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Surface hardening for improving the properties of components

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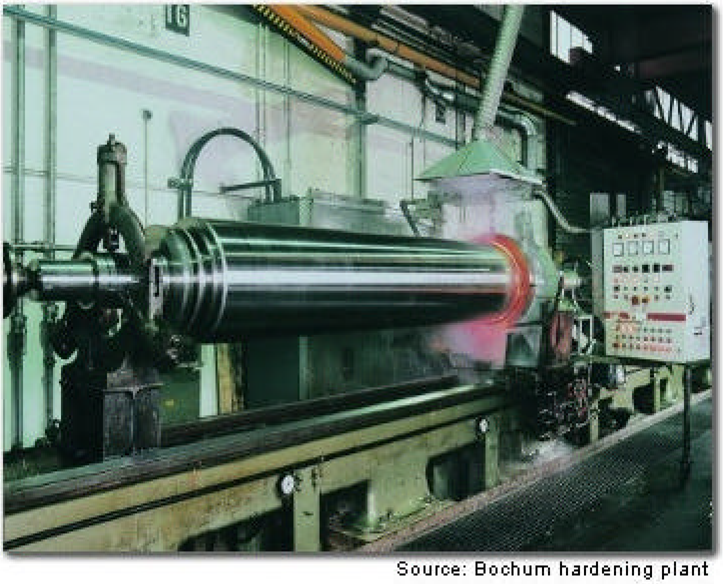
For many ferrous products that need a hard or low-wearing surface, hardening only the surface layer proves an adequate measure. Martensite surface hardening considerably increases the surface hardness of steels. This paper presents the methods that have been established and optimized over many years in flame and induction hardening.

1 Introduction

Martensite surface hardening is one of the oldest heat treatment methods for increasing surface hardness, improving wearing and sliding properties, enhancing fatigue and rolling strength, and improving the resistance of steels to impact and compressive forces. Martensite surface hardening is basically austenitization initiated in the surface layer, followed by quenching in a suitable medium in conditions enabling as much of the austenite as possible to transform into martensite and, if necessary, bainite. Directly after hardening, the workpiece is then generally subjected to low temperature tempering that reduces the brittleness of the hardened microstructure with minimum losses in hardness.

Depending on the sources used for generating the heat on the surface layers, we differentiate between flame hardening, induction hardening, laser beam hardening, electron beam hardening, and – where intrinsically generated heat is utilized – friction and grind hardening.

Whereas flame and induction hardening have been used for many years now, the laser and electron beam hardening methods developed over the last thirty to thirty-five years can still at best be described as infant technologies. At the present level of knowledge in the field of laser beam hardening we cannot help but conclude that the peculiarities of this method stand in the way of its broad introduction into industrial practices and, in particular, in the services sector. There are recognizable advantages, and the future will bring areas of application where a simple guided beam is used to harden areas that are otherwise difficult to access or are too narrow for existing technologies. One typical example is the partial hardening of cylinder liners for large diesel units. What we observe here is an abrupt transition between the hardened surface layer and the hardened core. The effects of this hardness gradient on the engineering properties of laser hardened surface layers have not yet been investigated to any great degree.



Source: Bochum hardening plant

Figure 1
Modern microprocessor based technology ensures reproducible hardening results from the new induction hardening machine at the Reese hardening plant in Bochum

The potential uses of electron beam hardening can be evaluated in the same manner as laser beam hardening. Yet we must consider in addition the requisite high vacuum technology, which involves essentially higher costs for the integration in industrial processes.

In the case of grind hardening [1], this has been a topic of discussion over the last few years as a new surface hardening method that can be integrated in today's processes. Depending on the process parameters, effective depths of hardening (martensite surface layer) of up to 2 mm are possible. The reproducibility of the results obtained so far with this heat treatment is satisfactory. However, unadapted grinding tools are still limiting at present the effectivity of this method. So the next few years will not be seeing it as an alternative to induction or flame hardening.

The four job hardening plants of the Reese Group have for many years now been enjoying great success in providing their customers with flame and induction hardening services (**Figure 1**). Inhouse development projects have culminated in optimized methods and solutions tailored to specific components.

2 Induction and flame hardening

This section describes the two methods of induction hardening and flame hardening and the differences between them.

2.1 General

The fundamental differences between induction hardening and flame hardening lie in the methods adopted to heat the surface layer to the quenching temperature.

With induction hardening, an alternating magnetic field generated by a current carrying conductor (the inductor), whose form and dimensions must be adapted to obtain the required heating effects, heats the surface layer by inducing eddy currents in the outer rim zones of the workpiece (skin effect). A source of alternating current supplies the heating element with the required power at the required frequency. Once the eddy currents induced in the workpiece have reached a certain intensity, the surface of the workpiece heats up rapidly. This generation of heat takes place directly in the surface layer of the workpiece. The thickness of the surface layer through which the full induced current flows is defined as the penetration depth. This calculable value is a function of the frequency, conductivity, and the magnetic properties of the workpiece's materials. This dependence on the frequency gives rise to the established subdivision into medium and high frequency hardening methods. The medium frequencies range from about 100 Hz to 10 kHz; for frequencies higher than 100 kHz we speak of HF hardening. When currents are induced at a fixed penetration depth, varying the heating power and the heating time gives rise to a reproducible heating depth which, depending on the quenching conditions and the hardenability characteristics of the

Source: Bochum hardening plant

Figure 2
Surface hardening with a burner

workpiece's materials, finally leads to the formation of the required induction hardened layer with a defined effective depth of hardening (Rht).

In the case of flame hardening, the surface of the workpiece is heated with a suitable burner supplied with a mixture of fuel gas and technically pure oxygen (**Figures 2 and 3**). With this method, heating is generated primarily by radiation: owing to the high transfer rate of 1000 to 6000 W/cm^2, heat conduction plays only a subordinate role. The effective depth of hardening is defined primarily by the performance of the burner. Other influencing parameters are the distance between the burner and the workpiece surface, the feed rate, and the austenitizing time.


Source: Bochum hardening plant

Figure 3
Flame hardening of a cable drum

For both methods the effective depth of hardening is defined under DIN 50 190 as the distance between the surface of a hardened workpiece and the point at which the hardness corresponds to an appropriately defined limit value. In general, this limit value is taken to be the Vickers hardness (HV1) corresponding to 80% of the minimum surface hardness. The metallographic processes leading to the increase in hardness of the surface layer are the same for both methods. Once the maximum possible homogeneity of austenite has formed in the surface layer, the workpiece is quenched at a supercritical cooling rate to give rise – as explained above – to the maximum possible proportion of martensite. The quenching medium is usually water, but a mixture of water and synthetic polymers is finding application in an increasing number of cases. Here, the polymer concentration varies between 6 and 12% depending on the composition of the steel, but also on the geometry of the workpiece. Whichever is more convenient for the obtained effective depth of hardening, either the Vickers or Rockwell C method is used to test the hardened surface.

In the case of induction hardening, the frequency, power, and heating time as well as the transformation characteristics of the steel can all be combined to achieve effective depths of hardening from 0.3 to 10 mm, and this value can be as high as 50 mm when the mains frequency is used. In some special cases, also through hardening is possible. Flame hardening can reach effective depths of penetration in carbon steels ranging from 2 to 4 mm. In alloy steels, effective depths of hardening can be as high as 30 mm depending on the alloy content.

A great variety of steels and cast iron classes are suitable for surface hardening. Although DIN 17 212 and EN 8670 contain a list of the "Flame and Induction Hardening Steels", they are far from exhausting the full range of steels suitable for surface hardening. These are all unalloyed steels for quenching and tempering with carbon contents from 0.35 to 0.70% by mass; low alloy steels, of which the steels 34CrMo4, 42CrMo4, and 50CrV4 are the classical representatives; yet also certain cold work steels such as 85Cr7, 85CrMo7, 100Cr6, and X125CrVMo12 1. Some special engineering cases involve the partial surface hardening of rust and acid proof steels such as X20Cr13, X35CrMo17, X46Cr13, and X90CrMoV18. But there are certain restrictions on the use of the free-cutting steels 35S20 and 60S20: the sulphured inclusions frequently arranged in rows in semi-finished workpieces increase these steels' susceptibility to superficial cracking.

Flame and induction hardening of steel castings and cast iron has also enjoyed a successful introduction. The optimal materials are spheroidal graphite cast iron with tensile strengths between 600 and 800 N/mm^2 (German standards GGG-60 to GGG-80). These materials guarantee that the combined carbon content required for adequate surface hardening is greater than 0.5% by mass and that the initial microstructure is predominantly pearlite or, in the case of GGG-80, a microstructure suitable for quenching and tempering. Also a Brinell hardness greater than 240 of the initial as-cast condition can be taken as a criterion for adequate hardenability. In principle, the carbon content can be considered to correspond to the required surface hardness and the alloy content to the required effective depth of hardening. These considerations then facilitate the optimal choice of materials, thus minimizing costs without affecting the quality. For example, only when the effective depth of hardening needed for a certain fatigue strength cannot be obtained with a carbon steel, will the next higher quality, i.e. an alloy steel, be chosen. These decisions should involve consultations with the commissioned heat treatment providers at the earliest possible date. Qualified contact personnel are available at all times at all Reese hardening plants. The table in the following provides an initial overview of steels and cast iron classes suitable for surface hardening together with the obtainable surface hardnesses and effective depths of hardening.

Also the heat treatment given to the workpiece before surface hardening should be considered. Since both flame and induction hardening are short-time heat treatment methods, it must be ensured that the initial microstructure can rapidly transform into homogeneous austenite during the heating stage. The best results (including those conducive to strength) are obtained with quenching and subsequent tempering. In special cases, above all where steels with higher carbon contents are involved, normalized steels can also be used. However, steels with 100% pearlite spheroidization should be avoided wherever possible as candidates for surface hardening.

Also important before surface hardening is the clean state of the workpiece's surface. A general inspection should ensure that it is metallically clean and free of swarf, greases, and other soiling matter. There are no specific requirements as regards the surface roughness, this is stipulated solely by subsequent operations. Deep grooves at the edges of hardened zones may be significant in the context of crack formation. In no event may the surface layer be either carburized or decarburized, unless of course the initial product is a carburized workpiece.

Compared with the elegance of clean and eco-friendly induction hardening, which thanks to modern process computer control can be easily integrated into the industrial chain for mass produced parts, flame hardening presents itself more as a robust method. Nevertheless, its potential range of variations and the progress achieved in its development will make it difficult to replace for some time to come.

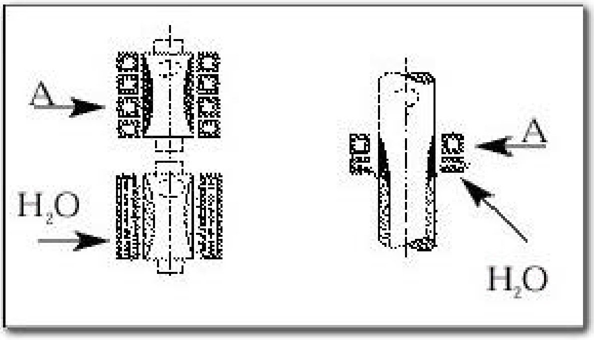


Figure 4
The induction hardening operations:
Full surface hardening (left) and progressive hardening (right)

2.2 Induction hardening

At the Reese hardening plants, only the most suitable process technology [2] is used for induction surface hardening. The solution required for the specific hardening job must lie within the limits set by the respective materials engineering, electrical, and thermal considerations, fulfil all engineering requirements, and adhere to the quality parameters. Only so can costs be minimized for the hardened product.

In principle, there are two variants finding application in HF and MF hardening. These are full surface hardening (a stationary method) and progressive hardening. All other designations that have been coined for the various practical realizations in the heat treatment of particular workpieces can be assigned to either of these two basic variants. **Figure 4** illustrates these two basic variants in diagrammatic form. "A" marks the inductors and "H_2O" the quench nozzles [3].

Full surface hardening is conducted in two stages. The first stage involves the inductively induced heating of the surface layer to the required quenching temperature. Directly afterwards, or after a compensation time based on the workpiece's material, the second stage quenches the whole heated surface. One particular example is the partial hardening of crankshafts.

Source: Bochum hardening plant

Figure 5
Induction hardening of a shaft

In progressive hardening, heating to the quenching temperature and quenching take place almost simultaneously. This requires a continuous relative motion between the workpiece and the quench nozzles fixed rigidly to the inductor. The area of the workpiece heated by the inductor then enters the quenching zone, where supercritical cooling gives rise to the microstructure for the induction hardened layer. The optimal transformation of the microstructure is defined by the relative speed between the workpiece and the inductor-quench unit, i.e. the time for the heated surface of the workpiece to enter the quenching zone.

When the workpiece rotates during progressive hardening, then we have combined spin and progressive hardening. This variant of progressive hardening is used, for example, for the surface hardening of shafts (**Figure 5**), axles, pins, connecting rods, and rollers. Purely progressive hardening is used primarily for hardening guide ways, machine beds, and guide beads.

Another, special variant of progressive hardening is circumferential slip hardening. This is used for hardening slide ways on rings, sprockets, and bushes. Here the workpiece rotates slowly past the inductor-quench unit. At both edges of the hardened zone there is a slip area of between 10 and 20 mm that exhibits a lower hardness value. So that this lower hardness value cannot have any detrimental effect on the product’s proper functioning, this slip zone is placed wherever possible under an angle of 30–45°. In many cases it is also relief-ground.

Gaining in importance is the induction surface hardening of gear teeth (**Figure 6**). Here, tooth profiles are hardened to minimize wearing, and / or the roots of the teeth hardened to enhance their load bearing strength. For some special gear pairs, the tooth profiles of gears are often hardened together with the roots of the pinion’s teeth. The effective depth of hardening is defined as a function of the gear’s module. The Reese hardening plant in Bochum can induction-harden gearwheels and sprockets with modules up to 60, diameters up to 5500 mm, and masses up to 13 t. What must be considered here is that the applicability of induction surface hardening on gearwheels is defined by the loads on the respective component.

According to the present level of knowledge, the load bearing capacity of induction hardened quenched and tempered materials is only 20% lower than case hardened steels, whereby in case hardening the additional qualities of strength and ductility for the surface and core can be defined

Source: Bochum hardening plant

Figure 6
Induction hardening of tooth profiles and roots

independently of each other by the selection of materials and the heat treatment method. In other words, the potential cost benefits of induction hardening are offset by drawbacks respecting the strength of the hardened components. Consequently, total costs that include such aspects as lightweight engineering, material procurement, and warehousing must be recalculated from case to case.

With respect to the internal stresses that induction hardening sets up in the workpiece's surface layer, not only the effective depth of hardening, but also the development of hardness from the surface to the core is of significance. In particular, workpieces designed for cyclic loading should run through a process control sequence ensuring that a gentle transition is generated between the surface microstructure and the heat treatable microstructure of the base metal. As a rule, compression stresses are set up in the induction hardened layer that become tensile stresses at the edges of the hardened zone. This therefore gives rise to the requirement that the edges of hardened zones must never be near fillets, notches, or grooves, but that these areas must be included in the hardened zone.

With partial induction surface hardening, dimensional and shape changes occur to a far less degree than with volume hardening. However, even here the volume changes brought about by the microstructural transformations in the induction hardened layer have the same relevance as with every other martensite hardening. The Reese hardening plants integrate computer aided solutions to compensate for any dimensional changes that cannot be justified by the technology. In this case, a practical combination of parameters from production technology, materials engineering, and heat technology ensures that the thermal expansion of shafts and threaded spindles, which would be as high as 6 mm during the heat treatment, is kept to less than 0.2 mm. This new possibility of defining in advance material properties and dimensional changes and of integrating these as far back as in the green sand mould will greatly assist the operator in minimizing subsequent metalworking and the associated tool costs. Depending on the workpiece's geometry, warpage can be limited to a great degree by suitable precautions taken on the hardening machine. These precautions include suitable forced guides for the workpiece and a resilient inductor mount following precisely the coupled distance between the inductor and the workpiece. The overall result of the heat treatment is defined to a great extent by the uniformity of the hardened surface layer and its dimensional fidelity. After careful sampling, the Reese hardening plants employ modern control technologies ensuring reproducible, uniform hardened surface layers. Exact inductor adjustments at the respective surfaces of the workpiece ensure a warp free formation of the hardened surface layer. These adjustments often necessitate considerable investments in the development and construction of the inductor or the whole inductor-quench unit.

The Reese hardening plants manufacture their own inductors that are then adapted precisely to each specific job. In the case of repetition parts, an attempt is made to assign inductors and quench nozzles to a workpiece family. This procedure of course assumes that the dimensions of the part specified on the drawing are binding. The same also applies to agreed deviations for the exact positioning of the workpiece during the hardening process, even if the subsequent effects have not been given tolerances on the drawing. Experience has shown that direct contact with the customer helps to realize simple and economical solutions by influencing the design of the hardening zones as early as the development stage.

2.3 Flame hardening

Just as with induction hardening, flame hardening also involves several different operating methods depending on the type of motion between the burner and the workpiece. Which operating method is used depends primarily on the shape of the workpiece (**Figure 7**). Specific hardening variants are the stationary method, spin method, progressive method, the circumferential progressive method, and the Vorschub-Schlupfhärten.

With the stationary method, both the burner and the workpiece are stationary for the whole duration of heating. Afterwards the burner yields its place to quench nozzles, or the workpiece is submerged in a cooling bath. This method is used primarily for hardening smaller surfaces and is ideal for series produced parts.

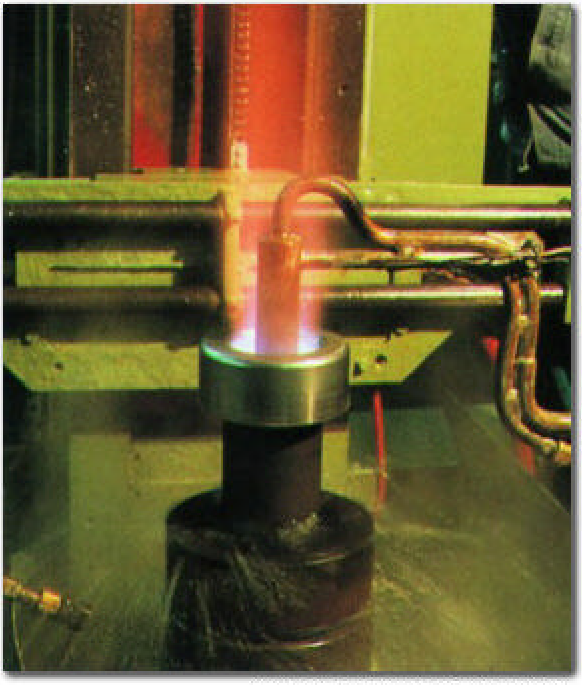
The spin method is used for circular workpieces that rotate for the whole duration of the hardening process. These workpieces are rollers, cylinders, and bearing surfaces.

With the progressive method, only a narrow linear strip is heated along the workpiece, which is then quenched. Such workpieces include guide ways, dies, and slide ways on machine beds.

With the circumferential progressive method, cylindrical parts are first heated by moving through an annular or segmented burner arrangement and then immediately quenched by nozzles arranged at the same positions.

The progressive slip method operates in the same manner as the analogous unit for induction heating, but the combination of inductor and nozzles is replaced with a stationary burner-quench unit. Again, the edges of the hardening zone exhibit lower hardness values which must be taken into consideration in the design of the parts.

In the specific case of large impellers, the Bochum hardening plant has developed a method that has been gaining in practical importance. This method generates a special surface layer composite endowing impellers with the optimal material properties, namely a surface layer of martensite which has undergone an isothermal transformation to produce a base layer of a tough and hard microstructure from the lower bainite range. This combination of tough and hard properties in the base layer serves not only to increase the number of stress cycles needed to generate cracks, but also impedes their propagation. Hence, the useful life of these impellers could be extended many times over, and the risk of failure minimized.



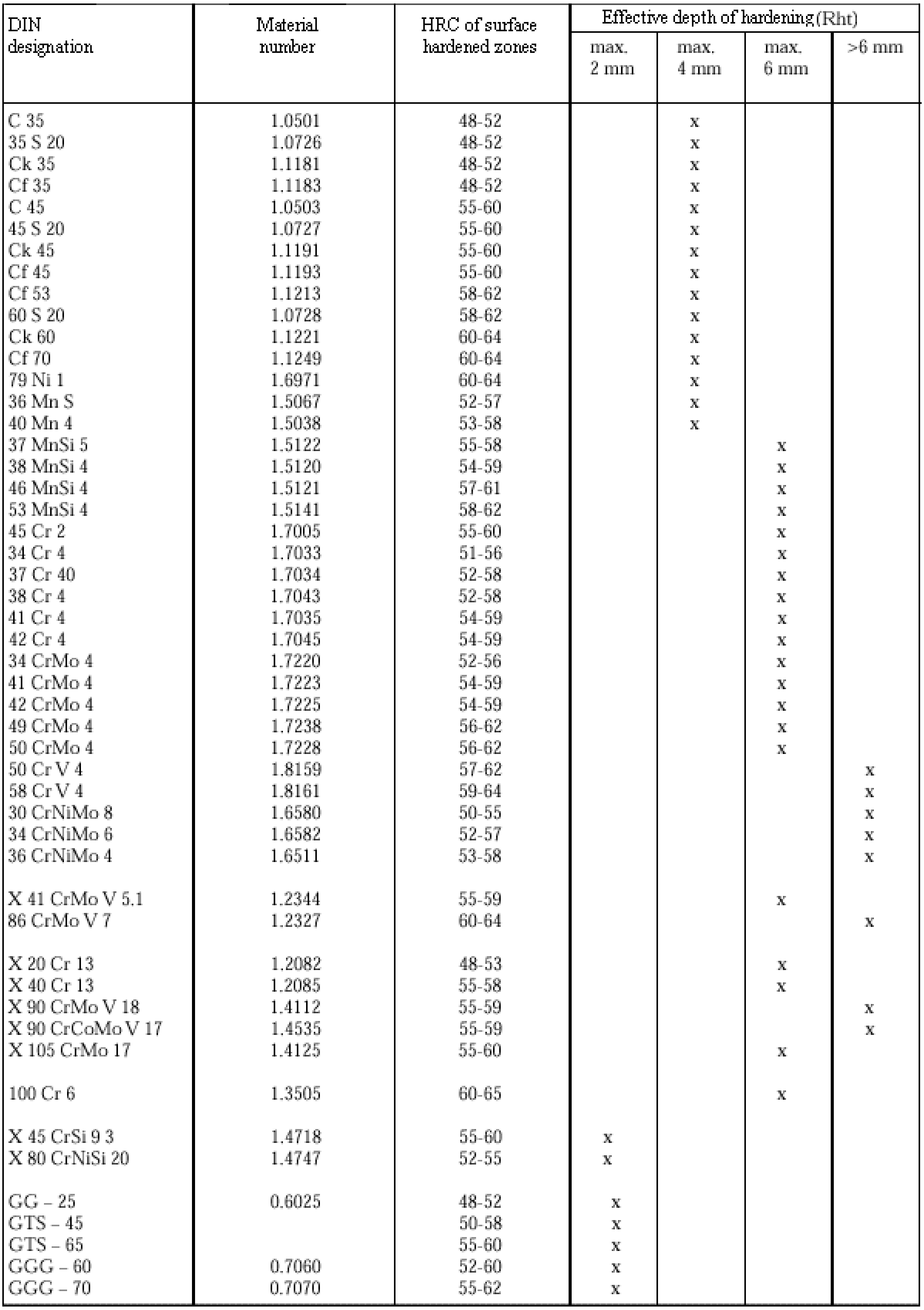
Source: Bochum hardening plant

Figure 7
Flame hardening of a hub

3 Finishing methods

Since the martensite surface layers generated by induction and flame hardening are relatively brittle, the hardened surface layer usually undergoes subsequent stress relieving or tempering. Tempering takes place at a temperature between 120 and 150 °C, as a rule in conventional electric resistance furnaces. Yet the utilization of residual heat to relieve stresses is also possible. In an increasing number of cases, short-term induction tempering has been successfully used on series produced parts. The decision as to which finishing method to use depends on the part itself. Stress relieving or tempering initiates the transformation of tetragonal martensite into cubic martensite and, at a quenching temperature greater than 240 °C, the transformation of the remaining austenite. Subzero refrigeration after surface hardening, followed by low temperature tempering also brings about the transformation of the remaining austenite without essential losses in hardness. One typical example is the induction hardening of cold rollers with the progressive method.

To a certain restricted extent, mechanically adjusting parts with induction hardened surfaces can also be employed as a means to correct warpage. The parts can be adjusted either before or after stress relieving or tempering. Adjusting methods include beating out, straightening, and pressing in a flattener or on a dressing bench. Only many years of experience can adequately foresee the outcome. With the aim of straightening large components, the Reese hardening plant in Bochum operates the largest precision straightening press in Germany. With a maximum press force of 8000 kN this computer controlled press can straighten high strength components with diameters exceeding 300 mm and lengths up to 10 m. The obtained straightening precision is 0.02 mm.



DIN designation	Material number	HRC of surface hardened zones	Effective depth of hardening (Rht)			
			max. 2 mm	max. 4 mm	max. 6 mm	>6 mm
C 35	1.0501	48-52		x		
35 S 20	1.0726	48-52		x		
Ck 35	1.1181	48-52		x		
Cf 35	1.1183	48-52		x		
C 45	1.0503	55-60		x		
45 S 20	1.0727	55-60		x		
Ck 45	1.1191	55-60		x		
Cf 45	1.1193	55-60		x		
Cf 53	1.1213	58-62		x		
60 S 20	1.0728	58-62		x		
Ck 60	1.1221	60-64		x		
Cf 70	1.1249	60-64		x		
79 Ni 1	1.6971	60-64		x		
36 Mn S	1.5067	52-57		x		
40 Mn 4	1.5038	53-58		x		
37 MnSi 5	1.5122	55-58			x	
38 MnSi 4	1.5120	54-59			x	
46 MnSi 4	1.5121	57-61			x	
53 MnSi 4	1.5141	58-62			x	
45 Cr 2	1.7005	55-60			x	
34 Cr 4	1.7033	51-56			x	
37 Cr 40	1.7034	52-58			x	
38 Cr 4	1.7043	52-58			x	
41 Cr 4	1.7035	54-59			x	
42 Cr 4	1.7045	54-59			x	
34 CrMo 4	1.7220	52-56			x	
41 CrMo 4	1.7223	54-59			x	
42 CrMo 4	1.7225	54-59			x	
49 CrMo 4	1.7238	56-62			x	
50 CrMo 4	1.7228	56-62			x	
50 Cr V 4	1.8159	57-62				x
58 Cr V 4	1.8161	59-64				x
30 CrNiMo 8	1.6580	50-55				x
34 CrNiMo 6	1.6582	52-57				x
36 CrNiMo 4	1.6511	53-58				x
X 41 CrMo V 5.1	1.2344	55-59			x	
86 CrMo V 7	1.2327	60-64				x
X 20 Cr 13	1.2082	48-53			x	
X 40 Cr 13	1.2085	55-58			x	
X 90 CrMo V 18	1.4112	55-59				x
X 90 CrCoMo V 17	1.4535	55-59				x
X 105 CrMo 17	1.4125	55-60			x	
100 Cr 6	1.3505	60-65			x	
X 45 CrSi 9 3	1.4718	55-60	x			
X 80 CrNiSi 20	1.4747	52-55	x			
GG – 25	0.6025	48-52	x			
GTS – 45		50-58	x			
GTS – 65		55-60	x			
GGG – 60	0.7060	52-60	x			
GGG – 70	0.7070	55-62	x			

Table
Obtainable surface hardnesses and effective depths of hardening for surface hardenable steels and cast iron classes

4 Concluding remarks

The Reese hardening plants, whose quality management is certified in accordance with DIN EN ISO 9001, gives a high priority to quality assurance. As a result, all surface hardened parts are subjected to a stringent outgoing goods inspection. Besides the checks on the requisite surface hardness, these inspections include the determination of the effective depth of hardening on sample parts in accordance with DIN 50 190, diverse crack detection measures, and metallographic examinations. Unfortunately, designers still attach too little importance to surface hardening. Notwithstanding, these inhibitions can easily be overcome in direct consultation with specialists in the field of heat treatment. The use of modern surface hardening technology and the corresponding knowhow in this field can offer better and more economical solutions to your heat treatment problems than, for example, conventional case hardening.

References

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[2] Liebmann, G.: Induktionshärtungsschichten. Verschleißkatalog 1997, Arbeitsblatt 1.3
[3] Company brochures from Elotherm GmbH in Remscheid

The author

Dr.-Ing. G Liebmann was born in 1932 and studied materials engineering as an external student at the Bergakademie Freiburg. In 1979 he received his doctorate at the same institute. Until 1991 he worked as a research assistant at the material laboratories of VEB Carl Zeiss Jena (now Jenoptik GmbH) where he ran the department for heat treatment. At the end of 1991 he assumed the post of head engineer at Härterei Reese Weimar GmbH & Co. KG, where he has been entrusted with confidential duties since 1992. In 1996 he was elected to the managing board of AWT.