depth is required.

[Powder carburizing](#) is done by placing the component in a container packed with powder which is made up of a compound of wood carbon and barium carbonate. The process requires extensive manual handling.

Hardening

There are three different ways of hardening carburized material, and there are also variations on these methods.

[Direct hardening](#) entails hardening the material directly from the carburizing temperature. This means that the austenitizing temperature is extremely high and that the result will be a coarse structure, particularly in the high-carbon-content surface. This method is seldom used.

Direct hardening can also entail the rapid cooling of the material to suitable austenitizing temperatures for the high carbon content surface zone (620 to 850°C) after carburizing. The temperature is allowed to become uniform throughout the component, and it is subsequently hardened to martensite. This means that the core material does not receive correct austenitizing.

Direct hardening is very common among component manufacturers such as in the automotive industry.

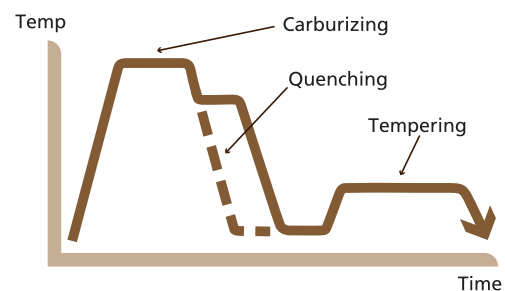


Figure 21 – Direct hardening.

Single hardening means that the material is cooled to room temperature without permitting martensite to form. Afterwards conventional austenitizing and martensite hardening are performed. Austenitizing is undertaken to attain optimum results in the surface zone.

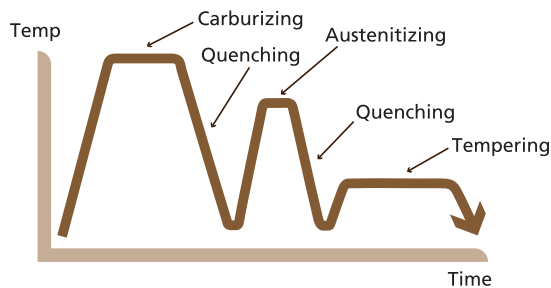


Figure 22 – Single hardening.

Double hardening means that the material is direct hardened after carburizing and afterwards undergoes conventional martensite hardening.

In general case hardening results in higher degrees of residual martensite than through hardening. Direct hardening, following the adaptation of the hardening temperature, has become increasingly common and imposes considerable demands on the grain growth of the material.

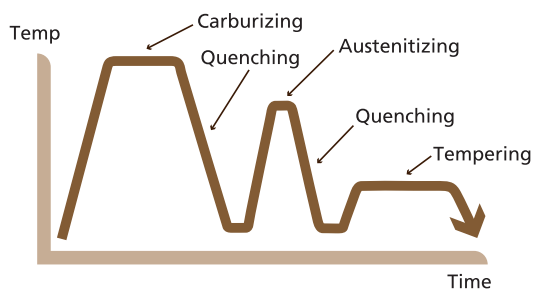


Figure 23 – Double hardening.

HARDENING AND TEMPERING

Hardening and tempering comprises two stages.

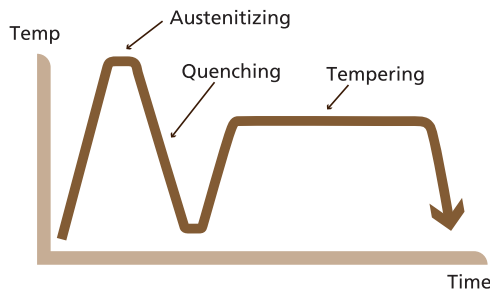


Figure 24 – Hardening and tempering.

The primary stage entails conventional martensite hardening. The second stage is tempering which is usually undertaken in the temperature range 500 to 650°C.

Tempered material is often surface hardened in order to attain a high surface hardness in combination with a tough and strong core. [Hardening](#) is performed in the normal manner in martensite hardening.

Austenitizing is adapted to the alloying content of the material, and quenching is done in oil or water, depending on the hardenability.

[Tempering](#) is performed at a high temperature, which means that the formation of martensite regresses considerably towards ferrite and cementite. Since tempering never occurs at temperatures in the proximity of the transformation temperature, pearlite cannot form.

Tempering offers good possibilities for adapting strength to toughness. Hardness is selected to permit the satisfactory machining of the material with metal cutting tools. The degrees of hardness are normally within the range of 180 to 400 HB.

Many years ago, a hardness of 330 HB was estimated to be the highest level for tempered steel to be machined with cutting tools. Machining methods have progressed since then and the limit has been pushed upwards.

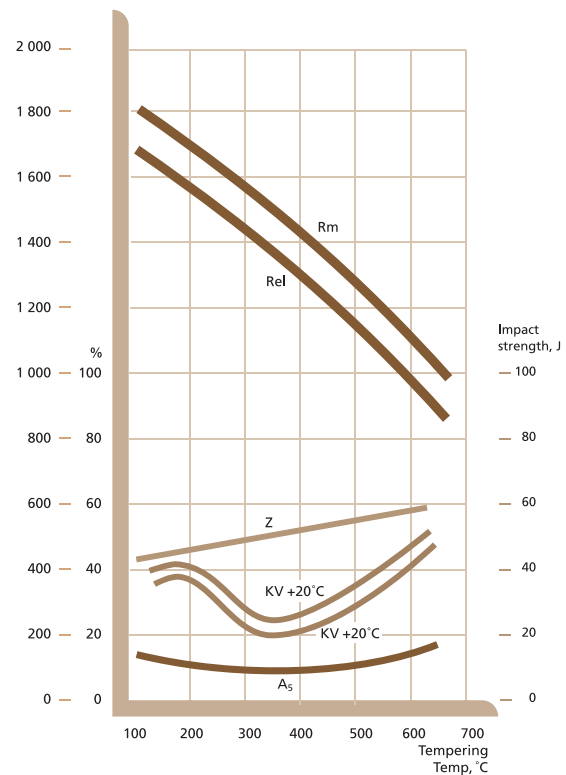


Figure 25 – Tempering diagram 34CrNiMo6. Testrod – 35 mm, hardened in oil from 860°C.

Furthermore, there is always a minimum limit to the sulfur content in hardened and tempered steel, which offers a controlled amount of sulfide-type micro-inclusions, which are beneficial for machining purposes.

Hardening and tempering is often performed by the steel manufacturer. Different heat treatment equipment can give different hardening and tempering results regarding the consistency in strength and internal stresses.

Hardening of bars in bundles or layers results in increased crookedness during hardening and requires more powerful straightening (resulting in increased stresses) than single rod hardening during rotation.

If there are stringent demands on straightness and freedom from stresses, stress relieving annealing is performed after tempering and straightening. This applies to special material, for rifle barrels, for instance, as well as axles with stringent straightness requirements which are to be induction hardened.

MARTENSITE HARDENING

Martensite hardening is the most common hardening method in use.

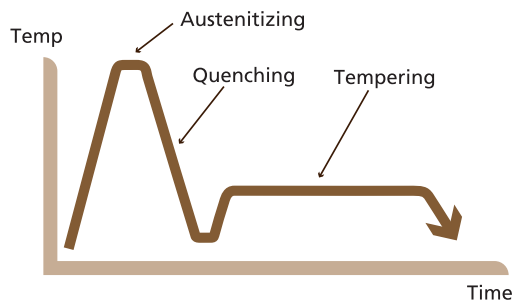


Figure 26 – Martensite hardening.

Martensite hardening comprises two stages, austenitizing and quenching. Austenitising is applied in accordance with the composition of the material. Quenching is determined by several factors.

To permit martensite hardening, the cooling rate must be sufficiently high in order to avoid the formation of pearlite and bainite. The critical cooling rate depends on the composition of the steel and on austenitizing.

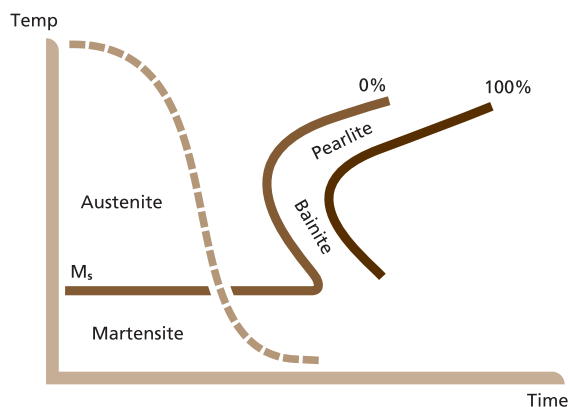


Figure 27 – Martensite hardening.

The usual cooling media used in hardening are water, oil and salt. Water is the most powerful cooling media and is often used with an addition of salt or some polymer (Aqua-quench) to further increase the cooling rate. However, the cooling rate can become so high that the risk of distortions (changes in shape) and cracks is very great. Water hardening is used only for basic shapes and low-alloyed steel.

[Oil](#) is the most common cooling medium used in hardening and has a powerful cooling capacity. There are a great number of different hardening oils offering various cooling characteristics. Oil provides a sufficient cooling rate for most applications.

A [salt bath](#) is often used with a temperature about 150 to 200°C and provides rapid cooling, but a rather soft martensite formation. When the geometry of the component is complicated or when there are stringent requirements for distortion and warping, martempering is used.

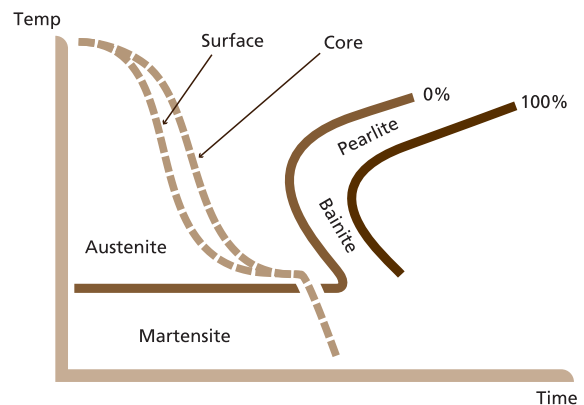


Figure 28 – Martempering.

In martempering there is rapid cooling to a temperature above M_s , the temperature evens out between the surface and core, and martensite formation is then performed by air cooling.

The result of martensite hardening is critically dependent on austenitizing, which must be carefully adapted to ensure good results, particularly in the case of hypereutectoid steel.

AUSTEMPERING

High-carbon content [bainite](#), which forms at a low temperature has a high hardness and is rather tough. Compared with martensite formation, bainite formation is a slow process. The risks of hard cracks is therefore very small in austempering.

In austempering, the steel is austenitized in the usual manner and afterwards rapidly cooled to a temperature just above M₁ (the martensite formation temperature). Cooling is done in a salt bath in order to bypass the pearlite and bainite “noses”.

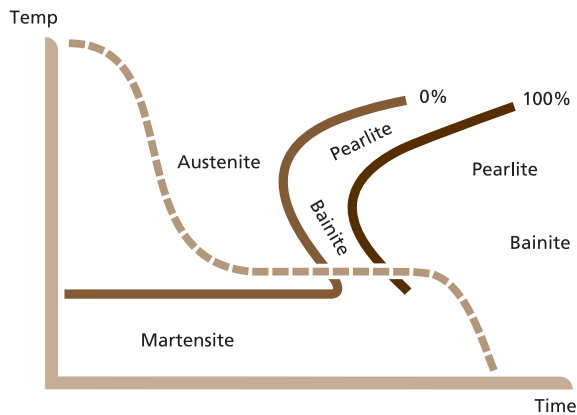


Figure 29 – Bainite hardening.

During the initial minutes in the salt bath, a lot of stirring is needed to ensure that the temperature of the steel components decreases and they are allowed to lie (still) for 1-7 hours, depending on the steel grade and transformation temperature. The hardness is also greatly dependent on the transformation temperature.

From the table relating to steel grade 100CrMo7, cooled down from 850°C, it is possible to read the following relationship between the salt bath temperature, transformation time and hardness.

Salt bath temp °C	Transformation time	Hardness	
		HV	HRC
300	1/2	545	54
350	1	710	60
200	4	780	62

Steel grades 100Cr6 and the more alloyed versions eg. 100CrMo7, 100CrMo7-3 and 100CrMo7-4 are often austempered. The salt bath temperatures are usually between 220 to 250°C.

Generally, in industrial hardening the hardnesses shown in the table are not attained since these values have resulted from laboratory tests. 57 to 60 HRC are the common hardness values of austempered roller-bearing type components. Decades of experience have shown that bearings, tools and structural parts with these degrees of hardness have long service lives.

The time required for bainite transformation is long, and this means that the costs of bainite hardening are higher than for martensite hardening. One of the disadvantages of austempering is that the alloying elements that offer a good combination of increased hardenability and reasonable bainite transformation times are expensive - Mo is the chief element used.

7 – INDUCTION HARDENING

Induction hardening differs from other forms of hardening in only one real respect - the manner in which the heat is supplied. This is, however, a rather significant difference from many points of view.

In inductive heating, heat is created inside the actual material - all other heat treatment methods supply heat by means of radiation/convection. The supply of energy in induction heating is done by placing the material in an electric field of alternating current (AC). This is usually carried out by putting a coil around or besides the material.

The electric field creates eddy currents and material is heated through its resistance to the currents as well as the magnetic losses (hysteresis) that occur.

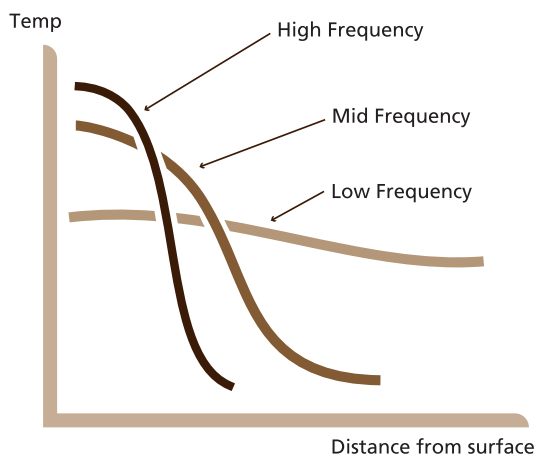


Figure 30 – Temperature penetration depending on induction frequency.

When AC is transmitted through a wire connection, the bulk of the current is transported in the surface layer. With direct current (DC), the current is distributed equally over the cross-section.

The higher the AC frequency then the higher the resulting current.

Induction heating can also be used to through-heat heavy sections (low frequency) or to heat very thin surface layers (very high frequency). It is used, for example, for heating billets for rolling or for hardening sewing needles.

[Depth of hardness](#) in induction hardening is greatly determined by three factors, namely, the frequency used, the combination of effect and time, and the hardness of the material in combination with the cooling used.

The [frequency](#) determines the depth at which the heat in the material is generated. If a low frequency is used it is not possible to achieve a hard layer since the heat is quickly conveyed into the material.

[Hardenability](#) and cooling determine the maximum depth that is possible to attain. A material with low hardenability can never provide a deep hard layer.

In induction hardening it is also possible to attain everything ranging from through hardening to extreme outer surface hardening. Induction hardening offers the possibility of transferring very high power. In conventional furnace heating, the power transferred to the surface is in the range of a few W/cm². With induction heating it is possible to attain power up to 5 to 6 kW/cm².

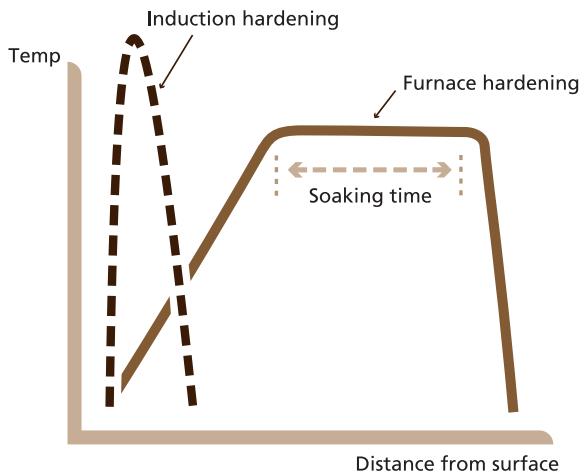


Figure 31 – Comparison between Induction and Furnace hardening.

This means that heating speeds in the surface zone are in the region of a few hundred °C per second. This rapid heating shifts the transformation points to considerably higher temperatures. In order to attain the same metallurgical results as achieved in furnace heating, the austenitizing temperature must therefore be considerably higher than in furnace heating.

Induction hardening often offers several advantages:

- Suitable for heavy sections which can only be hardened by local hardening.
- Provides high surface hardness in cases in which through hardening is not desirable.
- Permits substantial cooling so that low-alloyed steel grades can be used.
- Using material with a suitable carbon content means there is no need to use in-carbonization. there are, however, cases in which carburized surface layers are induction hardened. This results in fewer distortions than in case hardening.
- Permits large hardness depths which cannot be attained in case hardening.
- Suitable for complex sections.
- Reduced distortions than in hardening after through-heating.
- Environmentally positive.
- High energy efficiency.
- Suitable for automation that offers consistent results.

8 – SHELL HARDENING AND FLAME HARDENING

[Shell hardening](#) is a variation on martensite through hardening in which complete through-hardening is intentionally not attained. A material is selected which has too low a through-hardening ability for the particular dimension in question.

Following conventional austenitizing and quenching (as in the case of martensite hardening) the result will be a hardened surface layer with martensite, and a core zone of pearlite/bainite.

[Flame hardening](#) is in principle very similar to induction hardening with the difference that heat is supplied in the form of a welding flame. Heating proceeds more slowly than in induction heating and is considerably more difficult to control.

9 – HARDENABILITY

When hardening bars of a specific steel grade but with different dimensions, the hardness will vary. The figures give an example of the hardness profile in bars of SAE 6150 (50CrV4) after water hardening.

In dimensions up to 25 mm diameter (1 inch) the result will be 60 hRC right through the bar. This is equivalent to complete martensite hardening at this particular carbon content (0.42%). In the case of larger dimensions, the hardness decreases as the diameter increases. This is because the cooling speed decreases in line with increasing dimensions.

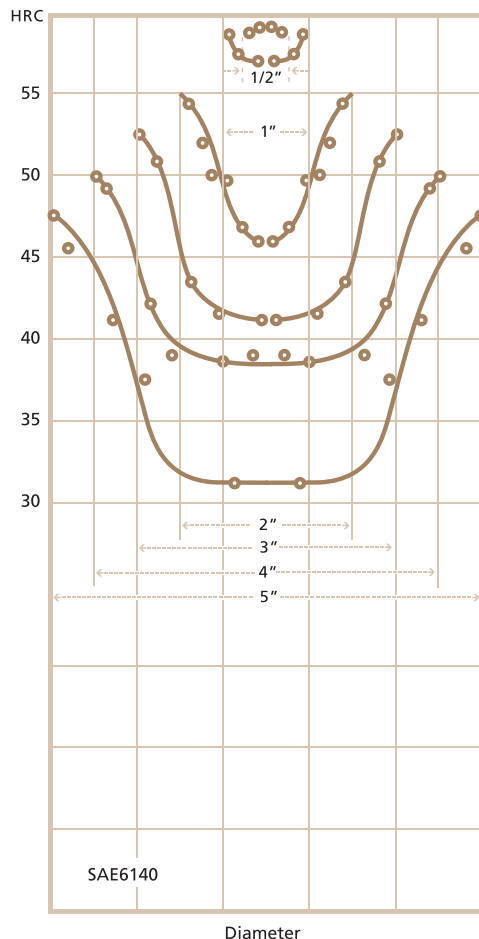


Figure 32 – Hardness profile in a 6140 bar after water quench depending on bar diameter.

In a comparison of the CCT diagram for SAE 6140 the decarburization curves for both 1/2 inch and 1 inch go straight down into the martensite range, while the cooling curves for larger dimensions go increasingly into the bainite and/or pearlite ranges. For SAE 6140 the critical diameter (D_0) for complete martensite formation with water hardening evidently lies somewhere between 1 inch and 2 inches. The critical diameter is a measure of the hardenability of the steel grade. The hardness result for a particular steel grade is also very dependent on the cooling medium (oil, water, etc.), the stirring intensity and the surface condition (oxide scale, fine turned, etc.).

In order to uniformly classify the hardenability of different steel grades, the concept of the ideal critical diameter (the D_i value) has been introduced. The D_i value indicates the critical diameter with the best possible cooling medium and optimum stirring and the best possible surface. By means of the diagrams in handbooks, the D_i value can be converted into a practical D_0 value. The most commonly used D_i value refers to just 50 percent martensite in the center of the bar.

The effect of alloying elements on hardenability

The D_i value for a steel depends on the composition of the steel and the grain size during hardening. Various formulae have been proposed for the calculation of hardenability, the D_i value, from the steel analysis. Most take this form:

$$D_i = D_i (\text{carbon steel}) f_{Mn} \cdot f_{Mc} \cdot f_{Cr}$$

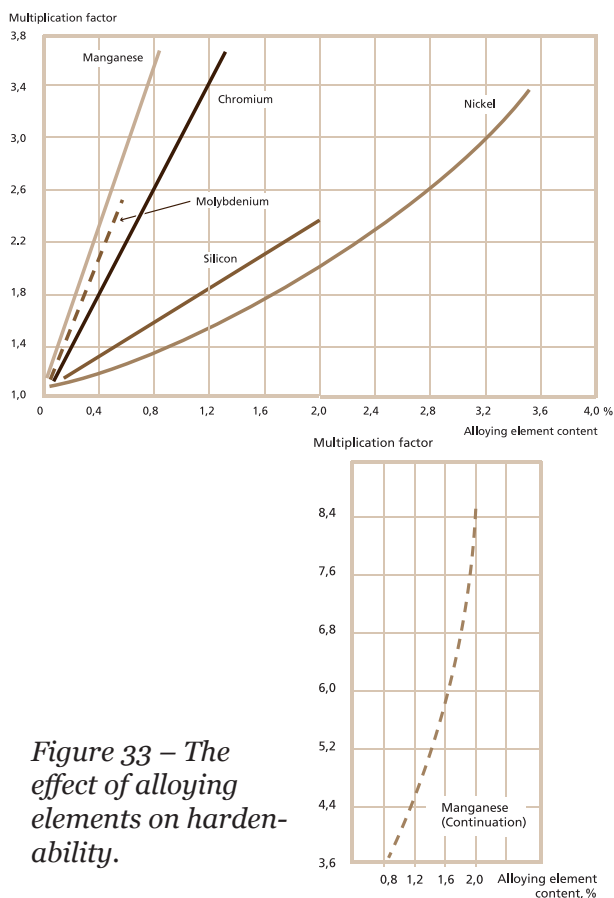


Figure 33 – The effect of alloying elements on hardenability.

That is, the D_i value is a product of the D_i value for carbon steel and the factors for each of the alloying elements included.

The carbon content greatly affects the hardenability. Increased grain size (lower ASTM figure) increases hardenability. Unfortunately, it also decreases the toughness of the material and therefore can seldom be used. The alloying elements manganese, molybdenum and chromium have the greatest influence on hardenability.

The diagram is a result of Grossman's experiments and is based on the hardenability criterion of 50 percent martensite in the core.

Hardenability testing

There are several methods of testing the hardenability of a steel. Two methods are shown here.

Hardenability test according to Grossman

In the determination of hardenability according to Grossman, a number of steel rods of varying diameters are hardened in a particular cooling medium. By metallographic investigation, the rod with 50 percent martensite in the center is selected. The diameter of this rod is referred to as the critical diameter (D_c). By using data in handbooks for the particular cooling method, the D_c value can be converted to a D_i value, the ideal critical diameter.

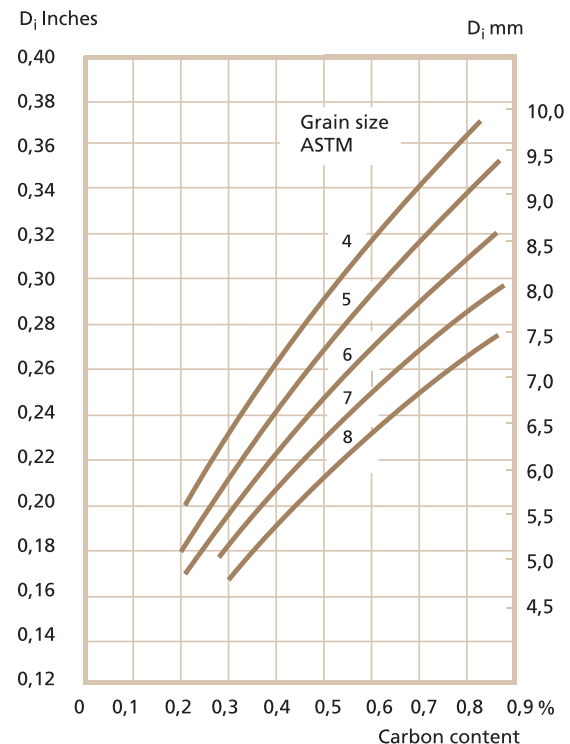


Figure 34 – Critical Grossman diameter (D_i) depending on ASTM grain size and Carbon content.

Hardenability test according to Jominy

Grossman's method is expensive and is seldom used although it is the most precise method. The most commonly used method was developed by Jominy. In this test only one test rod is used with a diameter of 25 mm and a length of 100 mm. After heating to the hardening temperature with a usual soaking time of 20 minutes, one end of the test rod is cooled by a jet of water as illustrated. The cooling rate is reduced throughout the rod, calculated from the cooled end.

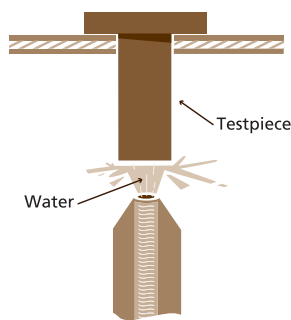


Figure 35 – Jominy test.

The hardness is then measured along the test rod after 0.4 mm grinding and entered in the diagram as a function of the distance from the cooled end. The Jominy diagram for SAE 8620 / 20NiCrMo2-2 is shown in the figure.

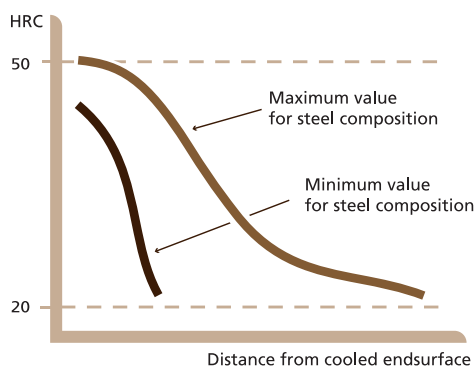


Figure 36 – Jominy curve.

The upper line represents the maximum value for the steel composition and the lower line the minimum value. Combined, the two lines form the Jominy band or hardenability band.

The hardenability band many of the Ovako grades as eg Ovako 152 is more narrow than for standard SAE 8620, which is due to the narrower analysis limits.

Conversion to the Di value

Extensive comparative tests have made it possible to translate the results from Jominy testing to the circumstances that exist during actual hardening. Handbooks contain conversion diagrams which compare the cooling rates at various Jominy intervals with cooling rates at various depths in rods of different diameters. The effect of different cooling media are also included. Therefore, the Jominy test results can be converted to the Di value, among others.

10 – TEMPERING

Tempering is always required after martensite hardening. In principle, tempering involves the regression of martensite towards ferrite and cementite.

The higher the tempering temperature used, the closer the original structure is approached. The tempering used in "conventional" martensite hardening is carried out in the temperature range 150 to 230°C. In hardening and tempering, tempering is performed at 550 to 650°C.

[Low temperature tempering](#) has two basic aims, firstly, to remove the largest stresses from the material and secondly, to stabilize the structure. There are two primary things happening during this type of tempering. Martensite is slowly broken down and an iron carbide phase begins to separate simultaneously as the carbon content of the martensite decreases. The iron carbide, consisting of very small particles, is not exactly "conventional" iron carbide - it is somewhat deficient in iron and is called ϵ -carbide.

The retained austenite in the material is transformed into bainite, and this transformation becomes increasingly complete with increasing temperature and the longer the time used.

[High temperature tempering](#) leads to substantial martensite disintegration and cementite is formed during the depletion of carbon in the martensite.

The tempering temperature and time are to a certain extent interchangeable. An increased tempering temperature means that the time can be reduced substantially. The temperature has a direct effect, while the time has a logarithmic effect. The relationship between hardness (and mechanical properties) and tempering is described in the tempering diagram.

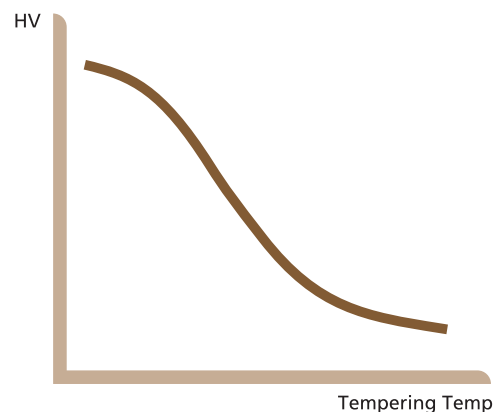


Figure 37 – Hardness vs Temperature.

Similar diagrams for most steels are provided in [Steel Navigator](#).

TEMPER BRITTLENESS

The transformations that occur from tempering affect not only the hardness but also toughness. The marked reduction in toughness which occurs during tempering at certain temperatures is usually referred to as temper brittleness. For typical carbon steel grades there are two areas for temper brittleness:

270 to 370°C brittleness

This brittleness range can be observed in most unalloyed and low-alloyed steels as well as tool and structural steels. The temperature range coincides with the range within which retained austenite is transformed into bainite and presumably it is mechanisms in connection with this transformation which contribute to the reduction in impact strength.

400 to 550°C brittleness

This brittleness range is referred to in most cases when the temper brittleness is mentioned in connection with alloyed structural steel. The development during embrittlement is dependent on both the temperature as well as the time during tempering.

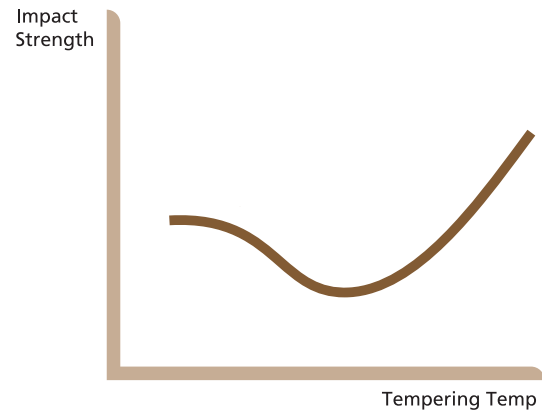


Figure 38 – Impact strength vs temperaure

This brittleness range differs from the previous case in as level of brittleness is dependent on the cooling rate after tempering. Even if the steel has been tempered at a higher temperature, a slow cooling through the critical temperature area can cause deterioration of the impact strength.

For some steels, such as the higher alloyed hardened and tempered steels in larger dimensions, this brittleness can be avoided by cooling in oil or water after tempering.

11 – NITRIDING

Through nitriding, suitably alloyed steel is given a high nitrogen content on the surface even at temperatures under A1 by enabling a high surface hardness (1,000 to 1,200 HV) to be attained. Nitriding is primarily used for machine components and other parts for which high surface hardness is required. The components to be nitride are in general hardened and tempered, and often toughened. A steel must contain one or more of the alloying elements aluminum, chromium and vanadium if it is to be nitride. These elements have a greater capacity to combine with nitrogen than iron and therefore they readily form nitrides.

Nitriding is carried out in flowing ammonia (NH_3) at a temperature of 500 to 550°C, for a period of 25 to 100 hours. At this temperature the ammonia is dissolved and some of the liberated atomized nitrogen is absorbed by the steel. A thin surface layer receives a relatively high nitrogen content which means that iron nitrides are also formed in large quantities. The nitrogen diffuses inwards during extended soaking times from this layer and forms nitrides with the alloying elements in a zone in the steel that grows in line with the time, and attains high hardness and wear resistance because of the fine distribution of the nitride particles.

The iron nitride enriched outer surface, which is brittle and does not attain the same high hardness, is often machined away. Nitriding can also be performed in a nitrogen producing salt bath (cyanide bath at 500 to 550°C), which requires a shorter period of time.

Nitride steel is also usually alloyed with molybdenum in order to avoid temper brittleness in connection with prolonged heating at 500 to 550°C.

There are several nitriding processes in use, including:

- Tenifer treatment
- Sulfinuz treatment
- Acid-Sulf treatment
- Powder nitriding
- Ion-implantation

[Carbonitriding](#) is a combined process between nitriding and carburizing in which the main emphasis is on carburizing. Carbonitriding is performed in a carburizing gas which is mixed with ammonia. It is normally carried out at temperatures of about 800 to 850°C.

12 – DECARBURIZING

Decarburizing is a negative secondary effect which occurs during the conditioning of steel containing substantial amounts of carbon at a high temperature. Decarburizing is the reverse of carburizing. If there is a larger "carbon quantity" in the atmosphere than in the material, the carbon content of the material will increase - carburizing. If there is less carbon in the atmosphere than in the material, the carbon content of the material will decrease - decarburizing.

As in the case of carburizing, decarburizing depends on temperature and time - decarburizing is determined by the diffusion of the carbon in the steel.

Decarburizing in steel occurs in two different processes, during heating for rolling, and during heat treatment. In heating ingots, efforts are made to suppress decarburizing by carefully adapting the heating cycle to the rolling speed.

In heat treatment the demands are often even higher (since the final dimensions have almost been attained) and often some form of protective gas is used during treatment such as soft annealing and hardening.

Several different types of protective gas are used. They act as neutralizers in relation to the material - they neither carburize or decarburize. Usually a compound of N_2 , H_2 , H_2O , CO and CO_2 is used. The concentrations of these gases is adjusted to ensure that the carbon activity in the gas is in equilibrium with the carbon content in the material at the heat treatment temperature.

Usually decarburizing is determined by evaluation of the microstructure evaluation or by hardenability measurements.

13 – DIMENSIONAL CHANGES AND DIMENSIONAL STABILITY

Two types of dimensional changes occur in steel in conjunction with heat treatment and usage. They result either from stresses in the material (caused by conditioning or earlier heat treatment) or by the transformation sequence.

Hardening

In hardening, a volume increase occurs in connection with quenching. Martensite hardening results in a larger volume change than austempering. For a 1% carbon steel the volume change will be:

- Austenite martensite 4.2%
- Austenite - bainite 3.2%
- Austenite - pearlite 2.4%

This volume change can cause problems for intricately shaped parts. Also, the transformations give rise to large stresses in the material.

In bainite hardening the transformation occurs almost simultaneously in the surface and core, and, after hardening, the material contains only small stresses. If the transformation occurs first in the center and then in the surface, this will result in tensile stresses in the surface and compressive stresses in the core. This occurs, for example, during case hardening.

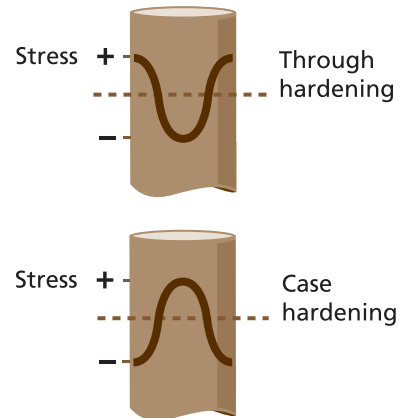


Figure 39 – Stress levels throughout a bar, depending on hardening type.

Why is this?

If the change occurs first in the surface and then in the core, this results in compressive stresses in the surface and pressure in the core. This occurs, for example, during through hardening to martensite.

Why is this?

Parts having a varying shape can give rise to deformations and cracks since the size of the stresses is affected by the thickness of the material. In case-hardened steel the core has a low carbon content and the surface a high carbon content. The lower the carbon content, the higher the M_s temperature. The higher the M_s temperature, the earlier the transformation starts.

In cases of through hardening, the transformation begins in the surface since this cools fastest. The M_s temperature is equal in the surface and core.

Usage

During usage the part alters its dimensions. The higher the temperature, the faster the change.

A martensite hardened part contains two components that are unstable, namely, martensite and retained austenite. Martensite regresses towards ferrite and carbide during the volume reduction. Retained austenite forms bainite during the volume increase. The sum of these changes gives the total volume change and it can be positive or negative, depending on the amount of retained austenite in the material.

The same situation applies during tempering, and tempering sets the basis for the manner in which the part behaves during operation. The tempering temperature must therefore be adapted carefully to the operating conditions in order to attain maximum dimensional stability.

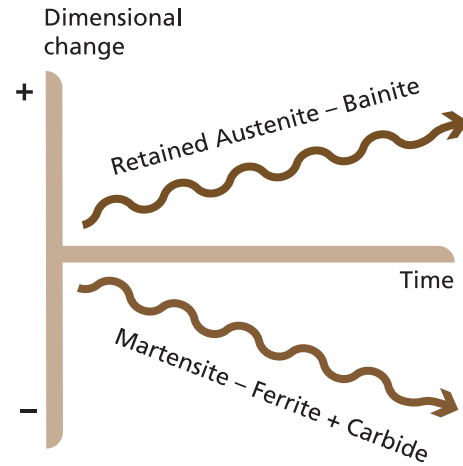


Figure 40 – Dimensional changes over time, depending on type of phase transformation.

14 – THEORY, PART 2

The basis for describing what happens during most forms of heat treatment is found in the changes which occur in iron when the temperature or carbon content are changed. These changes are described in the iron-carbon diagram shown here.

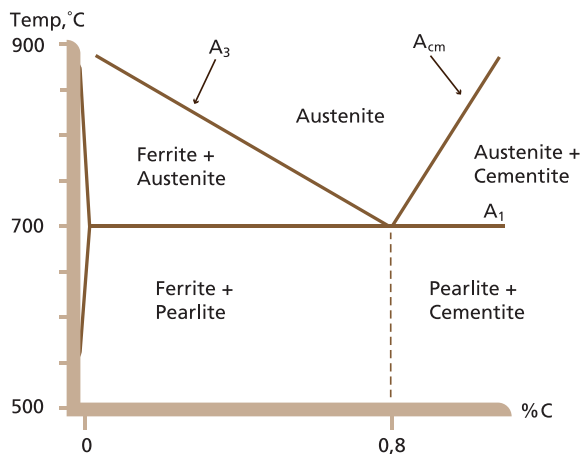


Figure 41 – Iron – Carbon (Fe - C) phase diagram.

This diagram simply shows the structure that is stable in the steel at a particular temperature.

There are many materials which are found in several natural forms. One of the most common, apart from iron, is carbon. A diamond or the lead (graphite) in a pencil are essentially the same material in different forms.

Similarly, iron has two stable forms these are called ferrite and austenite. Ferrite is also called α -iron and austenite is called γ -iron.

Ferrite is stable at room temperature, magnetic and can contain very small amounts of carbon. It is stable at temperatures up to approximately 720°C.

Austenite is non-magnetic and can contain several percent carbon in a solid solution. It has a greater volume than ferrite.

Most heat treatment methods utilize the transformations between ferrite and austenite in some way. The iron-carbon diagram contains three "transformation" lines, A₁, A₃, and A_{cm}. These lines describe when a certain transformation in steel occurs.

The A₁ line shows at what stage ferrite is transformed into austenite. Note that what has been said so far applies only when steel is heated or cooled slowly. If steel is heated from room temperature to approximately 720°C nothing happens to the structure of the steel – although stresses and various other factors can be affected.

Ferrite can contain (almost) no carbon at all. If the carbon content is increased in the material the carbon must go somewhere else. Iron and carbon can together easily form a chemical compound, iron carbide. In a low-alloyed, or pure, carbon steel, this carbide has a composition consisting of three parts iron and one part carbon - Fe₃C. This iron carbide, which is found in some form in all steels, is called cementite.

Cementite is found in two main forms in steel – either as thin plates, "lamellae", which is the "natural" form or as globular particles "spheroids", which is a product of some form of heat treatment. In addition, cementite can also appear in the form of a continuous network which is formed naturally at higher carbon contents.

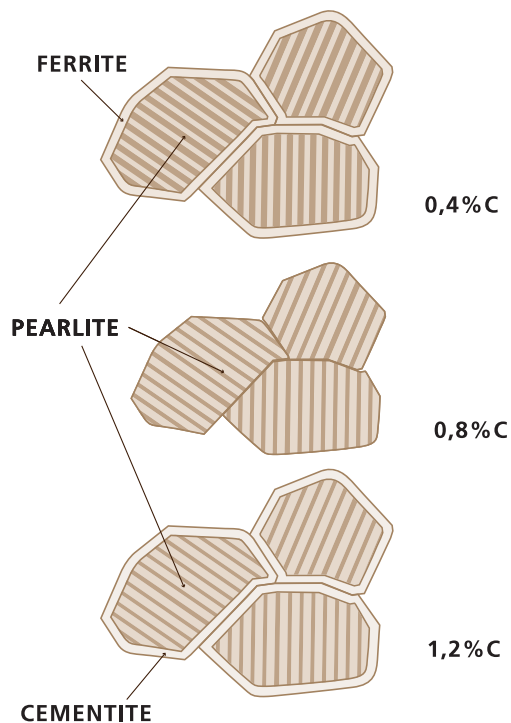


Figure 42 – Ferrite- Cementite and Pearlite structures depending carbon content.

Cementite is formed only together with ferrite in a stable form. When cementite is found together with austenite it is gradually dissolved, and the carbon in the cementite ends up in the austenite which, as opposed to ferrite, can dissolve carbon.

Ferrite and cementite together form one of the most common structural constituents in steel - pearlite. Pearlite consists of cementite lamellae which are separated by thin ferrite plates. Pearlite has the property of containing the same total carbon content for a particular type of steel.

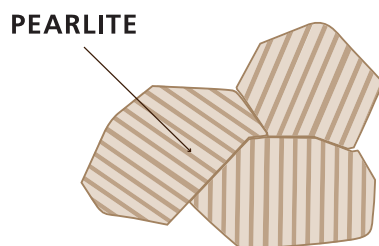


Figure 43 – Pearlite.

The carbon content of pearlite is called the eutectoid composition. In the case of a pure carbon steel, the pearlite always has a carbon content of 0.85%. Most alloying elements reduce the carbon content of pearlite.

Given these structural constituents, ferrite, pearlite, cementite, austenite it is possible to treat the structure of the material in all situations in which the material is heated and cooled slowly.

Take, for example a carburizing steel that contains about 0.2% carbon. When it is rolled to form tube, ring, bar or wire this occurs at temperatures well above 1,000°C. During the rolling process, the steel is therefore completely austenite. All the carbon is dissolved in the austenite and the steel is non-magnetic. When the rolling is completed, the steel is in most cases allowed to cool freely in the air.

During the cooling process, the structure will first consist of austenite grains. The size of these grains depends on a number of factors which are principally dependent on rolling. The steel contains 0.2% carbon. Pearlite contains 0.8% carbon. This means that the steel must contain more ferrite than that contained in the pearlite. This "excess ferrite" is separated first, and it begins to separate just when the temperature has decreased down to the A2 line. In the case of 0.2% C, this will be at approximately 870°C. This ferrite stays in the grain boundaries of the austenite, and as the temperature decreases an increasing amount of this grain-boundary ferrite is formed. This continues until the temperature reaches 750°C. Then all the austenite is transformed into ferrite - and ferrite cannot contain any carbon.

At 750°C all the material which has not become ferrite is transformed - immediately - into pearlite. Nothing happens after this. Therefore, at room temperature, just as at exactly 720°C, the structure will consist of a network of ferrite which exists in the earlier austenite grain boundaries, and inside these grains pearlite.

The sudden transformation to pearlite is commonly called the eutectoid reaction, and the ferrite which is earlier precipitated is therefore referred to as proeutectoid ferrite, or grain-boundary ferrite.

A steel which has exactly 0.8% carbon is easily handled. During rolling the steel is completely austenitic - all the carbon is dissolved in the austenite. When it is cooled freely in air nothing happens until 720°C. At this point the entire structure is transformed in one step into pearlite.

Above 0.8% carbon, the sequence will be similar to steel with a carbon content under 0.8% percent C, but with one important difference - there is now excess carbon instead of a deficiency.

Take a ball-bearing steel that contains 1% carbon, and during rolling it is completely austenitic. During cooling in air nothing happens before the Acm line is crossed just below 800°C. At Acm the cementite begins to precipitate in the austenite's grain boundaries and an increasing amount of cementite is separated until it reaches about 720°C. At 750°C there is no pearlite formation and nothing subsequently occurs during cooling. At room temperature, as at 720°C, the structure will be composed of cementite, which exists in the original grain boundaries, and pearlite inside the grain. The cementite which is precipitated in the original grain boundaries is called consistent grain boundary cementite.

The above processes form the basis for almost all types of heat treatment.

It is most important to realize that all forms of heat treatment are aimed at achieving specific properties through manipulating the transformations between ferrite – pearlite/ austenite.

Hardening is one example of this. By substantially increasing the cooling rate it is possible to prohibit the precipitation of ferrite/ cementite (depending on the carbon content) and pearlite formation from occurring. The carbon in the austenite is frozen solid and a completely different structure, martensite or bainite is obtained.

Soft annealing is another example. By reducing the cooling rate it is possible to "fool" the carbon to come out of the austenite and obtain globular carbides instead of pearlite. The properties of pearlite can be varied within a broad range, despite the constant carbon content, by varying the cooling rate.

The lower the temperatures at which the transformation occurs, the thinner will be the cementite lamellae and the greater the hardness. The structure which is attained during the most common form of hardening, when martensite is formed, is not stable.

At room temperature iron cannot dissolve carbon. Hence, martensite (and bainite) survive at room temperature, and continually strive to form ferrite and cementite. At room temperature, however, this occurs very slowly, but the temperature does not have to be increased very much for the sequence to become clearly visible.

The transformations under discussion, α to γ at A_1 , complete transformation to austenite for steel with less than 0.8% C at A_3 , and complete transformation of steel with more than 0.8% C at A_{cm} , are similar for all steels.

However, the temperatures and carbon contents at which they occur are affected by various factors. The most important of these is the rate at which heating or cooling occurs, and the alloying content of the steel. Most alloying elements reduce the pearlite's carbon content.

In most cases, the heating rate is of no importance (important exceptions are induction heating and flame hardening).

In order to describe what occurs during cooling at various rates, two methods have been developed.

[TTT diagrams](#) show what happen in a particular steel when it is rapidly cooled to a certain temperature and then held at that temperature.

[CCT diagrams](#) show what happens when the steel is cooled using different, but constant cooling rates. This will be studied in greater detail later.

The iron-carbon diagram, and the sequences shown there, forms the basis for all types of heat treatment. By understanding this basically very simple representation of the behavior of steel during heating and cooling it is possible to take a major step towards understanding heat treatment.

AUSTENITIZING

Most heat treatment methods utilize the transformation between the room temperature form of the iron (ferrite) and the high-temperature form (austenite).

Austenitizing has a single aim, namely, to impart to the steel a composition that gives the desired properties after cooling.

- In heating of the steel, nothing happens before 750°C. At this temperature pearlite is transformed into austenite.
- If the carbon content of the steel is 0.8% carbon the entire structure will be austenitic.
- If the carbon content is less than 0.8% C there will be excess ferrite. This is gradually dissolved, and the entire steel will be austenitic at the A₃ line in the iron-carbon diagram.
- If the carbon content of the steel is greater than 0.8% percent carbon there will be excess carbide. This is gradually dissolved and at A_{cm} the entire steel will be austenitic.

Therefore, the temperatures used for various types of heat treatments are determined primarily by the carbon content of the material. Naturally, the alloying content is also a factor since the various transformation temperatures in the iron-carbon diagram are affected by the alloying content.

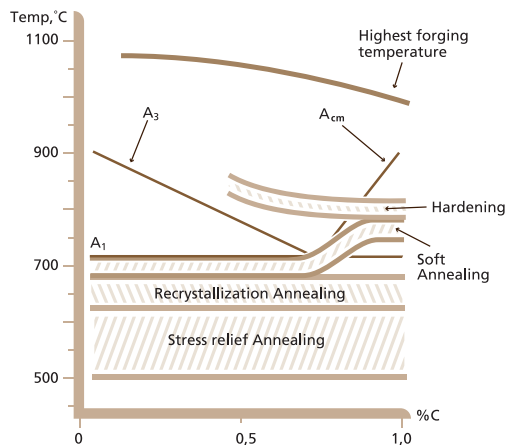


Figure 44 – Temperature range for heat treatment.

As shown by the diagrams there are distinct differences between steel with less than 0.8% C and steel with higher carbon contents.

Hardening is a good example of this. For steel with carbon contents below 0.8% C, the steel becomes completely austenitic before hardening - the austenitizing temperature lies above A₁.

When the carbon content is greater than 0.8% the steel is kept between A₁ and A_{cm}, which means that the structure consists of austenite and carbide residues.

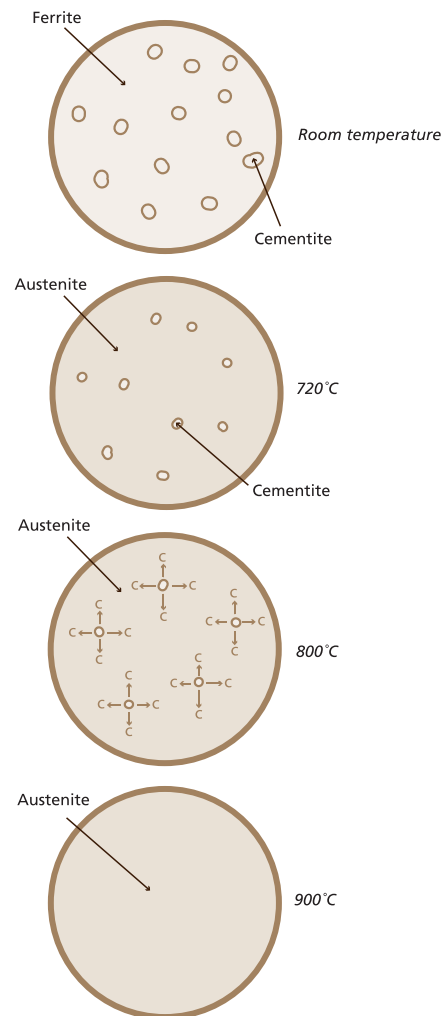


Figure 45 – 1 % Carbon steel, soft annealed.

The reason is that if the carbon content in the austenite becomes greater than 0.7%, the formation of martensite will be complete.

The most important point is that every heat treatment procedure and different steel grades impose major requirements on the correct austenite composition. Very often the tolerance range for the temperature at austenitizing is about $\pm 2^{\circ}\text{C}$.

The transformations which occur during austenitizing are also dependent on time. Correct austenitizing can therefore be defined as a combination of temperature and the time (soaking time) that the steel will be held at that temperature. The soaking time is often used as an equalization factor and its extent depends on the mass of the material (material thickness). The austenitizing process is also affected by the heating rate. In the case of heating in ordinary furnaces there are no great differences, but in the case of rapid heating, inductive heating for example, the differences will be great.

Rapid heating means that the transformations ferrite to austenite and ferrite/carbide solution simply cannot "keep up", but are instead shifted towards higher temperatures. The austenitizing temperature must therefore be much higher during rapid heating than during a slow process in order to attain the same result.

Grain growth occurs during austenitizing. The original pearlite (or ferrite) grains are transformed into austenite grains. The higher the temperature used the faster will be the grain growth.

In steels with carbon contents greater than 0.8% the carbide residues act as "brakes" and the grain growth therefore occurs more slowly at a given temperature under Ac_m.

PEARLITE, BAINITE AND MARTENSITE FORMATION

The main constituents of steel are ferrite, pearlite, bainite and martensite. Ferrite is chiefly pure iron. Ferrite can contain alloying elements, but not carbon.

A ranking of the product attained after increasing cooling rates will give the following result: pearlite – bainite - martensite. In principle, the cooling rate determines the structure achieved after a certain amount of austenitizing for a particular steel composition.

Pearlite

Pearlite is formed through the precipitation of thin plates. These thin plates consist of iron carbides - cementite. They increase in thickness and length and then reduce the austenite surrounding the growing cementite plate. This austenite becomes ferrite. This creates a layer of alternating cementite and ferrite – a lamellar structure.

The lower the temperature at which pearlite forms (the faster the cooling process), the thinner will be the plates in the pearlite - this will be fine lamellae. In most steels pearlite is formed down to a temperature of about 550°C.

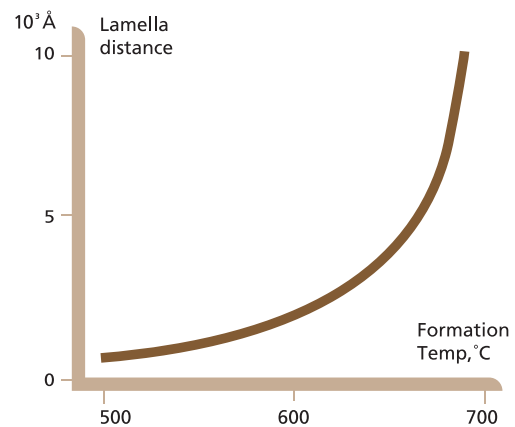


Figure 46 – Pearlite formation – Lamella distance.

The diagram shows the relationship between the lamellae distance in the pearlite and the formation temperature.

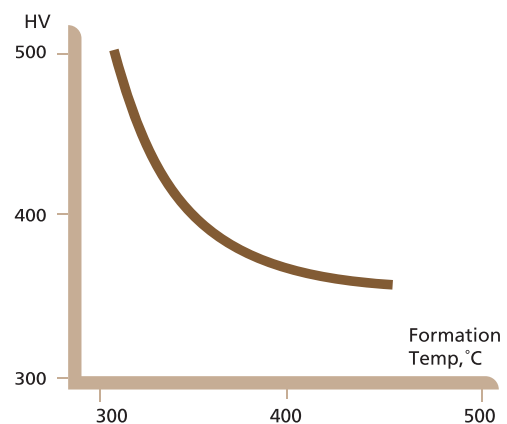


Figure 47 – Pearlite formation – Hardness.

The finer the pearlite lamellae, the harder they will be. As an example, the figure shows the relationship between hardness and the formation temperature of pearlite for grade 50CrV4.

Bainite

Under temperatures of approximately 550°C bainite begins to form and this continues down to a temperature at which martensite Ms begins to form. The formation of bainite begins with the formation of cores of ferrite which, in the upper part of the temperature range, grow out from the grain boundaries in the form of plates.

The austenite around this ferrite is enriched with carbon and when a sufficiently high carbon content is attained cementite is formed.

At lower temperatures the bainite forms “needles” in the austenite, and bainite also begins to form inside the austenite grain. As in the case of pearlite, there is a great difference between the bainite which is formed near the pearlite range and that which is formed near the martensite range.

High temperature bainite is similar to low temperature pearlite and low temperature bainite is very like martensite.

As in the case of pearlite, hardness increases with decreasing bainite formation temperatures, the diagram shows this relationship for grade 50CrV4.

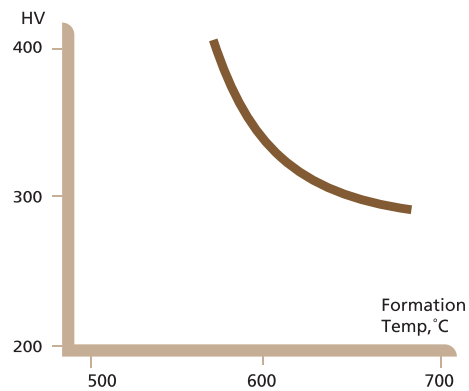


Figure 48 – Bainite formation – Hardness.

Martensite

If the material is cooled so quickly that pearlite or bainite are unable to form, a new product, martensite, is formed. Martensite takes the form of long thin plates that look like needles. The higher the austenitizing temperature used, the larger these needles will be.

The amount of martensite formed and its composition and properties is determined by the alloying content of the steel and by the austenitizing.

The figures show some aspects of martensite formation:

- the relationship between the temperature at which the martensite begins to form (M_s) and the amount of martensite which is formed for a 0.7% carbon steel.
- the relationship between the carbon content of the austenite (not that of the steel) and the M_s temperature.
- the relationship between the carbon content of the martensite and the amount of martensite residues.
- the relationship between the carbon content of the martensite and its hardness.

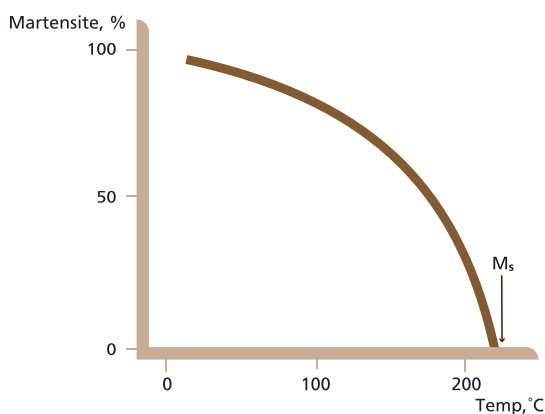


Figure 49 – Martensite formation – Temperature.

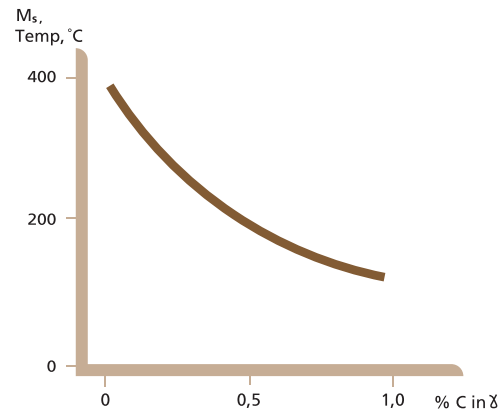


Figure 50 – M_s – Martensite vs Austenite carbon content.

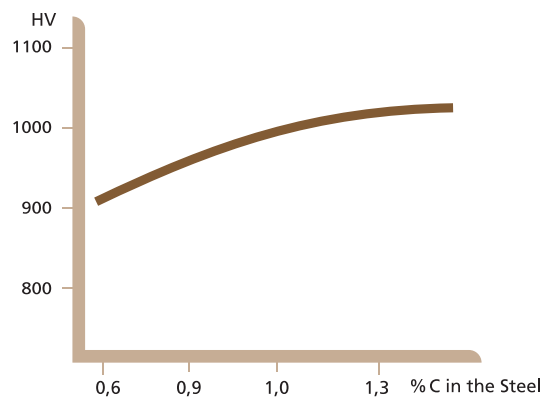


Figure 51 – Martensite hardness – Martensite carbon content.

Retained Austenite

The martensite formation is never complete. The share of austenite which is not transformed into martensite is called retained austenite. The retained austenite is soft and is unstable at room temperature (and even more so at an increased temperature). The composition of the austenite (i.e. the alloying content in the steel together with the austenite conditions) determine how much retained austenite will be formed.

In the case of high-carbon steel or alloyed steels this means that the degree of hardness, in relation to the austenitizing temperature, will be a maximum.

For these types of steel (for example alloyed carburizing steel) there is a definite range within which the maximum hardness is attained.

For low-carbon steels only the area under the austenitizing limit is critical.

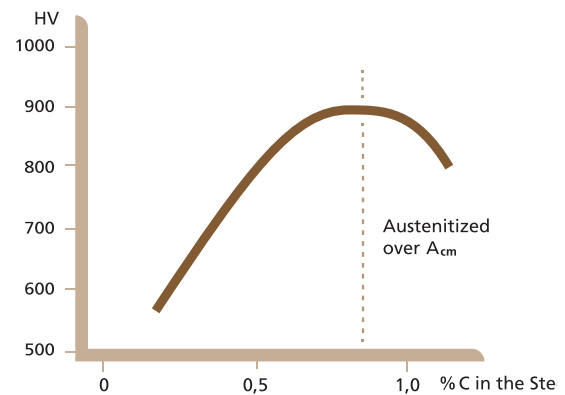


Figure 52 – Hardness in relation to Carbon content.

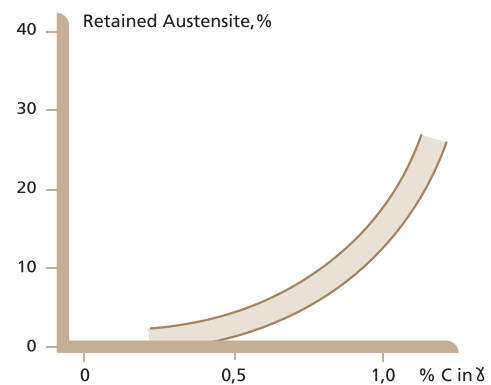


Figure 53 – Retained Austenite – Austenite carbon content.

15 – TTT AND CCT DIAGRAMS

There are two major methods for illustrating the transformation sequence in steel.

TTT diagram

This method shows what happens to an austenitized steel when it is cooled to a certain temperature and held there. Cooling to a holding temperature is done rapidly and the transformations which then occur are isothermal, i.e. they occur at a constant temperature.

By performing a series of tests at different temperatures, the time for initial and finalized transformation can be determined.

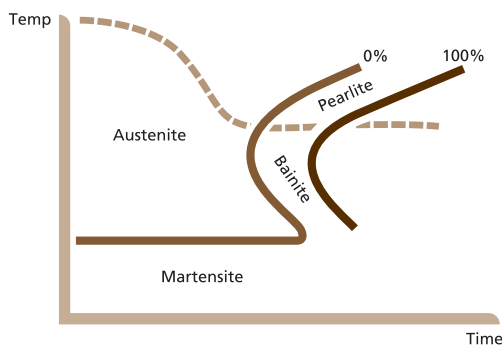


Figure 54 – TTT-Diagram.

The figure shows the essential appearance of such a diagram. The designation TTT originates from the term “time temperature transformation”. The diagram describes the relationship between transformation, temperature and time.

The designation M_s means that martensite begins to form as soon as the temperature goes below this point. Complete martensite formation is never achieved in ordinary hardening, and M_f (finalized martensite formation) is often never indicated.

CCT diagram

In determining the CCT diagram, the transformation sequence for an austenitized steel during continual cooling can be studied. The cooling rate is kept constant and the time and temperature for the transformations is determined. Through a long series of tests with varying cooling rates the CCT diagram can be constructed.

The figure illustrates the basic appearance of such a diagram.

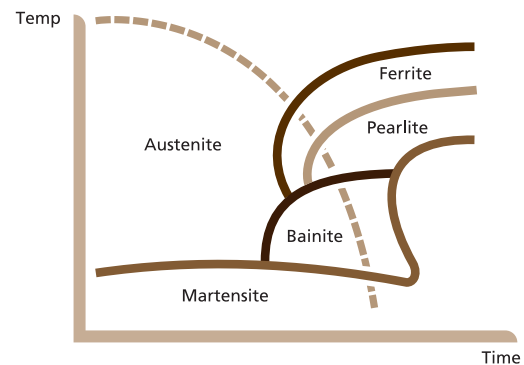


Figure 55 – CCT-Diagram.

The designation CCT originates from Continuous Cooling Transformation, i.e. transformation during continuous cooling.

For a particular steel the CCT and TTT diagrams are available - so in principle, such diagrams need only be created once for a particular steel grade. However, the austenitizing sequence affects the appearance of the diagram. The original structure prior to austenitizing must be checked to see that it is the same type as that which is to be studied. Also, the austenitizing time and the temperature must be similar.

Alloying effect

The figure attempts to show how various alloying elements affect the transformation in a TTT diagram.

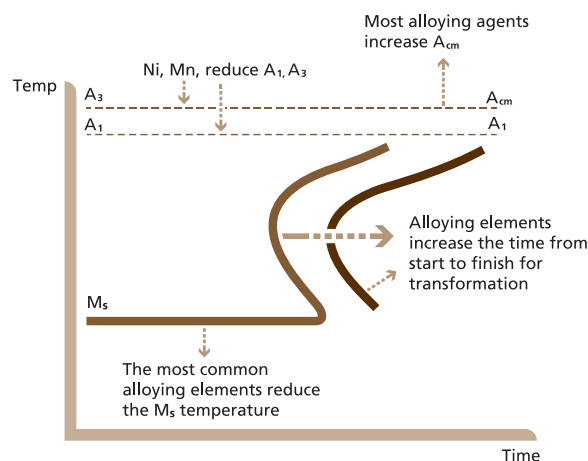


Figure 56 – Alloying elements effect on Transformations.

In any case it is a complicated process to obtain a suitable combination of alloying elements in order to attain the desired heat-treatment properties at the minimum cost.

Applications

Two practical examples.

In the first case we want to determine the amount of time and the temperature to be used in austempering of grade 42CrMo4.

Austempering is an isothermal process so we use a TTT diagram. TTT diagrams for most steels will be available in literature produced by manufacturers.

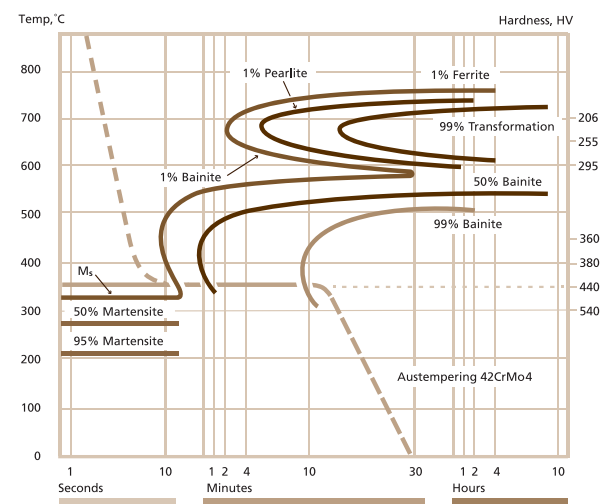


Figure 57 – Diagram for Isothermal transformation.

The figure shows the TTT diagram for 42CrMo4, austenitized at 840°C. The Ms temperature is 325°C so the austempering temperature must be greater than this - 350°C would be suitable.

At 350°C bainite starts to form after about 10 seconds, 50% of the structure has become bainite after about 1 minute, and the bainite transformation is completed after about 6 minutes.

By extrapolating the isothermals the expected hardness can be read, in this case about 440 HR.

Austempering of grade 42CrMo4 can therefore be carried out at 350°C with a soaking time in the bainite bath of about 6 minutes, with a resulting hardness of about 440 HV.

In the second case, we need to determine what the hardness at the core will be in an axle with a diameter of 60 mm for steel grade 16NiCrS4 after case hardening. At the same time we want to know what the structure of the core material will be. The type of case hardening to be used is double hardening, i.e. carburization followed by cooling to room temperature, and then hardening is done from 850°C in oil.

The figure shows the CCT diagram for 16NiCrS4. The CCT diagram is used since cooling is continuous.

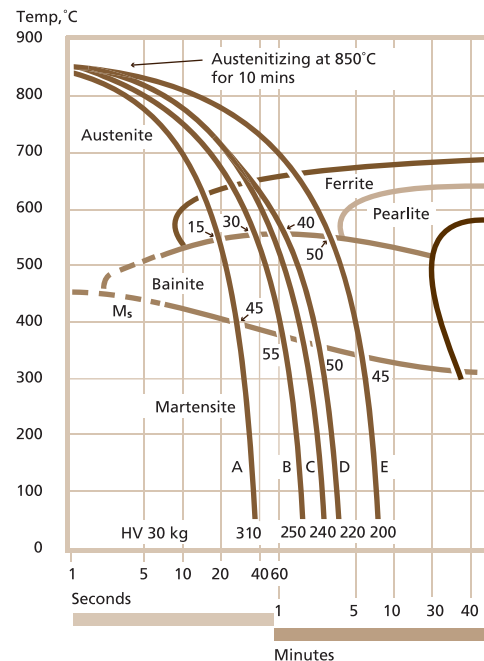


Figure 58 – CCT-diagram for 16NiCrS4.

The CCT diagram is provided with auxiliary lines. In our case the table shows that the cooling curve C, which applies to oil hardening, and the center of a 63 mm diameter component are very close.

Following the curve C, this first meets the transformation line between austenite and ferrite. Grade 16NiCrS4 has only 0.15% C and ferrite begins to separate in the austenite grain boundaries. This occurs after a cooling time of approximately 35 seconds.

After further cooling the C curve passes through the next transformation line which indicates that ferrite is no longer formed, but bainite. This occurs after 60 seconds. The C curve indicates how much ferrite will be formed when bainite transformation begins. In this case it is 35%.

After 60 seconds of cooling the structure consists of 35% ferrite and 65% austenite. This austenite is now transformed into bainite, and this continues until the C curve crosses the next transformation line. This occurs after a total cooling time of about 1.5 minutes.

At this stage 55% of the structure is transformed into bainite and a total of 35% ferrite and 55% bainite has been formed. There remains 10% austenite which has not been transformed.

Diameter mm centre	Cooling medium oil 12,5 mm	
	Below the surface	
30	A	A
63	B	C
100	D	E

This residual austenite is now transformed into martensite. The expected hardness is indicated at the end of the cooling curve. In the case of curve C the expected hardness will be 240 HV.

Therefore, the result will be a core hardness of about 240 HV, and the structure in the core will consist of 35% ferrite, 55% bainite and 10% martensite.

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