Selecting Materials
for Punching and Forming Tools and the Heat Treatment thereof

Deutsche Edelstahlwerke

Member of Swiss Steel Group

Economic efficiency is a key aspect of all industrial processes.

Due to rising cost pressure, it is necessary to keep a closer eye than ever on costs. In terms of toolmaking, this means that demands are growing all the time in relation to material selection, as well as heat and surface treatment.

Choosing economical steel does not in any way involve using the cheapest steel. It is far more important to select the most suitable material for the intended purpose. If the wrong material has been chosen, this often only emerges when the tool is in operational use, potentially resulting in significant extra costs.

When selecting a tool steel, it is important to keep in mind that the tool must not break during use or chip around the cutting edge. Similarly, permanent deformation and premature changes to the tool surface as a result of wear and tear or corrosion need to be excluded. Steel availability should also be checked. Due to the cost situation, steel manufacturers are being forced to limit their product ranges. In recent years, however, various highly versatile tool steels have been developed, which enable tool steel portfolios to be restricted without compromising on technical properties. This ultimately has considerable benefits for toolmakers.

Stresses on tools

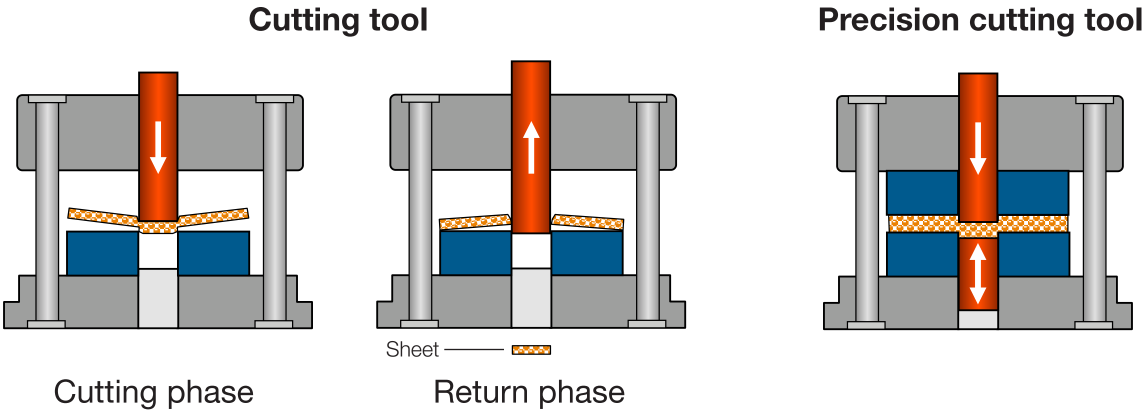
In order to choose the appropriate steel for an application, it is vital to be aware of the tool stresses that arise during individual operations.
The diagrams below and on the pages that follow illustrate the relevant principles.

Cutting

The cutting surfaces of the punch and cutting plate penetrate the sheet to be cut, initially deforming it elastically and later plastically in the shear zone. When the deformability of the material to be cut is exceeded, fine cracks form at first which spread out and expand as cutting continues. Eventually the material fractures and separates. Because around only a third of the sheet thickness is cut during the cutting process (the rest breaking off due to tensile stresses), a burr appears on the pieces. This may snag on the tool when the cutting punch is pulled back so that the punch comes under undesired, dangerous tensile stresses. Corrective action can be taken here by using precision cutting tools which significantly reduce this burr. Cutting tools are subjected to pressure during the cutting process. If cycle times are high, this stress may occur suddenly.

Materials suitable for cutting tools not only need high compression strength; they must also provide adequate resistance to impact. Relative movements that occur between the tool's cutting surfaces and the sheet to be cut always result in friction, and therefore wear and tear, when pressure is applied simultaneously. Depending on the tool area that is affected, distinctions are made between wear to the end face, lateral surfaces, and crater wear. Marked wear to the lateral surfaces can be particularly unfortunate because it requires intensive regrinding. This is why there is demand for high wear resistance when it comes to tool steels used for cutting tools.

From this brief description, it can be concluded that tool steels for cutting tools should exhibit the following properties:
» high hardness
» high compression strength
» adequate impact strength
» high wear resistance



Cutting process (principle)

Cold-forming technology

In cold extrusion, predominantly rotation-symmetric workpieces are produced from blanks such as discs, rod lengths or preforms. Possible procedures are:

» direct impact extrusion
» indirect impact extrusion
» combination of direct and indirect impact extrusion

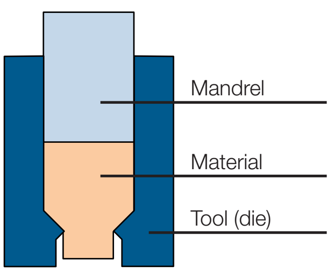
These are shown in the diagram below. The main difference lies in the direction of movement. Tools consist of multiple component parts. The material to be formed is placed in the die. In the case of the impact extrusion of rods or tubular impact extrusion, the mandrel compresses the material through the die. When extruding cup-shaped sections, the mandrel shapes the inner surface of the workpiece. The pressure plate must absorb the mechanical load and distribute it evenly. The moulding cycle exerts enormous forces on the workpiece, creating a bursting effect within the die which needs to be absorbed by one or more casings that reset the die. The demands on specific tool parts can be summarized as follows:

Die:
» high fatigue strength
» high wear resistance

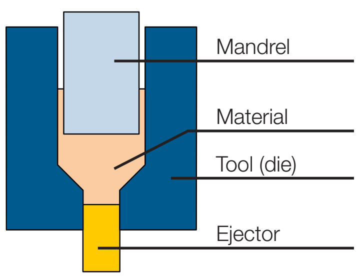
Mandrel:
» high wear resistance
» high compression strength

Casing:
» high tensile strength
» high toughness

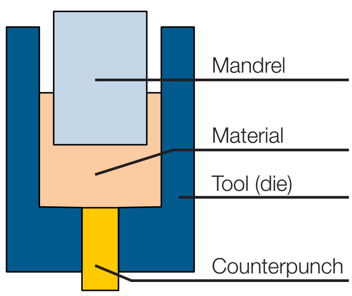
Direct impact extrusion



Indirect impact extrusion



Direct/indirect impact extrusion

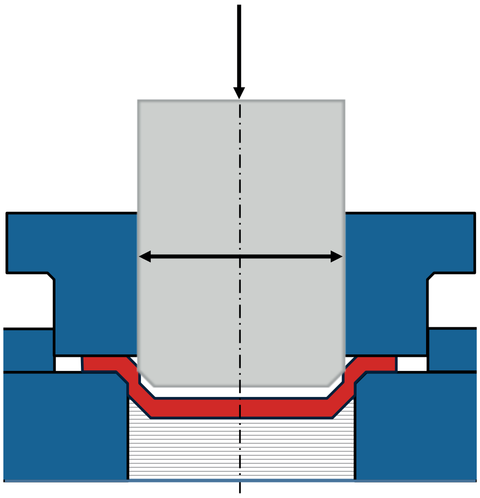


Impact extrusion (principle)

Deep drawing

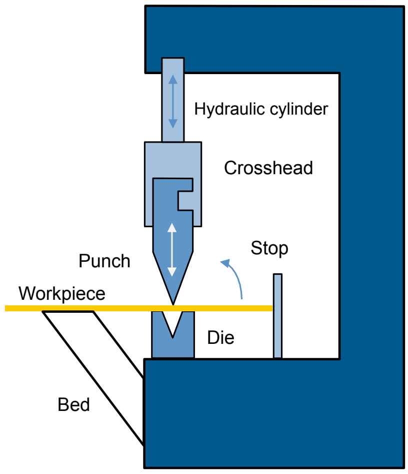
The basic design of deep-drawing tools is as follows:
» drawing punch
» blank holder
» draw die

The strain on the drawing punch largely arises due to pressure. The blank holder and draw die are subject to wear mainly on the edges.


Deep-drawing process (principle)

Bending/folding

When bending or folding, there is essentially no change in sheet thickness. This means that friction between the workpiece and tool, and therefore wear resistance, is of minor significance here. Tools are subjected to pressure and must therefore have high compression strength. Toughness is also an important factor. To ensure this **compression strength**, a high hardness is set for the tools.

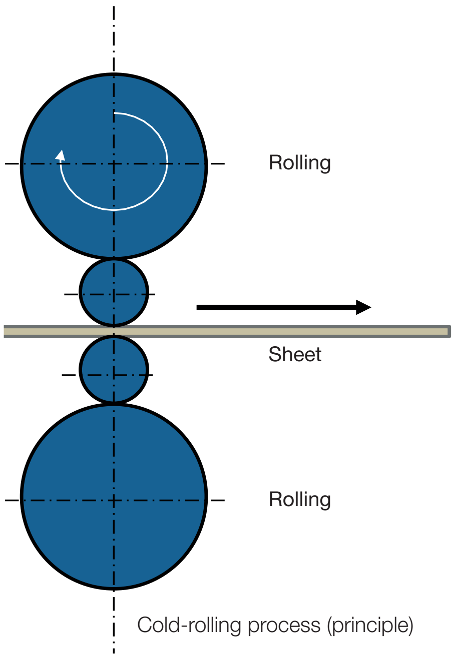


Bending (principle)

Cold rolling

In the case of **rolling** a distinction is made between profile rolling and flat rolling. Flat rolling is used to cold-roll sheets, strips and similar products.

A typical example of the use of profile rolling is to produce thread rolls for applying threading to workpieces. The roller surfaces must be exceptionally **hard** to withstand wear from the materials being formed. Essentially, tools must be **tough** enough to absorb the bending stresses that arise. Often the Cryodur 2379 and Rapidur 3343 steels are used for these purposes.



Cold-rolling process (principle)

Cold rolls

Material properties

Hardness and wear resistance on the one hand and toughness on the other are conflicting property requirements. Finding a satisfactory balance between them often involves compromise.

Wear resistance

Friction between the tool and workpiece partially wears out the working and cutting surfaces of tools, thereby limiting their service life. That is why wear resistance is an important property of tool steels. However, it cannot be clearly defined and it is not material-specific. Frequently, using a tool causes several overlapping types of wear, which are often compounded by heating. Because wear resistance depends on a number of external factors, it is not possible to extrapolate universal wear resistance from the results of different methods of testing wear. Instead, findings will always say more about the case that is undergoing testing.

The wear resistance of a tool steel depends on its chemical composition, the microstructure (carbides), its hardness and surface quality, as well as the type of load. In this context, it can be stated that the harder the steel, the greater its wear resistance. Changing the hardness of the surface area (by way of nitriding, coatings, surface hardness, for example) increases wear resistance.

Wear resistance is highly dependent on the carbon content of the steel. Because it is responsible for martensite formation, carbon is the element that determines the hardness of steel. In addition, carbon in steels with higher contents of alloys (particularly Cr, Mo, V, W) tends to form very hard carbides. As fine particles, these are more or less embedded in the steel and help to increase wear resistance considerably.

There is also a direct relationship to the heat treatment condition and therefore the steel's structural constitution.

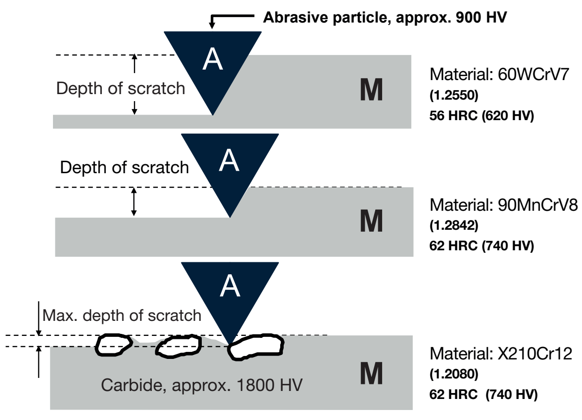


Diagram: Wear resistance

Grade	Hardness	Wear resistance	Toughness
Cryodur 2067	++	++	+
Cryodur 2080	+++	+++	O
Cryodur 2101	++	++	+
Cryodur 2243	+	+	+++
Cryodur 2363	++	++	+
Cryodur 2379	+++	+++	+
Cryodur 2436	+++	+++	O
Cryodur 2510	++	++	+
Cryodur 2516	++	++	+
Cryodur 2550	+	+	++
Cryodur 2767	+	+	+++
Cryodur 2842	++	++	+
Cryodur 2990	+++	++	++
Rapidur 3343	+++	+++	+

Comparison of toughness and wear resistance given standard working hardness

Toughness

It is not possible to establish a universal definition of toughness either. In relation to tool steels, toughness needs to be understood as the ability of a material to avoid cracking by way of slight plastic deformation when exposed to a load. There are a number of ways of describing toughness. For steels exhibiting low hardness, toughness can be directly assumed from the values determined in the tensile test for percent elongation at fracture A5 or percent reduction of area at fracture Z. A simple method for testing hard steel grades under sudden stress is the impact bending and notched-bar test using various different sample shapes. For steels with hardness values exceeding 55 HRC – which most of the cold-work and high-speed steels here always achieve – these tests do not provide reliable results. In these cases, therefore, static flexure or torsional tests are employed which use the measured plastic activity to gauge toughness.

Hardness and wear resistance on the one hand and toughness on the other are conflicting property requirements. Finding a satisfactory balance between them often involves compromise. In practice, this usually involves referring to working hardness, as well as specific surface treatments.

Materials

During the punching and forming processes covered in this brochure, the tools are not generally exposed to higher temperatures.
As result, mainly cold-work tool steels are used in this area supplemented by high-speed tool steels and, occasionally, hot-work tool steels.

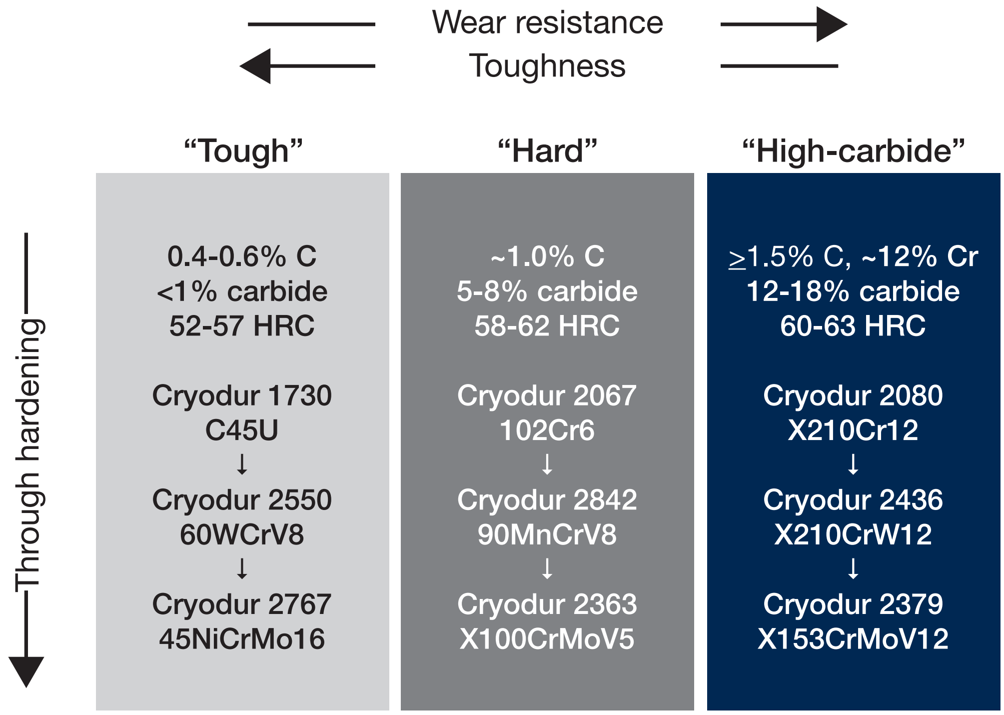
Cold-work tool steels are non-alloyed or alloyed steels where the surface temperature is typically less than 200 °C in use. Hot-work tool steels are defined as alloyed steels where the surface temperature typically exceeds 200 °C in use. Due to their chemical composition, high-speed tool steels have the highest red hardness and tempering resistance, and can therefore be used at temperatures of around 600 °C.

Cold-work tool steels are preferred for tools used to make workpieces without cutting from ferrous and non-ferrous metals (e.g. cutting, punching, drawing or spinning tools).

High-speed tool steels are mainly used for cutting tools, as well as for parts subjected to particularly high loads in forming tools. Because applications for these groups of steels overlap, a more detailed description is warranted here.

Developing materials based on requirements has led to a wide range of cold-work steels, some of which exhibit only minor differences in alloy composition or properties. In the past, repeated attempts were made to reduce this variety in the interest of improving cost-effectiveness.

These days, non-alloyed cold-work tool steels are of limited importance. Except for iron, they contain almost only carbon – the element solely responsible for martensite formation and therefore hardness. During hardening these steels attain a high level of hardness on the periphery as a result of quenching, but remain soft at the core. They are therefore known as shell-hardenable. Applications extend to areas where the combination of a hard surface and soft core is desirable.



Classification of common cold-work steels

In addition to carbon, alloyed cold-work tool steels contain amounts of the carbide-forming elements chromium, molybdenum, vanadium, and occasionally also tungsten, all of which improve the wear resistance of these steel grades. Elements such as nickel and manganese also contribute to high hardness values across larger cross-sections (through hardening). The effect of such elements is to make the steel grades slow to transform. In practical terms, this is beneficial because it means more mild quenching mediums (oil, air, salt bath) are suitable for bringing about martensitic hardening. Of the alloyed cold-work tool steels, ledeburitic chromium steels – which contain more than 1 % carbon and 12 % chromium – occupy a special position. Due to their carbide content they are highly wear-resistant. They are somewhat less toughness than the alloyed cold-work tool steels mentioned previously. That is why, when planning to utilize these steels, it is important to check whether the selected steel is tough enough or whether the hardness needs to be modified in some specific way.

High-speed tool steels are also used for many punching and forming tools. Originally developed for non-cutting tools, these exhibit particularly high wear resistance, high hardness at elevated temperatures and thus good tempering resistance. High-speed tool steels have a carbon content of between 0.8 % and 1.4 %. The main alloy elements are tungsten, molybdenum, vanadium and cobalt. The associated high carbide content results in very high wear resistance. The steel matrix is composed in such a way that it offers high tempering resistance.

Cold-work tool steels

Cold-work tool steels can be divided roughly into the following groups: non-alloyed, low or medium-alloy, oil-hardened and high-alloy, ledeburitic steels.

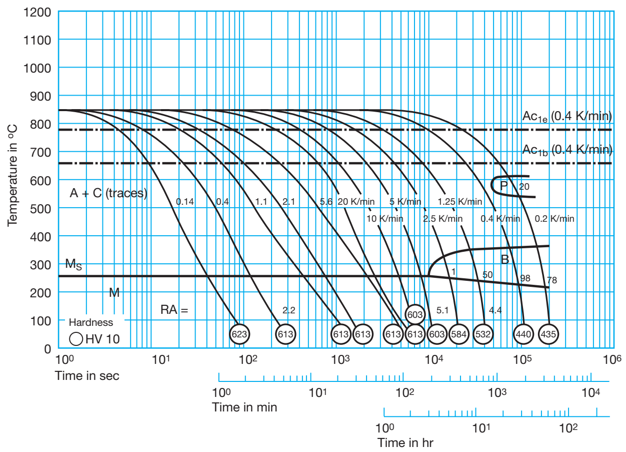
Name	DIN reference	Chemical composition (standard values in %)									
		C	Si	Mn	Cr	Mo	Ni	V	W	Co	Ti
Cryodur 1730	C45U	0.45	0.30	0.70							
Cryodur 2067	100Cr6	1.00	0.20	0.35	1.50						
Cryodur 2080	X210Cr12	2.00			12.00						
Cryodur 2101	62SiMnCr4	0.65	1.10	1.10	0.70						
Cryodur 2243	61CrSiV5	0.60	0.90	0.80	1.10			0.10			
Cryodur 2357	50CrMoV13-15	0.50	0.30	0.70	3.35	1.60		0.25			
Cryodur 2363	X100CrMoV5	1.00			5.30	1.10		0.20			
Cryodur 2379	X153CrMoV12	1.55			12.00	0.70		1.00			
Cryodur 2436	X210CrW12	2.10			12.00				0.70		
Cryodur 2516	120WV4	1.20			0.20				1.00		
Cryodur 2550	60WCrV8	0.60	0.60		1.10				2.00		
Cryodur 2709	X3NiCoMoTi18-9-5	< 0.03				5.00	18.00			10.00	1.00
Cryodur 2721	50NiCr13	0.55			1.10	0.10	3.20				
Cryodur 2767	45NiCrMo16	0.45			1.40	0.30	4.00				
Cryodur 2833	100V1	1.00	0.20	0.20				0.10			
Cryodur 2842	90MnCrV8	0.90		2.00	0.40			0.10			
Cryodur 2990	~X100CrMoV8-1-1	1.00	0.90		8.00	1.00		1.60			
Thermodur 2343	X37CrMoV5-1	0.38	1.00		5.30	1.30		0.40			
Rapidur 3343	HS6-5-2C	0.90	0.30	0.30	4.10	5.00		1.90	6.40		

From the group of non-alloyed steels, only **Cryodur 1730** shall be briefly mentioned here. To be hardened, it needs to be water-quenched (water-hardenable, shell-hardenable). It combines a hard surface with a tough core. During the tempering process which must be carried out to achieve the necessary toughness, hardness quickly falls according to the temperature selected for tempering.

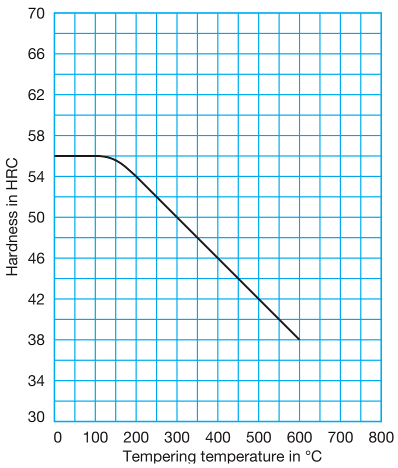
The cold-work tool steel **Cryodur 2067** contains 1 % carbon and 1.5 % chromium. This steel is slower to transform than the one previously mentioned. It is quenched using oil rather than water. Nevertheless its hardening depth remains low. Due to its chromium content, it forms carbides which increase the steel's wear resistance.

Both **Cryodur 2542** and **Cryodur 2550** are very similar in terms of chemical composition and therefore properties. For this reason, Cryodur 2542 is only rarely used nowadays. Cryodur 2550 is oil-hardenable, which means it can be hardened by means of an oil quench. Due to its toughness, it is used in tools such as chisels which experience a sudden load or if the toughness of higher-alloy steels is inadequate for the intended application.

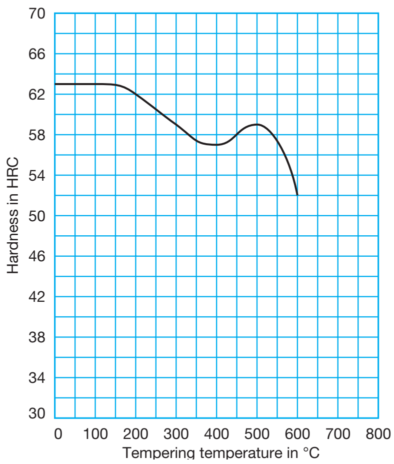
Time-temperature-transformation (TTT) diagram for Cryodur 2767



Tempering diagram for Cryodur 2767



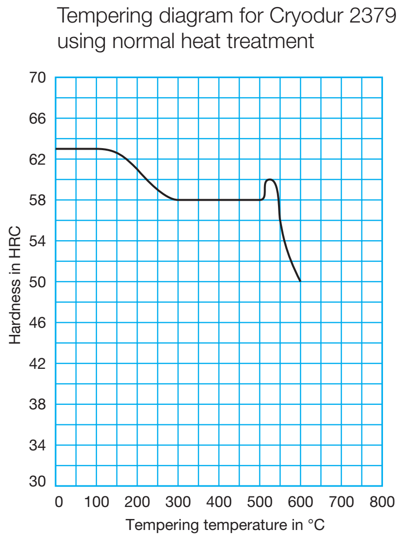
Tempering diagram for Cryodur 2363

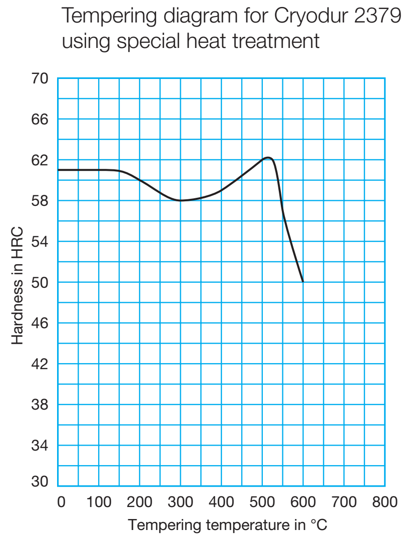


Due to its 4.0 % nickel content the high-alloy **Cryodur 2767** steel is characterized by high hardenability along with good toughness. It is therefore preferred in cutting tools for thick materials. The TTT diagram for this steel indicates the slow transformation of this steel with the areas of pearlitic and bainitic transformation beginning only after very long periods. This fact is beneficial for heat treatment as the steel can be hardened using very mild quenching mediums such as air, oil or a salt bath (180 - 220 °C). During tempering, the hardness of this steel changes according to its tempering curve. In the interest of achieving good toughness, temperatures between 250 and 350 °C should be avoided when tempering because the steel experiences embrittlement within this range. Because this steel is preferred for tools in large sizes, the ESR (electroslag remelting) variant of this steel should be used when toughness requirements are very high. Due to its solidification characteristics, this remelting process results in materials featuring very high levels of homogeneity and isotropy.

An important alloyed cold-work tool steel is **Cryodur 2363**. Due to its composition of 1.0 % carbon and approx. 5 % chromium plus 1.0 % molybdenum, it fills the gap between medium-alloy and high-alloy, ledeburitic chromium steels.

Owing to the steel's high carbon content, it achieves a high level of hardness as well as high carbide content and wear resistance. It is therefore given preferential use in all cases where tools are exposed to mixed loads. Usually this steel is hardened at temperatures between 930 and 970 °C and then tempered to the working hardness according to its tempering diagram. Given another rise in hardness at tempering temperatures of around 500 °C, however, this diagram indicates the potential for subjecting this steel to secondary hardening.





In order to carry out this secondary hardening properly, however, a hardening temperature of between 1020 and 1040 °C must be selected and tempering must be performed at least twice at temperatures of 510 to 530 °C. Although this treatment initially has no appreciable effect on mechanical/technical characteristics such as strength, hardness or toughness, it opens up the prospect of subjecting this steel to subsequent surface treatment (nitriding in plasma, for example) at temperatures of around 500 °C without affecting the steel's properties in any significant way.

As ledeburitic cold-work tool steels, **Cryodur 2080** and **Cryodur 2436** are extremely similar, the only difference being that tungsten content of Cryodur 2436 (0.7 %). Their high carbide contents provide high wear resistance and make them important tool steels for cutting tools and other tools prone to high wear. The tungsten content of Cryodur 2436 steel makes it easier to harden compared to Cryodur 2080.

Due to its tungsten content, Cryodur 2436 requires a somewhat higher hardening temperature. If oil quenching will be used, Cryodur 2080 can be hardened at 930 to 960 °C. Given thinner dimensions (thickness < 30 mm), air cooling is also possible. This may be favourable, particularly in terms of causing minimal distortion. In this case, a hardening temperature of 950 to 980 °C must be selected. This temperature range is also used for Cryodur 2436, which contains tungsten.

Cryodur 2379 is another ledeburitic cold-work tool steel. It exhibits good toughness as well as maximum wear resistance, giving it outstanding cutting edge retention. The tempering diagram for this steel indicates

Guide rails

the possibility of secondary hardening, which is primarily always applied if tools are to be nitrided.

Whereas for 'normal' primary hardening temperatures of between 1000 and 1050 °C are needed, secondary hardening calls for higher hardening temperatures, namely 1050 to 1080 °C. A more detailed description of the processes involved in secondary hardening is given in the section covering the heat treatment of steels. The TTT diagrams in these two cases indicate a broad range for metastable austenite between the pearlite and bainite or martensite area. As a consequence, oil, air or a salt bath of 500 to 550 °C may be used as a quenching medium during hardening. This causes exceptionally low hardening stresses and therefore only minimal distortion. The procedure for martempering (with salt bath) is also described in more detail in the section about the heat treatment of steels. Due to its spectrum of properties, Cryodur 2379 has tapped into a wide range of applications. As universal plate, it can largely replace the Cryodur 2080 and 2436 steels and therefore usefully helps to limit the variety of types as desired on all sides.

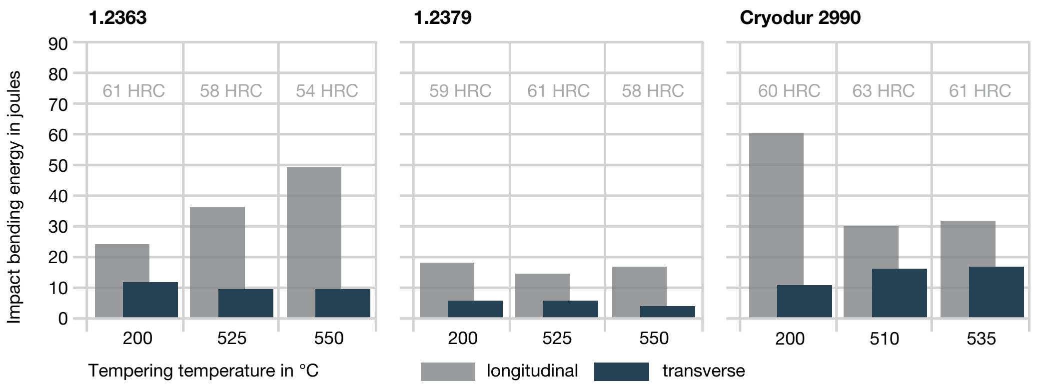
Cryodur 2990 is characterized by particularly high hardness, strength and adhesive wear resistance. The improved toughness compared to Cryodur 2379 achieves enhanced fracture strength. This prolongs service life. Cryodur 2990 has the ideal property profile for sheet metal working and for all punching, cutting and shearing tools, such as rotary shear blades, punches and dies, and progressive dies. Other cold-work applications are also possible (thread rolling, deep drawing, etc.). Cryodur 2990 is characterized by good EDM properties and good inductive hardenability.

Property comparisons

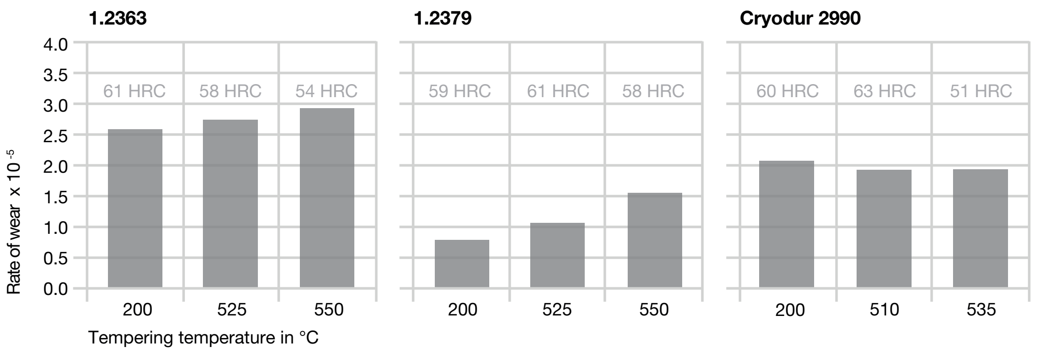
Cryodur 2990 stands out due to its special chemical composition and the resultant fine, homogeneous microstructure.

Cryodur 2990 is characterized by extraordinary hardness, strength and high wear resistance. With its enormous toughness, it also stands for high resistance to failure and thus for longer service lives and higher production quantities of the tool.

1.2363 *1.2379* *Cryodur 2990*



High toughness combined with higher hardness



Very good wear resistance (both abrasive and adhesive). For example, "Rod/disc test to compare the abrasive rate of wear."

High-speed and hot-work steels

Rapidur 3343, a high-speed steel, has become the standard steel for punching and forming applications.

It features an exceptionally well-balanced alloy composition with a high content of carbide-forming chromium, molybdenum, vanadium and tungsten in addition to carbon. This composition means that the steel is supplied (soft-annealed) with a carbide content of some 20 %. The steel's high wear resistance comes courtesy of this high carbide content.

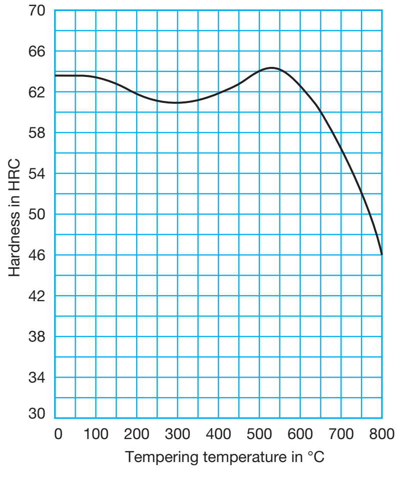
The data sheet shows that much higher austenitizing temperatures are required to harden high-speed steels than is the case for cold-work steels. The high thermal stability of the carbides present in high-speed steels is the cause of this, of which considerable quantities need to dissolve during austenitizing. Performing hardening on high-speed steels requires special care. After hardening, Rapidur 3343 steel attains a hardness of approx. 64 to 66 HRC. The high chromium and molybdenum content results in good through hardening.

This steel's tempering curve indicates a distinct maximum for secondary hardening of between 520 and 560 °C.

The level and temperature setting of this maximum depend on the hardening temperature. Tempering to the desired tempering hardness needs to be carried out at least twice (three times is better) at tempering temperatures exceeding the secondary hardening maximum.

In the range of manufacturing operations described here, **Thermodur 2343 EFS**, a hot-work steel, is also used. It exhibits high tempering resistance and stands out for its very good level of toughness.

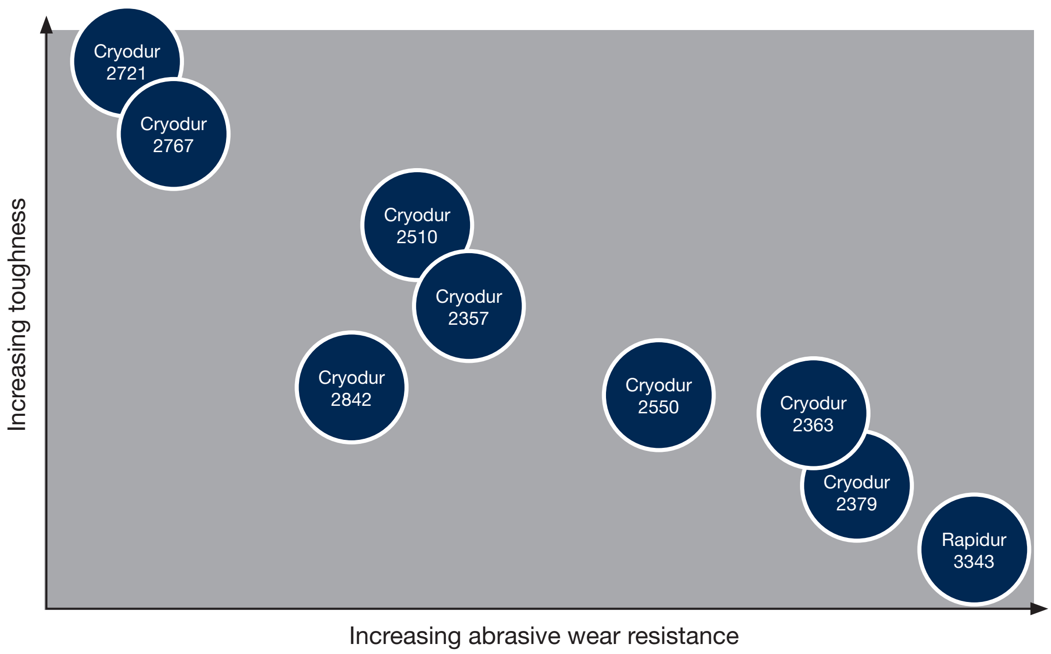
Tempering diagram for Rapidur 3343



Material selection

To make the most appropriate choice from the wide range of tool steels available, it is necessary to compare their properties based on tool requirements.

The diagram contrasts the wear resistance and toughness of a number of tool steels for cold-work applications.



Cutting:

The choice of steel and working hardness depends on the thickness and strength of the material to be cut. The greater the thickness and strength of the material being cut, the higher the loads on the tool, especially the stress peaks at the cutting edges.
The toughness of the tool material must therefore also increase accordingly. This prerequisite can be satisfied by lowering tool hardness. It also makes sense to switch from alloys with higher carbon content to those containing less. In the smaller size range, highly wear-resistant 12 % chromium steels are used predominantly. For greater sheet thicknesses, Cryodur 2550, Cryodur 2767 and Cryodur 2842 are tougher materials that fulfil requirements. Of the 12 % chromium steels, Cryodur 2379 features equally good wear resistance and higher toughness compared to Cryodur 2080 or Cryodur 2436. As a result, the two other steels are largely being replaced by Cryodur 2379. In terms of usage, the crossover points between the various steels are obviously fluid, with the areas of application overlapping for multiple steels.

For the machining of austenitic workpiece materials and dynamo sheets, tool hardness should be increased by 1 to 2 HRC.
Due to lower blade clearance, precision cutting tools are exposed to higher loads than ordinary cutting tools, making the use of the Rapidur 3343 and Cryodur 2379 steels appropriate for these types of tools.

Deep-drawn cans

Shearing

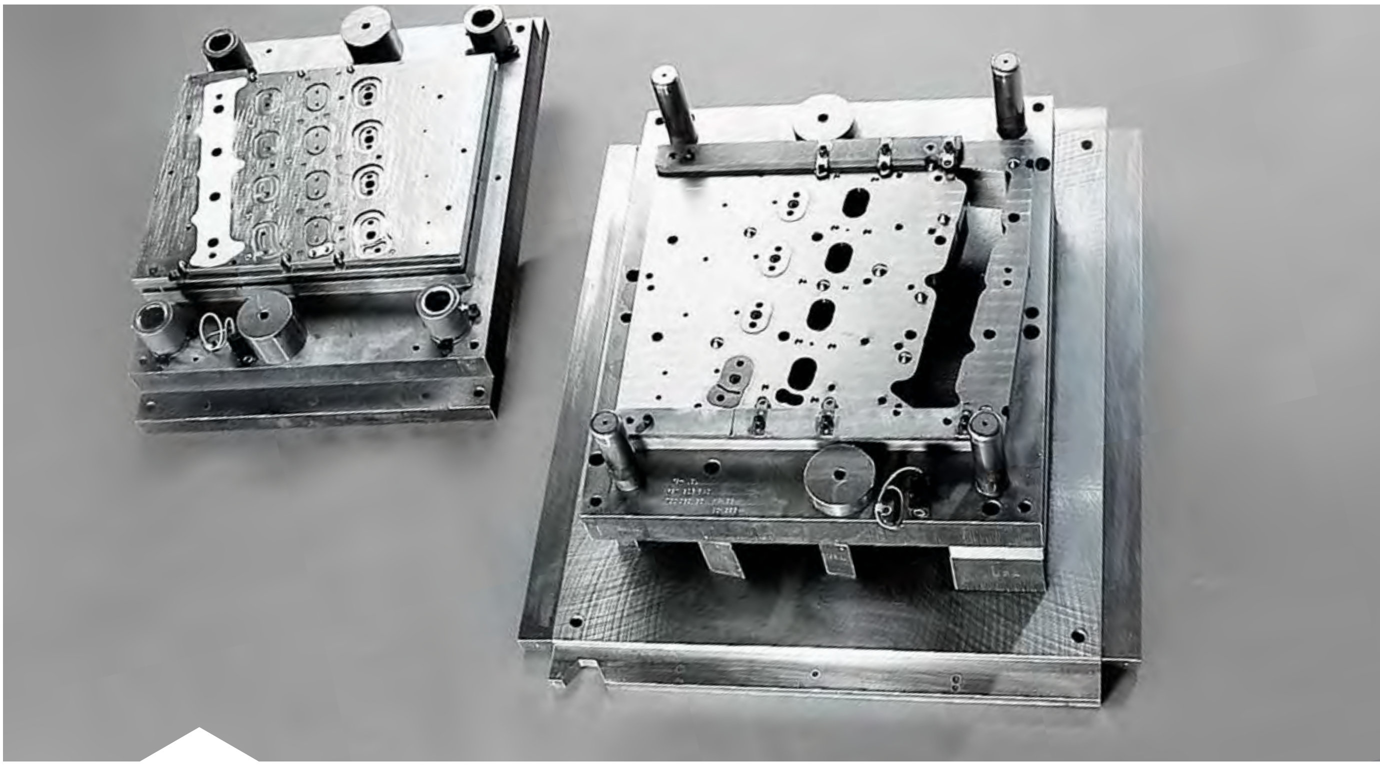
As a shaping technique that separates without cutting, shearing is similar to actual cutting. Tools must feature a high level of wear resistance and adequate toughness. Here too, values for working hardness are determined by the type, thickness and hardness of the material being cut. Steels used include the ledeburitic cold-work tool steels, particularly Cryodur 2379, but also high-speed tool steels like Rapidur 3343. The comparison of materials again demonstrates the usability of Cryodur 2379, which is replaced by the tougher Cryodur 2363, Cryodur 2842, Cryodur 2550 and Cryodur 2767 steels only when requirements regarding toughness are higher (thicker material to be cut).

Cold extrusion

Recommendations for selecting steel for cold extrusion tools include various steels for different tools depending on actual requirements. Dies subjected to pressure and wear require materials that feature sufficient protection against wear and high compression strength. For single-piece dies, which are chiefly subjected to wear, the carbon steels Cryodur 1545 and Cryodur 2833 still meet requirements. In the case of more complex tool stresses comprising pressure, wear and bursting loads, the die insert (sleeve) must be able to withstand the wear stress. Ledeburitic chromium steels, especially Cryodur 2379, have proved effective here. This steel in particular superbly combines the properties of hardness and wear resistance with more than adequate toughness. Reinforcement rings must be able to absorb high tensile stresses, which demands tool steels with sufficient toughness. Cryodur 2767 has proven itself in this regard, being extremely tough due to its high nickel content of 4 %. The hot-work tool steel Thermodur 2343 has also demonstrated its effectiveness based on good toughness. An additional feature is that the latter steel may be heated to up to 550 °C for the purpose of shrinking due to its tempering behaviour.

Deep drawing

Primarily, ledeburitic cold-work steels are used for deep-drawing tools. Again Cryodur 2379 has become a standard material.

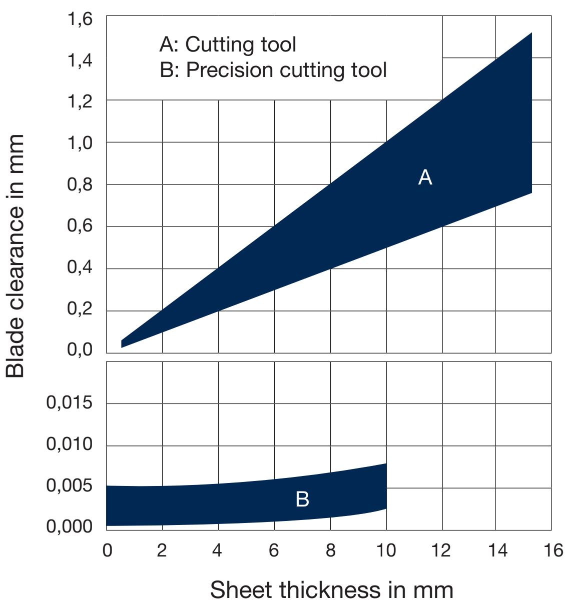


Punching tool

Blade clearance

To prevent the workpiece from compressing during cutting and to keep friction low, the working area of the cutting plate needs to be bigger than the cross-section of the punch. The distance between the cutting edges of the die and the punch is known as the blade clearance. Its size depends on the workpiece's properties and thickness, as well as the cutting process. The narrower the blade clearance, the cleaner the cutting area is. If the blade clearance is too small, the amount of force required increases sharply due to the greater friction and compression of the material being processed. This may result in the cutting edges chipping or blunting prematurely. A blade clearance that is too large is just as detrimental because the material being separated may press into the interstices, leading to major bursting stresses and potentially a premature rupture of the cutting plates. The diagram gives the standard values for blade clearance for cutting and precision cutting tools subject to sheet thickness. When cutting soft materials the blade clearance should be at the lower limit and when cutting higher-strength materials it should be at the upper limit of the relevant range.

Recommended blade clearance depending on sheet thickness



Overview: Choice of steel for cutting, punching, shearing

Material to process	Thickness	Grade	Hardness (HRC)
Sheet steel, strip steel, aluminium and aluminium alloys, copper and copper alloys	up to 4 mm	Cryodur 2080 Cryodur 2436 Cryodur 2516	58 – 62 58 – 62 59 – 63
	up to 6 mm	Cryodur 2379 Cryodur 2363	56 – 60 56 – 60
	up to 12 mm	Cryodur 2510 Cryodur 2842	56 – 60 56 – 60
	over 12 mm	Cryodur 2550 Cryodur 2767 Cryodur 2243 Cryodur 2101	54 – 58 48 – 52 52 – 59 50 – 58
Transformer and dynamo sheet, dynamo strip	up to 2 mm up to 6 mm	Cryodur 2436 Cryodur 2379	60 – 63 58 – 62
Austenitic steel grades	up to 4 mm	Cryodur 2379 Rapidur 3343	60 – 62 60 – 64
	up to 6 mm	Cryodur 2379 Rapidur 3343	58 – 62 58 – 62
	up to 12 mm	Cryodur 2550	54 – 58
	over 12 mm	Cryodur 2767	50 – 54
Metallic sheet and strip	up to 4 mm	Cryodur 2379 Cryodur 2516 Rapidur 3343	60 – 62 59 – 63 60 – 64
	up to 6 mm	Cryodur 2379 Rapidur 3343	58 – 62 58 – 62
	up to 12 mm	Cryodur 2379 Rapidur 3343 Cryodur 2243 Cryodur 2101	56 – 60 56 – 60 52 – 59 50 – 58
Plastics, wood, rubber, leather, textiles and paper		Cryodur 2080 Cryodur 2379 Cryodur 2436 Cryodur 2510 Cryodur 2550 Cryodur 2842	58 – 63 58 – 62 58 – 63 57 – 61 54 – 58 58 – 63

Overview: Choice of steel for back-up tools (components)

Tools	Grade	Working hardness in HRC or working strength in N/mm²
Pressure piece, pressure plate, spacer	Cryodur 2842	56 – 60 HRC
Stripper, stripper plate	Cryodur 2842 Cryodur 1730	58 – 60 HRC ca. 650 N/mm²
Spring-loaded bolt, punch guide, guide rod, guide post	Cryodur 2842 Cryodur 2210 Formadur 2162	58 – 62 HRC 58 – 62 HRC 58 – 60 HRC
Ejector, ejector plate	Cryodur 2210 Cryodur 2842	56 – 60 HRC 56 – 60 HRC
Punch holder, base plate	Cryodur 1730	ca. 650 N/mm²
Blank holder	Cryodur 2379 Cryodur 2842	58 – 62 HRC 58 – 62 HRC

Overview: Choice of steel for cold extrusion tools

Tools	Grade	Working hardness in HRC
Single-piece dies	Cryodur 1545 Cryodur 2833	60 – 64 60 – 64
Die insert, punch	Cryodur 2379 Cryodur 2436 Cryodur 2721 Rapidur 3343	58 – 62 58 – 62 54 – 58 60 – 64
Reinforcement ring	Thermodur 2343 Cryodur 2709 Thermodur 2714 Cryodur 2767	46 – 52 52 – 56 48 – 52 48 – 52
Shear blade	Rapidur 3343	60 – 64
Shear sleeve	Cryodur 2363 Cryodur 2379 Cryodur 2550 Rapidur 3343	56 – 60 58 – 62 54 – 58 60 – 64

Heat treatment of cold-work tool steels

Heat treatment is a key step in tool production. It is what gives tool steels the properties required to achieve the desired output in future operational use. Heat treatment comes at the end of the production process. Errors at this stage can often result in irreparable damage to the (nearly) finished tool. The fact that lots of damage to tools can be attributed to improper heat treatment clearly shows how important it is to describe in-depth the processes and procedures of heat treatment.

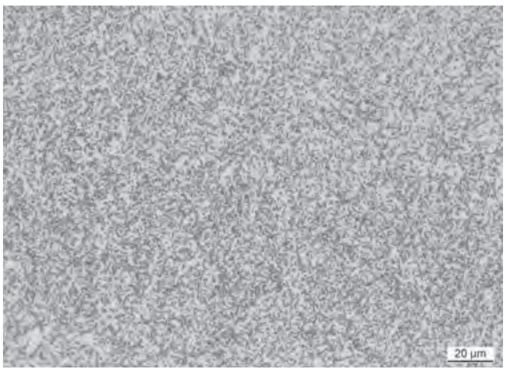
Heat treatment conditions

Apart from a few exceptions, tool steels are supplied to toolmakers in a soft-annealed condition. Depending on their chemical composition, in this state the steels exhibit a maximum hardness of 180 to 250 HB. Only high-speed steels will have hardnesses of 240 to 300 HB due to the very high amount of alloy elements they contain. Steels can be machined effectively in this condition. At this stage they are, however, unsuitable for the actual application.

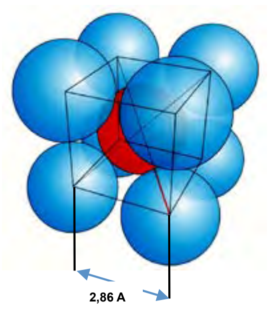
From a metallographic perspective, in a soft-annealed condition all the carbon in the steel is set in the form of carbides. The carbides are present as fine, spherical particles in a ferritic matrix. Because the matrix is virtually free from carbon, hardness is low. This gives the steels in this condition good machinability.

In order to convert a steel to a hardened state, it must undergo various transformations. When it comes to hardening, carbon is the most important alloy element. Because its atom size is considerably smaller than that of iron, in the iron lattice structure it fits into interstitial positions (gaps).

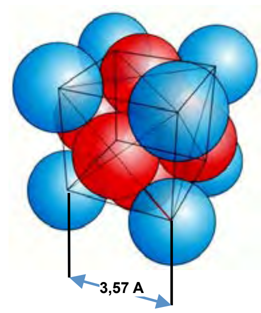
At room temperature, iron exists in a body-centred cubic (b.c.c.) matrix (ferrite) exhibiting a parameter of 0.286 x 10^{-9} m. Above 911 °C it transforms to a face-centred cubic (f.c.c.) matrix (austenite) at a parameter of 0.357 x 10^{-9} m. During this transformation, two unit cells of ferrite form a new unit cell of austenite. Between the spherical iron atoms there are vacancies in which carbon can be stored.



Annealed structure



Body-centred cubic (b.c.c.) matrix



Face-centred cubic (f.c.c.) matrix, maximum packing density

The mesh effect of austenite enables it to dissolve (store) up to 2.1 % carbon. In ferrite, however, only a maximum of 0.02 % C can be dissolved and at room temperature just 0.00001 % C. This differing ability to dissolve carbon into vacancies is consciously utilized in the process of hardening steels. Steels practically always contain more carbon than can be dissolved in ferrite at room temperature. In a soft-annealed condition, this carbon is present in the form of carbides (compounds of C with the elements Fe, Cr, Mo, V, W). If the steel is now heated beyond its transformation temperature so that it becomes austenitic, carbon can now be stored in vacancies within the austenite. This carbon must be provided by the carbides, i.e. the carbides diffuse their carbon out to the austenite while at the same time other carbide elements find their way into the austenite. Plenty of time is needed for the processes of ferrite/austenite transformation and the carbon solution. The steel is cooled down rapidly (quenched) from the austenitizing temperature (hardening temperature). The carbon dissolved at high concentration in the austenite endeavours to compensate for its declining solubility as the temperature falls by wanting to leave the interstitial positions in the austenite.
Rapid cooling prevents this back diffusion, however, and the carbon remains in a state of forced dissolution. The iron lattice structure is under extreme stresses as a result. It is no longer able to transform from austenite lattice to iron lattice and is instead flipped over to a deformed structure (martensite) in fractions of a second.

Although steel hardened in this way is very hard, it is also extremely brittle.
The steel must therefore be tempered. For this purpose, the steel is heated again but to a much lower temperature than during hardening. As the temperature rises, the carbon atoms are initially released from the deformed lattice and are able to form carbides by combining with the free alloy elements.

In the case of some high-alloy steels (high-speed steels, for example), what are known as special carbides may arise, leading to a distinct secondary hardening maximum. The deformed martensitic lattice loses deformation as a result, which is associated with a certain loss of hardness.

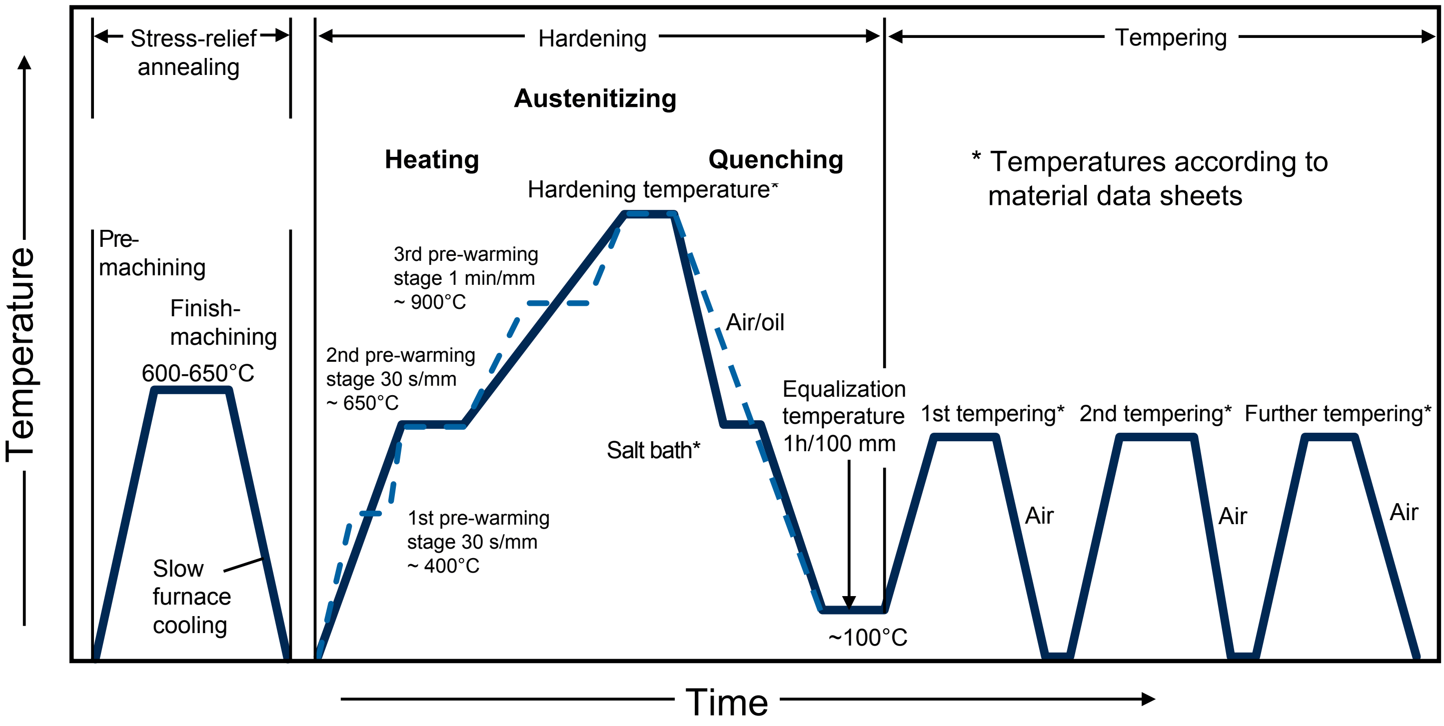
During the preceding hardening, often not all austenite is transformed to martensite. In high-alloy steels in particular, austenite is slow to transform, meaning that some residual austenite may still be present after hardening in addition to martensite. Because the tempered martensite loses deformation, during cooling down from the tempering temperature the residual austenite may transform to martensite, which undergoes the process described above during the second tempering process.

Heat treatment process

The first step in the heat treatment process is stress-relief annealing. The cutting and non-cutting processes applied to make the tool have caused stresses in the tool being treated. If these stresses are not resolved prior to hardening, significant distortions or cracks in the tool are unavoidable.
In stress-relief annealing, tools are heated slowly and thoroughly to 600 - 650 °C and held at this temperature for a minimum of two hours. For larger tools, a holding time of at least one hour is recommended per 50 mm wall thickness. Subsequent cooling must occur slowly in a furnace to avoid new stresses from forming. Strain relief almost always involves a change in shape which must be resolved as part of subsequent finish-machining.

Tool hardness is determined by three subprocesses:

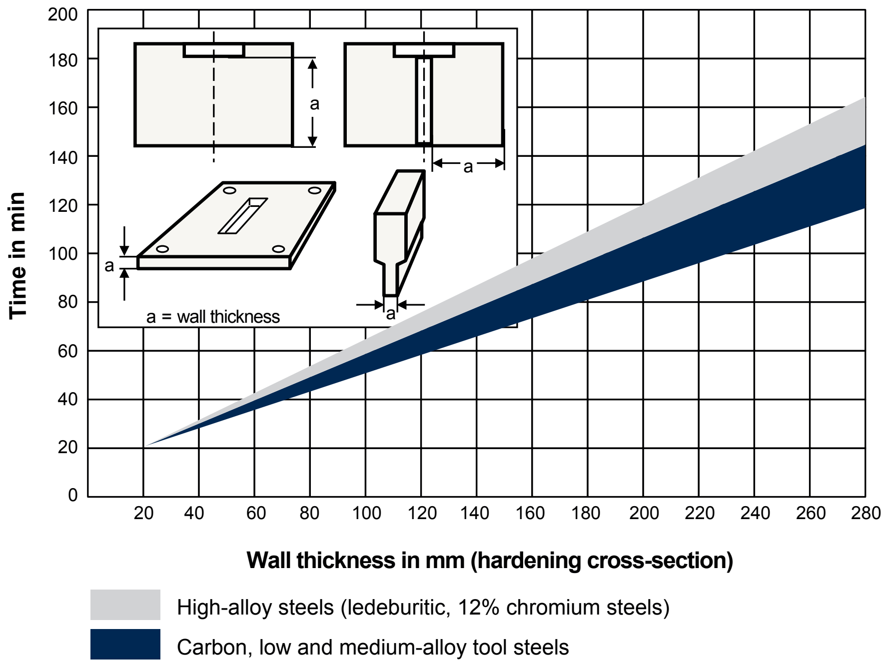
» **heating to hardening temperature**
» **austenitizing and**
» **quenching**



Time-temperature sequence diagram for the heat treatment of ledeburitic chromium steels

Heat is quite crucial with regard to hardening temperature. The thermal conductivity of high-alloy steels is relatively low. This means that considerable temperature differences can emerge between the edge and the core when heating up large tools. Rapid heating would therefore result in severe temperature stresses, which could lead to distortion or cracks. Building multiple pre-heating stages into the heating process equalizes the temperature across the entire cross-section. Depending on the selected steel and tool for hardening, up to three pre-heating stages may be required. Heating from the final pre-warming stage to hardening temperature needs to happen as quickly as possible. The tool must be held at the hardening temperature long enough for the necessary amount of carbides to dissolve in the austenite following temperature equalization. It should not be held for too long, however, because temperatures this high may cause damaging grain growth. The diagram on the page opposite provides information on the correct holding time once hardening temperature has been reached at the tool's surface.

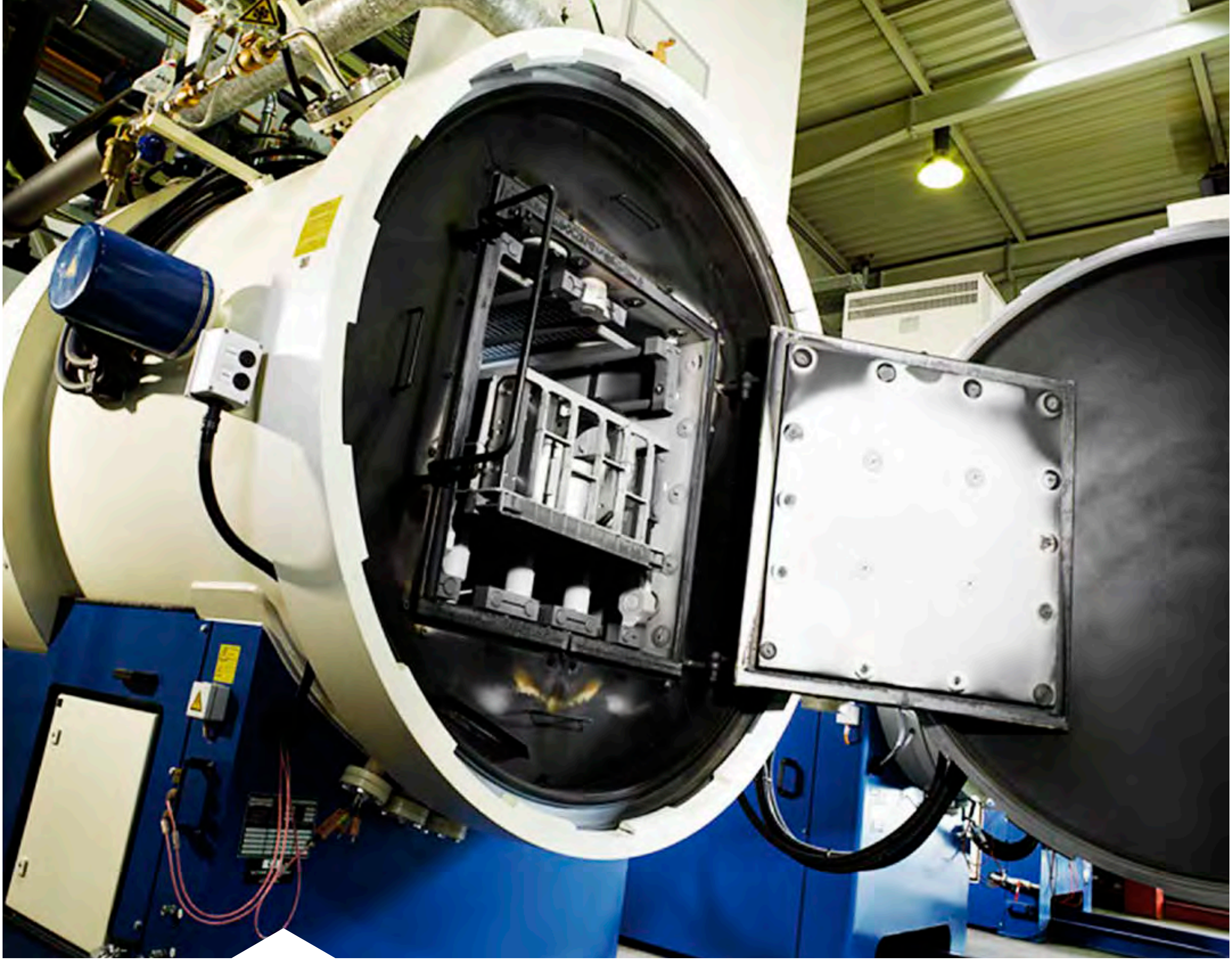
Quenching to form the hard martensite desired must be effected swiftly. If cooling is too rapid, though, it may again result in severe temperature stresses, potentially leading to distortion or cracks. The chosen quenching medium therefore depends on the steel. There is a basic rule for the quenching speed: It should be as slow as possible but as fast as necessary. Hardened tools must not be cooled to room



Holding period after reaching hardening temperature at the tool's surface

temperature. Instead they should be caught at approx. 100 °C and held until the martensite transformation is complete.

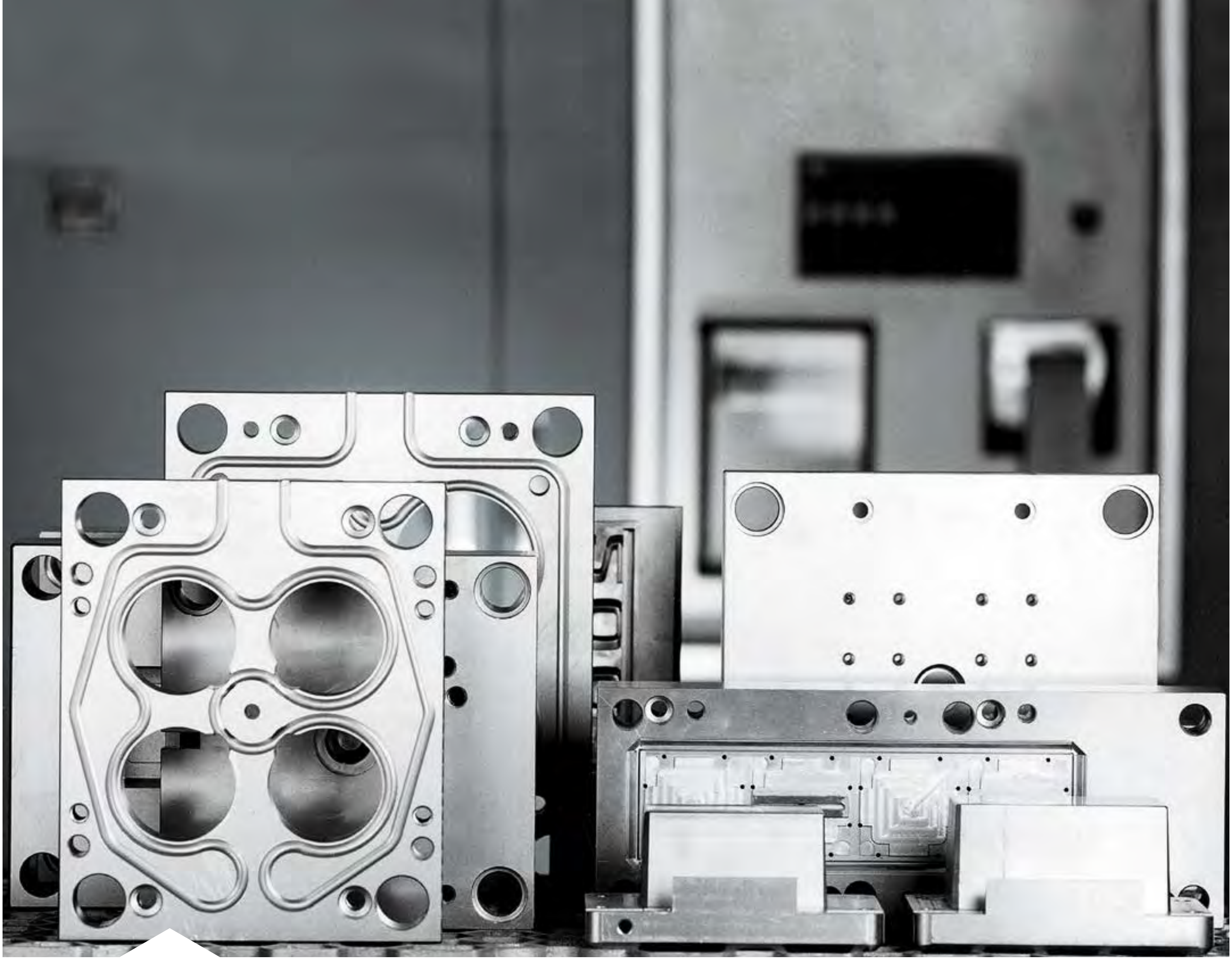
One hour per 100 mm wall thickness can be assumed as the equalization time, although longer periods will not be detrimental. Again, the reason for this lies with the limited thermal conductivity of tool steels, which means that the core of tools cools more slowly than the periphery. Without equalization there is a risk that the core of tools remains austenitic, whereas the edges are already completely martensitic. The potential result: extreme stresses or cracks if the core also becomes martensitic. To minimize changes in dimensions during quenching from the hardening temperature, as well as the risk of cracking, it is recommended to always make quenching as mild as possible and no more abrupt than necessary. To that end, step quenching (martempering) is useful for tools of complicated shape made of alloyed steels. Tools are placed in a molten salt bath or a tempered oil bath, the temperature of which is just above the martensite start temperature. This interrupts the cooling process in the tool's outer layer. The core, however, cools down to the edge temperature, resulting in full temperature equalization. Stresses arising during this cooling are largely dissipated in the still relatively soft austenite. Following temperature equalization, tools are removed from the salt bath and cooled in air. Only then does the austenite transform to martensite.



Vacuum furnace

The data sheets for some steels specify temperatures of between 180 and 220 °C for martempering although their Ms temperatures are above this range. In this case, only very mild quenching is involved. Other steels, particularly high-alloy steels like Cryodur 2363, Cryodur 2379, Cryodur 2436, and the Rapidur high-speed steels, require a salt bath temperature of 500 to 550 °C. This temperature, which is considerably higher than Ms, can be understood on taking a closer look at the TTT diagrams for the continuous cooling of these steels. Within this temperature range, the stated steels show a distinct area of metastable austenite between the pearlitic and bainitic stage. The tool can be held within this temperature range for as long as desired without undergoing transformation, thereby ensuring adequate temperature equalization. The subsequent cooling in air is still fast enough for martensite formation.

When hardening is complete, the tools must be tempered to achieve the case hardness and toughness. The tempering temperature selected depends on the steel and desired working hardness. The tool needs to spend one hour per 20 mm wall thickness at the tempering temperature before cooling in still air. It works well to temper tools at least twice, and in many cases even three times, in order to largely eliminate the remaining austenite.



Proper heat treatment is essential

Heat treatment units

Various types of furnace are used to carry out heat treatments.

Muffel furnaces heated using gas or electric have a simple furnace design. They are suitable for temperatures up to approx. 1000 °C. Because no special atmosphere can be set in this furnaces, tool surfaces need to be protected against oxidation and decarburization.

During heat treatment in salt-bath furnaces, the heat transfers molten salt to tools. Good heat transfer will achieve rapid heating. Salt baths are used at up to approx. 1350 °C and can therefore also be used for hardening and tempering. Tool surfaces are not decarburized or oxidized. Any salt residue must, however, be cleaned off quickly and thoroughly or corrosion may occur. Accurate temperatures are a further benefit of this type of furnace. Due to their size, salt baths are usually restricted to small tools.

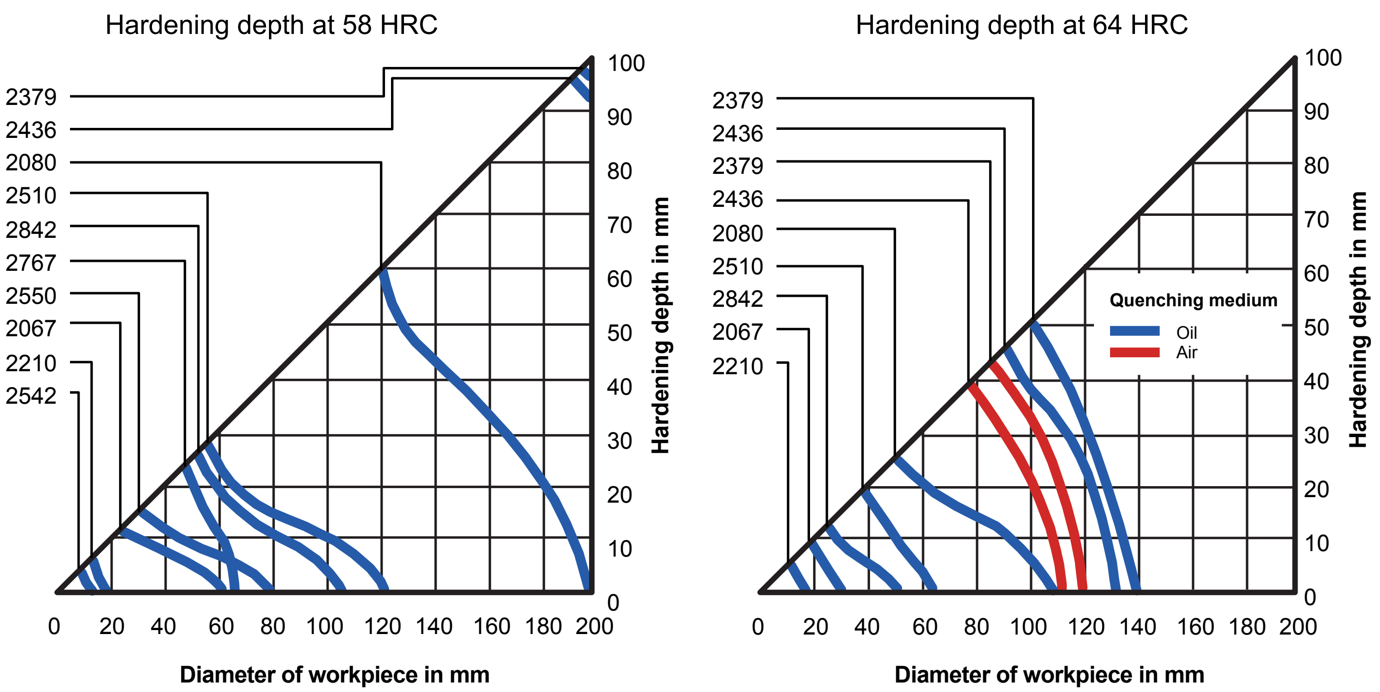
Another point to note about this procedure is that the salts used contain cyanogen compounds involving high environmental constraints. Vacuum furnaces are gaining prominence. Tools being treated are heated in a container under vacuum and brought up to hardening temperature. This type of heating, which is backed by an additional convection heater at the lower temperature range depending on the design of furnace, is considerably slower than with a salt bath – something to bear in mind with large tools. Cooling in this furnace is usually done by nitrogen at a pressure of up to 6 bar (but sometimes up to 20 bar), which flows into the furnace chamber for quenching to occur. A specific advantage of this procedure is that following this type of heat treatment, tool surfaces are taken right down to bright metal and any distortions are minor due to the relatively mild quenching. This method is always used if tools require only minimal post-treatment following heat treatment.

Hardenability

The hardenability of tool steels is dependent not only on the carbon content but also on the cross-section. Martensite is formed on the periphery during quenching, thereby achieving a high level of hardness there, while heat is conducted only slowly from the core, which means that martensite formation is no longer able to occur there. Areas exposed to slow cooling therefore have a considerably lower hardness level. This is the reason why many tools do not attain the desired hardness across the entire cross-section, something to keep in mind in vacuum hardening especially.

The diagram for determining working hardness shows the attainable working hardness based on tool diameter and quenching medium. If, for example, a hardness of 64 HRC is required for a tool made of Cryodur 2379 with a diameter of 120 mm in its untempered state, follow a vertical line up from the horizontal axis (diameter of workpiece) to the appropriate steel curve. From this point of intersection, move across to the vertical axis where the working hardness (30 mm) can be read off. After hardening, a round workpiece with a diameter of 120 mm made from Cryodur 2379 will thus exhibit a hardness of 64 HRC to a depth of up to 30 mm. The intersection of the steel curve with the axis at an angle of 45° yields the diameter to be through-hardened on the horizontal axis (100 mm).

The following graphic shows the hardenability of tool steels during hardening.



Effect of hardening depth on the diameter of the workpiece for Cryodur cold-work steels

Distortion and changes in dimension

These two phenomena are very important in the heat treatment of tools. Although the two terms describe different processes, they are often interlinked. Whereas distortion can be kept in check by technical means – by way of mild and uniform cooling, for example, or in the structural design of tools – changes in dimension are based on the processes occurring during microstructural transformations.

The changes in microstructure and dimensions associated with heat treatment processes are described below. Information is also provided on how to avoid distortion and cracking. It should be noted that, according to EN 10052, dimensional change refers to "the change in dimension of a component without change in shape". By contrast, changes in shape are characterized by changes of curvature and angles.
Distortion is defined as change in shape and dimensional change.

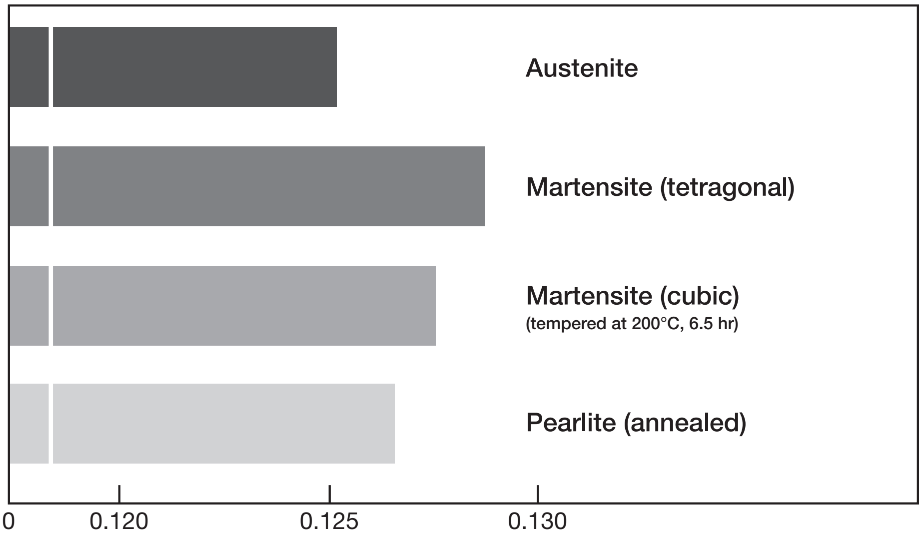
Changes in dimension during heating and cooling

Heat treatment processes involve temperature changes which result in changes in volume within the material due to thermal expansion. In addition to thermal expansion, the state of the solution or precipitation changes, which involves a change in lattice constants and therefore also a change in volume.

Changes in volume due to thermal expansion

If heating or cooling run so slowly that the resulting temperature stresses are eliminated elastically, there will be no measurable change in volume on the workpiece after heat treatment is complete.

In the case of faster changes in temperature, the temperature differences that always occur in real tools cause internal stresses to form. These internal stresses may exceed the yield strength of the material being treated and are then eliminated plastically. In an extreme case, tensile strength is exceeded, making cracking a possibility. Normally, however, only changes in dimension dependent on size are a consequence. During quenching, the tensile stresses occurring at the edges have a minimal effect on the surface to volume ratio (spherical shape), i.e. a cylinder shrinking in length and increasing in diameter. Because the core cools down last, the edge comes under compressive stress (stress reversal), while tensile stresses form in the core. As a consequence, for a ferritic, austenitic steel compressive stresses will be present in the edge area and tensile stresses in the core.



Specific volume in cm³/g
Steel featuring 0.8% C and different microstructures

Changes in volume due to microstructural transformation

During slow heating and cooling processes, temperature stresses remain at a low level. Nevertheless changes in dimension are possible. The cause: the change in structure intended through heat treatment also manifests itself as a change in volume. In this way, the annealed structure (starting as pearlite) transforms to austenite while holding at the hardening temperature and the volume shrinks. During cooling, tetragonal martensite forms and the volume increases. A decrease in volume takes place in parallel to the tempering process as the tetragonal martensite transforms to cubic.

Linearly, this means a change in dimension independent of size occurs during slow temperature changes, e.g. when hardening alloyed steels in air. This is unavoidable and must be planned into the manufacture of machine tools.

Concurrent thermal expansion and microstructural transformation

Where microstructural transformation is an issue in addition to thermal expansion (normal case), the time sequence is important. If, for example, the transformation in a cylinder takes place prior to the maximum temperature stress, the ferrite-pearlite structure present will be compressed into a barrel shape. By contrast, if transformation occurs after the maximum stress, the austenite is pressed into a barrel shape during the subsequent increase in volume due to martensite formation. This starts at the edge and offsets the pressure temperature stresses building up there following stress reversal or actually reverses them so that they ultimately come to pass in the core.
In the case of through-hardening steels, the residual stress at the surface generally consists of a tensile stress which always brings the risk of cracking.

When transformation stresses coincide with the highest temperature stresses, the latter have a greater effect if transformation proceeds in the core before the edge. By contrast, if the edge transforms before the core, the transformation stresses dissipate the temperature stresses or reverse these so that a bobbin shape appears. In practical terms, a large number of overlappings are conceivable in affected borderline cases.

Influence of the material

The increase in volume as a result of the change in structure (martensite formation) rises with the dissolved carbon content. With medium-alloy steels, a disproportionate positive change in dimension may be counteracted by a reduction in hardening. For that to happen, a suitable tool steel grade must be selected for the specific tool cross-section so that sufficient hardening takes place in the core without through hardening and the formation of pearlite.

Another possibility for counteracting the increase in volume due to martensite is to generate high residual austenite content. With the carbon content fixed by the alloy system, the proportions of martensite and austenite in e.g. ledeburitic chromium steels can be varied over a wide range based on the chosen hardening temperature. This is because, with increasing austenitizing temperature (state of solution), the end of martensite formation falls below room temperature. In the process, the loss of hardness from the softer austenite is largely compensated for by the hard carbides, which account for 20 % of the volume. It should be noted that in bar steel the latter is elongated in the direction of deformation. During rapid cooling, they prevent the steel matrix from shrinking due to their low thermal expansion. Tools therefore grow more on the axis of a bar than transversely.

It must be pointed out here that for many tools it is not possible to control the increase in volume beyond achieving specified residual austenite. The reason for this is its instability which means that lengthy heating during use or caused by external stresses may transform residual austenite to martensite. The result: an increase in tools with potential problems.

Changes in dimension during tempering

During the tempering of a hardened steel, the martensite loses volume first as a result of the precipitation of carbides. At higher tempering temperatures, the residual austenite degrades to martensite and the volume increases. The progression depends on the type of steel, the hardening temperature, i.e. the ratio of martensite to residual austenite, the tempering time, and the internal stress state.

In addition to the volumetric decreases, a reduction in hardness can be seen at the same time (martensite relief). For hot-work and high-speed steels, this reduction in hardness at higher temperatures is overcompensated for by the precipitation of special carbides (secondary hardening).

When residual austenite transform to martensite during tempering, this creates considerable internal stresses due to the different volumes. In use this may lead to cracking in this untempered martensite (brittle). As a result, higher-alloy steels where residual austenite may form must be tempered at least twice.

Changes in shape

In comparison to changes in dimension, changes in shape involve a loss of symmetry. Unlike changes in dimension, they are not inherent in the system. In many cases, it is possible to influence them. Changes in shape tend to occur more in thin or asymmetrical tools.

Changes in shape due to residual stresses

Internal stresses distributed asymmetrically, which are produced through straightening or machining procedures, for example, can be eliminated plastically (distortion) during heating to hardening temperature. This is because solidity falls with increasing temperature. In an extreme case, cracking may even arise if there is overlapping with temperature and transformation stresses.

Changes in shape due to asymmetrical internal stresses are avoidable if any other residual stresses are taken into consideration during the production sequence and heating to hardening temperature. Stress-relief annealing following rough machining and step heating has proved effective in achieving a temperature distribution that depends on the cross-section as little as possible.

Changes in shape due to incorrect removal or partial decarburization on one side

In the case of larger dimensions especially, segregation means that the core exhibits a different chemical composition than the edge. If removed incorrectly, this may result in distortion even if heat treatment is optimal in other respects. The reason for this is the greater tendency for residual austenite to form in areas of core segregation. Ingots intended for heat treatment should not therefore be separated into several layers.

Due to the resulting reduced resistance to changes in shape, forming processes (rolling, forging) in the manufacturing of steel products must run at high temperatures.

Due to diffusion, decarburization is always present in the edge area. Machining allowances must take this issue into consideration. A false economy on the necessary machining allowances may lead to cracking in the edge area where it is exposed to high loads (tensile stresses) from additional structural stresses (volumetric differences), or adequate processing occurs on one side only, which may lead to significant distortions due to the resulting increase in volume by way of partial decarburization.

Changes in shape due to incorrect rest in furnace or uneven heating/cooling

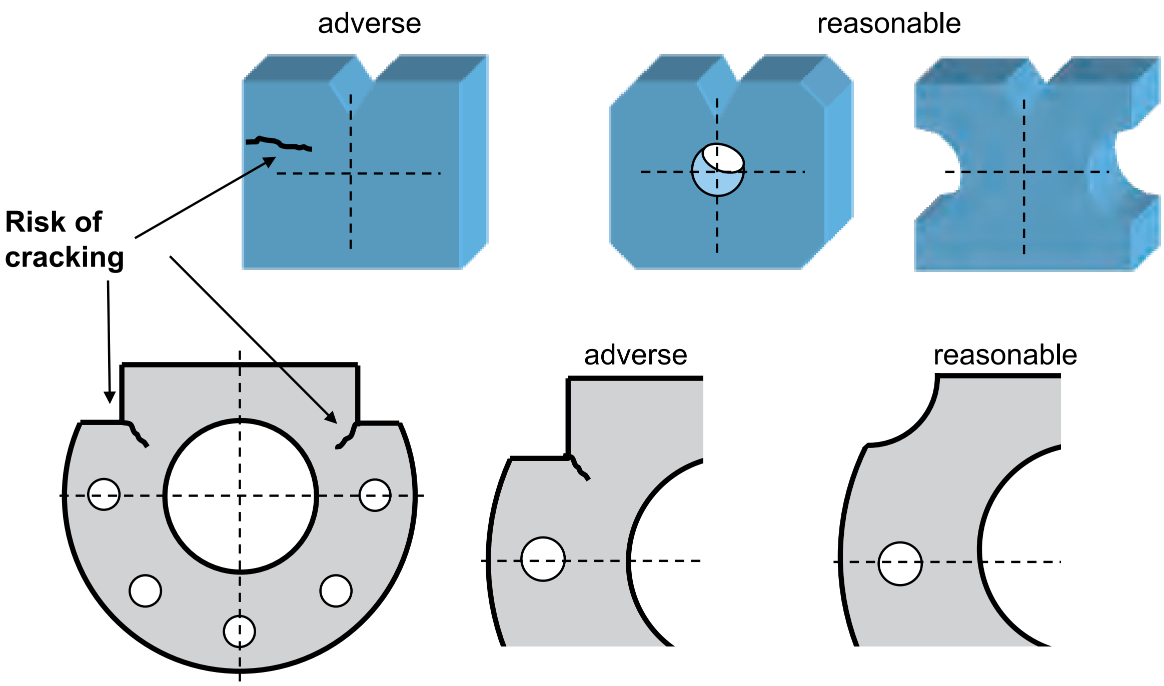
If heating at the heat treating temperature is not uniform, e.g. due to monodirectional irradiation, a change in shape may occur. A suitable rest creates an additional source of risk because sag is possible under its own weight due to reduced solidity at the high temperature. Uneven cooling is another reason for changes in shape.

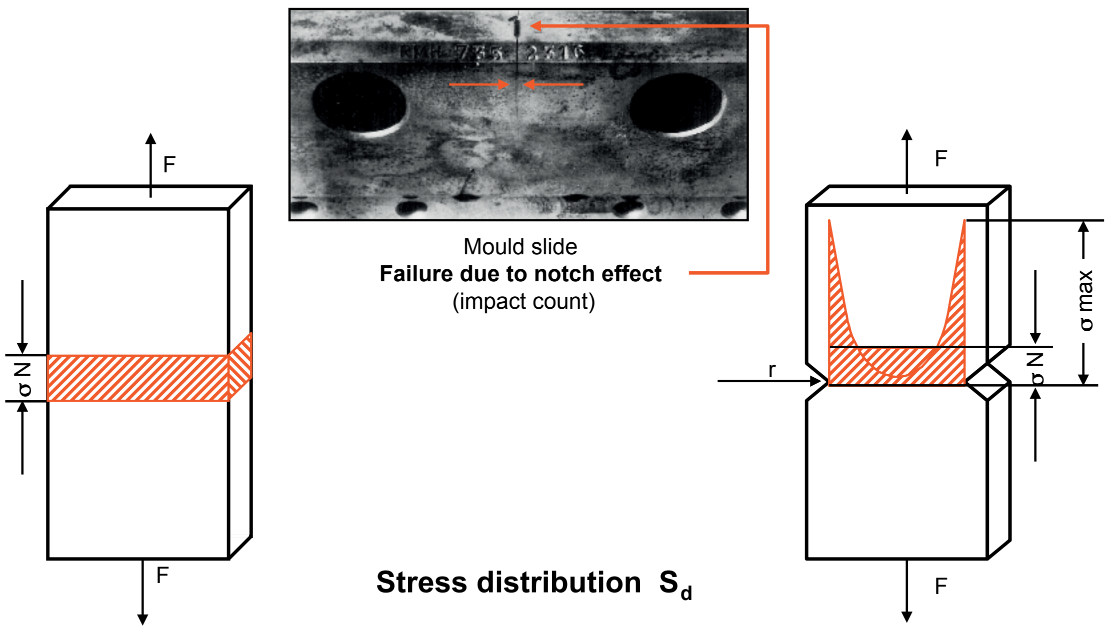
The potential faults addressed here must be heeded by heat treatment facilities. Correct batch loading and suitable heating and cooling systems are vital requirements in ensuring low distortion from hardening.

Design suitable for heat treatment

The stresses that arise during hardening and therefore changes in dimension and shape depend on the size and shape of the tools. If some basic rules are considered when designing tools, numerous risks associated with heat treatment can be avoided:

» aim for reasonable distributions of mass (e.g. by way of additional bores or notches)
» avoid sharp-edged changes of cross-section (e.g. with chamfering, folding, impact counts)
» aim for shapes which are as symmetrical as possible
» provide equipment for correctly handling tools to be treated.



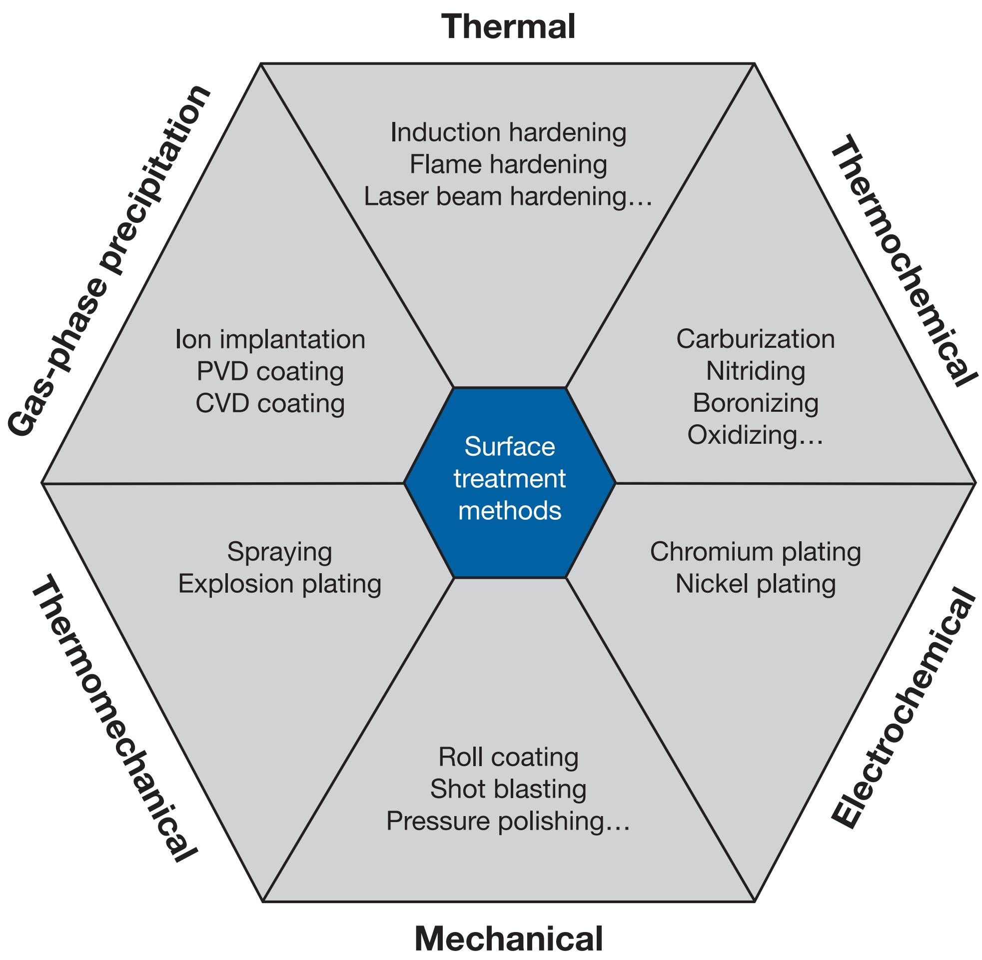


S_d in a flat without notch

S_d in a notched flat with small radius

Summary

In terms of performance characteristics and tool service life, it is absolutely crucial to carry out heat treatment correctly. A variety of methods and units enable optimal heat treatment of tools, taking into consideration the behaviour of steel grades during transformation and some basic rules. Targeted treatment of tool surfaces can be used to achieve specific properties in these areas.



Overview of surface treatment methods

Influence of surface treatments

There are many different methods of surface engineering which can be used to improve the specific surface characteristics of tools. Special procedures (PVD) may be used to apply substances such as TiN to tools in layers just a few µm in thickness. Their extremely high hardness results in an appreciable increase in wear resistance, which can give tool performance a significant boost. Nitriding of tools plays a very important part. In this process, nitrogen is added to the edge layer of tools, thereby considerably increasing wear resistance. This can have positive effects in the case of cutting tools in particular, because the tendency to form cold pick-up is avoided. When using nitriding, however, please note that it reduces the toughness of the edge area considerably. With all applications of PVD coating and nitriding methods, the fact that these processes run at high temperatures is a consideration. PVD coatings are performed at temperatures around 500 °C and nitriding in the range between 400 and 600 °C. These methods may only be used with tool steels that feature adequate tempering resistance. Of the cold-work steels presented in this brochure, only Cryodur 2363 and Cryodur 2379 are classified as nitridable if they have previously been subjected to special heat treatment (hardening at 1050-1080 °C, tempering at temperatures above the secondary hardening maximum). Due to the high process temperature for liquid nitriding (570 °C), this method is associated with risk. The preference is then to choose gas nitriding (510 °C) or plasma nitriding.

Tool steel weight comparisons (kg/m)

Dimen-sions in mm	square	round	hexagonal	octagonal
5	0,196	0,154	0,170	0,163
6	0,283	0,222	0,245	0,234
7	0,385	0,302	0,333	0,319
8	0,502	0,395	0,435	0,416
9	0,636	0,499	0,551	0,527
10	0,785	0,617	0,680	0,650
11	0,950	0,746	0,823	0,789
12	1,130	0,888	0,979	0,936
13	1,327	1,042	1,149	1,099
14	1,539	1,208	1,332	1,275
15	1,766	1,387	1,530	1,463
16	2,010	1,578	1,740	1,665
17	2,269	1,782	1,965	1,879
18	2,543	1,998	2,203	2,107
19	2,834	2,226	2,454	2,348
20	3,140	2,466	2,719	2,601
21	3,462	2,719	2,998	2,868
22	3,799	2,984	3,290	3,148
23	4,153	3,261	3,596	3,440
24	4,522	3,551	3,916	3,746
25	4,906	3,853	4,249	4,065
26	5,307	4,168	4,596	4,396
27	5,723	4,495	4,956	4,741
28	6,154	4,836	5,330	5,099
29	6,602	5,185	5,717	5,469
30	7,055	5,549	6,118	5,853
31	7,544	5,925	6,533	6,250
32	8,038	6,313	6,961	6,659
33	8,549	6,714	7,403	7,082
34	9,075	7,127	7,859	7,518
35	9,616	7,553	8,328	7,966
36	10,714	7,990	8,811	8,428
37	10,747	8,440	9,307	8,903
38	11,335	8,903	9,817	9,391
39	11,940	9,378	10,340	9,891
40	12,560	9,865	11,877	10,405
41	13,196	10,364	11,428	10,932
42	13,847	10,876	11,992	11,472
43	14,515	11,400	12,570	12,024
44	15,198	11,936	13,162	12,590
45	15,896	12,485	13,767	13,169
46	16,611	13,046	14,385	13,761
47	17,341	13,619	15,017	14,336
48	18,086	14,205	15,663	14,983
49	18,848	14,803	16,323	15,614
50	19,625	15,414	16,996	16,258

Dimen-sions in mm	square	round	hexagonal	octagonal
51	20,418	16,036	16,915	16,915
52	21,226	16,671	17,585	17,585
53	22,051	17,319	18,267	18,267
54	22,891	17,978	18,963	18,963
55	23,745	18,750	19,772	19,772
56	24,618	19,335	20,394	20,394
57	25,505	20,031	21,129	21,129
58	26,407	20,740	21,877	21,877
59	27,326	21,462	22,638	22,638
60	28,260	22,195	23,412	23,412
61	29,210	29,210	25,296	24,198
62	30,175	30,175	26,133	24,998
63	31,157	31,157	26,982	25,881
64	32,154	32,154	27,846	26,637
65	33,170	33,170	28,720	27,480
66	34,200	34,200	29,610	28,330
67	35,240	35,240	30,520	29,190
68	36,300	36,300	31,440	30,070
69	37,370	37,370	32,370	30,960
70	38,460	38,460	33,310	31,870
71	39,570	39,570	34,270	32,780
72	40,690	40,690	35,240	33,710
73	41,830	41,830	36,230	34,660
74	42,990	42,990	37,230	35,610
75	44,160	44,160	38,240	36,580
76	45,340	45,340	39,270	37,560
77	46,540	46,540	40,310	38,560
78	47,760	47,760	41,360	39,560
79	48,990	48,990	42,430	40,590
80	50,240	50,240	43,510	41,620
81	51,500	51,500	44,500	42,670
82	52,780	52,780	45,710	43,730
83	54,080	54,080	46,830	44,800
84	55,390	55,390	47,970	45,890
85	56,720	56,720	49,120	46,990
86	58,060	58,060	50,280	48,100
87	59,420	59,420	51,460	49,220
88	60,790	60,790	52,650	50,360
89	62,180	62,180	53,850	51,510
90	63,580	63,580	55,070	52,680
91	65,010	65,010	56,300	53,850
92	66,440	66,440	57,540	55,040
93	67,900	67,900	58,800	56,250
94	69,360	69,360	60,070	57,460
95	70,850	70,850	61,360	58,690
96	72,350	72,350	62,650	59,930

Dimen-sions in mm	square	round	hexagonal	octagonal
97	73,860	58,010	63,960	61,190
98	75,390	59,210	65,290	62,460
99	76,940	60,340	66,630	63,740
100	78,500	61,650	67,980	65,030
102	81,670	64,150	70,730	67,660
104	84,910	66,680	73,530	70,340
106	88,200	69,270	76,390	73,070
108	91,560	71,910	79,300	75,850
110	94,980	74,600	82,260	78,690
112	98,470	77,340	85,280	81,580
114	102,02	80,130	88,350	84,520
116	105,63	82,960	91,480	87,510
118	109,30	85,850	94,660	90,550
120	113,04	88,780	97,900	93,650
122	116,84	91,770	101,19	96,790
124	120,70	94,800	104,53	99,990
126	124,63	97,880	107,93	103,25
128	128,61	101,01	111,38	106,55
130	132,66	104,20	114,89	109,90
135	142,50	112,35	123,60	118,40
140	153,86	120,84	133,25	127,46
145	164,20	129,10	142,96	136,70
150	176,60	138,70	153,00	146,30
160	201,00	157,80	174,00	165,50
170	225,90	178,20	196,50	187,90
180	254,30	199,80	220,30	210,70
190	283,40	222,60	245,40	243,80
200	314,00	246,60	271,90	260,10
220	379,90	298,40	329,00	314,80
240	452,20	355,10	391,60	374,60
260	530,70	416,80	459,60	439,50
280	615,40	483,40	533,00	509,90
300	706,50	554,90	611,80	585,30
320	803,80	631,30	696,10	665,90
340	907,50	712,70	785,90	751,80
360	1071,0	799,00	881,00	842,00
380	1133,0	890,00	982,00	939,00
400	1256,0	986,00	1088,0	1040,0
450	1589,0	1248,0	1377,0	1317,0
500	1962,0	1541,0	1699,0	1626,0
600	2826,0	2219,0	2447,0	2341,0
700	3846,0	3021,0	3331,0	3187,0
800	5024,0	3926,0	4351,0	4162,0
900	6358,0	4994,0	5507,0	5268,0
1000	7850,0	6165,0	6798,0	6503,0

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