

**(R) Carbon and Alloy Steels**

1. **Scope**—This SAE Information Report describes the processing and fabrication of carbon and alloy steels. The basic steelmaking process including iron ore reduction, the uses of fluxes, and the various melting furnaces are briefly described. The various types of steels: killed, rimmed, semikilled, and capped are described in terms of their melting and microstructural differences and their end product use. This document also provides a list of the commonly specified elements used to alloy elemental iron into steel. Each element's structural benefits and effects are also included. A list of the AISI Steel Products Manuals is included and describes the various finished shapes in which steel is produced.

2. **References**

2.1 **Applicable Publications**—The following publications form a part of this specification to the extent specified herein.

2.1.1 AISI MANUALS—Available from the Iron and Steel Society, 410 Commonwealth Drive, Warrendale, PA 15086, Telephone (412) 776-1535.

- Bar Steel: Alloy, Carbon, and Microalloy Steels: Semifinished, Hot-Rolled Bars, Cold Finished Bars, Hot-Rolled Deformed and Plain Concrete Reinforcing Bars
- Plates and Rolled Floor Plates: Carbon, High-Strength Low-Alloy and Alloy
- Carbon Steel Pipe, Structural Tubing, Line Pipe, Oil Country Tubular Goods
- Sheet Steel: Carbon, High-Strength Low Alloy, and Alloy: Coils and Cut Lengths (Including Coated Products)
- Strip Steel: Carbon, High-Strength Low Alloy, and Alloy
- Tin Mill Products
- Carbon Steel, Wire and Rods
- Cold Rolled Flat Steel Wire
- Railway Track Material
- Stainless and Heat Resisting Steels
- Tool Steels
- Steel Specialty Tubular Products
- Hot-Rolled Structural Shapes, H-Piles and Sheet Piling

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2.1.2 ASTM PUBLICATION—Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM A 29—Specification for Steel Bars, Carbon and Alloy, Hot-Wrought and Cold-Finished, General Requirements for

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

3.1 **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%. For fine grain carbon steels, minimum or maximum levels of grain refiners (Al, Cb, V) can be specified. 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 detrimental for special applications, the maximum acceptable content of these incidental elements should be specified by the purchaser.

3.2 **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.

4. **Steelmaking Processes**—These fall into two general groups: acid or basic, according to the character of the furnace lining. Thus electric processes may be either acid or basic. Basic oxygen, as the name implies, is an exclusively basic process. 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. The following are the principal steelmaking processes used in the United States:

4.1 **Basic Electric**—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 on 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.

- 4.2 Basic Oxygen**—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.
- 4.3 Ladle Refining**—Today the majority of steels are actually refined to final chemistry and cleanliness requirements in a ladle refining facility. This facility takes the ladle of steel which was tapped from the electric arc furnace (EAF) or basic oxygen furnace (BOF), and through the use of the ladle as a vessel further refines the steel. Through the use of optional electric arc reheating capability, inert gas stirring, and optional degassing capabilities; the ladle of steel is trimmed to the final chemistry requirements and inclusions are removed for cleaner steel. The ladle refining station is the facility which actually makes the specific grade of steel to the customer's specification.
- 4.4 Other**—Another method increasing in use in the production of stainless, tool, and specialty steels is ESR (electroslag 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.

The AOD (argon oxygen decarburization) process has become an important 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.

- 4.5 Vacuum Treatment**—The use of vacuum treatment can be employed with electric furnace, BOF, and ladle metallurgy furnace steelmaking, 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 infrequently utilized since the advent of ladle metallurgy facilities. It is referred to as "vacuum carbon deoxidation" (VCD). While this process will also remove hydrogen from the liquid steel, it serves the added purpose of deoxidizing the steel. These steels exhibit improved cleanliness compared with conventional product.

In today's modern steelmaking practices, the steel cleanliness is usually achieved in the ladle metallurgy treatment, and VCD treatments are not frequently used. During the ladle metallurgy treatment, the liquid steel is constantly being stirred via argon gas or induction stirring. This induces the liquid steel to have contact with the artificial slag cover on the ladle, the artificial slag captures the inclusions in the steel and prevents them from reentering the molten steel.

**4.6 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 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 water cooled copper molds. The partially solidified slab, bloom, or billet is continuously extracted from the mold by an up and down oscillating movement of the mold. Solidification is completed by cooling the moving cast shape through a water cooling spray system. Several strands may be cast simultaneously, depending on the heat size and section size. A reduction in size may be carried out by hot working the product prior to cutting the standard into lengths. Chemical segregation is minimized, due to the rapid solidification rate of the strand cast product.

Good casting practice should include measures to protect the molten steel from reoxidation (exposure to air). These measures include, but are not limited to, ladle to tundish shrouding, artificial tundish slag, tundish to mold shrouding, and mold powder. The shrouding technique can employ ceramic shrouds, gaseous shrouds or some combination of both.

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

Some strand casting machines can incorporate electromagnetic stirring (EMS) in the molds and/or below the molds. The EMS stirs the molten steel within the solidified shell. Also below the mold or prior to complete solidification soft or hard reduction of the strand can be employed. These steps help to improve as-cast center quality, reduce segregation, and promote the formation of an equiaxed grain zone.

The process of strand casting steel has become the predominant process for the manufacture of steel products. This is due to the advances in the technology of strand casting both from a production aspect and material quality aspect. The quality of strand cast material has become at least equivalent, and in many cases better than the traditional ingot casting process.

**4.7 Ingot Casting**—This process has been designed to meet a variety of conditions of manufacture. Ingots are usually cast as square or rectangular in cross section with rounded corners. Occasionally they are cast in round cross sections. They are usually tapered and cast big end up and hot topped. Ingot steel is subject to internal variations in chemical composition and structure due to the natural phenomena which occur as the steel solidifies.

Shrinkage in the ingot during solidification results in the formation of a central cavity known as pipe. Primary pipe is located in the upper portion of the ingot. Under some conditions, another shrinkage cavity, known as secondary pipe, may form in the ingot below but not connected with the primary pipe. Secondary pipe is normally not exposed to the air and therefore not oxidized. This allows it to be welded during hot working of the ingot, and results in no detriment to the integrity of the product. Primary pipe is controlled by the hot topping system and any remnants are cropped during the ingot breakdown.

There are two methods of ingot production, bottom pouring and top pouring. In bottom pouring, the molten steel flows through a center sprue or trumpet into a runner system filling the ingots from the bottom. Generally there are multiple ingots filled simultaneously from one runner system. The molten steel in the ingot molds is covered by a bottom pouring flux compound.

Additionally, the teeming stream can be shrouded to reduce the potential for steel reoxidation and the generation of exogenous inclusions. Once the ingots are filled, a hot topping compound is applied to each ingot.

Top pouring is accomplished by filling each ingot individually by teeming the molten steel directly into the top of each ingot much like filling a glass of water. Once the mold is filled, a hot topping compound may be applied to each ingot. Shrouding of the teeming stream is generally more difficult and not as effective in top pouring.

**5. Steel Processing**—After the molten steel has solidified into a solid in either the strand casting process or the ingot process the as-cast product is processed into a finished product through several stages. These include primary rolling, inspection, conditioning, hot-rolling, and sometimes cold finishing.

**5.1 Primary Rolling, Inspection, and Conditioning**—Cast blooms and ingots are reduced into billets by hot-rolling. This is called primary rolling, and it is also a phase where manufacturers have an opportunity to inspect and enhance the surface of the billet by conditioning.

Primary rolling involves the reheating or “soaking” of the ingot or cast bloom followed by the reduction of the heated section by rolling in continuous or reversing type primary mills. In a continuous mill, the section is continuously passed through one or more strands to produce the billet or bloom. In a reversing mill, the section is alternately passed forward and backward, reducing the section into a billet or bloom.

Generally, at some point in the primary rolling process, the surface of the section is inspected and conditioned. Inspection is the process of detecting surface imperfections and conditioning is the means of removing them. Inspection of the surface may be visual or automatic by magnetic particle or other means. Conditioning generally involves the removal of surface imperfections by grinding, torching, or other means.

Ultrasonic testing of billets can also be performed to test internal quality of the billets.

**5.2 Hot-Rolling**—Hot-rolling initially involves the reheating of billets in continuous furnaces that tightly control temperature and atmosphere to limit surface decarburization. Heated billets exit the furnace and pass through a series of rolling stands for reduction into the bar section, which goes on to a cooling bed or into a coiling tub. Interstand cooling, tension-free rolling and continuous, electronic dimensional measuring with feedback are some of the measures employed to achieve high quality, hot-rolled product.

**5.3 Cold Finishing**—Some products receive additional processing through cold finishing operations. These operations are designed to enhance the steel’s surface quality and/or mechanical properties.

**6. 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 less important.

Carbon steel may be obtained in a number of fundamental qualities, which reflect various degrees of the quality conditions mentioned. 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. Superimposed on 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 Steel Products Manual Section. Titles of these manuals are listed in Section 2.

- 7. Types of Steel**—In steelmaking, the principal 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 produced. All alloy steels and strand cast steels are killed steels. Killed steels refers to those steels which have a deoxidizing element (such as aluminum or silicon) added to eliminate the gaseous oxygen. Carbon steel may be produced as killed, semi-killed, or rimmed. The vast majority of steels are of the killed type.
- 7.1** 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 on the steelmaking practices used. Alloy steels are of the killed type, while carbon steels may be killed or may be of the following types:
- 7.2** 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.
- 7.3** Semi-killed 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 that accompanies solidification.
- 7.4** Capped steels have characteristics, which combine some features of rimmed and semi-killed 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 semi-killed 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.
- 8. Commonly Specified Elements**—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.
- 8.1 Carbon** is present in all steel and is the principal hardening element. The hot-rolled strength and hardness increase significantly with increased carbon content, particularly at the low and medium carbon levels. Ductility and weldability decrease with increasing carbon content. Carbon also determines the level of hardness or strength attainable by quenching. Carbon segregates, and because of its major effect on properties, carbon segregation is frequently of more significance and importance than the segregation of other elements.

- 8.2 Manganese** contributes to strength and hardness, but to a lesser degree than carbon. The amount of increase in these properties is dependent upon the carbon content, that is, higher carbon steels are affected more by manganese than lower carbon steels. Increasing the manganese content decreases weldability, but to a lesser extent than carbon. Manganese tends to increase the rate of carbon penetration during carburizing and enhances hardenability in quenching. Manganese is generally beneficial to surface quality, particularly in resulfurized steels. Manganese has a moderate tendency to segregate during solidification.
- 8.3 Phosphorus** in appreciable amounts increases the hot-rolled strength and hardness, but at the sacrifice of ductility and toughness. Increased phosphorus content in quenched and tempered steels is also detrimental to ductility, toughness, and fatigue. Consequently, for most applications, phosphorus is maintained below a specific maximum. This varies with the grade and quality level. In certain low carbon, free machining steels, higher phosphorus content is specified for its effect on machinability. Phosphorus has a pronounced tendency to segregate.
- 8.4 Sulfur** lowers ductility and toughness in the transverse direction as the content increases. Weldability decreases with increasing sulfur. Sulfur is very detrimental to surface quality, particularly in the lower manganese steels. For these reasons, a maximum sulfur content is specified for most steels. However, for some steels, sulfur is added to improve the machinability. Sulfur also has a pronounced tendency to segregate. Sulfur occurs in steel primarily in the form of manganese sulfide inclusions. Obviously, greater frequency of such inclusions is to be expected in the resulfurized grades.
- 8.5 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. Semi-killed 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.
- Silicon can help improve toughness and reduce relaxator in heat-treated spring steels.
- 8.6 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%.
- 8.7 Lead** is an element sometimes added to carbon and alloy steels through mechanical dispersion during teeming or casting for the purpose of improving the machining characteristics of such steels. When so added, the range is generally 0.15 to 0.35%.
- 8.8 Boron** is added to steel in small amounts (0.0005 to 0.0030%) to increase hardenability. Special melting and heating techniques are essential to obtain the desired hardenability results. Boron does not measurably affect the hot-rolled, normalized, or annealed properties of steel. Boron is most effective as a hardenability agent in lower carbon steels.
- 8.9 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.

- 8.10 Nickel**, when used as an alloying element, 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.
- 8.11 Molybdenum** promotes hardenability of steel and is useful where hardenability control is essential. When molybdenum is in solid solution in austenite prior to quenching, the reaction rates for transformation become considerably slower as compared with carbon steel. It widens the temperature range of effective heat treated response since it has a tendency to form stable carbides. Molybdenum provides hardenability with a minimum detrimental effect on cold-forming characteristics. Molybdenum steels in the quenched condition require higher tempering temperatures to obtain the same degree of softness as comparable carbon and alloy steels. It also increases the tensile and creep strengths of steel at high temperatures. Alloy steels that contain 0.15% to 0.30% molybdenum show a minimized susceptibility to temper embrittlement.
- 8.12 Vanadium** increases the hot-rolled mechanical properties of steel and may be used to enhance hardenability. It can be used to inhibit austenitic grain growth through the formation of precipitates. The grain growth inhibiting effects promote a fine grain structure that imparts strength and toughness to steels. However, the precipitates of Al, Cb, and/or Ti offer a more effective means of austenitic grain coarsening resistance. Vanadium is also used in some microalloy steel since its ability to produce vanadium carbonitride precipitates from hot forging or hot-rolling temperatures imparts strength and hardness levels comparable to quench and tempered steels. It can be used in combination with columbium, aluminum, and/or titanium.
- 8.13 Aluminum** is primarily used as a deoxidizer and austenitic grain refiner. In increased amounts, it combines readily with nitrogen to form aluminum nitrides which combines readily with nitrogen to form aluminum nitrides which contribute to high surface hardness and superior wear resistance.
- 8.14 Selenium** is added to enhance machinability. It combines with manganese sulfide inclusions to modify their shape to be more globular; it also combines with manganese to form manganese selenides, which are inclusions which behave like manganese sulfides and are beneficial to machining.
- 8.15 Tellurium** is added to enhance machinability. Its main purpose is to modify the shape of the manganese sulfides. However, tellurium will form iron tellurides, which result in hot shortness problems and require special hot-rolling considerations.
- 8.16 Bismuth** is added to enhance machinability. It behaves much like lead in that it is present in a finely dispersed form in the solid steel.
- 8.17 Calcium** is added to steel to promote the strand castability of aluminum grain refined steel. It forms calcium aluminate inclusions which remain liquid at steel casting temperatures, as opposed to alumina inclusions which are solid at casting temperatures. The alumina inclusions build up on nozzles and shrouds and cause clogging problems. Calcium is also added to strand cast or ingot steels to modify the alumina inclusions from a hard, brittle stringer to a softer, globular inclusion which is less detrimental to carbide tooling during machining operations.