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Carbon and Alloy Steels

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MATERIALS REPORT

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Ø CARBON AND ALLOY STEELS

1. STEEL:

Steel is a malleable alloy of iron and carbon which has been made molten in the process of manufacture and which contains approximately 0.05-2.0% carbon, as well as some manganese and sometimes other alloying elements.

1.1 Carbon Steel: Steel is considered to be carbon steel when no minimum content is specified or required for aluminum, chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium, or any other element added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40%; or when the maximum content specified for any of the following elements does not exceed the following percentage: manganese, 1.65%; silicon, 0.60%; copper, 0.60%. Boron may be added to killed fine grain carbon steel to improve hardenability.

In all carbon steels, small quantities of certain residual elements, such as copper, nickel, molybdenum, chromium, etc., are unavoidably retained from raw materials. Those elements are considered incidental. However, if any of these elements are considered detrimental for special applications, the maximum acceptable content of these incidental elements should be specified by the purchaser.

1.2 Alloy Steel: Steel is considered to be 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 in which a definite range or definite minimum quantity for any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels: aluminum and chromium up to 3.99%; cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect.

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2. STEELMAKING PROCESSES:

These fall into two general groups, acid or basic, according to the character of the furnace lining. Thus, open hearth or electric processes may be either acid or basic. Basic oxygen is a relatively recent addition to the list of steelmaking processes and, as the name implies, is exclusively basic. The choice of an acid or basic furnace is usually determined mainly by the phosphorus in the available raw materials and the content of phosphorus permissible in the finished steel.

Phosphorus is an acid-forming element and, in its oxide form, will react with any suitable base to form a slag in the steelmaking furnace. In basic processes, the metallurgist and steelmaker take advantage of this chemical behavior by oxidizing the phosphorus with iron oxide, which yields up its oxygen to the phosphorus. This permits the iron to remain as part of the steelmaking bath, while the acid phosphoric oxide is separated by floating up into the molten basic lime slag. In acid processes, furnaces are generally lined with silica, which is acid in nature and will not tolerate the use of basic materials for fluxes. Since an acid slag has no affinity for impurities such as phosphorus, the steel cannot be dephosphorized by fluxing and the content of this element remains at the level contained in the raw material, or may be concentrated somewhat in the finished steel due to loss of other materials from the original metallic charge.

Most iron ores in the United States are of a phosphorus content suitable only for basic steelmaking processes; hence, all of the nation's wrought steel is so made. A small proportion is low enough in phosphorus that steel could be made from it by acid processes, although such steels invariably would have higher residual phosphorus levels than steels made in basic lined furnaces. The following are the principal steelmaking processes used in the United States with approximate percentage of total raw steel production in 1977.

2.1 Basic Open Hearth: 16%: Because of its flexibility to accommodate iron produced from available ores and basic fluxes for removal of objectionable elements such as phosphorus and sulfur, the basic open hearth was the most widely used steelmaking process. It is used to produce all SAE carbon and alloy steels, except compositions designated as electric furnace grades.

2.2 Basic Electric: 22%: The principal advantage of this process is optional control in the furnace permitting steel to be treated under oxidizing, reducing, or neutral slags, and pouring off and replacement of slags during the process. In this manner, and depending upon specified requirements, objectionable elements may be substantially reduced and a high degree of refinement obtained in the steel bath. Practically all grades of steel can be made by the basic electric furnace; and the process with or without supplementary processes is used for producing SAE wrought stainless steels.

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2.3 Basic Oxygen: 62%: Steelmaking capacity by this process was first introduced in the United States and Canada in 1954 and has been growing at a substantial rate. It is now the most popular method of steel production. The prime advantage of this process is the rate at which steel can be produced. The nature of the process is such that large quantities of molten iron must be readily available, since refining is accomplished by the exothermic reactions of high-purity oxygen with the various elements contained in the molten iron. In respect to its essential chemical composition and metallurgical characteristics, steel of a specified grade which has been made by the basic oxygen process is similar to basic open hearth steel of the same grade. The differences between these two processes are chiefly in the design of the furnace employed and in the relative extent to which high-purity oxygen is used as a refining agent.

2.4 Other: Another method increasing in use in the production of stainless, tool and specialty steels is ESR (Electro-Slag Refining). In this process, as-cast electric furnace melted electrodes are progressively melted and solidified in a water cooled copper mold under a blanket of molten flux. Melting results from the heat generated by the resistance of the molten flux to electric current passing between the electrode and the solidifying ingot. Refining occurs as the electrode melts and droplets of molten metal pass through the flux and their impurities are removed by reaction with the flux. The progressively solidified ingot thus produced is very homogeneous and sound, and may be directly processed into mill products.

In recent years the AOD (argon oxygen decarburization) process has become an important new steel refining system for specialty steel grades. Originally employed to replace electric furnace basic slag practice for stainless steels, it is now refining alloy, tool, silicon-iron, electrical and other specialties. The AOD system refining vessel simply accepts molten iron from whatever source is available, that is, electric furnace, BOF, blast furnace or cupola and completes all chemical and refining stages.

The process is based on the principle that when argon gas is mixed with oxygen and injected into the melt, the inert gas dilutes the carbon monoxide resulting from the oxidation of carbon and reduces its partial pressure. This shifts the reaction equilibrium to favor the oxidation of carbon over other oxidizable metals such as chromium. As a result, a higher chromium content can be charged in the melt allowing the conservation of ferrochromium and making this attractive in the economic production of stainless steel.

AOD melting also allows control of hydrogen in flake sensitive grades to the point that the need for long anneals is eliminated.

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2.5 Vacuum Treatment: The use of vacuum treatment in the United States has grown rapidly since the first production installation. It can be employed with any of the principal steelmaking processes and is adaptable to all grades of carbon and alloy steel.

There are two types of treatments commonly used. The first is simply "vacuum degassing" the steel to remove hydrogen gas and avoid the necessity for long slow cooling cycles for heavy sections such as blooms, billets, and slabs. The reduced hydrogen content provides steel with improved internal soundness and resistance to internal rupturing or "flaking." The second treatment is referred to as "vacuum carbon deoxidation." While this reprocess will also remove hydrogen from the liquid steel, it serves the added purpose of deoxidizing the steel. The low pressure in the vacuum chamber forces the carbon and oxygen dissolved in the liquid steel to combine to form gaseous carbon monoxide which is then removed through the vacuum system. Steels deoxidized in this manner do not require the large additions of silicon and aluminum used in conventional practice, and the products produced from VCD treated steels exhibit improved microcleanliness compared with the conventional product. The VCD treatment is commonly used in producing bearing and aircraft quality steels, and steels for other critical applications.

2.6 Strand Casting: This process involves the direct casting of steel from the ladle into slabs, blooms, or billets. In strand casting, a heat of steel is tapped into a ladle in the conventional manner. The liquid steel is then teemed into a tundish which acts as a reservoir to provide for a controlled casting rate. The steel flows from the tundish into the casting machine and rapid solidification begins in the open-ended molds. The partially solidified slab, bloom, or billet is continuously extracted from the mold. Solidification is completed by cooling the moving steel surface. Several strands may be cast simultaneously, depending upon the heat size and section size. A reduction in size may be carried out by hot working the product prior to cutting the strand into lengths. Chemical segregation is minimized, due to the rapid solidification rate of the strand cast product.

When two or more heats are cast without interruption, the process is called continuous strand casting.

3. QUALITY CLASSIFICATIONS:

Technically, quality, as the term relates to steel products, may be indicative of many conditions, such as the degree of internal soundness, relative uniformity of composition, relative freedom from detrimental surface imperfections, and finish. Steel quality also relates to general suitability for particular applications. Sheet steel surface requirements may be broadly identified as to the end use by the suffix E for exposed parts requiring a good painted surface, and the suffix U for unexposed parts for which surface finish is unimportant.

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3. (Continued):

Carbon steel may be obtained in a number of fundamental qualities which reflect various degrees of the quality conditions mentioned above. The quality designations for various products are listed in Table 1. Some of those qualities may be modified by such requirements as austenitic grain size, special discard, macroetch test, special hardenability, maximum incidental alloy elements, restricted chemical composition, and nonmetallic inclusions. In addition, several of the products have special qualities which are intended for specific end uses or fabricating practices, that is, scrapless nut quality, axle shaft quality, gun barrel quality, or shell quality.

Alloy steels also may be obtained in special qualities, some of which are listed in Table 1. Superimposed upon some of these qualities may be such requirements as extensometer test, fracture test, impact test, macroetch test, nonmetallic inclusion tests, special hardenability test, and grain size test.

For complete descriptions of the qualities and supplementary requirements for carbon and alloy steels, reference should be made to the latest applicable AISI Steel Products Manual Section. Titles of these manuals are listed at the end of this SAE Information Report.

4. TYPES OF STEEL:

In most steelmaking processes the primary reaction is the combination of carbon and oxygen to form a gas. If the oxygen available for this reaction is not removed prior to or during casting, the gaseous products continue to evolve during solidification. Proper control of the evolution of gas determines the type of steel.

4.1 Killed steel is a type of steel from which there may be only a slight evolution of gases during solidification of the metal. Killed steels have more uniform chemical composition and properties than the other types. However, there may be variations in composition, depending upon the steelmaking practices used. Alloy steels are of the killed type, while carbon steels may be killed or may be of the following types.

4.2 Rimmed steels have marked differences in chemical composition across the section. The typical structure of rimmed steel results from a marked gas evolution during solidification of the outer rim, caused by a reaction between the carbon in the solidifying metal and dissolved oxygen. The outer rim is lower in carbon, phosphorus, and sulfur than the average composition, whereas the inner portion, or core, is higher than the average in those elements. The technology of manufacturing rimmed steels limits the maximum contents of carbon and manganese and those maximum contents vary among producers. Rimmed steels do not retain any significant percentages of highly oxidizable elements, such as aluminum, silicon, or titanium.

Rimmed steel products, because of their chemical composition and their surface and other characteristics, may be used advantageously for the manufacture of finished articles involving cold bending, cold forming, deep drawing and, in some cases, cold heading applications.

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4.3 Semikilled steels have characteristics intermediate between those of killed and rimmed steels. During the solidification of semikilled steel, some gas is evolved and entrapped within the body of the ingot. This tends to compensate for the shrinkage which accompanies solidification.

4.4 Capped steels have characteristics which combine some features of rimmed and semikilled steels. After pouring, the rimming action is stopped after a brief interval by means of mechanical or chemical capping. The thin lower carbon rim has surface and forming properties comparable to those of rimmed steel, whereas the uniformity of composition and properties more nearly approaches that of semikilled steels. Capped steel products, because of their chemical composition, surface, and other characteristics, may be used to advantage when the material is to withstand cold bending, cold forming, or cold heading.

5. <u>COMMONLY SPECIFIED ELEMENTS</u>:

It is the purpose here to outline briefly the effects of various elements on the steelmaking practices and steel characteristics. The effects of a single element on either practice or characteristics are modified by the influence of other elements. These interrelations, frequently of a synergistic nature, must be considered when evaluating a change in specified composition. However, to simplify this presentation, the various elements will be discussed individually. The scope of this discussion will permit only suggestions of the modifying effects of other elements or of steelmaking practices on the effects of the element under consideration. Aluminum, titanium, and columbium, though not specified in SAE standard steels, are at times present to achieve deoxidation or fine grain size.

5.1 <u>Carbon</u>: The amount of carbon required in the finished steel limits the type of steel that can be made. As the carbon content of rimmed steels increases, surface quality becomes impaired. Killed steels in approximately the 0.15-0.30% carbon content level may have poorer surface quality and require special processing to attain surface quality comparable to higher or lower carbon content steels. Carbon has a moderate tendency to segregate, and because of its major effect on properties, carbon segregation is frequently of more significant importance than the segregation of other elements. It is the principal hardening element in all steel. Tensile strength in the as-rolled condition increases as the carbon increases up to about 0.85% carbon. Ductility and weldability decrease with increasing carbon.

5.2 Manganese has a lesser tendency for macrosegregation than any of the common elements. Steels above 0.60% manganese cannot be readily rimmed.

Manganese is beneficial to surface quality in all carbon ranges (with the exception of extremely low carbon rimmed steels) and is particularly beneficial in resulfurized steels. It contributes to strength and hardness, but to a lesser degree than does carbon, the amount of increase being dependent upon the carbon content. Increasing the manganese content decreases ductility and weldability, but to a lesser extent than does carbon. Manganese has a strong effect on increasing the hardenability of a steel.

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5.3 Phosphorus segregates, but to a lesser degree than carbon and sulfur. Increasing phosphorus increases strength and hardness and decreases ductility and notch-impact toughness in the as-rolled condition. The latter adverse effects are greater in quenched and tempered higher carbon steels. Higher phosphorus is often specified in low-carbon free-machining steels to improve machinability.

5.4 <u>Sulfur</u>: Increased sulfur content lowers transverse ductility and notch impact toughness, but has only a slight effect on longitudinal mechanical properties. Weldability decreases with increasing sulfur content. This element is very detrimental to surface quality, particularly in the lower carbon and lower manganese steels. For these reasons, only a maximum limit is specified for most steels. The only exception is the group of free-machining steels, where sulfur is added to improve machinability, in which case a range is specified.

Sulfur has a greater segregation tendency than any of the other common elements.

Sulfur occurs in steel principally in the form of sulfide inclusions. Obviously, greater frequency of such inclusions is to be expected in the resulfurized grades.

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5.5 Silicon is one of the principal deoxidizers used in steelmaking and, therefore, the amount of silicon present is related to the type of steel. Rimmed and capped steels contain no significant amounts of silicon. Semikilled steels may contain moderate amounts of silicon, although there is a definite maximum amount that can be tolerated in such steels. Killed carbon steels may contain any amount of silicon up to 0.60% maximum.

Silicon is somewhat less effective than manganese in increasing as-rolled strength and hardness. Silicon has only a slight tendency to segregate. In low carbon steels, silicon is usually detrimental to surface quality, and this condition is more pronounced in low-carbon resulfurized grades.

5.6 Copper has a moderate tendency to segregate. Copper in appreciable amounts is detrimental to hot working operations. Copper adversely affects forge welding, but it does not seriously affect arc or acetylene welding. Copper is detrimental to surface quality and exaggerates the surface defects inherent in resulfurized steels. Copper is, however, beneficial to atmospheric corrosion resistance when present in amounts exceeding 0.20%.

5.7 Lead is an element sometimes added to carbon and alloy steels through mechanical dispersion during teeming for the purpose of improving the machining characteristics of such steels. When so added, the range is generally 0.15-0.35%.

5.8 Boron is added to fully killed steel to improve hardenability. Boron-treated steels are produced to a range of 0.0005-0.003%. Whenever boron is substituted in part for other alloys, it should be done only with hardenability in mind, because the lowered alloy content may be harmful on some applications. Boron is most effective in lower carbon steels.

5.9 Chromium is generally added to steel to increase resistance to corrosion and oxidation, increase hardenability, improve high-temperature strength, or improve abrasion resistance in high carbon compositions. Chromium is a strong carbide former. Complex chromium-iron carbides go into solution in austenite slowly; therefore, a sufficient heating time before quenching is necessary.

Chromium is essentially a hardening element, and is frequently used with a toughening element such as nickel to produce superior mechanical properties. At higher temperatures, chromium contributes increased strength, but is ordinarily used for applications of this nature in conjunction with molybdenum.

5.10 Nickel, when used as an alloying element in constructional steels, is a ferrite strengthener. Since nickel does not form any carbide compounds in steel, it remains in solution in the ferrite, thus strengthening and toughening the ferrite phase. Nickel steels are easily heat treated because nickel lowers the critical cooling rate. In combination with chromium, nickel produces alloy steels with greater hardenability, higher impact strength, and greater fatigue resistance than are possible with carbon steels.

5.11 Molybdenum is added to constructional steels in the normal amounts of 0.10-0.60%. When molybdenum is in solid solution in austenite prior to quenching, the reaction rates for transformation become considerably slower as compared with carbon steel. Molybdenum steels in the quenched condition require higher tempering temperatures to obtain the same degree of softness as comparable carbon and alloy steels. Alloy steels which contain 0.15-0.30% molybdenum show a minimized susceptibility to temper embrittlement.

5.12 Vanadium is one of the strong carbide forming elements. It dissolves to some degree in ferrite, imparting strength and toughness. Vanadium steels show a much finer structure than steels of a similar composition without vanadium. Vanadium gives other alloying effects of importance, namely increased hardenability where it is in solution in the austenite prior to quenching, a secondary hardening effect upon tempering, and increased hardness at elevated temperatures.

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6. AISI STEEL PRODUCTS MANUALS:

The American Iron and Steel Institute's Technical Committee cooperates with the SAE Iron and Steel Technical Committee on standardization of compositions and related data on steels used in the automotive industries.

AISI publishes Steel Products Manual Sections as listed below. Copies are available to steel users from the American Iron and Steel Institute, 1000 16th St., NW, Washington, DC 20036.

Alloy, Carbon, and High-Strength Low Alloy Steels, Semifinished for Forging; Hot Rolled Bars; Cold Finished Steel Bars; Hot Rolled Deformed and Plain Concrete Reinforcing Bars
Plates; Rolled Floor Plates: Carbon, High Strength, Low Alloyed, Alloy Steel
Alloy Steel Plates
Carbon Steel Pipe, Structural Tubing, Line Pipe, Oil Country Tubular Goods
Sheet Steel; Carbon, High Strength Low Alloy and Alloy (Coils and Cut Lengths)
Strip Steel; Carbon, High Strength, Low Alloy and Alloy
Tin Mill Products
Wire and Rods, Carbon Steel
Cold Rolled Flat Steel Wire
Railway Track Materials
Wrought Steel Wheels and Forged Railway Axles
Alloy Steel Sheets and Strip
Stainless and Heat Resisting Steels
Tool Steels
Wire and Rods, Alloy Steel
Flat Rolled Electrical Steel
Steel Specialty Tubular Products

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