High-Quality Tool Steel
Hot Forming and Heat Treatment

saarschmiede
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CONTENTS

Hot Forming

FORGING

For each steel the temperature range within which forging must be carried out is stated.

The pieces to be forged must slowly be brought to the initial forging temperature. This has to be considered even more the higher the steel is alloyed, as the heat conductivity decreases normally with the alloying content. If heating is carried out too fast, internal cracks and other defects can occur.

Forging must be finished roughly near the minimum temperature stated. The initial forging temperature should be coordinated with this. If the required minimum temperature is reached before finishing the forging process, re-heating must be carried out.

After forging, practically all hot-work steels must be cooled slowly to avoid tension cracks.

For high-alloyed and thus very transformation-resistant steels a special preliminary heat treatment may become necessary. For this, the pieces are to be caught at 500 to 550 °C coming from the forging operation and to be charged into a furnace which is at the temperature equal to the shortest pearlite transformation time (pearlite nose) in the isothermal TTT (time-temperature-transformation) diagram. The holding time is to be determined 3 or 4 times as long as stated in the TTT diagram.

WORKING ALLOWANCE

Hot forming leads to a certain scaling and decarburization on the steel surface. Moreover, minor surface defects, such as pits, grooves and others, may remain. So as to avoid insufficient surface hardness of the tools or heat treatment cracks, it is advisable to carry out chip machining prior to hardening.

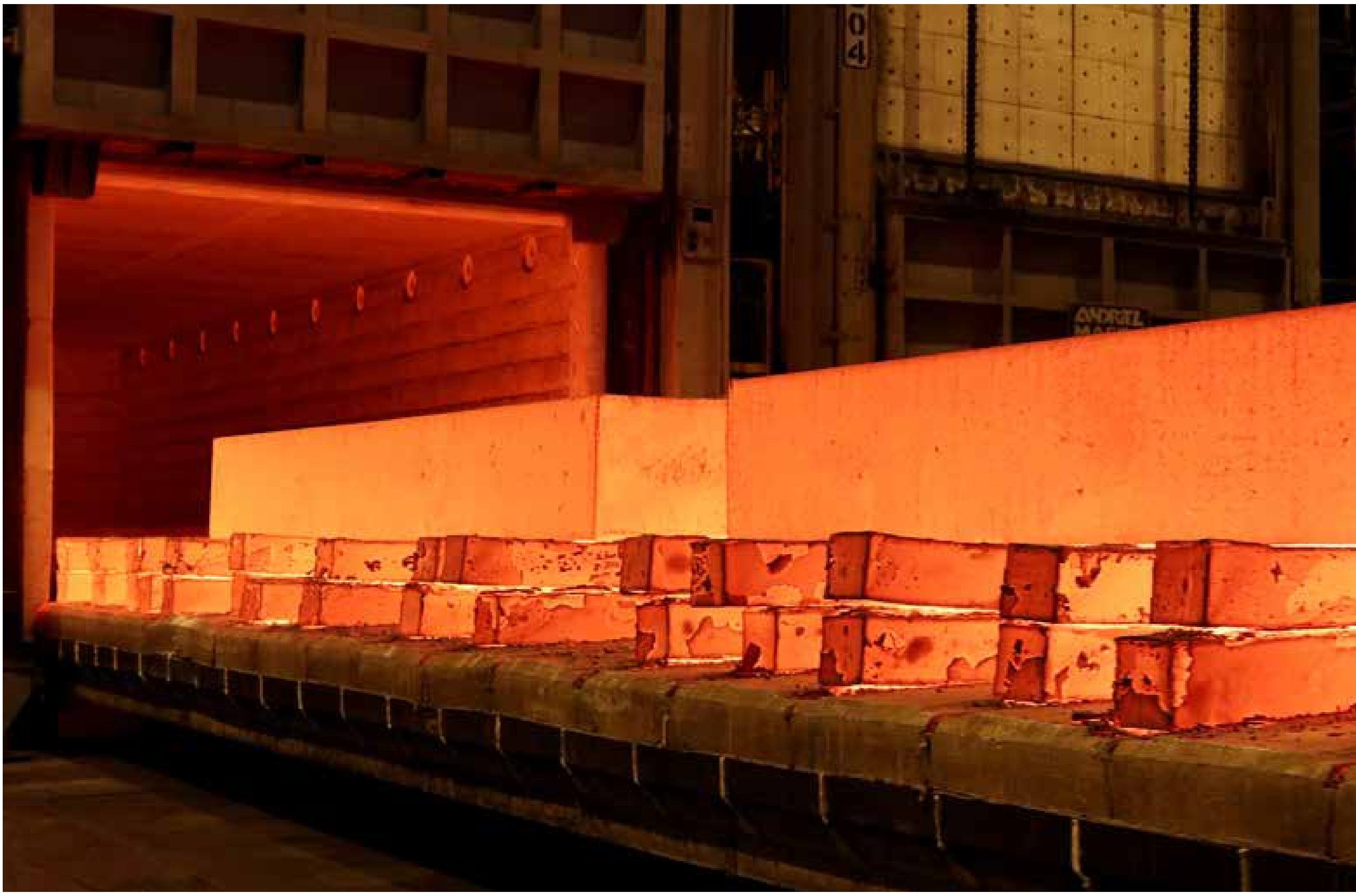
For ordering, the relevant material allowances must therefore be taken into consideration. The **ordering dimension**, the dimension defined by the customer, is dependent on the **finished dimension**, i.e. the intended dimension of the tool after finish-machining as well as the type of design.

Concerning the suppliable types of design, the following can be distinguished:

- Rolled or forged
- Rough-machined
- Micro-finished

The ordering dimensions for bars in rolled or forged as well as rough-machined condition may be taken from DIN EN ISO 4957.

It is acceptable for finished machined bars to deviate from customers ordering dimension according to DIN EN 10278.



Basic Principles of Heat Treatment

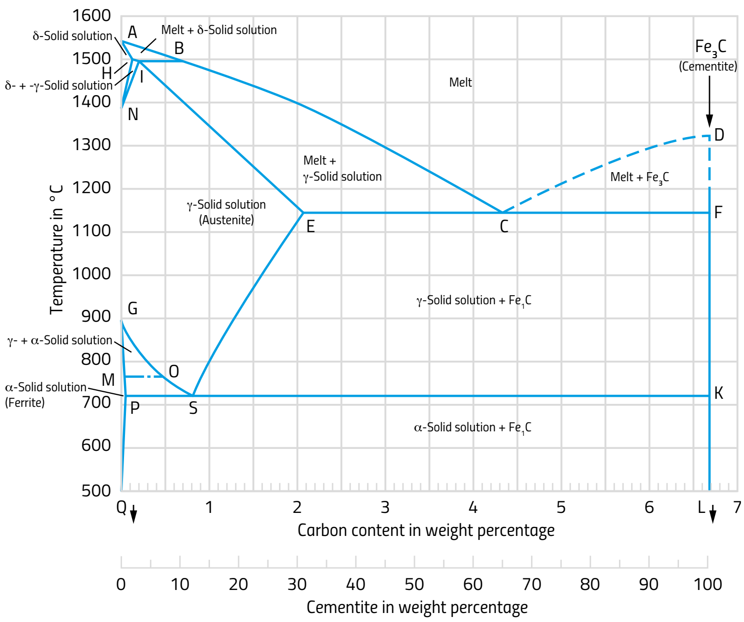
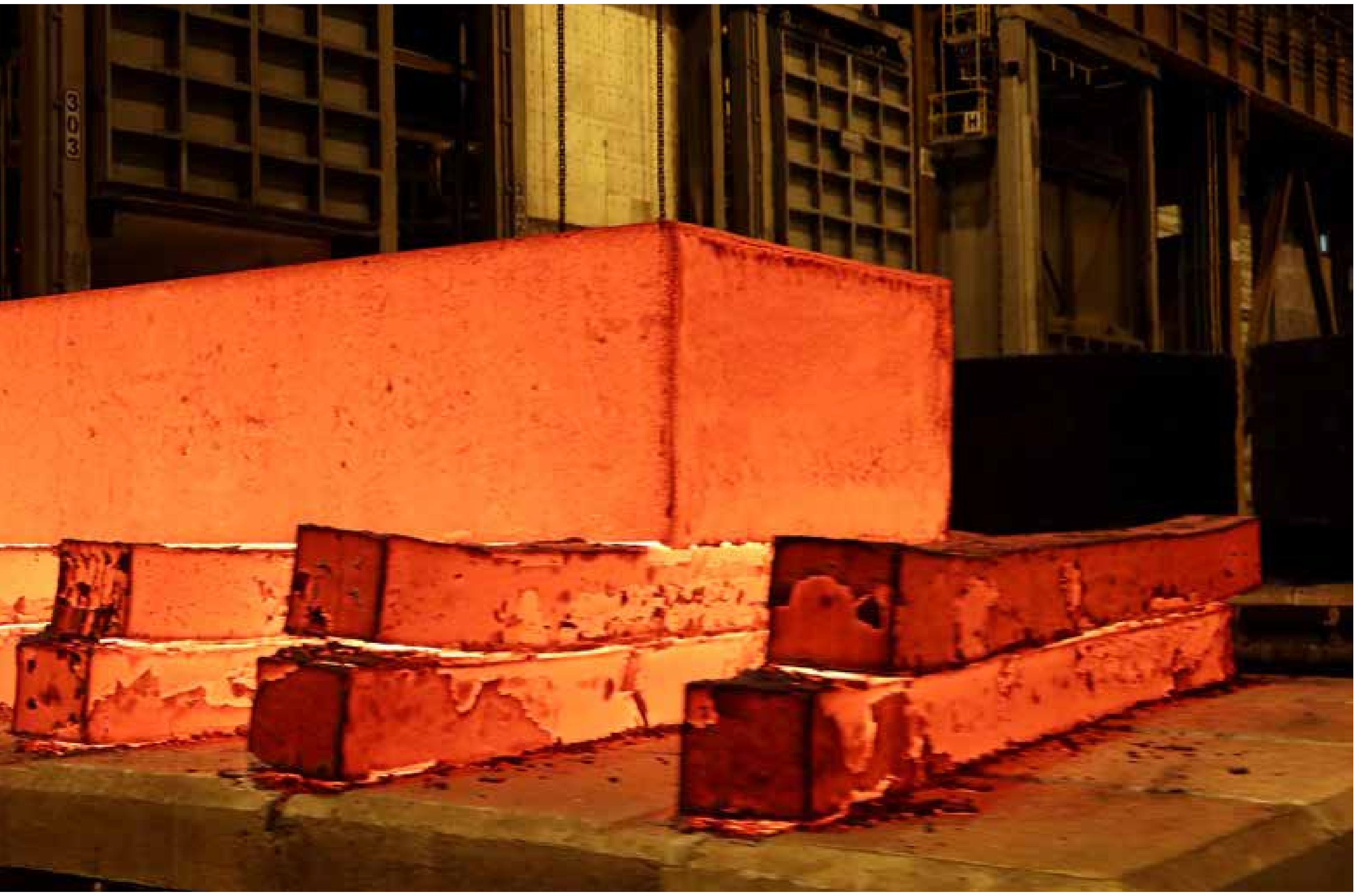


Figure 1
Phase diagram
Iron-carbon

Steels are iron-carbon alloys whose properties can be influenced through changes of the chemical composition (C-content and addition of alloying elements) and through heat treatment. Thereby, a multitude of tool steels is created which meet every requirement. To understand the different kinds of heat treatment, it is necessary to become familiar with the processes which occur in steels during heating and cooling.

The phase diagram iron-carbon **(Figure 1)** forms a first basis for heat treatment. It shows the structure components and volumes under conditions of equilibrium. From the phase diagram it can be deduced that austenite, and in hypereutectoid steels austenite and cementite, are present at temperatures above the GSK line (see diagram). During very slow cooling, which again leads to conditions of equilibrium at room temperatures, a transformation of the austenite into other types of structure occurs.



Steels with C-contents of below 0.8 % precipitate ferrite from the austenite area during cooling, and the residual austenite disintegrates below 723 °C into pearlite. At a carbon content of 0.8 % only pearlite is formed as a mixture of ferrite and cementite. In steels with C-contents of above 0.8 % pearlite and cementite are formed, whereby the secondary cementite is precipitated at the grain boundaries.

Through the addition of other alloying elements the transformation temperatures and the lines of equilibrium can be altered and the formation of carbide can be influenced.

The phase diagram does not give any information about the structure of steels cooled down fast from the austenite area. With higher cooling speed the transformation of the austenite does not occur according to the equilibrium ratios and leads to other kinds of structure – sorbite, troostite, bainite, martensite – which are not shown in the Fe-C-phase diagram. The transformation processes are described in the TTT diagrams; they form a further basis of heat treatment.

In the isothermal TTT diagrams the time in the logarithmic scale is entered on the x-axis and the temperature on the y-axis.
The curves shown therein mark the transformation behavior of the supercooled austenite at isothermal heat treatment as previously explained.

In **Figure 2 to 3** it is shown in what way these diagrams are developed. Small samples heated to austenitizing temperature – normally the hardening temperature – are quickly submerged in a salt bath held at the desired transformation temperature according to **Figure 2**. They are kept in the bath for increasing periods of time and then quenched in salt water. Following this, hardening measurement and structure examination are performed. In this, the time of the start of the transformation B and its finish E are determined. This can also be carried out in a dilatometric way. Such series of experiments are carried out for a range of temperatures. For example, **Figure 3** shows the result for a steel with 0.55 % C and 1.04 % Mn. In **Figure 3** all points B and, respectively, E are connected with each other. With this, the TTT diagram has already been outlined.

Its statement is further explained using the example of the isothermal TTT diagram for the steel grade 1.2542 (45WCrV7) as shown in **Figure 4**. Firstly, it turns out that the austenite can be supercooled below Ac1 if it is cooled sufficiently fast. The supercooled state remains at first even during the isothermal treatment. Only while exceeding the "rise time", i.e. to the right of the "transformation start" line, is a new structure component formed. In **Figure 4**, this is initially ferrite at higher temperatures, e.g. at 700 °C, later pearlite is formed. Transformation in this case ends after

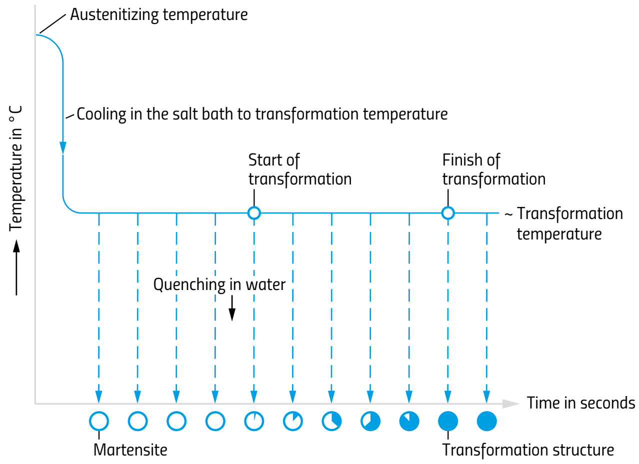


Figure 2
Diagram of the determination of the transformation start time and finish at isothermal heat treatment

450 s (= 7½ mins.). For temperatures of 350 °C for example, transformation into bainite starts after a holding time of around 30 s. This is finished after 3,000 s (= 50 mins.). Below the Ms line martensite is formed. It forms spontaneously on reaching transformation time. Its amount – in 1st approximation – is dependent only on temperature and not on time. In **Figure 4**, for example, at 235 °C 50 % and at 100 °C 90 % martensite are preserved. Especially for hot-work steels at cooling to room temperature, i.e. at hardening, 100 % martensite can practically never be achieved. There remains a certain amount of "retained austenite", whose transformation – frequently only in parts – can be induced through a deep cooling treatment.

TTT DIAGRAMS FOR CONTINUOUS COOLING

The continuous TTT diagrams are important resources for the practical heat treatment, especially hardening.

These diagrams are to be read in the direction of the marked-in cooling curves which (in the case of round bars) are to be aligned, depending on the diameter and on the quenching medium applied, to the individual section areas, e.g. rim, mid-radius and center. The fast coolings are marked by so-called parameters, the slower ones through direct statement of the cooling speed. The parameters come about through division of the cooling time from 800 to 500 °C by 100 (e.g. parameter 0.15: the curve for which cooling from 800 to 500 °C needs 15 s).

The diagrams state which transformations happen in a steel depending on the cooling speed and which hardness comes about after achieving ambient temperature (circled numbers on the lower curve end). Also the constituents of the microstructure including the retained austenite are stated in the diagrams.

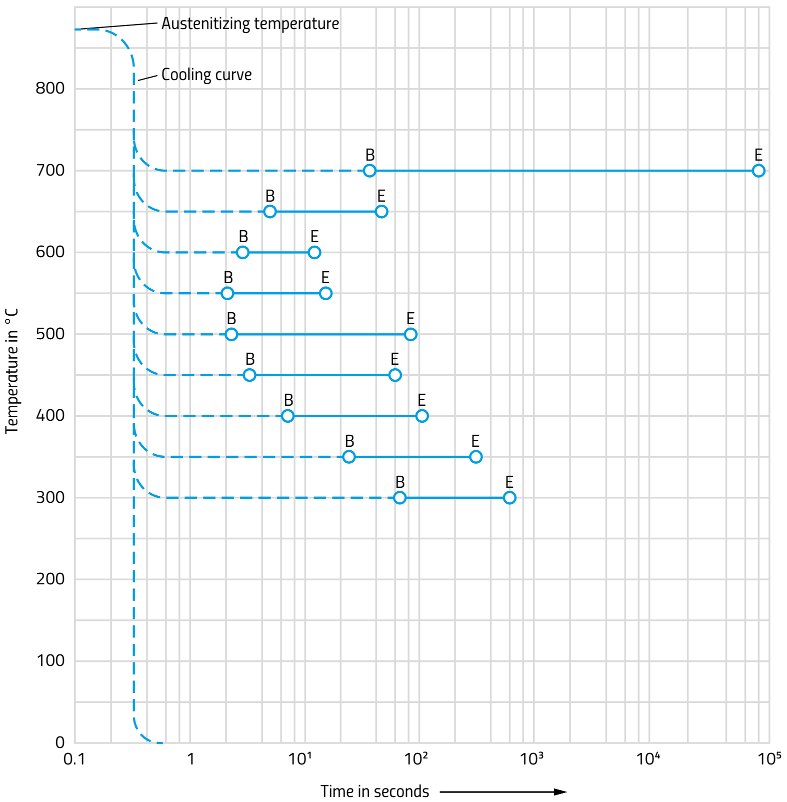


Figure 3
Development of an isothermal TTT diagram for a steel with 0.55 % C and 1.04 % Mn

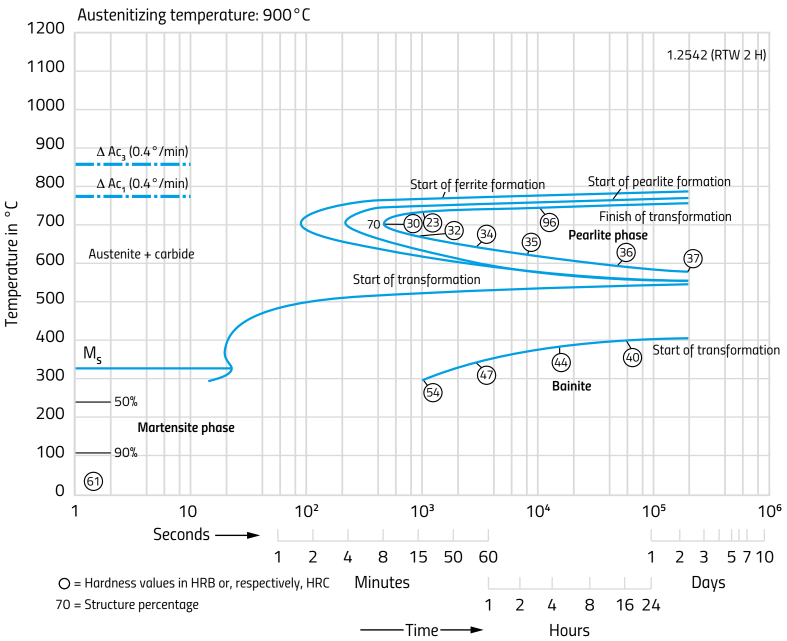


Figure 4
Isothermal TTT diagram for the steel 1.2542 (45WCrV7)

Figures 5–7 make clear the typical differences which occur in the TTT diagrams of steels of different hardenability. For the water hardening steel 1.1625 (C80W2) in **Figure 5**, the complete conversion in the pearlite phase occurs already in fast cooling (parameter 0.03). For the oil hardening steel 1.2542, cooling must amount to only max. 10 °C/min. according to **Figure 6**. For the air hardening steel 1.2767/RABW (45NiCrMo16), however, the pearlite conversion proceeds so slowly that even at 0.2 °C/min. only 20 % of pearlite is generated.

It should be emphasized that the diagrams displayed include a certain scatter range due to a case of analysis and is only valid for the stated austenitizing conditions and a normal state of pre-treatment. Higher austenitizing temperatures push conversion, especially the pearlite phase, back, they therefore improve hardenability.

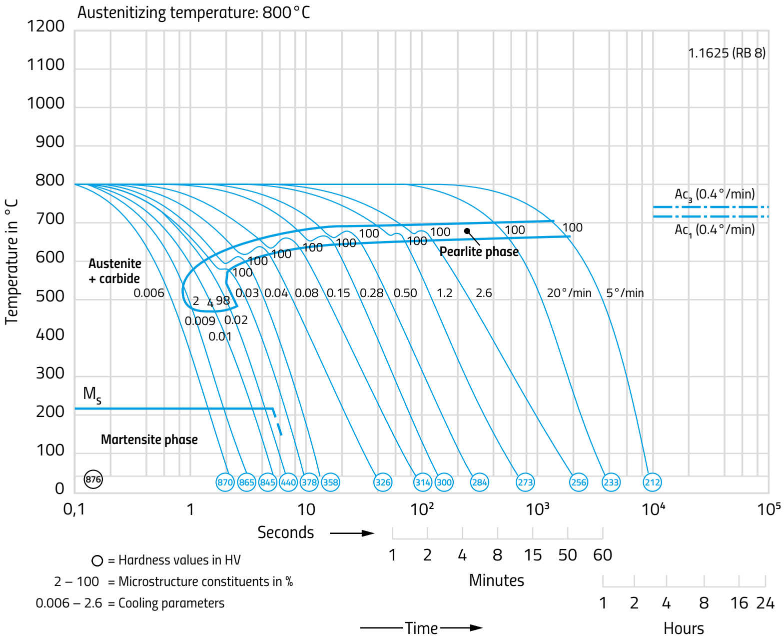


Figure 5
Continuous TTT diagram for water hardening steel.
1.1625 (C80W2)
0.85 % C, 0.15 % Si, 0.20 % Mn

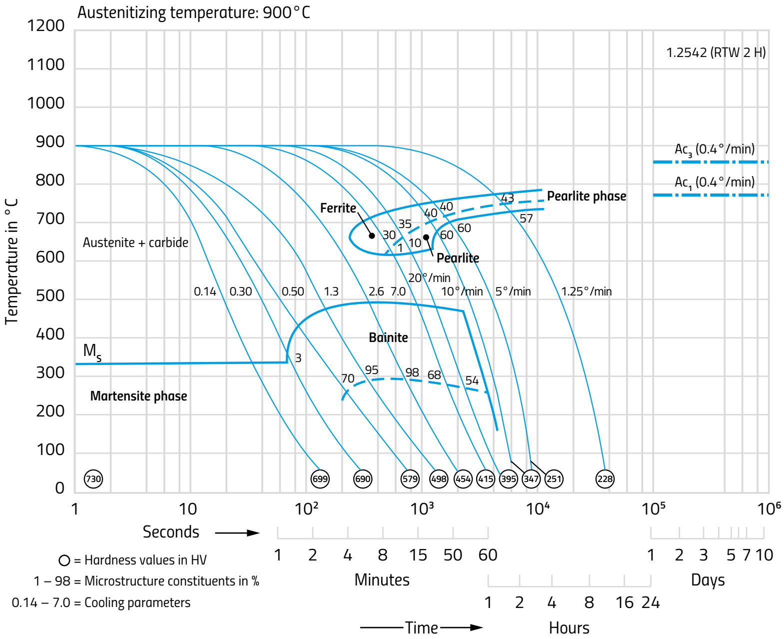


Figure 6
Continuous TTT diagram for oil hardening steel.
1.2542 (45WCrV7)
0.45 % C, 0.95 % Si, 1.10 % Cr, 0.17 % V, 1.90 % W

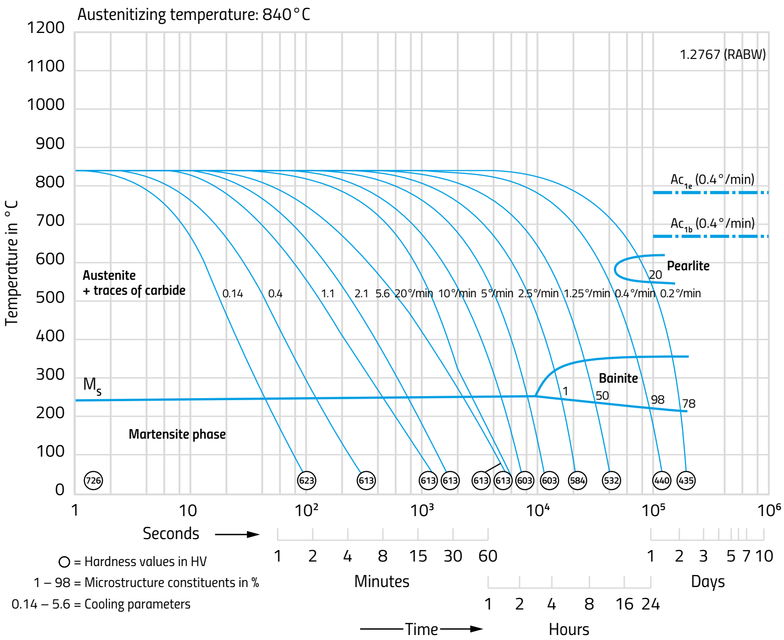


Figure 7
Continuous TTT diagram for air hardening steel.
1.2767/RABW (45NiCrMo16)
0.45 % C, 1.35 % Cr, 0.23 % Mo, 3.9 % Ni

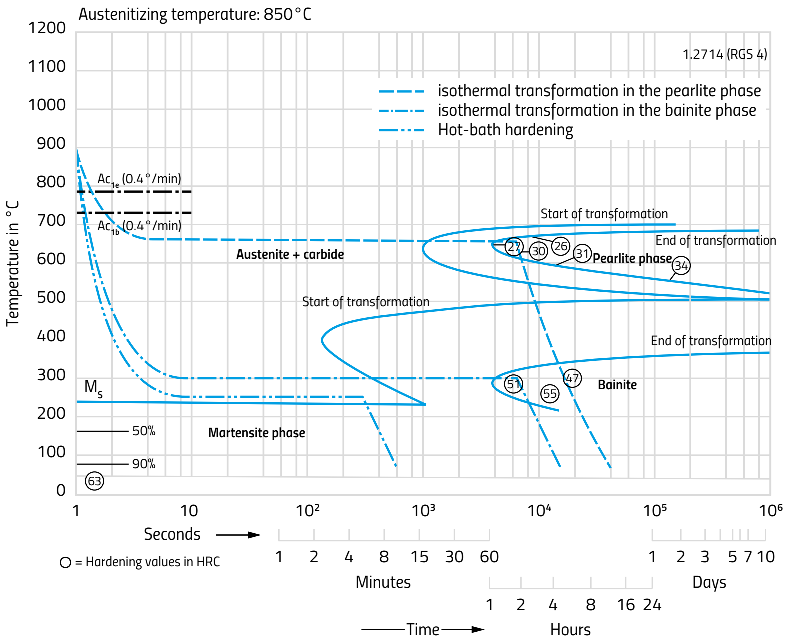


Figure 8
Isothermal TTT diagram and types of heat treatment 1.2714/RGS 4 (55NiCrMoV7)

PRACTICAL APPLICATION OF THE TTT DIAGRAMS FOR CONTINUOUS COOLING

So as to be able to transfer the statements of the TTT diagrams to the hardening of tool steels one must know the cooling speed of water, oil and air hardening. For round bars this can be stated relatively exactly. If one at first concentrates on the core zone it is possible to use the following table. It states for water, oil and air hardening the cooling parameters λ[1] or, respectively, the cooling speeds v in the core depending on the diameter.

		Ø (mm) for cooling in		
λ respectively v[1]		water[2]	oil[2]	air
0.01		10		
0.03		18		
0.06		25	10	
0.10		35	18	
0.20		50	30	
0.35		70	45	
0.50		85	60	
0.70		105	70	
1.00		130	90	10
2.00		180	130	18
3.00		230	170	25
5.00		300	220	40
7.00		360	280	55
9.00	20 °/min.	420	320	65
18.00	10 °/min.	600	500	130
36.00	5 °/min.	900	750	220
72.00	2.5 °/min.	1300	1150	400
144.00	1.25 °/min.	1900	1700	700
225.00	0.80 °/min.	2400	2200	1000
450.00	0.40 °/min.	3500	3300	1900

In order to determine the cooling speed or the cooling parameter on various section areas, the following **Figures 9 to 13** are to be consulted.

They are valid for water, oil, and air cooling and round bars of 50 to 800 mm diameters.

The broken line refers to the core of the round rods.

For the cooling parameter or the cooling speed determined in this way, the structure and the hardness to be reached after conversion can be determined in the TTT diagram. Some examples can clarify the possibilities of application:

Example 1: Which surface hardness can be reached with the oil hardening steel 1.2542 on a cylindrical work piece with a diameter of 100 mm?

According to **Figure 11** the parameter for a diameter of 100 mm and a distance from the edge of 5 mm amounts to 0.29. In the continuous TTT diagram for 1.2542 **(Figure 6)** a cooling curve with a parameter of 0.30 is found. For this parameter a hardness of 690 HV and a structure with 97 % martensite and 3 % bainite is achieved.

[1]The cooling parameters or, respectively, speeds are attached to the cooling curves on the 500 °C isotherms in the TTT diagram.
[2]Workpiece moderately moved.

Example 2: A cylindrical die of 400 mm diameter from steel 1.2767/RABW is air hardened. Which hardness and which structure are to be expected at the edge and in the core?

According to **Figure 13**, edge and core cool down with nearly the same speed of 2.5 °C/min for a diameter of 400 mm. According to the TTT diagram for continuous cooling **(Figure 7)** this cooling generates in the core 1 % bainite, 94 % martensite and 5 % residual austenite for a hardness of 584 HV. For the edge it can be deduced that 95 % martensite and 5 % residual austenite for a hardness of about 600 HV can be achieved.

All these data are valid for the hardened condition before tempering.

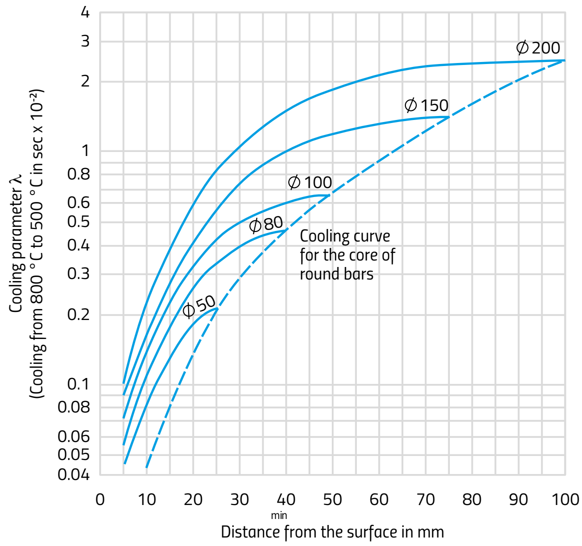


Figure 9
Water quenching

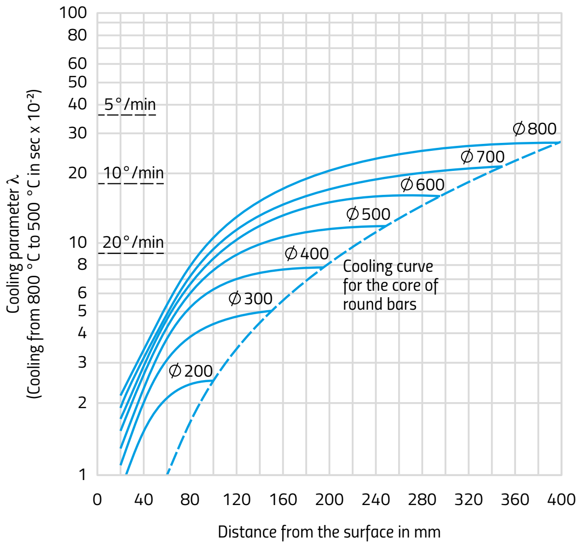


Figure 10
Water quenching

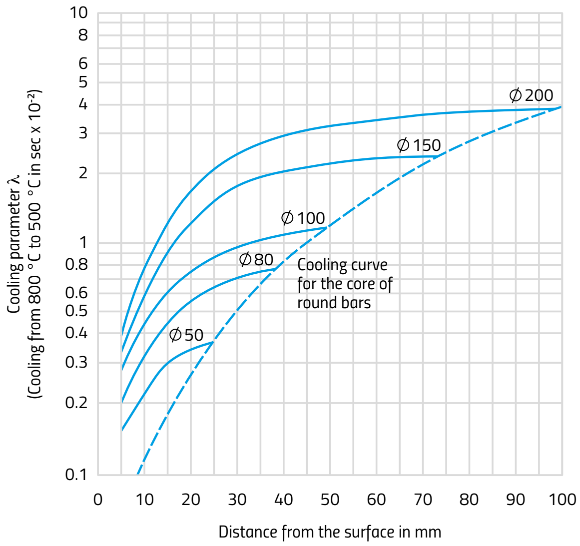


Figure 11
Oil quenching

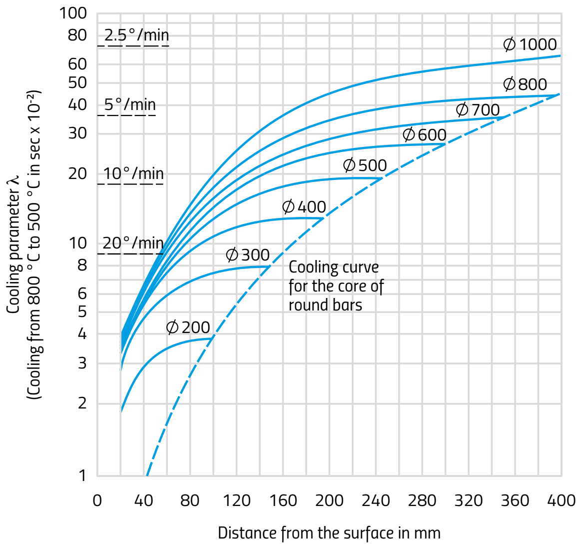


Figure 12
Oil quenching

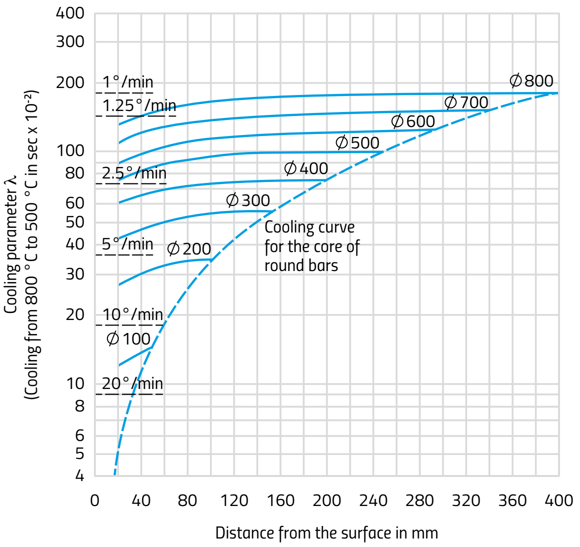


Figure 13
Air quenching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Types of Heat Treatment

Already the design of the tools by the design engineer should take the heat treatment into consideration. Large differences in section, especially with sharp transitions and edges are to be avoided as they lead to locally high stresses.

A clean surface of the tools is very important. Scratches create grooving effects and cause crack formation. Scale, corrosion and other residues contaminate could have a harmful effect on the heat treatment process.

In this brochure, treatment instructions for every type of steel are provided for the hot forming and heat treatment. These instructions are guidelines and do not exclude special measures in individual cases.

NORMALIZING

When a tool steel has been hot-formed one more time in the course of further processing, normalizing before soft-annealing is expedient. Normalizing equalizes differences in structure and/or refines a coarse grain. Through this, an initial structure, as uniform as possible, is achieved for the subsequent heat treatment. For this, the tools are slowly and thoroughly heated to normalizing temperature. It is about 30 °C above the hardening temperature. They are held at this level for about ½ hour and subsequently cooled in air.

A complete transformation in the pearlite stage is the prerequisite for the desired grain refinement. Only this transformation leads to the desired grain refinement; not,

however, the transformations in the bainite phase and the martensite phase.

It can be determined from the continuous TTT diagram, whether a complete or nearly complete pearlitic transformation through normalizing can be reached for the given dimensions for a certain steel. According to the TTT diagram for continuous cooling from the austenite area, higher-alloyed and thus transformation-resistant steels are to be cooled so slowly that the steel transforms completely in the pearlite phase. The same effect can be reached with an isothermal tempering transformation in the pearlite phase through the application of the isothermal TTT diagram. Cooling down from the normalizing temperature into the range of the pearlite formation can be carried out in the furnace or through recharging. It is expedient to select as austenitizing temperature a temperature which lies between 20° and 40 °C above Ac_{1e} (Ac_{1e} is defined in the TTT diagrams). As this is lower than the austenitizing temperatures referred to in the TTT diagrams, the transformation takes place faster than stated in the TTT diagrams. This means that there is a welcome safety factor.

SOFT ANNEALING

The soft-annealed condition is the most appropriate for machining and chipless processing of the steels. Moreover, it is favorable for subsequent hardening. Tool steels are thus delivered in general in soft-annealed condition. Soft annealing on the part of the customer is taken into account only if the steel is reforged or a second hardening is carried out by the customer. During soft annealing the steel is slowly heated to the required temperature – in the vicinity of the transformation temperature Ac_{1b} – and held on this level for two to four hours, then slowly – 10 to 20 °C/h – cooled down to around 500 °C in the furnace and subsequently cooled in air. Suitable measures are to be taken against scaling and decarburization.

The soft-annealing temperatures for a lot of steels are stated in our brochures. Soft-annealed steel has a characteristic structure, so-called granular or globular cementite.

STRESS RELIEVING

Components with complicated forms or widely differing sections will always warp more or less strongly during hardening. So as to prevent warping through treatment stresses during later heat treatment, a stress relieving of the components in rough-machined condition is recommended. For this, temperature should be 600 to 650 °C. Holding time: Depending on wall thickness one to several hours, with subsequent furnace cooling.

The so-called stress relieving, however, is often not sufficient to reduce possible internal stresses, which may be present in the component for other reasons. Thus, it is expedient to austenitize the rough-machined component in particularly critical cases, to air-cool it and to subsequently soft-anneal it so as to enable finish-machining. In the course of this "pre-tempering", the complicated component will deform under stress reduction. Through finish-machining, it can be adjusted to the correct dimensions. Self-evidently, sufficient material allowances are necessary. For final tempering, the usual grinding tolerances are generally sufficient.

Through frequent and regular stress relieving, the service-life of hot-forming tools in operation can be considerably extended. This heat treatment is expediently carried out at about 30 to 50 °C below the tempering temperature.

HARDENING

When the tools arrive for hardening they are mostly finished or nearly finish-machined save for a small grinding allowance. So as to be able to reach the desired properties of the tools with the least possible risk of rejects, the heat treatment must be carried out with the highest possible care.

SURFACE PROTECTION

During heat treatment, chemical processes occur with heightened speed at high temperatures. Thus, during heat treatment the problem arises of keeping the thermochemical influence of the heating media on the steel surface of a workpiece neutral. Even if the surface of the workpiece has remained blank during hardening, the surface area may be chemically changed and damaged through partial decarburization, carburization, oxygen and nitrogen intake **(Figure 14)**.

The various heating media such as firm packaging media, hardening salts and inert gases display a more or less neutral behavior and are thus manageable to varying degrees **(Figure 14)**. Many years of experience and continuous control of heating media will yield good, steady results.

The highest degree of surface protection of workpieces is reached in vacuum furnaces.

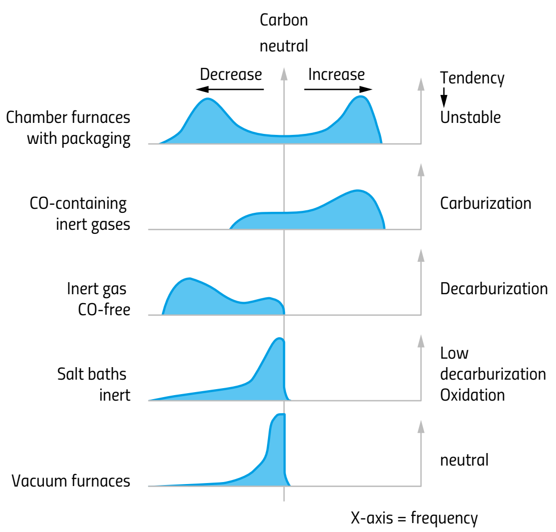

Figure 14
Influence on the surface in various hardening processes

HEATING TO HARDENING TEMPERATURE

The higher the alloying elements in a steel, the lower its heat conductivity. This is why tool steels, which are in general highly alloyed, must be heated carefully. If hardening is not carried out from heat treatment facilities with controlled heating speed, the tools are to be preheated in single or multiple steps. We state the most favorable preheating temperatures for the different tool steels.

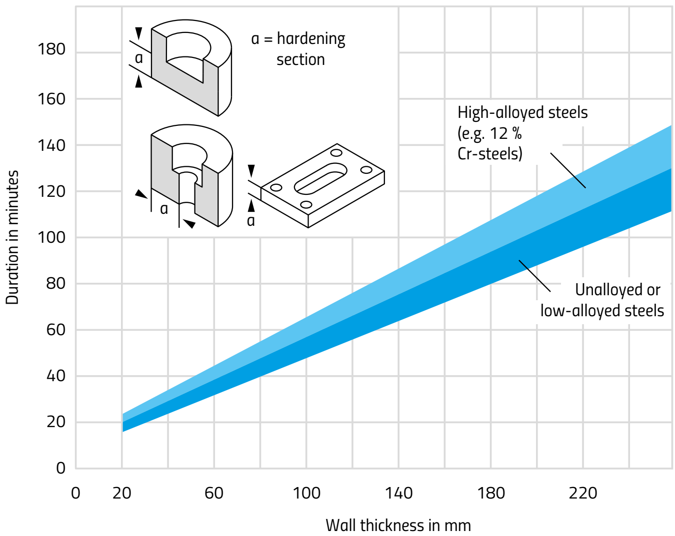

Figure 15
Guiding values for the holding time after reaching the hardening temperature on the surface, or the immersion time in the salt bath respectively, in dependence of the wall thickness.

For salt facilities it is recommended to preheat the components in a furnace at 300 to 400 °C before charging them into a salt bath with the prescribed preheating temperature. Preheating may however be omitted in the case of small, simply shaped tools, if the prescribed hardening temperature in the salt bath does not exceed 850 °C. If heating is not carried out in salt baths but in furnaces such as retort, chamber, bogie hearth or similar furnaces in packaging, with inert gas or in vacuum, the prescribed preheating temperatures are also to be set as steps. The workpieces are to be held on these temperatures up to full soaking.

The tool has to be fully heated up to the prescribed hardening temperature after preheating. The hardening furnace must be controlled in such a way that the thinner sections of a component, which inevitably rush ahead in the heating, are not over-heated or excessively held. Holding time, which starts with the achievement of the temperature of the complete component, is dependent on the steel grade and the chosen temperature within the prescribed range. In the case of simply-shaped tools, the upper hardening temperature limit can be selected most of the time, yet in the case of tools with strongly varying sections the lower hardening temperature range is to be preferred. Therefore, holding times in the former case are shorter than in the latter. Unalloyed and low-alloyed steels must be held on the hardening temperature for significantly shorter periods due to the risk of overheating (grain coarsening) than high-alloyed, Cr-, Mo-, V-, W-carbide containing hot-work steels. For these, the solution of the carbides, important for the achievement of optimal tempering resistance, needs significantly more time.

Figure 15 serves as an indication for the determination of the holding time after reaching the hardening temperature on the surface or the immersion time in the salt bath.

QUENCHING

Quenching must be performed with the prescribed hardening agent. If hardening in water is prescribed, its temperature should be at 20 to 40 °C. For the internal hardening of bore holes, suitable sputtering equipment must be installed. Hardening oils are to have higher temperatures according to the prescriptions of the manufacturer. As soon as the temperature has decreased to 60 to 100 °C, the components are to be removed from the quenching bath and immediately tempered. In the case of compressed or blast air quenching, perfect dryness of the air must be ensured.

HOT-BATH HARDENING

Hot-bath hardening offers particular advantages. For this, quenching is carried out in an intermediate bath which is held at a temperature in the transformation-resistant range of the isothermal TTT diagram. For example, for the steel grade 1.2379 (X153CrMoV12) the temperature of 450 to 500 °C is considered favorable, in which the supercooled austenite is stable. For higher-alloyed steels such as high-speed and hot-work steels a salt melt with a melting point of roughly 430 °C at a temperature of 500 to 550 °C is used. For lower-alloyed oil hardenable steels a salt melt with a melting point of 140 °C is used at a temperature between 160 to 200 °C.

The workpieces are held in these baths at least to full thermal equilibrium and subsequently cooled down to room temperature.

Hot-bath hardening, which can be carried out not only after heating in a hardening salt bath but also from other furnaces, offers the advantage of reduced dimension changes, weaker warping, the smallest risk of cracks and a clean surface.

TEMPERING

Tempering means holding the hardened steel at temperatures below A_{c1}, mostly with subsequent air cooling.

Tempering causes a reduction of stress and a gain in toughness through the transformation of the "tetragonal" martensite in the less crack-prone "cubic" form. Therefore, tempering must in all cases be carried out immediately after hardening.

Moreover, through tempering a microstructure stable against heat affection is achieved, which is particularly important for hot-forming tools. The precondition for the microstructure stability is that the tempering temperature selected is at least 30 to 50 °C higher than the working temperature of the tool. For this, however, the interchangeability of temperature and time, which exists to a certain extent, must be taken into consideration.

For example, a one-hour tempering at 600 °C has something like the same effect as a tempering treatment at 500 °C over a period of 400 hours. This example shows that the influence of temperature is much stronger than that of time.

Multiple tempering increases toughness.

For higher-alloyed steels and tempering temperatures of over 500 °C, a second tempering at about 30 °C below the temperature of the first tempering is required. This is necessary due to the presence of retained austenite after hardening, which, during cooling after the first tempering, transforms into the tetragonal martensite. This is converted into the less brittle cubic martensite during the second tempering.

Immediately after hardening the tools must best be tempered in a convection air furnace, in a fluid bath (oil) or in salt baths. The temperatures are to be taken from the tempering diagrams of the individual steel grades. The tempering time is dependent on the material thickness. The components are to be slowly heated to tempering temperature and are to be held for at least one hour per 25 mm thickness at this temperature.

CASE HARDENING

Case hardening means a hardening after prior carburizing, where appropriate with simultaneous nitriding of the surface. Case hardened tools are preferably employed as structural steels for plastics processing, i.e. where high core toughness and a wear resistant surface are required together.

The carburizing consists of a carbon concentration through holding at a temperature above the conversion points A_{c1} or A_{c3} in carbon-emitting media. Depending on the type of medium employed this is referred to as gas, bath or powder carburizing. The carburizing depth is determined by the duration of the carburizing and the activity of the carburizing medium. In general, the case hardening temperatures lie at 870 to 930 °C, however also higher temperatures are occasionally applied.

As a rule, tool steels are case hardened according to 2 processes:

1. **Direct hardening** consists of a hardening of the carburized workpiece at the end of the carburizing process, whereby the hardening temperature may lie lower than the carburizing temperature; however it must still be above $\mathbf{A_{r3}}$ of the case.
2. In **single hardening** the work piece is cooled after carburizing to below $\mathbf{A_{r1}}$ and subsequently quenched from the hardening temperature of the case.

THERMAL CYCLE DIAGRAM

The heat treatment processes described may be easily shown through thermal cycle diagrams for individual steel groups.

1. Hot-Work Steels

With respect to heat treatment hot-work steels can be subdivided into two groups:

- Hot-work steels with a hardening temperature of above 950 °C (high-alloyed hot-work steels, **Figure 16**).
- Hot-work steels with a hardening temperature below 950 °C; this includes most of the die steels (**Figure 17**).

Double tempering is required for hot-work steels with a hardening temperature of over 950 °C (high alloyed steels), for such with a hardening temperature below 950 °C (die steels) it is expedient. The principle of multiple tempering increases the toughness in these cases, too.

2. Alloyed Cold-Work Steels

With respect to heat treatment cold-work steels just like hot-work steels can be subdivided into two groups:

- High-alloyed cold-work steels with hardening temperature of above 900 °C. This includes for example the high-chromium-alloyed steels of the type 2 % C–12 % Cr, as well as steels with a Cr-content of above 5 %, such as 1.2362 (X63CrMoV5-1) or 1.2363 (X100CrMoV5) (**Figure 18**).
- Low-alloyed cold-work steels with hardening temperatures of below 900 °C. This group includes most of the cold-work steels, such as 1.2842 (90MnCrV8), 1.2067 (102Cr6), 1.2419 (105WCr6), 1.2767/RABW (45NiCrMo16) and so on (**Figure 19**).

3. Unalloyed Tool Steels (Figure 20)

Unalloyed steels have low effective hardening depth; they are water-hardening steels. The quenching effect of water and thus the hardness of the tool can be increased through the addition of salt (10–12 % salt solution). Oil-quenching is considered only for few grades and in this case only for very small thicknesses.

4. Case-Hardened Steels

Case hardening has already been described before.
The two thermal sequence diagrams for

- direct hardening (**Figure 21**)
- single hardening (**Figure 22**)

will demonstrate the two processes.

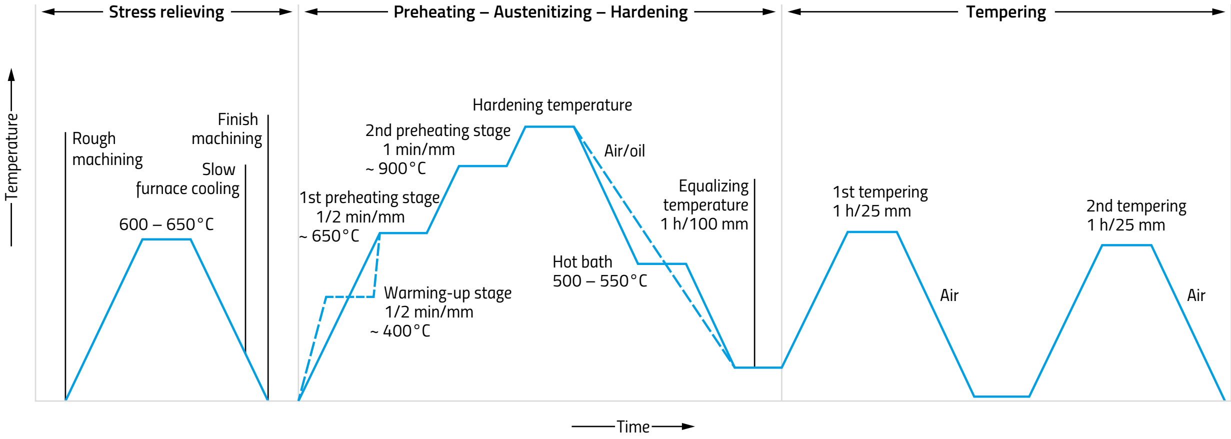

Figure 16
Thermal sequence for the heat treatment of hot-work steels with a hardening temperature of above 950 °C

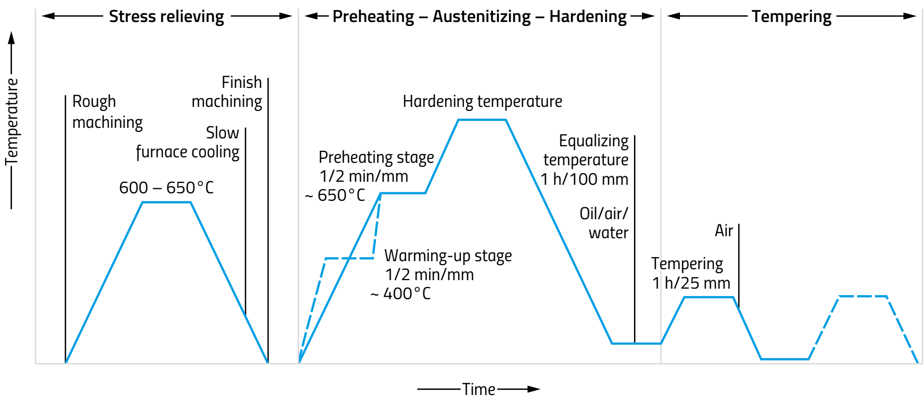

Figure 17
Thermal sequence for the heat treatment of hot-work steels with a hardening temperature below 950 °C

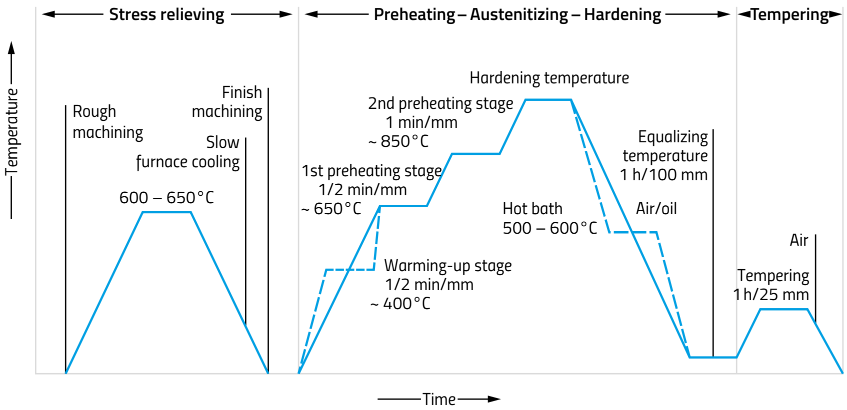

Figure 18
Thermal sequence for the heat treatment of high-alloyed cold-work steels with hardening temperatures of about 900 °C

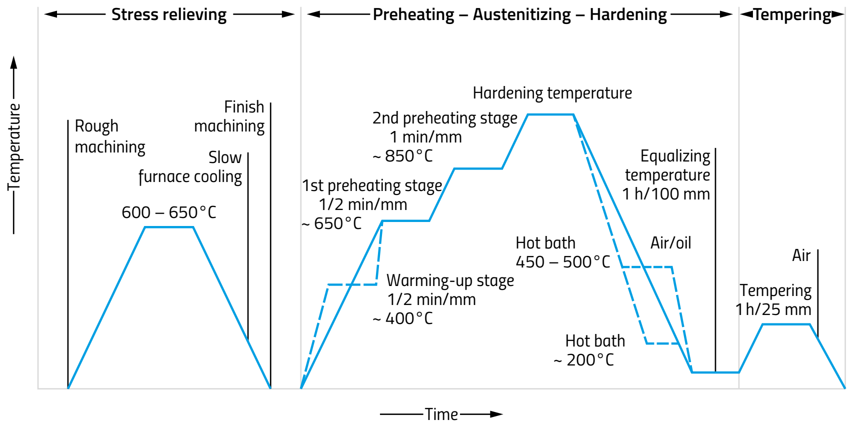

Figure 19
Thermal sequence for the heat treatment of low-alloyed cold-work steels with hardening temperatures of up to 900 °C

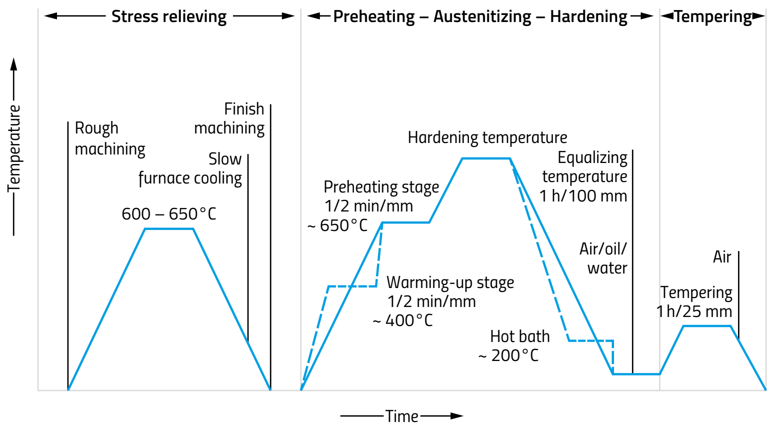

Figure 20
Thermal sequence for the heat treatment of unalloyed tool steels

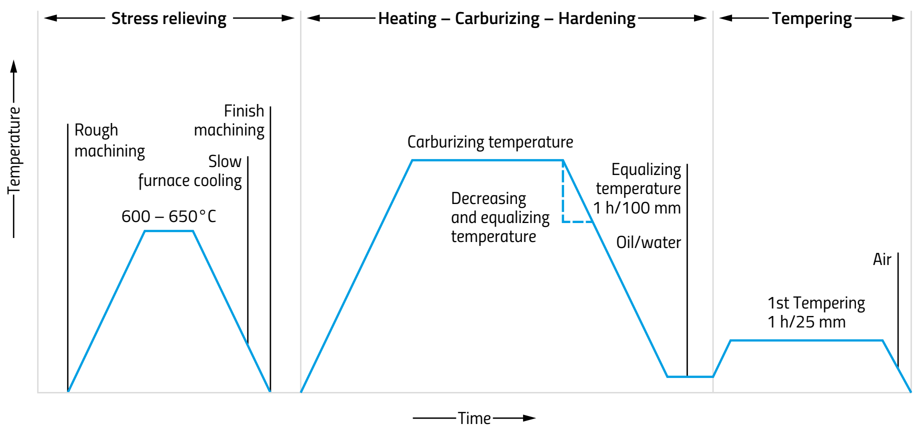

Figure 21
Thermal sequence for direct hardening

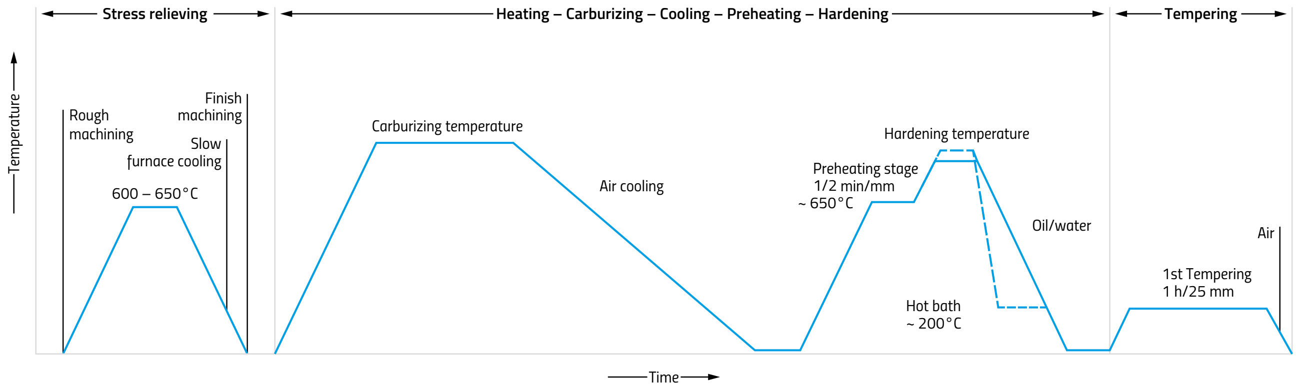

Figure 22
Thermal sequence for single hardening

EXAMPLES FOR APPLICATION

The opposition between toughness and wear resistance properties forces a reasonable compromise in the material selection and the determination of hardness. In many cases, the resulting wear resistance of the tool is not sufficient for cost-efficient work life. Through surface treatments on the finish-machined tool decisive improvements can however be achieved. From the multitude of possible processes only 4 shall be mentioned here, which have already met with a broader application or have recently gained greater importance: nitriding, hard chromium plating, coating with hard metals and steam tempering. With surface treatment, not only an increase of the wear resistance is achieved through partially considerable hardness increases. At the same time the sliding properties are improved and corrosion resistance is increased.

These surface treatment processes are extensively described in literature. In the following, especially their effects on the surface properties of the steels will therefore be shown.

NITRIDING

One of the most frequent processes for tools today is nitriding. Depending on the process – gas or salt bath nitriding, ionitriding – treatment temperatures of around 450 to 580 °C are applied. Therefore, only steels with sufficient tempering resistance are suitable for such treatment, preferably those with a distinctive secondary hardness maximum. On the one hand, the material must be tempered sufficiently highly before nitriding so that during the final treatment no dimensional changes caused by structural changes occur, which would make post-treatment of the tools necessary. On the other hand, the base material must retain a sufficiently high hardness so that a sufficient support effect for the superhard surface layer is guaranteed.

In **Figure 23** the tempering diagrams of some tool steels are contrasted. Of these materials the steels 1.2842 and 1.2080 (X210Cr12) are not suited for nitriding, the remaining steels can be treated.

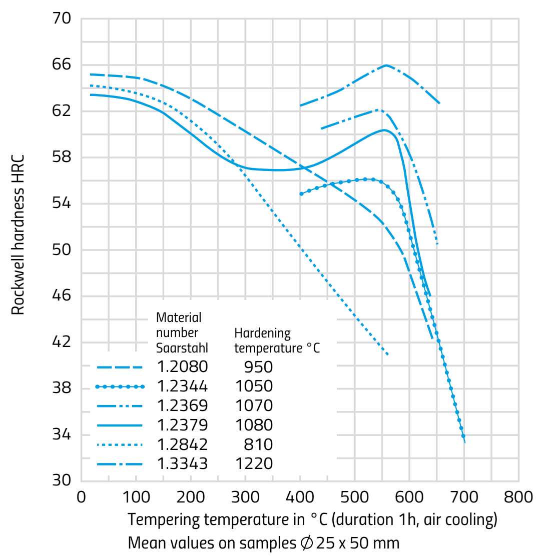

Figure 23
Tempering behavior of tool steels

Due to the advantage of short treatment times, often salt bath nitriding according to the Tenifer process is applied for materials. Depending on material and treatment time, surface hardnesses of 1,000 to 1,300 HV and nitriding depths (diffusion zone) up to around 150 µm are reached. In order to prevent flaking on the cutting edge of cutting tools, the meeting of two nitrided surfaces should be avoided through regrinding of one surface.

HARD CHROMIUM PLATING

For hard chromium plating the surface hardnesses are in the range of 1,000 to 1,200 HV. The treatment is carried out at around 50 °C so that the basic structure is not affected. Adhesion is not always sufficient as a diffusion zone with the base material will not be created. A more sophisticated method exists under the name Duralloy, with which hardnesses of 1,200 to 1,400 HV can be set. Adhesion has been improved against the traditional processes. As a rule, chromium thicknesses of 5–20 µm thickness are generated. Tools chromium plated according to this process in some instances reach considerably increased efficiency.

COATING WITH HARD MATERIALS

Very high hardnesses of around 2,000 to 4,500 HV can be set if hard materials such as TiC, TiN or WC are emitted from the gas phase to the tool surface. The two best-known possibilities are the CVD and the PVD processes.

In the chemical vapor deposition process (CVD) the coating material is generated through the chemical reaction of gaseous components. The treatment temperatures lie around 1,000 °C so that for tool steels only those with hardening temperatures within or above this range can be coated. Due to the unavoidable changes in dimension and form through conversion and temperature stresses, only geometrically simple tools can be treated as the low coating thickness (around 5 µm) does not permit finishing.

In the physical vapor deposition process (PVD) the metallic hard material component is present in solid form. It is brought into the steam phase through physical processes (evaporating, sputtering, ion-plating) where it deposits on the tool surface after bonding with the reactant. Against the CVD process the PVD process has the advantage that the coating temperatures (around 350 to 550 °C) lie within the range of the tempering temperatures of high-alloyed tool steels. The tools can therefore be coated after the heat treatment is finished.
The increase in efficiency through coating with hard materials is considerable. As an example a research result by Sato and collaborators is quoted **(Figure 24)**. For punching holes into plates of various thicknesses applying stamps of a 12 % Cr-steel the influence of the TiC layer coated according to the CVD process was examined. The diagram shows that through coating the number of punches performed until regrinding is increased between 4 and 20 times depending on the thickness of the plates.

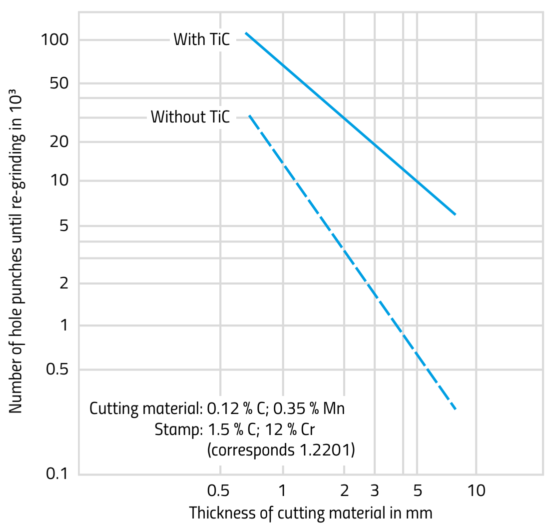

Figure 24 Tempering behavior of tool steels

Hard material layers can also be deposited through a kind of spark discharge hardening whereby the surface is heated only to a depth of a few µm. In this process TiC or WC is deposited through spark discharge between the tool and a vibrating electrode. Layer thicknesses up to around 80 µm are achievable; due to the high surface roughness regrinding must be performed.

STEAM TEMPERING

Steam tempering is a surface treatment process which is applied nearly exclusively for high-speed tool steel. For this, an extremely thin oxide film of some thousandths mm thickness is deposited on the tools.

This oxide film reduces the tendency for adhesion and cold-weldability of the tools as well as their abrasive wear.

The treatment is carried out in convection furnaces into which dry steam is introduced. The temperatures must lie below the latest tempering temperature, i.e. they are slightly above 500 °C.
The process is especially suitable for small tools such as spiral drills and screw taps, broaches, reamers, counter-sinks and such.

GRINDING

The high operational speeds which are usual during grinding on modern grinding machines significantly increase the risk of burning the tools in case of too high forward feeds.

In the case of hard tool steel and high-speed steel, it is mostly the dreaded grinding cracks created due to improper grinding operation, especially due to too hard disks. In the case of case-hardened components, the case may splinter off due to unsuitable grinding.

For the selection of the disks, the following principle applies: Use hard disks for soft steel, use soft disks for hard steel.

For rough grinding use coarse-grained, for fine grinding use fine-grained discs. Too hard and too fine discs heat up the steel too much and cause grinding cracks. When in doubt, the selection of the grinding discs should be determined by the producer.

Hardened tools from high-speed steel as well as such of high-quality cutting steel, also case-hardened tools, for which in most cases a clean grinding is necessary, must be ground with abundant water cooling. For cooling no soap-like coolants should be used if possible. Yet, the use of a grinding emulsion is recommended.

One can immediately realize on the ground surface whether the grinding was carried out properly or improperly. If the ground surface displays a yellowish to brownish color, grinding was carried out with an excessively deep chip, i.e. with too much heat generation. If hardened tools show such surfaces, they are tempered through grinding, i.e. they have become soft, and they mostly contain grinding cracks. This can be recognized through slight etching with weak acids.

ELECTRICAL DISCHARGE TEXTURING

During electrical discharge machining the material on the surface of the tool becomes fusible. As a consequence there remain from the outside to the inside a solidification area with cast structure, a hardness increase and a high-tempered layer. Below exists the unaffected base material.
The so-called white zone almost always contains tension cracks. The heat-affected layer generated through scrubbing should by all means be removed through one or more coating erosion steps with low performance.
Moreover, a final stress relieving of the tool of around 30 to 50 °C below tempering temperature is recommended as also after coating erosion an affection of the surface – even if small – remains.

ELECTRICAL DISCHARGE MACHINING

Electrical discharge machining is a further technique with extraordinary results if tools with geometrically difficult forms are cut out of plates. In this process the affection of the tool surface is small and thus less problematic. Nevertheless, the unrestricted application of electrical discharge machining is not free of risks. Larger tools always contain more or less high inherent stresses after heat treatment. During eroding this stress condition is seriously disrupted; the stresses released by this can cause cracks. This is shown schematically in **Figure 25** (upper half). This risk can be considerably reduced if before heat treatment stress removal cuts are carried out, which are aligned to the contours of the tool (**Figure 25** lower half). This measure leads to a considerably reduced stress field after heat treatment; the danger of crack formation during eroding is reduced.

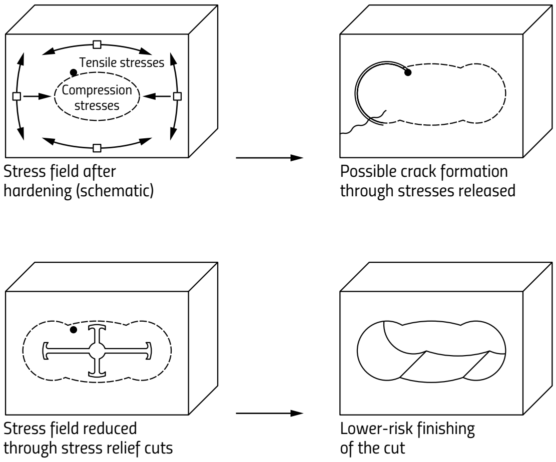

Figure 25
Risk of cracks during electrical discharge machining of large tools

INFLUENCE OF THE MOST IMPORTANT ALLOY ELEMENTS ON THE PROPERTIES OF TOOL STEELS (SCHEMATIC)

Indirect influences, i.e. the affection of toughness through hardenability, are not considered in this scheme which merely carries orienting character.

ALLOYING ELEMENTS		HARDNESS AFTER QUENCHING	WEAR RESISTANCE	THROUGH-HARDENABILITY	TOUGHNESS	TEMPERING RESISTANCE	HIGH-TEMPERATURE STRENGTH
C	solved	⊕⊕⊕⊕	⊕⊕	⊕	⊖⊖	○	○
	unsolved (carbide)	⊕⊕	⊕⊕⊕⊕	⊖	⊖⊖	○	○
Cr	solved	○	○	⊕⊕⊕⊕	○	⊕⊕⊕	⊕
	as alloy carbide	⊕	⊕⊕⊕⊕	⊖	⊖	○	⊕
Si		○	○	⊕	○	⊕	○
Mn		○	○	⊕⊕⊕⊕	○	○	○
Ni		○	○	⊕⊕⊕⊕	⊕⊕⊕⊕	○	○
Mo	solved	○	○	⊕⊕⊕⊕	○	⊕⊕⊕	⊕⊕⊕⊕
	as alloy carbide	⊕	⊕⊕⊕⊕	⊖	⊖	○	⊕⊕
W	solved	○	○	⊕	○	⊕⊕⊕	⊕⊕⊕⊕
	as alloy carbide	⊕	⊕⊕⊕⊕	⊖	⊖	○	⊕⊕
V	solved	○	○	⊕⊕	○	⊕⊕⊕⊕	⊕⊕⊕⊕
	as alloy carbide	⊕⊕	⊕⊕⊕⊕	⊖⊖	⊖	○	⊕⊕

Negative	⊖⊖
Slightly negative	⊖
No influence	○
Slightly positive	⊕
Moderately positive	⊕⊕
Positive	⊕⊕⊕
Strongly positive	⊕⊕⊕⊕

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