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General Characteristics and Heat Treatments of Steels

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MATERIALS REPORT

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Ø GENERAL CHARACTERISTICS AND HEAT TREATMENTS OF STEELS

1. SCOPE:

The information and data contained in this report are intended as a guide in the selection of steel types and grades for various purposes. Consideration of the individual types of steel is preceded by a discussion of the factors affecting steel properties and characteristics.

SAE steels are generally purchased on the basis of chemical composition requirements (SAE J403, J404 and J405). In many instances, as in the case of steels listed in SAE J1268 and J1868, hardenability is also a specification requirement. This information report can be used as a reference for determining the general characteristics and applications of commonly used SAE steels. The use of the typical heat treatments listed in Tables 1 through 7 is recommended. These and other heat treatments commonly used on steel are briefly described at the end of this section.

2. REFERENCES:

All of the heat treatments briefly described in this article are discussed in detail in Metals Handbook - Ninth Edition - Volume 4 - Heat Treating, published by ASM International.

3. FACTORS AFFECTING PROPERTIES AND CHARACTERISTICS OF STEEL:

3.1 Hardenability: Hardenability, or response to heat treatment, is one of the most important characteristics of heat treated steels. Hardenability is the property of steels that determines the depth and distribution of hardness induced by quenching the steel from above the transformation temperature. Hardenability is usually measured by the end quench test described in SAE J406. Specified hardenability bands for standard carbon and alloy steels are shown in SAE J1268 and J1868.

3.1 (Continued):

The chemical composition and grain size of the steel completely determine its hardenability with almost all of the elements making varying degrees of contribution. Many elements are discussed in SAE J411; however, carbon, boron, manganese, chromium, and molybdenum have the strongest effect. Boron is a particularly potent hardenability agent. Typical additions in the range of 0.0005 to 0.003% will have a major effect on hardenability. Boron is most effective in lower carbon steels; it becomes less effective as carbon content increases. Carbon-manganese-boron steels generally fill a gap between plain carbon and alloy steels in terms of hardenability. Empirical relationships can be used to calculate or predict the hardenability for a given chemistry of steel. Actual depth and distribution of hardness will depend on quench severity.

Hardenability should not be confused with hardness per se or with maximum hardness. The maximum hardness obtainable with any steel quenched at the critical cooling rate depends only on the carbon content. That is to say, the maximum martensitic hardness obtainable on hardened steels is governed by the carbon content at the surface. It has been established that, under the conditions of scale-free heating, complete solution and achievement of critical cooling rate, maximum hardness is attained at about 0.60% carbon. If the material is decarburized, scaled, or overheated, or if it is quenched at less than the critical cooling rate, full hardness will not be achieved.

The term hardening implies that the hardness of the material is increased by suitable treatment, usually involving heating to a suitable austenitizing temperature followed by cooling at a certain minimum rate which depends upon the alloy content. If quenching is complete, the resulting structure is untempered martensite. If the quenching conditions produce a minimum of 90% martensite, followed by proper tempering, it may be reasonably expected that the surface hardness and the cross sectional hardness will have achieved the commercial possibilities for that material and section size. Smaller percentages of martensite will result in a corresponding reduction in mechanical properties.

3.2 Grain Size: When used in reference to heat-treated steels, the term grain size implies austenitic grain size. It is an important parameter governing mechanical properties. A fine austenitic grain size will improve toughness, ductility, and fatigue strength, but will reduce hardenability. The inherent austenitic grain size is determined by the choice of deoxidizer or grain refiner used in the steel making process. With few exceptions, steels to be heat treated should have a fine austenitic grain size.

Ferritic grain size is a parameter that is important to nonheat treated steels as it will affect formability, toughness, and ductility. Fine grain steels are stronger but will have less formability and ductility.

3.3 Microstructure: Microstructure means the quantity, size, shape, and distribution of various phases in the steel. It depends totally on the chemistry, hardenability, heat treatment, and cooling rates employed. Ferrite, the purest form of iron in steel, is the softest and lowest strength constituent with highest ductility. Martensite, supersaturated solution of carbon in iron, is the hardest. Controlled diffusion of carbon from martensite achieved by controlling the heat treatment (tempering time and temperature) softens the steel and improves ductility. Slow cooling from high temperatures causes the carbon to precipitate out as iron carbide or cementite which is a hard phase. A mixture of ferrite and lamellar or plate-like cementite is called pearlite.

Austenite is a term applied to the solid solution of carbon in gamma iron (or face centered cubic) and is present in carbon steels when they are heated above the A3 transformation temperature. Retained austenite is austenite that remains in the microstructure after a part is quenched from its austenitizing temperature. It is a softer microstructure constituent.

3.4 Cleanliness: Cleanliness is a measure of nonmetallic oxides, sulfides, coarse nitrides, silicates, and other such inclusions developed during the steelmaking process. Depending on their size, shape, population, and distribution, nonmetallic inclusions may adversely affect toughness, ductility and fatigue properties. Cleanliness is of utmost importance in critical components under high stresses, impact, cyclic loading or low temperatures.

3.5 Surface Quality: Surface quality, a measure of the surface condition of steel, is important in cyclic loading, contact fatigue and wear resistance applications. It is also very important in applications requiring surface coating, plating, painting, or aesthetics in exposed parts. Surface conditioning or scarfing of ingots, slabs, blooms, and billets may be utilized to improve surface quality.

3.6 Homogeneity: Chemical and microstructural homogeneity and soundness (absence of voids, pinholes, and porosity) are important in predicting the consistency of product performance and integrity. Proper deoxidation and stirring of molten steel alleviate some of these problems.

4. CHARACTERISTICS OF PLAIN CARBON STEELS:

4.1 Group I (SAE 1005, 1006, 1008, 1010, 1012, 1013): These steels are the lowest carbon steels of the plain carbon type and are selected when cold formability or drawability is the primary requisite. These steels have relatively low tensile values. Within the carbon range of the group, strength and hardness will increase with increase in carbon and with cold work. Such increases in strength are at the sacrifice of ductility or the ability to withstand cold deformation.

When under 0.15% carbon, the steels are susceptible to grain growth and consequent brittleness if they are cold worked during forming and subsequently heated to temperatures between 1100°F (595°C) and the lower transformation temperature. If coarse grains develop, they can be refined by heating above the A3 transformation temperature and then cooling.

4.1 (Continued):

Cold rolled sheets are made from the lower carbon steels in the group. They have excellent surface appearance and are used in automobile panels, appliances, and so forth. The machinability of bar, rod, and wire products in this group is improved by cold drawing. In general, these steels are considered suitable for welding or brazing but may suffer strength reductions either locally in the heat affected zone or overall, depending upon process details.

4.2 Group II (SAE 1015, 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1025, 1026, 1029, 1513, 1522, 1524, 1526, 1527): Steels in this group have increased strength and hardness and reduced cold formability compared to the lowest carbon group. For heat treating purposes, they are commonly known as carburizing or case hardening grades.

Selection of one of these steels for carburizing applications depends on the nature of the part, the properties desired, and the processing practices preferred. Increase in carbon content of the base steel results in greater core hardness with a given quench. Increase in manganese improves the hardenability of both the core and the case.

In this group, the intermediate manganese grades (0.60 to 1.00) machine better than the lower manganese grades. For carburizing applications, SAE 1016, 1018 and 1019 are widely used for water quenched parts. SAE 1022 and the 1500 series in this group are used for heavier sections or with thin sections where oil quenching is desired.

In cold-formed or cold-headed parts, the lowest manganese grades offer the best formability at a given carbon level. The next higher manganese types (SAE 1018, 1021 and 1026) provide increased strength.

These steels are used for numerous forged parts. In general, these steels are suitable for welding or brazing prior to carburizing. If welding is to be performed after carburizing, the area to be welded must be protected from the carburizing media during the process. An alternative to protection is to machine away the area to be welded after carburizing, but before hardening.

A typical application for carburized plain carbon steel is for parts requiring a hard wear resistant surface, but with little need for increased mechanical properties in the core; e.g., small shafts, plungers, and lightly loaded gearing.

4.3 Group III (SAE 1030, 1035, 1037, 1038, 1039, 1040, 1042, 1043, 1044, 1045, 1046, 1049, 1050, 1053, 1536, 1541, 1548, 1551, 1552): Steels of the medium carbon type are selected for uses where higher mechanical properties are needed. They are frequently further hardened and strengthened by heat treatment or by cold work. Steels in this group are suitable for a wide variety of automotive applications. Selection of the particular carbon and manganese level is governed by a number of factors. Increase in mechanical properties required, section thickness or depth of hardening ordinarily necessitate either higher carbon, higher manganese, or both. The heat treating practice used, especially the quenching medium, also has a great effect on the steels selected. In general, any of the grades over 0.30% carbon may be induction or flame hardened.

The lower carbon and manganese steels in this group find wide usage for certain types of cold-formed parts. In nearly all cases, the parts cold formed from these steels are annealed, normalized, or quenched and tempered prior to use. Stampings are usually limited to flat parts or simple bends. The higher carbon grades are frequently cold drawn to specified mechanical properties for use without heat treatment for some applications.

All of these steels can be used for forgings, the selection being governed by the section size and the mechanical properties desired after heat treatment. Thus, SAE 1030 and 1035 are used for many small forgings where moderate properties are desired. SAE 1536 is used for more critical parts where a higher strength level and better uniformity is essential. The SAE 1038, 1052, 1053 and 1500 groups are used for larger forgings. They are also used for small forgings where high hardness after oil quenching is desired. Suitable heat treatment is necessary on forgings from this group to provide machinability.

These steels are also widely used for parts machined from bar stock. They are used both with and without heat treatment, depending upon the application and the level of properties needed. As a class, they are considered good for normal machining operations. It is possible to weld these steels by most commercial methods, but precautions should be taken to avoid cracking from rapid heating or cooling.

4.4 Group IV (SAE 1055, 1059, 1060, 1065, 1069, 1070, 1074, 1075, 1078, 1080, 1085, 1086, 1090, 1095, 1561, 1566): Steels in this group are of the high carbon type which are used for applications where the higher carbon is needed to improve wear characteristics and where strength levels required are higher than those attainable with the lower carbon groups.

In general, cold forming methods are not practical with this group of steels as they are limited to flat stampings and springs coiled from small-diameter wire. Practically all parts from these steels are heat treated before use. Variations in heat-treating methods are required to obtain optimum properties for particular composition and application.

Typical uses in the spring industry include SAE 1065 for pretempered wire, SAE 1064 for small washers and thin stamped parts, SAE 1074 for light, flat springs formed from annealed stock, and SAE 1080 and 1085 for thicker flat springs. SAE 1085 is also used for heavier coiled springs.

4.4 (Continued):

Because of good wearing properties when properly heat treated, the high carbon steels find wide usage in the farm implement industry. Typical applications are plow beams, plow shares, scraper blades, discs, mower knives, and harrow teeth.

5. CHARACTERISTICS OF FREE-CUTTING CARBON STEELS:

This class of steels is intended for uses where improved machinability is desired as compared with carbon steels of similar carbon and manganese content. Machinability refers to the effects of hardness, strength, ductility, grain size, microstructure, and chemical composition on cutting tool wear, chip formation, ease of metal removal, and surface finish quality of the steel being cut. Lower costs are achieved either by increased production through greater machining speeds and improved tool life, or by eliminating secondary operations through an improvement in finish.

These steels contain sulfur for chip formation and, in the 1200 series, phosphorus to increase the strength and reduce the ductility of ferrite so chips will break up more easily. Calcium is also used to improve shape of the sulphides. The use of other additions such as lead, bismuth, or selenium has declined due to environmental restrictions. Sulfur and phosphorus negatively affect weldability, cold forming, forging, and so forth. Lead in steel wire causes a poor quality, low-strength welded or brazed joint. The lower carbon grades can be used for case hardening operations while the grades over 0.30 carbon can be quenched and tempered or induction hardened.

Machinability improves within the 1100 series as sulfur goes up. Sulfur combines mostly with the manganese and precipitates as sulfide inclusions. These inclusions favor machining by causing the formation of a broken chip and by providing a built-in lubricant that prevents the chips from sticking to the tool and undermining the cutting edge. By minimizing this adherence, less power is required, finish is improved, and the speed of machining may often be doubled as compared with a similar nonresulfurized grade. The 1200 series steels are both rephosphorized and resulfurized. Phosphorus is soluble in iron and promotes chip breakage in cutting operations through increased hardness and brittleness. Steels high in phosphorus are notoriously notch sensitive. As with carbon, an excessive amount of phosphorus can raise strength and hardness levels so high as to impair machinability. Hence, the 1200 series phosphorus content is limited to either a 0.04-0.09% or 0.07-0.12% range and carbon is limited to 0.13% maximum for the same reason.

5.1 Group I (SAE 1108, 1110, 1117, 1118): Steels in this group are used where a combination of good machinability and response to heat treatment is needed. These varieties can be used for small parts that are to be carbonitrided. SAE 1117 and 1118 carry more manganese for better hardenability, permitting oil quenching after case hardening heat treatments.

5.2 Group II (SAE 1137, 1139, 1140, 1141, 1144, 1146, 1151): This group of steels has characteristics comparable to carbon steels of the same carbon content. They are widely used for parts where a large amount of machining is necessary, or where threads, splines, grooves, or other operations offer special tooling problems. SAE 1137, for example, is widely used for nuts, bolts, and studs with machined threads. The higher manganese SAE 1137, 1141, and 1144 offer greater hardenability, the higher carbon types being suitable for oil quenching for many parts. All of these steels may be selectively hardened by induction or flame heating, if desired.

6. COMMON CONSTRUCTIONAL ALLOY STEELS (OTHER THAN STAINLESS AND AUSTENITIC):

A steel is classified as an alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: manganese 1.65%, silicon 0.60%, copper 0.60%; or, when there is specified a definite range or a minimum quantity of chromium (up to 3.99%), nickel, molybdenum, aluminum, cobalt, columbium, titanium, tungsten, vanadium, or zirconium. The total alloy content of constructional alloy steels is generally less than 5%.

The principal uses of alloying elements in the common construction steels are: 1) to develop maximum mechanical properties with minimum distortion and cracking or, 2) to develop special qualities such as resistance to tempering, increased toughness, or decreased notch sensitivity in the hardened and tempered condition, as compared with a carbon steel of equivalent carbon content similarly heat treated, or both.

Alloy steels are not generally specified for use without appropriate heat treatment. Some special properties which certain alloying elements influence are: retardation of transformation, lowering of transformation temperature, resistance to creep at elevated temperatures, retention of toughness at subzero temperatures, resistance to wear, and the effect on hardness and machinability. Other special properties may be imparted by the proper choice of alloying elements. As stated previously, hardenability is a prime consideration in the selection of alloy steels.

Properties such as ease of annealing, degree of hardening from cold working, ease of machining, and so forth, may be peculiar to composition or heat treatment, or both. The choice of steel for a given application is more often dictated by an overall economic consideration than by any other factor.

6.1 Carburizing Grades of Alloy Steels:

6.1.1 Properties of the Case: The properties of carburized and hardened cases depend on the carbon and alloy content, the depth of case, the structure of the case, and the degree and distribution of residual stresses. The carbon content of the case depends on the details of the carburizing process along with the response of iron and the alloying elements. The original carbon content of the steel has little or no effect on the carbon content produced in the case. The hardenability in the case, therefore, depends on the alloy content of the steel and the final carbon content produced by carburizing.

6.1.1 (Continued):

When heating for hardening results in complete carbide solution in the case, the effect of alloying elements on the hardenability of the case will in general be the same as the effect of these elements on the hardenability of the core. An exception is that boron significantly increases the hardenability of the low carbon core, but has little effect on the hardenability of the higher carbon case. Other less dramatic exceptions involve alloy interactions, which may enhance core hardenability but not case hardenability. It is also true that some elements, which raise the hardenability of the core, may tend to produce more retained austenite and consequently somewhat lower indentation hardness in the case.

Alloy steels are frequently used for case hardening because the required surface hardness can be obtained by moderate rates of cooling, which can result from an oil quench. This may mean less distortion than would be encountered with water quenching. It is usually desirable to select a steel that will attain a minimum surface hardness of Rockwell C 58, after carburizing and oil quenching. Where section sizes are large, a high hardenability alloy steel may be necessary; for medium and light sections, a low hardenability steel will suffice.

In general, case hardening alloy steels may be divided into three classes as far as the hardenability of the case is concerned. The three classes are: 1) low hardenability, such as the 4000, 5000, 5100, 6100, and 8100 series; 2) intermediate hardenability, such as the 4300, 4400, 4500, 4600, 4700, 8600, 8800, and 94B00 series; and 3) high hardenability, such as the 4800 and 9300 series. (The 8800 series is borderline with the high hardenability class.) Since the original carbon content has little effect on the case carbon level (and case hardenability) after carburizing, there is no significant difference between the case hardenabilities of two steels having similar alloy content, but varied original carbon percentage, e.g., 4815 and 4820 steels.

The steels having high case hardenability generally have reasonably high core hardenabilities, although the core hardenability is dependent upon the carbon content of the basic steel as well as the alloy content. These steels are used particularly for carburized parts having thick sections, such as heavy-duty truck drive pinions and gears and large roller bearings. Good case properties can be obtained by oil quenching. These steels are likely to have substantial amounts of retained austenite in the case after carburizing and quenching. The amount of retained austenite may be held to reasonable limits by controlling the carbon content of the case to produce near eutectoid case, by refrigerating the parts, or by reheating and quenching after carburizing. Lower case hardenability steels are used in smaller parts that are less heavily loaded. Steels with intermediate case hardenability are used for tractor and automotive gears, piston pins, ball studs, universal crosses, and roller bearings. Satisfactory case hardness should be produced in most cases by oil quenching.

6.1.2 <u>Core Properties</u>: The core properties of case hardened steels depend on the carbon and alloy content of the original steel and the severity of the quench. Many of the generally used types of alloy case hardening steels are made with two or more carbon contents so a choice of core hardness is provided. The most desirable hardness for the core depends on the design and function of the individual part. In general, where high compressive loads are encountered, relatively high core hardness is beneficial in supporting the case. Lower core hardnesses may be desirable where more than normal toughness is essential.

The case hardening steels may be divided into three general classes with respect to hardenability of the core. For hardenability of individual steels, see SAE J1268. Because H-bands have not been established for all steels, it is impossible to give an accurate comparative rating of hardenability of all the steels in any one group. Low hardenability core steels include SAE 4023, 4024, 4027*, 4028*, 4118*, 4422*, 4615, 4617, 4626*, 5115, 5120*, 6118*, and 8615. The steels followed by a "*" are borderline and might be considered medium hardenability.

Medium hardenability core steels include SAE 4032, 4427, 4620, 4720, 4815 (borderline with high), 8617, 8620, 8622, and 8720. High hardenability core steels include SAE 4320, 4718, 4817, 4820, 8625, 8627, 8822, 9310, 94B15, and 94B17. SAE 94B15 and 94B17 have been classed as high hardenability steels in the core because of the marked effect of boron on the hardenability of low carbon steels.

6.1.3 <u>Heat Treatment</u>: With few exceptions, the alloy carburizing steels are made to fine grain practices, and most are, therefore, suitable for direct quenching from the carburizing temperature of 1700°F (925°C) or from a reduced temperature of 1500-1600°F (815-870°C). If the carburizing is to be done at temperatures above 1700°F (925°C) and the parts are direct quenched, careful studies should be made of the suitability of the products so treated. Several other types of heat treatment involving single and double quenching are also used for some of these steels. See Table 3.

6.2 <u>Nitriding Grades of Alloy Steels</u>: A nitrided case is desirable for parts requiring resistance to sliding wear. Furthermore, since nitriding is carried out at relatively low temperatures (925-1050°F or 495-565°C), and no quenching after nitriding is required, this process produces very little distortion. However, nitriding produces a relatively shallow case (0.008-0.012 in or 0.2-0.3 mm).

The following steels can be nitrided for specific applications:

a. aluminum containing low-alloy steels

b. medium carbon, chromium containing low-alloy steels; e.g., SAE 4100, 4300, 5100, 6100, 8600, 9300, and 9800 series

c. hot work die steels containing 5% chromium; e.g., H11, H12, H13

6.2 (Continued):

d. 400 series stainless steels

e. austenitic 300 series stainless steels

f. precipitation hardening stainless steels; e.g., 17-4 PH or A-286

A very hard, low ductility nitrided case is produced from aluminum containing steels where a chromium containing steel produces a lower hardness case with improved ductility. Except for martensitic stainless, all steels that are to be nitrided must first be hardened and tempered. The tempering temperature is usually 50°F (10°C) higher than the maximum nitriding temperature to ensure that the core hardness is not reduced during the nitriding operation. Typical nitriding applications include gears designed for low contact stresses, spindles, seal rings, and pins.

6.3 Directly Hardenable Grades of Alloy Steel: These steels may be considered in five groups on the basis of approximate mean carbon content of the SAE specification. In general, the last two figures of the specification agree with the mean carbon content. Consequently, the heading "0.30-0.37 Mean Carbon Content of SAE Specification" includes steels such as SAE 1330 and 4137.

It is necessary to deviate from the preceding plan in the classification of the carbon-molybdenum steels. When these steels are used, it is customary to specify higher carbon content, for specific applications, than would be specified for other alloy steels because of the low alloy content of these steels. For example, SAE 4047 is used for the same applications as SAE 4140 and 5140. Consequently, in the following tables and discussion, the carbon-molybdenum steels are shown in the groups where they belong on the basis of applications rather than carbon content.

For the present discussion, steels of each carbon content are divided into two or three groups on the basis of hardenability. Transformation ranges and consequently heat-treating practices vary somewhat with different alloying elements even though the hardenability is not changed.

6.3.1 0.30-0.37 Mean Carbon Content: These steels are frequently used for water quenched parts of moderate section size and for oil quenched parts of small section size. Typical applications are connecting rods, steering arms and steering knuckles, axle shafts, bolts, studs, screws, and other parts requiring strength and toughness where the section size is small enough to permit obtaining the desired mechanical properties with the customary heat treatment. Steels falling into this classification may be subdivided into two groups on the basis of hardenability.

Low hardenability steels in the 0.30-0.37 mean carbon content classification include SAE 1330, 1335, 4037, 4130, 5130, 5132, 5135, and 8630. Medium hardenability steels in this same carbon range include SAE 4135, 4137, 8637, and 94B30.

6.3.2 <u>0.40-0.42 Mean Carbon Content</u>: In general, these steels are used for medium and large size parts requiring a high degree of strength and toughness. The choice of the proper steel depends on the section size and the mechanical properties that must be produced. The low and medium hardenability steels are used for average size automotive parts such as steering knuckles or axle shafts. The high-hardenability steels are used particularly for large axles and shafts and for large aircraft parts. These steels are usually considered for oil quenching, although some large parts made of the low and medium hardenability classifications may be quenched in water under properly controlled conditions. These steels may be roughly divided into three groups as follows, on the basis of hardenability:

a. Low hardenability steels in the 0.40-0.42 mean carbon content classification include SAE 1340, 4047 and 5140.

b. Medium hardenability steels in the 0.40-0.42 classification include 4140, 4142, 50B40, 8640, 8642 and 8740.

c. High hardenability steels in this classification include SAE 4340.

6.3.3 <u>0.45-0.50 Mean Carbon Content</u>: These steels are used primarily for gears and other parts requiring fairly high hardness as well as strength and toughness. Such parts are usually oil quenched. A minimum of 90% martensite in the as-quenched condition is desirable. These steels are as follows:

a. Low hardenability steels in the 0.45-0.50 mean carbon content classification include SAE 5046, 50B44, 50B46, and 5147.

b. Medium hardenability steels in the 0.45-0.50 classification include SAE 4145, 5147, 5150, 81B45, 8645, and 8650.

c. High hardenability steels in this classification include SAE 4150 and 86B45.

6.3.4 <u>0.50-0.60 Mean Carbon Content</u>: These steels are used primarily for springs and hand tools. The hardenability necessary depends on the thickness of the material and the quenching practice. These steels are as follows:

a. Medium hardenability steels in the 0.50-0.60 mean carbon content classification include SAE 50B50, 5060, 50B60, 5150, 5155, 51B60, 6150, 8650, 9254, and 9260.

b. High hardenability steels in this classification include SAE 4161, 8655, and 8660.

6.3.5 1.02 Mean Carbon Content: These are straight chromium electric furnace steels used primarily for the races and balls or rollers of antifriction bearings. They are also used for other parts requiring high hardness and wear resistance. The compositions of the three steels are identical except for a variation in chromium with a corresponding variation in hardenability. These steels are as follows:

a. The low hardenability steel in the 1.02 mean carbon content classification is SAE 50100.

b. The medium hardenability steels in this classification are SAE 51100 and 52100.

6.3.6 Heat Treatments: Typical treatments are given in Table 4.

6.3.7 Resulfurized Steel: Some of the alloy steels (SAE 4024 and 4028) are resulfurized to give better machinability at a relatively high hardness.

7. CHARACTERISTICS OF WROUGHT STAINLESS STEELS:

The composition and corresponding physical characteristics of these steels can be divided into several broad groups or types as follows:

7.1 Stainless Chromium-Manganese-Nickel Austenitic Steels (Not Hardenable): These steels are austenitic at room temperature and higher and cannot be hardened by thermal treatment. Table 5 gives typical heat treatments for the following steels:

a. SAE 30201 is an austenitic chromium-manganese-nickel stainless steel usually required for flat products. It is nonmagnetic in the annealed condition but may be magnetic when cold worked. SAE 30201, as with 30301, can be used to obtain a high-strength product by cold rolling. It is well suited for corrosion-resistant structural members requiring high strength with low weight and has excellent resistance to a wide variety of corrosive media, showing behavior comparable to stainless grade SAE 30301. With high ductility and excellent forming properties, it has been used for automotive trim, automotive wheel covers, railroad passenger car bodies and structural members, truck trailer bodies, and cookware.

b. SAE 30202, like its corresponding chromium-manganese-nickel stainless steel SAE 30304, is a general purpose stainless steel. It has good corrosion resistance and deep drawing qualities. It is nonhardenable by thermal treatments but may be cold worked to high tensile strengths. In the annealed condition, it is nonmagnetic but slightly magnetic when cold worked. Applications for this stainless steel are hub caps, railcar and truck trailer bodies, and spring wire.

7.1 (Continued):

c. SAE 30301 is capable of developing high tensile strength, while retaining high ductility by moderate to severe cold working. It is often used in the cold rolled or cold drawn condition in the form of sheet, strip, and wire. It is nonmagnetic when annealed but is magnetic when cold worked. Its corrosion resistance is not quite equal to SAE 30302. This steel is used for applications requiring a combination of high strength and excellent forming properties such as in structural members, automotive trim, and wheel discs and rings. It is used for flat and wire springs, windshield wiper arms, grills, steering wheel spokes, and similar applications. It is also used for cream separators and milking machine parts.

d. SAE 30302 is the general-purpose stainless steel of this type. Its corrosion resistance is better than that of SAE 30301, and it is the most widely used of all the chromium-nickel stainless and heat-resisting steels. It is used for deep drawing largely in the softer tempers. It can be worked to high tensile strength but with lower ductility than SAE 30301. It is nonmagnetic when annealed but is magnetic when cold worked. This steel is used on automotive parts where excellent corrosion resistance or good forming and drawing properties are required. It is used for hub caps, radiator grills, windshield wiper parts such as tension bars and binder strips, hose clamps, antennas, control cables, fender guards, fire walls, and hydraulic tubing. It is used for other similar parts that have severe forming requirements combined with a need for corrosion resistance.

e. SAE 30303 has elements added to improve its machining and nonseizing characteristics. This steel, the free machining modification of SAE 30302, is recommended for the manufacture of parts produced on automatic machines. It can be forged but requires much more care than is necessary with SAE 30302. Its corrosion resistance is slightly inferior to that of SAE 30302. It is nonmagnetic when annealed but is slightly magnetic when cold worked. It is used for screws, nuts, carburetor parts, aircraft fittings, water pump shafts, and other machined parts requiring some corrosion resistance. It is not recommended for applications involving severe cold working, cold upsetting, or welding.

f. SAE 30304 is a lower carbon steel similar to SAE 30302 but has superior welding properties for certain types of equipment. It is nonmagnetic when annealed but slightly magnetic when cold worked. It is used for diesel injection pump valve springs, roller chains, parachute hardware, and welded parts that can be heat treated after welding or parts that are not liable to damage by intergranular corrosion if heat treating after welding is not performed. This steel is also available with 0.03-0.05% carbon for certain applications.

7.1 (Continued):

g. SAE 30305 is similar to SAE 30302 and 30304, but because of a higher nickel content does not harden as rapidly with cold working as either of the similar grades. It also has much less change in magnetic permeability when cold worked. Because of its lower work hardening tendency, it is better suited for spun parts, multiple drawing operations, severe cold heading, and parts requiring large amounts of cold deformation.

h. SAE 30309 has higher corrosion and oxidation resistance than SAE 30304. It is resistant to oxidation at temperatures up to about 2000°F (1095°C). It is nonmagnetic when annealed but may be slightly magnetic when cold worked. It is used primarily in high temperature applications such as thermocouple wells, heat exchangers, glass lehr belts, and aircraft cabin heaters.

i. SAE 30310 has very high corrosion and heat resisting properties. As with SAE 30309, it resists oxidation at temperatures up to about 2000°F (1095°C). It is more stable and somewhat stronger at high temperatures and is more safely hot worked than SAE 30309. It is nonmagnetic when annealed or cold worked. It is used in such applications as diesel injector cup wipers, jet engine burner liners, and nozzle vanes.

j. SAE 30316 is similar to SAE 30304 in fabricating qualities. However, it has superior corrosion resistance to other chromium-nickel steels when exposed to sea water and many types of chemical corrodents, especially those of a reducing nature. It also has superior strength at elevated temperatures. It is nonmagnetic when annealed but is slightly magnetic when cold worked. It is used in applications such as wire screens, dye making and chemical processing equipment, and in elevated temperature service, especially where strength is important, up to about 1500°F (815°C). This steel has a specified molybdenum content which, when combined with low carbon content, stabilizes against intergranular carbide precipitation in welding. It is available with less than 0.05% carbon for certain applications.

k. SAE 30317 is similar to SAE 30316 but with greater corrosion resistance in many environments and with somewhat greater high temperature strength. It is primarily used for paper making equipment and scrubber components.

l. SAE 30321 has a specified titanium content. Its properties are similar to those of SAE 30304 except that it can be recommended for use in the manufacture of welded parts requiring immunity to intergranular attack and where heat treating after welding is not feasible. It may also be used where temperatures in the range of about 800-1650°F (425-900°C) are encountered in fabrication or service and where the possibility of intergranular corrosion exists. It is nonmagnetic when annealed but is slightly magnetic when cold worked. It has been used for exhaust manifolds, manifold flanges, and high temperature bolts and locknuts.

7.1 (Continued):

m. SAE 30330 alloy in the wrought and cast form is used for high temperature oxidation resistance essentially over 1650°F (900°C) and utilized in the construction of heat treating baskets, similar items, and heat treating furnace parts.

n. SAE 30347 is similar to SAE 30321 except it contains columbium instead of titanium. The columbium-bearing alloy is used in the same applications as SAE 30321 except that it does not cold form as satisfactorily.

7.2 Stainless Martensitic Chromium Steels (Hardenable): These alloys combine carbon and chromium to produce a hardenable, high-strength stainless steel after proper heat treatment. They are ferritic at room temperature but become austenitic at elevated temperature. They can be rapidly cooled to produce a hard, martensitic structure in the same manner as other hardenable steels. Since they can be heat treated to produce martensite, they are commonly known as martensitic stainless steels.

a. SAE 51410 is the general-purpose steel of this type. It can be hardened by heat treating to develop a wide range of mechanical properties. 39/45 RC is about the maximum useful hardness obtainable. It has fair machining properties and corrosion resistance, although in this respect, it is inferior to SAE 51430. Best corrosion resistance is obtained in the heat-treated condition. It is magnetic in all conditions. It is used in applications requiring high strength combined with moderate resistance to corrosion. Possessing fair strength and good oxidation resistance to about 1200°F (650°C), it is used in manifold stud bolts, heat control shafts, steam valves, bourdon tubes, and gun mounts.

b. SAE 51414 has somewhat better corrosion resistance than SAE 51410. It will attain slightly higher mechanical properties when heat treated than SAE 51410 and develop a maximum useful hardness of about 41/43 RC. It is magnetic in all conditions. It is used in the form of tempered strip and in bars and forgings for heat-treated parts for valve trim and stems.

c. SAE 51416 is similar to SAE 51410. It can be heat treated to a maximum hardness of about 39/41 RC. Elements have been added to improve its machining and nonseizing characteristics at some sacrifice in corrosion resistance and weldability. It is the most readily machinable of all the stainless steels and is suited for use on automatic screw machines. It is magnetic in all conditions. This steel is available in bars, wire, and forgings and is used for water pump shafts, carburetor needle valves, heat control valve shafts, manifold parts, and other parts requiring a hardenable, free machining corrosion and heat-resisting steel. Free-machining types are not recommended for welding.

7.2 (Continued):

d. SAE 51420 is capable of being hardened to a wide range of mechanical properties depending on the actual carbon and chromium contents. With low side of carbon range and chromium, the grade behaves similarly to SAE 51410. With 12.5%, or higher, chromium and 0.35% carbon, the maximum heat treating response expected is about 53/56 RC. It offers its maximum corrosion-resistant properties only in fully hardened conditions. It is magnetic in all conditions. This steel is used in wire cutter blades, garden shears, cutlery, hardened pump shafts, water pump parts, glass and plastic molds, bomb shackle parts, and drive screws.

e. SAE 51420F is similar to SAE 51420 except that elements have been added to improve its machinability.

f. SAE 51431 is a nickel-bearing chromium steel capable of being heat treated to a maximum useful hardness of about 42/44 RC. Its corrosion resistance is superior to that of the other hardenable grades such as SAE 51410, 51420 and 51440. It is magnetic in all conditions and used for aircraft bolting, cable terminals, bomb shackle parts, and other parts requiring a hardenable steel with high mechanical properties and superior corrosion resistance.

g. SAE 51440A is hardenable to a greater quenched hardness than SAE 51420 and has greater toughness than SAE 51440B or 51440C. It can be hardened to a maximum of about 56/59 RC. Maximum corrosion resistance is obtained only from a polished surface on fully hardened material. Magnetic in all conditions, this steel is used for cutlery, paint spray nozzles, and some types of bearings.

h. SAE 51440B is hardenable to a greater quenched hardness than SAE 51440A and has greater toughness than SAE 51440C. Maximum corrosion resistance is obtained only from a polished surface on fully hardened material. Depending upon carbon content, it can be hardened to 53/58 RC. It is magnetic in all conditions and used for balls and races.

i. SAE 51440C acquires on heat treatment the highest quenched hardness and greatest wear resistance of any corrosion or heat resistant steel. It can be hardened to 55/60 RC and is corrosion resistant only in the fully hardened and polished condition. It is magnetic in all conditions. This steel is used for diesel engine pump parts, instrument parts, crankshaft counterweight pins, valve trim, ball bearings, races, and other parts requiring a hard wear and corrosion resistant surface.

j. SAE 51440F is similar to SAE 51440C except that elements have been added to improve its machinability and nonseizing characteristics. This steel is used for carburetor parts.

7.2 (Continued):

k. SAE 51501 is used for its heat-resistance, corrosion-resistance, and good mechanical properties at elevated temperatures. It is produced with about 0.5% molybdenum to improve its toughness. It can be heat treated to various hardnesses depending on the carbon content. It is magnetic in all conditions. It is used in service up to about 1200°F (650°C). A 0.15% maximum carbon type is used for tubing in oil stills and heat treat exchangers. High carbon types are used for valve stems, valves, and hot or cold work dies and mandrels. This steel is not a true stainless steel.

7.3 <u>Stainless Ferritic Chromium Steels (Not Hardenable)</u>: The third group contains more chromium and less carbon than the second group. Nickel, if present, is incidental. By virtue of this high-chromium and low-carbon content, several of these steels are ferritic at room and elevated temperatures. As they do not transform to austenite, they cannot be hardened by heat treatment and are known as ferritic stainless steels. Table 6 shows typical heat treatments for these steels.

a. SAE 51409 has excellent weldability and formability characteristics. Its corrosion resistance is superior to carbon and low-alloy steels but not as high as SAE 51430. It is not normally considered hardenable by cold working or heat treatment. Its ductility is as good as SAE 51430, and it is magnetic. It is primarily used in muffler, manifold, catalytic converter, and exhaust pipe applications but is being used in an increasing number of other automotive applications such as filter bodies and thermostat components. This steel is the largest tonnage stainless presently used in automotive parts.

b. SAE 51430 has superior corrosion and heat resistance, as compared with SAE 51410. Its ductility is fair, but it is resistant to destructive oxidation up to about 1500°F (815°C). Magnetic in all conditions, this steel is used for parts requiring only a moderate draw, such as moldings, windshield wiper yokes, heat control valves, shafts and bushings, fasteners of all types, wire strainer screens, and fender guards.

c. SAE 51430F is similar to SAE 51430 except that elements have been added to improve its machinability and nonseizing characteristics. It is less amenable to both cold and hot work than SAE 51430 and is used for oil burner nozzles and other machined parts requiring good corrosion or heat resistance. This type of steel is not recommended for welding.

d. SAE 51434 is similar to SAE 51430 in ductility and heat resistance. It is magnetic in all conditions. More resistant to road salt attack than SAE 51430, it is used as trim and other exterior parts. A modification of SAE 51434 is SAE 51436, which has the ability to reduce a "roping" characteristic found in SAE 51430 and 51434 when the alloys are stretched. SAE 51436 is used in "stretch-bent" automobile trim applications.

7.3 (Continued):

e. SAE 51442 is somewhat superior in corrosion and heat resistance than SAE 51430. It has good resistance to oxidation up to 1600°F (870°C). This steel is magnetic in all conditions.

f. SAE 51446 has the maximum amount of chromium, consistent with commercial malleability. It is used primarily for the manufacture of parts that must resist high temperatures in service without scaling but which are not highly stressed. It resists destructive oxidation up to a temperature of about 2000°F (1095°C). This steel is used for glass seals, salt bath electrodes, thermocouple wells, combustion chambers, and other parts where resistance to oxidation is important but where the need to carry a load is negligible.

g. Type 466 is a 11.50% chromium ferritic stainless steel. By dual stabilizing with titanium and columbium, the alloy chemistry is balanced to provide a very low titanium content resulting in a significant reduction in objectionable titanium-related surface defects that are sometimes associated with titanium (only) stabilized Type 409 alloys. In some instances, weldability appears to be improved. The low titanium content in 466 alloy also improves brazing characteristics. The mechanical property and corrosion data indicate 466 alloy has the same general corrosion resistance and formability properties as Type 409. Like all ferritic stainless steels, this steel is highly resistant to stress corrosion cracking.

Straight chromium steels (16% or more) and chromium-nickel steels having 18% or more chromium are subject to development of the sigma phase when exposed to temperatures of 1000°F (540°C) or higher for extended time periods. This phase is an intermetallic compound that increases hardness, but decreases ductility, notch toughness, and corrosion resistance. Its presence can lead to service failure. This phase can be eliminated by heating to about 1650°F (900°C).

7.4 Precipitation Hardened Stainless Steels: Precipitation hardened stainless steels can be hardened through low temperature heat treatments and offer high strength in addition to excellent corrosion resistance. The martensitic group is most widely used and includes SAE 17400 and SAE 15500. The semiaustenitic group was developed for increased formability before the hardening heat treatment and includes SAE 17700. All grades are available in sheet, strip, plate, bar, and wire.

a. SAE 17400 is a precipitation hardenable stainless steel that is used in a variety of applications such as valves, gears, aircraft fittings, pump shafts, and jet engine parts. Typical composition is 16% chromium, 4% nickel, 3% copper, and the balance iron. Niobium plus tantalum ranges from 0.15 to 0.45. Maximum strength is obtained after solution treating to 1900°F (1040°C), cooling to room temperature, reheating for 1 h at the precipitation temperature of 900°F (480°C), and cooling to room temperature. Higher precipitation temperatures may also be selected to obtain better ductility and toughness.

7.4 (Continued):

b. SAE 15500 is very similar to SAE 17400 in suggested heat treatment and properties. However, when the aerospace and nuclear industry require stringent cleanliness with excellent transverse mechanical properties, SAE 15500 is the choice because of the practice of remelting this steel in a vacuum or with a protective flux. Also, the SAE 15500 chemistry is adjusted to eliminate delta ferrite, which improves the transverse mechanical properties in any test location.

c. SAE 17700 - For better fabricability in the solution-treated condition, SAE 17700 is offered with the ability to be precipitation hardened. Typical applications include aircraft skins, structural parts, jet engine parts, springs, diaphragms, bellows, fasteners, and whip antennae. For maximum strength, SAE 17700 can be used in the fully cold worked condition and precipitation heat-treated at 900°F (480°C) for 1 h and cooled to room temperature. Other heat treatments exist for solution annealed products that necessitate the forming characteristics of a 300 series stainless steel. Typical composition for this grade is 17% chromium, 7% nickel, and 1% aluminum.

d. SAE 15700 is a semiaustenitic, precipitation hardenable stainless steel that has similar mechanical properties and forming characteristics to type SAE 17700. The modified chemistry of 15% chromium, 7% nickel, 2.5% molybdenum, and 1% aluminum makes precipitation heat treating somewhat simpler along with better ductility in weldments. End uses include retaining rings, springs, diaphragms, bellows, fasteners, and instrument parts.

e. SAE 35000 is a semiaustenitic chromium-nickel-molybdenum stainless steel. SAE 35000 combines the corrosion resistance and formability characteristics of the austenitic stainless steels with the strengths of the martensitic stainless steels. Relatively low temperature heat treatments of this precipitation hardening stainless steel have eliminated many of the problems associated with normal heat treating procedures. While the primary hardening mechanism is the formation of martensite, from the proper control of the austenite to martensite transformation, tempering treatments furnish additional hardness and strength. The chemistry of this grade results in about 10% ferrite to be stable throughout processing.

f. SAE 35500 is a semiaustenitic chromium-nickel-molybdenum stainless steel. SAE 35500 combines the corrosion resistance and formability characteristics of the austenitic stainless steels with the strengths of the martensitic stainless steels. Relatively low temperature heat treatments of this precipitation hardening stainless steel have eliminated many of the problems associated with normal heat treating procedures. While the primary hardening mechanism is the formation of martensite, with proper control of the austenite to martensite transformation, tempering treatments furnish additional hardness and strength. The ferrite phase is generally absent from this grade. This can result in a higher strength cold rolled product.

7.5 Age Hardenable Martensitic Steels (Maraging): The 18% nickel maraging steels belong to a loosely knit family of iron-base alloys that are strengthened by a combination of martensite formation followed by an aging treatment. Yield strengths up to and well beyond 300 ksi (2070 MPa) are available when these steels are in the aged condition.

a. SAE 93120 is a member of the 18% nickel-cobalt-molybdenum-titanium maraging martensitic steels that offer the best combination of mechanical properties and heat treatment. The titanium-aluminum or the cobalt-molybdenum-titanium contents of these steels serve as the hardening agents. Depending on composition and product form, strengths of 200-300 ksi (1380-2070 MPa) yield strength and 210-310 ksi (1450-2140 MPa) tensile strength, accompanied by 15-5% elongation, are possible with these alloys.

b. SAE 36200 is a chromium-nickel maraging steel. It contains sufficient chromium to exhibit the corrosion and oxidation resistance of the stainless steels. SAE 36200 is martensitic in the annealed condition with good toughness and ductility. Increased strength is achieved by low temperature heat treatments.

7.6 Stainless Steels Possessing Special Machinability Features: This group represents proprietary modifications of standard SAE steels to provide steels of special machining characteristics in comparison to the standard free-machining counterparts. These steels are particularly suited for parts made in automatic screw machines. Table 7 shows typical heat treatments for these steels.

a. Type 203-EZ is a chromium-nickel-manganese free machining stainless steel. It is austenitic and does not respond to thermal treatments. This steel is nonmagnetic when annealed, but slightly magnetic when cold worked.

b. Types 303Ma, 303Cu and 303 Plus X are modifications of SAE 30303. They are austenitic and do not respond to thermal treatments. These steels are nonmagnetic when annealed, but slightly magnetic when cold worked.

c. Type 416 Plus X is a modification of SAE 51416. This steel is martensitic and hardenable by thermal treatments to RC 40 minimum. It is magnetic in all conditions.

8. HEAT TREATMENTS APPLIED TO STEEL:

8.1 Normalizing: The normalizing process consists of:

a. Uniformly heating steel to a temperature high enough to obtain complete transformation to austenite.

b. Holding at the austenitizing temperature until the mass is of equal temperature throughout.

8.1 (Continued):

c. Air cooling, allowing free air circulation to give uniform cooling. Normalizing temperatures are dependent on the steel grade, while holding time at temperature will vary with the mass being heat treated. Hence, normalizing cycles and subsequent steel properties may vary considerably with steel grade, part size, individual furnace conditions, and cooling facilities.

Normalizing is generally performed to obtain desired mechanical properties but is also used for the following functions:

1. Modify and refine coarse as-rolled or forged structures.
2. Improve hardening characteristics by refining grain size and homogenizing microstructure.
3. Improve machining characteristics. This treatment is especially beneficial for 0.15-0.40% carbon steels.

8.2 <u>Annealing</u>: When the term "annealing" is applied without qualification, the term implies full annealing. Full annealing consists of austenitizing and then cooling uniformly and slowly, through the transformation range. In isothermal annealing, the heating is the same as used for a full anneal, but the steel is held for a given time at a constant temperature in the upper transformation range before being cooled at a uniform rate. This practice produces a coarse pearlite structure that greatly improves machinability of medium carbon steels. Spheroidizing is an annealing process where steel is slowly cooled to a point below the A1 transformation temperature, and under suitable conditions of temperature and time, produces a spheroidal or globular form of carbide in steel and is recommended prior to machining steels higher than 0.60% carbon.

Recrystallization annealing is another form of subcritical annealing. The part is heated to a temperature just below the A1 transformation temperature and held for a predetermined length of time. It is most effective on hardened or cold worked steels that recrystallize readily to form new ferrite grains. The rate of softening increases rapidly as the temperature approaches the transformation temperature.

In addition to producing desired mechanical properties, improving machinability, and obtaining the desired microstructure, the various forms of annealing are frequently used to improve the cold forming properties of steels.

8.3 Carbon Restoration: Carbon restoration or carbon correction is, in reality, a carburizing treatment for restoring carbon to the decarburized skin found on some grades of hot rolled, cold drawn, or cold drawn and annealed steel products. The process was originally applied to medium carbon steels where substantial differences in carbon content can occur between the base metal and the decarburized zone. The intent is to adjust the carbon potential of the furnace atmosphere to the carbon content of the steel being treated.

Although carbon restoration can be applied to any product that the available equipment can accommodate, its usual application is to bars and rods in either coils or cut lengths. The carbon-restored product will approximate the mechanical properties of annealed bars or rods of the base carbon level. In any application, it is well to keep in mind that the surface condition of the carbon-restored product, with respect to seams, is the same as that of the hot rolled or cold drawn stock before the process started.

8.4 Case Hardening: In this report, case hardening refers to heat treatments utilizing gases or molten baths, and includes carburizing, nitriding, and carbonitriding.

Gas carburizing is accomplished by heating the work to austenitizing temperature and subjecting the hot steel to an atmosphere containing carbon monoxide and methane. The depth of case is determined by carburizing time, carburizing temperature, carbon potential of the atmosphere, and to some extent, the type of steel being carburized.

The time required to achieve a desired case depth can be significantly shortened by elevating the temperature well into the austenite range (1800-1900°F or 980-1040°C); however, temperature is usually reduced towards the end of the cycle to control carbon diffusion and to prevent cracking and excessive distortion. Also, undesirable grain growth can occur during high temperature carburizing.

The most commonly used carburizing atmosphere is a mixture of endothermic carrier gas (a product resulting from the burning of natural gas and an insufficient amount of air for complete combustion) and a source of carbon such as natural gas or propane. Another carburizing atmosphere is produced by introducing a liquid hydrocarbon into nitrogen gas at high temperature. Vacuum carburizing involves removing air from the furnace chamber and then introducing the carburizing gas or agent under partial pressure.

Ion (or plasma) carburizing is a relatively new alternative to gas carburizing. The workpieces are placed in a vacuum chamber and the parts electrically isolated from the vessel walls. Application of a high voltage causes the treatment gas to become ionized. Under these conditions, the vessel wall acts as the anode and the workpieces act as the cathode. Positive ions of treatment gas bombard the workpiece, causing carbon to penetrate the surface. Selective carburizing can be accomplished by masking off portions of the workpiece from the bombarding action.

8.4 (Continued):

Liquid carburizing is accomplished by immersing the work in a molten salt bath containing sodium cyanide (NaCN) in an inert carrier salt. This process is performed at 1650-1750°F (900-955°C). At this temperature carbon from the cyanide is chemically active, while the nitrogen is inert. Disposal problems of these salts often make this process less attractive.

Gas carbonitriding introduces both carbon and nitrogen into the metal surface, producing a harder and more wear resistant surface than can be accomplished by carburizing alone. Ammonia (NH_3) gas is introduced into the carburizing atmosphere. At high temperature, the ammonia gas breaks up and chemically active nitrogen gas forms iron nitrides at the steel surface. Carbonitriding is carried out at lower temperatures and for shorter periods of time than carburizing, and less distortion is usually evident. Case depths of 0.003 to 0.03 in (0.075 to 0.75 mm) are typical. Since nitrogen is also an austenite stabilizer, increased levels of retained austenite are possible.

Liquid carbonitriding (also known as cyaniding) involves immersion of the work in a molten bath containing NaCN and a carrier salt. The process differs from liquid carburizing in that it is carried out at lower temperature (1500-1550°F or 815-845°C). At this temperature, both carbon and nitrogen from the cyanide are chemically active with the iron.

Gas nitriding is accomplished by introducing ammonia into the furnace at approximately 1000°F (540°C). At this temperature, the nitrogen available from the ammonia is chemically active with the steel, forming a very hard iron nitride white layer that is 0.0001 - 0.0008 in (0.0025 - 0.02 mm) thick at the surface. A hardened case is formed below this layer. Depending on time at temperature, this case may be as much as 0.012 - 0.016 in (0.3-0.4 mm) thick. Liquid nitriding uses the same molten salt bath immersion process as liquid carburizing and carbonitriding, but at a temperature of only 950-1050°F (510-565°C).

Ion nitriding is analogous to ion carburizing. The process is performed in a vacuum furnace. High voltage electrical energy ionizes the treatment gas and nitrogen ions bombard the surface of the workpiece.

The carburizing processes are completed by either direct quenching into a suitable liquid medium or cooling to room temperature, reheating, and quenching. Nitrided cases do not need quenching after the nitride operation. Since nitriding is performed at a much lower temperature and quenching is not required, distortion during nitriding is much less than with carburizing and hardening.

Carburizing is generally preferable to the other case hardening processes when a case having high strength and particularly high crushing load resistance is desired. When high resistance to wear is most important, a carbonitrided or nitrided steel surface is preferred.

8.5 Through Hardening: Carbon and alloy steel may be hardened by quenching from the austenitizing temperature. Generally, steels having 0.30% or more carbon are through hardened. Steels capable of being quenched to high hardness throughout their cross section are described as "through hardened".

The level of "as quenched" surface hardness is dependent on the carbon content, the quench intensity and the quenching temperature. Hardnesses at various depths under the surface are also dependent on these factors plus the hardenability of the steel. Hardenability is determined by alloy content.

To prevent surface decarburization, a protective atmosphere having a carbon potential nearly equal to the carbon content of the work is commonly utilized in batch and continuous furnaces used for through hardening. Subsequent tempering is required to achieve desired hardness, ductility and toughness.

8.6 Selective Heating and Hardening: Carbon and alloy steels may be subjected to selective hardening when a hard case and comparatively soft core are desired, or when only a portion of the steel surface is to be hardened. Hardening is accomplished by rapidly heating the area to be hardened to austenitizing temperature, then quenching rapidly before the heat can diffuse.

8.6.1 Induction Hardening: Selective heating is most commonly accomplished by means of an inductor that carries a high frequency alternating current. Depending on the application, the frequency generally ranges from 60 to 500 000 Hz. Steel in the immediate vicinity of the inductor is heated rapidly by induced eddy currents. The inductive heating machine may be designed to cause the work to revolve or traverse past the inductor, so that a large surface can be heated by a relatively small inductor. In some induction heating setups, both the work and inductor remain stationary during the heating cycle. Relatively low frequency current is used for deep heating, whereas high frequency current is used for shallow heating. The area to be hardened is heated until the required depth of hardening reaches austenitizing temperature. The work is then quenched, either by flooding with, or immersing into, a quenching medium.

8.6.2 Flame Hardening: Selective heating can also be accomplished by a hot flame from one or a series of torch nozzles. Oxygen plus acetylene (or one of several commercially available torch heating gases) are used as the source of energy.

8.6.3 Laser and E.B. Hardening: Two relatively new, more sophisticated methods now coming into use for selective heating are the laser beam and the electron beam. In either case, the high energy beam is directed at the area to be heated. If the area is heated to a very shallow depth, the surface can be "self quenched" whereby the cold mass of the part causes the hot surface to cool very rapidly without any external quenching. If deeper depths are heated, conventional quenching methods must be employed.

Hardened parts can be selectively softened by any of these methods. The parts are simply heated to the required temperature and allowed to cool in air.

8.7 Deep Freezing: If a carburized or through hardened part contains a high level of retained austenite (greater than approximately 30%), surface hardenesses can be significantly increased by cooling the work to a temperature of -40°F (-40°C) or lower, thus converting nearly all retained austenite in the structure to hard martensite. It is often necessary to temper or retemper after deep freezing.

8.8 Tempering: Most "as quenched" carburized, through hardened, and selectively hardened steel is subjected to a tempering heat treatment to convert the very hard, brittle untempered martensite to a tempered condition that is softer and more ductile. Hardness reduction is dependent on tempering temperature, and on time at temperature, which can vary from a few seconds to several hours. Carburizing grade steels are usually tempered at 250-400°F (120-205°C), while steels having 0.30% or more carbon content are tempered at 700-1100°F (370-595°C), depending on the hardness level desired.

Some steels become brittle when tempered at 400-700°F (205-370°C). Susceptibility to this condition, known as blue brittleness, should be investigated before a steel is tempered within this temperature range.

8.8 Austempering: This heat treatment is used when a combination of fairly high hardness (35-55 RC) and good toughness is essential. It is not used on steels having 0.40% or less carbon content, and is applicable only to steels and cast irons having certain time-temperature transformation characteristics.

The work is heated to austenitizing temperature and quenched very quickly in a salt or oil bath maintained at a temperature just above the Ms (start of martensite transformation) temperature. The steel is held at this temperature for sufficient time to form a structure having a high percentage of hard, tough lower bainite and then cooled to room temperature.

8.9 Martempering and Marquenching: When freedom from distortion is important and some hardness reduction from that obtained by conventional quenching can be accepted, a steel part is quenched into hot oil or molten salt (at a temperature at or just below the MS temperature). This process, known as martempering, is not a replacement for tempering. Martempered parts are cooled to room temperature and then given a conventional tempering treatment. When martempering is applied to carburizing grade steels, it is sometimes referred to as marquenching.

8.10 Quenching: An important parameter in the determination of "as quenched" hardness for a steel part is the quench severity. The level of severity is dependent upon the quenching medium used, the quenchant temperature, the temperature of the steel being quenched, and the quenching pressure (rate at which the quenchant is supplied to the metal surface).

In order of increasing severity, commonly used liquid quenchants are molten salt, oil, soluble oil-water mix, polymer solutions, water, brine, and caustic soda solution. It is usually desirable to obtain the greatest quench severity that can be used without subjecting the steel to cracking, objectionable distortion, or excessive stresses that cannot be overcome by subsequent tempering.

8.10 (Continued):

Some high-hardenability steels are quenched in forced air, or even in still air. Some tool steels can be quenched in fluidized beds of rapidly agitated small solid particles.

8.11 Stress Relieving: This operation consists of uniformly heating a part or structure to a temperature below the transformation temperature and holding for a predetermined length of time. The time must be long enough to equalize temperature throughout the part and followed by uniform cooling at a fairly slow rate, usually by air cooling. Stress relieving temperatures vary from 300-1300°F (150-705°C) depending on the type of steel being treated. (Temperatures above the transformation temperature will remove the effects of prior heat treatment.) This operation is used to relieve residual stresses that may have resulted from manufacturing processes such as cold working, welding, or heat treatment. No change in the basic microstructure is expected.

The phi (Ø) symbol is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. If the symbol is next to the report title, it indicates a complete revision of the report.

TABLE 1 — Typical Treatments for Case Hardening Grades of Carbon Steels

UNS No.	SAE Steels[a]	Carburizing Temperature, °F	°C	Cooling Medium	Reheat Temperature, °F	°C	Cooling Medium	Carbonitriding Temperature, °F[b]	°C[b]	Cooling Medium	Temper °F	°C[c]
G10100	1010	—	—	—	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10150	1015	—	—	—	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10160	1016	1650–1700	900–925	Water or Caustic	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10180	1018	1650–1700	900–925	Water or Caustic	1450	790	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G10200	1020	1650–1700	900–925	Water or Caustic	1450	790	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G10220	1022	1650–1700	900–925	Water or Caustic	1450	790	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G10260	1026	1650–1700	900–925	Water or Caustic	1450	790	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G10300	1030	1650–1700	900–925	Water or Caustic	1450	790	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G11170	1117	1650–1700	900–925	Water or Oil	1450–1600	790–870	Water or Caustic[d]	1450–1650	790–900	Oil	250–400	120–205
G11180	1118	1650–1700	900–925	Oil	1450–1600	790–870	Oil	—	—	—	250–400	120–205
G15130	1513	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15220	1522	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15240	1524	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15260	1526	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15270	1527	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205

[a] Generally, it is not necessary to normalize the carbon grades for fulfilling either dimensional or machinability requirements of parts made from the steel grades listed in the table although, where dimension is of vital importance, normalizing temperatures of at least 50°F above the carburizing temperatures are sometimes required.

[b] The higher manganese steels such as 1118 and the 1500 series are not usually carbonitrided. If carbonitriding is performed, care must be taken to limit the nitrogen content because high nitrogen will increase their tendency to retain austenite.

[c] Even where recommended tempering temperatures are shown, the temper is not mandatory on many applications. Tempering is generally employed for a partial stress relief and improves resistance to cracking from grinding operations. Higher temperatures than those shown may be employed where the hardness specification on the finished parts permits.

[d] 3% sodium hydroxide.