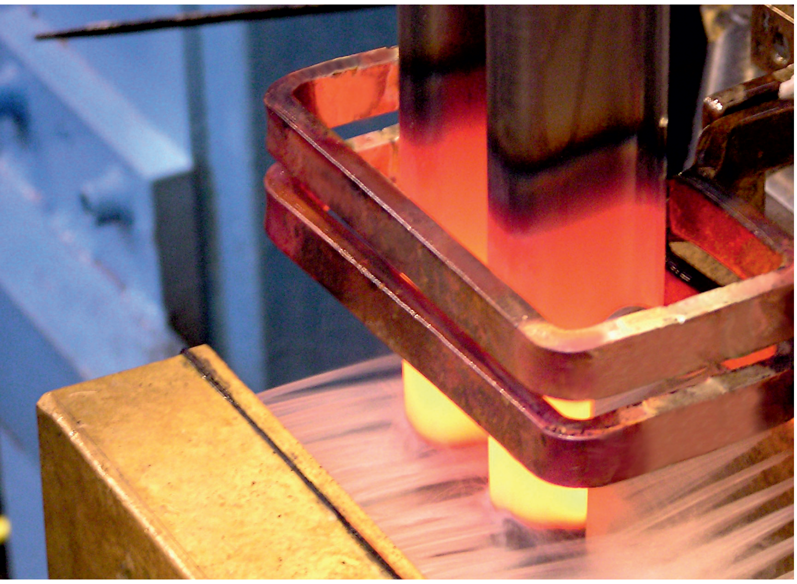
What is induction heating?



Induction heating is one of a wide range of electrical heat used in industry and household today. The main applications of the process are in the steel and metal-working industries.

Clean and fast heat being supplied to the heated workpiece meets the considerably increased requirements with regard to environmental protection. The surroundings is not exposed to any thermal and atmospheric pollution. The particular advantage of this process is to produce the heat inside the workpiece without the need for any external heat source.

According to the physical law of induction an alternating magnetic field is generated around each electrical conductor through which an alternating current is flowing. By considerably increasing these magnetic fields, metals brought into close proximity will be heated by eddy currents produced within the metal. Heating by induction makes use of the capability of the magnetic field to transmit energy without direct contact. This means heating is not done by contact transmission such as known in resistance heating in light bulbs, heating plates or electrical furnaces where the direct current flow causes resistance wires to glow.

A basic problem of induction heating is to create a sufficiently intense electro-magnetic field and to position the component to be heated within the center of the field in such a way as to obtain optimum transmission of energy from the electrical conductor to the workpiece. Normally this is achieved by forming the electrical conductor also referred to as inductor or coil with one or more turns. The workpiece is positioned in the centre of the coil, thus concentrating the magnetic field onto the component. The field will then force the electrical current to flow within the workpiece. According to the law of transformation, the strength of the current flow in the component is equal to that in the coil. To create a sufficiently strong magnetic field, th current flow in the coil must be very high (1000 – 10.000 A), normally a current of this intensity would cause the coil to melt; by comparison, 10 A is the current flow within a 2000 W heating furnace. In order to avoid this problem, the coils are made of water cooled copper tubing. Another method of creating a strong alternating magnetic field is to increase the frequency of the current. Normally the electrical mains supply to both household and industry operates at a frequency of 50 Hz, i.e. the current will change direction 50 times per second. Depending upon the application, an induction heating equipment will operate at a frequency of between 50 and 1 million Hz.

These high frequencies, which are not available from the normal mains electrical supply, are obtained by means of generators: medium frequency generators in the range up to 10.000 Hz and high frequency generators above this level. It may be asked why such a large frequency range is necessary and why not all induction heating processes cannot be carried out at the same frequency. This is due to a physical reason as well, i.e. the so called skin effect. The electrical current flows into the outer skin of the workpiece only, this means the center of the workpiece remains theoretically cold.

The thickness of the layer in which the current flows in turn is dependent on the frequency. At low frequencies, the layer is thick, i.e. the workpiece is penetrated by the current almost to the centre, and consequently heated through. At very high frequencies, the current flows at the surface only and the penetration depth is in the range of 0 to 1 mm. This effect is made use of in order to use the frequency appropriate for the application.

The most common applications utilising induction heating technology are:

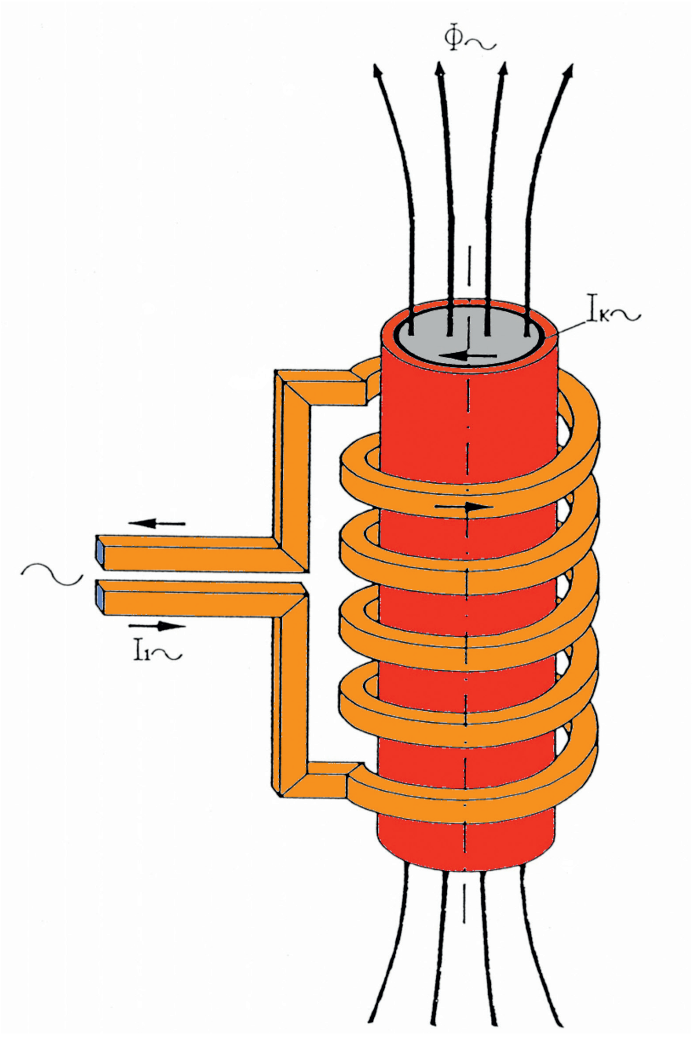
- Melting of steel and non ferrous metals at temperatures up to 1500 °C.
- Heating for forging to temperatures up to 1250 °C.
- Annealing and normalising of metals after cold forming using temperatures in the range of 750 – 950 °C.
- Surface hardening of steel and cast iron workpieces at temperatures from 850 – 930 °C (tempering 200-300 °C) and soft and hard soldering at temperatures up to 1100 °C, moreover, special applications such as heating for sticking, sintering.

While for melting, forging and annealing mostly medium frequency is used as energy source, for hardening and soldering applications it depends on the requirements whether high or medium frequency can or is to be used.

Summary:

Induction heating provides a heat source which is very easily controllable, can be limited to partial heating zones and creates reproducible heat-up processes. This provides the opportunity to build heating equipment with a high level of automation which allows to be integrated in a production line, such as machine tools.

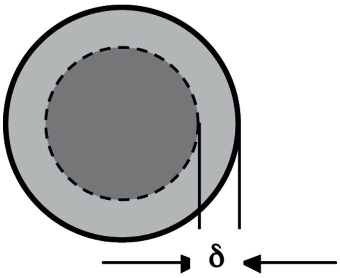
Induced eddy current



Transferable power at different heating processes

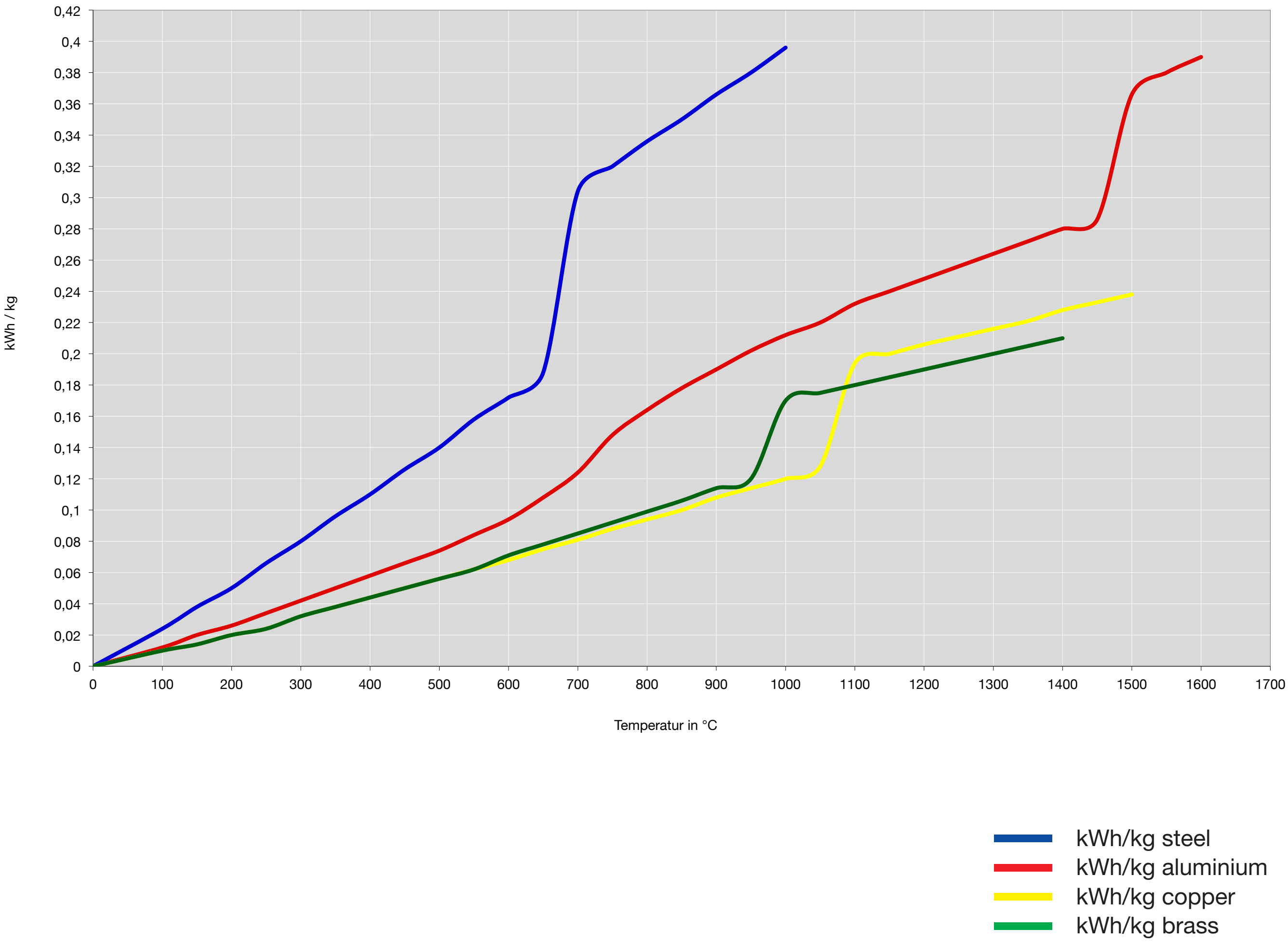
Type of heating	**Power transmission (W/cm²)**
Convection (Carrying heat, by molecular movement)	5 x 10^{-1}
Radiation (electric furnace, box-type furnace)	8
Thermal conduction, touch (hot plate, salt bath)	20
Infrared point emitters	2 x 10^{2}
Flame (burner)	10^{3}
Induction heating	10^{4}
Laser (CO2)	10^{8}
Electron jet	10^{10}

Penetration depths (mm) at different materials depending on frequency and temperature (δ)

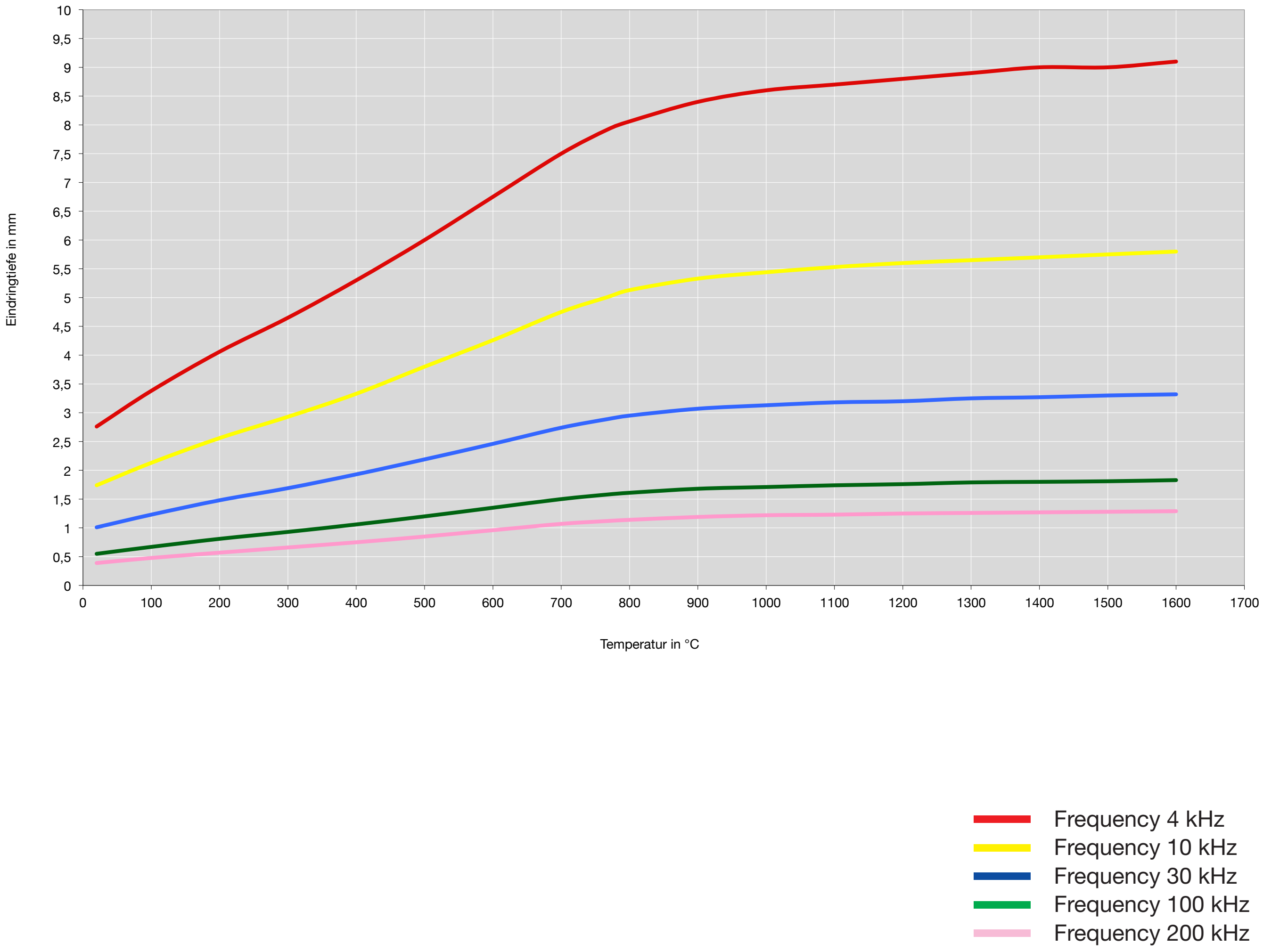


Temp.	Copper 20° C	Copper 1100° C	Steel 20° C	Steel 600° C	Steel 800° C	Steel 1500° C	Ni-Cr	Graphite	Alu 20° C
μ	–	–	60–80	40	1	1	–	–	–
50 Hz	10	32							
500 Hz	2,97		1,38		22,50				3,89
500 Hz	2,91	9,4	3,78	7,75	22,50	26	20,6	65	
500 Hz	2,2	7	2,9	5,8	17,5	20	16	50	
500 Hz	1,68	5,44	2,18	4,31	13	15	11,87	37,6	–
500 Hz	1,59	5,14	2,06	4,12	12,3	14,4	11,25	35,6	–
500 Hz	1,19	3,86	1,55	3,1	9,22	10,65	8,4	26,7	–
500 Hz	1,13	3,65	1,46	2,93	8,73	10	8,0	25,3	1,38
10 kHz	0,7	2,22	0,82	1,83	5,53	6,32	5,05	15,8	0,87
12 kHz	0,65	2,1	0,84	1,68	5,03	5,88	4,6	14,5	–
500 kHz	0,1	0,32	0,13	0,26	0,78	0,9	0,7	2,25	–
700 kHz	0,08		0,037		0,600				0,104
2500 kHz	0,043		0,020		0,320				0,055

Theoretical energy requirement of various materials
(i = in kWh/kg + kcal/kg)



Current penetration depths of different frequencies in steel



Energy sources for induction heating

Depending on the current penetration depth required the operating frequency of the induction installation is determined. The range of the applicable frequencies reaches from the value of the mains frequency (50 Hz) to the short-wave range (3 MHz) and is divided in three sections:

• Low frequency	50 Hz – 500 Hz
• Medium frequency	500 Hz – 50 kHz
• High frequency	50 kHz – 3 MHz

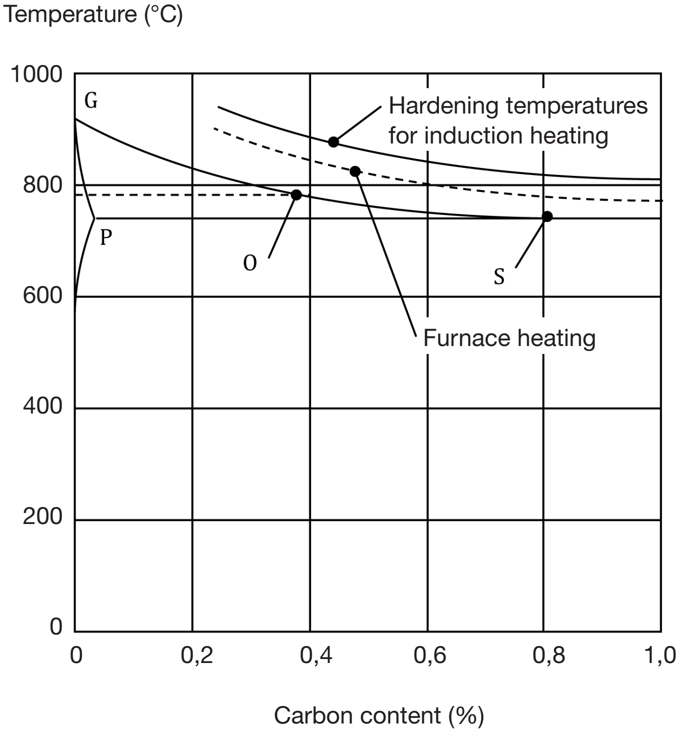
Induction equipment with higher frequencies have to generate these frequencies from the mains frequency via converters. In order to do so, the following processes are available:

Process	**Frequency in kHz**	**Efficiency in % (Volllast)**	**Power in kW**
Frequency multiplier (statical frequency converter)	0,15 0,25 0,45	88 – 93	up to 3.000
Thyristor inverter and transistorized inverter	0,5 – 25	90 – 95	up to 15.000
HF- transistorized inverter	50 – 800	88 – 92	up to 1.000
High frequency (tube generator)	1.000 – 3.000	60 – 70	up to 250

Hardening process in the material

In induction heating, the process in the material is the transforming and/or quench-hardening process known for the iron-carbon materials. First, the steel will be heated to temperatures above the GOS-line (figure 3.4). In this process, the originally present cementite-ferrite-crystal mixture forms a homogenous mixed crystal, the austenite. The carbon, which was bound in the cementite (Fe3C) is atomically detached in the austenite. The following cooling down process must be done so fast that the carbon remains detached after the crystal transformation and the transformation of the austenite to perlite and ferrite is suppressed. This results in the hardening structure martensite. Martensite is the carrier of the increased hardness. The considerable increase of hardness due to the formation of martensite becomes obvious and of practical use only when the carbon content of the steel exceeds 0,35 %. The hardening yield continues to increase up to carbon contents of 0,7 %. Carbon contents higher than 0,7 % do not result in any considerable increase of hardness. On the contrary, higher carbon contents, particularly in combination with alloy elements, cause the transformation of austenite to martensite to be shifted to lower temperatures such way that this is not yet entirely completed at room temperature. Due to this, a more or less large quantity of austenite (residual austenite) remains in the structure which reduces the total hardness due to its low hardness.

Extract from the iron-carbon diagram



The martensite being a result of quench hardening is hard, but also very brittle. Its specific volume is larger than that of the original structure. This causes unavoidable changes in the dimensions of the hardened part and internal tensions when the workpiece is only locally martensitic due to surface hardening. These tensions are overlapped by tensions which are caused by the considerable differences of temperature in the workpiece in the heating and quenching process. The totality of tensions causes the hardening distortion and possibly hardening cracks.

Tempering at temperatures of 150 – 200 ° C will change the martensite structure. The martensite experiences a considerable stress relief without any substantial hardening reduction. This has a very positive effect on the mechanical features (stretch and toughness). The workpiece is less sensitive to shock and cracks are hardly to be expected.

Although in induction hardening the same process is done in the workpiece as in the other transformation hardening processes, the necessarily preceding austenitizing process is very limited in time as a result of the fast heating. When a workpiece is heated in the furnace to hardening temperature, the time required for through hardening is in general sufficient to austenize the structure completely. On the basis of the usual ferrite-perlite structure of the steel, this means that with increasing temperature and dwell time beyond the transformation point first the perlite is transformed into austenite and then increasingly the ferrite. Since both structure components have a very different carbon content (perlite ≈ 0,9 and ferrite < 0,01) this difference of concentration of carbon must compensate by diffusion in the austenite come into being. The compensation process depends on time and temperature. It goes slow closely above the transformation temperature and faster at increased temperatures. Are in the steel besides the iron carbide (cementite) any carbides from alloy elements (e.g. chrome) present, the austenitizing process will take longer due to the dissolution of the carbides either starting with delay or going slower.

Steel provides the optimal requirements for the hardenability, provided the austenitizing process

1. dissolves and transforms the perlite and ferrite
2. largely dissolves the alloy carbides
3. all differences in concentration (carbon and alloy elements) are compensated.

Both, a dwell time longer than required (overtimes) and a too high austenitizing temperature cause a coarse austenite grain unless the dwell time is reduced at the same time (overheating). The risk of forming a coarse grain as a result of increased hardening temperatures, as applied for a faster austenitizing in induction hardening, however does not exist as long as there are undissolved rests of carbide present.

Comparison of the induction, flame, dip, case and nitride hardening processes

Induction hardening cannot and is not to replace those surface hardening processes being generally in use. It is an additional hardening process which is used for those applications where there is a benefit, both in technical and economic respect. The advantage becomes the more obvious the smaller the surface to be hardened on a workpiece is, compared with its total surface. The following is a summary of the advantages and disadvantages of the different surface hardening processes. The decision which hardening process is advantageous for a specific workpiece can be taken by the processing company only and, in case of doubt, after having consulted experts for such processes.

Induction hardening

Advantages

Uniform heating of the parts of the component to be hardened. Short heating times and as a result thereof the formation of a minimum amount of scale. In many cases no subsequent work is necessary. Due to short-time heating the formation of coarse grain as a result of overtimes and overheating is avoided. Safe control of heat input. The temperatures required are kept. The distortion is generally low. In comparaison with case hardening, expensive alloyed case hardening steels can be replaced by cheap heat-treatable steels. Partial hardening is mostly possible even on most difficult workpiece shapes. The hardening machines and generators can be directly integrated in the production lines. The space requirement is low, easy and clean operation with no health hazards.

The hardening installation is always ready for operation and, with careful routine maintenance, safe in operation. The hardening machines can be manufactured such way to allow for fully automatic operation.

Disadvantages

The purchase costs for a hardening installation are high and can only be amortized through a good utilization and/or major quantities of workpieces to be processed. When hardening heat-treatable steels a zone of low strength (soft zone) might occur between the core and the hardened outer zone. Different inductors have to be used for the different processes. Hardening components with large changes in sections can be difficult.

Flame hardening

Advantages

Low capital costs. The heating times are relatively short. The distortion is low.The minimum hardness depths that can be obtained are more limited downwards than with induction hardening. Within limits, selective hardening of specific areas of the component is possible. The hardening plant and equipment can be installed in a production line. Low space requirements and simple operation. The installation is always ready for operation. The hardening machines can be partly automated.

Disadvantages

Due to variations in the burner gas pressure and mixture the heating flame temperature is not always constant causing the hardening depth to vary. The hardening of bores is difficult and can only be carried out on large diameters. For hardening different components different burners have to be used. When hardening heat treatable steels, a tempering zone (soft zone) occurs between the core and the hardened outer layer.

Dip hardening

Advantages

Low heat treatment costs. Short process times. The distortion is low.

Disadvantages

Selective hardening is only possible in certain instances. The complete component is surface hardened as it is impossible to mask areas which should not be hardened. It is not possible to obtain a perfect hardened layer at points where there is a change in section or notches in the component. The hardening works can only be carried out in a special hardening shop involving additional transportation cost. The fumes of the dip baths are harmful to the health. The hardened components require subsequent work.

Case hardening

Advantages

The hardened layer, although relatively thin, is uniform over the component. Selective hardening can be achieved, dependent upon the component shape. The core strength is increased at the same time when the surface is hardened. Higher efficiency in general on parts whose whole surface is to be hardened.

Disadvantages

High operating costs, long annealing times. Severe distortion can occur as the whole component will be heated. Areas which are not to be hardened must be covered or the hardened layer must be removed before the hardening process. The process can only be carried out in a special hardening shop involving additional transportation cost. In order to receive a clean surface the hardened workpieces need subsequent work.

Nitride hardening (gas nitriding)

Advantages

Uniform hardness depth irrespective of the shape of the component. As the process temperature is low (approx. 500 °C), distortion on stress-relieved annealed components is insignificant. No quenching is necessary. Very high hardness values can be achieved and will remain nearly the same at temperatures above 500 °C. The resistance to wear is very high in accordance with the high hardness. Nitrited components do not have to be reworked after hardening.

Disadvantages

High operating costs. Only special steels can be used. The annealing times are very long, depending on the hardness depth between 1 – 4 days are necessary. The whole component is heated through. The hardened layer is thin. The hardness reduces considerably in the zones below 0,2 mm. The surfaces do not withstand high surface pressure as they tend to collapse under pressure. Sections not to be hardened have to be coated by tinning or nickeling. The surface of the component must be perfectly clean before nitriding. The process can only be carried out in a special hardening shop, involving additional transportation costs.

Cooling curves of water, mineral oil and aqueous solutions

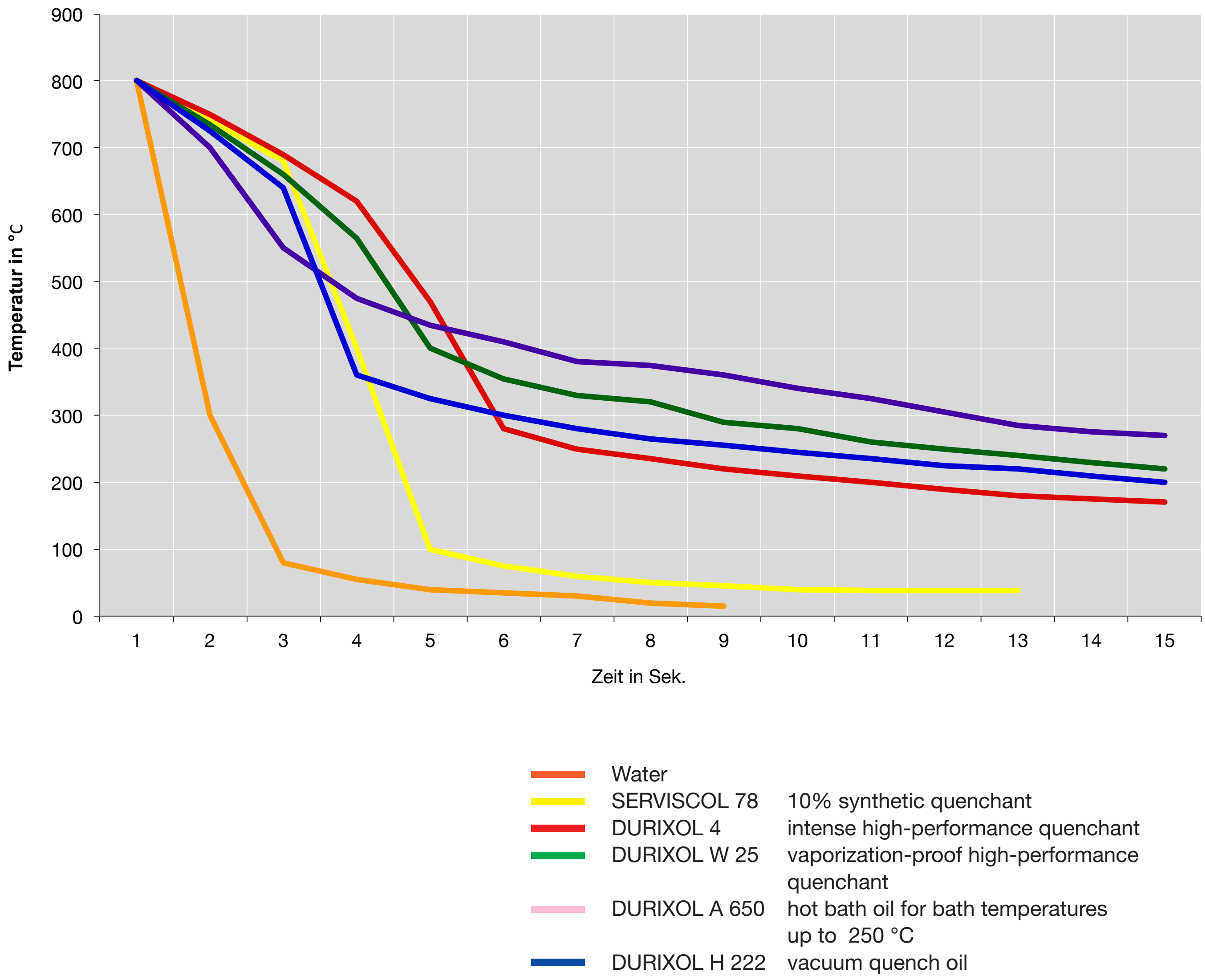


Table to compare hardness values according to Rockwell, Vickers, Brinell, tensile strength

Rockwell	Vickers	Brinell	tensile strength R_m
HRC	HV	HB	N/mm²
20	240	228	770
21	245	233	785
22	250	238	800
23	255	242	820
24	260	247	835
25	265	252	850
26	270	257	865
27	280	266	900
28	285	271	915
29	295	280	950
30	300	285	965
31	310	295	995
32	320	304	1030
33	330	314	1060
34	340	323	1095
35	345	330	1115
36	355	335	1140
37	365	340	1150
38	370	352	1190
39	380	361	1220
40	390	371	1255
41	400	380	1290
42	410	390	1320
43	420	399	1350
44	430	409	1385
45	445	423	1450
46	460	437	1485
47	470	447	1520
48	480	456	1555
49	500	475	1630
50	510	485	1665
51	520	495	1700
52	545	515	1780
53	560	532	1845
54	580	551	1920
55	600	570	1995
56	610	580	2030
57	630	599	2105
58	650	620	2180
59	670	-	-
60	700	-	-
61	720	-	-
62	740	-	-
63	770	-	-
64	800	-	-
65	830	-	-
66	860	-	-

Inductively hardable steels

DIN-term	material-number	HRc-values	analysis									
			C	Si	Mn	P	S	Cr	Mo	Ni	V	C
			%	≤ %	≤ %	≤ %	≤ %	%	%	%	%	%
heat-treatable steels												
C 35	1.0501	🟥 51 – 57	0,35	0,35	0,80	0,045	0,045					
35 S 20 [1]	1.0726	🟥 50 – 55	0,35	0,40	0,90	0,060	0,250					
Ck 35	1.1181	🟥 51 – 57	0,35	0,35	0,80	0,035	0,035					
Cf 35	1.1183	🟥 51 – 57	0,35	0,35	0,80	0,025	0,035					
C 45	1.0503	🟥 56 – 61	0,45	0,35	0,80	0,045	0,045					
45 S 20 [1]	1.0727	🟥 55 – 60	0,45	0,40	0,90	0,060	0,250					
Ck 45	1.1191	🟥 56 – 61	0,45	0,35	0,80	0,035	0,035					
Cf 45	1.1193	🟥 56 – 61	0,45	0,35	0,80	0,025	0,035					
Cf 53	1.1213	🟥 58 – 63	0,53	0,35	0,70	0,025	0,035					
60 S 20 [1]	1.0728	🟦 58 – 62	0,60	0,40	0,90	0,060	0,250					
Ck 60	1.1221	🟦 59 – 64	0,60	0,35	0,90	0,035	0,035					
Cf 70	1.1249	🟦 60 – 64	0,70	0,35	0,35	0,025	0,035					
79 Ni 1	1.6971	🟦 60 – 64	0,79	0,30	0,55	0,025	0,025	0,15		0,15	0,05	
36 Mn 5	1.5067	🟥 52 – 56	0,36	0,35	1,50	0,035	0,035					
40 Mn 4	1.5038	🟥 53 – 58	0,40	0,50	1,10	0,035	0,035					
37 MnSi 5 [2]	1.5122	🟩 55 – 58	0,37	1,40	1,40	0,035	0,035					
38 MnSi 4 [2]	1.5120	🟩 54 – 58	0,38	0,90	1,20	0,035	0,035					
46 MnSi 4 [2]	1.5121	🟩 57 – 60	0,46	0,90	1,20	0,035	0,035					
53 MnSi 4 [2]	1.5141	🟩 58 – 62	0,53	1,00	1,20	0,035	0,035					
45 Cr 2	1.7005	🟩 56 – 60	0,45	0,40	0,80	0,025	0,035	0,50				
34 Cr 4	1.7033	🟩 51 – 55	0,34	0,40	0,90	0,035	0,035	1,05				
37 Cr 4	1.7034	🟩 53 – 58	0,37	0,40	0,90	0,035	0,035	1,05				
38 Cr 4	1.7043	🟩 53 – 58	0,38	0,40	0,90	0,025	0,035	1,05				
41 Cr 4	1.7035	🟩 54 – 58	0,41	0,40	0,80	0,035	0,035	1,05				
42 Cr 4	1.7045	🟩 54 – 58	0,42	0,40	0,80	0,025	0,035	1,05				
34 CrMo 4	1.7220	🟩 52 – 56	0,34	0,40	0,80	0,035	0,035	1,05	0,25			
41 CrMo 4	1.7223	🟩 54 – 58	0,41	0,40	0,80	0,025	0,035	1,05	0,25			
42 CrMo 4	1.7225	🟩 54 – 58	0,42	0,40	0,80	0,035	0,035	1,05	0,25			
49 CrMo 4	1.7238	🟩 57 – 62	0,49	0,40	0,80	0,025	0,035	1,05	0,25			
50 CrMo 4	1.7228	🟩 57 – 62	0,50	0,40	0,80	0,035	0,035	1,05	0,25			
50 Cr V 4	1.8159	🟨 57 – 62	0,50	0,40	1,10	0,035	0,035	1,05			0,15	
58 Cr V 4	1.8161	🟨 58 – 63	0,58	0,35	1,10	0,035	0,035	1,05			0,09	
30 CrNiMo 8	1.6580	🟨 50 – 54	0,30	0,40	0,60	0,035	0,035	2,00	0,35	2,00		
34 CrNiMo 6	1.6582	🟨 53 – 56	0,34	0,40	0,70	0,035	0,035	1,55	0,25	1,55		
36 CrNiMo 4	1.6511	🟨 54 – 57	0,36	0,40	0,80	0,035	0,035	1,05	0,25	1,05		
tool steels												
X 41 CrMo V 5,1	1.2344	🟩 55 – 59	0,41	1,00	0,40	0,015	0,010	5,00	1,30		0,50	
86 CrMo V 7	1.2327	🟨 60 – 64	0,86	0,35	0,45	0,030	0,030	1,75	0,30	0,10		
X 20 Cr 13	1.2082	🟩 48 – 53	0,20	0,50	0,40	0,035	0,035	13,00				
X 40 Cr 13	1.2083	🟩 55 – 58	0,40	0,50	0,40	0,030	0,030	13,00				
stainless steels												
X 90 CrMo V 18	1.4112	🟨 55 – 58	0,90	1,00	1,00	0,045	0,030	18,00	1,15			
X 90 CrCoMo V 17	1.4535	🟨 55 – 58	0,90	1,00	1,00	0,045	0,030	16,50	0,50	0,25	0,25	ca. 1,5
X 105 CrMo 17	1.4125	🟨 56 – 60	1,05	1,00	1,00	0,045	0,030	17,00	0,60		0,10	
rolling bearing steels												
100 Cr 6	1.3505	🟩 62 – 65	1,00	0,35	0,40	0,030	0,025	1,55				
valve steel												
X 45 CrSi 9-3	1.4718	🟦 56 – 60	0,45	3,50	0,50	0,030	0,025	9,50				
X 80 CrNiSi 20	1.4747	🟦 52 –55	0,80	2,75	1,00	0,030	0,030	20,00		1,50		
casting material												
GG-25	0.6025	🟦 48 – 52	Please ask for an additional instruction sheet									
GTS-45		🟦 51 – 57										
GTS-65		🟦 56 – 59										
GGG-60	0.7060	🟦 53 – 59										
GGG-70	0.7070	🟦 56 – 62										

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[1] higher hardening variations are possible [2] good transmutations, but danger of cracks for strong shaped pieces

Carburized steels suitable for partial hardening, e.g. Ck 15, 16 MnCr 5, 20 MnCr 5, 15 CrNi 6, 20 MoCr 4 etc.

Dry powdered metals iron-carbon basis hardening is possible

Key for hardening depths:
🟦 max. 2 mm
🟥 max. 4 mm
🟩 max. 6 mm
🟨 über 6 mm