



GEAR MATERIALS AND HEAT TREATMENT

By

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T A B L E O F C O N T E N T S

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3. Surface-hardening methods
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The desired load carrying capacity of a gear, and especially the stresses in the teeth, determine the necessary strength requirements imposed on the material selected, and the heat treatment to which it is to be subjected.

A great variety of materials can be used for the production of gears, but for technical and economic reasons steels have attained a major importance. The wide selection available, together with the ease with which their properties can be finely and extensively influenced, renders them capable of offering a host of practical possibilities.

Let us first call some simple metallurgical facts back to mind:

The transformation which the structure of steel undergoes during heating and subsequent cooling, particularly the formation of martensite on quenching, are essential for the hardening and tempering of steel. In quench hardening, two properties of the steel are of special significance and should be clearly distinguished. The first, the maximum hardness of a steel which is the hardness of martensite, depends almost exclusively on its carbon content, provided that the cooling rate is above the critical (Fig. 1); the second, the hardenability, determines the depth of the hardened zone or the diameter of a cross-section which can be hardened through.

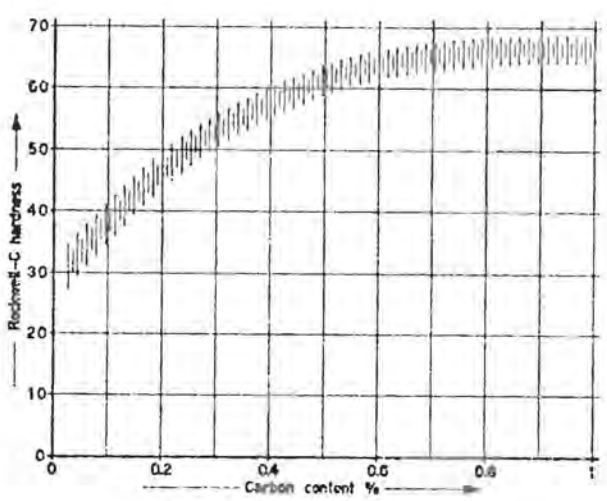


Fig. 1 Maximum hardness (hardness of martensite) as a function of carbon content.

This second property is essentially a function of the total alloy content and also, to a certain extent, of the grain size. The hardenability can best be evaluated by the end quench test devised by W. E. Jominy. Cylindrical test pieces of 1 inch (25 mm) diameter and 4 inches (100 mm) long are heated to harde-

ing temperature, suspended vertically and quenched from the bottom end with a water jet. While the lower end is subjected to a very high cooling rate, the opposite face of the test piece cools slowly. The rate of cooling diminishes along the test piece; rapidly in the immediate vicinity of the quenched end, then more and more gradually with increasing distance. Fig. 2 allows an approximation of the hardness in pieces of different sizes, as obtained with different quenching media.

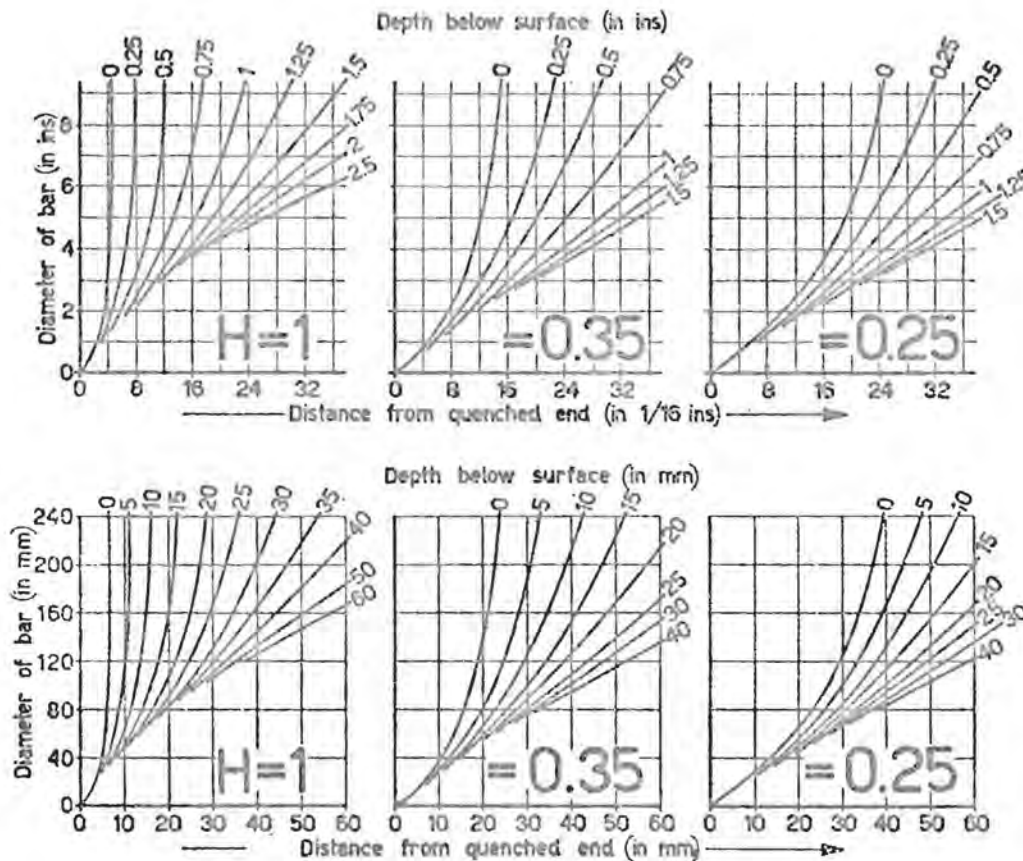


Fig. 2 Diagram to derive the hardness variation over the cross-sections of round bars from the hardness curve obtained on a Jominy test bar having the same hardness.

Quenching severities:  $H = 1$  (water),  $H = 0.35$  (oil),  
 $H = 0.25$  (martemper bath)

Hardness measurements along end quench test specimens give a good idea of the effects of different alloy contents. Fig. 3 for instance shows that the maximum hardness (hardening capacity) depends only on the carbon content. The gradient of the hardness curve with increasing distance from the quenched end is a function of the hardenability, which depends on the alloy content. The higher the hardenability, i. e. the flatter the hardness curve, the lower is the cooling rate necessary to obtain a high hardness compared with the maximum hardness of the steel. It follows then that the quenching medium has to be adjusted to the composition of the steel or its hardenability and to the cross-

section of the part. Large cross-sections cool more slowly than small ones, and the cooling rate is higher at the surface than inside. With the common quenching media of water, oil, marquenching bath (consisting of hot oil or molten salt) and air, arranged in decreasing order of severity, very great differences in hardness are obtained.

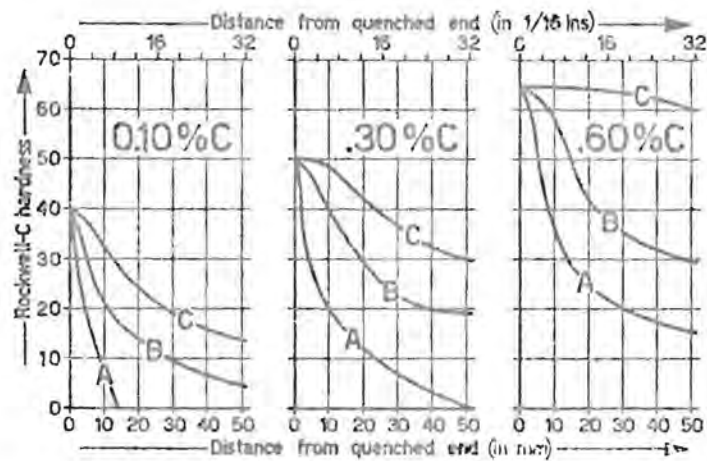


Fig. 3 Influence of chemical composition on the hardness curves of end quenched test specimens. Analysis: A: 0.5 Mn 0.3 Si; B: 0.5 Mn 0.3 Si, 1.0 Cr, 1.0 Ni; C: 0.5 Mn 0.3 Si, 1.0 Cr, 1.0 Ni, 0.3 Mo

Parts made of unalloyed steel A (Fig. 3) must be quenched in water to obtain any significant hardness increase even in a thin surface zone, whereas oil quenching may be adequate for other steels under certain circumstances.

Where gears are concerned, the stresses determining the selection and treatment of the material are limited to the tooth flanks (wear) and the fillet (bending). It has, therefore, become general practice to use not only steels with uniform properties over the whole cross-section (such as unalloyed and alloyed direct-hardening steels), but also steels for which a treatment to increase the resistance to these stresses can be limited to the critical points.

Such steels are broadly classified as steels for surface-hardening. The individual processes are: case-hardening, nitriding, carbo-nitriding, induction and flame hardening. All these processes, with the exception of nitriding, are based on hardening through the formation of martensite.

## 2. STEELS FOR SOFT OR QUENCHED AND TEMPERED GEARS

### 2.1 Steels Used in the Normalized Condition

For gears which have to carry only small specific loads, unalloyed or lean alloy steels are often used in the normalized condition. Normalizing is the term applied to the process of heating the steel (after hot working) to the temperature range of austenite (as for hardening), and allowing it to cool in air. This causes the austenite to transform into ferrite and pearlite at relatively high temperatures during cooling, with the result that no hardening takes place. Table 1 (1a/1b) shows hardenability bands (end quench test) for different steel groups. For use in the normalized condition, only the two groups A and B can be considered, the latter only for heavy parts; these steels have the lowest hardenability. Their strength is to a great extent dependent on the carbon content. For welded gears, low carbon steels are given preference. MAAG does not apply such steels for rotating parts.

Table 1 a

Hardness curves of end quenched specimens of various steel groups	Standard steel designations				Chemical composition (in %)							
	Germany DIN	France AFNOR	England BS 970	USA AISI/SAE	C	Mn	Si	P*) S	Cr	Ni	Mo	
	A3	St 70	C60 d (En 9)	1063	≈0.50	—	—	d				
	A3	C 60	C60 e (En 9K)		0.57—0.65	0.50—0.80	0.15—0.35	e				
	A3	Ck 60	(x)C60 f		0.57—0.65	0.50—0.80	0.15—0.35	f				
	A2	St 60	C45 d (En 8)	1044	≈0.40	—	—	d				
	A2	C 45	C45 e (En 8K)		0.42—0.50	0.50—0.80	0.15—0.35	e				
	A2	Ck 45	(x)C45 f		0.42—0.50	0.50—0.80	0.15—0.35	f				
	A1	St 50	C35 d (En 6)	1034	≈0.30	—	—	d				
	A1	C 35	C35 e (En 6K)		0.32—0.40	0.50—0.80	0.15—0.35	e				
A1	Ck 35	(x)C35 f	0.32—0.40		0.50—0.80	0.15—0.35	f					
	B2	37MnSi5	En 8 En 8K En 12  En 15	1335 1345	0.33—0.41	1.1—1.4	1.1—1.4	f				
	B1	38MnSi4			0.34—0.42	0.9—1.2	0.7—0.9	f				
	B2	36Mn5			0.32—0.40	1.2—1.5	0.15—0.35	f				
	B1				0.35—0.45	0.6—1.0	0.05—0.35	d,e		0.6—1.0		
	B1				0.35—0.45	0.6—1.0	0.05—0.35	e				
	B3				0.30—0.45	max. 1.5	0.05—0.35	e				
	B2				0.33—0.38	1.6—1.9	0.2—0.35	d,e				
	B3				0.43—0.48	1.6—1.9	0.2—0.35	d,e				
B2		0.30—0.40	1.3—1.7	0.1—0.35	d,e							
	C1	34CrMo 4	En 19A En 19	4135 4137 4140 4142 4145	0.32—0.37	0.5—0.8	0.15—0.35	f,g,h	0.9—1.2		0.15—0.25	
	C3	42CrMo 4			0.38—0.45	0.5—0.8	0.15—0.35	f,g,h	0.9—1.2		0.15—0.25	
	C1				35CD 4	0.32—0.38	0.6—0.8	< 0.4	f,g,h	0.85—1.15		0.20—0.30
	C3				42CD 4	0.39—0.45	0.6—0.8	< 0.4	f,g,h	0.85—1.15		0.20—0.30
	C2					0.35—0.45	0.5—0.8	0.1—0.35	f	0.9—1.2		0.20—0.35
	C2					0.35—0.45	0.5—0.8	0.1—0.35	f	0.9—1.5		0.20—0.40
	C1					0.33—0.38	0.7—0.9	0.2—0.35	f	0.8—1.15		0.15—0.25
	C2					0.35—0.40	0.7—0.9	0.2—0.35	f	0.8—1.15		0.15—0.25
	C2					0.38—0.43	0.75—1.0	0.2—0.35	f	0.8—1.15		0.15—0.25
	C3					0.40—0.45	0.75—1.0	0.2—0.35	f	0.8—1.15		0.15—0.25
	C3					0.43—0.48	0.75—1.0	0.2—0.35	f	0.8—1.15		0.15—0.25
	C2					0.32—0.40	0.5—0.8	0.15—0.35	f,g,h	0.9—1.2	0.9—1.2	0.15—0.25
	C2	36CrNiMo 4				0.32—0.40	0.5—0.8	0.15—0.35	f,g,h	0.9—1.2	0.9—1.2	0.15—0.25
	C1				35NCD 4	0.32—0.38	0.5—0.9	< 0.4	f,g,h	0.4—0.7	1.0—1.3	0.10—0.20
3 = Hardness curve in upper range												
2 = Hardness curve in middle range (cross-hatched)												
1 = Hardness curve in lower range												
6 = Hardness curve in whole shaded range possible												
					*) P <sub>max</sub> 0.050 0.040 0.035 0.030 0.025 S <sub>max</sub> 0.050 0.040 0.035 0.030 0.025 S+P <sub>max</sub> 0.090 0.070 0.065 0.055 0.050							

Table 1-b

Hardness curves of end quenched specimens of various steel groups	Standard steel designations				Chemical composition (in%)							
	Germany DIN	France AFNOR	England BS 970	USA AISI/SAE	C	Mn	Si	P*) S	Cr	Ni	Mo	
	D2	34CrNiMo 6 (42CrNiMo6) (30NiCrMo74)			4337 4340	0.30—0.38	0.4—0.7	0.15—0.35	f,g,h	1.4—1.7	1.4—1.7	0.15—0.25
	D3					0.38—0.45	0.4—0.7	0.15—0.35	f,g,h	1.4—1.7	1.4—1.7	0.15—0.25
	D2					0.28—0.35	0.4—0.7	0.15—0.35	f,g,h	0.9—1.2	1.8—2.1	0.20—0.30
	D1					0.35—0.40	0.6—0.8	0.20—0.35	f,g,h	0.7—0.9	1.65—2.0	0.20—0.30
	D1					0.38—0.43	0.6—0.8	0.20—0.35	f,g,h	0.7—0.9	1.65—2.0	0.20—0.30
	D6					0.35—0.45	0.45—0.7	0.10—0.35	f,g,h	0.9—1.4	1.3—1.8	0.20—0.35
D3	0.36—0.44	0.5—0.7	0.10—0.35	f,g,h	0.5—0.8	2.3—2.8	0.40—0.70					
	E1	30CrNiMo 8 (40CrNiMo 8)	32NCD 8 35NCD 14	En 26 En 27 En 28	0.28—0.34	0.3—0.6	0.15—0.35	f,g,h	1.8—2.1	1.8—2.1	0.25—0.35	
	E3				0.37—0.43	0.3—0.6	0.15—0.35	f,g,h	1.8—2.1	1.8—2.1	0.25—0.35	
	E1				0.28—0.34	< 0.5	< 0.4	f,g,h	1.9—2.4	1.9—2.4	0.6—0.8	
	E6				0.30—0.40	< 0.4	< 0.35	f,g,h	1.2—1.5	3.2—3.7	0.2—0.3	
	E3				0.36—0.44	0.5—0.7	0.1—0.35	f,g,h	0.5—0.8	2.3—2.8	0.4—0.7	
	E1				0.30—0.35	< 0.7	0.1—0.35	f,g,h	0.5—1.3	3.0—3.75	0.2—0.65	
E6	0.30—0.40	< 0.7	0.1—0.35	f,g,h	0.75—1.5	3.0—4.5	0.2—0.65					
	F2	(33NiCrMo185)	30NCD 16 40NCD 18	En 30B	0.30—0.36	0.4—0.7	0.15—0.35	h	1.1—1.5	4.0—5.0	0.30—0.45	
	F1				0.28—0.35	0.15—0.55	0.10—0.40	h	1.2—1.5	3.7—4.7	0.40—0.60	
	F1				0.28—0.34	0.4—0.6	0.10—0.35	h	1.1—1.4	3.9—4.3	0.20—0.40	
	F3				0.35—0.45	0.15—0.55	0.10—0.40	h	1.4—1.7	4.3—4.9	0.40—0.60	
<p>3 = Hardness curve in upper range </p> <p>2 = Hardness curve in middle range (cross-hatched)</p> <p>1 = Hardness curve in lower range </p> <p>6 = Hardness curve in whole shaded range possible</p>					<p>*)</p> <p>d e f g h</p> <p>P<sub>max</sub> 0.050 0.040 0.035 0.030 0.025</p> <p>S<sub>max</sub> 0.050 0.040 0.035 0.030 0.025</p> <p>S + P<sub>max</sub> 0.090 0.070 0.065 0.055 0.050</p>							



The selection of steels for direct-hardening is dictated by the following metallurgical considerations:

The minimum hardness which must be obtained after quenching, in order to guarantee sufficient toughness after tempering, depends on the desired strength,\* the more complete has to be the formation of martensite on quenching, producing also greater hardness. The relationship is shown in Fig. 4.

\*The higher the necessary strength

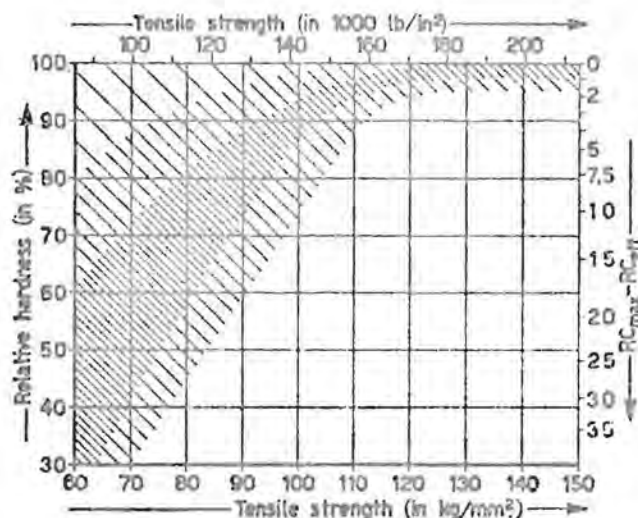


Fig. 4 Required relative hardness in percent and the corresponding hardness difference of  $RC_{max} - RC_{eff}$  as a function of the strength of quenched and tempered steels.

The required tensile strength is represented by the abscissa; the ordinate gives the relative hardness or the equivalent difference between the maximum hardness of martensite and the Rockwell C hardness obtained. In order to maintain good toughness, these values should always remain within the shaded field.

The hardenability shown by the hardness bands of end quench test bars for 6 steel groups in table 1 has (in connection with Fig. 2 and with Fig. 4 showing the desirable relative quenched hardness) a fundamental significance for selecting the suitable cross-sections and strength levels of various direct-hardening steels.

Table 2 contains recommendations for the maximum diameters of round bars, maximum wall thickness of gear rims (tyres) and maximum thickness of forged wheel discs for the different steel groups and strength levels. Where several steel groups are recommended for the same strength level and the same cross-section, the operating or acceptance conditions determine the selection: if high shock or bending stresses are to be expected, the resulting requirement for high fatigue strength and toughness relative to the desired tensile strength can be met by a steel of good hardenability. If, on the other hand, wear resistance is of primary importance, a steel from the group having lower hardenability is adequate; in this case a class with higher carbon content is to be preferred.

Dimensions		Tensile strength in 1000 lb/in <sup>2</sup> (kg/mm <sup>2</sup> )						
in.	mm	85 to 105 (60 to 75)	100 to 120 (70 to 85)	115 to 135 (80 to 95)	130 to 150 (90 to 105)	140 to 165 (100 to 115)	155 to 180 (110 to 125)	170 to 190 (120 to 135)
Bar diameter								
> 1.5 to 3	> 40 to 80	A1,A2	A3,B,C	B1,C	C	C3,D	D	D
> 3 to 5	> 80 to 120	A2	A3,B,C	B3,C,D	C3,D	D	D,E	D2,D3,E
> 5 to 7	> 120 to 180	B,C1	C	C2,C3,D	D	D,E	D2,D3,E	E
> 7 to 10	> 180 to 250	B,C1	C	C2,C3,D	D,E	E	E	E
> 10	> 250	B2,B3,C	C2,C3,D	D	D2,D3,E	E	E	E,F
Thickness of gear rims								
> 0.8 to 1.5	> 20 to 40	A1	A2,B	C	C,D	D	D	D
> 1.5 to 2.5	> 40 to 60	A2	B,C	C,D	C,D	D	D	D,E
> 2.5 to 3.5	> 60 to 90	A2,B	B,C	C,D	D	D	D,E	E
> 3.5 to 5	> 90 to 120	B,C	C,D	D	D	D,E	D,E	E
> 5	> 120	B,C	C,D	D	D,E	E	E	E,F
Width of massive gear discs								
> 0.5 to 1	> 12.5 to 25	A1,A2	A2,B	B,C	C	C,D	C,D	D
> 1 to 2	> 25 to 50	A1,A2	B,C	C	C,D	D	D	D
> 2 to 4	> 50 to 100	A2	B,C	C,D	C,D	D	D	D,E
> 4 to 8	> 100 to 200	A2,B	C	C,D	D	D,E	E	E
> 8	> 200	B	C	D	D	D,E	E,F	E,F

Table 2 Recommendations for the application of groups A to F of direct-hardening steels (Table 1 a and 1 b)

Heavy gears and pinions of coarse pitch can be machined as annealed with an allowance of about 0.040 in. (1 mm), and then quenched and tempered to the desired tensile strength before finish machining. Under these conditions much higher cooling rates occur at critical points (tooth root) than if the blanks were quenched, hence permitting the use of a steel of lower hardenability.

### 3.1 General

With the exception of nitriding, the methods of interest are based on quench hardening. For surfaces requiring maximum wear resistance, a hardness of at least Rockwell C 60 is generally considered necessary (exception to this rule, see under "Nitriding"). A steel which must attain this hardness by the formation of martensite must therefore contain a minimum of 0.45 % carbon (compare Fig. 1). In many cases, however, a lower hardness of about Rockwell C 50 is accepted, permitting the use of lower carbon steels.

Hardening by martensite formation is performed by two fundamentally different major processes. In the case-hardening process the workpieces are made of steel with a carbon content of 0.1 to 0.25 %. Their surface is carburized by diffusion at high temperature from solid, liquid or gaseous carbon-containing media. In the other process, a local heating of the surface is effected by means of either induction currents (induction hardening) or a gas torch (flame hardening). Contrary to case-hardening the steel used for induction or flame hardening must already contain a sufficient amount of carbon, i.e. it is in fact a direct-hardening steel.

### 3.2 Case-hardening Methods

In the carburizing process, the medium containing the carbon may be solid, liquid or gaseous. Each medium has its specific application according to convenience. Temperatures used are always above 1380° F (750° C), usually between 1560 and 1830° F (850 and 1000° C).

The depth of the carburized layer depends on temperature and time. The higher the temperature, the more rapid is the diffusion rate of carbon atoms, under the influence of the carbon gradient, within the austenite lattice. The carbon content within the carburized layer decreases gradually from the surface towards the core. The depth at which the original carbon content of the steel is reached is called the total depth; it is to be distinguished from the useful carburizing depth. Although the total depth may be regarded as the natural limit of carburization, its absolute value is difficult to ascertain, which leads to widely scattered assessment results, and renders it useless as a practical measure for the carburizing depth. Various limits are employed for determining the useful carburizing depth. It is convenient to set the limit at 0.35 % carbon. The useful carburizing depth can then be accordingly defined as the perpendicular distance below the surface of that point within the carburized layer, at which the carbon content has sunk to 0.35 %. This useful carburizing depth does not necessarily coincide with the hardening depth (Eht), which will be dealt with later. The carbon content of 0.35 % employed as criterion yields, for totally martensitic hardening, a hardness of about 55 RC (compare Fig. 1)

The useful carburizing depth is about half the total depth. For most carburizing processes it can be expressed approximately in terms of time: Useful carburizing depth =  $K_T \sqrt{t}$  mm; where  $K_T$  is a constant dependent on the temperature and the material, and  $t$  the carburizing time in hours.  $K_T$  amounts to about 0.275 at 850° C, 0.4 at 900° C and 0.525 at 950° C. These constants serve as working reference points for the CARBO-MAAG<sup>R</sup> process for plain carbon steels and carburizing depths of more than 0.5 mm. For the conventional endogenerator process these constants are about 10 to 15 % lower.

It follows for instance, that the effective carburizing depth at 1740° F (950° C) is almost twice\* at 1560° F (850° C). \*that

### 3.2.1 Pack Carburizing

Carburizing in a solid medium is the oldest process and, in certain cases still in current use. Charcoal and certain kinds of specially treated coke are mainly used. The mechanism of carburizing consists of the initially present oxygen combining with the carbon to form carbon dioxide (CO<sub>2</sub>). This reacts with the excess carbon at higher temperatures to form carbon monoxide: CO<sub>2</sub> + C → 2 CO. The carbon monoxide (CO) then reacts with the steel, delivering carbon atoms to the steel surface: 2 CO → (C) + CO<sub>2</sub>, and the remaining carbon dioxide is regenerated by the carbon to carbon monoxide. It is therefore a gaseous medium to which the carburization can be directly attributed.

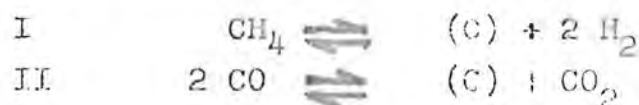
### 3.2.2 Liquid Carburizing (salt bath)

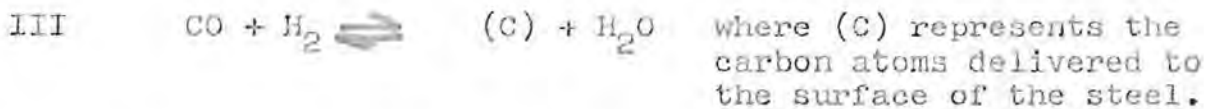
Carburizing baths contain molten salt mixtures, the effective constituent being sodium cyanide (NaCN). This salt melts at 1020° F (550° C) and decomposes at temperatures near 1830° F (1000° C) more or less rapidly, according to the nature of the other additives. The field of practical application is between the above temperatures. Above 1560° F (850° C) the supply of carbon dominates; with higher temperature the carburizing effect increases, whereas below 1300° F (700° C) more nitrogen (N) is released.

Heating of components in salt baths takes place quickly, in contrast to gas carburizing, and in still greater contrast to pack carburizing. Case-hardening baths are therefore of particular advantage when the heating time constitutes an appreciable proportion of the total time of treatment, i.e. for small case depths from 0.004 to 0.032 in. (0.1 up to 0.8 mm). Their use will also depend on the size of the component, being usually reserved for treating small components.

### 3.2.3 Gas Carburizing

In the gas carburizing methods, the carbon can be supplied by carbon monoxide (CO) or methane (CH<sub>4</sub>), in which case the following reactions may take place:





Whereas the reactions I and II take place extremely slowly, the reaction III is rapid, so that it is this latter, above all, which is decisive for gas carburizing, as recent research has revealed.

Gas carburizing methods can be classified into 3 main groups:

- a) generator processes
  - b) drip-feed processes
  - c) processes using solid gasifying compounds
- a) In the generator processes the gases are produced in a suitable gas generator from a town or natural gas supply, or from hydrocarbons such as methane (natural gas) propane, butane, etc., and brought to the carburizing furnace either in the necessary composition or as a carrier gas. In the latter case, a certain amount of a strong carburizing gas is added in the furnace. Such carrier gas processes have the advantage that it is possible to add the more active carburizing medium automatically, by means of dew-point or  $\text{CO}_2$  control apparatus, in such a way that the required carbon potential can be maintained. The carbon potential is defined as the carbon content of a very thin iron strip which is in equilibrium with the respective gas at a given temperature. When large surfaces are to be carburized (requiring large amounts of carburizing medium), the carrier gas process with an automatic control postulates the availability of a very large quantity of carrier gas, with the consequent encumbrance of an over-sized, uneconomic generator whose susceptibility to failure can cause high maintenance expenses. From the economic point of view, therefore, it is normally preferable to select a process not requiring a generator.
- b) In the drip-feed process the carburizing gases are produced in the carburizing furnace itself by thermal cracking of organic compounds, which are preferably liquid under normal conditions, and which are introduced continuously or intermittently. These processes have the advantage of simple and economical equipment and operation. The automatic feeding of the carburizing liquid, which is controlled by the C potential, was based earlier on the hot resistance wire method, because it was never considered possible to adjust the C potential in the drip-feed process on the basis of the  $\text{H}_2\text{O}$  or  $\text{CO}_2$  content. However, a process has been developed by the MAAG company, based on drip-feeding two very easily crackable organic liquids or mixtures of liquids into the furnace simultaneously.
- The one liquid generates a gas which has only a slight or no carburizing effect, and which serves simply to maintain a constant pressure above atmospheric. The other liquid generates the carburizing gas. The liquids are so chosen that the cracking liquid yields the same gas composition as results

from the cracking of the carrier gas liquid alone. Thus, the relative quantities of these two liquids, as far as they are determined by the consumption of the automatically controlled carburizing medium, are therefore irrelevant, which in conventional generator carrier gas processes is not the case. The new process has been applied with great success; its reliability has been proven under extreme conditions where charges having very different surface areas were to be carburized in immediate succession. The automatic control of the supply of carburizing medium compensates continuously for the consumption, which is dependent on the area. The MAAG carburizing process, i.e. the principle of simultaneous use of a pressurizing liquid alongside the carburizing liquid itself (trade-mark CARBO-MAAG<sup>R</sup>), has also been successfully applied to chamber furnaces. Its possibilities of application are numerous, enabling the adjustment of any C potential above 0.4 % in a sure and simple manner. Of all the controllable gas carburizing processes, the CARBO-MAAG<sup>R</sup> process displays the most rapid rate of transfer of carbon from the gas atmosphere to the surface of the steel.

- c) In the granulate process a solid carburizing medium is introduced into the furnace; the oxygen of the air reacts with it to form carbon dioxide at moderately low temperatures and carbon monoxide at higher temperatures. The carbon monoxide carburizes the steel, but only slowly. By way of combination with a drip feed process, an acceleration is achieved, but without form of control.

### 3.3 Particular Aspects of Case-hardening

#### 3.3.1 Case-hardening Steels and their Hardenability

Case-hardening steels are best classified by using hardenability as a criterion in the same manner as direct-hardening steels. There are, however, a greater number of factors to be considered, primarily the hardenability of the carburized case with its carbon content decreasing towards the core, i.e. the case hardenability. Whereas the hardenability of the base composition determines the core strength and presents no further problems, the case hardenability, which requires more searching examination is a deciding factor for the maximum surface hardness and, in combination with the carbon distribution, also for the gradient of the hardness curve in the casehardened layer.

Whilst increasing carbon content generally raises the maximum hardness and hardenability (see Introduction), steels containing a certain amount of manganese or chromium suffer a decrease in hardenability if the carbon in the carburized case exceeds a certain percentage. This is probably caused by the formation of carbides of high manganese and chromium content, which causes Mn- and Cr-depletion of the austenite matrix. Molybdenum and nickel do not possess this adverse property.

A further consideration is the formation of retained austenite at higher carbon contents, which causes a reduction of the maximum hardness (even at high cooling rates) and decreases the re-

sidual compressive stresses. The various alloying elements behave very differently in this respect: chromium, manganese and nickel promote the formation of retained austenite, whereas molybdenum, a very efficient alloying element, has little influence.

These main factors influencing the case hardenability refer to higher carbon contents. The lower the cooling rate at the surface, i.e. the larger the size of the parts quenched in oil or in a martempering bath, the more important is the hardenability at medium carbon contents, for example at 0.35 %, the limit for the useful carburizing depth. This fact is often overlooked, and in the quest for adequate core strength in large gears, it occurs all too frequently that a steel of higher original carbon content is selected, without paying any consideration to case hardenability.

Molybdenum-bearing case-hardening steels are being more and more used recently, a tendency closely connected with the growing trend towards direct quenching from the carburizing temperature.

The core strength of thin components or at corners of components, a problem connected with the machinability of the core material after hardening, is still another aspect of the hardenability of case-hardening steels. It is possible that difficult machining operations still remain to be performed on the non-carburized core of pinions and gears for precision drives after case-hardening. Under such circumstances the core hardness must be no higher than BHN 310. But most standard alloy carburizing steels, after oil or salt bath hardening, reveal hardness values in small cross-sections or at edges of the parts, which at times greatly exceed the permissible, hence preventing subsequent machining. In such cases, the only solution is to resort to a case-hardening steel of very low carbon content (0.11 % maximum) but containing alloying elements which for a given carbon penetration curve, allow a maximum case hardenability even by martempering. For this purpose a steel with the following composition gives very good results: C 0.11 % maximum, Ni 1.75 % Cr 0.45 to 0.65 %, Mo 0.50 to 0.70 %.

Table 3 shows the chemical composition of carburizing steels frequently used, with data on core strength and surface hardness for cylindrical bars of 1, 2 and 10 ins. (25, 50 and 250 mm) diameter. Alongside a hardening temperature above the  $A_c 3$  point (single quenching), water quenching is assumed for the unalloyed steels and oil quenching for alloyed steels. Further details are given in Table 3.

Table 3

Material designation	a) b)	Ck 15 (1015)	8617 8620	20MoCr4 25MoCr4	16MnCr5 20MnCr5	4317 4320	14NiCr14 En36	15CrNi6	10NiCrMo7 15NiCrMo7	18CrNi8	14NiCr18 En 39
<b>Chemical Composition (approximate analysis)</b>											
according to standard		DIN (SAE)	SAE	DIN	DIN 17210	SAE	DIN 1662 BS 970	DIN 17210	SAE	DIN 17210	DIN 1662 BS 970
C	a) b)	0.15	0.17 0.20	0.20 0.25	0.16 0.20	0.17 0.20	0.14	0.15	0.10 0.15	0.18	0.14
Si		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mn		0.40	0.80	0.70	1.2	0.50	0.40	0.50	0.50	0.50	0.40
Cr		—	0.50	0.40	1.0	0.50	0.75	1.5	0.50	2.0	1.1
Mo		—	0.20	0.45	—	0.25	—	—	0.55	—	—
Ni		—	0.55	—	—	1.75	3.5	1.5	1.7	2.0	4.5
<b>Tensile Strength before Machining (before carburizing)</b>											
in 1000 lb/in <sup>2</sup> :											
Annealed	a) b)	max.65 max.70	max.97 max.104	max.101 max.107	max.101 max.107	max.100 max.107	max.107	max.107	max.85 max.107	max.114	max.121
Quenched and tempered	a) b)	— —	85-107 93-114	85-107 93-114	75-101 83-101	85-107 93-114	93-114	93-114	78-100 93-114	100-121	114-128
in kg/mm <sup>2</sup> :											
Annealed	a) b)	max.46 max.49	max.68 max.73	max.71 max.75	max.71 max.75	max.70 max.75	max.75	max.75	max.60 max.75	max.80	max.85
Quenched and tempered	a) b)	— —	60-75 65-80	60-75 65-80	53-71 58-71	60-75 65-80	65-80	65-80	55-70 65-80	70-85	80-90

<b>Mechanical Properties in Case-hardened Condition</b>											
<i>for 1 in. (25 mm) diameter:</i>											
Core strength in 1000 lb/in <sup>2</sup>	a) b)	64-93 78-107	100-135 107-150	114-150 135-185	128-164 142-185	128-164 142-185	135-185	135-192	114-142 135-185	170-206	164-206
Core strength kg/mm <sup>2</sup>	a) b)	45-65 55-75	70-95 75-105	80-105 95-130	90-115 100-130	90-115 100-130	95-130	95-135	80-100 95-130	120-145	115-145
Case hardness in Rockwell C	0.4% C 0.7% C 1.0% C	48-57 58-65 60-68	48-56 63-66 63-66	50-56 63-66 63-66	50-57 62-66 60-64	55-60 64-66 62-64	55-60 60-65 59-64	55-60 60-65 59-64	55-60 64-66 64-66	55-60 59-64 59-63	55-60 59-64 59-63
<i>for 2 ins. (50 mm) diameter:</i>											
Core strength in 1000 lb/in <sup>2</sup>	a) b)	60-85 71-100	88-124 95-135	107-135 121-164	114-142 121-164	114-142 121-164	128-171	128-171	107-135 128-171	164-206	156-200
Core strength kg/mm <sup>2</sup>	a) b)	42-60 50-70	62-87 67-95	75-95 85-115	80-100 85-115	80-100 85-115	90-120	90-120	75-95 90-120	115-145	110-140
Case hardness in Rockwell C	0.4% C 0.7% C 1.0% C	40-52 (50)-64 (52)-66	45-55 63-65 61-64	44-53 63-66 62-65	47-55 62-65 58-63	54-59 64-66 62-64	55-60 60-64 59-63	55-60 60-64 59-64	55-60 64-66 64-66	55-60 59-64 58-62	55-60 59-64 58-62
<i>for 10 ins. (250 mm) diameter:</i>											
Core strength in 1000 lb/in <sup>2</sup>	a) b)	55-78 64-93	71-100 85-114	85-121 100-128	85-107 93-121	93-114 100-128	107-150	107-150	85-114 107-150	142-185	135-178
Core strength kg/mm <sup>2</sup>	a) b)	39-55 45-65	50-70 60-80	60-85 70-90	60-75 65-85	65-80 70-90	75-105	75-105	60-80 75-105	100-130	95-125
Case hardness in Rockwell C	0.4% C 0.7% C 1.0% C	30-50 (40)-62 (47)-64	32-43 58-63 50-58	33-43 60-64 58-63	35-45 59-63 48-58	52-58 63-65 61-63	54-60 59-63 59-63	54-60 59-63 59-63	55-60 63-66 62-65	55-60 59-63 58-62	55-60 59-63 58-62
Quenching in		Water	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil



### 3.3.2 Case Depth: Carbon and Hardness Penetration

For a given carbon penetration curve within the carburized layer, different steels can supply different hardness penetration curves according to the hardenability of the relevant steel at the various levels of carbon content. Hence a given useful carburizing depth, such as was defined does not always correspond with the same effective case depth. Effective case depth is understood as the perpendicular distance below the surface of that point within the carburized layer, at which the hardness has reached the conventional limit of 550 VHN. This rule is the most widespread in Europe, and is already accepted in the standards of many countries, or is due to be adopted as standard in the near future.

Fig. 2 for the evaluation of the end quench test, and hardness distribution curves along end quench test pieces of various carbon contents, allows comparison as to how closely carbon penetration and hardness penetration coincide. Table 3 provides a useful guide with respect to the case hardness for various case carbon contents and for various sizes of workpiece.

For the desired effective case depth of gears, general practice as well as controlled experiment has shown that the following empirical rule holds:

For diametral pitch from 24 to 3 (modules 1 to 8):

$$\text{effective depth: } \frac{0.15}{p} + u_s \text{ (in)} = 0.15 \times m + u_s \text{ (mm)}$$

For diametral pitch below 3 (modules over 8):

$$\text{effective depth: } \frac{0.0885}{\sqrt{p}} + u_s \text{ (in.)} = 0.425 \sqrt{m} + u_s \text{ (mm)}$$

This relation is shown graphically in Fig. 5,  $u_s$  in the grinding allowance per flank, which is dependent on the pitch and the shape of the gear, but which should not exceed the value of  $u_s - 0.016$  in. (0.4 mm), however coarse the pitch.

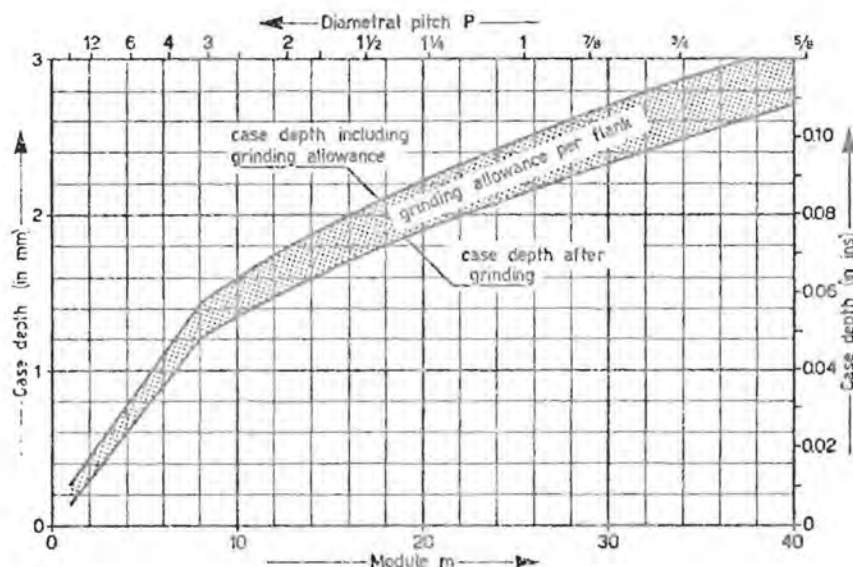


Fig. 5 Depth and grinding allowance as a function of the pitch

In dealing with the dimensional changes which take place due to heat treatment, distinction must be made between avoidable and unavoidable changes. The avoidable dimensional changes are termed distortion. This occurs due to:









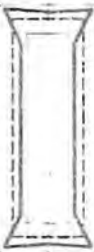
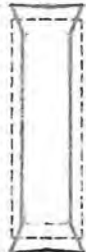
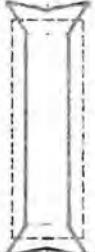





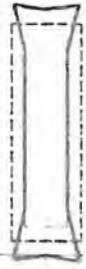

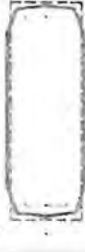


- a) internal stresses which are released during heating up to carburizing or hardening temperature,
- b) warping on account of inadequate heat-up control or poor support of the parts in the furnace,
- c) heterogeneity in the steel, arising from extreme segregation or non-symmetrical solidifying of the ingot.

The unavoidable dimensional changes, which appear in changes of volume and shape, are caused by:

- a) transformation, which causes volume change,
- b) thermal stresses developing during cooling, which give rise to plastic deformation,
- c) transformation and thermal stresses mutually superimposed during cooling, whence dimensional changes can take place ranging from the negative extreme, through zero, to the positive extreme, according to the type of steel, the work-piece size and the treatment.

Degree of dimensional change increases with the severity of action of the cooling medium. Oil quenching therefore causes milder dimensional changes than does water quenching. Still smaller are the dimensional changes incurred in a hot quench bath called marguenching bath, in which salt solution or oil of at least 150° C is employed.

In the case of the unavoidable dimensional changes, it is quite obvious that the time-temperature transformation characteristic of the steel plays a major role in connection with point c). This characteristic is largely governed by the alloy content. Fig. 6 provides a working basis for estimating the susceptibility of variously alloyed steels to dimensional change, with reference to simple bars of 50, 100 and 200 mm diameter. For purpose of comparison, other groups of steels are also represented, in order to show that case-hardening steels belong to those steel types most sensitive to dimensional change. In this figure the dimension changes are given in o/oo (parts in a thousand), and the same starting datum (0) is used for all bar diameters. This datum is indicated by the chain lines, whilst the longitudinal profiles after hardening in oil are drawn with continuous lines. The lines marked +2 and -2 o/oo permit the dimensional changes occurring during hardening to be estimated sufficiently accurately. There are interesting fixed relationships expressed in these dimensional changes, closer study of which,

Abmessung mm	EINSATZSTÄHLE				VERGÜTUNGSSTÄHLE		
	Ck 15	16MnCr5	10NiCrMo7	14NiCr14	Ck 45	42Cr Mo4	42CrNiMo6
∅ 50×250 mm							
∅ 100×500 mm							
∅ 200×1000 mm							

Massänderung in %



Massänderungs - Tendenz bei Oel-  
härtung verschiedener Stähle



however, is beyond the scope of this discourse. Within the case-hardening steel group it is apparent that dimensional change increases greatly with increasing alloy content, or with increasing hardenability. This is even revealed within the same kinds of steel, in that the possible variation in composition from heat to heat has a strong influence on the time-temperature transformation characteristic. Since this also has a decisive influence on the hardness curves of end quench specimens, this testing method is an excellent means of predicting the probable dimensional change characteristics of a given heat of

steel: Components of case-hardening steels grow during quenching in the direction coinciding with their maximum expansion; that is - long pinions in the axial direction, large gears or gear rims in the tangential or radial direction. The greater the hardenability, the more pronounced the growth. Accordingly their dimensions diminish in the direction at right angles. Too pronounced a shrinkage of the gearing of a long pinion can be prevented by way of an axial bore. Such hollow pinions behave partly as a ring, giving precedence to growth in the tangential or radial direction, and partly as a shaft, thereby affording a certain amount of compensation.

With regard to dimensional change, then, lean alloy case-hardening steels behave favourably. For large pinions and gears, however, this fact cannot be fully exploited, due to inadequate hardenability of the case. A low hardenability of steels for large gears and pinions - and hence acceptable dimensional change characteristics - should not, therefore, be sought in leanness of alloying elements, but in low carbon content. The alloy content must be high enough to permit the achieving of a good case hardenability, even with a carburized layer of medium carbon content. The steel 10NiCrMo7 is one such case-hardening steel with which good results have been obtained.

#### 3.3.4 Carburizing Allowance and Grinding Allowance

If the carburized layer has to be partially removed from a gear after carburizing, in order to permit further machining operations after hardening, a carburizing allowance must be provided. This depends of course on the case depth. Since even a small increase in carbon content of the core material considerably increases the tensile strength in the hardened condition, the carburizing allowance must be so chosen that the carburized layer is completely removed even if the depth reaches its permissible maximum. Since the total carbon penetration depth is roughly twice as deep as the useful carburizing depth, it is advisable to provide for a carburizing allowance three times the prescribed case depth.

An empirical rule for the grinding allowance us is:

$$\begin{aligned} \text{Grinding allowance us} &= 0.0043 + \frac{0.015}{p} \quad (\text{in.}) \\ &= 0.11 + 0.015 \times m \quad (\text{mm}) \\ &\quad \text{for diametral pitch } p \text{ from } 2.5 \text{ on or} \\ &\quad \text{module } m < 10 \\ &= 0.008 + \frac{0.006}{p} \quad (\text{in.}) \\ &= 0.20 + 0.006 \times m \quad (\text{mm}) \\ &\quad \text{for diametral pitch } p \text{ below } 2.5 \text{ or} \\ &\quad \text{module } m > 10 \end{aligned}$$

Wheel discs for which a more or less marked increase of diameter is expected during hardening, according to the steel or cast of steel used (and with reference to the hardenability), may be allotted a smaller us than solid shaft pinions, which are more liable to shrink.

### 3.4 Induction and Flame Hardening

#### 3.4.1 Steels for Induction and Flame Hardening

Parts which have to be hardened only partially by quenching after local heating must be made of a steel, as mentioned, which already contains the carbon necessary to achieve a high hardness. According to Fig. 1 in order to attain a Rockwell C hardness of at least 50, a carbon content of 0.30 % is required; Rockwell C 55 calls for 0.36 % C, and RC 60 for at least 0.45 % C. Fig. 1 is, however, valid only for normal heating up to hardening temperature. For quick heating (such as occurs in induction hardening), hardness values 1 to 2 RC units higher are usually attained.

In principle, all direct-hardening steels as listed in Table 1 are suited for induction hardening. The quenching method to be chosen depends on the hardenability and therefore on the carbon and alloy content. Today organic additives are available by which the quenching effect of water can be adapted to the steel in question. The quick heating and cooling imposes considerable stress on the material, and therefore care should be taken that clean steels (at least corresponding to b or better to f or g in Table 1 a and b).

The core properties of induction and flame hardened steels are dependent on the cross-section. Selection of a steel will depend therefore on the desired core properties and surface hardness. The highest permissible core strength is limited on the one hand by factors already discussed under "Direct-hardening Steels", and on the other hand by the temperature of the Ac 1 point (lower critical point). The higher the required core strength, the lower must be the Ac 1 point of the steel, i. e. the higher must be the content of alloy elements (such as nickel), which lower the Ac 1 point. The direct-hardening steels contained in Table 1 give (partly because of a relatively modest carbon content) insufficient hardness values when surface




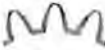
-hardened. It is nevertheless possible to select steels from these tables and to prescribe a carbon content adequate for the desired surface hardness. Attention must also be drawn to the fact that by heat treating after rough cutting the teeth, a steel from a lower materials group may be used than indicated in Table 2.

### 3.4.2 Applications of Induction and Flame Hardening

In induction hardening, heating is restricted to the area to be hardened, being effected by high or medium frequency currents induced in a thin surface layer by means of coils of suitable shape. The effective depth of penetration of the induced currents is inversely proportional to the square root of the frequency. This already implies a differentiation between high frequency (over 50 kc/s) and medium frequency (from line frequency up to 10 kc/s) induction hardening: medium frequency should be applied for relatively deep hardening layers and high frequency for small hardening depths, the boundary lying between about 0.04 and 0.06 in. (1 and 1.5 mm heating depth).

In the case of flame hardening the surface is heated by a flame generated from town gas or with oxy-acetylene equipment. Heat penetration to desired depth takes place purely by thermal conduction. From this point of view flame hardening would compare with induction hardening at infinitely high frequency, but of limited heating power. There are important differences, however, in the adaptability of the heating element to the shape of the surface, partly to the advantage and partly to the disadvantage of flame heating: induction heating permits a close following of the tooth contour (also with small pitches) by adapting the shape of the intensifier and by correct choice of frequency; the adaptability of a flame is insufficient for this purpose. On the other hand, flame heating offers certain other advantages, particularly in the case of spin heating.

Induction and flame hardening processes are subdivided as shown in Table 4. This chart indicates the main features of the various processes.

Process and hardened area	Effect and application	Induction hardening by		Flame hardening Diameter and diametral pitch $P$ (module $m$ )
		high frequency Diameter and diametral pitch $P$ (module $m$ )	medium frequency Diameter and diametral pitch $P$ (module $m$ )	
Spin hardening exclusive of tooth root 	Increase of wear resistance of tooth flanks. Bending fatigue strength not influenced. Permissible bending stress not higher than for normally quenched and tempered parts of the same steel.	Diameter according to generator power; width of gear $\frac{1}{2}$ in. to 4 ins. (10 to 100 mm); $P \geq 8$ ( $m \leq 3$ )	Diameter according to generator power; width of gear $1\frac{1}{2}$ in. to 6 ins. (35 to 150 mm); in certain cases up to 16 ins. (400 mm); $P \geq 5$ ( $m \leq 5$ )	Diameter generally up to 18 ins. (450 mm); with special machines $P \geq 4$ ( $m \leq 6$ ) in special cases $P \geq 2$ ( $m \leq 12$ )
Spin hardening including tooth root 	Increase of wear resistance of tooth flanks and of bending fatigue strength in the tooth root. Permissible bending stress 30 to 50% higher than if normally quenched and tempered. Partly replaces case-hardened gears.	Diameter according to generator power; width of gear $\frac{1}{2}$ in. to 4 ins. (10 to 100 mm); $P \geq 5$ ( $m \leq 5$ )	Diameter according to generator power; width of gear $1\frac{1}{2}$ in. to 4 ins. (35 to 150 mm); in certain cases up to 16 in. (400 mm); $P \geq 5$ ( $m \leq 5$ )	Diameter up to 18 ins. (450 mm); $P \geq 4$ ( $m \leq 6$ ) in special cases $P \geq 2\frac{1}{2}$ ( $m \leq 10$ )
Progressive hardening of both flanks 	Increase of wear resistance of tooth flanks. Bending fatigue strength not influenced. Permissible bending stress not higher than for normally quenched and tempered parts of the same steel.	Diameter unlimited $P \leq 12$ ( $m \geq 2$ )	Diameter unlimited $P \leq 5$ ( $m \geq 5$ )	Diameter unlimited $P \leq 4$ ( $m \geq 6$ )
Progressive tooth root hardening 	Increase of wear resistance of tooth flanks and of bending fatigue strength in the tooth root. Permissible bending stress 30 to 50% higher than if normally quenched and tempered. Partly replaces case-hardened gears.	Diameter unlimited $P \leq 12$ ( $m \geq 2$ )	Diameter unlimited $P = 5$ to $7\frac{1}{2}$ ( $m = 5$ to 30)	Diameter unlimited $P \leq 2\frac{1}{2}$ ( $m \geq 10$ )

3.5.1 General

Nitriding of steel consists of the introduction of nitrogen into the surface via a gas phase (usually ammonia) or by molten salt bath, which contains nitrogen compounds such as cyanide and cyanate. Nitrogen diffuses into the steel and causes precipitation of nitrides in the outer layer, due to the limited solubility of nitrogen in steel. Hardness is thereby increased, depending on the alloying composition of the steel. Pure iron or steels without alloy show no appreciable increase of hardness, although a "white layer" of nitride and a diffusion zone are formed. The relatively low nitriding temperature of 930 to 1080° F (500 to 580° C) has the advantage that distortion is extremely slight. Besides increasing the hardness, nitriding also causes a considerable improvement of fatigue strength.

3.5.2 Nitriding Steels

Since nitriding is applied principally to increase the surface hardness for the purpose of minimizing wear, special steels - nitriding steels - have been developed which contain elements enabling the highest possible surface hardness to be obtained. Aluminium is the most important of the elements in common use. Conventional nitriding steels contain about 0.5 to 1.2 % Al. Aluminium has a very pronounced tendency to form nitrides, yielding hardness values of 900 to 1200 VHN. Other powerful nitride forming elements are chromium, molybdenum and vanadium; but they do not produce such a high surface hardness as aluminium. Chromium and molybdenum in particular, besides having a tendency towards nitride formation, are characterized by markedly improving hardenability, by which the core properties and the conditions for the formation of a sound nitrided layer can be very favourably influenced.

Nitriding steels are introduced into the nitriding medium in the quenched and tempered condition. If the preliminary heat treatment is performed after premachining, a finishing allowance of at least 0.08 to 0.12 in. (2 to 3 mm) has to be provided, in order that no trace of decarburization is detectable on the surface after finishing-machining. Decarburized or partly decarburized surfaces cause very brittle nitrided layers. The common nitriding steels are listed in Table 5. The aluminium - free steels included are used in particular when, in later operation, the nitride layer is to be subjected to impact loading under locally high surface pressures, since the disadvantage of limited surface hardness is outweighed by the advantage of higher surface toughness. Apart from these nitriding steels proper, a number of Cr-alloy and Mo-alloy direct-hardening steels, as per Tables 1 a and 1 b are also used for gears; for example DIN 42CrMo4, 34CrNiMo6, SAE 4140, 4340 etc.



Table 5 Guide for Nitriding Steels

Designation of Steel			USA	Alloy Content						Tensile strength kg/mm <sup>2</sup>	Yield point min. kg/mm <sup>2</sup>	Nitrid hardne HV min.	
D	F	GB		C	Al	Cr	Mo	V	Ni				φ mm
DIN	AFNOR	BS970											
34 CrAMo5			Nitralloy G	0.30- 0.37	0.8- 1.2	1.0- 1.3	0.15- 0.25			60	80- 100	60	950
	30CAD6 12	(En41A)		0.28 0.35	1.0- 1.3	1.5- 1.8	0.25- 0.40			60- 120	85- 105	65	950
41CrAlMo7	40CAD6 12	(En41B)	Nitralloy 135 mod AMS 6470 SAE 7140	0.38- 0.45	0.80- 1.2	1.5- 1.8	0.25- 0.40			100	95- 110	75	950
									100- 160	85- 105	65		
34CrAlNi7				0.30- 0.37	0.8- 1.2	1.5- 1.8	0.15- 0.25		0.85- 1.15	70- 250	80- 100	60	950
31CrMoV9				0.26- 0.34	-	2.3- 2.7	0.15- 0.25	0.1- 0.2		40	110- 130	90	750
									40- 100	100- 120	80		
									100- 160	90- 110	70		
									160 250	80- 95	60		
32CrMo12	30CD12	(En40B)		0.28-	-	2.8-	0.3-			100	110- 130	90	800
									100- 160	100- 120	80		
									160- 250	90- 110	70		
39CrMoV13				0.35- 0.42	-	3- 3.5	0.8- 1.1	0.15- 0.25		70	130	110	800

### 3.5.3 Nitriding Processes

The conventional nitriding process with ammonia was previously applied almost exclusively to special nitriding steels, while bath cyaniding (nitriding in molten salt) was used also for other steel types, in particular for the nitriding of tools and small components subject to wear. It has since been recognized that reduced frictional wear cannot alone be attributed to high hardness, but that nitrided steel surfaces, even without appreciable hardness increase, are more wear resistant than harder layers not containing nitrogen. Latter years have therefore seen an increased application of nitriding to unalloyed steels or steels containing only a small amount of chromium or molybdenum. The hardness of such steels (initial hardness 150 to 300 VHN) is increased only to 300 to 500 VHN; their resistance to frictional wear is nevertheless vastly improved. Furthermore, in spite of the modest increase in hardness, the fatigue strength is also considerably increased. The nitriding of aluminium-free, unalloyed or low alloy steels - whether case-hardening or direct-hardening steels - is also known as "tufftriding" (Tenifer-process, trade name).

As already mentioned, it has been carried out mostly in molten salt baths at temperatures of 1020 to 1080°F (550 to 580°C). Experience has shown, however, that nitriding of such steels in ammonia - especially with certain additives - at the same elevated temperatures, has a similar effect as a salt bath.

In France, a similar salt bath process has been developed, in which sulphide is additionally formed in the outermost surface

layer. It is called the sulfinuz process. The purpose of forming an outermost layer of high sulphur content is primarily to improve the running-in properties; the remaining effects are the same as in "tufftriding". The duration of these salt bath treatments are usually limited to 2 to 3 hours. Since somewhat higher temperatures are used than in conventional nitriding, and since the steels used for these treatments are void of, or contain only small quantities of nitride forming elements, the growth of the case is accelerated.

Fig. 7 and 8 compare the nitriding rates for aluminium-bearing, nitriding steel at 930° F (500° C) in ammonia with tufftrided, unalloyed and low alloy aluminium-free steels. In tufftriding and sulfinuzing, a white layer of high wear resistance is formed on the surface. Grinding should therefore be avoided after these treatments; the parts should be stress relieved before final machining, to prevent distortion during the nitriding process. Large gears are not suited to tufftriding or to the sulphinuz process. However, gears which have undergone the conventional nitriding treatment, where the outermost layer does not have the same beneficial effect on sliding as in tufftrided parts, can very well be ground.

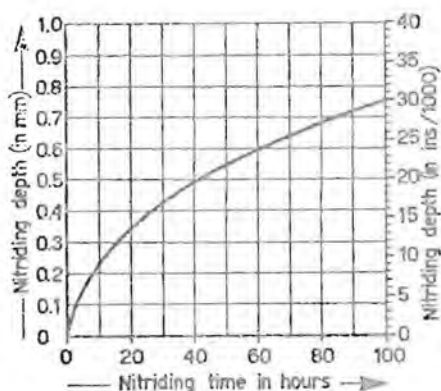
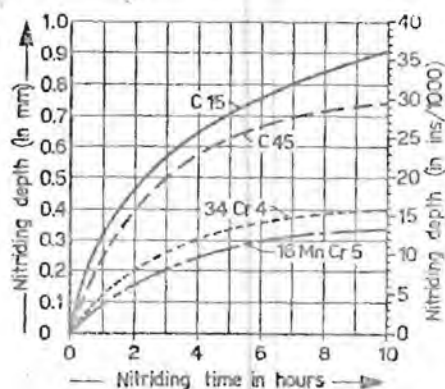


Fig. 7 Nitriding depth vs. nitriding time for aluminium-bearing nitriding steel at 930° F (500° C) (as given by Krupp).

Fig. 8 Nitriding depth vs. nitriding time at 1050° F (570° C) during tufftriding (as given by Finnern) (26)



The application of the different surface treatments, especially for large gears, are guided by two aspects:

- a) Loading and strength of the teeth
- b) Size and shape of the gears
- c) Equipment available

Recommendations are summarized in Table 6; hardening of the tooth root is assumed.

The final choice of treatment will naturally also be influenced by the equipment available:

- a) For highest tooth strength requirements, case-hardening (carburizing and quenching) is the surest method of increasing the wear resistance of the tooth flanks, and at the same time of improving the bending fatigue strength. Case-hardening is limited by its tendency to cause dimensional change and distortion during hardening, and therefore warrants a second assessment from the size and shape aspect. Nitriding has, without doubt, the same characteristics with regard to strength, but its application is limited due to the thinness of the hard case. Induction and flame hardening improve the wear resistance notably and, if carried out correctly, also increase the bending fatigue strength of the teeth.
- b) Susceptibility to dimensional change in case-hardening is to a great extent dependent on the shape and size of the gears. The greater the diameter and the narrower the gears, the more prone they are to distortion. But if the necessary hardening equipment is available, wheel rims up to a diameter of 2 - 3 m could be carburized and hardened.

Shaft pinions usually distort less and are typical of parts to be carburized. Case-hardening should be confined as far as possible to the field shown in Chart 6 i.e., gears above 48 ins. (1200 mm) in diameter should only be case-hardened.\* Surface-hardening by nitriding should be applied for parts particularly liable to distort, e.g. for narrow gear discs and gear rims up to relatively large diameters. Due to the small depth of the hardened case, it is not advisable to use nitriding for too coarse pitches.\* if appropriate equipment is available

Induction hardening (HF and MF) can be used even for very large diameters and pitches. Flame hardening can be used for the same range of diameters as medium frequency hardening, for diametral pitches below 2 1/2 (above module 10).