

Linn



High Therm

The Hardener's Guide

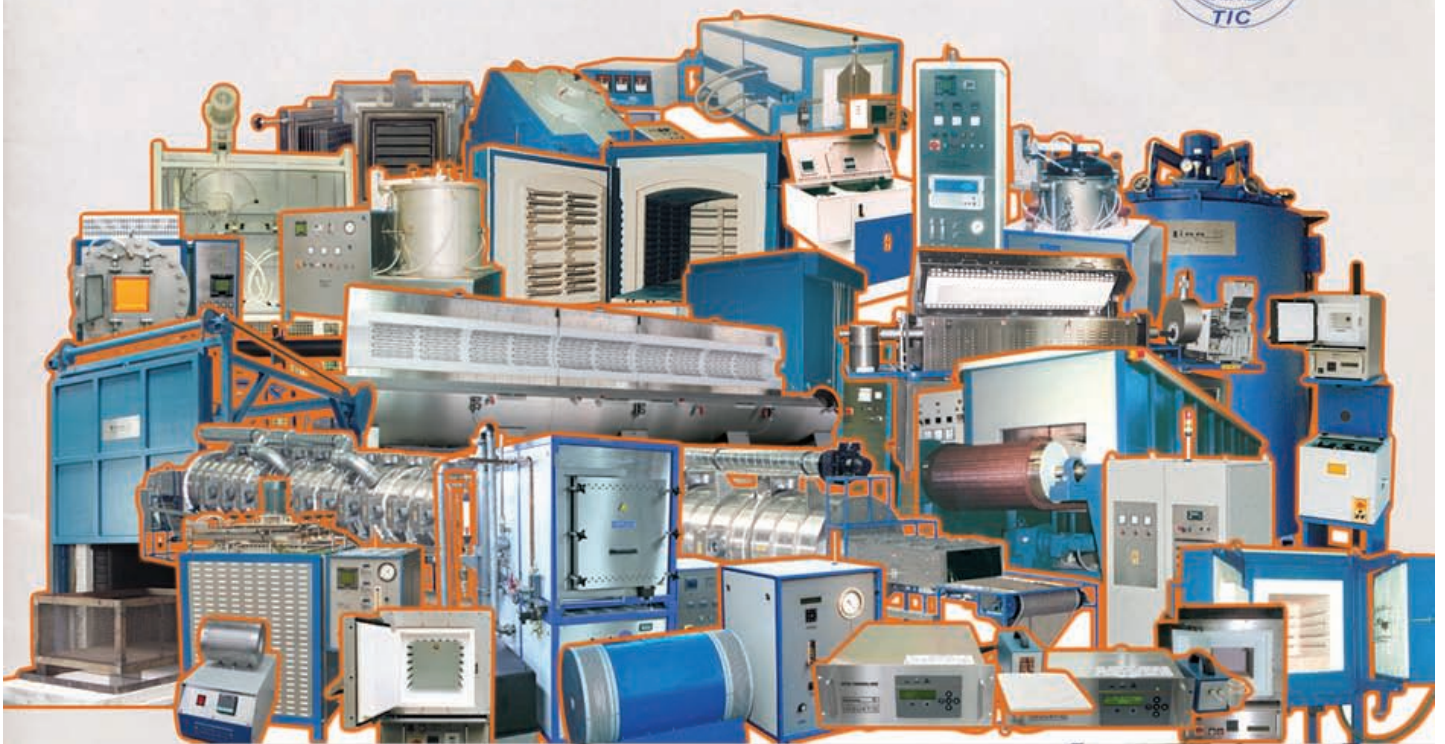


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PREFACE

Beyond the year 2000, the use of metallic materials, in particular ferrous materials, will continue to dominate a multitude of industrial sectors. The technological and design demands that are made on metallic materials, primarily determined by the trend towards lightweight construction and miniaturization, can generally only be achieved through suitable refining processes. A prime position amongst these refining processes is that of

heat treatment

before or during the processing of the materials into components or tools.

The objectives for heat treatment can be quite diverse. The processing and machining characteristics of the materials can be improved or the condition of the material can be altered so that, e.g. the hardness, the yield strength, the tenacity or the wear resistance can optimally take into account the various conditions of use in practice.

A number of processes are available for carrying out heat treatment work. A basic division into two large groups is possible:

1. Changing the conditions of the material without changing the chemical composition, and
2. Changing the condition of the material with simultaneous alteration of the chemical composition in the skin layer.

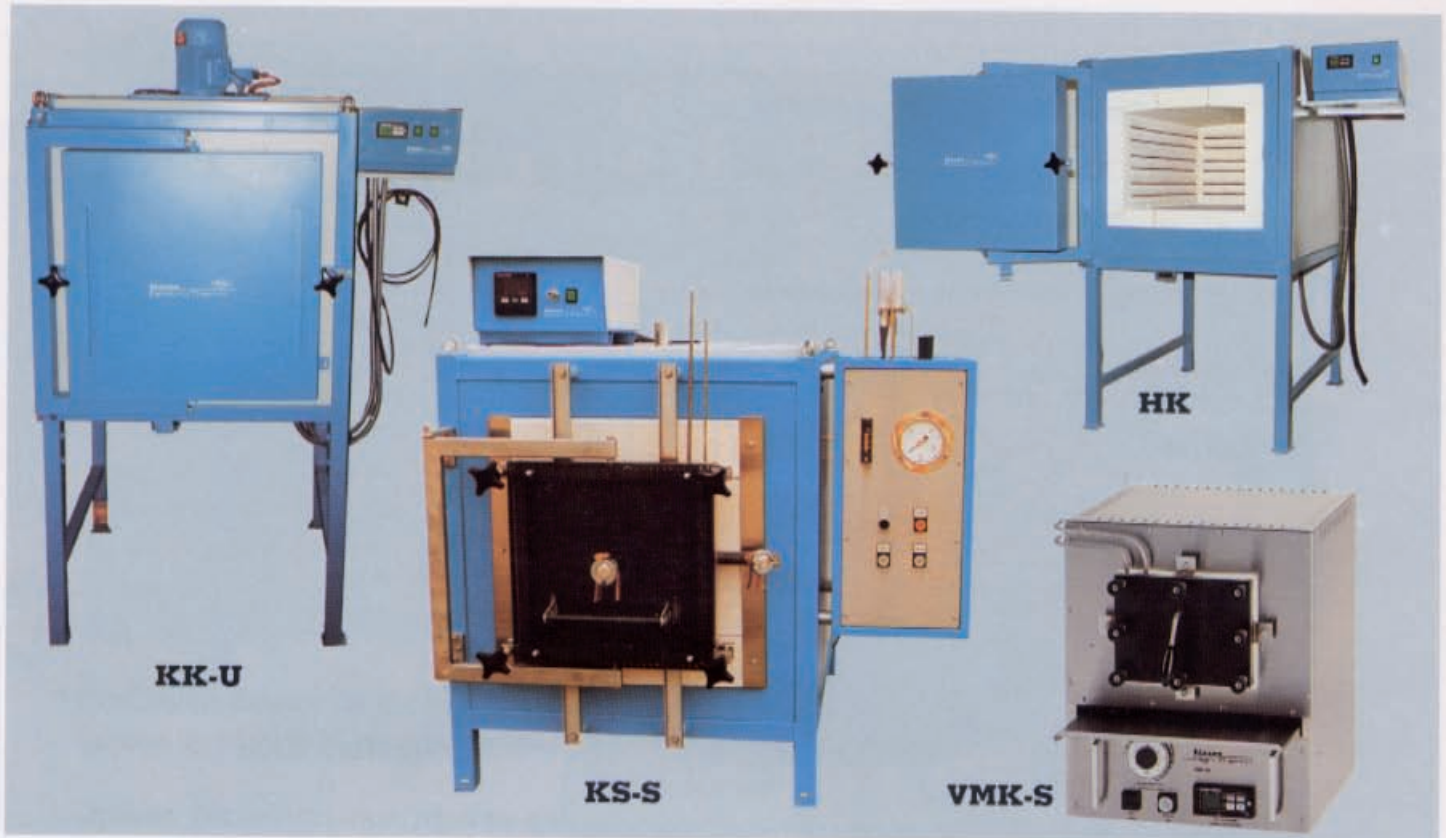
The users of

Linn Hardening and Tempering Furnaces

are given below several guidelines for effective and successful heat treatment in a generally intelligible manner. Emphasis is placed here on those processes that come under the first group, and are based on radical heating of the workpieces. These include the annealing process, hardening, tempering and hardening with subsequent tempering. Thermochemical processes are only dealt with in a supplementary manner.

Some examples of Linn Hardening and Tempering Furnaces are given below.

Linn Hardening and Annealing Furnaces



HK: Solid small-chamber furnace for annealing, hardening, powder carburizing and stress relief. T_{\max} 1200 °C; optionally up to 1300 °C, lifting door and inert gas version.

KS-S: Chamber furnace with heat resistant, gas-tight steel muffle for operation under controlled atmosphere. T_{\max} 1050 °C. Extensive options such as after-burner, exhaust, burn-off and vacuum operation, cooling trap in the gas outlet.

VMK-S: Fibre-insulated universal furnace up to 1050 °C, optionally 1100 °C, with heat resistant, gas-tight steel muffle insert for operation under controlled atmosphere, water-cooled door flange. Optionally vacuum-tight for temperatures up to 700 °C, after-burner, exhaust and gas feeding.

KK-U: Chamber furnace with forced convection for heat treatment with very good temperature distribution and fast heat transfer, T_{\max} 850 °C. Opt. 950 °C.

AK/AHK: Solid small-chamber furnace for annealing tempering and soft annealing. Typical applications: in hardening shops, test workshops and laboratories. Air circulation by means of a fan fitted in the door for improved temperature distribution and improved heat transfer T_{\max} 800 °C.

Options: Temperature increase to 950 °C; AHK version with second swivel door without fan, for temperature up to 1200/1300 °C, alternately for tempering or hardening, charging plate.



Linn Hardening and Tempering Furnace



Heatlab KKH

Vacuum chamber furnace for heat treatment under vacuum or in controlled atmosphere with forced gas cooling up to max. 6 bar over pressure, T_{\max} 1300 °C, or for use as a brazing furnace.

Options:

- Graphite version up to 1900 °C
- Molybdenum cold wall version up to 1600 °C
- Integrated gas re-cooling and circulation
- Process control according to customer specifications



Continuous furnace for the heat treatment of small components (e.g. springs) as a continuous belt furnace up to 1100 °C or as a continuous roller-hearth furnace up to 1350 °C

Options: Air recirculation, separate guideways, multi-zone heating



Electric furnace for the hardening of machine blades and similarly long components up to 1320 °C

Options: Multi-zone heating, air recirculation, two doors' for pushing through

1. A certain amount of theory is essential!

To understand the processes for heat treating ferrous materials, some theoretical observations are initially provided and some basic terms are explained.

1.1. The crystal lattice of iron

In their solid form, our metallic materials generally have a crystalline structure. The geometric arrangement of the atoms, which we shall view as the smallest components in our theoretical discourse, are precisely specified in the crystal lattice. With ferrous materials, they are always cubic in nature and depending on the temperature form a **cubic space centred** (csc) or a **cubic face centred** (cfc) lattice. The conversion from the csc to the cfc lattice occurs during heating and cooling when exceeding, respectively falling below a temperature of 911 °C. Where the structure is concerned, one talks of the conversion from ferrite (α iron) to austenite (γ iron). The ferrite converts during heating to austenite and when cooled austenite converts to ferrite.

Fig. 1 shows both of the characteristic atom lattices of iron. Apart from the 4 corner atoms, the **cubic space centred** elementary cell of ferrite contains one atom in the centre of the cube. The corner distance of the atoms (lattice spacing) is 0.286 nm. In addition to the already known 4 corner atoms, the **cubic face centred** elementary cell of austenite also has one iron atom in the centre of each face. Due to this lattice structure of austenite, the atoms are more tightly packed together and the specific volume is smaller than that of ferrite, the effect of which we shall deal with later on. The lattice distance is 0.357 nm.

The technical ferrous materials, suitable for heat treatment, generally consist of alloys, which form mixed crystals. Depending on whether one iron atom is replaced by a foreign atom, or foreign atoms are inserted in the lattice gaps, one speaks of substitution mixed crystals or interstitial mixed crystals. An exchange of the atoms is only possible, where the foreign atoms are of a similar size to the iron atoms. These include, e.g. the elements Cr, V and Mo, to name but a few. Where the foreign atoms are smaller than the iron atoms, an interstitial deposit in lattice gaps takes place. The most important element here however is carbon. Nitrogen and hydrogen are also important in this context.

To summarize this mini lattice guide, every expert in heat treatment can proudly claim of being able to store and move fixed atoms in a crystal lattice. Who else can do that?

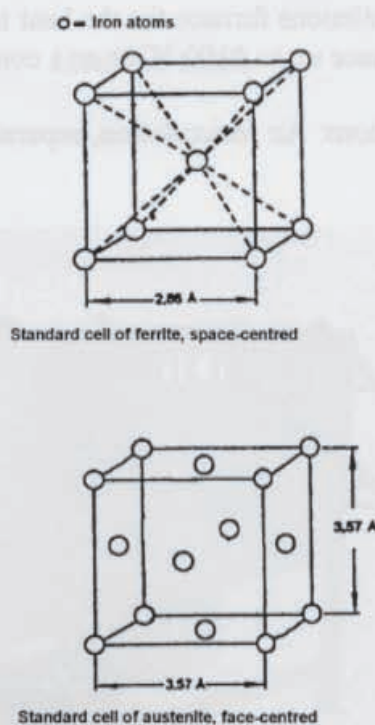


Fig. 1

1.2. The iron carbon diagram

Amongst the alloy elements, which determine the characteristics of steel, as already indicated, carbon takes first place. Its decisive importance for heat treatment can be derived, as a function of the temperature, from the constitutional diagram iron-carbon/system iron-iron carbide (cementite) (Fig. 2). This shows the stability ranges of iron and cementite in equilibrium. For the heat treatment expert, the range up to 2.06 weight % carbon is of interest. With temperatures above the curve GSE, the iron-carbon alloys are present in an austenitic state. This is known as a solid solution. From a carbon content $> 0.8\%$, in addition to austenite, undissolved carbides are also present, which only dissolve once the curve SECD is exceeded.

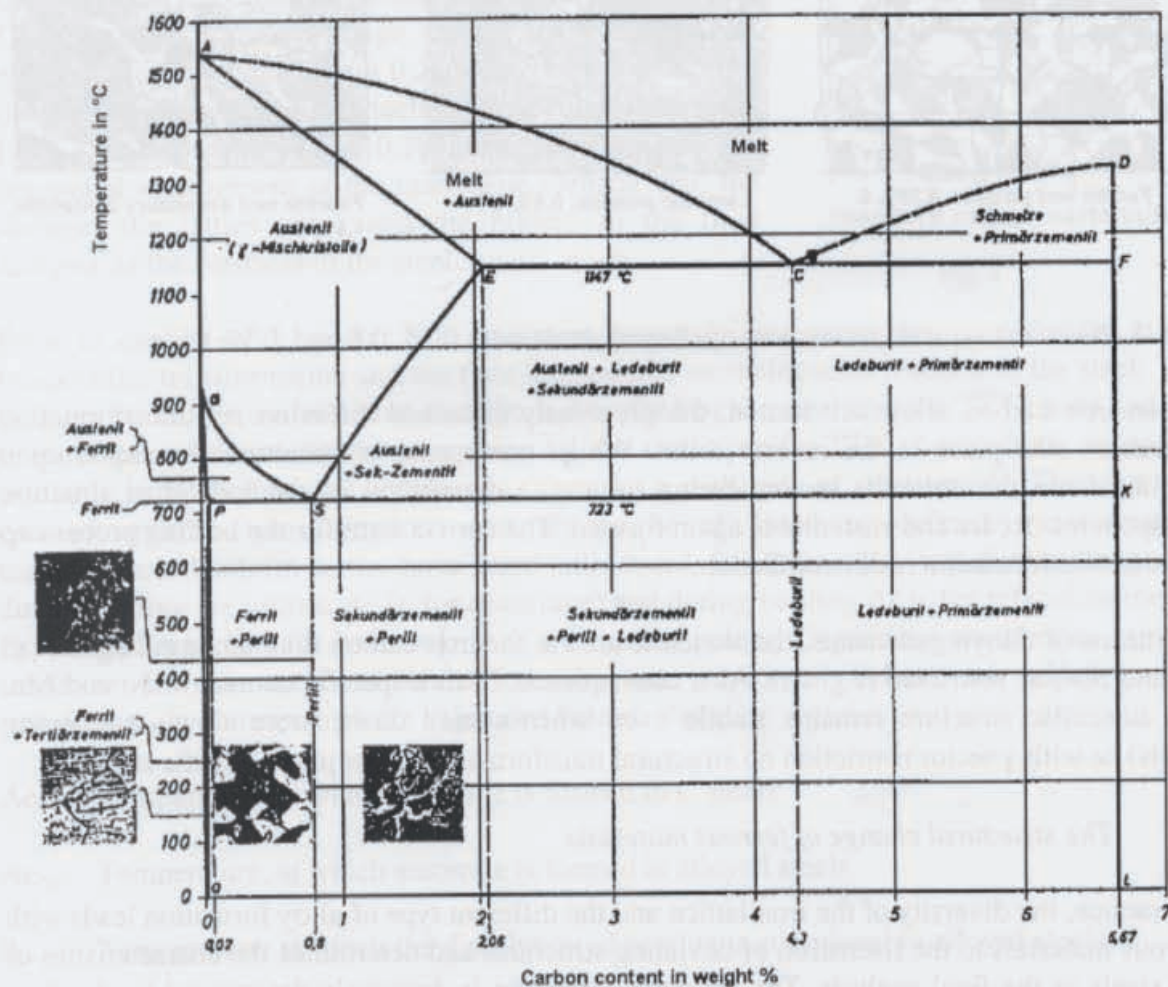


Fig. 2

In steel with 0.8% carbon, when cooling down from the austenitic sector, upon falling below a temperature of 723 °C, without preprecipitation of pearlite, a mixture of ferrite and streaky cementite is formed (point S). With carbon contents $< 0.8\%$, ferrite is initially deposited from the austenite along the curve GS, which with the carbon enriched austenite is transformed into pearlite after falling below the curve PS, so that a mixed structure of ferrite and pearlite is then present here. If the C content exceeds 0.8%, cementite is formed along the curve SE until the austenite reduced to 0.8% carbon is also transformed into pearlite upon falling below the curve SK. The produced structure consists of secondary cementite, deposited from the granular limits of the former austenite granules, and pearlite.

The specified processes during the cooling of iron-carbon alloys are always preceded by carbon diffusion in the solid (austenite). Ferrite is formed in the carbon reduced zones and cementite (iron carbide) in the carbon enriched areas.

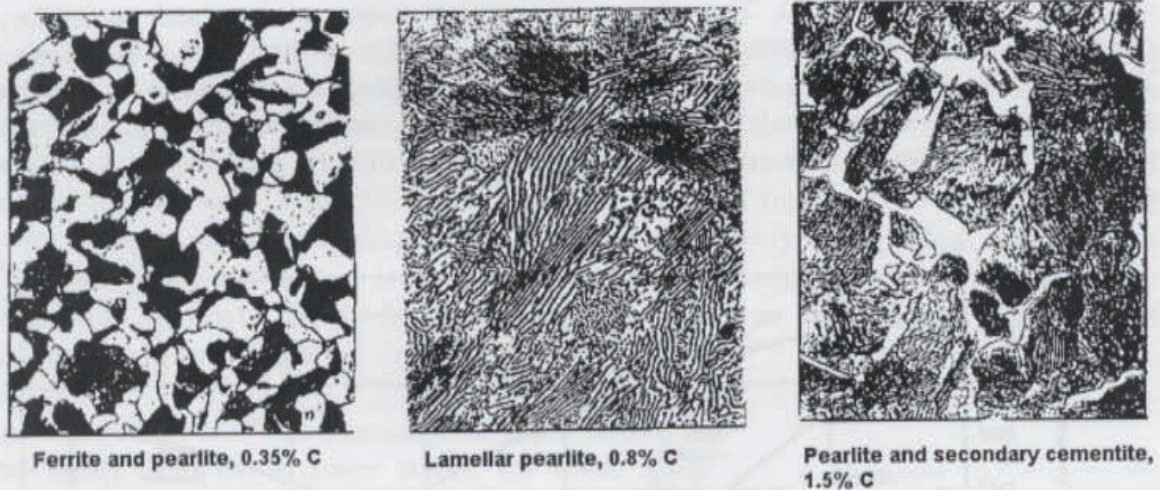


Fig. 3

Fig. 3 shows the typical structure of unalloyed steels with 0.35, 0.8 and 1.5% C

When iron carbon alloys are heated, the previously described diffusion and transformation processes take place in the reverse order. Whilst one speaks of structural formation upon cooling from the austenite sector, during heating, a dissolution of the individual structure components occurs and austenite is again formed. The correct term for the heating process up to austenite formation is austenitization.

By means of alloying elements, the austenite area in the iron-carbon diagram is enlarged (e.g. Ni and Mn) or restricted (e.g. Cr). As a consequence, from a specific content of Ni and Mn, the austenitic structure remains stable even when cooled down more slowly (austenitic steels) or with γ sector restriction no structural transformation takes place (ferritic steels).

1.3. The structural change of ferrous materials

In practice, the diversity of the iron lattice and the different type of alloy formation leads with ferrous materials to the formation of deviating structures and determines the characteristics of the steels in the final analysis. The structure formation is decisively determined by the time factor. Reference to this has already been made in the explanation of the iron-carbon diagram. The structures presented there only applied for the state of equilibrium, that is there was always adequate time available for diffusion of the carbon. If the steel is cooled more rapidly, the carbon only has a short diffusion time. The movement of the carbon atoms is restricted. With a cooling velocity of around 15 °C per second, the transformation from austenite to ferrite and the precipitation of carbides is more or less suppressed. The pearlite formation is shifted to temperatures below 723 °C, and also takes place with lower carbon contents than 0.8 weight %. The pearlite structure becomes increasingly finely striated with increasing cooling velocity. Even briefer diffusion paths lead in the end to bainite. The austenite changes to ferrite without prior carbon reduction, with simultaneous precipitation of carbides, whereby the ferrite structure deviates slightly from the known cubic form.

With very high cooling velocities, the austenite transforms into martensite. This is a structure that is produced within fractions of a second due to supercooling (quenching), with needle shaped crystals and is extremely hard. The formation of iron carbide is evidently totally suppressed by this. The carbon is still in the mixed crystal, even though according to the iron-carbon diagram, at room temperature no more carbon is soluble in the ferrite mixed crystal. Accordingly, a forced solution of carbon is present that causes a distortion in the cubic iron lattice. A tetragonal element cell is formed, which is characterized by a defined deposition of carbon atoms resulting in the elongation of one axis of the cubic element cell and a uniform reduction of both the others. Fig. 4 shows the martensite lattice with the probable location of the C atoms. Naturally, this tetragonal distortion is dependent on the carbon content. It rises with the increased C content. Within the range up to 1.8% carbon, an elongation of the C axis from 0.286 nm to about 0.306 nm occurs with simultaneous reduction of both the other axes from 0.286 nm to about 0.283 nm. The greater the tetragonal enlargement of the martensite element cell, the stronger the lattice stress and the higher, in the final analysis, is the hardness of the steel.

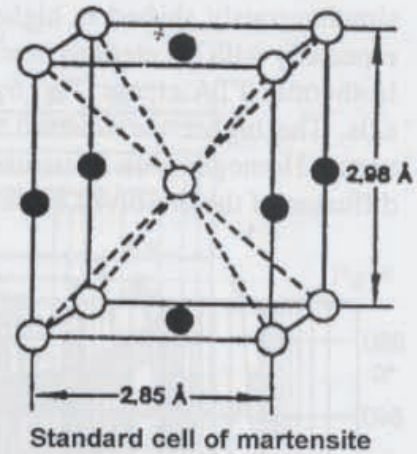


Fig. 4

Prior to dealing with special heat treatment processes, we must also consider the time-temperature transformation and the time-temperature austenitization reaction of the steel. The time-temperature transformation reaction is described by the steel specific TTT charts and the time-temperature austenitization reaction by the steel specific TTA charts. Both charts are available as isothermic and continuous charts for a multitude of steel brands. The start and end of specific transformations can always be allocated to defined transformation temperatures. Uniform terms have been introduced for these. The transformation points during heating are termed A_c (c for chauffage) and during cooling A_r (r for refroidissement). Especially important for heat treatment are the A_c points. Depending on whether pure C steels or alloyed steels are under consideration, additional indices are added to the transformation points, which are explained below:

- A_{c1} : Temperature, at which austenite is formed in C steels
- A_{c1b} : Temperature, at which austenite is formed in alloyed steels
- A_{c1c} : Temperature, at which the dissolution of pearlite is completed in alloyed steels
- A_{c3} : Temperature, at which the transformation of ferrite into austenite is completed
- A_{cm} : Temperature, at which the cementite has been completely transformed into solution

1.3.1. The TTA chart

The TTA charts enable conclusions to be made for the austenitization temperature and time required for hardening. 2 types of time-temperature austenitization charts are available for the heat treatment technique. In the continuous TTA chart (Fig. 5), austenitization is registered by continuous heating with different heating velocities from room temperature. It is clearly evident that the transformation starts earlier with increased heat velocity, but is simultaneously shifted to higher temperatures. One aspect that must be taken into account, especially with accelerated heating processes.

Isothermal TTA charts (Fig. 6) are read off in a time related manner in parallel to the time axis. The higher the selected temperature, the earlier the start of transformation and vice versa. Homogeneous austenite is only achieved after prolonged soaking times through diffusion of the dissolved carbon atoms.

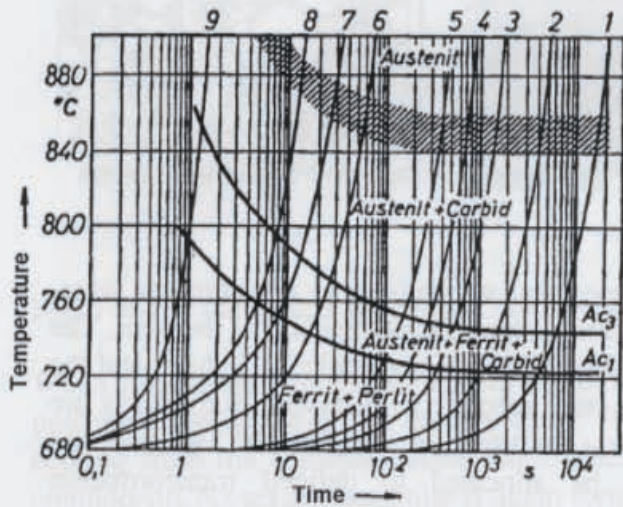


Fig. 5

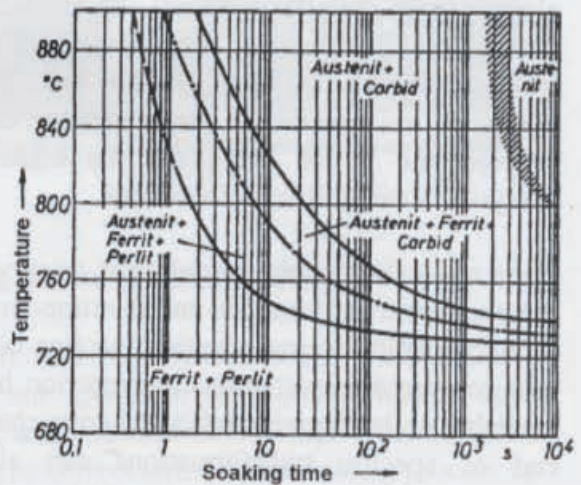


Fig. 6

As a matter of principle, it must be pointed out that the TTA charts are steel specific and are only valid for a specific initial structure. Fig.7 shows the curve for the austenite transformation of one type of steel with differing formation of the annealed structure by means of a dilatometric recording. The closely striated lamellar pearlite transforms at lower temperatures and in the more restricted temperature range into globular shaped pearlite.

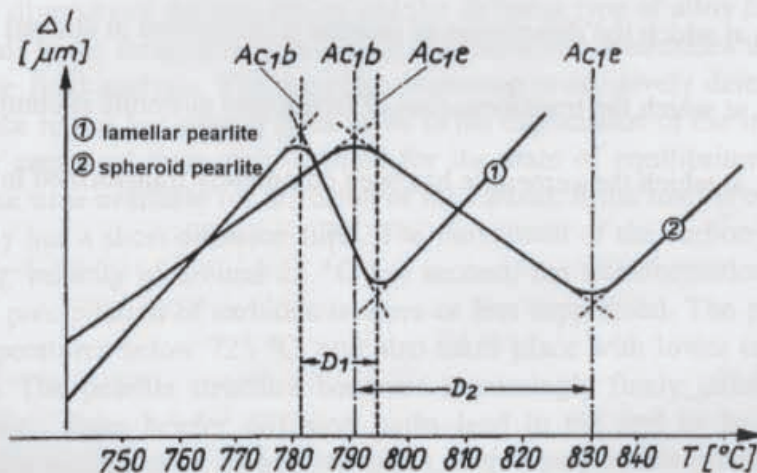


Fig. 7

1.3.2. The TTT chart

Whilst the austenite formation during heating is described with the TTA charts, the transformation of steel during cooling (quenching) from the heterogeneous austenite sector is described with the TTT charts. Here too, we differentiate between continuous and isothermal charts. Figs. 8 and 9 show a comparison of both charts.

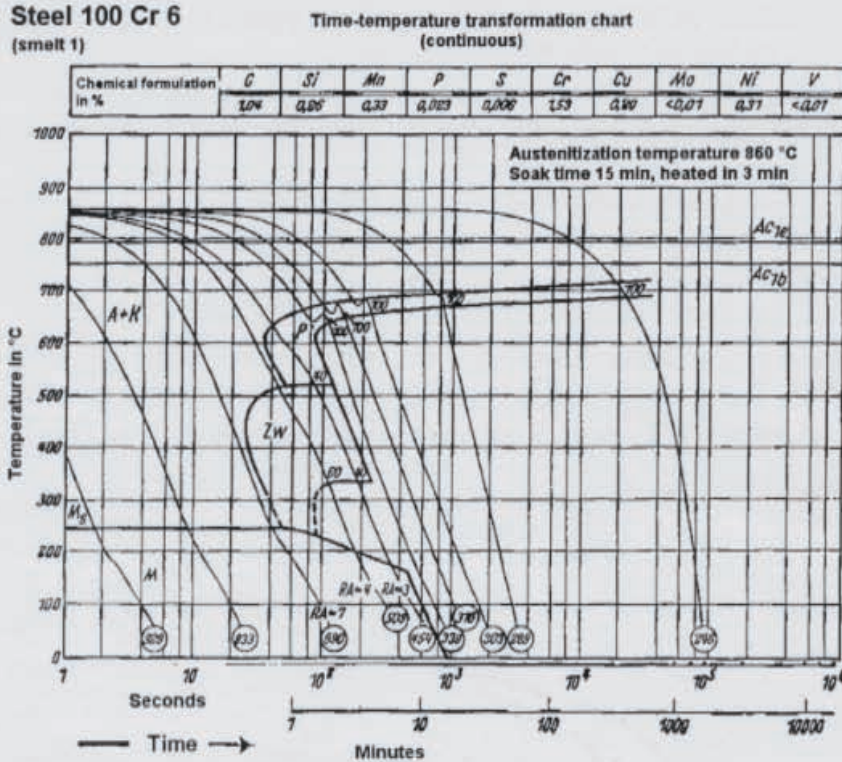


Fig. 8

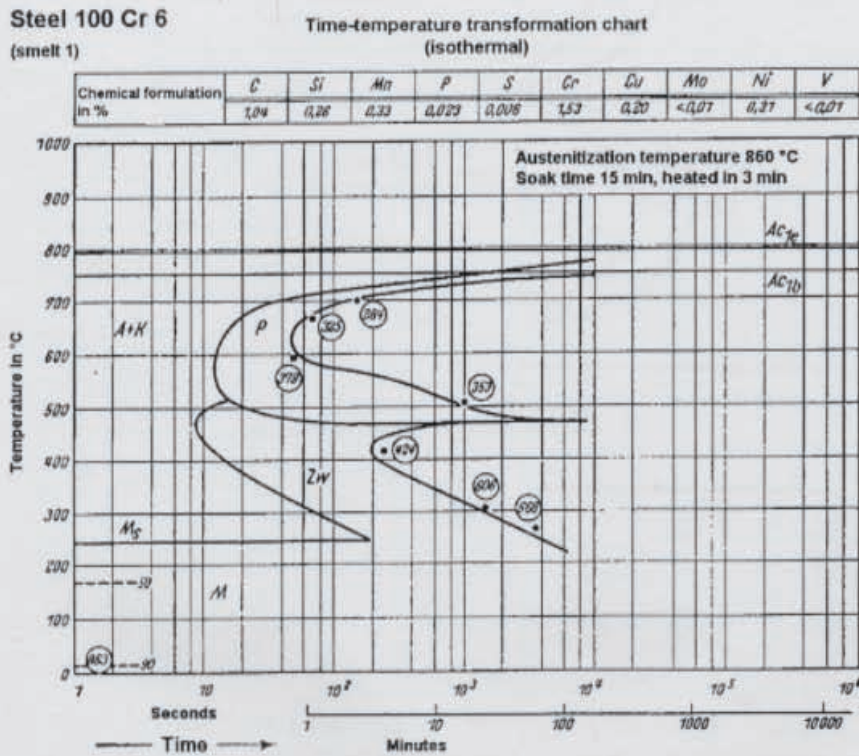


Fig. 9

For the practitioner, it is important to know that the isothermal chart may only be read parallel to the time axis and the continuous chart along the recorded cooling curves, and that both are only strictly valid for one type of steel with the stated chemical formulation. In general, the following information can be obtained from the TTT charts.

- Start and end of transformation with indication of the produced structure
- Structure quantities in % in way of the intersecting points of the pertinent cooling curve with the lines for the end of the transformation
- Achievable hardness in HV or HRC after the end of the transformation
- Temperature for the start (Ms) of martensitic transformation
- Cooling velocities as parameters or in °C/min.

Changes in the transformation behaviour are possible by altering the austenitization conditions. The location of the transformation ranges is considerably influenced by the various alloying elements of the steel. This is shown diagrammatically in Fig. 10.

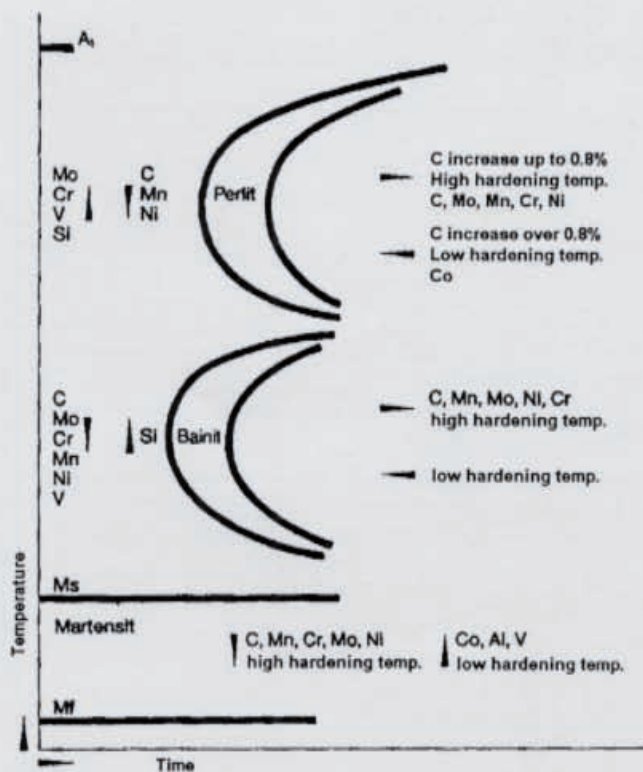


Fig. 10

With the TTT charts, the hardening expert is provided with an aid from which a mass of valuable information can be obtained for practical work. Unfortunately, far too little of this information is utilized.

1.4. The hardenability

The reaction of steel to austenitization and fast quenching is described as the hardenability. This is a steel specific characteristic, which determines the hardness that can be achieved in way of the workpiece surface and across the cross-section. The potential hardness increase and the maximum hardness obtainable is derived from this.

The potential hardness increase describes the maximum hardness of a steel that is achievable under optimum conditions. This is primarily determined by the amount of carbon dissolved in the austenite. Fig. 11 shows the achievable surface hardness after quench hardening, as a function of the carbon content. From a C content of $> 0.6\%$ full martensitic hardness is achieved.

The maximum hardness obtainable describes the possible hardness within the workpiece. This is determined by the critical cooling velocity for martensite formation in the individual workpiece cross-sections during quenching and, apart from the carbon content, is also dependent on the content of alloying elements. Fig. 12 shows the maximum hardness behaviour obtainable for an alloyed tool steel as a function of the characterizing cross-sections. Greater cross-sections lead to shell hardening.

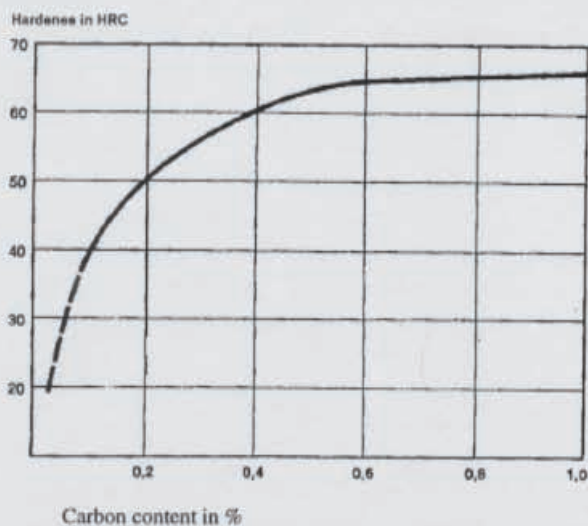


Fig. 11

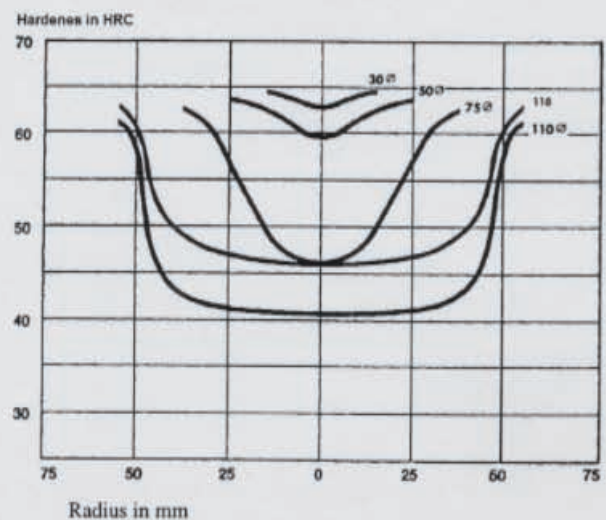


Fig. 12

With these final observations on the hardness obtainable, we have completed the theoretical section and now come to the "hot" part of heat treatment.

2. The terminology for steel and the classification and designation of steel

Prior to dealing with heat treatment in practice, it is essential to have some idea about the classification of steel and to be informed about the most important aspects concerning the designations of steel together with its abbreviations. That is to say, we must briefly deal with the classification and designation of steel.

According to EURONORM, steel is the term used to describe all ferrous materials, which are suitable for heat forming and, with the exception of a few Cr enriched types, have a maximum C content of 2 weight %.

Depending on the material balance sheet (chemical formulation), one speaks of *unalloyed* (pure C steels) and *alloyed steels*, which are further subdivided according to their service properties in *base*, *high-grade* and *stainless steel*.

In our case, we shall limit ourselves to an explanation of the application specific steel designations for unalloyed and alloyed, heat treatable and tool steels.

The basis for the steel abbreviations used in DIN EN 10027 is their chemical formulation. The prefixed numeral indicates the mean carbon content x 100, this is followed by the abbreviation of the added alloying elements. The numerals appended to the alloying symbols are the mean values of the alloying additives, taking into account the following multipliers:

Co, Cr, Mn, Ni, Si and W	= x 4
Al, Cu, Mo, Ti, V, Nb, Ta, Be, Pb and Zr	= x 10
N, P, S and Ce	= x 100
B	= x 1000

Where the content of Al < 0.1%, Mn < 1.0%, Si < 0.5% and Ti < 0.15%, this is unalloyed steel. Low alloyed steels generally do not have more than 5% of alloying ingredients.

High-alloy steels always exceed the 5% limit. Where an alloying element is present in the steel with > 5%, no multipliers are used and the letter "X" appears prior to the numeral with the carbon content.

Several examples are now given to make it easier to understand.

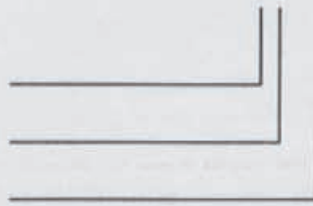
Example 1:

Ck 60 (EN 10083-1; DIN 1652-4)

Mark for unalloyed steel

Stainless steel with low P and S

% carbon x 100



This is an unalloyed high-grade steel with 0.6% carbon

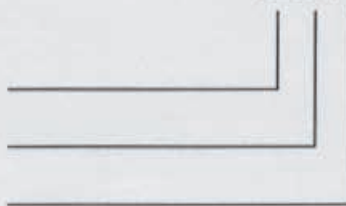
Example 2:

50CrV4 (DIN 17221)

% carbon x 100

Alloying element

% alloying element x factor



This is an alloyed heat treatable steel with 0.5% carbon, 1% chromium and < 0.2% vanadium

Example 3:

40CrMnMoS8-6 (DIN 17350)

% carbon x 100

Alloying element

% alloying element x factor



This is a tool steel with 0.4% carbon, 2% chromium and 1.5% manganese as well as < 0.2% molybdenum and sulphur

Example 4:

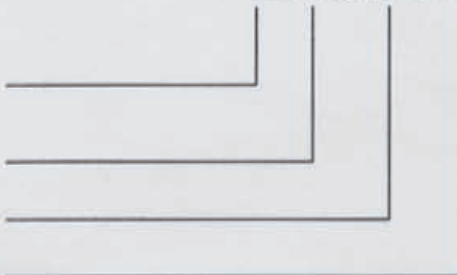
X155CrVMo12-1 (DIN 17350)

Mark for alloyed steel > 5%

% carbon x 100

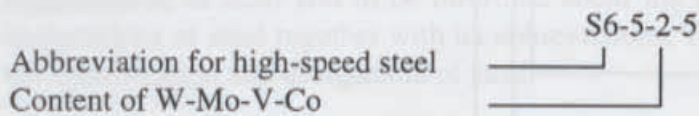
Alloying element

% alloying element



This is a high-alloy tool steel with 1.55% carbon, 12% chromium, 1% vanadium and 0.6% molybdenum.

The new abbreviations for high-speed steel deviates completely from the aforementioned. No indication of the carbon content is given. Instead of the "X" for high-alloy steels, a "S" is inserted, followed by details of the content for W, Mo, V and Co. An example is given below:



Additional letters and numerals are used for describing the special characteristics of steel. For the heat treating expert, some of the added codes are important. Here are some examples of these:

- BG heat treated to ferrite-pearlite
- G soft annealed
- GKZ annealed to globular carbide
- K cold-drawn
- N normalized
- S stress-relieve heat treated
- U untreated
- V hardened and tempered
- W tool steel

The steel abbreviation "100Cr6 GKZ" thus implies that this is a tool steel with 1% carbon and 1.5% chromium, which has been subjected to special annealing up to the globular formation of cementite.

This completes this section. Some heat treatable and tool steels are listed in a tabulated manner below, with details of the heat treatment. From the multitude of data obtainable from both tables, and from the differing manner of showing the tables for the individual steel groups, one can see the multifarious nature of heat treatment in practice.

Unlegierte Werkzeugstähle

Unalloyed Tool Steel		Kurzname	Weichglühen Recuit d'adoucissement	Härten mit Abschrecken in		Härteannahme Prise de dureté pick up of hardness	Einhärtetiefe Profondeur de pénétration de tempe Hardness penetration	Anlassen
Stoff-Nr.	Norme No.	Symbole	°C	Trempe à		HfC	mm	Faire revenir Temper
Standard No.	Symbol	Wasser Eau Water		Öl Huile Oil	°C			
1.1520	C 70 W1		680-710	•	-	63	2,5-3,5	180-300
1.1525	C 80 W1		680-710	•	-	64	2,5-3,5	180-300
1.1663	C 125 W		680-710	•	-	65	2,0-3,5	180-300

Vergütungsstähle

Heat-Treatable Steels		Kurzname	Weichglühen Recuit d'adoucissement	Normalglühen Normaliser Normalizing	Härtetemperatur mit Abschrecken in		Anlassen
Stoff-Nr.	Norme No.	Symbole	°C	°C	Température de traitement pour tremper à		Faire revenir temper
Standard No.	Symbol	DIN			Wasser Eau Water	°C	
1.0501		C 35	650-700	860-890	840-870	-	540-680
1.0503		C 45	650-700	840-870	820-850	-	540-680
1.0601		C 60	650-700	820-850	800-830	-	540-680
1.5223		42 MnV 7	640-680	860-890	840-870	-	480-650
1.6511		38 CrNiMo 4	650-700	850-880	820-850	-	540-680
1.7035		41 Cr 4	680-720	840-880	820-850	-	540-680
1.7225		42 CrMo 4	680-720	840-880	820-850	-	540-680
1.7707		30 CrMoV 9	680-720	850-880	840-870	-	540-680
1.8195		50 CrV4	730-780	840-970	820-850	-	540-680

Werkzeugstähle

Tool Steel

Stoff-Nr. Norme No. Standard No.	Kurzname Symbole Symbol DIN	Weichglühen Recuit d'adoucissement Soft annealing °C	Härten			Trempe			Hardening			Anlassen Faire revenir temper °C	Härtewerte HRC ca. Valeurs de dureté HRC ca. Hardening values HRC ca.			
			Wasser Eau Water	Öl Huile Oil	Luft Air Air	Wasser Eau Water	Öl Huile Oil	Luft Air Air	gehärtet trempé hardened	tempré hardened	fait revenir à °C tempered to °C		100	200	300	400
1.2067	100 Cr 6	740-770	-	•	-	-	•	-	-	•	100-180	64	64	63	50	-
1.2080	X 210 Cr 12	800-830	-	•	•	•	•	•	•	•	180-250	63	63	62	50	58
1.2083	X 42 Cr 13	750-800	-	•	-	-	•	-	-	-	150-300	58	58	57	54	-
1.2311	40 CrMnMo 7	580-600	-	•	-	-	•	-	-	180°C	500-650	64	63	60	58	58
1.2379	X 155 CrVMo 12 1	840-860	-	•	-	-	•	-	-	•	180-250	63	63	61	58	59
1.2601	X 185 CrMoV 12	800-830	-	•	-	-	•	-	-	•	180-250	63	63	61	58	59
1.2842	90 MnCrV B	690-720	-	•	-	-	•	-	-	•	150-250	64	64	62	58	-

Warmarbeit

Hot Forming

Stoff-Nr. Norme No. Standard No.	Kurzname Symbole Symbol DIN	Weichglühen Recuit d'adoucissement Soft annealing °C	Härten			Trempe			Hardening			Anlassen Faire revenir temper °C			Zugfestigkeit Résistance à la traction Tensile strength - N/mm ²			R _m Gebrauchshärte Résistance de service Working resistance N/mm ²		
			Wasser Eau Water	Öl Huile Oil	Luft Air Air	Wasser Eau Water	Öl Huile Oil	Luft Air Air	gehärtet trempé hardened	tempré hardened	fait revenir à °C tempered to °C	400	450	500	550	600	650		700	
1.2343	X 38 CrMoV 5 1	760-780	-	•	-	-	•	-	-	•	550-650	1950	1950	2060	1910	1620	1230	980	1180-1770	
1.2344	X 40 CrMoV 5 1.	750-780	-	•	-	-	•	-	-	•	550-650	2010	1960	2060	1960	1720	1320	1130	1180-1770	
1.2581	X 30 MCrV 9 3	740-780	-	•	-	-	•	-	-	•	600-700	1770	1570	1720	1770	1670	1470	1080	1180-1770	
1.2767	X 45 NiCrMo 4	610-630	-	•	-	-	•	-	-	•	350-650	56**	1620	1520	1420	1370	1270	1180	-	1180-1870

Schnellarbeitsstähle

High-Speed Steel Tools

Stoff-Nr. Norme No. Standard No.	Kurzname Symbole Symbol	Weichglühen Recuit d'adoucissement Soft annealing °C	Härtevorgang				Procédé de trempe				Operation of hardening				Anlassen Faire revenir Temper °C	Anlaßhärte Dureté arés revenu As tempered hardness >= HRC
			Anwärmen Echauffer Heat up °C	Vorwärmen 1. Stufe Préchauffage 1. degré Preheating 1. step °C	Vorwärmen 2. Stufe Préchauffage 2. degré Preheating 2. step °C	Härten °C	Trempe Öl Huile Oil	Härten °C	Trempe Wärmbad Bain Chaud Hot quenching 550 °C	Härten Luft Air Air	Anlassen Faire revenir Temper °C	Anlaßhärte Dureté arés revenu As tempered hardness >= HRC				
1.3343	S 6-5-2 (Dmo 5)	790-820	450-600	850	1050	1200-1240	•	•	•	•	•	•	540-560	64		
1.3344	S 6-5-3 (Emo 5 V 3)	770-820	450-600	850	1050	1200-1240	•	•	•	•	•	•	550-570	64		



3. Heat treatment in practice

After this "cold" theory, we now come to practical heat treatment. Even if things now become "hotter", it is not possible to do completely without charts and diagrams. Let us keep to the motto that a simple chart is frequently better than many words.

In the preface, the heat treatment process stage tasks were clearly defined. The material properties are altered by the heat treatment, so that good subsequent processing is possible during the production process, and the best behaviour is achieved during use (e.g. strength, wear etc.).

To achieve this successfully, specific technological sequences must be precisely complied with during practical heat treatment. These technological sequences are specified in the "heat treatment techniques". The steel used is the basis for their preparation. Other criteria are the size and the geometric shape of the workpieces as well as the plant technology available for the heat treatment. All in all the period of specific sectors determine the time-temperature sequences and thus has an effect on the specific type of heating and cooling to be used.

We have thus reached the most important individual processes of heat treatment, namely the heating and cooling of workpieces. The individual stages of heating and cooling, in accordance with DIN 17 022, are summarized in Fig. 13, whereby in the time and temperature dependent depiction, a differentiation is made between the workpiece surface and core. Fig. 14 additionally shows schematic cooling curves, such as those that can occur as a function of the various cooling possibilities.

The individual processes during heating and cooling of the workpieces are clearly defined in

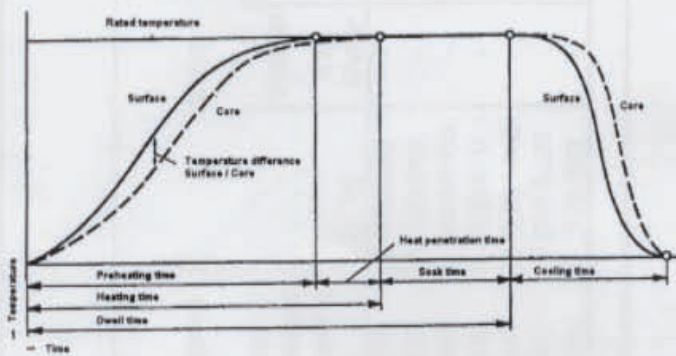


Fig. 13

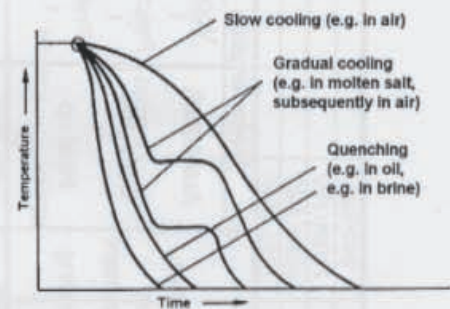


Fig. 14

The complete time from inserting the workpieces in the furnace heated to the rated temperature, until the start of quenching, is known as the dwell time. This consists of the heating time and the soak time. The heating time comes to an end when the rated temperature is achieved in the core of the workpiece. The heating time consists of the warm-up time, that is the time in which the required temperature is reached on the surface of the workpiece, and the heat penetration time. This is difficult to register, since it depends on a multitude of influencing variables. This includes the level of the rated temperature, the thermal conductivity of the material, the workpiece size, the coverage density in the furnace and the heat transfer. Accordingly, there are only very general details available on the heating time. Fig. 15 provides the heating time in a chamber furnace for characteristic cross-sections when heating from room temperature to 500, 600, 800, 850 and 1000 °C. These can be used as reference data. It is also possible to determine the heating and soaking time for various workpiece geometries via the form coefficients. Details are given in Fig. 16.

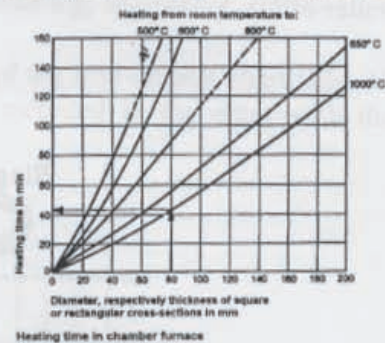
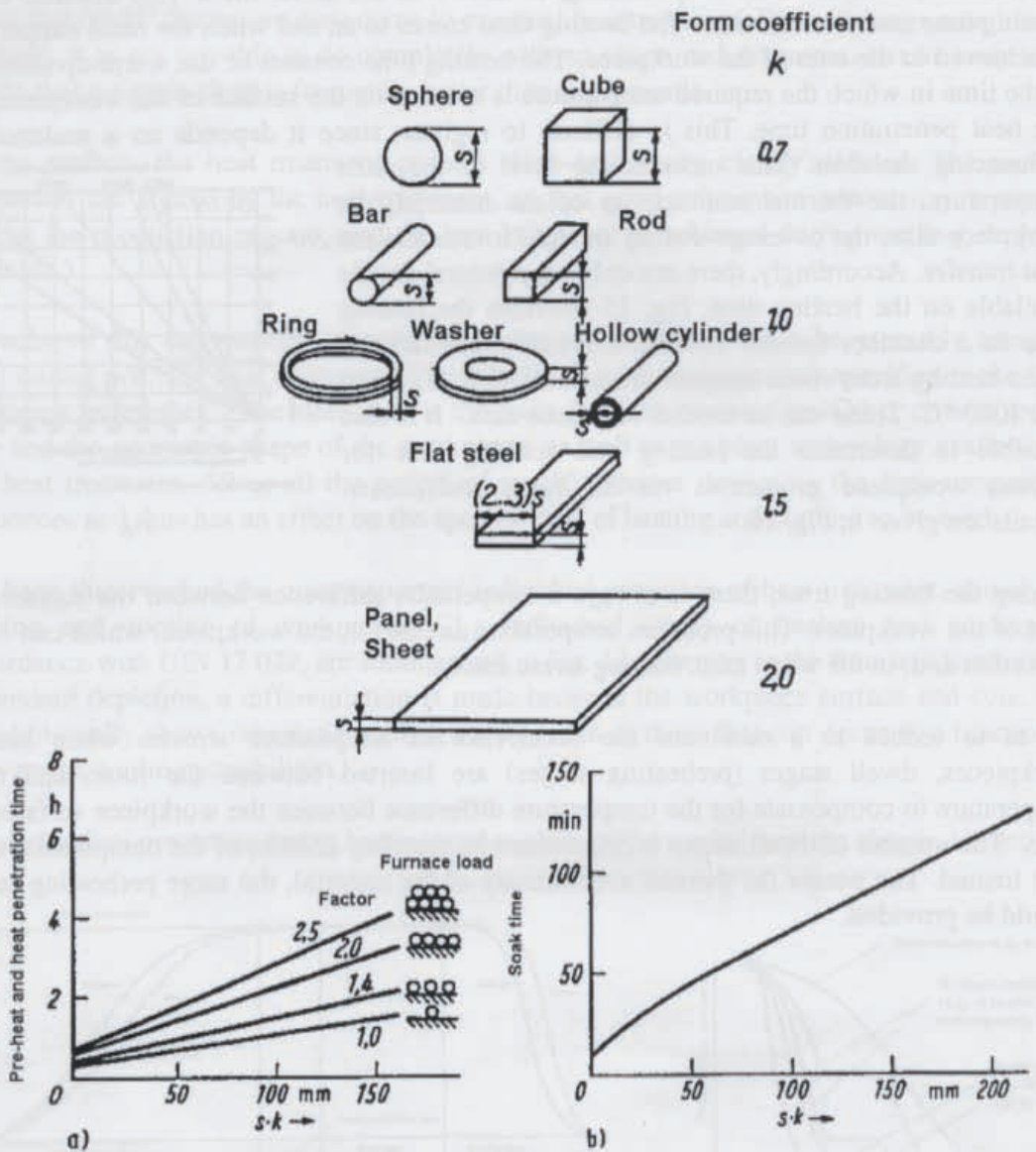


Fig. 15

During the heating time, there is always a temperature difference between the surface and core of the workpiece. This produces temperature stresses in the workpiece, which can cause distortion and, in the worst case, heating stress cracks.

So as to reduce to a minimum the occurrence of temperature stresses when heating workpieces, dwell stages (preheating stages) are inserted between the room and rated temperature to compensate for the temperature difference between the workpiece surface and core. The number of dwell stages is determined by the alloy content of the components to be heat treated. The poorer the thermal conductivity of the material, the more preheating stages should be provided.



a) Pre-heat and heat penetration time for heating to 600 °C for alloyed heat treatable steel

b) Soak time for normalizing and hardening

Recommended values:

Alloyed steel : 10 min for 10 mm diameter respectively thickness

Unalloyed steel : 15 min for 10 mm diameter respectively thickness

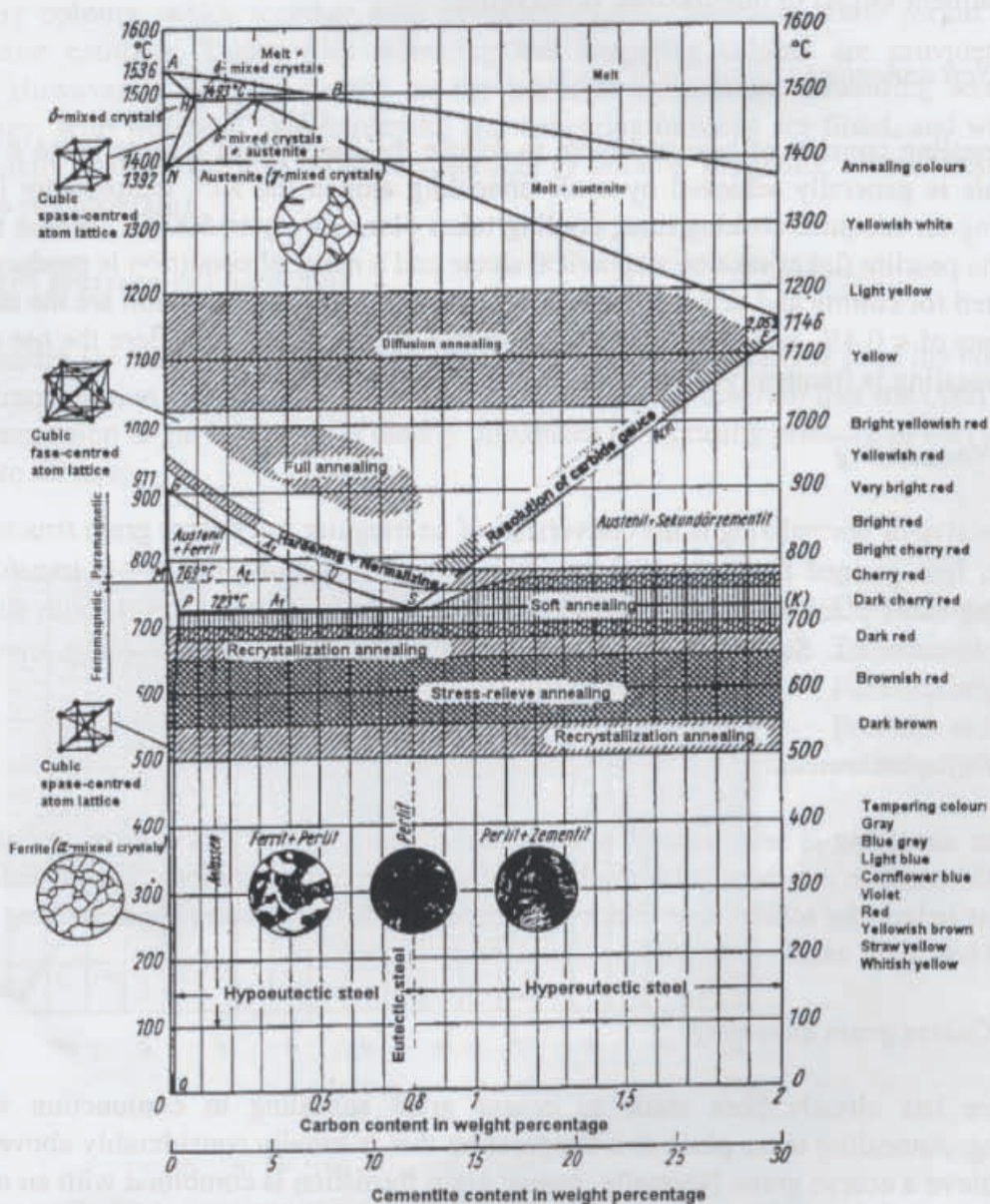
**Determining the time for heat treatment
(according to Blume)**

Fig. 16

3.1. Heat treatment processes

Based on the preferred applications of the Linn chamber furnace, the following heat treatment processes are to be discussed in more detail: Annealing, hardening, tempering, stress-relieve, subzero treatment and powder carburizing.

We shall start with a review of the well-known steel page of the iron-carbon chart (Fig. 17), using the most important annealing processes. They are recorded in the chart with their temperature ranges.



Steel page of the iron-carbon diagram with temperature ranges for the most important heat treatment processes (according to Blume)

Fig. 17

3.1.1. *Stress-relieve heat treatment*

As the heading indicates, during stress-relieve heat treatment, internal stresses are virtually eliminated in workpieces. A stress-free state is never achieved by this. That was the reason for replacing the heat treatment term "stress-free" with "low stress". Stress-relieve heat treatment takes place in the temperature range from 550 to 650 °C with subsequent slow cooling of the workpieces in a furnace to below 200 °C without a major alteration in the other material characteristics.

The stresses to be relieved, which can cause distortion during hardening and, in the worst case, can even result in cracks, are produced during the deformation processes (deformation at low temperatures), straightening processes and high volume machining. As a matter of principle, workpieces with complicated geometric shapes should be subjected to stress-relieve heat treatment as part of intermediate stress relief.

3.1.2. *Soft annealing*

Soft annealing consists of heat treatment to reduce the hardness of a material to a specified level. This is generally achieved by cycle annealing around the Ac1 temperature (723 °C). Following an adequate soaking time, cooling takes place slowly to 500°C. Whilst this takes place, the pearlite flakes take on a spherical shape and a material condition is produced that is best suited for cutting and deformation at low temperatures. One exception are the steels with C contents of < 0.4%, which tend to "smear" during turning or milling. Here the use of coarse grain annealing is frequently recommended.

3.1.3. *Normalizing*

The objective of normalizing is the conversion of an irregular and coarse grain structure into a uniform, fine grained ferrite-pearlite structure by twice carrying out $\alpha - \gamma$ transformation. Annealing takes place above Ac3, with hyper-eutectoidal steels above Ac1, with subsequent cooling in calm air. Steels which transform into martensite with air cooling, must not be normalized.

3.1.4. *Diffusion annealing*

Diffusion annealing is seldom used in the metal-working industry. It is used to balance out local differences in the chemical formulation of steel due to segregation. The annealing takes place just below the solidus line. Since the process is diffusion controlled, soaking times of up to 50 hours are usual.

3.1.5. *Coarse grain annealing*

Reference has already been made to coarse grain annealing in conjunction with soft annealing. Annealing takes place at a temperature that is usually considerably above Ac3, so as to achieve a coarse grain. Normally, coarse grain formation is combined with an unwanted loss of toughness. For this reason, coarse grain annealing should only be carried out where there are unbeatable difficulties during the metal cutting of steels with a low C content (e.g. case-hardened and heat treatable steels with C < 0.4%).

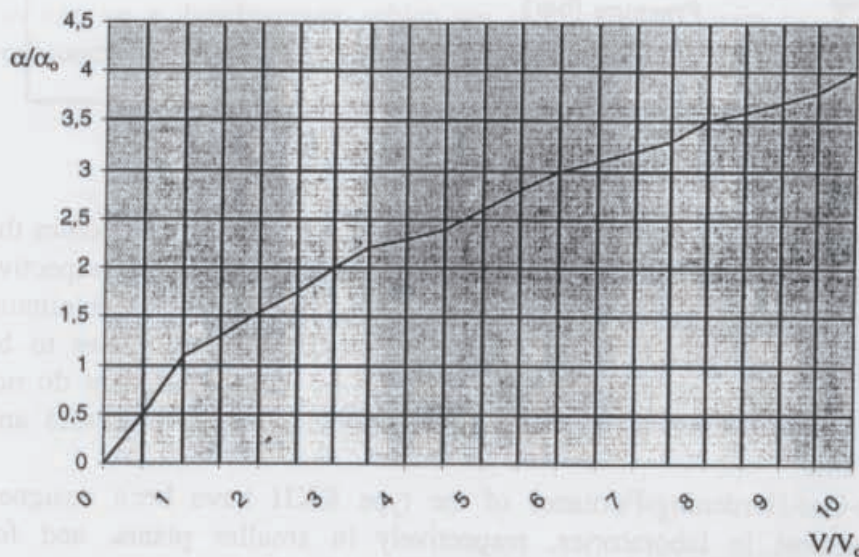
3.1.6. Recrystallization

Recrystallization annealing is defined as annealing at a temperature within the recrystallization sector after deformation has been carried out at a low temperature. Annealing is primarily carried out between the individual deformation stages during cold rolling or drawing, so as to counteract losses in toughness and strain hardening from cold work. No change in phase takes place during recrystallization annealing. The annealing temperature is dependent on the type of steel and is generally between 500 and 650 °C. A properly recrystallized structure is very fine-grained and where mechanical characteristics are concerned, is frequently preferred to the normalized varieties.

We have thus completed the chapter on "annealing" and can now turn our attention to "hardening". With reference to Fig. 17, attention must still be drawn to the annealing and tempering colours, which together with so-called thermo-chromium studs permit a rough temperature estimate. Tables with annealing and tempering colours are provided in the annexe. However, it is better to rely on the available temperature measuring and control technology, with which all Linn hardening and tempering furnaces are fitted, and which can be optionally also fitted with a program controller (9 storable programs, with a maximum of 20 ramps per program).

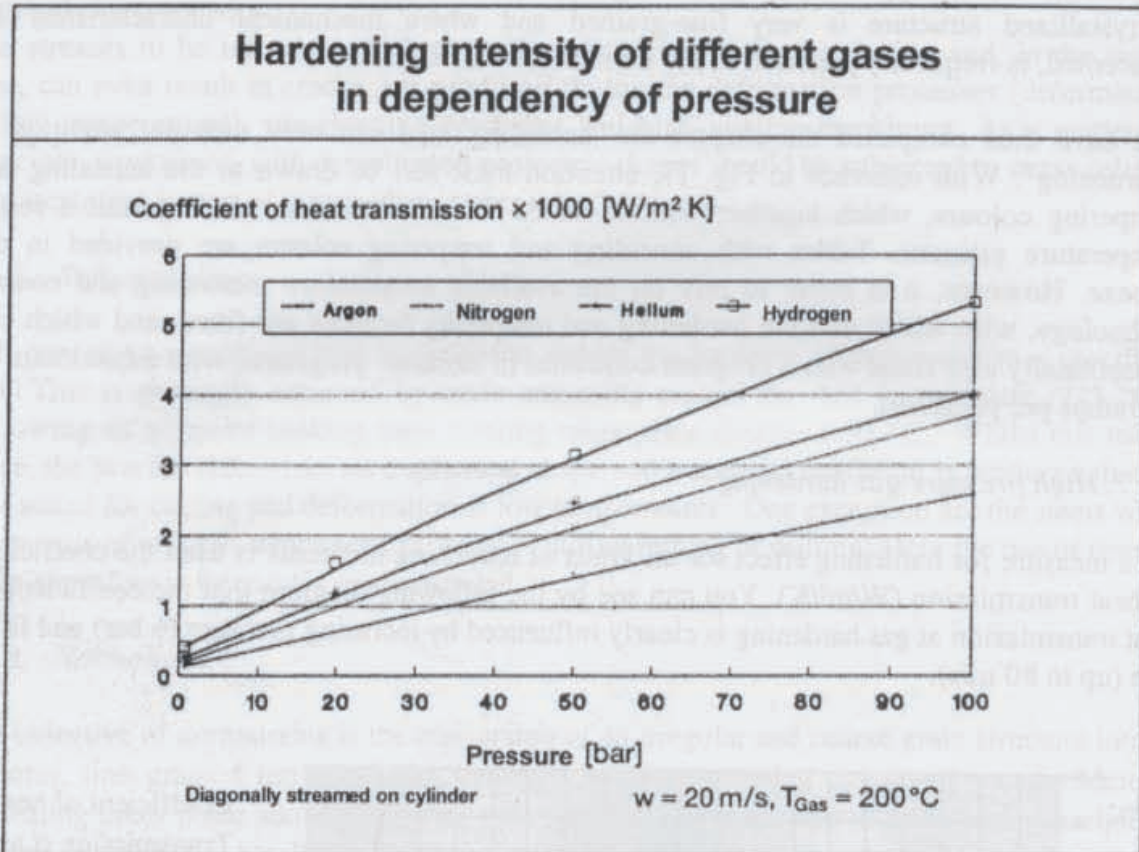
3.1.7. High pressure-gas-hardening

As a measure for hardening effect for all kinds of hardening mediums is used the coefficient of heat transmission ($W/m^2/K$). You can see by the following diagram that the coefficient of heat transmission at gas hardening is clearly influenced by increasing pressure (6 bar) and flow rate (up to 80 m/s).



Coefficient of heat Transmission α as Function of gas Pressure and gas velocity

There can also be an important influence caused by the type of gas used for hardening process. Especially by the application of light gases with high Thermal capacity and conductivity such as helium or hydrogen, the coefficient of heat transmission under equal conditions is increased by at least 40%. By additionally increasing pressure up to 20 bar using helium as hardening medium will be reached the same hardening velocities like by oil (1000 - 1500 W/m² / K).



As by variation of pressure, rotational speed of ventilator (rpm) and hardening medium the coefficient of heat transmission can exactly be adapted to the requirements of the respective steel grade and workpiece geometry it will be reached even hardness values at a minimum workpiece distortion. Another advantage of the High-Pressure-Gas-Hardening has to be emphasized: liquids and hardening mediums causing pollution of the environment do not have to be applied anymore. Moreover there are no additional cleaning processes and disposal of cleaning mediums

The Linn High-Pressure-Gas-Hardening-Furnaces of the type KKH have been designed specifically for heat treatment in laboratories, respectively in smaller plants, and for proceeding development.

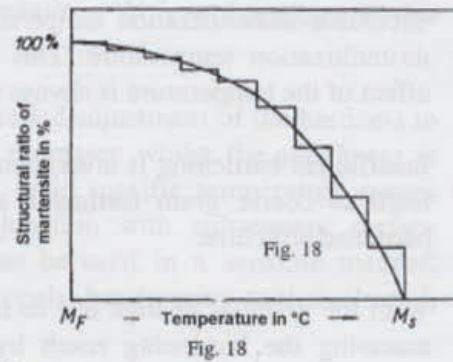
3.1.8. The hardening of components and tools

Hardening is understood to be austenitization with subsequent cooling at a velocity at which a considerable increase in hardness occurs through the formation of martensite in more or less large areas of the cross-section of a workpiece. Where cooling is carried out in sequence in two different coolants, without staying in the first coolant until thermal equilibrium has been obtained, one speaks of intermittent hardening. Where the cooling process is interrupted for temperature and/or stress compensation over

the workpiece cross-section, one speaks of interrupted hardening. Depending on the coolant used, one also speaks of water, oil, hot quenching and air hardening.

The formation of martensite from the austenite starts, as already noted in the theoretical section, upon reaching the M_s temperature and continues in accordance with the martensite mechanism, as shown in Fig. 18. Portions of new crystals with the characteristic acicular structure (Fig. 19) are created extremely fast (fractions of seconds) in the existing austenite (Fig. 19).

The martensite formation is completed upon reaching the M_f temperature. If the M_f point is not reached when quenching to room temperature, only partial martensite transformation occurs. The austenite that is not transformed, remains in the structure as "residual austenite". This can be of an advantage or can be a disadvantage, which we shall refer to again in conjunction with "subzero treatment".



Austenitization, that is to say the hardening temperature and soaking at the hardening temperature, have a considerable effect on the hardening outcome as well as on the cooling conditions. Accordingly, insufficient and excess hardening can occur due to an insufficient or excessive austenitization temperature, respectively inadequate or excessive soaking at the austenitization temperature. This is known as overheating, respectively over-timing. The effect of the temperature is always greater than the effect of the time.

Insufficient hardening is always combined with a loss of hardness. Excess heating and time leads to coarse grain formation and an increase in the residual austenite content in the hardened structure.

With the granular change due to improper austenitization, one has a simple verification for assessing the hardening result by means of a hardened fracture sample. If the fracture appearance is stringy to fine-grained and matt, the hardness is okay. A coarse-grained and sparkling fracture appearance always is an indication of excess heating or time.

One can also use the fracture sample in conjunction with hardness measurements, in a very simple manner to determine the best hardening temperature of a steel, in which the fracture samples from different temperatures, after the same soak time, are quenched and evaluated according to the fracture appearance and the achieved hardness. Fig. 20 shows an example for steel 145Cr6. The best hardening temperature is between 830 and 860°C.

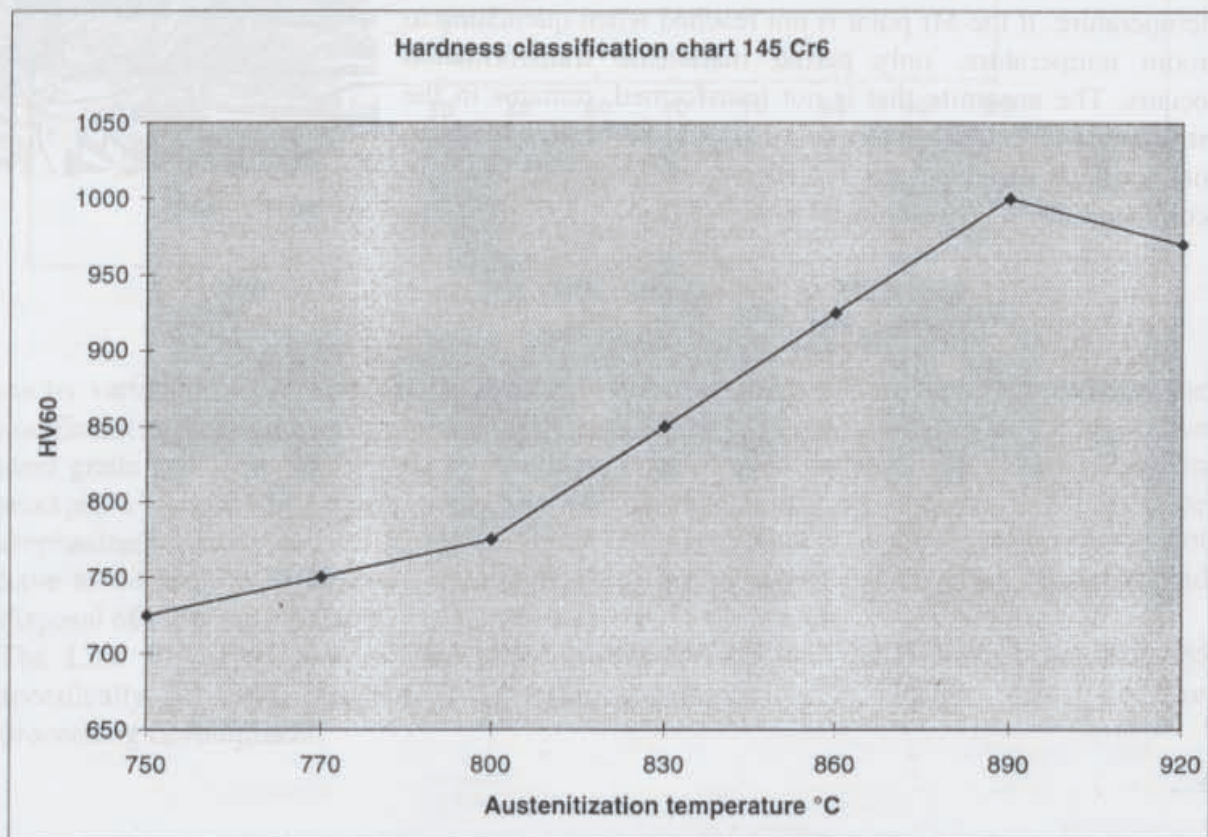


Fig. 20

3.1.9. The tempering of components and tools

According to DIN 17 014, tempering is understood to be the heating of a quench hardened ferrous product, one or more times, to a specific temperature $< A_{c1}$, and soaking at this temperature, followed by cooling at an appropriate rate.

The objective of tempering is a temperature and time controlled adjustment of the hardness to the required working hardness. The hardness generally decreases whilst the toughness is increased. One exception are secondary hardened steels. Over specific temperature ranges these experience increases in hardness which, in conjunction with subsequent surface treatment (nitriding, CVD or PVD coating) of tools, can be used in a sensible manner. Characteristic examples of this are high alloy cold work steels, hot forming tool steels and, especially, high-speed steels.

The change in characteristics of hardened steels due to tempering is based, with rising temperature, in sequence, on:

- The deposition of unstable carbides (E-carbide), combined with a reduction of the lattice stresses produced during the martensitic transformation (transition from tetragonal to cubic martensite).
- The transformation of the residual austenite.
- The precipitation of stable carbides and
- the final spheroidization of the stable carbides.

It is essential that tempering takes place immediately after hardening. If this principle is not observed, stress induced crack formation can occur. As a matter of principle, all higher alloyed types of steel should be tempered twice. The second tempering produces the required stress relief of the martensite formed from the initial residual austenite. Where the specified final hardness is already achieved after the initial tempering, the temperature for the second tempering should be set 20 to 30 °C lower. If the specified values have not yet been achieved, then the temperature for the second tempering should be set appropriately higher.

Alloy typical tempering curves (diagrammatic) are given in Fig. 21. The curves clearly show that the tempering stability of the steel rises in line with the increase in alloy content. The tempering temperatures to be used must be taken from the tempering curves, which the steel works generally provide. The tempering temperature level depends on the specified working hardness. Within certain limits, an exchange function can be set between the tempering temperature and soaking time. The relationships required in this regard are given in the bibliography. A precise temperature measurement is an absolute precondition for successful tempering. Approximate indications are provided by the already mentioned tempering colours.

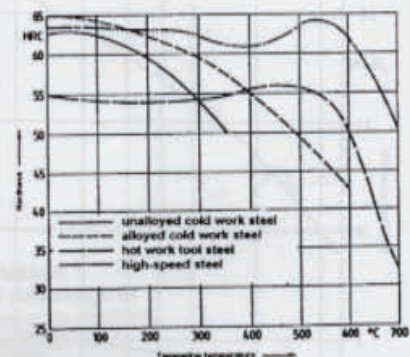


Fig. 21

3.1.10. Quench hardening

In conjunction with tempering, the topic of quench hardening must be mentioned. This consists of a combination of hardening + tempering, whereby the tempering temperature is generally above 550 °C. The objective of quench hardening is to considerably improve the ductility at a given tensile strength as compared with the hardened state. In hardening practice, the emeed yield strength is generally determined from a reevaluation of hardness measurements according to Brinell.

Suitable heat treatable steel must be selected from DIN E 17 200. Special attention must be given here to the hardenability of the individual types of steel, since the highest toughney is always achieved through the tempering of a pure martensitic hardness structure. The steel chosen must therefore take into account the size of the characteristic workpiece cross-section.

3.1.11. Subzero treatment

In conjunction with incomplete austenite transformation in martensite during hypercritical quenching, reference has already been made to subzero treatment. This is a form of treatment that must be carried out immediately after hardening, so as to transform the majority of the residual austenite into martensite. Subsequent tempering is absolutely essential. Where subzero treatment does not take place immediately after hardening, or where prior tempering takes place, the residual austenite is stabilized and the effectivity of subzero treatment is considerably reduced.

Subzero treatment should be carried out over a temperature range of -80 to -196 °C. Liquid nitrogen is used, which can be applied directly or indirectly.

Figs. 22 to 24 show the effect of subzero treatment during the heat treatment of tool steel 100Cr6. By means of a dilatometric chart, the primary martensite formation is shown during continuous cooling, starting at -39 °C and terminating at -116°C (curve 2). The residual austenite transformation occurs due to the discontinuous reduction compared with a high tempered reference sample (curve 1). Curves 1 and 2 in the next diagram show the residual austenite quantity before and after subzero treatment as a function of the austenitization temperature chosen during hardening. Concurrently, this clearly shows how the γ - α transformation occurs incompletely with an increasing degree of homogenization.

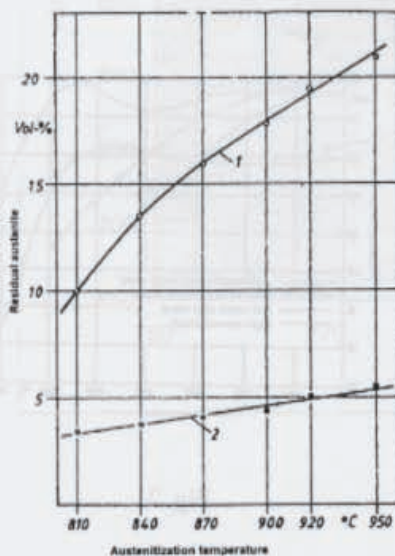


Fig. 22

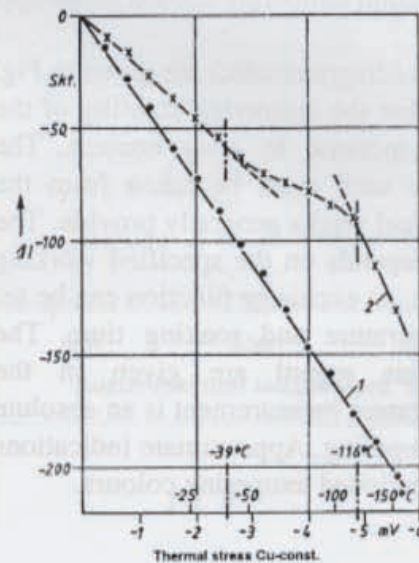


Fig. 23

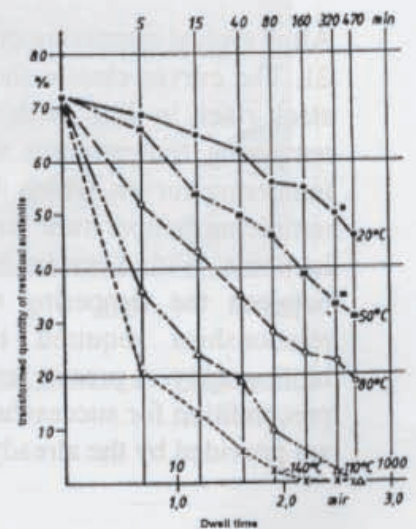


Fig. 24

It is subsequently demonstrated how rapidly thermal stabilization takes place. With rising storage temperature and increasing time, less residual austenite is transformed through subzero treatment.

Even though the effect of subzero treatment is considerable, this should be applied where it is truly sensible and, in the opinion of the author, this is virtually exclusively limited to the production of measuring tools, so as to achieve the highest measuring stability.

3.2. Time-temperature sequence charts

Now that the preferred heat treatment process implemented in the Linn hardening and tempering furnaces have been described. Without further comment, some TTF charts are listed to complete the process specification. The practitioner can see from these the individual stages that are needed for heat treatment, so as to achieve optimum and also certifiable results (Figs. 25-31).

1. Unalloyed tool steel
e.g. WNr. 11545, C105 W1

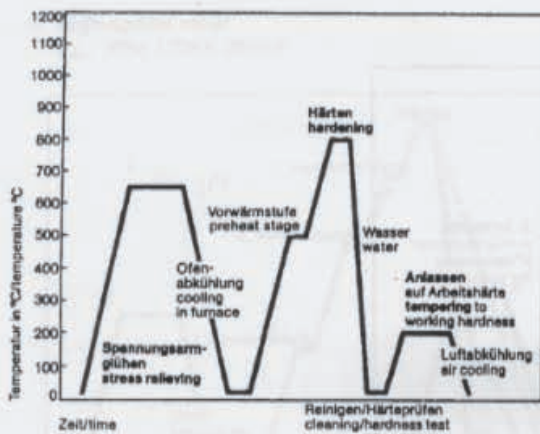


Fig. 25

2. Alloyed cold work steel - hardening temperature below 900 °C
e.g.: WNr. 1.2842, 90MnCrV8
WNr. 1.2510, 100MnCrW4

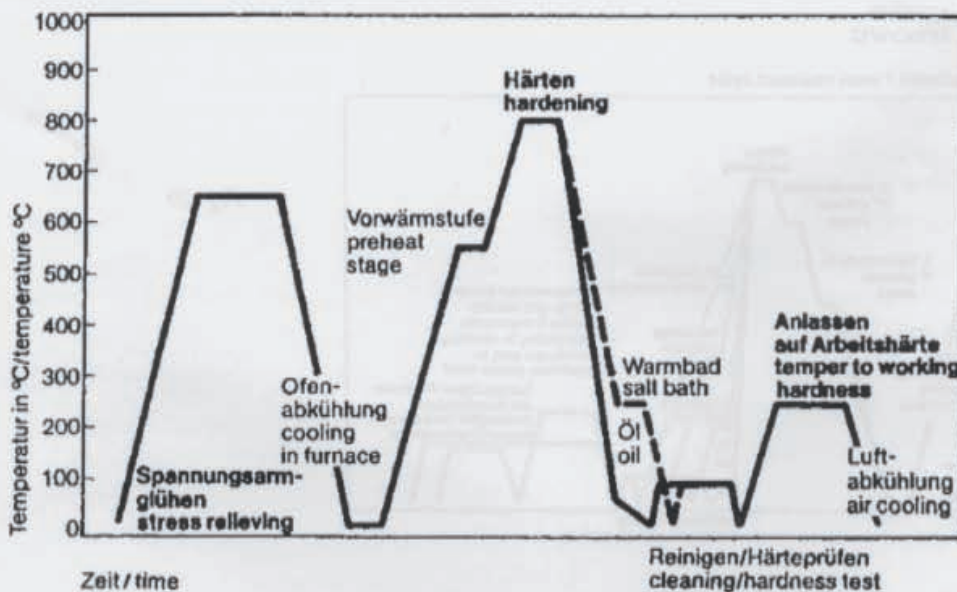


Fig. 26

WNr. 1.2379, X155CrVMo12
 WNr. 1.2601, X185CrMoV12

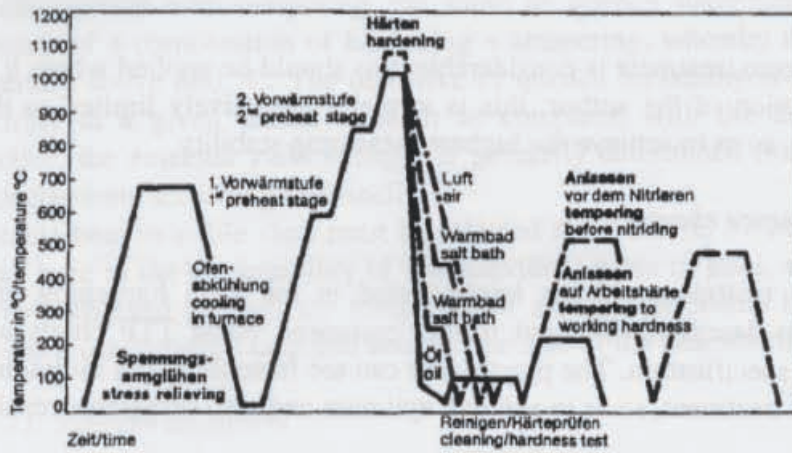


Fig. 27

3. Hot-work steel - hardening temperature below above 900 °C
 e.g.: WNr. 1.2714, 56NiCrMoV7

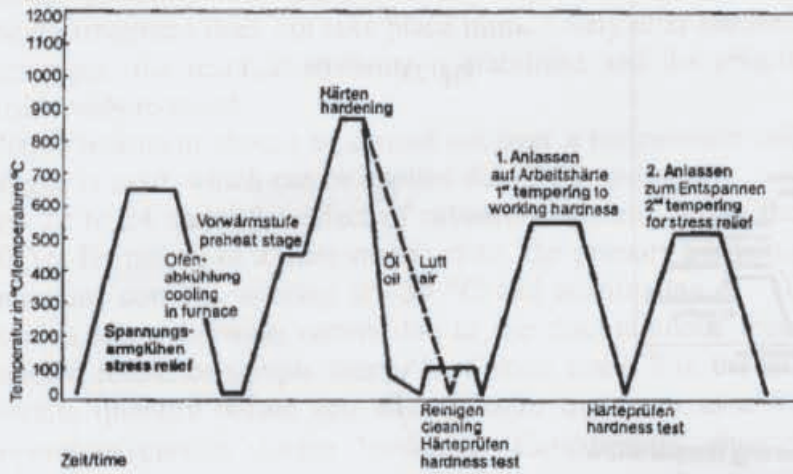


Fig. 28

4. Alloyed cold work steel - hardening temperature above 900 °C
 e.g.: WNr. 1.2080, X210Cr12
 WNr. 1.2436, X210CrW12

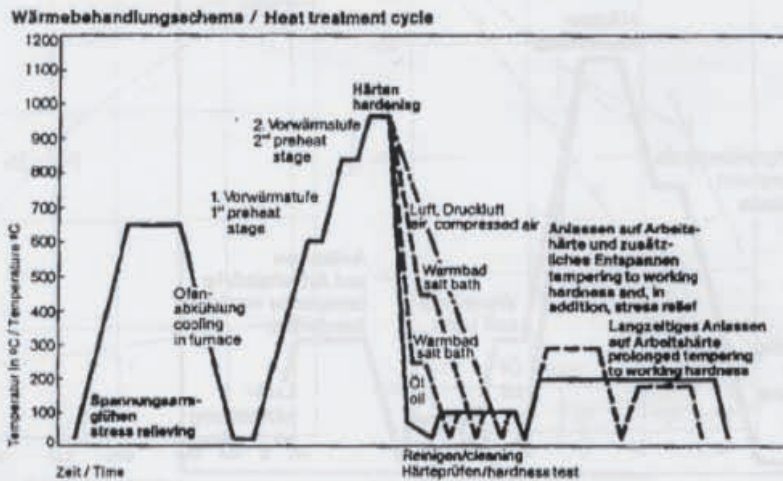


Fig. 29

5. Hot work steel - hardening temperature above 900 °C
 e.g.: WNr. 1.2344, X40CrMoV5 1
 WNr. 1.2343, X38CrMoV5 1

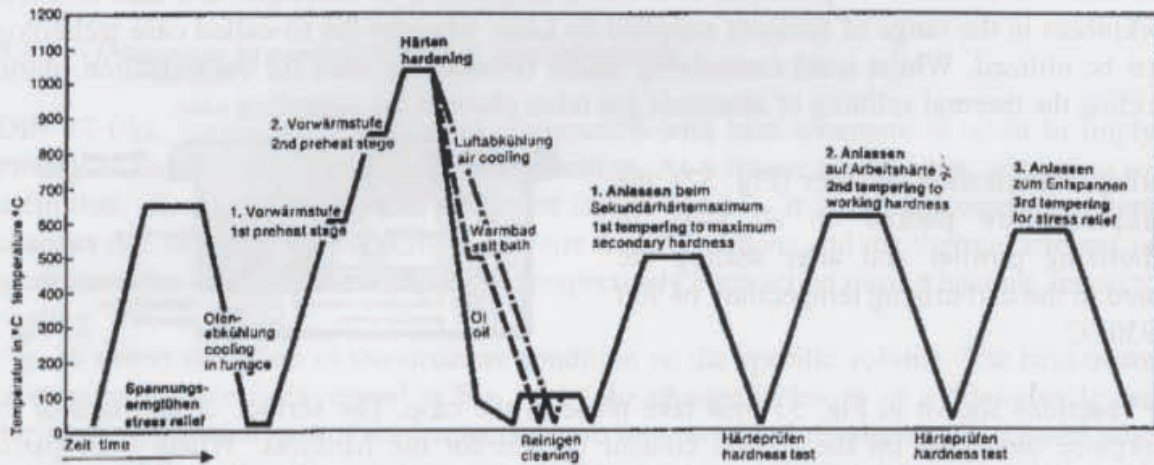


Fig. 30

6. High-speed steel
 e.g.: WNr. 1.3343, S6-5-2

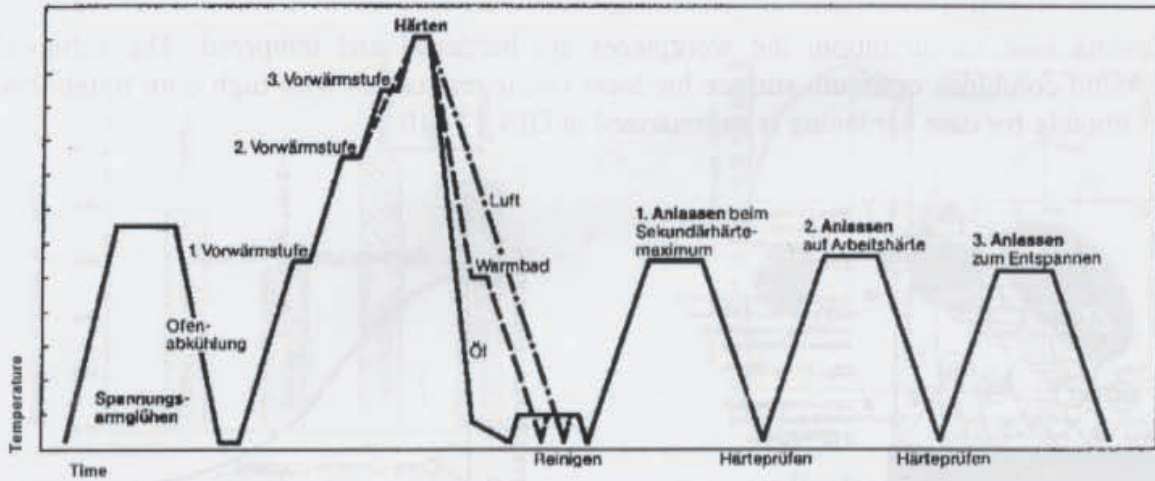


Fig. 31

3.3. Thermochemical treatment

As the preface already states, this narration will not deal in detail with the thermochemical treatment. As a matter of principle, it is however possible to carburize and also to nitride workpieces in the range of furnaces supplied by Linn, whereby the so-called case technology must be utilized. Whilst solid carburizing media (powder) is used for carburization, during nitriding the thermal splitting of ammonia gas takes place in the annealing case.

During carburization in cases (Fig. 32), the workpieces are packed on all sides in carburizing powder and after sealing are heated to the carburizing temperature of 900 to 930 °C.

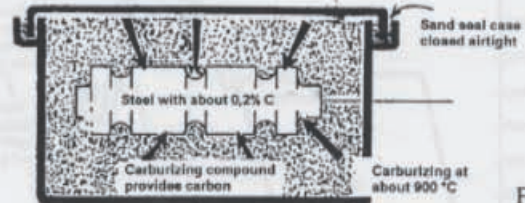


Fig. 32

The reactions shown in Fig. 33 then take place in the case. The surface of all sides of the workpiece then take on the carbon content needed for the hardness. Where only partial carburization is required, sections of the workpiece surface can be covered with the customary covering pastes. The rule of thumb is: a maximum layer thickness of 0.2 mm per hour can be achieved. The carbon content decreases towards the workpiece core. Fig. 34 provides a graph that shows a carbon characteristic curve.

Following case carburization, the workpieces are hardened and tempered. The achieved compound combines optimum surface hardness (wear resistance) with high core toughness. Steel suitable for case hardening is summarized in DIN 17 210.

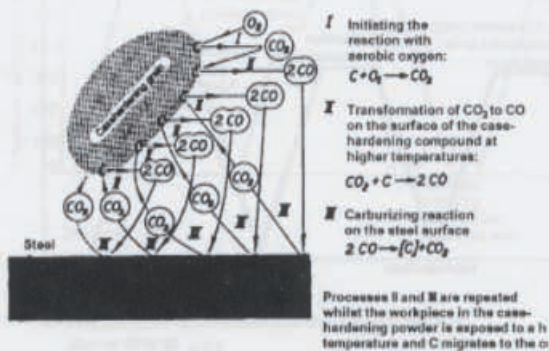


Fig. 33

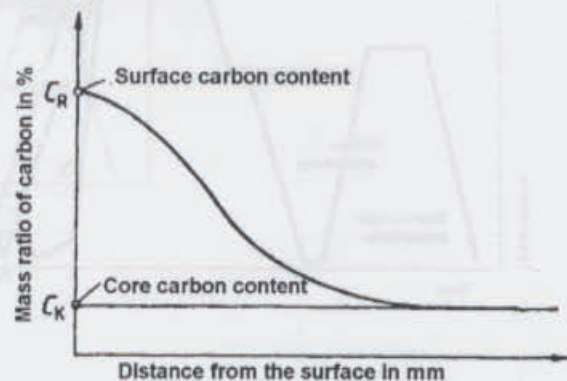


Fig. 34

Case nitriding provides the heat treating experts with a low distortion heat treatment process. By splitting the ammonia at temperatures between 480 and 530 °C, the surface of the workpiece is enriched with nitrogen atoms without exceeding the transformation temperatures, and iron nitride and nitrides of the alloying elements are formed, combined with an increase in the hardness of the workpiece surface. Highest surface hardness is achieved with Al alloyed steel (Al nitride). The nitrided surface layers are wear-resistant and are characterized by an increase in the resistance to corrosion. Special nitriding steels are listed in DIN 17 211.

Both processes play an outstanding part in modern heat treatment technology, whereby improved results are achieved, compared to case technology, through modern installation techniques with constant control and measurement of the reaction atmospheres.

3.4. Distortion in conjunction with heat treatment

DIN 17 014 states that distortion in conjunction with heat treatment is taken to imply the totality of changes in dimension and deformation. As a matter of principle, according to this definition, distortion during heat treatment is unavoidable. It is the outcome of volumetric changes due to the already specified structure transformations and the thermal stresses in the workpiece due to the different expansion respectively contraction during heating, respectively cooling.

Fig. 35 shows the effect of the structure condition on the specific volume. The heat treatment process in practice is expressed in Fig. 36 by the change in length of a dilatometric sample during the process stages of hardening, subzero treatment and tempering. Compared with the initial condition, the 10 mm long sample has become enlarged upon completion of the process by 0.012 mm. This is equivalent to an elongation of 0.12%, which is based purely on the structural transformation.

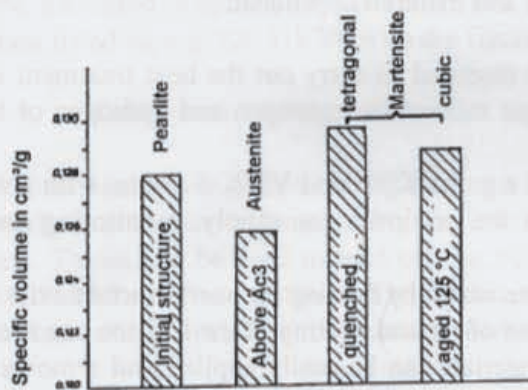


Fig. 35

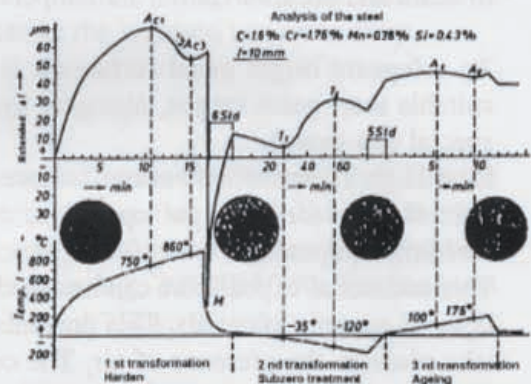


Fig. 36

The thermal stresses in the workpiece cause deformations due to partial stress relief in the sector of plastic deformation. Where this is concerned, all workpieces that deviate from the spherical form attempt to adapt their form to that of a sphere. Cubic shaped bodies bulge outwards. Prismatic components become shorter and thicker, whilst panels achieve this approximation by enlarging the panel thickness and reducing the panel area.

During the design phase, one has to take into account these distortions and attempt to construct in accordance with the heat treatment, by selecting the most suitable material and by specifying the best heat treatment process.

In addition, there is also the avoidable distortion, which can be caused by residual stresses in the supplied workpiece (non-symmetrical machining, material segregation, etc.), or by new stresses due to improper heat treatment (poor temperature distribution in the furnace, incorrect loading, non-uniform quenching).

The distortion problem must therefore be seen as complex, whereby account must be taken of the complete system of material, geometric shape of the workpieces and the heat treatment conditions.

To a limited extent, deformation can be corrected through straightening. Many years of practical experience often determine the success or failure in this regard. Straightening can be carried out before and after tempering. Straightening processes are hammering, straightening or pressing, in a straightening machine or on a straightening bench. With particularly deformation-sensitive components, chill hardening should be carried out from the outset.

3.5. *Surface reactions; protecting the workpiece surface*

The furnace atmosphere considerably affects the outcome of heat treatment. Except in a vacuum or under inert gases, reactions occur during heating between the metal surface and the air within the furnace, which oxidise the steel surface. The consequences are the formation of scale and bubbles, with particular disadvantages for the dimensional precision of the workpieces.

In addition, partial or complete decarburization of the workpiece surface can occur. This has a negative effect on the hardening result. We know from the theory, that an adequate quantity of carbon is the basic precondition for achieving the hardness. Both processes, the formation of scale and decarburization are temperature, time and material dependent.

To safeguard bright metal surfaces it is however essential to carry out the heat treatment in suitable inert gases (argon, nitrogen, hydrogen, gas mixtures of nitrogen and hydrogen or in special exo-gases).

Linn High Therm offers various furnaces for this, e.g. the KS-S and VMK-S series, with gas-tight sleeves for inert gas operation, as well as the pertinent gas supply, monitoring and bleeding equipment.

This additional expenditure can be avoided in some cases, by coating the metal surface with a layer of ceramic materials. This prevents the access of air and heating in the furnace can then take place in the presence of air. The ceramic materials can be easily applied and removed, whereby the surface quality is only slightly affected.

4. *The testing of heat treated components and tools*

In the previous chapters, we have repeatedly spoken of the hardness and tensile strengths of workpieces and tools. It is now time to briefly discuss the measurement of the hardness and the testing of the tensile strength in a hardening shop.

The hardness is normally measured in practice by means of the Rockwell process according to DIN 50103 or the Vickers process according to DIN 50133. Tempered components are tested according to the Brinell process and, in accordance with DIN 50150, these are generally converted into yield strength data.

During hardness measurement, the workpieces are not destroyed. All that is required is the preparation of a suitable measuring point by light grinding.

A brief description of the already mentioned hardness measuring processes are given below:

4.1. *Hardness according to Rockwell (HRC)*

Measurement of the Rockwell hardness involves the application of a spherical tipped conical diamond of 120° angle with a defined force against the surface of the workpiece. The Rockwell hardness is then determined from the difference in the penetration between the initial and the main load. On modern hardness measuring equipment, this can be read off directly from a dial (Fig. 37). The hardness is then listed as, e.g. 65 HRC.

4.2. *Hardness according to Vickers (HV)*

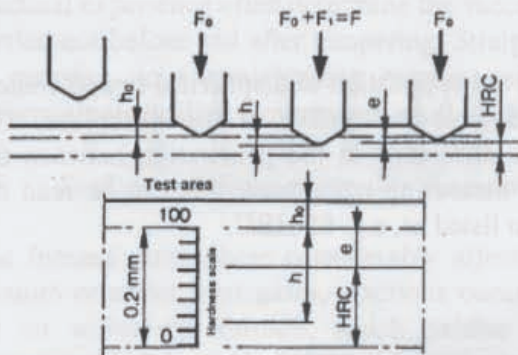
Measurement of the Vickers hardness involves the application of a diamond in the form of a square pyramid with an apical angle of 136° , with an adjustable test force against the surface of the workpiece which, when relieved, consists of measuring the diagonal of the produced impression with a measuring microscope. Mathematical relationships lead to the computation of the Vickers hardness, which can currently be read from tables as a function of the size of the measured diagonals (mean value) and the selected test force (Fig. 38). The hardness is then listed as, e.g. 820 HV30, with the figure 30 indicating the imposed test force in kp.

4.3. *Hardness according to Brinell*

Brinell hardness is determined by forcing a hardened steel sphere with a defined load into the workpiece surface and measuring the indentation of the sphere that is left behind after the test. Tables can be used to read off the Brinell hardness as a function of the size of sphere used and the defined test load. The hardness is then listed as, e.g. 200 HB5/750. The hardness is determined with a 5 mm diameter sphere and a test load of 750 kp (Fig. 39).

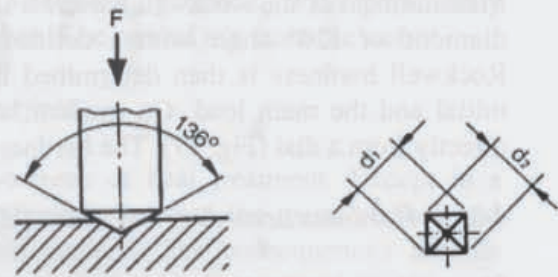
All hardness details are specified with an adequate tolerance, which also includes the mean measuring inaccuracy of the measuring process.

Even so, one should not forget the old expression "file hard". If one wishes to check whether the hardness is adequate, a good quality file has in practice often given the correct indication!



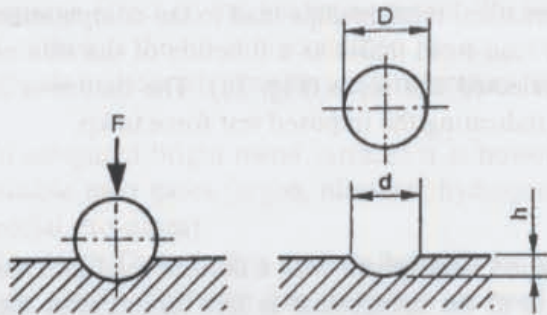
Principle of Rockwell test (HRC)

Fig. 37



Prinzip der Vickers-Prüfung (HV).

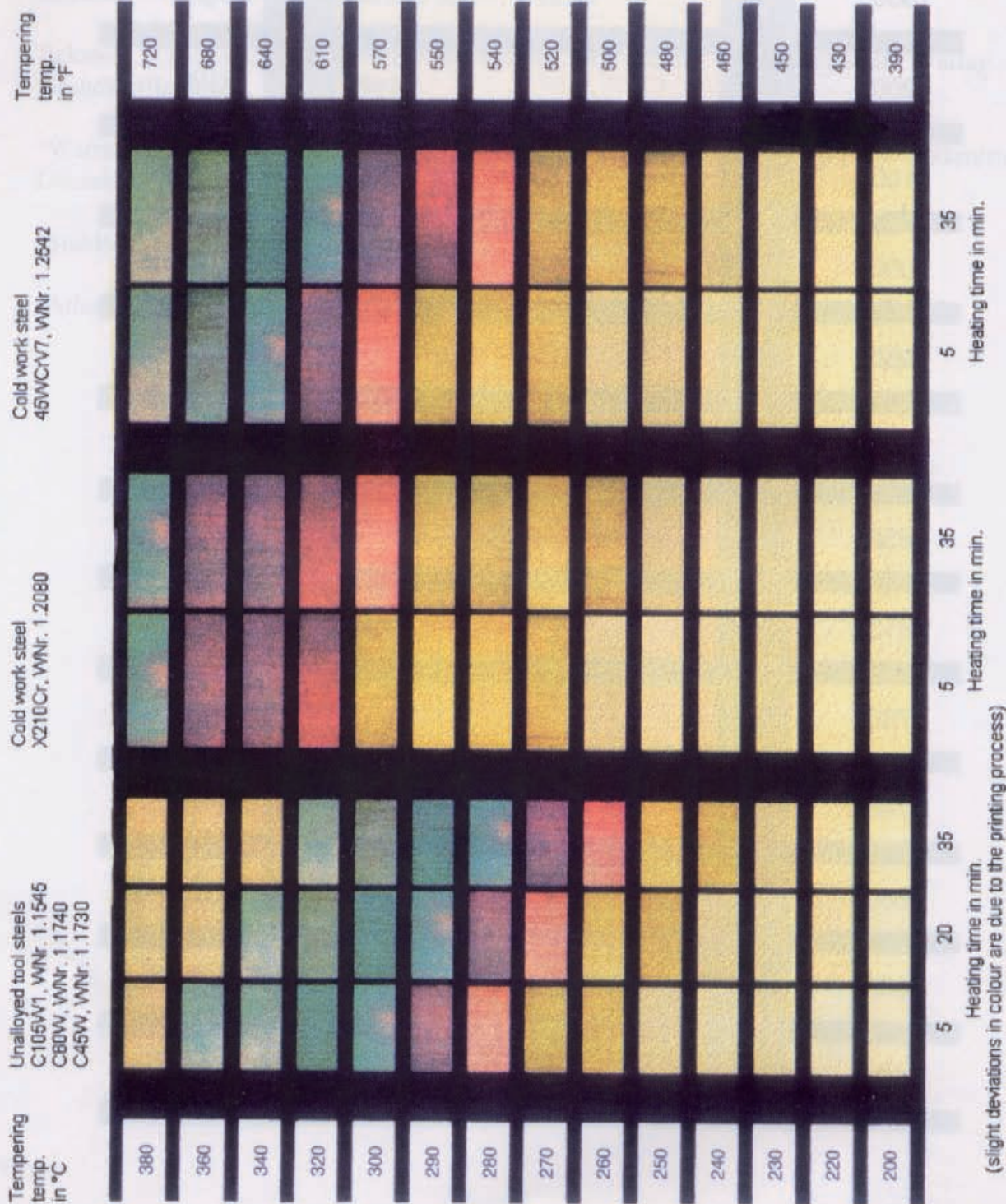
Fig. 38


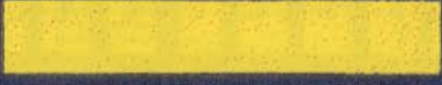













Principle of Brinell test (HB)

Fig. 39

Tempering colours



Annealing temperature in °C	Annealing colours	Annealing temperature in °F
1300		2370
1200		2190
1100		2010
1000		1830
950		1740
900		1650
850		1560
810		1490
780		1440
740		1360
680		1260
630		1170
550		1020

(slight deviations in colour are due to the printing process)

5. *Bibliography*

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