Selection of Material and Compatible Heat Treatments for Gearing

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Introduction

The manufacturing process to produce a gear essentially consists of; material selection, blank preshaping, tooth shaping, heat treatment, and final shaping. Only by carefully integrating of the various operations into a complete manufacturing system can an optimum gear be obtained. The final application of the gear will determine what strength characteristics will be required which subsequently determine the material and heat treatments. The following discussion will encompass the various heat treating procedures and will establish some basic guidelines for selection of the proper materials and process.

In general, the most common material used in gear manufacturing is steel. This type of gearing usually carries appreciable loads and the majority requires some type of subsequent heat treatment. Gears that are moderately loaded or where size and weight are of little consideration can be made of high quality cast iron. Gearing for special applications such as; corrosion resistance, electrical or magnetic properties, etc. will use a stainless steel, brass, bronze, plastic or phenolic materials.

Therefore, since the largest percentage of gears are made of steel, it seems applicable to concentrate this discussion on the selection of ferrous heat treatments and its application to gears.

The exploration of some definitions of heat treating processes from the fundamental and practical viewpoints will be expanded upon. Fundamentally, the phenomonen of heat treatment is the application of a controlled heating and cooling cycle to alter the material's physical properties to a desired characteristic. The material may be altered into a very soft, ductile state or on the other hand to a very hard, wear-resistance condition.

Selection Criteria

The choice of a proper material for a specific gear application is a very complex selection. The considerations of chemical composition, mechanical properties, processing attributes, and cost must all be included to make a final determination of the type of material to be used. To aid in this decision making process the final desired strength characteristics should be examined. Table I summarizes types of materials, various heat treatments, hardnesses rendered, and endurance limits as related to gear bending and contact stresses. As can be seen, case hardening heat treatments (carburizing, nitriding, or carbo-nitriding) render relatively high contract stresses and yield excellent bending strengths. This can be expanded upon if the geometry of a gear tooth is examined. Case hardening processes depend upon diffusion and therefore, where the high load bearing area or at the pitchline, the diffusion will go straight in. However, in the root area the diffusion will be outward and will result in somewhat less case than the pitchline thus increasing its bending capacity. It should be noted that the top of the tooth will have the heaviest case because the diffusion is inward.

In reviewing Table I, the harden and tempered materials, depending on the treatment, contact stresses in the range 95000 psi to 190000 psi and bending stresses of 13500 psi to 25000 psi, respectively can be obtained. It should be noted that the category of flame or induction hardening assumes the root area is not hardened for calculation and illustration purposes. However, in fact, these processes are selective hardening procedures and any desired hardness pattern can be achieved.

As pointed out earlier, there are many gears made of case iron, and heat treated to respected properties. In Table II the various types of cast irons, preliminary treatments, respected hardness ranges, types of applications, and secondary heat treatments are outlined. The important fact to remember is that the final hardnesses obtained are dependent on preliminary heat treatments and actual chemistries and resultant as-cast microstructures.

To further expand the selection criteria, it is important to have a perspective of what each type of treatment outlined in Table I costs. Because each gear design will require some type of special handling, and the fact of volume of produc-

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TABLE I

Steels, Heat Treatment, Endurance Limits

MATERIALS			MINIMUM HARDNESS		ENDURANCE LIM.	
TYPE	AISI CODE	HEAT TREATMENT	BHN	Rc	BEND psi.	CONTACT psi.
low—carbon steel .30%	10— 45— 11— 46— 15— 48— 25— 50— 33— 61— 41— 86— 43— 87— 44— 93—	carburized	614	60	30000	250000
			547	55	27500	200000
mild-carbon steel .3% .6%	11— 10— 41— 87— 43— 92— 46— 98— 61—	flame induction harden (unharden root fillet)	484	50	13500	190000
mild-carbon steel .3% .6%	(see above)	harden and temper	440	45	25000	190000
			300	33	19000	135000
			180	(8)	13500	95000
mild-carbon steel	41— 43— 46—	nitrided (300BHN core)	614	60	22000	160000
spec. nitride steel	64— nitralloy 125, 135, N, EZ	nitrided (250BHN core)	484	50	20500	130000
stain-less steel	200 300 (malcolmize) 400					
low-carbon steel	(carburizing grades)	carbo-nitride	614	60	26200	190000

tion will determine greatly on the actual cost, a rating system for basic cost understanding seems appropriate.

Table III, below, takes the five processes and rates each on a scale of 1 to 5, where 1 is less expensive and 5 is the most expensive.

It should be noted, Table III assumes that the processes class I-IV are a batch-type process and class V processes are labor intensive for low volume production.

To aid in the understanding of specific details of the various processes mentioned, the appendix includes a glossary of metallurgical terms and a summary of the series designations of the type of steels mentioned.

Hardening and Tempering

Gears made of steel can be hardened by the simple expedient of heating to above the critical temperature (Ac_3 transformation) holding long enough to insure the attainment of uniform temperature and solution of carbon in the austenite, and then cooling rapidly (quenching). Complete hardening depends on cooling so rapidly that the austenite, which otherwise would decompose on slow cooling, is maintained to relatively low temperatures. When this is accomplished, the austenite transforms to martensite on cooling through the Ms-Mf range. Rapid cooling is necessary only to the extent of lowering the temperature of the steel to well below any upper critical transformation points. Once this has been accomplished, slow cooling from then on can be employed to aid in avoiding excessive distortion or cracking. As quenched, the steel in a martensitic state is quite brittle and is rarely used without subsequent tempering. Tempering is the process of reheating hardened (martensitic) steels to some temperature below the lower critical. The tempering temperature depends upon the desired properties and the purpose for which the gear is to be used. If considerable hardness is necessary, the tempering temperature should be low;

TABLE II

CAST IRONS & RESPECTED HEAT TREATMENTS

TYPE	CLASS OR GRADE	HEAT TREATMENT	Hdn. (BHN)	APPLICATIONS	*SELECTIVE HEAT TREATMENT	Hdn. ( )
Malleable Iron	M3210 M4504 M5003	Air quench Temper	156 241	Transmission gears, Crank-shaft sections	Nitride Flame Induction	50 ↕ 60
	M5503 M7003 M8501	Liquid quench temper	187 302	High Strength wear resist Gears	Flame Induction	50 ↕ 60
Gray & White Iron	30 meehanite 40 Gunite 50 Ermalite 60 Ferro-steel Guniron	Normalized	Tube determined by strength Properties	Medium gear blanks - Large gear blanks	Flame Induction	50 ↕ 60
Duccile (Nodular) Iron DQ & T	80-55-06 120-90-02 D-7003 Quench &	Normalized Quench & Temper Normalized Specified Temper	As per TS Ys As per Ts Ys 241/302 Range	Gears, Pinions	Flame Induction	50 ↕ 60

* The surface hardness results obtained in selective hardening are dependent on preliminary heat treatments and actual chemistries of the castings.

if considerable toughness is required, the tempering temperature should be high.

TABLE III
PROCESS AND COST CLASS

Cost Class	Process
I	Harden & Temper (preliminary treatments included)
II	Carburizing
III	Carbo-nitriding
IV	Nitriding
V	Selective Hardening (Flame, Induction, Electron Beam, Laser)

The maximum hardness that can be obtained in completely hardened low alloy and plain carbon structural steels depends primarily on the carbon content. The relationship of maximum hardness to carbon content is shown in Fig. 1. As can be seen, the limitations of this process will restrict the final combination of physical properties that can be achieved (See Table I for steel designations and respective properties). Normally the hardening and tempering procedures are limited to steels with greater than .35% carbon contents for gearing applications.

Case-Hardening

Case hardening is a process of hardening a ferrous alloy so that the surface layer or case is made substantially harder than the interior or core. The chemical composition of the surface layer is altered during the treatment by the addition of carbon, nitrogen, or both. The case depths obtained can be designated in two distinctive ways; (1) Total Case Depth is the approximate total depth of carbon or nitrogen penetration, (2) Effective Case Depth relates to depth below the surface at which a specified hardness, or carbon, or nitrogen

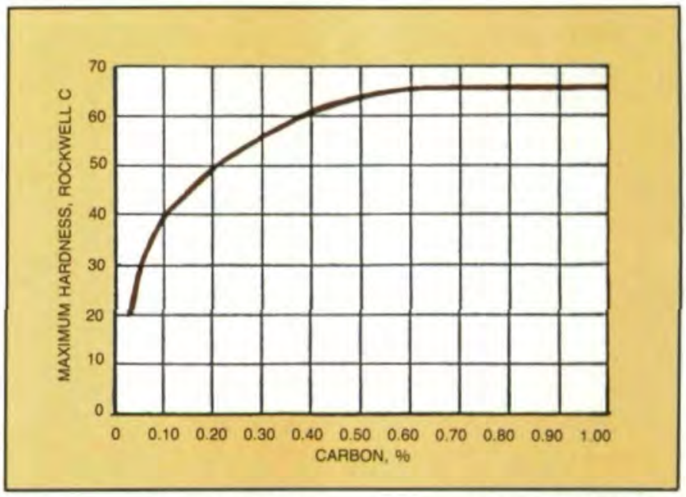


Fig. 1 – Burn, Moore, & Archer, Trans Am. Soc. Metal 3-26, 14 (1938)

content occurs (generally a specified effective hardness is 50 Rockwell "C").

a) Carburizing –

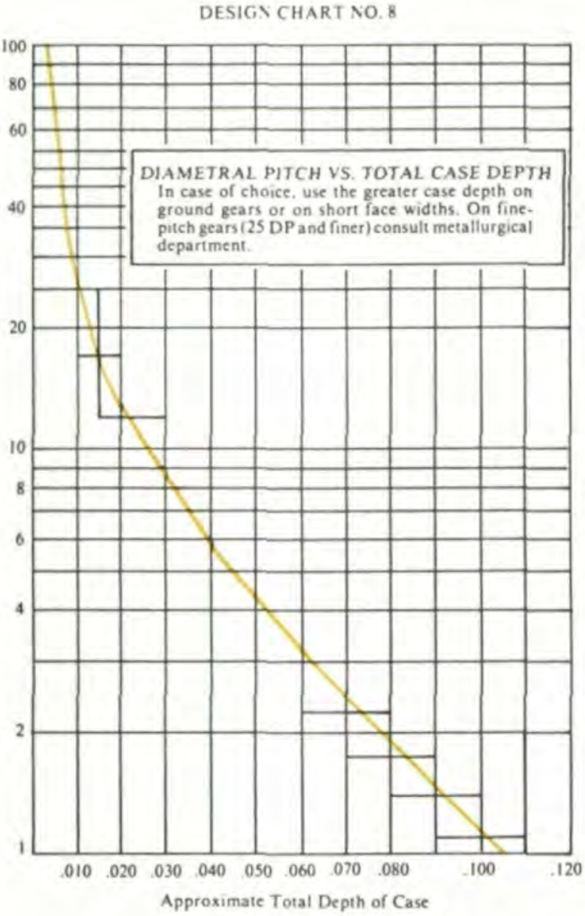
Carburizing is a process that introduces carbon into a solid ferrous alloy by heating the metal in contact with a carbonaceous atmosphere to a temperature above the Ac of the steel and holding at that temperature. The depth of penetration of carbon is dependent on temperature, time at temperature, and the composition of the carburizing agent. The operating temperatures range from 1500°F to 1800°F, and the time of the cycle range from minimum of 1 hour to 30 hours to develop .010" to .120" of total case depth. The actual cycle will depend on the parts characteristics and type of furnace equipment used. After carburizing, the steel will have a high carbon case (greater than .80% but less than 1.10%) graduating into the low-carbon core.

The graphs 1, 2, and 3 can be used for design aids when specifying a case depth for a specific gear. Note that Graph 1 references bevel gear diametral pitch versus total case depth to achieve overall strength characteristics. Whereas, Graphs 2 & 3 are more general for all types of gearing (both parallel *axis and bevel) referencing the effective case depth to* minimize case crushing and pitting.

A variety of heat treatments may be used subsequent to carburizing, but all of them involve quenching the gear to harden the carburized surface layer. The most simple treatment consists of quenching steel directly from the carburizing cycle; this treatment hardens both the case and core. Another simple treatment, and perhaps the one most frequently used, consists of slow cooling from the carburizing cycle, reheating to above the Ac_3 of the case and quenching; this treatment hardens the case only. A more complex treatment is to double quench first from above Ac_3 of the core and then from above the Ac_3 of case; this treatment refines the core and hardens the case. The plain carbon steels are almost always quenched in water or brine; the alloy steels are usually quenched in oil or equivalent synethic solutions. Although tempering, following hardening of carburized steel is sometimes omitted; a low-temperature tempering treatment at about 300°F is a good practice. Also is the dimensional stability, or a sub-zero exposure application is required, a cyrogenic cycle of 150°F should be implemented to assure full austenitic transformation, and a low temperature temper should follow.

Because of the complex design of gear, it may be desirable to carburize only certain areas. This can be accomplished by covering the surface with a media that prevents the passage of carburizing agent. This can be effectively done by copper

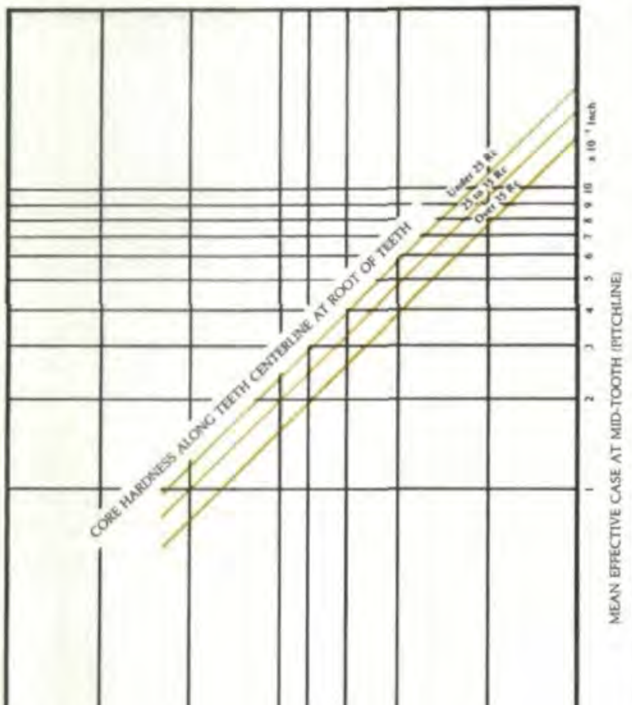
GRAPH 1



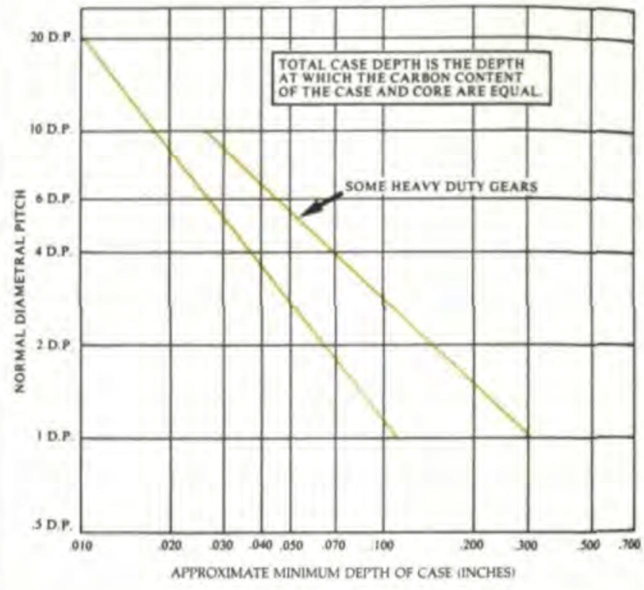
Diametral Pitch vs. Total Case Depth

*Data supplied by Gleason Works, Rochester, NY

GRAPH 2



GRAPH 3



plating, or there are several proprietary solutions or pastes that can cover the area to remain soft after carburizing and hardening. It is also possible to design the part with a false section thicker than the case depth and have it machined off before hardening, to guarantee an area to be soft. Table III summarizes the various carburizing grades of steels and their respected processing cycles.

b) Nitriding –

The nitriding process consists of the subjecting machined and preheat treated steel gears (core properties), to the action of a nitrogenous medium, usually ammonia gas, at a temperature of about 950°F to 1050°F to form a very hard surface. The surface-hardening effect is due to the absorption of nitrogen and subsequent heat treatment of the steel is unnecessary. The time required is relatively long, normally being one to two days. The case (total), even after two days of nitriding, is generally less than .020 inch and the highest hardness exists in surface layers to a depth of only a few thousandths of an inch.

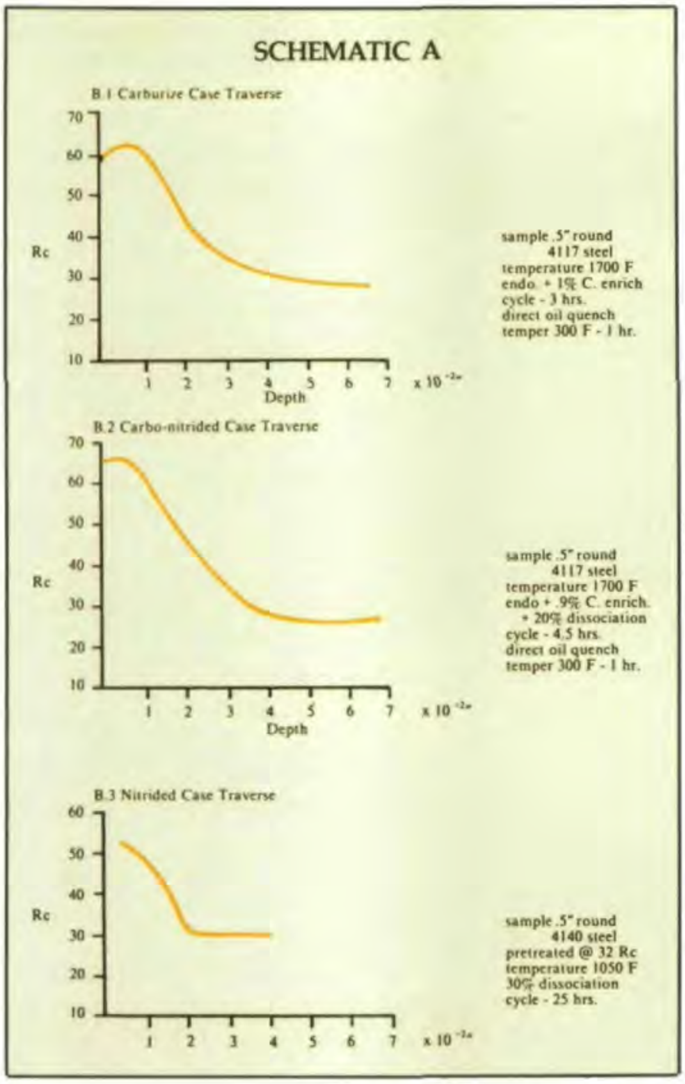
Special low-alloy steels have been developed for nitriding. (See Table I) These steels contain elements that readily combine with nitrogen to form nitrides, the most favorable being aluminum, chromium, and vanadium. The carbon contents are usually between .20% to .50%, although in some instances higher carbon contents are used where higher core hardness are required. Stainless Steels also can be nitrided. Because nitriding is carried out at a relatively low temperature, it is advantageous to use hardened, quenched and tempered steel as the vase material. Note, the steel should be tempered at a temperature higher than the nitriding temperature to assure no alteration of the established core properties. The resultant nitrided gear will have a strong, tough core with an intensely hard wear resisting case, usually much harder than what can be obtained by quench hardening carburize gears.

As in carburizing, selected areas can be stopped off to nitriding by tin, copper, bronze plating, or by the application of certain proprietary paints.

c) Carbonitriding –

Carbonitriding, also termed gas cyaniding, dry cyaniding, and nitrocarburizing is a process for case hardening a gear in a gas-carburizing atmosphere that contains ammonia in controlled percentages. A hard, superficial case can be obtained with introduction of nitrogen and carbon into the surface layers of the steel. The process is carried on above the Ac_1 temperature of the steel, and is practical up to 1700°F. The maximum case depth is rarely more than about .030 inch and the average depth is considerably less. Quenching in oil is sufficiently fast to attain maximum surface hardness; this moderate rate of cooling tend to minimize distortion. The process is applicable for plain carbon steels when higher hardness and distortion control is desirable. Also, for applications where the case is expected to highly abrasive wear conditions.

The same stop off procedures for selective carburizing or nitriding are applicable. In Schematic A, the graphs show the effect of carburizing, carbonitriding and nitriding of an 41xx series alloy steel and the comparable hardness gradients obtained.


SCHEMATIC A

B.1 Carburize Case Traverse

sample .5" round
4117 steel
temperature 1700 F
endo. + 1% C. enrich
cycle - 3 hrs.
direct oil quench
temper 300 F - 1 hr.

B.2 Carbo-nitrided Case Traverse

sample .5" round
4117 steel
temperature 1700 F
endo + .9% C. enrich.
+ 20% dissociation
cycle - 4.5 hrs.
direct oil quench
temper 300 F - 1 hr.

B.3 Nitrided Case Traverse

sample .5" round
4140 steel
pretreated @ 32 Rc
temperature 1050 F
30% dissociation
cycle - 25 hrs.

d) Case Hardening Distortions –

Distortion is always a problem in all heat treating processes, and its reduction or elimination is a very important factor in the manufacture of precision gears. There are two types of distortions which occur in gears. One is body distortion, which for gears is gauged in terms of out of round, out of flat, or runout. The second is the change of tooth slope or contact pattern.

In carburizing the distortion is the greatest because of the high volumetric changes that occur and severity of the quenching media used. Part fixturing in the heating cycle, quenching media cooling rate control, and controlled reheating and quenching can be implemented to aid in control distortions. Another alternative is mechanical die quenching to round up and flatten the hot plastic gear. The change in tooth shape is minimized by control of the variables which cause these changes. These variables are grain directionally, pre-treatments prior to carburizing materials hardenability, case depth and carbon control. If all of these variables are closing controlled, uniform results can be obtained and minor manufacturing changes can compensate for what distortion that does occur.

Because nitriding is a relatively low temperature process and warpage is not a problem. However, the surface of the steel will increase slightly in size during this treatment. Allowance can be made for the growth in the finished gear.

In carbonitriding the distortions are less than carburizing because of the relatively somewhat less case depth and severity of the quench for equivalent hardnesses.

Selective Surface Hardening

It is frequently desirable to harden only the surface of ferrous alloys without altering the chemical composition of the surface layers. If a steel has sufficient carbon to respond to hardening, it is possible to harden the surface layers only by very rapid heating for a short period, thus conditioning the surface for hardening by quenching. The desirable characteristic is that the only distortion that is contended with, is within the hardened area. Any type of hardenable steel can be selectively surface hardened. For best results, the carbon content should be at least 0.35%, the usual range being 0.40% to 0.60%. Cast Irons also can be surface hardening. (See Tables I and II) Since selective surface hardening has no effect on the core, it is absolutely essential that required core strength be established and a desirable microstructure that will respond in the short time duration be obtained.

a) Induction Hardening –

In induction hardening, a high-frequency current is passed through a coil surrounding the gear, the mechanism of electromagnetic induction is used for heating the surface. The depth to which the heated zone extends depends on the frequency of the current, and on the duration of the heating cycle. The proper heating cycle is surprisingly brief, usually a matter of a few seconds or minutes. The selective hardness pattern is accomplished by suitable design of the coils or inductor blocks. The gear is immediately quenched either by inline spray systems, or submerged tanks. Precise methods for controlling the operation, that is, rate of energy input, duration of heating, and rate of cooling, are necessary. The macrograph, in Fig. 2, illustrates the hardening pattern of a fine pitch gear.

Induction hardening equipment usually incorporates all of the above controls into an automatic operation. That is why the process lends itself economically to high volume work instead of small piece lots.

b) Flame Hardening –

Gears in larger sizes are usually flame hardened. Flame hardening is a process of using gas flames to impinge directly on the selected surface and heat to a suitable temperature before direct quenching. The rate of heating is very rapid, although not as fast as induction hardening. The flame hardening of gears will require some special fixtures or equipment to hold the burners in the proper location and the control of the heat pattern may be somewhat variable. This process is labor intensive and is not practical for high volume production.

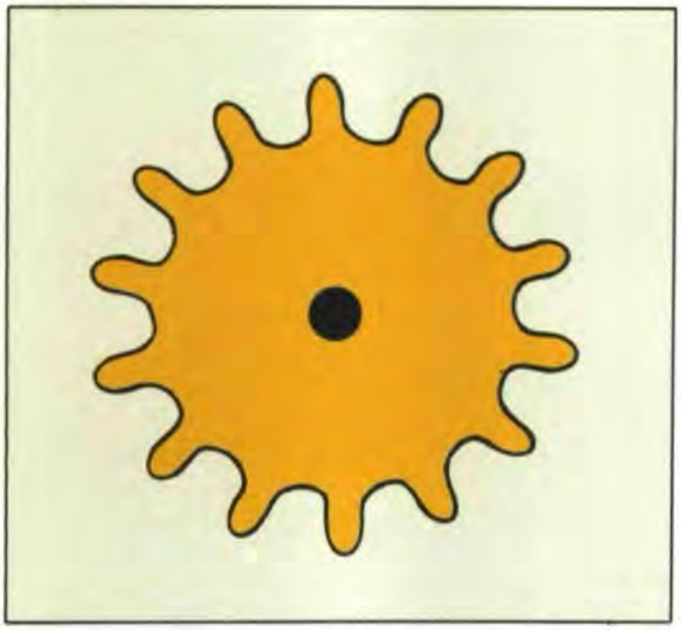


Fig. 2—(Photograph reduced, original size 4", diameter 4% Nital Etch.)

New Technology
and Special-Purpose Treatments

a) Special-Purpose Treatments –

The use of low temperature carbo-nitriding processes (less than 1200°F) have proved beneficial to certain gear applications requiring high-cycle-low load fatigue characteristics. The processes commercially available are called Tufftride, Lindur, and Melonite. Each render a very shallow high wear resistant compound zone (less than .001") with a total diffusion of approximately .030". Because of the very low temperature the distortions become minimal.

b) New Technology –

In the field of selective gear hardening the use of electron beams and lasers have been successfully used to localize, heat the gear tooth in special applications. The state of the art has not rendered itself to the commercial field at the present time.

A relatively new technology, that used physical vapor deposition applied to a nitrided layer, termed ion-nitriding, has become commercially available. The advantages of this type of nitriding are; energy consumption, shortening of cycles as compared to conventional nitriding, and the ease of shielding for selective nitriding. The disadvantages are; relatively costly equipment, and very complex and integrated controls.

Summary

The background material covered here and the interactions described will hopefully allow the reader to do some of his own "gear manufacturing system analysis." For instance, the manufacturing engineer should be able to refer to Table I or II and pick a compatible heat treating process for desired strength characteristics. Then eliminate the processes that inter-relate from the standpoint of cost and distortion restrictions. With this information he should be able to pick a series of materials that are compatible to the heat teatment and further his analysis into other processing attributes for the most desirable material for the gear application.

Obviously, there are many combinations and permutations of the various components of gear manufacturing. Hopefully, it has been shown that the heat treatment process and material selection must be approached in its entirety in order to be optimized.

Appendix

Glossary of Metallurgical Terms

Aging—Aging is a structural change, usually by precipitation, that occurs in some alloys after a preliminary heat treatment or cold working operation. Aging may take place in some alloys at room temperature in moderate time (days) or in others, may be done in shorter time at furnace temperatures. Over-aging may be done at a temperature above normal to produce some desirable modification of physical properties.

Air Hardening Steel—An alloy steel which will form martensite and develop a high hardness when cooled in air from its proper hardening temperature.

Aluminizing—Forming a corrosion and oxidation-resistant coating on a metal by coating with aluminum and usually diffusing to form an aluminum-rich alloy.

Annealing—A very general term describing the heating of metal to a suitable temperature, holding for a suitable time, and cooling at a suitable rate to accomplish the objective of the treatment. Annealing may done to:

A. Relieve stresses
B. Induce softness
C. Improve physical, electrical, or magnetic properties
D. Improve machinability
E. Refine the crystalline structure
F. Remove gases
G. Produce a specific microstructure

Atmosphere—The gaseous environment in which the metal being treated is heated for processing. Atmospheres are used to protect from chemical change or to alter the surface chemistry of steel through the addition or removal of carbon, nitrogen, hydrogen, and oxygen and to add certain metallic elements as chromium, silicon, sulphur, etc.

Austempering—A heat treating operation in which austenite is quenched to and held at a constant temperature (usually between 450°F and 800°F) until transformation to bainite is complete. In some steels at certain hardness levels, bainite is tougher than quenched and tempered structures.

Austenite—Austenite is the name given any solid solution in which gamma iron is the solvent. Austenite is a structure name and means nothing as to composition. Austenite is the structure from which all quenching heat treatments must start.

Austenitizing Temperature—The temperature at which steel is substantially all austenite.

Bainite – The product formed when austenite transforms between 450°F and 900°F. Bainite is an acicular aggregate of ferrite and carbide and varies in hardness between Rc 30 and Rc 55.

Banded Structure – A layering effect that is sometimes developed during the hot rolling of steel.

Bark – An older term used to describe the decarburized skin that develops on steel bars heated in a non-protective atmosphere.

Bright Annealing – Annealing work in a protective atmosphere so that there is no discoloration as the result of heating. In some atmospheres oxides may be reduced.

Brittle Tempering Range – Some hardened steels show an increase in brittleness when tempered in the range of about 450°F to 700°F even though some tempering causes some softening.

Carbonitriding – A heat treatment for steel which adds carbon and nitrogen from an atmosphere rich in such elements.

Carbon Steel – Steel which is essentially iron plus carbon with no intentionally added alloy. Also known as ordinary steel, straight carbon steel, or plain carbon steel.

Carburizing – Adding carbon to the surface of steel by heating it in contact with carbon-rich solids, liquids or gases.

Case – The surface layer of a steel whose composition has been changed by the addition of carbon, nitrogen, chromium, or other material at high temperature.

Case Hardening – A heat treatment in which the surface layer of a steel is made substantially harder than the interior by altering its composition.

Cementite – The common name for iron carbide, Fe_3C, the chemical combination of iron and carbon.

Cold Working – Plastic deformation of a metal at a temperature low enough so that recrystallization does not occur during cooling.

Core – The interior part of a steel whose composition has not been changed in a case hardening operation.

Critical Point – A temperature point at which a structure change either starts, is completed, or both when a material is being heated or cooled.

Critical Range – The temperature range between an upper and lower critical point for given material.

Decarburizing – The process (usually unintentional) of removing carbon from the surface of a steel, usually at high temperature, when in contact with certain types of atmosphere.

Dissociation – The chemical breakdown of a compound into simpler compounds or elements. One of the most common examples is the dissociation of ammonia (NH_3) into nitrogen and hydrogen.

Draw – The common term used interchangeably with Tempering.

Fatigue – Failure by progressive fracture caused by repeated applications or reversals of stress.

Ferrite – Ferrite is the name given any solid solution in which alpha iron is the solvent. Ferrite is strictly a structure name and means nothing as to composition.

Flame Hardening – A process consisting of heating a desired area, usually localized, with an oxyacetylene torch or other type of high temperature flame and then quenching to produce a desired hardness.

Grain Growth – Growth of some grains at the expense of others, resulting in an overall increase in average grain size.

Hardenability – The fundamental characteristic of a steel which determines the ease or preventing the transformation of austenite to anything else but martensite during the quench.

Homogenizing – An annealing treatment at fairly high temperature designed to eliminate or reduce chemical segregation.

Hydrogen Embrittlement – The brittleness induced in steel by the absorption of hydrogen, most commonly from a pickling or plating operation.

Inclusions – Particles of impurities (usually oxides, sulphides, silicates and such) which separate from the liquid steel and are mechanically held during solidification. In some grades of steel, inclusions are made intentionally high to aid machinability.

Induction Hardening – A form of hardening in which the heating is done by induced electrical current.

Interrupted Quench – Stopping the cooling cycle at a predetermined temperature and holding at this temperature for a specific time before cooling to room temperature. Usually done to minimize the likelihood of cracking, or to produce a particular structure in the part.

Isothermal Treatment – A type of treatment in which a part is quenched rapidly down to a given temperature, then held at that temperature until all transformation is complete.

Martempering or Marquenching – Martempering is a form of interrupted quenching in which the steel is quenched rapidly from its hardening temperature to about 450°F, held at 450°F until the temperatuare is uniform, then cooled in air to room temperature. Actual hardening does not occur until the air cooling starts and is accomplished with a minimum temperature differential. Martempering is indicated for low to medium alloy steels when distortion may be a problem.

Martensite – The very hard transformation product which forms austenite when a steel is quenched and cooled below about 450°F. Technically, martensite can be considered to be a supersaturated solution of carbon in tetragonal (distorted cubic) iron. Under the microscope it appears as an acicular or needlelike structure. Hardness of martensite will vary from Rc 30 to Rc 68 depending on the carbon content.

Microstructure – The structure of a metal as revealed at high magnification, usually at 100x and higher.

(continued on page 16)

SELECTION OF MATERIAL . . .

(continued from page 37)

Nitriding – The process of adding nitrogen to the surface of a steel, usually from dissociated ammonia as the source. Nitriding develops a very hard case after a long time at comparatively low temperature, without quenching.

Normalizing – The process of heating steel to a temperature above its transformation range, followed by air cooling. The purpose of normalizing may be to refine grain structure prior to hardening the steel, to harden the steel slightly, or to reduce segregation in castings or forgings.

Quenching – Cooling from high temperature, usually at a fast rate.

Secondary Hardness – The higher hardness developed by certain alloy steels when they are cooled from a tempering operation. This should always be followed by a second tempering operation.

Solution Treatment – Heating an alloy to high temperature to form a solution from an aggregate.

Spheroidizing – A heat treating process used to change all of the carbides in steel to rounded particles, or spheroids. A completely spheroidized structure is the softest and most workable structure for any composition.

Tempering – Reheating quenched steel to a temperature below the critical range, followed by any desired rate of cooling. Tempering is done to relieve quenching stresses, or to develop desired strength characteristics.

Work Hardness – Hardness developed in metal resulting from cold working.

Series Designation	Types
10xx	Nonsulphurized carbon steels
11xx	Resulphurized carbon steels (free machining)
12xx	Rephosphorized and resulphurized carbon steels (free machining)
13xx	Manganese 1.75%
*23xx	Nickel 3.50%
*25xx	Nickel 5.00%
31xx	Nickel 1.25%, chromium 0.65%
33xx	Nickel 3.50%, chromium 1.55%
40xx	Molybdenum 0.20 or 0.25%
41xx	Chromium 0.50 or 0.95%, molybdenum 0.12 or 0.20%
43xx	Nickel 1.80%, chromium 0.50 or 0.80%, molybdenum 0.25%
44xx	Molybdenum 0.40%
45xx	Molybdenum 0.52%
46xx	Nickel 1.80%, molybdenum 0.25%
47xx	Nickel .05%, chromium 0.45%, molybdenum 0.20 or 0.35%
48xx	Nickel 3.50%, molybdenum 0.25%
50xx	Chromium 0.25, 0.40 or 0.50%
50xxx	Carbon 1.00%, chromium 0.50%
51xx	Chromium 0.80, 0.90, 0.95, or 1.00%
51xxx	Carbon 1.00%, chromium 1.05%
52xxx	Carbon 1.00%, chromium 1.45%
61xx	Chromium 0.60, 0.80, or 0.95%, vanadi 0.12%, 0.10% min., or 0.15% min.
81xx	Nickel 0.30%, chromium 0.40%, molybdenum 0.12%
86xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.20%
87xx	Nickel 0.55%, chromium 0.05%, molybdenum 0.25%
88xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.35%
92xx	Manganese 0.85%, silicon 2.00%, chromium 0 or 0.35%
93xx	Nickel 3.25%, chromium 1.20%, molybdenum 0.12%
94xx	Nickel 0.45%, chromium 0.40%, molybdenum 0.12%
98xx	Nickel 1.00%, chromium 0.80%, molybdenum 0.25%

*Not included in the current list of standard steels.

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