ArcelorMittal USA

ArcelorMittal

Guidelines for fabricating and processing plate steel

Quenching and tempering

Forming

Thermal cutting

Welding

Important

The information provided herein is based on testing or ArcelorMittal USA's experience and is accurate and realistic to the best of our knowledge at the time of publication. However, characteristics described or implied may not apply in all situations. ArcelorMittal USA reserves the right to make changes in practices that may render some information outdated or obsolete. In cases where specific plate properties are desired, ArcelorMittal USA should be consulted for current information and/or capabilities.

Cover Photos: ArcelorMittal USA would like to thank Sun Steel Treating, Inc. and Logan Corporation for photographs from their facilities.

ArcelorMittal USA

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Preface

Guidelines for fabricating and processing plate steel

Plate steel is defined as a flat, as-rolled or heat treated product sold in cut lengths in thicknesses of at least three-sixteenths inch and widths of at least 48 inches. Plate steel is widely used in a variety of end-user markets. For plate to be utilized, it must be further processed after shipment from the steel mill. This processing may be performed by service centers, plate processors, fabricators or original equipment manufacturers (OEM). Four processes account for the majority of this additional processing: quenching and tempering, forming, thermal cutting and welding. The following book provides guidelines on these processes. Also, to provide an introduction to plate steel terminology, a brief review is presented on the characteristics of plate steel.

Characteristics of plate steel

Plate chemistry

Steel is essentially a combination of iron and carbon. The carbon content normally ranges between several hundredths and one percent. Many other elements are added in small amounts to vary the mechanical characteristics of the steel.

Plate steel generally falls in the category of either a carbon steel, a high strength low alloy (HSLA) or an alloy steel:

Carbon steels comprise those grades where no minimum content is specified or required for aluminum, boron, chromium, cobalt, columbium (niobium), molybdenum, nickel, titanium, tungsten, vanadium or zirconium, or any other element added to obtain a desired alloying effect; when the specified minimum copper does not exceed 0.40 percent; when the maximum content specified for any of the following elements does not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60.

HSLA steels are carbon steels with small additions, typically less than 0.1 percent of microalloying elements, vanadium, columbium or titanium. They may also contain small additions of copper, nickel and chromium for improved atmospheric corrosion resistance.

Alloy steels comprise those grades which exceed the above limits, plus any grade to which any element other than those mentioned above is added for the purpose of achieving a specific alloying effect. Carbon and HSLA steels usually have a lower base price than alloy steels and, therefore, are much more widely applied.

For structural applications, plates normally do not exceed 0.30 percent carbon and 1.50 percent manganese. Plates can be ordered to chemistry limits, but are more frequently ordered to ASTM International specifications, which also include mechanical properties. Besides the standard ASTM industry-wide specifications, there are additional code-writing bodies such as API, ASME, ABS, AASHTO, SAE, U.S. Military and others with their own specifications. Individual consuming company specifications are also accepted. ArcelorMittal USA also offers its own proprietary grades for a number of applications.

Effects of elements

The effects of the commonly specified chemical elements on the properties of hot-rolled and heat-treated carbon, HSLA and alloy plates are discussed here by considering the various elements individually. In practice, however, the effect of any particular element will often depend on the quantities of other elements present in the steel. For example, the total effect of a combination of alloying elements on the hardenability of a steel is usually greater than the sum of their individual contributions. This type of interrelation should be taken into account whenever a change in a specific analysis is evaluated.

Carbon is the principal hardening element in steel, with each additional increment of carbon increasing the hardness and tensile strength of steel in the as-rolled, normalized or quenched and tempered condition. For structural applications, the carbon level is generally less than 0.30 percent. For improved ductility, weldability and toughness, carbon contents below 0.20 percent are preferred. A compromise must be maintained between higher carbon levels required for tensile properties and lower carbon levels associated with improved ductility, weldability and toughness.

Manganese is present in all commercial steels, and contributes significantly to a steel's strength and hardness in much the same manner but to a lesser extent than does carbon. Its effectiveness depends largely upon, and is directly proportional to, the carbon content of the steel. Another important characteristic of this element is its ability to decrease the critical cooling rate during hardening, thereby increasing the steel's hardenability. Its effect in this respect is greater than that of any of the other commonly used alloying elements.

Plate chemistry

Manganese is an active deoxidizer and shows less tendency to segregate than most other elements. Its presence in a steel is also highly beneficial to surface quality in that it tends to combine with sulfur, thereby minimizing the formation of iron sulfide, the causative factor of hot-shortness, or susceptibility to cracking and tearing at rolling temperatures.

Phosphorus is generally considered an impurity except where its beneficial effect on machinability and resistance to atmospheric corrosion is desired. While phosphorus increases strength and hardness to about the same degree as carbon, it also tends to decrease ductility and toughness or impact strength, particularly for steel in the quenched-and-tempered condition. The phosphorus content of most steels is, therefore, kept below specified maxima, which range up to 0.04 percent.

In the free-machining steels, however, specified phosphorus content may run as high as 0.12 percent. This is attained by adding phosphorus to the ladle, commonly termed "rephosphorizing."

Sulfur is generally considered an undesirable element except where machinability is an important consideration and **resulfurized,** free machining steels may be ordered. Examples are Clean-Cut™ and C1119®. Whereas sulfides in steel act as effective chip-breakers to improve machinability, they also serve to decrease transverse ductility and toughness. Moreover, increasing sulfur impairs weldability and can have an adverse effect on surface quality.

ArcelorMittal USA produces **Integra®** and **Fineline™** quality plates with maximum sulfur levels as low as 0.001 percent with calcium treatment for inclusion shape control. By controlling sulfur levels, significant improvements in mechanical properties are possible. Impact and fatigue properties improve. Ductility increases, especially in the through-thickness direction. Weldability and formability also improve.

Fineline™ and Integra® steels, low sulfur with inclusion shape control

	Introduced	% Sulfur max.
Conventional		0.035
Electric furnace quality		0.025
Integra®	1980	0.006
Fineline™	1977	0.010
Fineline™ Double-O-Five	1985	0.005
Fineline™ Double-O-Two	1990 1991	0.002* 0.001**

All Fineline™ steels are vacuum degassed.
* Available in popular grades.
** Available in selected grades only.

Silicon is one of the principal deoxidizers used in the manufacture of carbon and alloy steels and, depending on the type of steel, can be present in varying amounts up to 0.40 percent. Silicon is also a ferrite strengthener and is sometimes added as an alloying element up to approximately 0.5 percent in plate steel.

Nickel is one of the fundamental steel alloying elements. When present in appreciable amounts, it provides improved toughness, particularly at low temperatures. Nickel lowers the critical temperatures of steel, widens the temperature range for effective quenching and tempering, and retards the decomposition of austenite. In addition, nickel does not form carbides or other compounds which might be difficult to dissolve during heating for austenitizing. All these factors contribute to easier and more successful thermal treatment. Because of the tight adherent scale formed on reheating nickel containing steels, the surface quality of plates with nickel is somewhat poorer than those without nickel. Nickel is also added to copper containing steels to prevent copper induced hot-shortness.

Chromium is used in alloy steels primarily to increase hardenability, provide improved abrasion resistance and promote carburization. Of the common alloying elements, chromium is surpassed only by manganese and molybdenum in its effect on hardenability. Chromium forms a carbide that gives high-carbon chromium steels exceptional wear-resistance. And because its carbide is relatively stable at elevated temperatures, chromium is frequently added to steels used for high-temperature applications. Chromium is also a very important alloy addition to stainless steels, such as ArcelorMittal USA's Duracorr.®

Molybdenum exhibits a greater effect on hardenability per unit added than any other commonly specified alloying element except manganese or boron. It is a nonoxidizing element, making it highly useful in the melting of steels where close hardenability control is desired. Molybdenum is unique in the degree to which it increases the high-temperature tensile and creep strengths of steel and thus it is used together with chromium in A387 alloy steels for high-temperature pressure vessels. Its use also reduces a steel's susceptibility to temper embrittlement.

Vanadium is widely used as a strengthening agent in HSLA steels. Vanadium additions are normally 0.10 percent or lower. Vanadium bearing steels are strengthened by both precipitation hardening and refining the ferrite grain size. Precipitation of vanadium carbide and nitride particles in ferrite can provide a marked increase in strength. Thermo-mechanical-controlled-processing (for example, control rolling) increases the effectiveness of vanadium. Vanadium is also effective in increasing the hardenability and resistance to loss of strength on tempering in the quenched and tempered steels. ArcelorMittal USA's T-1™ grades rely on vanadium additions.

Columbium (Niobium) is most often used in steels that receive controlled thermomechanical treatment. Small additions of columbium in the range from 0.02 percent to 0.04 percent provide a significant improvement in yield strength. For a given addition, columbium is approximately two times as effective as vanadium as a strengthener. When the steel is finished below about 1700°F, columbium improves notch toughness primarily by refining grain size. At higher finishing temperatures, it may be detrimental to toughness. ArcelorMittal USA's BethStar™ grades rely on both columbium and vanadium additions for strength and toughness.

Copper is added to steel primarily to improve the steel's resistance to atmospheric corrosion, such as ArcelorMittal USA's weathering steels. In the usual amount between 0.20 percent to 0.50 percent, the copper does not significantly affect the mechanical properties. In levels to 1.00 percent, copper (in combination with nickel) can increase strength by precipitation aging as in ArcelorMittal USA's Spartan™ and A710 steels. Copper contributes to hot-shortness (unless nickel is also added) and a more adherent mill scale which adversely affects surface quality.

Boron has the unique ability to increase the hardenability of steel when added in amounts as small as 0.0005 percent. This effect on hardenability is most pronounced at the lower carbon levels, diminishing with increasing carbon content. Because boron is ineffective when it is allowed to combine with oxygen or nitrogen, its use is limited to aluminum-killed and titanium treated steels. Unlike many other elements, boron does not increase the ferrite strength of steel. Boron additions, therefore, promote improved machinability and formability at a particular level of hardenability. It will also intensify the hardenability effects of other alloys and, in some instances, decrease costs by making possible the reduction of total alloy content. Examples of boron containing steels are ArcelorMittal USA's A514 and T-1™ grades.

Aluminum is used principally to control grain size and achieve deoxidation. The fine-grained steels produced by aluminum killing show improved notch toughness over coarse-grained steels.

Melting and casting

Entrapped gases are deleterious to mechanical properties of steel. Several techniques exist to remove oxygen from the molten steel. ArcelorMittal USA reserves the right to select the most suitable method to meet the requirements of individual specifications.

In most steelmaking processes, a primary reaction involves the combination of carbon and oxygen to form carbon monoxide. Proper control of the amount of gas evolved during solidification determines the type of steel. If no gas is evolved, the steel is termed “killed.” Increasing degrees of gas evolution characterize semi-killed capped or rimmed steel. All ArcelorMittal USA product is produced from killed steel, unless otherwise specified.

Killed steels are strongly deoxidized and are characterized by a relatively high degree of uniformity in composition and properties. Most strand-cast plate steel is killed. In ingot steels, metal shrinks during solidification, and a cavity or “pipe” forms in the uppermost portion. A refractory hot-top is placed on the mold before pouring and filled with metal after the ingot is poured. The pipe formed will be confined to the hot-top section of the ingot, which is removed by cropping during subsequent rolling. The most severely segregated areas of the ingot will also be eliminated by this cropping.

While killed steels are more uniform in composition and properties than any other type, they are nevertheless susceptible to some degree of chemical segregation. As in the other grades, the top center portion of the ingot will exhibit the greatest degree of positive chemical segregation.

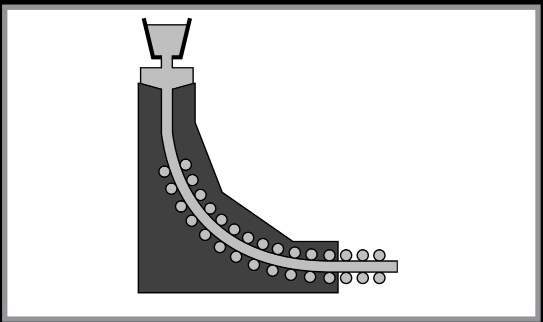
The uniformity of killed steel renders it most suitable for applications involving such operations as hot forging, cold extrusion, carburizing and thermal treatment.

Continuous casting

In traditional steelmaking, molten steel is poured into molds to form ingots. The ingots are removed from the molds, reheated and rolled into semifinished products — blooms, billets or slabs.

Continuous casting (also referred to as strand casting and slab casting) bypasses the operations between molten steel and the semifinished product. Molten steel is poured at a regulated rate via a tundish into the top of an oscillating water-cooled mold with a cross-sectional size corresponding to that of the desired slab. As the molten metal begins to freeze along the mold walls, it forms a shell that permits the gradual withdrawal of the strand product from the bottom of the mold into a water-spray chamber where solidification is completed. With the straight-type mold, the descending solidified product may be cut into suitable lengths while still vertical or bent into the horizontal position by a series of rolls and then cut to length. With the curved-type mold, the solidified strand is roller-straightened after emerging from the cooling chamber and then cut to length. In both cases, the cut lengths are then reheated and rolled into finished products as in the conventional manner.

Figure 2-1: Continuous slab caster



Heat treatment of plate steel

The versatility of steel is attributable in large measure to its response to a variety of thermal treatments. While a major percentage of steel is used in the as-rolled condition, thermal treatments greatly broaden the spectrum of properties attainable. Heat treatments fall into two general categories: (1) those which decrease hardness and promote uniformity by slow cooling and (2) those which increase strength, hardness and toughness by virtue of rapid cooling from above the transformation range. Annealing, normalizing and stress relieving fall in category 1, while quenching and tempering is a typical category 2 treatment. ArcelorMittal USA is equipped to normalize, anneal, stress-relieve, quench and temper, and normalize and temper plates.

Annealing indicates a single thermal treatment intended to place the steel in a suitable condition for subsequent fabrication. Annealing may be required where machining or severe forming is involved. The steel is heated to a temperature either slightly below or above the transformation temperature followed by slow cooling. The exact temperature and cooling rate or cycle depend on the properties desired by the purchaser.

Normalizing consists of heating the steel above its critical temperature range (typically 1650°F to 1700°F for plate steel) and cooling in air. This heat treatment is commonly specified to obtain uniform grain refinement and results in improved notch toughness compared to as-rolled steels. Normalizing is commonly specified for plates of pressure vessel quality.

Stress relieving consists of heating the steel to a suitable temperature after flattening or other cold working, shearing or gas cutting to relieve stresses induced by these operations. Stress relieving is primarily a function of temperature, with time at temperature a secondary factor. A typical stress relieving treatment for plate steel involves heating in the range of 1000°F to 1200°F followed by slow cooling. For quenched and tempered steels, the stress relief temperature should be maintained below the original tempering temperature of the plate.

Quenching and tempering is used to improve the strength and toughness of plate steel. The treatment consists of heating the steel to the proper austenitizing temperature (for example, 1650°F could be used for a 0.20 percent carbon steel), holding it at temperature to allow complete transformation to austenite, then quenching in water. ArcelorMittal USA uses various water-quenching processes, including roller quenching, platten quenching and a large water tank for quenching thick plate. After quenching, the steel is tempered at an appropriate temperature, normally in the range of 400°F to 1300°F. The purpose of tempering is to relieve internal stresses and improve ductility and toughness.

Thermo-mechanical-controlled-processing (TMCP)

As an alternative or substitute for heat treatments that require additional material handling and furnace facilities, improved properties can also be obtained through special processing techniques at the rolling mill.

Controlled-rolling

Controlled-rolling is widely practiced to increase strength and improve notch toughness of plate steel. A plate rolling practice, controlled-rolling tailors the time-temperature deformation process by controlling the rolling parameters. The parameters of primary importance are (1) the temperature for start of controlled-rolling in the finishing stand, (2) the percentage reduction from start of controlled-rolling to the final plate thickness, and (3) the plate finishing temperature.

As seen in Figure 2-3, controlled-rolling involves deformation at much lower finish rolling temperatures than hot rolling, usually in the range from 1300°F to 1500°F. In contrast, a normal hot-rolling practice takes advantage of the better hot workability of the material at higher temperatures. Hot-rolled plates are finished as quickly as possible, frequently at temperatures of 1800°F and above. For controlled-rolling, a hold or delay is generally taken to allow time for the partially rolled slab to reach the desired intermediate temperature before start of final rolling.

Controlled-rolling practices are designed specifically for use with microalloyed grades, which take advantage of the alloying element's influence on recrystallization and grain growth, in combination with the specific reduction schedule. Because of practical considerations, primarily mill load and delay times, control-rolled plates are not normally produced above about 1 in. thickness.

Controlled-finishing temperature rolling

The term "controlled-finishing temperature rolling" is used to differentiate from the term "controlled-rolling." Controlled-finishing temperature rolling is a much less severe practice than controlled-rolling and is aimed primarily at improving notch toughness for plate up to 2.5 inches thick. The finishing temperatures in this practice (approximately 1600°F) are higher than required for controlled-rolling. However, because heavier plates are involved, mill delays to reach the desired temperature are still encountered. By controlling the finishing temperature, fine-grain size can be obtained with resulting excellent notch toughness.

Accelerated cooling

Accelerated cooling is a controlled-cooling cycle (water cooling to a temperature of about 1000°F to 1100°F, followed by air cooling) immediately after the final rolling operation. (Schematically, this is shown in Figure 2-4.) Accelerated cooling after either controlled-rolling or controlled-finishing temperature rolling leads to additional structural refinement and, hence, an improved combination of properties.

Accelerated cooling can improve properties of plates in the approximate thickness range of 0.5 through 4 inches. A specification covering thermomechanically processed plates, including the accelerated cooling process, is ASTM A841. The 160-inch plate mill (Figure 2-2) at ArcelorMittal Burns Harbor in Indiana is capable of TMCP of a variety of plate steel grades.

Figure 2-2: ArcelorMittal Burns Harbor 160-inch plate mill

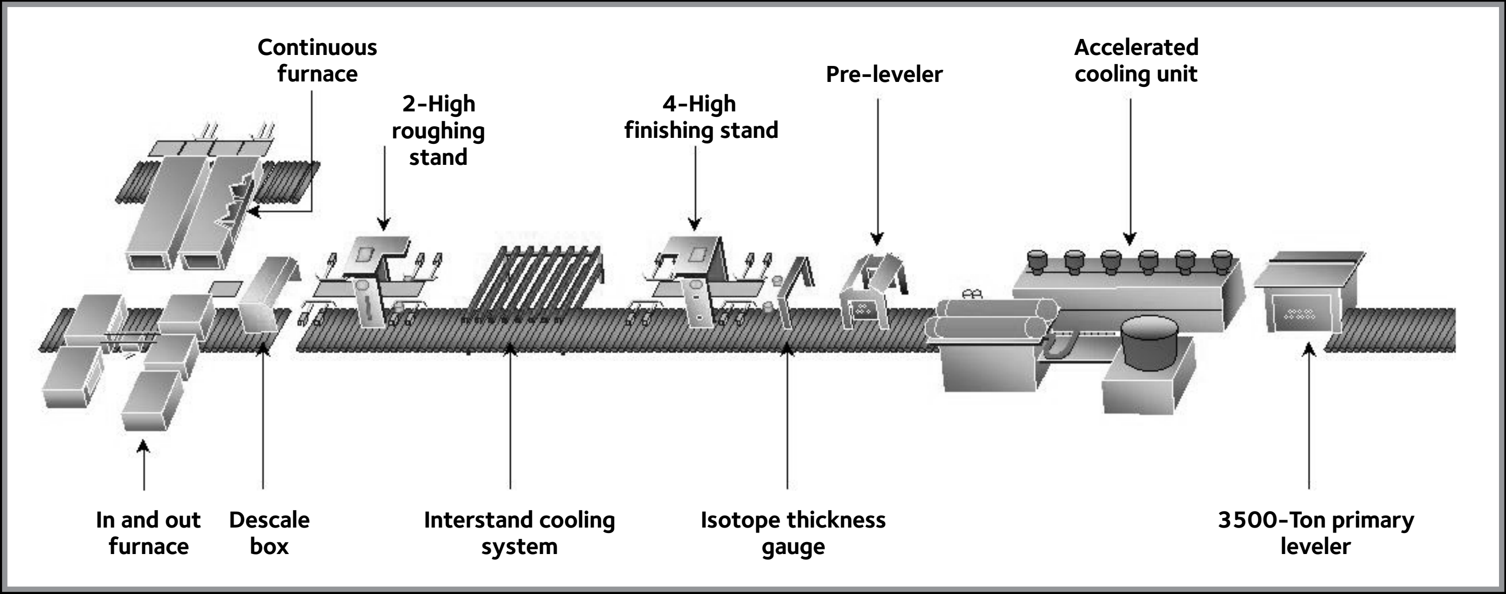


Figure 2-3: Schematic of temperature versus deformation plot showing differences between conventional hot rolling and controlled-rolling

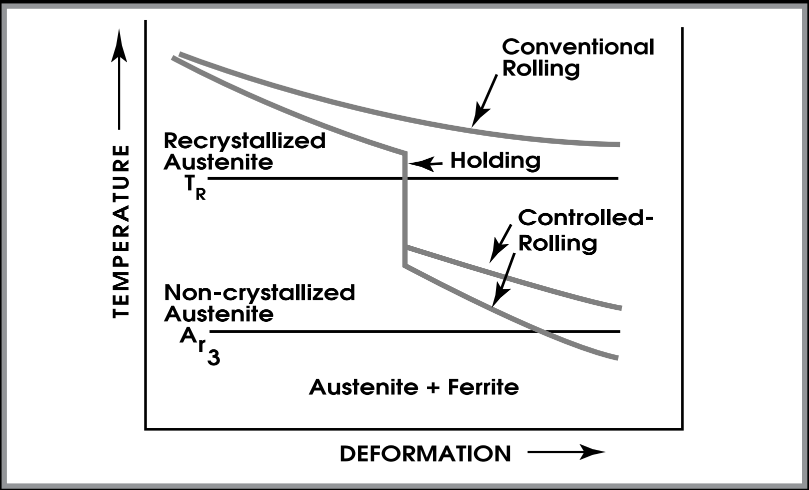
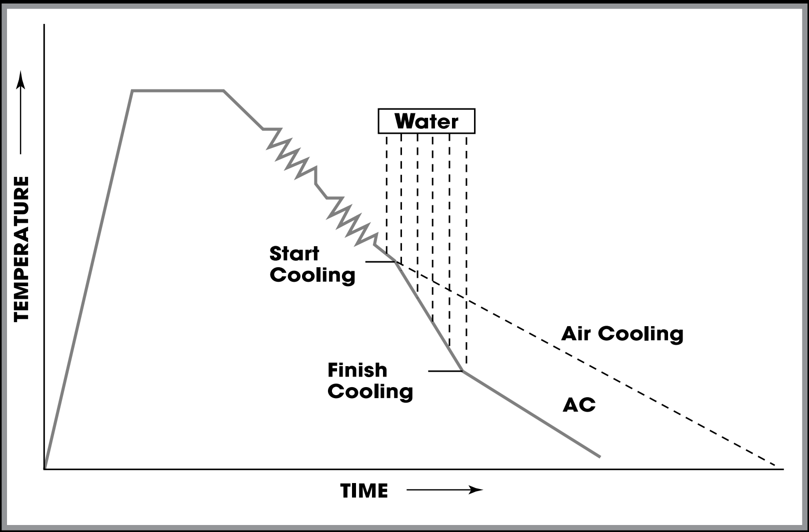


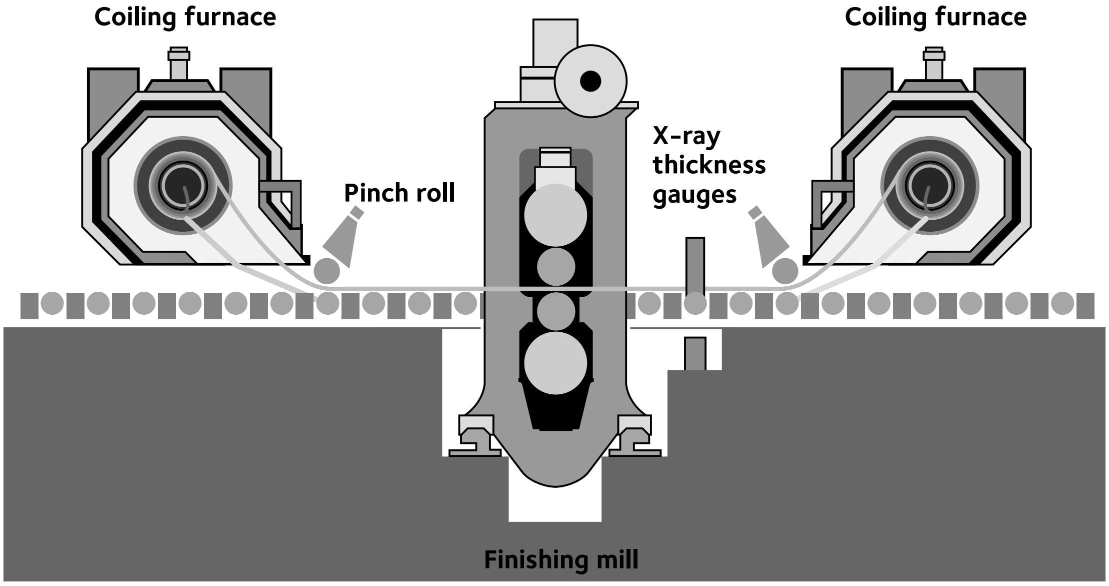
Figure 2-4: A schematic of accelerated cooling



Steckel mill rolling

The Steckel mill at ArcelorMittal Conshohocken in Pennsylvania is a very cost-effective rolling mill for producing thin plate (0.17 – .63 inch) in coiled form. As shown in Figure 2-5, heated coiling furnaces on either side of the 4-high finishing mill contain heated mandrels, which maintain heat in the product as the plate is passed from one side to the other and reductions in thickness are made. Because of this processing, the final product is more uniform than discrete plate production. The plate is accelerated cooled prior to coiling in a down coiler. These coils are processed on cut-to-length lines where the coiled plate is leveled and then sheared to width and length.

Figure 2-5: ArcelorMittal Conshohocken Steckel mill



Finishing mill capabilities
HGC, roll shift and bend
11,000,000 lbs. force

Coiling furnace capabilities
73 In. max. dia., 102 in. wide coil
42.6 ton capacity

Mechanical properties

Static properties

Yield and tensile strength are the primary mechanical properties of concern to the designer. These properties are obtained from standard tensile specimens that can be either full-plate thickness or 0.505-inch diameter or other sized round specimens. The tensile specimen also can be used as an indication of material ductility and formability by measuring elongation and reduction of area. Elongation and reduction of area are stated as percentages of the original gauge length and cross-sectional area, respectively. The ASTM specifications typically list requirements for yield strength, tensile strength and elongation for either 2-in. or 8-in. gauge lengths.

Flat tensile specimens are generally used for all plate grades up to approximately 0.75 inch thickness. For plate grades over 0.75 inch, either flat or 0.505-inch diameter round specimen type is at the producer's option.

Elevated temperature properties

Figure 2-6 shows a band of short-time tensile properties for typical structural steels such as A36. For temperatures up to 700°F, there is no appreciable loss in yield or tensile strength. At temperatures above 700°F, the steel shows a drop in strength. The short-time tensile results are not applicable for long-time service conditions of 700°F and higher, as creep becomes a factor and reduced stress levels must be considered. Design information is obtained from creep and creep rupture tests. Section VIII of the ASME Code for Pressure Vessels Division 1 provides allowable design stresses for steels over the temperature range from 650°F to 1200°F.

Toughness

Fracture toughness is a measure of a steel's capacity to carry load in the presence of a crack or crack-like notch. Notch toughness is an indication of a steel's capacity to absorb energy when a stress concentrator or notch is present.

Notch toughness

Notch toughness can be an important factor for applications of plate steel involving joints with restraint and lower temperature service. Structural steels are susceptible to a lowering of absorbed impact energy with decreasing temperature. This change in energy is accompanied by a transition from a ductile to a brittle-appearing fracture. The temperature at which some specified level of energy or fracture appearance occurs can be used to define a transition temperature. Transition temperature is an important concept because it defines a change in mode of fracture from one that is affected predominately by a shear mechanism (ductile fracture) to one that propagates primarily by cleavage (brittle fracture).

There are a number of methods for specifying material with adequate notch toughness. The most common approaches are Charpy V-Notch, drop weight, dynamic tear and drop weight tear testing and fracture mechanics. These are described in the following discussion.

Charpy V-Notch (CVN) testing is the most widely applied test for determining notch toughness following ASTM E23. The specimen is notched perpendicular to the plate surface. The direction (longitudinal or transverse) of the specimen axis is selected according to the appropriate specifications for plate steel. The specimen is held for 10 minutes at test temperature and then broken in the appropriate Charpy-type impact machine by a single blow of a freely swinging pendulum.

On breaking the Charpy specimen, three criteria are commonly measured. The loss of energy in the pendulum swing provides the energy in terms of foot-pounds (ft-lb) absorbed in breaking the specimen. The fracture appearance of the broken specimen in terms of ductile and brittle failure can be rated. In addition, the lateral expansion at the

Figure 2-6: Effect of temperature on the short-time tensile and yield strengths of A36 plate steel grades

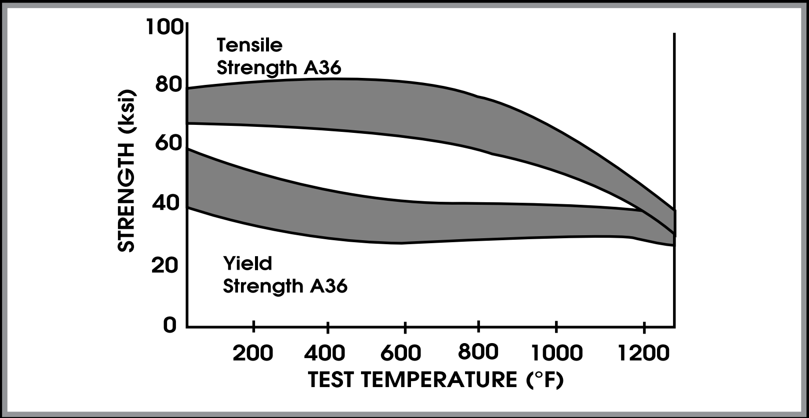
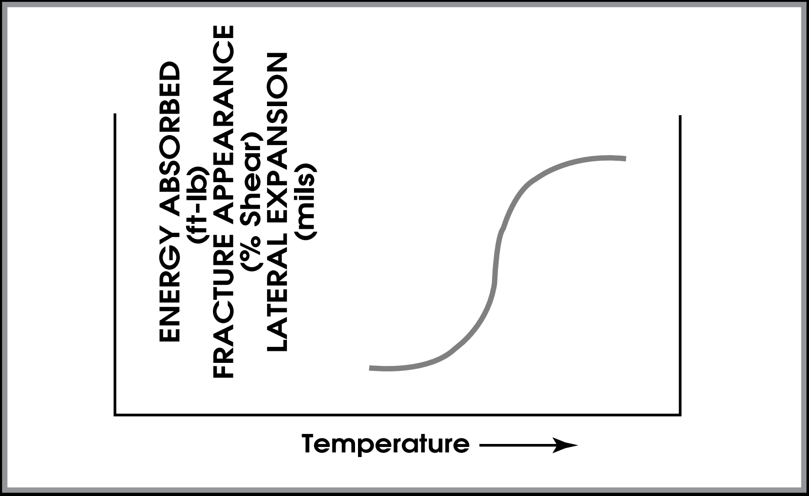


Figure 2-7: Typical Charpy transition curve



base of the fracture opposite the notch can be measured. Any of these criteria can be plotted versus temperature, as shown in Figure 2-7, to obtain the typical transition curve. The notch toughness varies with specimen orientation and requirements are generally negotiated between the customer and the supplier, with a given energy at a specified temperature being the most common criteria.

The Charpy testing approach suffers from the fact that a small specimen is tested in conditions that are not the same as the material in an actual structure. Therefore, the test results are most useful in rating material on a comparison basis. The dynamic tear test (ASTM E604) is sometimes of use for specialized applications because it uses a thicker specimen and a sharper notch. Available CVN guarantee levels for popular structural and pressure vessel steels are given in Chapters 11 and 12.

Drop weight testing is also used to characterize the toughness of plate steel by determining the nil-ductility temperature. This test is carried out in accordance with ASTM E208. Rectangular pieces are cut from the test plate and a crack starter bead is deposited across the specimen. A notch is machined across the weld bead. Specimens are tested as a function of temperature. A specimen is set on an anvil, welded surface down, and then struck by a guided, free-falling weight. A crack must initiate from the crack starter for the test to be valid. If the crack runs to the edge of the specimen, the specimen is considered a break (failure). The test is strictly a go/no-go result. The NDT (nil-ductility transition) temperature is defined as the maximum temperature at which a drop weight specimen breaks in the test.

There is no general correlation between the NDT temperature and the Charpy test. The physical significance of the NDT value to the designer is if a material is selected whose NDT is lower than the expected service temperature, brittle failure will not occur at a small crack subjected to yield stress levels under conditions of dynamic loading. Additionally, this information (NDT) can be used to determine tolerable crack size at lesser stress levels.

Actual application of this approach requires that the designer know the mode of fracture initiation, size of the structure, environmental conditions, strength level and residual stresses in structures having complex shapes and loading.

Unfortunately, there is no exact correlation between the drop weight test results and Charpy testing. The dynamic tear test does correlate better with drop weight results.[3] The choice between the Charpy test, dynamic tear test and the drop weight test still lies with the designer and is most frequently based on existing specifications and prior experience.

Fracture Mechanics

In recent years, the development of fracture mechanics has offered the design engineer a new tool for predicting crack growth under cyclic (fatigue) or increasing loading (as in a fracture test). The fracture mechanics approach was developed from the stress analysis of cracked bodies and presupposes linear elastic conditions, i.e. plastic deformation confined to a very small region near the crack tip. The fracture mechanics approach is based on the stress intensity factor K, which combines the effects of stress, crack length and geometry.[2] For the case of an axially loaded plate containing a central through crack, $K=\alpha\sigma\sqrt{\pi c}$ where α is a finite width correction factor, σ is the nominal or gross section stress, and c is the half-crack length. The units of K are psi $\sqrt{in.}$ or ksi $\sqrt{in.}$

Laboratory tests of compact-type (pin-loaded, edge crack specimens) or bend specimens enable one to determine the critical value of K at onset of unstable fracture. Provided the material is sufficiently thick to ensure a linear elastic load-deflection response and satisfies a variety of other criteria defined in ASTM Standard E399, the critical K value qualifies as being the lower bound or plane strain fracture toughness K_{IC}.

The linear-elastic fracture mechanics approach is most applicable to the toughness assessment of high-strength, low-toughness materials at ambient temperatures or lower-strength materials at very low temperatures. For materials that are too tough to obtain valid estimates of K_{IC} in the thicknesses of typical usage, other elastic-plastic fracture mechanics parameters such as the J-integral and crack tip opening displacement (CTOD) are possible alternatives for ranking material toughness.[2]

Whether using linear-elastic or elastic-plastic fracture mechanics approaches, each helps to define allowable stresses for a given range of operating conditions. The fracture mechanics approach can be used to calculate the crack growth rate and the critical crack size for a given load. This information can be used to define the inspection period required to find cracks before they could lead to failure under the operating loads.

At present, fracture toughness testing is not within the routine capability of the plate mills. Consequently, Charpy requirements are still the most widely accepted criteria for notch toughness.

Fatigue

Fatigue is the process by which a part, component or structure degrades or fails when it experiences cyclic loading. Fatigue can account for as much as 90 percent of all failures. In general, fatigue involves two stages: (1) the initiation of a crack and (2) its subsequent growth to failure. Failure ultimately occurs when the crack is large enough

that the uncracked section or ligament is unable to support the applied load. The relative importance of each stage of the cracking process depends on numerous factors, including the presence of stress raisers (welds, holes, changes in section), the strength of the material, the applied stress range, and the size of the member. In the case of unnotched specimens, initiation can occupy the largest fraction of life, while propagation is the dominant stage when notches are present.

Crack initiation occurs when plastic deformation accumulates in a local region. In absence of a stress raiser, plastic deformation changes flat surface to a notch-peak topography with many small cracks initiating at the base of the surface notches. As cyclic loading progresses, these small cracks join to form a larger one, which can grow in response to the applied cyclic loads. In the presence of a notch (hole, weld toe), this same sequence occurs at an accelerated rate. The number of loading cycles required for crack initiation depends on the material, cyclic load range, stress concentration factor of the notch and other factors.

Crack propagation is similar to crack initiation in that its driving force is the localized plasticity that occurs at the crack tip in response to the applied loads. As the tensile stress is increased, the crack grows and ultimately the crack-tip is enlarged or blunted. On unloading, the crack-tip radius is resharpened for the next loading cycle. The rate at which a crack grows during one loading cycle is usually expressed in terms of the range in stress intensity factor, ΔK (a function of the load range, crack length and the specimen geometry) and is typically insensitive to the strength of the material. There are numerous references dealing with the kinetics of crack propagation, i.e. plots of crack growth rate versus the range in stress intensity factor. For more details on crack growth, see the references listed at the end of this chapter.

Variables affecting fatigue

Some of the most important variables affecting fatigue are:

- Stress range — life decreases as stress range increases.
- Residual stresses — life decreases for tensile residual stress and increases for compressive residual stress.
- Notches or welds — reduce fatigue life.
- Material properties — long life fatigue strength (10^6 to 10^7 cycles) increases with increasing tensile strength in the *absence of a notch.*
- Corrosive environment—typically degrades fatigue performance.

In addition, other variables such as stress state, stress ratio, surface condition, microstructure, inclusions, grain size, heat treatment, and deoxidation practice can play a role in the fatigue process. However, the influence of these variables is generally of secondary importance relative to those listed above.

Material Effects in Fatigue, caused by the absence of a sharp notch, are primarily controlled by the tensile strength, with higher strength materials having proportionally higher long life (10^6 to 10^7 cycle) fatigue resistance. In the presence of a sharp notch, fatigue life is insensitive to differences in strength level because crack propagation, the dominant phase of life in this case, is insensitive to differences in strength level. In practice, manufactured products frequently have notches or details which act like notches. Thus, it is seldom possible to achieve greater fatigue life through material selection alone.

Changing materials to increase the fracture toughness increases the crack length at failure under a given loading condition and increases the margin of safety against overloads causing failure when cracks are small. However, increasing fracture toughness will not markedly lengthen fatigue life because the bulk of life is spent in crack growth when the crack is much smaller than the critical crack size.

Suggestions for controlling fatigue and fracture

Fatigue and fracture are best controlled by proper methods of design, fabrication and inspection. Improved material properties and quality will not compensate for poor performance in any of the following.

1. Design information may be obtained from the publications and specifications of the following agencies:

Agency	Type of information
SAE	Ground vehicles
ABS	Ships
ASME	Pressure vessels
AASHTO, AWS, AREA, AISC	Bridges, buildings
API	Offshore platforms

2. Every effort should be made to minimize the severity of notches or, at the least, to reduce the stress in the vicinity of the notch.
3. In the presence of a sharp notch, such as the toe of a weldment, most of the fatigue life will be spent in crack propagation. Several ways to improve the fatigue life of welded joints include:
   - Grinding off the butt weld reinforcement.
   - Dressing fillet welds and avoiding undercut.
   - Locating the weld in a low-stress region.
   - Avoiding joints with large variation in stiffness.
   - Avoiding use of intermittent welds.
   - Redesigning the weld joint to have lower fatigue susceptibility.
4. High-strength bolted friction joints have much greater fatigue resistance than most welded details.
5. In most instances, cracks initiate at notch-like areas on the surface of parts. Manufacturing practices to improve the properties of surface material (i.e., carburizing, nitriding, shot peening) can serve as a means of improving fatigue resistance. However, elimination of the presence of notches in areas of high stress is most important.
6. Measurement or estimation of the loading history, and testing of prototypes, are necessary for optimizing fatigue design in terms of weight, cost and safety.
7. Variability in properties within and between plates must be considered when setting design-allowable stresses.
8. Initial and periodic inspections are necessary to the development of a rational plan for controlling fatigue and fracture.
9. A thorough fatigue design will consider the possible influences of temperature and environment, as well as other phenomena such as fretting.

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3. A. D. Wilson, "Comparison of Dynamic Tear and CVN Impact Properties of Plate Steel," ASME J. of Eng. Mat. and Tech., April 1998.
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Corrosion and weathering performance

Corrosion and appropriate preventive measures are parameters that must be considered when deciding on a material for a particular application. Their importance varies according to the circumstances. While for the selection of plate steel, mechanical properties and weldability are of primary concern, there is hardly an application in which corrosion can be totally neglected.

Corrosion is defined as the destruction or deterioration of metal by electrochemical interaction with its environment.

- *Rusting* (atmospheric attack) — by alternate drying and wetting in air.
- *Underground or underwater corrosion* — electrochemical action between the steel and surrounding environment.
- *Stress corrosion cracking* — premature failure of a steel member under static load, in an aggressive environment.
- *Corrosion fatigue* — premature failure of a steel member under a cyclic load in an aggressive environment.

The corrosion of plate steel may be retarded by several methods.

- Preventing the plate steel from coming into contact with water or high humidity, thereby preventing rusting.
- Coating or plating the surface of the steel to prevent contact between the steel and its environment.
- Coating the steel with a sacrificial metallic coating — galvanizing with zinc.
- Cathodic protection by an impressed voltage or sacrificial anodes.
- Alloying the steel with copper and other elements to reduce or halt the loss of thickness by means of a tight self-healing oxide that protects the steel plate after a sufficient thickness of oxide has formed.

The type of corrosion of most concern to plate users is atmospheric attack or rusting of steels. In certain applications, however, underground and underwater corrosion and other corrosion-related phenomena, such as stress-corrosion cracking and corrosion fatigue, may also be important. The latter two occur in specific environments and manifest themselves as premature failure of structural members under static tensile and cyclic stresses, respectively.

Atmospheric conditions

Atmospheric corrosion occurs when unprotected steel is exposed to air containing moisture. The attack generally is uniform on plain surfaces, and may be affected by corners or other appurtenances. The damage can usually be measured in terms of loss of thickness in thousandths of an inch (mils) per year. However, the rate of attack varies with location and time and, therefore, it is not possible to describe accurately with an average value. Other parameters, such as time to exhibit a specified loss of thickness, are, therefore, employed to compare the atmospheric corrosion resistance of different steels.

The severity of atmospheric attack is a function of steel composition and the corrosivity of the atmosphere. The latter increases with the presence of:

- Industrial pollutants such as SO_2, H_2S, and chlorides.
- Nitrogen compounds.
- Airborne dusts and solids.
- Seawater spray.
- Increase in relative humidity above a certain critical level.

The washing effects of rain or heavy condensation may sometimes be beneficial in reducing corrosion. Other factors that may affect atmospheric corrosion are:

- Initial exposure conditions.
- The degree to which steel is sheltered from the atmosphere.
- Air movements and temperature.
- Details, pockets, corners, collection of debris.

Steel composition

In general, the process of manufacture and the slight variations in composition from heat to heat that usually occur in steels of the same quality are relatively unimportant factors with respect to atmospheric corrosion. *An important exception is the variation in copper and other alloying element content*.

The presence of copper increases the atmospheric corrosion resistance of steels through its ability to form a dense, adherent rust layer that acts as a self-healing barrier against further corrosion. As a rule, 0.2 percent copper in steel provides at least twice the atmospheric corrosion resistance of an otherwise similar steel without copper. Nickel, chromium, phosphorus, molybdenum and silicon, in the presence of copper, lead to further improvements in corrosion resistance.[1] This information has been used in the development of weathering steels, which are used in the unpainted condition in such applications as bridges and buildings.

Weathering Steel

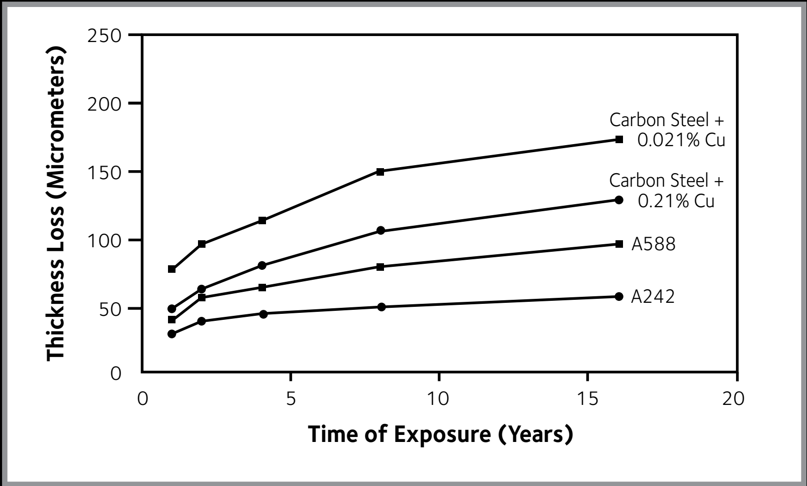
The superior corrosion resistance of weathering steels in marine, rural and industrial atmospheres has been clearly documented.[2] It has been shown that ASTM A588 Grade B weathering steel (Mayari-R50™ and Cor-Ten®) is:

- 6 to 19 times more durable than the steel without copper.
- 2 to 10 times more durable than the steel containing 0.21 percent copper.

These comparisons were made on the basis of a calculated time ratio to exhibit a 0.010 in. loss in thickness. The performance of Mayari-R50™ and Cor-Ten® meets the ASTM A588 specification, which describes the atmospheric corrosion resistance of weathering steel as approximately two times that of carbon structural steel with copper.

New York State Thruway bridge fabricated with A709 Grade HPS 70W weathering steel.

Figure 2-8: Atmospheric corrosion of plate steel in typical industrial environment



To demonstrate the advantages of weathering steels, four steels are compared in Figure 2-8, which shows loss of thickness due to atmospheric corrosion on exposure over a 16-year period.

Testing conducted by ArcelorMittal USA has shown atmospheric corrosion resistance is increased by alloying with the elements phosphorus, silicon, chromium, carbon, copper, nickel, tin and molybdenum. On the other hand, sulfur increases the corrosion rate in atmospheric corrosion.[3]

Presence of mill scale affects the rate of atmospheric corrosion during the initial stages of exposure, but it is not an important factor over a prolonged period. Similarly, ordinary variations in grain size and heat treatment are relatively unimportant in atmospheric corrosion.

To obtain maximum corrosion performance from weathering steel, several design considerations require close attention. The composition of fasteners, rivets and weld metal used in weathering steel structures and plate assemblies should be the same as that of the base metal. In certain applications, such as highway guide rail, galvanized fasteners have been used successfully with weathering steel.[4] Since a good exposure to the atmosphere is important in developing a protective rust layer, crevices and sheltered areas should be avoided as far as possible. Also, areas exposed to direct contact with corrodants such as chlorides or sea water spray may be unable to develop full protection, and this must be kept in mind during designing.

ArcelorMittal USA makes numerous grades of weathering steel:

ArcelorMittal USA weathering steel grades

A242 (Mayari-R™)
A514/A517 Grades E, F, P, Q
A588 (Mayari-R50™ and Cor-Ten®)
A709 Grades 50W, HPS 70W, HPS 100W
A710
A871
Mayari-R60™

See ArcelorMittal USA's Booklet 3791, "Weathering Steel," for greater detail.

Underwater conditions

Under total immersion conditions in natural waters, all ferrous structural plate materials corrode uniformly at about the same rate. In sea water, the rate is about a 0.005 in. loss of thickness per year. The rate of corrosion, however, is strongly dependent on such

environmental factors as the degree of aeration, agitation, presence of dissolved salts, pH, and presence of protective deposits and temperature. Presence of mill scale is highly injurious and may lead to pitting of steel by a galvanic action. In underwater, as well as underground corrosion, weathering steels and copper-bearing grades have no advantages over copper-free steels.

Coating

Painting provides sufficient protection to most structural steel in the atmosphere. More corrosion-resistant grades show better paint performance than the carbon steels. Good surface preparation and proper paint application practice are essential to ensure good protection. Paints and other protective coatings may also give satisfactory performance in underwater exposure conditions, but in such applications, recourse is usually made to other techniques such as cathodic protection, in which the metal structure is made the cathode of a galvanic couple by an impressed voltage or by sacrificial anodes. It should, however, be emphasized that cathodic protection and other corrosion-control techniques are matters to be decided by a qualified corrosion engineer. This article is in no way intended to be a guide to corrosion-prevention measures which are to be employed in applications of plate steel.

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1. H. E. Townsend: "Effects of Silicon and Nickel on the Atmospheric Corrosion Resistance of ASTM A588 Weathering Steel," *Atmospheric Corrosion, STP 1239*. W. W. Kirk and H. H. Lawson, Eds., American Society of Testing and Materials, pp 85–100, Philadelphia, 1995.
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Processing of plate steel

A review by the customer technical service department of ArcelorMittal USA has identified recent experience with customer problems in the processing of plate steel. This analysis identified four areas that stood out as most often causing cracking problems in customer plants. These processes and the cracking cause were as follows:

Quenching and tempering
Cracking of parts during quenching,
"quench cracking"

Forming
Cracking during cold, warm or hot forming

Thermal cutting
Cracking from heat-affected-zone,
"stress-cracking"

Welding
Hydrogen-assisted cold cracking

The following chapters provide detailed analysis of these problems and supply guidelines to prevent occurrence in customer shops.

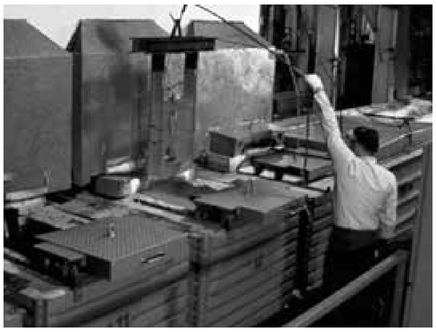
Quenching and tempering (Q&T) of ArcelorMittal USA steel

Dealing with quench cracking problems

The properties of medium carbon steel can be significantly improved by a quenching and tempering heat treatment. Quenched and tempered steels are the backbone of many industries using these steels to produce components that are hard and tough. However, the Q&T process subjects steels to enormous stresses, which can lead to cracking if good part design, and heat treating and quenching practices are not followed. This chapter presents guidelines for minimizing "quench cracking" in medium carbon and alloy steels, e.g. 4140 and 4340. These guidelines may also be appropriate for dealing with lower and higher carbon steels.

Appearance of quench cracks

Quench cracking appears in a quenched and tempered part, either between the quenching and tempering operations or after tempering. Quench cracking is caused by the interaction of factors related to part design, heat treating and quenching practices. During the quenching of steel in oil or water, very high stresses are caused by nonuniform cooling, thermally induced deformation and the actual martensite phase transformation. Most often all three mechanisms must be considered to prevent quench cracking. As shown in Figure 3-1a to 3-1c, when the carbon level of steel increases, the hardness capable of being achieved increases. The martensite formed, while being harder, is more brittle and susceptible to cracking. The actual cracking takes place at notches, holes, slots, grooves or the plate centerline and may be in various orientations. An example is shown in Figure 3-2.



Heat treating of parts made from plate steel.

Figure 3-1a: Relation of carbon content and percentage martensite to Rockwell C hardness

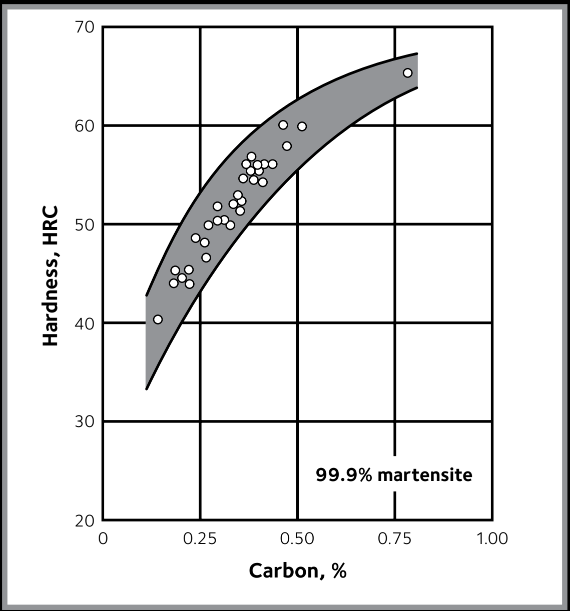
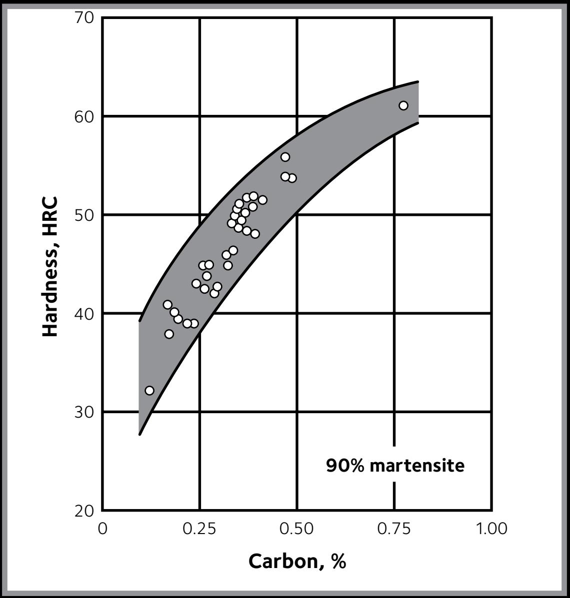
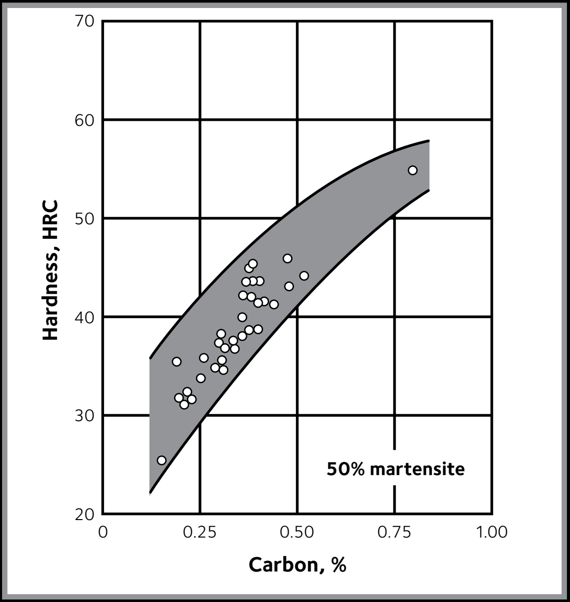


Figure 3-1b



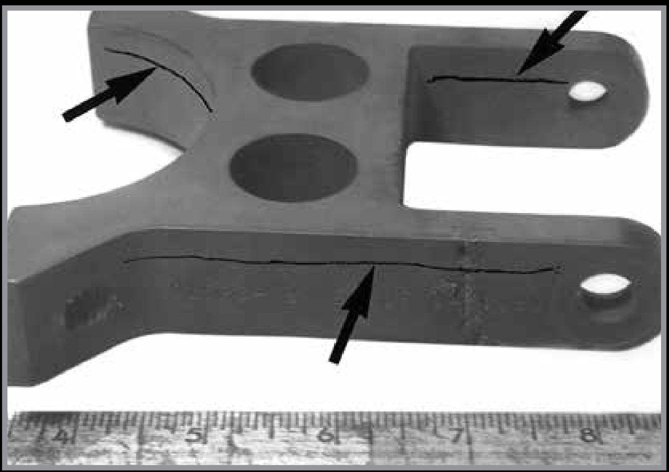
From *ASM Metals Handbook,* Volume 4, 1991

Figure 3-1c



From *ASM Metals Handbook,* Volume 4, 1991

Figure 3-2: Complex machined part with extensive quench cracking noted by arrows

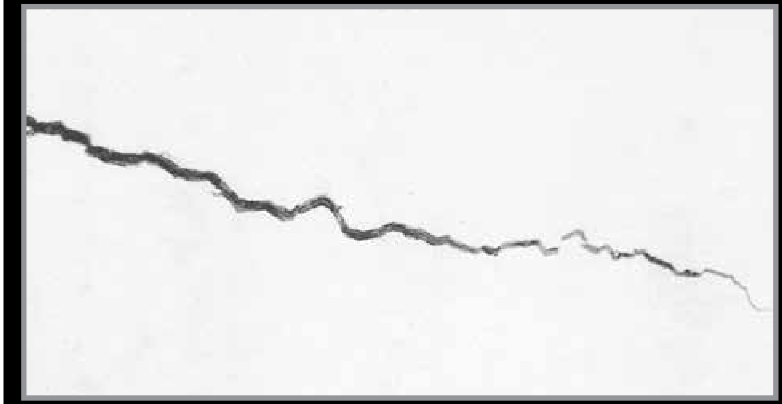


Cracking is artificially highlighted to improve visibility

Metallographically, quench cracking has a distinctive appearance and is most often intergranular in nature, as shown in Figures 3-3 to 3-5. A light gray temper scale is often noted within the crack.

If the crack existed before the Q&T operation, a region of decarburization near the crack would be created, as shown in Figure 3-6. The use of protective atmosphere furnaces may eliminate decarburization and the formation of temper scale at pre-existing cracks.

Figure 3-3: Unetched micrograph showing quench crack with some temper scale within crack



500X

Figure 3-4: Unetched micrograph showing interaction of quench crack with inclusions

500X

Figure 3-5: Etched micrograph showing intergranular nature of quench crack

100X

Quench cracking can also be associated with banding in the microstructure, as displayed in Figure 3-7. Banding is a naturally occurring condition in all medium carbon and alloy steels that results from the ingot or continuous casting process. Experience has shown the root cause of most instances of quench cracking is not the banded structure, but rather the heat treating or part design variables to be discussed below. While a quench crack may appear to propagate along a banded area, it is rare the crack was initiated by this microstructural feature.

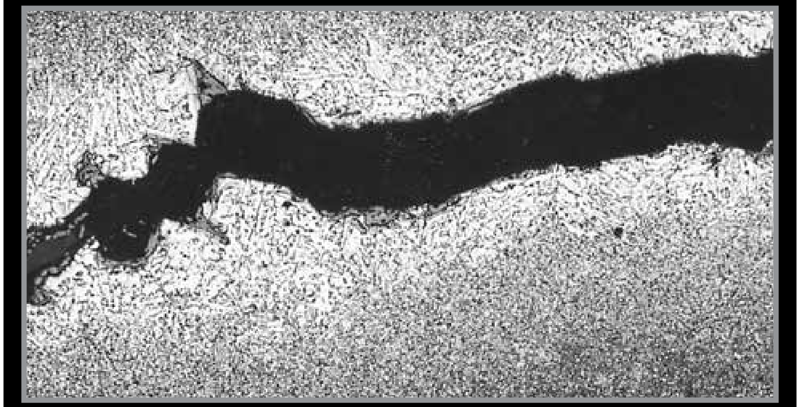
Heat treating parameters

Several operations or parameters in the Q&T process can influence the susceptibility to quench cracking.

Heating rate—If a part is heated too quickly or a cold part is placed in a very hot furnace, the thermal shock alone may initiate cracking. Susceptible steels and parts should therefore be charged in a warm furnace and the temperature should be gradually increased to the austenitizing temperature.

Austenitizing temperature—Heating of the part to a very high temperature can add thermal shock, as well as influence microstructural effects. Although most low carbon alloy steels are austenitized at 1650°F, 0.40 percent carbon alloy steels are best processed at 1525 to 1575°F. It is important actual furnace temperatures be checked with thermocouples on the part to be sure the part is not overheated.

Figure 3-6: Etched micrograph showing extensive decarburization area near crack, indicating this was a stress-crack from thermal cutting and not a quench crack



100X

Figure 3-7: Etched micrograph showing quench crack associated with typical banded microstructure

100X

Quenching media—Whereas most 0.20 to 0.30 percent carbon steels may be successfully quenched in water, higher carbon steels need special liquid quench media, such as oil. Some additives are available for oil, which develop varying cooling rates from that of pure oil. Caution should be used, since some of these modified oils may approach water in cooling efficiency. Furthermore, the cooling rate can be slowed further by heating the quenching liquid. Hot oil quenches at 150°F have been found to be particularly useful for susceptible steels and parts.

The choice of quench media is a balancing act. The cooling rate must be quick enough to give the through-hardening needed for the part design, but not so severe as to cause cracking. Agitation of the quenching liquid is also important to provide uniform cooling. It is important the part has been thoroughly cooled to approximately 150°F and the metallurgical transformation has been completed.

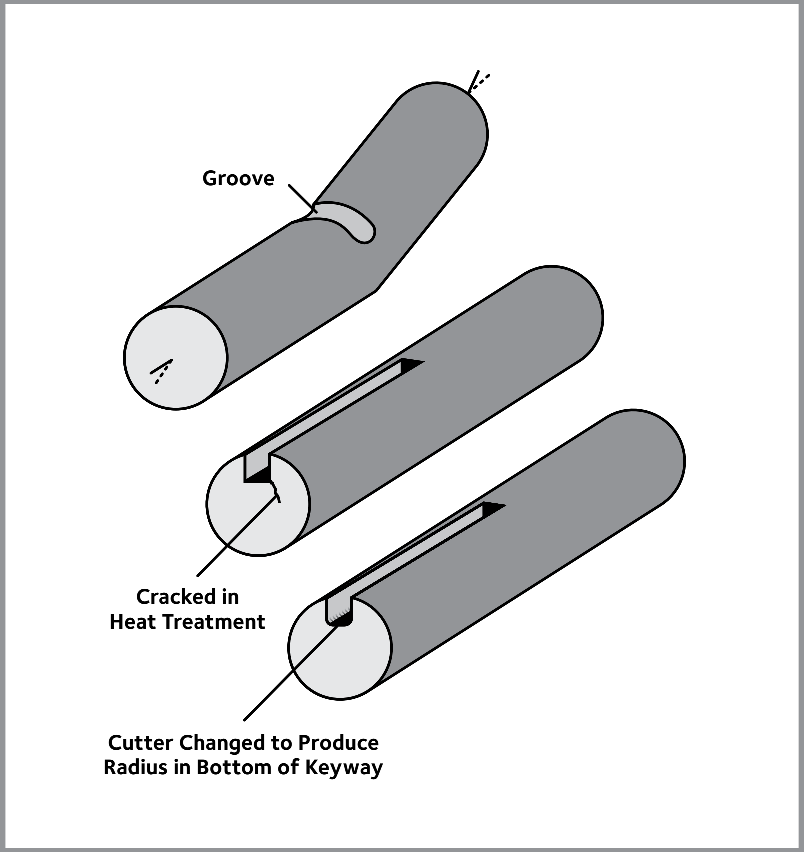
Time to temper—After a part has been quenched, it must be tempered very soon thereafter. The significant residual stresses in an as-quenched part can cause cracking during the delay before tempering. Tempering acts as a stress relieving operation to reduce these stresses. Very susceptible steels or parts should be tempered within eight to 24 hours after quenching. If this is not possible, a "snap temper" at 400°F will stabilize a part until a final higher tempering temperature treatment can be performed.

Part design

Very complex machined parts can be susceptible to quench cracking particularly in higher carbon steels. Often a small modification in the design of a part can reduce the problem.

Notches—Very sharp notches provide stress concentration where cracking can initiate. Well-radiused, gradual transitions in corners or slots are important (See Figure 3-8).

Figure 3-8: Grooves will cause a shaft to warp in heat treating (top). A keyway with sharp corners often initiates quench cracks (middle). This cracking is avoided by designing in a radius (bottom).



From *ASM Handbook,* Volume 4, 1991

Changes in cross-sections—Even when significant radii are provided between changes in cross-section, cracking may still result. A very small section will cool much more rapidly than a larger one. This may require a complete part redesign or use of a new steel.

Holes—Whether threaded or not, holes are areas where non-uniform cooling takes place during quenching. Cracking may occur in the holes or in regions near them. To minimize these problems, packing the holes with an insulating material (Kaowool, mud, steel wool) will lead to more uniform cooling. If this is not acceptable then flush quenching of holes is advisable.

Orientation during quenching—When parts are immersed in the quenching liquid, they should be inserted in a manner that leads to a uniform cooling along the piece.

General

Other operations can also influence the susceptibility to cracking of quenched and tempered parts. For example, if chromium or nickel plating is performed after Q&T, hydrogen may be picked up in the steel which leads to cracking that looks like quench cracking. To prevent these problems, plated parts should be "baked" to remove the hydrogen.

More detailed discussions of the metallurgy and mechanics of quench cracking problems are presented in the literature. The *ASM Handbook,* Volume 4, is a particularly useful reference source.

Forming of ArcelorMittal USA steel

Cold, warm and hot forming are important processes used in the conversion of plate steel to useable parts and machinery. One of the critical properties of steel is ductility, which allows it to be shaped. There are, however, a wide variety of steel grades and forming processes that may be utilized. Therefore, guidelines for the safe and effective processing of plate steel are appropriate. The following guidelines were developed with particular emphasis on those practices that minimize the potential for cracking during the forming operation.

Cold forming

Cold forming is a term that applies to forming operations performed at ambient shop temperatures, typically 50–90°F. Cold forming is also referred to as roll forming, press brake bending and cold pressing. These processes can be performed on carbon, high-strength low-alloy, alloy, stainless and clad plate steel. Guidelines for these processes are presented in three areas.

Steel properties—The mechanical properties of the particular steel grade being formed dictates the loads required for forming and the care that should be taken during the process. A low yield strength steel such as ASTM A36 (36 ksi minimum yield strength) will not require as high a load to form as higher strength steels, such as ASTM A514 (100 ksi minimum yield strength) or ArcelorMittal USA Hardwear® 400F (nominal 140 ksi yield strength). The bend forming loads can be estimated from formulas, displayed in Figure 3-9. The higher loads in high strength steels dictate more care should be taken because of the greater stored energy in a piece during forming. Furthermore, higher strength level steels tend to demonstrate more "spring-back" during the process.

Cold bending of plate steel.

Figure 3-9: Bend load formula for determining press load

$$P = (0.833 \times U \times t^2 \times L)/W$$

P = estimated press load, tons

U = ultimate tensile strength, ksi

t = thickness of plate

L = length of plate to bend, inches

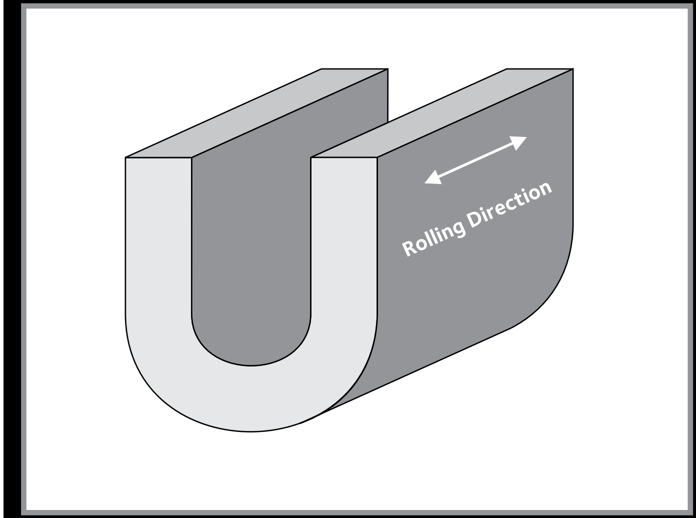
W = width of die opening, inches

Steel ductility, measured as percent elongation in a tensile test, is also an important property. Higher tensile ductility levels allow more deformation during bending, particularly in the outer/tensile surface. Most often ductility decreases with increasing yield strength. Moreover, steel toughness, as measured by the Charpy V-Notch impact test, is useful in predicting cracking tendency during forming of plate. If a steel has sufficient toughness it will be more resistant to crack propagation from stress concentrations on the work-piece. Metallurgical processes such as heat treatment, low sulfur processing (including inclusion shape control) and fine grain practices can improve toughness and minimize cracking problems during forming. The benefits of forming at warmer shop temperatures is a result of the influence of toughness on formability. This will be discussed on page 29.

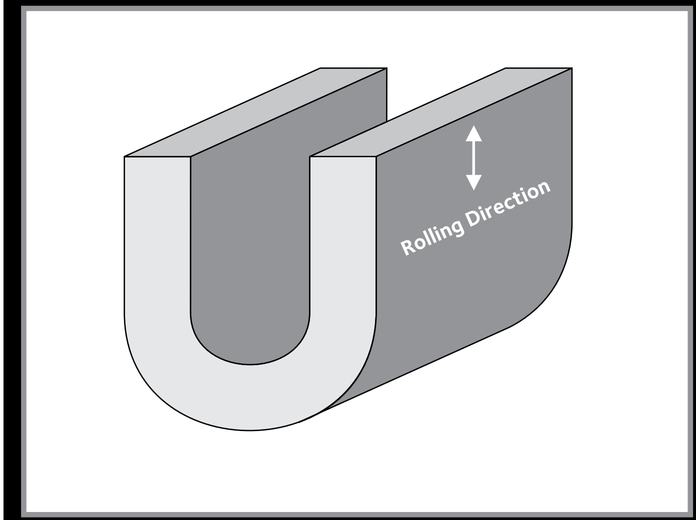
Plate characteristics—Specific characteristics of the actual plate being formed also influence its formability.

- **Thickness**—Thicker plates not only require increased forming loads, but also are more susceptible to cracking because of higher surface tensile stresses and typically lower toughness of thicker plates.
- **Orientation**—Hot rolling of plate steel results in directionality of properties being created. Non-metallic inclusions in conventional structural steels are elongated in the primary rolling direction. These become sites for localized deformation and eventual cracking. Thus there is an optimum forming orientation for severe bending applications, as shown in Figure 3-10.

Figure 3-10: Orientation of bend with respect to rolling direction



Bad direction, longitudinal bend



Good direction, transverse bend

Figure 3-11: Approximate depths of heat affected zones in oxygen cut steels

Thickness (inches)	Oxy-fuel cut edge HAZ depth (inches)*		
	Low carbon steels	High carbon steels	Alloy steels
Under 0.5	Under 0.03125	0.03125	0.0625 and greater
0.5	0.03125	0.03125 to 0.0625	0.125 and greater
6	0.125	0.125 to 0.25	0.25 and greater

* Depth of hardened coarse grain HAZ is considerably less

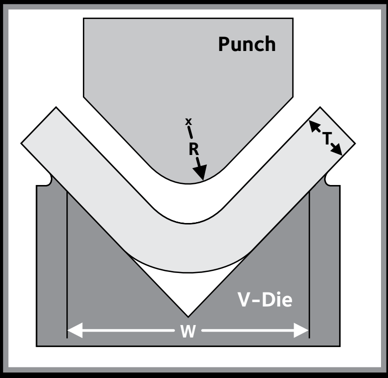
Figure 3-12: Example of cracking in HAZ that lead to failure of bend

- **Edge condition**—A major cause of cracking during forming is the condition of the plate edge in the vicinity of the bend. An oxy-fuel gas-cut or plasma-cut edge has a hardened, low toughness heat affected zone (HAZ), which may initiate a crack during forming. The hardened edges should be removed by localized grinding or heat treatment. Even sheared plates may have a remnant, cold worked edge that should be removed by grinding. Figure 3-11 shows the approximate depths of the HAZ in oxygen cut edges. Figure 3-12 shows an example of an untreated gas-cut edge that cracked in the HAZ and led to failure of an A515 Grade 70 plate during forming.
- **Surface condition**—The surfaces of as-rolled and/or heat treated plates may have pits, scratches or gouges caused by processing or handling. The tensile/outer surface in the vicinity of the bend should be inspected and gross defects smoothed out by grinding. Other surface conditions such as die stamps, arc strikes or areas where lifting lugs may have been attached would have similar concerns.

Forming practices—The techniques and equipment used in cold forming can have a significant influence on successful processing.

- **Forming parameters**—The design of the forming operation includes the radius of the punch and the geometry of the die, as demonstrated in Figure 3-13. Guidelines for forming of popular structural grades were developed by an AISI study. These results are summarized and published in ASTM A6 Appendix X4.

Figure 3-13: Important parameters in bend forming



Punch bend forming severity ratio–R/T
Die bend forming severity ratio–W/T

- **Die conditions**—If the surface of the female die is heavily gouged, smooth metal movement is inhibited. The surfaces of the V-die should be ground smooth. To further assist metal sliding over the V-die surfaces, lubrication may be utilized. Forming waxes and greases are available for these applications.
- **Clad products**—In severe cold forming applications for roll-bonded clad, a weld bead, tying in the two clad layers, will minimize the potential for separation of the layers.

Warm forming

Increasing the local or general temperature of the formed part can be helpful in difficult forming applications, as long as specific guidelines are followed. Warm forming is most often used to describe forming done at elevated temperatures that does not significantly change the properties of the base plate.

Reduced loads—Forming loads can be reduced if the temperature of the work-piece is increased to 900°F or higher. However, if the temperature used is too high, the strength and hardness of the base plate will be reduced. Refer to the mill test report for the heat treatment history of the plate. As a general guideline, do not heat as-rolled or normalized steels above 1050°F, and do not heat quenched and tempered steels to within 50°F of the mill tempering temperature. In the case of ArcelorMittal USA's quenched and tempered Hardwear® steel, which is tempered at 400°F, a maximum forming temperature should be 350°F.

Reduced cracking—As was mentioned earlier, steel toughness is an important property to resist cracking during forming. Because ferritic steels go through a transition in toughness versus temperature, the effective toughness of a steel can be enhanced by increasing the temperature. This is shown schematically in Figure 3-14. Typically increasing the forming temperature to the range of 200–300°F can significantly improve the toughness of the steel and minimize certain cracking problems.

Hot forming

When very thick plates must be formed, the required loads may be beyond machine capability. Hot forming allows a significant reduction in these loads because the typical temperatures used (1600–2000°F+), result in a major drop in the yield strengths of all steel products. However, exposure of the plate steel to these higher temperatures results in a significant change in the properties and microstructure of the base plate.

Steel chemistry—In very challenging hot-forming applications, the copper level in the steel is critical. A problem called "copper-checking" occurs in structural steels when the copper level is over 0.15 percent (and there is no matching nickel level). Susceptible applications include head spinning and "fluing" or swagging of nozzle openings in

Figure 3-14: Schematic CVN curve showing better toughness at higher temperatures.

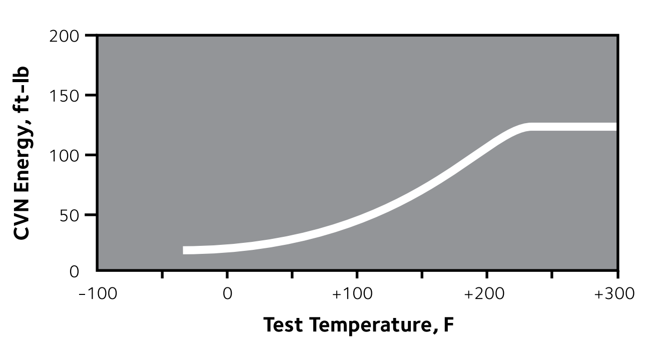


Figure 3-15: Nozzle openings showing Cu-checking problem

pressures vessels. Steels used in these applications should be ordered with a copper restriction of 0.15 percent maximum. An example of this problem is shown in Figure 3-15.

Forming practices—Because the plate steel is being heated to such a high temperature, there are several guidelines to observe.

- The uniformity of heating is very important. Also, care must be taken to make sure there is no direct impingement of the burner flame on the steel surface.
- Because the steel may be at high temperatures for a period of time, the atmosphere conditions in the furnace should be monitored (fuel/air ratios). Excessive localized oxidation of the steel can result in pitting of the steel surface.

Heat treatment of finished part—Because the properties of the base plate change during the hot forming operation, subsequent heat treatment of the formed part may be required.

- **Normalizing**—If the hot forming operation was intended to act as a normalizing heat treatment as well, the steel mill should have been requested to run a capability lab test on the plate. Use of the same heating temperature is important. Furthermore, a normalizing heat treatment requires air cooling after heating. Formed parts should not be stacked and should be positioned to allow uniform cooling. Sometimes fan cooling may be required to achieve the cooling rate necessary to achieve mechanical properties.
- **Quenching and tempering**—If a hot formed part must be quenched and tempered, the mill capability test heat treatment must be followed. A uniform and effective water quench of the part is required. Water circulation and a large enough vessel to hold sufficient water are important. The water temperature should not exceed 100°F to ensure an effective quench. The tempering temperature and time must also be followed to assure achieving mechanical properties.

Thermal cutting of ArcelorMittal USA steel

Thermal cutting, burning, or oxy-fuel cutting (OFC) of plate steel with an oxygen torch is a combination of oxidation and melting. Chemically produced intense heat is generated by the rapid oxidation of iron with a stream of high purity oxygen. This reaction is exothermic; that is, heat is given off as the combination takes place. The majority of the information in this chapter deals with OFC. Some guidelines are also provided for plasma and laser beam cutting.

Burning begins by heating a small portion of the plate surface to red hot (approximately 1600°F) with an oxy-fuel gas flame and directing a stream of high purity oxygen against it. Oxidation, or burning, begins almost instantly. The heat from the reaction is so intense that a considerable amount of adjacent metal is melted and flows away from the cutting slot, or kerf, with the oxidized material. This "slag" typically may contain 30 percent melted steel and 70 percent iron oxides (FeO, Fe_2O_3 and Fe_3O_4).

The conventional cutting torch is equipped with a tip that contains a cutting oxygen orifice surrounded by a ring of small oxy-fuel gas ports. A number of gases are commonly used for the oxy-fuel mix including acetylene, MPS, natural gas, propane and propylene. Flames from the oxy-fuel ports help initiate the cut, descale the plate, add heat to maintain cutting and shield the oxygen stream. After initiation of the reaction, the kerf cut through the plate section will continue to advance as long as the oxygen stream is supplied.

Oxy-fuel cutting of plate steel.

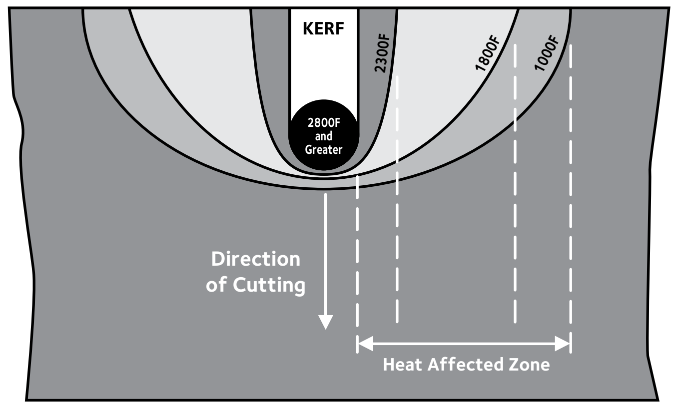
Cutting process parameters

For burning, one pound of iron requires 4.6 ft^3 of oxygen. Oxygen consumption will vary depending on the quality of cut desired. For average straight line cutting of low carbon steel, consumption varies with the thickness of the plate and is lowest in the 4- to 5-inch range. The quantity of oxygen available for reaction decreases as it flows through the cut.

If oxygen flow is sufficient and properly directed—and, if cutting speed is not excessive—the cut face remains vertical and the rate of cutting will be approximately constant. If the cutting speed is too fast and/or oxygen flow is insufficient, the lower portion of the cut reacts slowly and "drag" marks become pronounced. A slower cutting speed increases the amount of heat retained and results in an improved quality cutting edge. Various cutting tips are available depending on the plate thickness to be cut. Equipment manufacturers provide a suggested range of cutting speeds, as well as gas flow rates that should be used with their products.

During cutting, the heat from the process causes an area near the kerf to heat up to temperatures that cause metallurgical transformation of the steel. This heat-affected-zone (HAZ) is shown schematically in Figure 3-16. The depth of the HAZ is influenced

Figure 3-16: Schematic of thermal cutting process



Creation of a heat affected zone

Figure 3-17: Approximate depths of heat affected zones in oxygen cut steels

Thickness (inches)	Oxy-fuel cut edge HAZ depth (inches)*		
	Low carbon steels	High carbon steels	Alloy steels
Under 0.5	Under 0.03125	0.03125	0.0625 and greater
0.5	0.03125	0.03125 to 0.0625	0.125 and greater
6	0.125	0.125 to 0.25	0.25 and greater

* Depth of hardened coarse grain HAZ is considerably less

by the cutting parameters (slower cutting speed results in a larger HAZ, but with lower hardness) and the grade of steel being cut. Figure 3-17 shows the effect of steel grade on the approximate depths of these HAZs. The quality of the HAZ (hardness, cracking) is influenced by cutting parameters and whether preheating and post heating are needed or were performed.

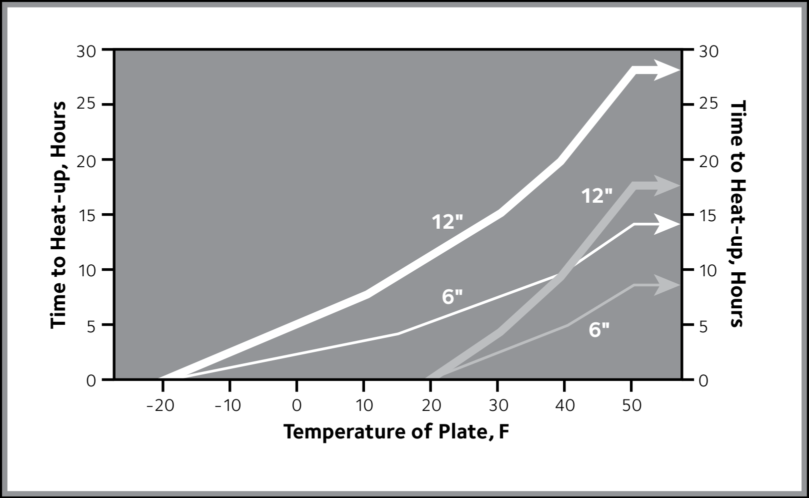
Preheating and post heating

When thermal cutting plate in certain combinations of thickness and chemical composition, special preheating and/or post-heating practices may be necessary. The use of preheating can:

- Increase the efficiency of the cutting operation by permitting increased travel speed and decreased consumption of oxygen and fuel gas.
- Decrease the migration of carbon to the cut surface by lowering the temperature gradient in the steel adjacent to the cut.
- Reduce or prevent hardening of the cut surface by reducing the cooling rate.
- Reduce distortion.
- Reduce thermally-induced stresses, thereby minimizing the formation of thermal "stress-cracks."

It is essential that preheat temperature be fairly uniform throughout the section in the area to be cut. Also, cutting should be started as soon as possible to take advantage of the heat in the plate. It is particularly important in thick plates to have the complete cross-section heated to the appropriate temperature. This is also important when bringing cold plates onto the fabrication floor when a nominal +50°F plate temperature is required. Figure 3-18 demonstrates a significant length of time can be required for a cold plate to warm-up to the +50°F minimum plate cutting temperature.

Figure 3-18: Warm-up of plate to +50°F before cutting



6- and 12-inch thick plates at -20°F or +20°F
Fabricating shop at +60°F

It is recommended all preheating be done in a furnace or on a special preheat table. If furnace or table capacity is not available, local preheating in the vicinity of the cut will be of some benefit. Local preheating may be accomplished by passing the cutting torch flames over the line of the cut until the desired preheat temperature is reached or by using a hand held torch. All local preheating should be done slowly and moderately to avoid high temperature gradients and additional thermal stresses.

Using a proper post heat treatment can eliminate most metallurgical changes caused by the cutting heat. These include tempering of hardened edges and relieving stresses at the cut edge. Post heat treatment should be performed in a furnace or by the use of special multiple flame heating torches *as soon as possible after cutting.*

Metallurgical influences on cut edge quality

The need for special cutting practices, including preheating and post heating, to prevent the occurrence of hard cut edges or "stress-cracking," are dictated by a number of parameters.

Carbon content—As carbon level increases the need for processing precautions increases.

Alloy level—As more alloy elements are added to a steel, the need increases.

Plate thickness—Thicker plates require special care.

Sulfur level—Steels with intentional additions of sulfur (free-machining) require more care.

Plate toughness—A plate in the as-rolled condition requires more care than after it is heat treated.

Part design—Parts with sharp corners or notches need care to prevent cracking.

Typically, a combination of two or more of these conditions dictates the need for additional care (preheating and post heating) when thermal cutting.

NOTE: When laying out ArcelorMittal USA mill edge plate for cutting, take measurements from the centerline of the plate to reliably establish area of good metal.

Guidelines for thermal cutting

The charts on pages 36 and 37 summarize ArcelorMittal USA's recommended preheat and post heat practices for carbon, HSLA and alloy plate steel. These guidelines are based on a combination of steel carbon content, carbon equivalent, thickness and ArcelorMittal USA's experience. Even these guidelines cannot ensure complete freedom from problems. Good shop thermal cutting practices are essential.

Further processing of thermal cut plates

After thermal cutting plates or plate parts, further guidelines for consideration during subsequent processing are:

- If the grade and thickness requires post heat treatment for the part, the remaining usable plate "skeleton" may also need attention to prevent cracking in storage.
- If the cut edges are going to be part of a cold formed part, the tension corner of the edge and any notches should be ground prior to forming.
- If a saw cutting or machining operation will start at a thermally-cut edge, stress relief of the edge or starting of the cut with an abrasive saw may be needed to penetrate the hardened HAZ.

Plasma-arc cutting

Plasma-arc cutting (PAC) is a thermal-cutting process that uses a high temperature, high voltage constricted arc to melt material and high velocity gas to blow it away. Since its introduction in the 1950s, PAC has seen significant development, and with new technologies such as oxygen-PAC and improved equipment design, higher quality cuts and cutting speeds at lower operating costs have been achieved. As a result, more steel fabricators are using PAC, especially in the up to 1.5 inch thickness range. In this thickness range, PAC competes favorably with other thermal-cutting processes such as laser beam cutting (LBC) and OFC. The gases typically used to cut steel are nitrogen, air, carbon dioxide and oxygen.

Cut quality is influenced to a great extent by process variables and the PAC equipment should be operated and maintained strictly according to manufacturers' recommendations. The most common material-related problems found during PAC are:

- Distortion.
- Dross formation.

Distortion—can be minimized by:

- Ensuring the plate is free from residual stresses.
- Employing a cutting sequence to distribute thermally induced strains evenly.
- Using a water shield or cutting under water.

Dross formation—can be minimized by:

- Using oxygen plasma rather than nitrogen or air plasma.
- Limiting Si content to less that 0.1 percent, if using nitrogen or air plasma.
- Minimizing magnetic handling of the plates, to ensure low levels of residual magnetism in the plate.

Laser beam cutting

Laser beam cutting (LBC) is a thermal-cutting process that removes material by locally melting (or vaporizing) with the heat from a laser beam, and using a gas jet to blow the molten or vaporized material away. Plain carbon and low alloy steels are most commonly cut using oxygen as the cutting gas and the exothermic reaction of iron with oxygen provides additional energy to enhance the cutting action. In the past, use of LBC was limited to steels of thickness 0.25 inch and less using laser power levels of 1.5 kW or less. With recent advances made in laser technology, higher laser power levels have been achieved and fabricators now cut 1 inch steel in production.

As with plasma-arc cutting, cut quality is significantly influenced by process variables and the equipment manufacturers' recommendations should be strictly followed for operation and maintenance of the LBC system. Again like PAC, the most common material-related problems found during LBC are:

- Distortion.
- Dross formation, poor cut edge quality.

Distortion—can be minimized by:

- Ensuring the plate is free from residual stresses.
- Employing a cutting sequence to distribute thermally induced strains evenly.

Dross formation—is minimized and cut edge quality improved when:

- Surface scale is uniform and tightly adherent, and the surface is free from mechanical indentations (stamping, gouges, deep scratches), thick paint/thermal chalk markings and heavy rust.
- Si content is low (up to 0.04 percent).
- Modest levels of Cu and Ni are present in the steel.
- There is no gross segregation or large inclusions in the steel.

In most cases, hot-rolled steels are found to cut better in the as-rolled condition than the shot-blasted condition. However in some cases, heat-treated (quenched and tempered) steels give more consistent cuts in the shot-blasted condition. When shot blasting has to be carried out, using a smaller shot size provides more consistent cuts. Sand blasting is not recommended on plates to be laser cut.

Popular ASTM specifications

ASTM specifications	Type A–Alloy C–Carbon H–HSLA	Thickness (inches) +50°F minimum plate temperature[1]	Preheat 300°F gas cut hot	Preheat 300°F–gas cut hot immediately[2] HT edges[4]
A36, A709-36	C	15 and under	over 15	—
A131	C	2 and under	—	—
A202	A	2 and under	—	—
A203	A	6 and under	—	—
A204	A	4 and under	—	over 4
A225	A	6 and under	—	—
A242	C	4 and under	—	—
A283	C	15 and under	over 15	—
A284	C	12 and under	—	—
A285	C	2 and under	—	—
A299	C	2 and under	over 2	—
A302	A	2 and under	over 2–4	over 4
A353	A	2 and under	—	—
A387–11, 12, 21, 22	A	—	2 and under	over 2
A387–5, 9, 91	A	—	2 and under	over 2
A455	C	¾ and under	—	—
A514–A, B, F&H (T-1™), P	A	2.5 and under	—	—
A514–E&Q (T-1C™)	A	3 and under	over 3	—
A515	C	15 and under	—	—
A516	C	15 and under	—	—
A517–A, B, F&H (T-1™), P	A	2.5 and under	—	—
A517–E&Q (T-1C™)	A	3 and under	over 3	—
A529	C	0.5 and under	—	—
A533	A	2 and under	over 2–4	over 4
A537	C	6 and under	—	—
A542	A	—	2 and under	over 2
A543 (HY80, HY100)	A	4 and under	over 4	—
A553	A	2 and under	—	—
A562	A	2 and under	—	—
A572, A709-50	H	3 and under	over 3	—
A573	C	1.5 and under	—	—
A588, A709-50W, HPS 50W	H	3 and under	over 3	—
A612	C	1 and under	—	—
A633	H	6 and under	—	—
A656	H	3 and under	—	—
A662	C	2 and under	—	—
A678	H	6 and under	—	—
A710	A	8 and under	—	—
A724	C	2 and under	—	—
A736	A	4 and under	—	—
A737	H	6 and under	—	—
A738	C	2.5 and under	—	—
A808	H	3 and under	—	—
A709-HPS 70W	H	2 and under	over 2	—
A871	H	1⅜ and under	—	—

Popular ASTM chemistry only grades				
	Type A–Alloy C–Carbon H–HSLA	Thickness (inches)		
ASTM A830 grades		+50°F minimum plate temperature[1]	Preheat 300°F gas cut hot	Preheat 300°F – gas cut hot immediately[2] HT edges
1006–1025	C	15 and under	—	—
1030	C	8 and under	over 8	—
1040	C	—	1 and under	over 1[3]
1045	C	—	1 and under	over 1[3]
1060	C	—	—	all thicknesses[3]
ASTM A829 Grades				
4130	A	1.5 and under	1.5 to 6	over 6[3]
4140	A	—	1 and under	over 1[3]
4142	A	—	1 and under	over 1[3]
4150	A		—	all thicknesses[3]
E4340	A	—	—	all thicknesses[3]
E6150	A	—	—	all thicknesses[3]
8615	A	8 and under	—	—
8617	A	8 and under	—	—
8620	A	8 and under	—	—
8625	A	8 and under	—	—
8630	A	—	2 and under	over 2[3]
ArcelorMittal USA Proprietary Grades				
Clean-Cut™ 20	C	2 and under	over 2	—
C1119®	C	2 and under	over 2	—
Clean-Cut™ 45	C	—	1 and under	over 1[4]
C1144™	C	—	1 and under	over 1[4]
BethStar™	H	3 and under	—	—
Spartan™, HSLA 80/100	A	8 and under	—	—
MTD® 1	A	—	1 and under	over 1[4]
MTD® 2	A	—	1 and under	over 1[4]
MTD® 3	A	—	—	all thicknesses[4]
MTD® 4	A	—	—	all thicknesses[4]
Hardwear® 400F	A	2 and under	over 2–3	—
Hardwear® 500F	A	1 and under	over 1–3	—
T-1™ Abrasion Resistant	A	20.5 and under	over 20.5	—
MIL-A-12560	A	20.5 and under	over 20.5	—
MIL-A-46100	A	1 and under	over 1–2	—

Notes: Recommended practices are based on Tables 10 and 11, Iron and Steel Society Steel Products Manual—Plates, and/or ArcelorMittal USA's experience.

1. When preheating is not required, plates should be at a temperature of at least 50°F. (During winter months, plates brought in from outside storage may require several days to warm up, depending on thickness).
2. Edges must be heat treated (HT) immediately after cutting to soften the edges. If unable to heat treat edges immediately, material must be kept hot until heat treated.
3. Heat to 1100°F/1325°F, hold 0.5 hr./in., air cool. An anneal or sub-critical anneal may be substituted.
4. Heat to 1050°F ± -25°F, hold 0.5 hr./in., air cool.

Welding of ArcelorMittal USA steel

Dealing with hydrogen-assisted cold cracking

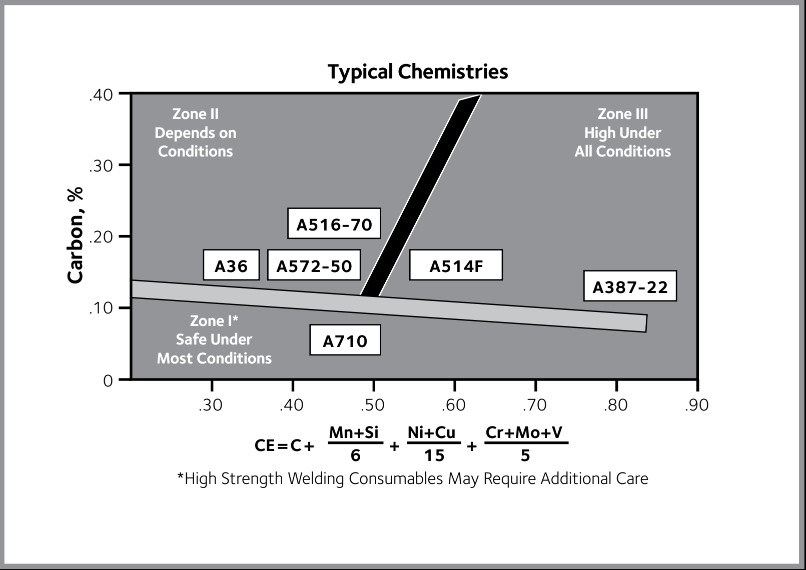
Welding is of critical importance in the fabrication of structures from plate steel. Most popular structural steels are readily weldable with well-established shop practices and welding materials. However, under a combination of circumstances—including the grade of steel, welding consumables being used, weld joint design or environmental conditions—cracking of weldments may occur. A popular way to identify a potentially susceptible grade of steel is to calculate a carbon equivalent and refer to a diagram such as that shown in Figure 3-19. However, this is at best only a first step in dealing with a welding situation where susceptibility to weld cracking is of concern. There are numerous reference sources for guidance in the welding of steels, four of which are noted at the end of this chapter. In this chapter, we focus on dealing with hydrogen-assisted weld cracking problems that are most frequently encountered in welding of structures fabricated from plate steel.

Cracking in Weldments

Cracks occur in the weld and base metal of fabricated weldments when localized stresses exceed the ultimate strength and/or toughness of the material. These cracks may be in the longitudinal or transverse direction with respect to the weld axis and generally are divided into two categories:

Welding of plate steel.

Figure 3-19: Influence of carbon level and carbon equivalent on susceptibility to hydrogen-assisted HAZ cracking of plate steel



From Graville

Hot cracks develop at elevated temperatures, i.e. they commonly form during solidification of the weld metal.

Cold cracks, or "delayed" cracks, develop after solidification of the fusion zone as the result of residual stresses. Cold cracks generally form at some temperature below 200°F (93°C), sometimes several hours, or even days, after welding. The time delay depends upon the grade of steel, magnitude of welding stresses and the hydrogen content of the weld and heat-affected zone (HAZ).

Delayed cracking normally is associated with dissolved hydrogen and can occur in the weld metal, generally when filler metals with high yield strength levels are used, or in the heat-affected zone of the base metal due to diffusion of hydrogen from the weld metal to the base metal during the welding process (Figure 3-20). Examples of typical delayed cracks, as in Figures 3-21 and 3-22, include:

- **Toe cracks** which are generally cold cracks that initiate approximately normal to the base metal surface and then propagate from the toe of the weld where the residual stresses are higher. These cracks are generally the result of thermal shrinkage strains acting on a weld heat-affected zone that has been embrittled. Toe cracks sometimes occur when the base metal cannot accommodate the shrinkage strains that are imposed by welding.

Figure 3-20: Weldment terminology

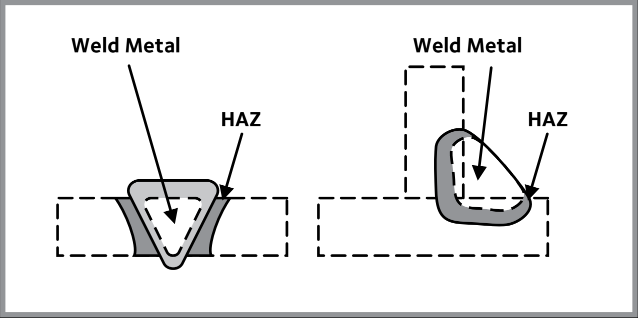
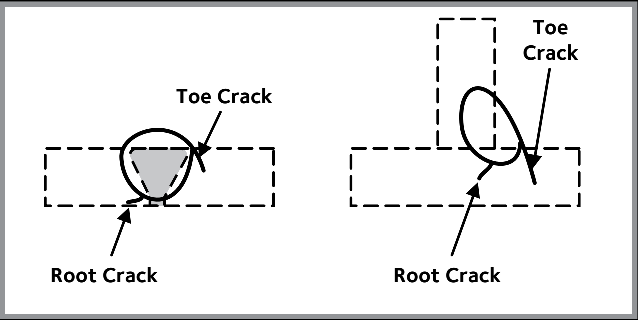
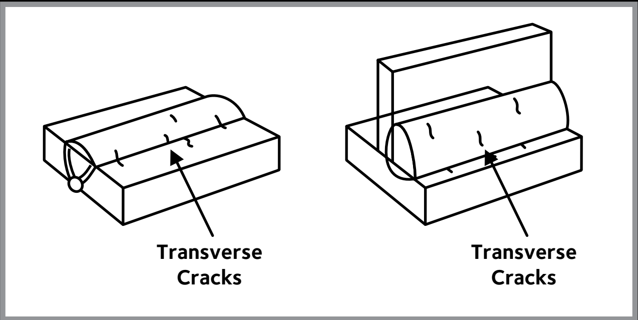


Figure 3-21: Weldment terminology and types of cracks

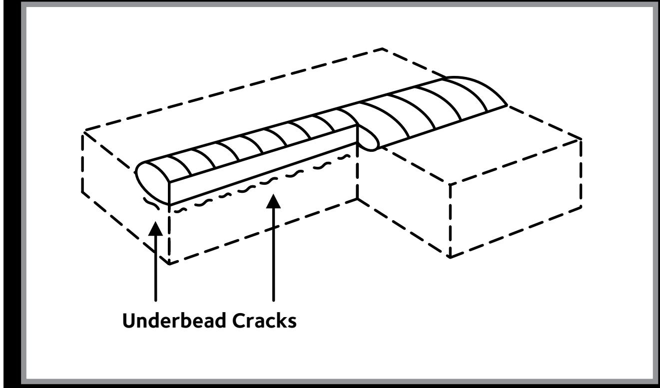


Toe and root cracks



Transverse cracks

Figure 3-22: Weldment terminology and types of cracks



Underbead cracks

- **Root cracks**, which run longitudinally, originate in the HAZ of the root of the weld.
- **Transverse cracks** are nearly perpendicular to the weld axis. They may be limited entirely to the weld metal or may propagate from the weld metal into the heat-affected-zone and the base metal. Transverse cracks are normally related to hydrogen embrittlement.
- **Underbead cracks** are generally cold cracks that form in the heat-affected zone. They may be short and discontinuous, or may extend to form a continuous crack. Usually found at irregular intervals under the weld metal, they do not always extend to the surface.

The occurrence of any of the aforementioned cracking requires hydrogen in solid solution, a crack susceptible microstructure and high residual stresses.

Hydrogen can be absorbed from the atmosphere in large amounts by carbon and alloy steels at the elevated temperatures associated with welding. As the steel cools, it retains less and less hydrogen in solution and “rejects” the excess hydrogen. When steel is held at elevated temperatures or slow cooled, hydrogen atoms can escape back into the atmosphere by the process known as diffusion. However, rapid cooling, associated with most welding processes, tends to “trap” the hydrogen, where it acts to embrittle and weaken the steel structure. A greater potential for cracking exists in a brittle material (high-strength, high-hardness) subjected to high residual stresses (restrained joints).

The ability of a steel to form the hard metallurgical constituent known as martensite or other hard phases is, in general, dependent on the carbon equivalent (CE) of the steel and the cooling rate imposed upon it in cooling from the transformation temperature. The higher the CE and the faster the cooling rate, the higher the tendency for hard, brittle phases to form during cooling. Since the metallurgical characteristics of the base metal can influence heat-affected zone crack susceptibility and these characteristics are determined, in large part, by the steel’s chemistry, small changes in chemical composition of the base and filler metals (hydrogen content) can appreciably increase cracking tendency. And, since steel is melted to a composition range, there can be a significant difference in crack susceptibility between plates produced from several heats of the same steel grade.

In the welding of plate steel, the plate acts as a giant “heat sink” and actually “sucks” heat away from the weld. The thicker the plates and more complex the design of the weld joint, the bigger the heat sink, the faster the cooling rate, and the greater the tendency to form martensite. These factors also lead to the formation of higher residual stresses in the weldment and, when combined with a restrained joint, can significantly increase the susceptibility for cracking.

Sources of hydrogen in welding

During the welding process, hydrogen can enter the molten weld pool from a variety of sources. These sources include:

- Moisture, oil, grease, rust or scale on the base metal surfaces.
- Moisture in the atmosphere (rainy or humid days), which allows infiltration of moisture into the shielding atmosphere surrounding the arc zone.
- Moisture in the electrode coating or core ingredients of flux-core wire.
- Hydrogen from cellulose in the flux or electrode coatings.
- Moisture in the flux of submerged arc welding.
- Drawing lubricant or protective coatings on bare wire or flux-core wire.

Minimizing hydrogen damage

Hydrogen damage (cracking) can be minimized by establishing and enforcing welding practices and procedures that prevent excess hydrogen from entering the weld puddle and by taking steps that permit any dissolved hydrogen to diffuse out slowly. Typical methods to achieve this include:

1. Thorough cleaning of the base metal (weld joint and adjacent area) by grinding and brushing.
2. Exclusive use of low hydrogen electrodes and/or low hydrogen welding processes.
3. Proper drying and storing of welding electrodes, fluxes and gases and proper maintenance of equipment such as wire feeders.
4. Welding procedures that lower welding stresses.
5. Employing a combination of welding and thermal treatments that promote the escape of hydrogen by diffusion. This also can modify the microstructure to make it more resistant to hydrogen cracking.

    - Preheating and maintaining minimum interpass temperature.
    - Slow cooling or maintaining preheat after welding.
    - Post-weld heat treatment.

Low hydrogen welding practices

Electrodes—All electrodes having low hydrogen coverings should be purchased in hermetically sealed containers. Immediately after opening, electrodes should be stored in a ventilated oven held at 250°F (121°C) minimum. After containers are opened or after electrodes are removed from the holding oven, electrode exposure to the atmosphere should not exceed supplier recommendations. The following maximums are provided for reference:

- Electrodes exposed to the atmosphere for longer time periods should not be used unless they have been rebaked. Wet electrodes should be discarded.
- Electrodes should be rebaked no more than once.

Exposure maximums

Carbon steel		Alloy steel	
E70XX	4 hrs.	E70XX-X	4 hrs.
E70XXR	9 hrs.	E80XX-X	2 hrs.
E70XXHZR	9 hrs.	E90XX-X	1 hr.
E7018M	9 hrs.	E100XX-X	0.5 hr.
		E110XX-X	0.5 hr.

- Carbon electrodes should be rebaked at 500–800°F (260–427°C) for a minimum of two hours.
- Alloy electrodes should be rebaked at 700–800°F (371–427°C) for a minimum of one hour.
- Electrodes of any classification lower than E100XX-X (except E7018M and E70XXH4R) used for welding high strength plate steel, such as ASTM A514, A517 & A709-100 &100W, should be baked before use at 700–800°F (371–427°C) for a minimum of one hour, regardless of how the electrodes are furnished.

Bare wire and flux core wire—Remove oil, grease, drawing compound and dirt from the bare wire or flux core wire.

Flux—New fluxes are available that allow weld deposits with low hydrogen levels (less than 5 ml/100 g). These are particularly useful with higher strength alloy electrodes.

- Flux for SAW should be dry and free of contamination from dirt, mill scale or other foreign material.
- Flux should be purchased in packages that can be stored for at least six months, under normal conditions, without affecting its welding characteristics or weld properties.
- Flux from a damaged package should be discarded or dried before use in a ventilated oven, using supplier recommendations; generally baking at 700–800°F (371–427°C) for a minimum of one hour.
- Flux should be placed in dispensing system immediately upon opening a package.
- When using flux from an open package, the top one inch should be discarded.
- Flux that becomes wet should be discarded.
- Clean, unfused, reclaimed flux should be dried as described above before reuse.

Preheat—Even with all the controls described above for minimizing hydrogen in the consumables, high carbon steels (over 0.30 percent C), alloy steels, high-strength steels
(100 ksi/690 MPa yield strength and above), thick plates (over 1 inch or 25 mm) or highly-restrained weldments may require preheat to prevent cracks or fissures due to hydrogen. The primary purpose of preheat is to retard the cooling rate in the heat-affected zone and weld metal. In multi-bead welds, subsequent beads may be deposited on metal that has been preheated by preceding beads, but the first and most important bead is deposited on cold steel unless a preheating procedure is adopted. Preheating has the advantages of:

- Drying the joint of any retained moisture.
- Burning off any organic compounds.
- Increasing the diffusion rate of hydrogen.
- Slowing the weldment cooling rate.

Calculations have established the cooling rate from a preheated plate temperature of 200°F (93°C) is only 85 percent the rate from a plate at the ambient temperature of 75°F (24°C). It is 70 percent for a 300°F (149°C) preheat. This slower cooling rate modifies the heat-affected zone microstructure to make it more crack resistant and lowers the level of residual stresses in the weldment.

Preheating temperatures used are based on experience or codes, such as the AWS D1.1 and D1.5. Typically, shop ambient temperatures of 50–60°F (10–16°C) are appropriate to some thickness. The preheat temperatures should then increase with thickness, for example, 150°F (66°C), 225°F (107°C), 300°F (149°C). For high carbon and high alloy steels, preheating temperatures as high as 600°F (360°C) may be required. Furthermore, the higher residual stresses that result with certain joint

designs and higher strength welding consumables may require higher preheats to avoid delayed cracking even for carbon steels that usually require minimal preheat.

Methods for preheating—The preheat method used is also important. Preheating may be applied in several fashions, with oxy-fuel (rosebud) torches being one of the most common. Various types of electric resistance heaters or blankets are also available.

One of the by-products of combustion is moisture. When a flame is applied to cold steel, condensation usually occurs in the region. It is important to drive this moisture ("chase the chill") from the weld zone. Also, flame preheating from only one side of the plate may cause condensation on the opposite side of the joint, causing moisture to be picked up in the first, or "root," pass.

Preheat temperature measurement can be accomplished in several ways, the most common being the use of Tempil sticks (crayons that melt at the prescribed temperature). It is important to remember the proper preheat temperature has not been reached and the steel is not ready to weld until the Tempil sticks melt at a minimum distance of 3 inches on either side of the joint, as well as the back side.

Once welding begins, the weld joint should not be allowed to cool below the preheat temperature (now the minimum "interpass" temperature) until the welding is complete. If the welding operation is interrupted for any reason, the above preheating operation should be repeated until the minimum preheat temperature is re-established.

Slow cooling and post-weld heat treatment

The same thick, high-strength restrained weldments that require preheat may also require slow cooling and/or post-weld heat treatment (PWHT). Again, this preheat/post heat combination serves the purpose of reducing residual stresses, allowing the diffusion of dissolved hydrogen and modifying the microstructure of the heat affected-zone to render it more crack resistant.

The most common methods of slow cooling involve maintaining minimum preheat temperature on the joint for several hours after the welding has been completed and/or wrapping the completed weldment with an insulating blanket to retard the cooling rate.

While the preheat and slow cool methods described above help in reducing the formation of martensite, a certain amount is unavoidable in thick, high CE steels. In these instances, post-weld heat treatment (PWHT) may be necessary. PWHT, also known as "stress relieving" or "tempering," is usually accomplished by heating the weldment to a temperature below its tempering temperature or other temperature which may affect the base metal properties. However, for PWHT to be of value in reducing hydrogen in the weldment it must be performed immediately after the weld has begun to cool. Other critical aspects of any PWHT include:

- Temperature of the furnace for charging the weldment.
- Heat up rate.
- PWHT temperature and range.
- Hold time at temperature.
- Cooling rate.

Applicable codes and specifications, job requirements and qualification test requirements generally govern the specific PWHT cycle selected. Some steels, such as ASTM A514 and A710, can be embrittled by PWHT. It is recommended the choice of PWHT be made only after review by a welding engineer.

More specific welding information

Chapters 11 and 12 provide more detailed welding information for popular structural and pressure vessel plate steels.

References

The following references are excellent resources for additional information on the welding of steels.

1. R. D. Stout. *Weldability of Steels,* 4th edition, Welding Research Council, New York, NY, 1987.
2. ASM International. *ASM Handbook,* Volume 6, Welding, Brazing and Soldering, Materials Park, OH, 1993.
3. American Welding Society. D1.1–96, 1996, *Structural Welding Code–Steel,* Miami, FL, 1996.
4. American Welding Society. D1.5–96, 1996, *Bridge Welding Code,* Miami, FL, 1996.

Welding and other data

Welding and other data are provided for structural and pressure vessel plate steel grades. This information includes welding electrode and preheat guidelines, and typical carbon equivalent levels. This welding information may be more stringent than AWS D1.1. Furthermore, although some grades may be welded with other than low hydrogen practices, ArcelorMittal USA recommends use of low hydrogen welding practices for all plate steel welding. Also provided are available Charpy V-Notch levels that can be ordered and, where available, typical stress-strain curves and atmospheric corrosion data. Please refer to ArcelorMittal USA if additional data is desired.

Structural plate steel
Plate steel grades produced following
ASTM A6 general requirements

Pressure vessel plate steel
Plate steel grades produced following
ASTM A20 general requirements

Welding and other data on structural plate steel grades

Standard specification for carbon structural steel

Welding data
Suggested welding consumables for arc welding processes

Manual shielded metal-arc low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-Arc	Notes
E70xx, E70xx-x	F6xx-Exxx, F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS	Only low hydrogen electrodes shall be used when welding A36 more than 1 in. (25.4 mm) thick for dynamically loaded structures.

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
Over ¾ to 10.5 incl	70°F	70°F	
Over 10.5 to 20.5 incl	150°F	150°F	
Over 20.5	225°F	225°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

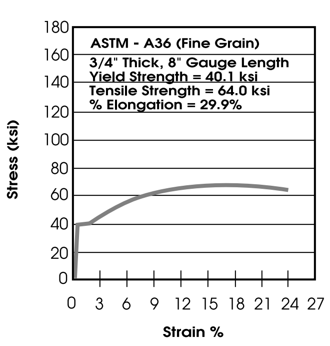
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Thickness ilnches)	Typical carbon equivalent values
Up to 10.5 incl	0.33 to 0.37
Over 10.5 to 20.5 incl	0.35 to 0.39
Over 20.5 to 15 incl	0.38 to 0.42

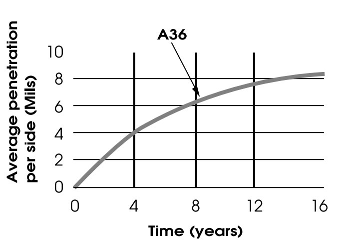
Shaded area denotes availability of A36 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 4 incl	shaded	shaded	shaded	shaded	shaded	shaded	shaded
Over 4 to 8 incl	shaded	shaded	shaded	shaded	shaded	shaded	
Over 8 to 12 incl	shaded	shaded	shaded	shaded	shaded	shaded	

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Description
Specification covers plates, shapes and bars. Only data applicable to plates is shown. This specification, which describes an as-rolled plate steel grade, is approved for use by the Department of Defense.

Year introduced
1960

Special features
This specification permits the addition of copper to enhance corrosion resistance. A special paragraph relating to the use of this grade for bridge base plates is included in the specification. If the plate is used for this purpose, refer to the specification for more information.

Normal uses
A popular "workhorse" grade, it is used widely for various applications. For bridges, this grade is specified as A709 Grade 36.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description
Specification covers a grade of steel for plates, shapes and bars. Only data applicable to plate is shown. A242 is a high-strength, low-alloy grade that has approximately four times the corrosion resistance of carbon steels without copper. ArcelorMittal USA's trade name for Type 1 is Mayari-R™ and Cor-Ten®. This specification is approved for use by the Department of Defense.

Year introduced
1941

Special features
This specification allows the customer to request proof of corrosion resistance from the plate producer.

Normal uses
A corrosion-resistant steel whose oxide forms a protective coating. Used in many painted and unpainted applications (buildings, bridges, industrial equipment, railroad rolling stock).

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

ASTM color code
Blue

Standard specification for high-strength, low-alloy structural steel

Welding data
Suggested welding consumables for arc welding processes

Structure type	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
Structure will not be painted after fabrication	E8016-B1, E8018-B1, E8018-W	F7xx-Exxx-W	See AWS D1.1	E80T1-W	* These rods can be used in unpainted structures in single-pass fillet welds to 0.25 inch maximum and in single-pass groove welds of 0.25 inch maximum since these welds have high base metal dilution.
Structure will be painted after fabrication*	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exxx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
Up to ¾ incl	70°F	70°F
Over ¾ to 10.5 incl	70°F	70°F
Over 10.5 to 20.5 incl	150°F	150°F
Over 20.5 to 4 incl	225°F	225°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding Carbon Equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

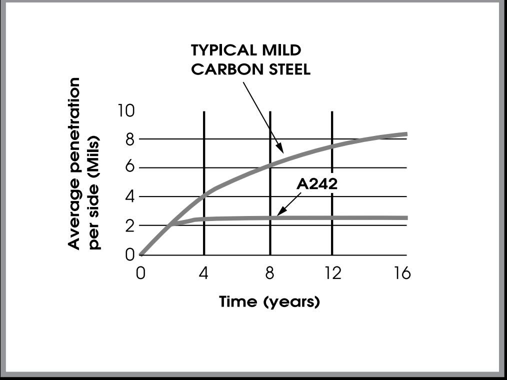
Thickness (inches)	Typical carbon equivalent values
Up to 4	0.30 to 0.44

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Shaded area denotes availability of A242 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 4							

Typical industrial atmospheric corrosion data



Standard specification for low and intermediate tensile strength carbon steel plates

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A, B, C, D	E70xx, E70xx-x	F6xx-Exxx, F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
A, B, C, D	Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
	Over ¾ to 10.5 incl	70°F	70°F	
	Over 10.5 to 20.5 incl	150°F	150°F	
	Over 20.5	225°F	225°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

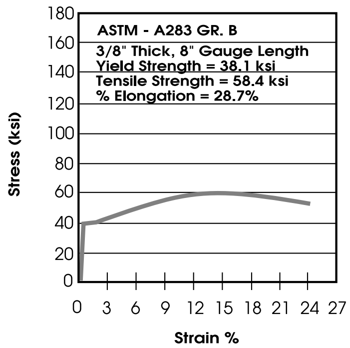
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A	Up to 15	0.12 to 0.18
B	Up to 15	0.15 to 0.25
C	Up to 15	0.17 to 0.29
D	Up to 15	0.24 to 0.37

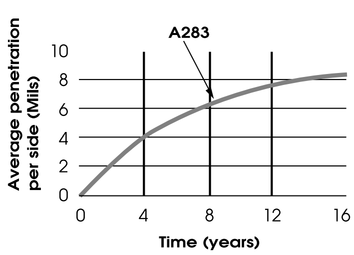
Shaded area denotes availability of A283 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 4	shaded	shaded	shaded	shaded	shaded	shaded	shaded
Over 4 to 18 incl	shaded	shaded	shaded	shaded	shaded	shaded	
Over 8 to 12 incl	shaded	shaded					

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Description
Specification covers four grades of steel for plates, shapes and bars. Only data applicable to as-rolled plate steel grades is shown.

Year introduced
1946

Special features
This specification permits the addition of copper to enhance corrosion resistance.

Normal uses
An inexpensive "utility" grade of steel used widely in many non-demanding applications.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

ASTM color code
Grade: D—Orange

Description
Specification covers a grade of steel for plates. It is an alloy steel grade, fully killed, fine grain (ASTM Number 5 or smaller). It is heat treated by quenching and tempering. The heat treating temperatures are reported on the test certificates. The specification permits 14 compositions, of which ArcelorMittal USA produces Grades A, B, D, E, F, H, P and Q. The specification is approved for use by the Department of Defense. The pressure vessel version of this specification is A517.

Year introduced
1964

Special features
A quenched and tempered alloy grade with a high strength-to-weight ratio.

Normal uses
Industrial applications where high strength, low weight and high impact values are required. Machinery, mining equipment and other demanding applications. The chemistries of the A514 grades are often used to produce abrasion resistant grades to minimum Brinell requirements. Welding information is also provided for them. For bridges, this grade is specified as A709 Grade 100 or 100W.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Grades A, E, P — Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Grades B, F, H, Q — It is important to note this grade of steel may be susceptible to cracking in the heat-affected zone of welds during post-weld heat treatment (stress relief). Therefore, ArcelorMittal USA recommends careful consideration be given to this phenomenon by competent welding engineers before stress relieving is applied to weldments of this grade. Also, it is not recommended for service at temperatures lower than -50°F or higher than 800°F.

ASTM color code
Red

Standard specification for high yield strength, quenched and tempered alloy steel plate, suitable for welding

This specification permits varied chemistries called Grades A, B, C, E, F, H, J, K, M, P, Q, R, S and T. (ArcelorMittal USA makes only ASTM A514 Grades A, B, E, F, H, P and Q.)

Welding data
Suggested welding consumables for arc welding processes

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
Up to 20.5 incl	E11015-x, E11016-x, E11018-x	F11xx-Exx-xx	ER110S-x	E11xTx-x	See Special notes section for concerns about post-weld heat treatment.
Over 20.5	E10015-x, E10016-x, E10018-x	F10xx-Exx-xx	ER100S-x	E10xTx-x	

Deposited weld metal shall have a minimum impact strength of 20 ft-lb (27.1J) at 0°F (-18°C) when Charpy V-Notch specimens are required.

Suggested minimum preheat and interpass temperatures for welding

Thickness (inches)	Produced to A514 tensile properties	Produced to minimum brinell hardness requirements for abrasion resistant applications
Up to ¾ incl	50°F	100°F
Over ¾ to 10.5 incl	125°F	150°F
Over 10.5 to 20.5 incl	175°F	200°F
Over 20.5	225°F	250°F

A preheat or interpass temperature above the minimum shown may be required for highly restrained welds—preheat or interpass temperatures should not exceed 400°F for thicknesses up to 1.5 inch or 450°F for thicknesses over 1.5 inch.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

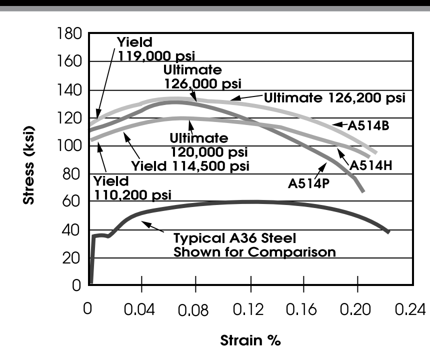
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A	Up to 1.25	0.45 to 0.55
B	Up to 1.25	0.40 to 0.53
E	Up to 6	0.70 to 0.80
F	Up to 2.25	0.50 to 0.60
H	Up to 2	0.50 to 0.60
P	Up to 4	0.60 to 0.70
Q	Up to 6	0.75 to 0.85

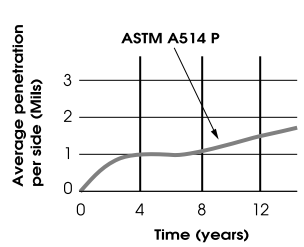
Shaded area denotes availability of A514 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches)	Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 6								

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Standard specification for high-strength carbon-manganese steel of structural quality

Welding data
Suggested welding consumables for arc welding processes

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
Up to 1	E70xx E70xx-x	F6xx-Exxx, F7xx-Exxx, F7xx-Exx-xx	ER70S-x,	E6xT-x, E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
Up to ¾ incl	None*	None*
Over ¾ to 1 incl	150°F	50°F

Notes

* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

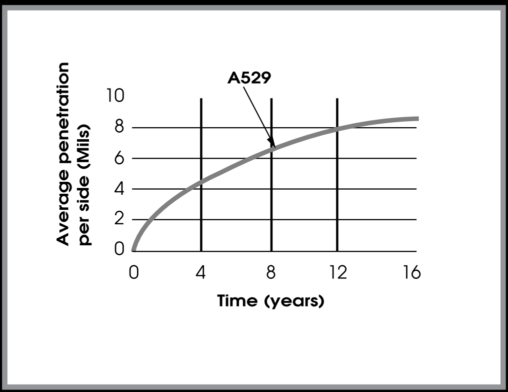
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Thickness (inches)	Typical carbon equivalent values
Up to 1	0.37 to 0.42

Shaded area denotes availability of A529 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 1							

Typical industrial atmospheric corrosion data



Description
This specification covers a grade of plate steel, shapes, sheet piling and bars. Only data applicable for an as-rolled steel plate grade is shown. This specification is approved for use by the Department of Defense.

Year introduced
1964

Special features
A low-cost grade limited to 0.5 inch thickness, used occasionally for non-demanding applications.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

ASTM color code
Grade: 50—Black and yellow
55—Black and red

Description

This specification covers four grades of high-strength, low-alloy structural steel shapes, plates, sheet piling and bars. Only data applicable to plate steel is shown here. The specification defines four microalloy types. ArcelorMittal USA routinely makes Type 1 and Type 2. This specification is approved for use by the Department of Defense.

Year introduced

1966

Special features

This grade is available in four strength levels. The addition of copper is permitted to enhance corrosion resistance.

Normal uses

A widely used structural grade. It is a natural successor to A36 when the strength of a component must be increased. For bridges, this grade is specified as A709 Grade 50.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

ASTM color code

Grade: 42—Green and white
50—Green and yellow
60—Green and gray
65—Green and blue

Standard specification for high-strength, low-alloy columbium-vanadium structural steel

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
42, 50	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	Deposited weld metal shall have a minimum impact strength of 20 ft-lb (27.1J) at 0°F (-18°C) when Charpy V-Notch specimens are used. This requirement is applicable only to bridges.
60, 65	E8015-x, E8016-x, E8018-x	F8xx-Exx-xx	ER80S-x	E8xTx-x	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
42, 50	Up to ¾ incl	70°F	70°F
	Over ¾ to 10.5 incl	70°F	70°F
	Over 10.5 to 20.5 incl	150°F	150°F
	Over 20.5 to 4 incl	225°F	225°F
60, 65	Up to ¾ incl	70°F	70°F
	Over ¾ to 1.25 incl	150°F	150°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

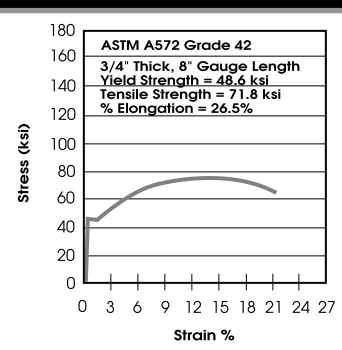
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
42	Up to 6	0.32 to 0.41
50	Up to 10.5 incl	0.32 to 0.41
	Over 10.5 to 4 incl	0.39 to 0.43
60	Up to 1.25	0.41 to 0.51
65	Up to 0.5 incl	0.41 to 0.51
	Over 0.5 to 1.25 incl	0.42 to 0.50

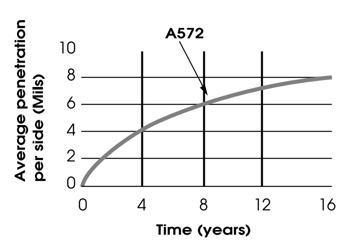
Shaded area denotes availability of A572 grade 50 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 10.5 incl	■	■	■	■	■	■	■
Over 10.5 to 3 incl	■	■	■	■	■		
Over 3 to 4 incl	■	■	■	■	■		

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Standard specification for structural carbon steel plates of improved toughness

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux Cored-arc
58	E70xx	F6xx-Exxx, F7xx-Exxx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS
65, 70	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
58	Up to ¾ incl Over ¾ to 10.5 incl	None* 70°F	None* 70°F
65, 70	Up to ¾ incl Over ¾ to 10.5 incl	None* 70°F	None* 70°F

Notes: * When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

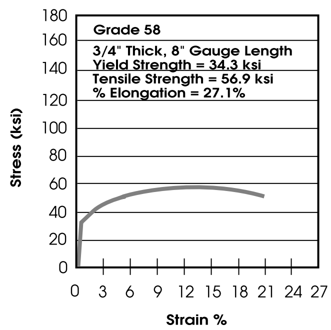
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
58	Up to 0.5 incl Over 10.5 to 4 incl	0.21 to 0.26 0.30 to 0.35
65	Up to 0.5 incl Over 0.5 to 10.5 incl	0.30 to 0.34 0.32 to 0.37
70	Up to 0.5 incl Over 0.5 to 10.5 incl	0.33 to 0.44 0.40 to 0.48

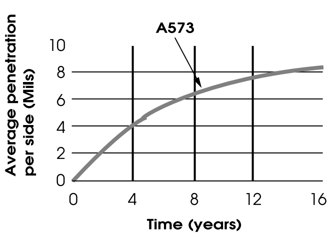
Shaded area denotes availability of A573 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 10.5	shaded	shaded	shaded	shaded	shaded	shaded	shaded

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Description
A specification for three grades of plate steel described by ASTM as having improved notch toughness through the use of fine grain practice. A573 is made to three tensile strength levels.

Year introduced
1968

Special features
None

Normal uses
This grade is not frequently ordered.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description

Specification covers a grade of steel for plates, shapes and bars. Only data applicable to plates is shown. A588 is a high-strength, low-alloy grade produced in three strength levels. ASTM describes this grade as being approximately four times as corrosion resistant as carbon steel without copper. When required, the customer can obtain evidence of its corrosion resistance from ArcelorMittal USA. A588 can be made in Grades A through K. ArcelorMittal USA makes Grade B under the trade name Mayari-R50™. Mayari-R60™ and Cor-Ten® is modified A588 Grade B with yield and tensile strength higher than A588 specifies. This specification is approved for use by the Department of Defense.

Year introduced

1968

Special features

A high-strength, corrosion-resistant grade, the oxide of which forms a protective coating. This grade, while similar to A242, is available in greater thicknesses.

Normal uses

This corrosion-resistant steel, the oxide of which forms a protective coating, is used in many painted and unpainted applications (buildings, bridges, industrial equipment, railroad rolling stock). For bridges, this grade is specified as A709 Grade 50W.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements, such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

ASTM color code

Blue and yellow

Standard specification for high-strength, low-alloy structural steel with 50 ksi (345 mpa) minimum yield point to 4 inches (100 mm) thick (Specification allows thicknesses to 8 inches with reduced yield point.)

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
All	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x	F7xx-Exxx or F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	Special welding materials and procedures, e.g. E80xx-x low alloy electrodes may be required to match the notch toughness of the base metal, or for atmospheric corrosion and weathering characteristics.

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B	Up to ¾ incl	70°F	70°F
	Over ¾ to 10.5 incl	70°F	70°F
	Over 10.5 to 20.5 incl	150°F	150°F
	Over 20.5 to 8 incl	225°F	225°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

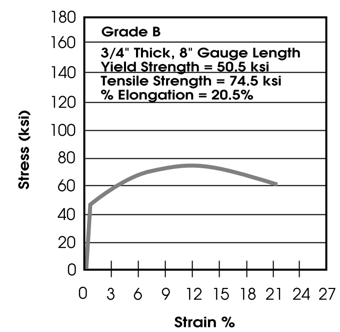
Grade	Thickness (inches)	Typical carbon equivalent values
A, B	Up to 10.5 incl	0.28 to 0.45
	Over 10.5 to 4 incl	0.33 to 0.47
	Over 4 to 8 incl	0.35 to 0.50

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

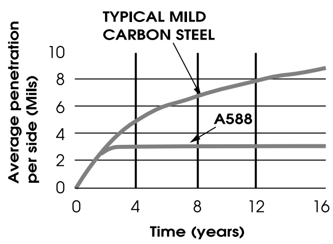
Shaded area denotes availability of A588 grade B plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-60°F
Up to 4 incl	■	■	■	■	■	■	■
Over 4 to 6 incl	■	■	■	■	■	■	
Over 6	■	■	■	■	■		

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Standard specification for normalized high-strength low-alloy structural steel plates

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
A, C, D	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	Deposited weld metal shall have a minimum impact strength of 20 ft-lb (27.1J) at 0°F (-18°C) when Charpy V-Notch specimens are used.
E	E8015-x, E8016-x	F8xx-Exx-xx	ER80S-x	E8xTx-x	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, C, D	Up to 10.5 incl	70°F	70°F
	Over 10.5 to 20.5 incl	150°F	150°F
	Over 20.5 to 4 incl	225°F	225°F
E	Up to ¾ incl	70°F	70°F
	Over ¾ to 10.5 incl	150°F	150°F
	Over 10.5 to 20.5 incl	225°F	225°F
	Over 20.5 to 6 incl	300°F	300°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

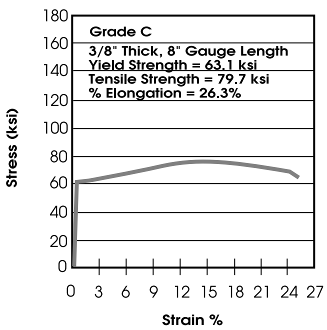
Grade	Thickness (inches)	Typical Carbon Equivalent Values
A	Up to 4	0.34 to 0.42
C	Up to 4	0.37 to 0.45
D	Up to 4	0.40 to 0.50
E	Up to 6	0.45 to 0.55

Shaded area denotes availability of A633 grades C and E plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

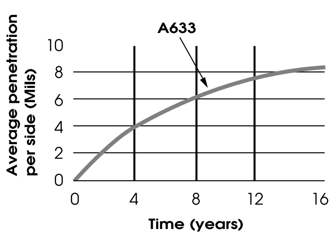
Grade	Thickness (inches)	+70°F	+40°F	0°F	-20°F	-40°F	-60°F	-80°F
C	Up to 4	■	■	■	■	■	■	■
E	Up to 3 incl	■	■	■	■	■	■	■
E	Over 3 to 6 incl	■	■	■	■			

This table is for Normalized, 0.010 percent maximum sulfur.

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Description
Specification covers a grade of steel for plates only. The data shown pertains to plates. The specification allows four chemistries, all of which are produced by ArcelorMittal USA. Generally furnished in the normalized condition, the specification permits the plate to be sold without normalizing when the customer plans to normalize the plate after fabrication. ArcelorMittal USA will furnish normalizing instructions on the paperwork accompanying the order. The specification also permits the addition of copper to improve the corrosion resistance of the grade. The pressure vessel version of this specification if A737.

Year introduced
1970

Special features
Specification requires normalizing.

Normal uses
Particularly well-suited for low-temperature use where notch toughness is a requirement and when strength/weight ratios must be maximum for the application.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Description

Specification covers a grade of steel for plates. Produced as killed steel with fine grain practice, it is available in four strength levels. ASTM allows two types based on composition. ArcelorMittal USA produces Type 7 by a controlled-rolling process (see Chapter 4), which results in a plate having formability, weldability and remarkable impact toughness properties.

Year introduced

1972

Special features

A high-strength, low-alloy steel grade with excellent mechanical and fabricating properties.

Normal uses

Demanding structural applications where strength-to-weight ratios are maximized. Frequency used as a replacement for some quenched and tempered plate steel grades. Its formability allows replacement of multi-piece weldments with formed parts.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Standard specification for hot-rolled structural steel, high-strength, low-alloy plate with improved formability

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
50	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	If impact properties are required, other electrode/ flux combinations, as designated in AWS, can be specified; for example, F7A4-Exx-xx specifies 20 ft-lb at -60°F.
60	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	
70	E8015-x, E8016-x	F8xx-Exx-xx	ER80S-x	E8xTx-x	
80	E10018-x	F10x-Exx-xx	ER100S-x	E100T1-K3, E100T1-K5	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
50	Up to 20.5	70°F	70°F
60	Up to 1.25	70°F	70°F
70	Up to 1	70°F	70°F
80	Up to ¾	70°F	70°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

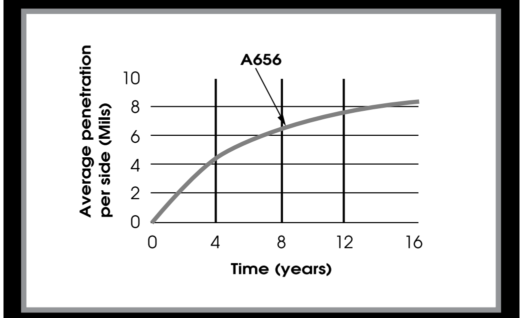
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
50	Up to 20.5	0.27 to 0.31
60	Up to 1.25	0.28 to 0.32
70	Up to 1	0.30 to 0.34
80	Up to ¾	0.37 to 0.41

Shaded area denotes availability of A656 grade 80 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to ¾							

Typical industrial atmospheric corrosion data



Standard specification for low-carbon, low-sulfur, high-strength plate steel for improved toughness, weldability and formability

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
50	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	If impact properties are required, other electrode/flux combinations, as designated in AWS, can be specified; for example, F7A4-Exx-xx specifies 20 ft-lb at 60°F.
60	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS	
70	E8015-x, E8016-x	F8xx-Exx-xx	ER80S-x	E8xTx-x	
80	E10018-x	F10xx-Exx-xx	ER100S-x	E100T1-K3, E100T1-K5	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
50	Up to 20.5	70°F	70°F
60	Up to 1.25	70°F	70°F
70	Up to 1	70°F	70°F
80	Up to ¾	70°F	70°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

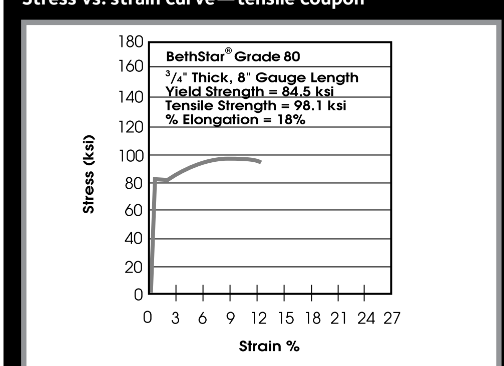
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
50	Up to 20.5	0.27 to 0.31
60	Up to 1.25	0.28 to 0.32
70	Up to 1	0.30 to 0.34
80	Up to ¾	0.37 to 0.41

Shaded area denotes availability of BethStar™ grade 80 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to ¾							

Stress vs. strain curve—tensile coupon



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Description
ArcelorMittal USA's BethStar™ steels are proprietary grades of steel used for plates only. BethStar™ is produced as killed steel with fine grain practice, and is available in four strength levels. They are produced by a controlled-rolling process (see Chapter 4), which results in plates having excellent formability, weldability, and impact toughness properties. BethStar™ grades are more restrictive versions of A656.

Year introduced
1983

Special features
A high-strength, low-alloy steel grade with excellent mechanical and fabricating properties.

Normal uses
Demanding structural applications where strength-to-weight ratios are maximized. Frequently used as a replacement for some quenched and tempered plate steel grades. Its formability allows replacement of multi-piece weldments with formed parts.

Impact toughness
Impact toughness requirements are included in the specification.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description

Specification covers a carbon grade for plates made to a fine grain practice. The specification allows three compositions of which ArcelorMittal USA produces all three. The plate is heat treated by quenching and tempering to develop the high strength levels. The specification permits the addition of copper to improve the corrosion resistance of the plate.

Year introduced

1973

Special features

A high-strength steel with notch toughness.

Normal uses

Demanding structural, industrial and machinery applications where weight reduction is important and notch toughness is a design consideration.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for quenched and tempered carbon steel and high-strength, low-alloy structural steel plates

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-Arc
A	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS
B	E8015-x, E8016-x, E8018-x	F8xx-Exx-xx	ER80S-x	E8xTx-x
C, D	E9015-x, E9016-x, E9018-x	F9xx-Exx-xx	ER90S-x	E9xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A	Up to ¾ incl Over ¾ to 10.5 incl	70°F 100°F	70°F 100°F
B, C	Up to ¾ incl Over ¾ to 10.5 incl Over 10.5 to 2 incl	100°F 150°F 225°F	100°F 150°F 225°F
D	Up to ¾ incl Over ¾ to 10.5 incl Over 10.5 to 3 incl	100°F 175°F 250°F	100°F 175°F 250°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

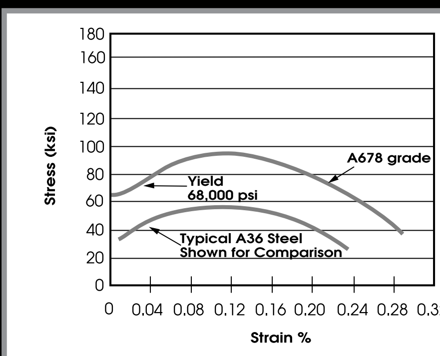
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A	Up to 10.5	0.31 to 0.35
B	Up to 20.5	0.32 to 0.37
C	Up to 2	0.39 to 0.45
D	Up to 3	0.39 to 0.47

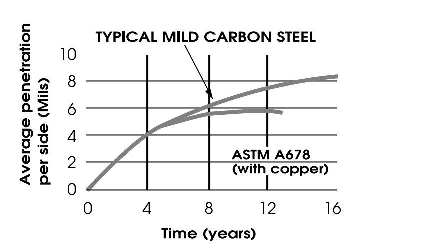
Shaded area denotes availability of A678 grade B plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-50°F
Up to 20.5							

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Standard specification for age-hardening low-carbon nickel-copper-chromium-molybdenum-columbium alloy structural steel plates

Welding data
Suggested welding consumables for arc welding processes

Grade Class	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
A Class 1 Class 3	Up to ¾ Up to 2 incl	E10015-x, E10016-x, E10018-x	F10xx-Exx-xx	ER100S-x	E10xTx-x	See Special notes section for concerns about post-weld heat treatment.
A Class 3	Over 2	E8015-x, E8016-x, E8018-x	F8xx-Exx-xx	ER80S-x	E8xTx-x	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
A Class 1, 3	Up to 4 incl Over 4 to 8 incl	None 50°F	None 50°F	Choice of welding consumable may dictate preheat requirements.

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Class	Thickness (inches)	Typical carbon equivalent values
1, 3	Up to 8	0.42 to 0.48

Description
A high-strength alloy plate specification that provides outstanding formability, weldability and toughness, it has excellent CVN toughness and is readily weldable, requiring no preheat for many applications. It is particularly well-suited for critical applications such as Navy surface vessel hull plates and fracture-critical components on offshore drill rigs. The pressure vessel version of this specification is A736.

Year introduced
1974

Special features
This precipitation hardened grade has an excellent combination of strength, toughness and weldability. Other chemistries for higher strength levels are also available under the ArcelorMittal USA trade name Spartan.™

Normal uses
Naval surface vessel hull plates. May be ordered to military specification Mil-S-24645 (SH), which requires high strength and impact properties, for approved use in critical structural applications.

Impact toughness
The test results for Class 1 shall meet an average minimum value of 20 ft-lb at -50°F for longitudinal specimens. For transverse specimens, the test results shall meet an average minimum value of 15 ft-lb at -50°F. Impact toughness guarantees are available for both classes at test temperatures down to -120°F. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is produced with Fineline™ quality to achieve improved properties. It is important to note this grade of steel may be susceptible to cracking in the heat-affected zone of welds during post-weld heat treatment (stress relief) or elevated temperature service. Also, post-weld heat treatment of elevated temperature service may degrade heat affected zone toughness. Therefore, ArcelorMittal USA recommends careful consideration be given to these phenomena by competent welding engineers before application.

Description

Specification covers a grade of steel plates. A808, a high-strength, low-alloy grade of steel is made to fine grain practice. The plate may be made by controlled-finishing temperature rolling practice. The specification identifies two levels of sulfur content. The supplemental specification lists the Charpy impact values available.

Year introduced

1982

Special features

A grade which may be substituted for more expensive normalized grades (A633) in certain applications.

Normal uses

Uses are in applications where notch toughness is an important design consideration.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Standard specification for high-strength, low-alloy carbon, manganese, columbium, vanadium steel of structural quality with improved notch toughness

Welding data
Suggested welding consumables for arc welding processes

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-Arc
Up to 20.5	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
Over ¾ to 10.5 incl	70°F	70°F	
Over 10.5 to 20.5 incl	150°F	150°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

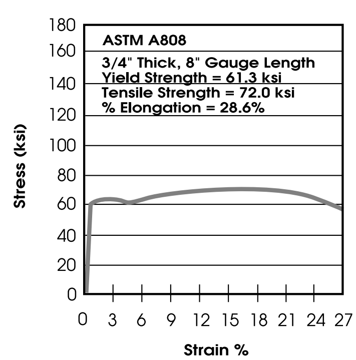
Grade	Thickness (inches)	Typical carbon equivalent values
All	Up to 20.5	0.30 to 0.44

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

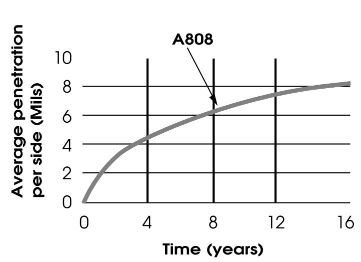
Available longitudinal Charpy toughness levels for A808 plate

Type	Temperature	Avg. absorb energy (ft-lb)
Restricted sulfur (0.010% max.)	-20°F -50°F	55 45
Regular sulfur	-20°F -50°F	40 30

Stress vs. strain curve—tensile coupon



Typical industrial atmospheric corrosion data



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Standard specification for high-strength, low-alloy structural steel with atmospheric corrosion resistance

This specification permits varied chemistries called Types 1, 2, 3 and 4. (ArcelorMittal USA makes only Types 1 and 2.)

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
60 unpainted after fabrication	E8018-W, E8016-B1, E8018-B1	F7Ax-Exxx-W, F7xx-Exxx-W	See AWS D1.1	E80T1-W	
60 painted after fabrication	E7015, E7016, E7018, E7028	F7xx-Exxx	ER70S-x	E7xT-x except -2, -3, -10, -GS	E7015, -16, -18 or -28 can be used for unpainted structure in single-pass fillet welds to 0.25 inch maximum and in single-pass groove welds of 0.25 inch maximum since these welds have high base metal dilution.
65 unpainted after fabrication	E8018-W, E8016-B1, E8018-B1	F8xx-Exx-W	See AWS D1.1	E80T1-W	
65 painted after fabrication	E8015, E8016, E8018	F8xx-Exx-xx	ER80S-x	E8xTx-x	

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
60	Up to ¾ incl	70°F	70°F
	Over ¾ to 10.5 incl	70°F	70°F
	Over 10.5 to 20.5 incl	150°F	150°F
	Over 20.5 to 8 incl	225°F	225°F
65	Up to ¾ incl	70°F	70°F
	Over ¾ to 10.5 incl	150°F	150°F
	Over 10.5 to 20.5 incl	225°F	225°F
	Over 20.5 to 4 incl	300°F	300°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
60	Up to 20.5 incl	0.42 to 0.53
60	Over 20.5 to 6 incl	0.47 to 0.57
65	Up to 10.5 incl	0.42 to 0.53
65	Over 10.5 to 4 incl	0.47 to 0.53

Shaded area denotes availability of A871 grade 60 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Thickness (inches) / Temp.	+70°F	+40°F	+10°F	0°F	-20°F	-30°F	-60°F
Up to 4 incl	shaded	shaded	shaded	shaded	shaded	shaded	shaded
Over 4 to 6 incl	shaded	shaded	shaded	shaded	shaded	shaded	

CONTINUED

Description
Specification covers a grade of steel for plates. Only data applicable to plates is shown. A871 is a high-strength, low-alloy grade produced in two strength levels. ASTM describes this grade as being approximately four times as corrosion resistant as carbon steel without copper. When required, the customer can obtain evidence of its corrosion resistance from ArcelorMittal USA. A871 can be made in Grades 60 and 65.

Year introduced
1987

Special features
A high-strength, corrosion-resistant grade whose oxide forms a protective coating similar to A588.

Normal uses
This corrosion-resistant steel, whose oxide forms a protective coating, is used in many painted and unpainted applications.

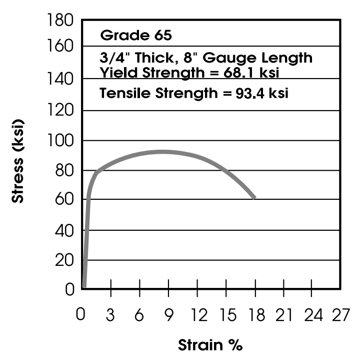
Impact toughness
Impact toughness requirements are included in the basic specification. To 0.5 inch 15 ft-lb at 0°F, over 0.5 inch 15 ft-lb at -20°F. Other requirements need to be inquired. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Standard specification for high-strength, low-alloy structural steel with atmospheric corrosion resistance

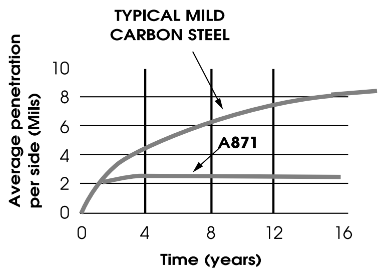
CONTINUED

Stress vs. strain curve—tensile coupon



A representative stress vs. strain curve for a typical 8 in. gauge tensile coupon.

Typical industrial atmospheric corrosion data



Standard specification for premium abrasion-resistant plate steel available in two grades, Hardwear® 400F and Hardwear® 500F

Welding data
Suggested welding consumables for arc welding processes

Thickness	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
All	E7015, E7016, E7018, E7028, E7015-x, E7016-x, E7018-x	E7xx-Exxx or E7xx-Exxx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature (°F) See special notes

	Hardwear® 400F heat input (KJ/Inch)					Hardwear® 500F heat input (KJ/Inch)			
Individual Plate Thickness (inches)	30	35	40	45	Over 45	30	35	40	45
0.5	60	60	60	60	60	200	200	200	200
5/8	60	60	60	60	60	250	200	200	200
¾	60	60	60	60	60	300	250	200	200
1	60	60	60	60	60	350	300	250	200
1.25	60	60	60	60	60	400	300	250	200
10.5	60	60	60	60	60	400	350	300	250
2	200	200	200	200	200	400	400	350	300

Suggested minimum preheat and interpass temperature (°F) See Special notes

	Hardwear® 400F heat input (KJ/Inch)					Hardwear® 500F heat input (KJ/Inch)			
Combined plate thickness (inches) $t_1 + t_2 + t_3$	30	35	40	45	Over 45	30	35	40	45
¾	60	60	60	60	60	200	200	200	200
1	60	60	60	60	60	250	200	200	200
1.25	60	60	60	60	60	300	250	200	200
10.5	60	60	60	60	60	350	300	250	200
2	60	60	60	60	60	400	350	300	300
20.5	60	60	60	60	60	400	350	300	250
3	200	200	200	60	60	400	400	350	350
4	250	250	250	200	200	400	400	400	400

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

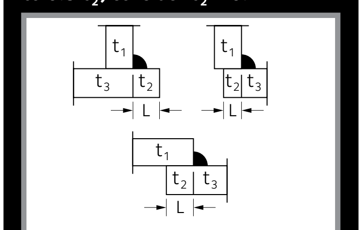
Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical C.E. values
400F	Up to 3	0.44 to 0.51
500F	Up to 3	0.53 to 0.58

If L is less than or equal to 0.5 t_2, consider t_2 = 0.



Description
ArcelorMittal USA Hardwear® steels are proprietary grades produced by quenching and tempering to achieve two nominal Brinell hardness levels, 400HB and 500HB.

Year introduced
1989

Special features
High hardness for abrasive resistance with low sulfur levels for improved weldability and formability.

Normal uses
Abrasive resistant applications in mining, quarries and earth-moving.

Impact toughness
Impact requirements may be furnished at an extra charge.

Special notes
This grade is always produced as Fineline™. Both tables must be consulted and the higher preheat value used. Preheat temperature based on shielded metal-arc welding (SMAW) process and E7018 electrode. E7018 electrodes must be stored in an oven at 250°F ± 25°F. Maximum exposure—four hours out of the can or out of the oven. Preheat minimum temperature may be reduced by 50°F (but not less than 50°F) using gas metal-arc welding process, ER70S-3 electrode and Ar-CO_2 gas. Maximum preheat should be 400°F to retain hardness properties. 35 KJ/inch represents approximately a 0.25 inch fillet weld (SMAW).

Welding and other data on pressure vessel plate steel grades

Standard specification for pressure vessel plates, alloy steel, molybdenum

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A, B	E70xx, E70xx-x	F6xx-Exxx, F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS
C	E80xx	F8xx-Exx-xx	ER80S-x	E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B	Up to 1 incl	50°F	50°F
	Over 1 to 2 incl	100°F	100°F
	Over 2	200°F	100°F
C	Up to 1 incl	100°F	100°F
	Over 1 to 2 incl	200°F	200°F
	Over 2	300°F	300°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A	Up to 1 incl	0.42 to 0.48
	Over 1	0.44 to 0.56
B, C	Up to 1 incl	0.43 to 0.50
	Over 1	0.46 to 0.56

Description
Specification covers molybdenum alloy plate steel intended particularly for boilers and other pressure vessels.

Year introduced
1937

Special features
This steel is available in three different strength levels.

Normal uses
Particularly well suited for boilers. A popular grade used for elevated temperature applications.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description

Specification covers carbon plate steel of low and intermediate tensile strengths. These plates are intended for fusion welded pressure vessels. This specification has been approved by the Department of Defense for listing in the DOD Index of Specifications and Standards.

Year introduced

1946

Special features

This grade is available in three different strength levels.

Normal uses

A widely used, low-cost pressure vessel grade.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

Plates are normally supplied in the as-rolled condition. This steel may be made by killed, or semi-killed, steel practices. This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for pressure vessel plates, carbon steel, low and intermediate tensile strength

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A, B, C	E60xx, E70xx, E70xx-x	F6xx-Exxx, F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
A, B, C	Up to ¾ incl Over ¾ to 10.5 incl Over 10.5	None* 50°F 150°F	None* 50°F 150°F	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

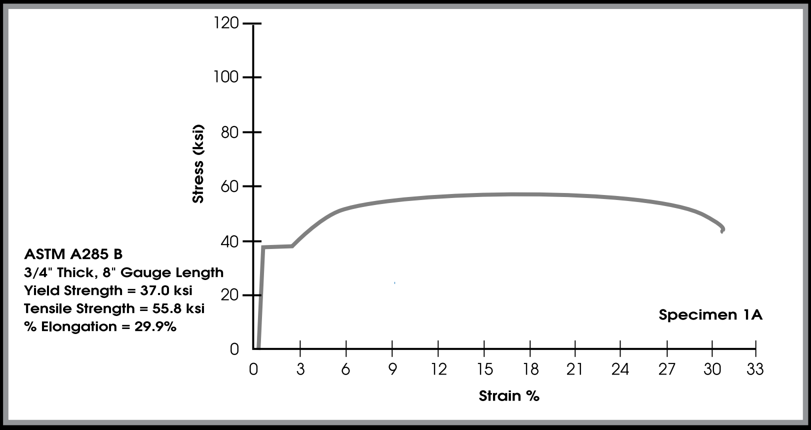
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A, B, C	Up to 10.5 incl Over 10.5 to 20.5 incl Over 20.5 to 15 incl	0.14 to 0.37 0.14 to 0.39 0.14 to 0.42

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon.

Grade	Thickness (inches)	Lowest test temp. °F	Impact values (ft-lb) Avg. 3 specimens	Minimum for one specimen
A	Up to 1 incl Over 1 to 2 incl	+40 +60	10 10	7 7
B	Up to 1 incl Over 1 to 2 incl	+50 +70	10 10	7 7
C	Up to 1 incl Over 1 to 2 incl	+60 +80	10 10	7 7

Stress vs. strain curve—tensile coupon



Standard specification for pressure vessel plates, carbon steel, manganese-silicon

Welding data
Suggested welding consumables for arc welding processes

Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
E80xx-x	F8xx-Exx-xx	ER80S-x	E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
Up to 0.5 incl	100°F	100°F
Over 0.5 to 1 incl	200°F	200°F
Over 1 to 2 incl	300°F	300°F
Over 2	300°F	300°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Thickness (inches)	Typical carbon equivalent values
Up to 8	0.38 to 0.57

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon.

Thickness (inches)	Lowest test temp. °F	Impact Values (ft-lb) Avg. 3 specimens	Impact Values (ft-lb) Minimum for one specimen
Up to 1 incl	-75	15	12
Over 1 to 2 incl	-75	15	12
Over 2 to 3 incl	-50	15	12
Over 3 to 5 incl	0	15	12
Over 5 to 8 incl	+30	15	12

Produced to fine grain practice.

Description
Specification covers manganese-silicon carbon plate steel for use in welded boilers and other pressure vessels. In 1997 the requirement for production to a fine austenitic grain size was added to the specification.

Year introduced
1947

Normal uses
Welded boilers and pressure vessels.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description
Specifications cover manganese-molybdenum-nickel alloy plates intended particularly for welded boilers and other pressure vessels. This specification has been approved by the Department of Defense to replace Specification QQ-S-691C and for listing in the DOD Index of Specifications and Standards.

Year introduced
1947

Special features
This steel is available in four grades having different strength levels.

Normal uses
Welded boilers and pressure vessels.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for pressure vessel plates, alloy steel, manganese-molybdenum and manganese-molybdenum-nickel

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A, B, C, D	E80xx-x	F8xx-Exx-xx	ER80S-x	E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B, C, D	Up to 0.5 incl	50°F	50°F
	Over 0.5 to 1 incl	200°F	200°F
	Over 1 to 2 incl	300°F	300°F
	Over 2	350°F	350°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Grade	Thickness (inches)	Typical carbon equivalent values
A, B, C, D	Up to 2 incl	0.45 to 0.68
	Over 2	0.45 to 0.68

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Standard specification for pressure vessel plates, alloy steel, chromium-molybdenum

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
2, 12, 11	E8018-B2	F8xx-Exx-xx	ER80S-x	E8xTx-x
22	E9018-B3	F9xx-Exx-xx	ER90S-x	E9xTx-x
5	E502-15	#	#	#

Refer to ArcelorMittal USA.

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches) Up to ¾ incl	Over ¾
2, 11, 12, 22	200°F	300°F to 600°F
5	300°F	400°F to 700°F

Suggested post-weld heat treatment (PWHT) for arc welding

Grade	All Thicknesses	Notes
2, 12	1200°F to 1300°F for 1 hr/in	Cool to preheat temperature or below before PWHT.
11, 22	1275°F to 1350°F for 1 hr/in	
5	1300°F to 1375°F for 1 hr/in	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
11	Up to 6	0.55 to 0.65
12	Up to 12	0.45 to 0.55
22	Up to 12	0.80 to 0.90
5	Up to 6	1.10 to 1.30

Description
Specification covers chromium-molybdenum, alloy plates which are annealed, normalized and tempered or quenched and tempered depending on grade. The plates are intended primarily for welded boilers and pressure vessel designs for elevated temperature and hydrogen service.

Year introduced
1955

Special features
Produced as numerous grades and classes with increasing levels of chromium and molybdenum. Grades 9 and 91 are also available.

Normal uses
Recommended for welded pressure vessels.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties. The impact toughness of this specification is strongly influenced by chemistry, heat treatment and required post-weld heat treatment (PWHT). Contact ArcelorMittal USA with your specific requirements.

Special notes
This grade is available with Fineline™ quality to achieve improved properties.

Description
Specification covers high tensile strength carbon manganese plate steel intended for welded pressure vessels.

Year introduced
1961

Special features
A higher tensile strength steel, limited to 0.75 inch thickness.

Normal uses
Recommended for welded pressure vessels.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for pressure vessel plates, carbon steel, high-strength manganese

Welding data
Suggested welding consumables for arc welding processes

Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
E80xx-x	F8xx-Exx-xx	ER80S-x	E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
Up to ¾	100°F	100°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

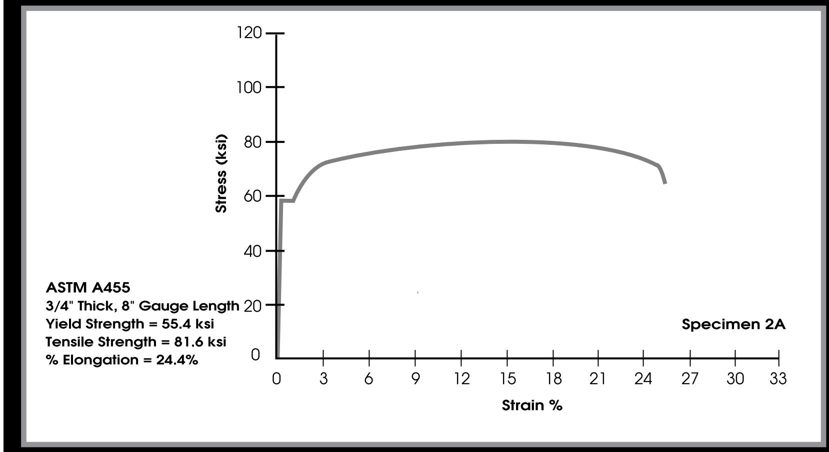
Thickness (inches)	Typical carbon equivalent values
Up to ¾	0.40 to 0.49

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon

Thickness (inches)	Lowest test temp. °F	Impact Values (ft-lb) Avg. 3 specimens	Impact Values (ft-lb) Minimum for one specimen
Up to ¾	+25	13	10

Lateral expansion requirements.

Stress vs. strain curve—tensile coupon



Standard specification for pressure vessel plates, carbon steel, for intermediate and higher temperature service

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
60, 65, 70	E70xx, E70xx-x	F7xx-Exxx, E70xx-x	ER70S-x, F7xx-Exx-xx	E6xT-x, E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
60, 65	Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
	Over ¾ to 10.5 incl	50°F	50°F	
	Over 10.5 to 20.5 incl	150°F	150°F	
	Over 20.5	225°F	225°F	
70	Up to ¾ incl	50°F	50°F	
	Over ¾ to 10.5 incl	150°F	150°F	
	Over 10.5 to 20.5 incl	250°F	250°F	
	Over 20.5	250°F	250°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

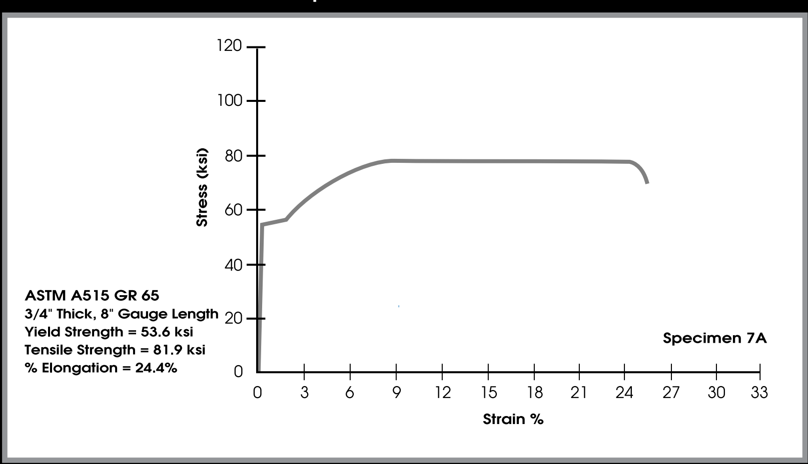
Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
60	Up to 15	0.19 to 0.45
65	Up to 15	0.27 to 0.45
70	Up to 15	0.31 to 0.49

Stress vs. strain curve—tensile coupon



Description
Specification covers carbon-silicon plate steel primarily for intermediate and higher temperature service in welded boilers and other pressure vessels. This specification has been approved by the Department of Defense to replace Federal Specification QQ-S-691C and listed for listing in the DOD Index of Specifications and Standards.

Year introduced
1964

Special features
This specification is available in three grades having different strength levels and is always produced to coarse austenitic grain size practices.

Normal uses
A popular specification used when welded boilers and pressure vessels require intermediate and higher temperature steel.

Impact toughness
Impact toughness requirements are not available for this specification because it is produced to coarse, austenitic grain size practices.

Description

Specification covers carbon plate steel intended primarily for service in welded pressure vessels. This specification has been approved by the Department of Defense to replace Federal Specification QQ-S-691C for listing in the DOD Index of Specifications and Standards.

Year introduced

1964

Special features

This specification is available in four different strength levels. The steel is made using a fine austenitic grain size practice.

Normal uses

A popular specification used where improved notch toughness is important at lower temperatures.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties. Post-weld heat treatment requirements may also influence available Charpy impact properties.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for pressure vessel plates, carbon steel, for moderate and lower temperature service

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
55, 60, 65, 70	E70xx, E70xx-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E6xT-x, E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
55, 60, 65	Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
	Over ¾ to 10.5 incl	50°F	50°F	
	Over 10.5 to 20.5 incl	150°F	150°F	
	Over 20.5	225°F	225°F	
70	Up to ¾ incl	50°F	50°F	
	Over ¾ to 10.5 incl	150°F	150°F	
	Over 10.5 to 20.5 incl	250°F	250°F	
	Over 20.5	250°F	250°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
60	Up to 15	0.31 to 0.42
65	Up to 15	0.35 to 0.42
70	Up to 15	0.36 to 0.46

Shaded area denotes availability of A516 plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Grade	Thickness (inches)	+70°F	+40°F	+0°F	-20°F	-40°F	-60°F	-75°F
50, 60	Up to 2 incl	■	■	■	■	■	■	■
	Over 2 to 5 incl	■	■	■	■	■	■	
	Over 5 to 12 incl	■	■	■	■	■		
65, 70	Up to 1 incl	■	■	■	■	■	■	
	Over 1 to 3 incl	■	■	■	■	■	◐	
	Over 3 to 8 incl	■	■	■	■			
	Over 8 to 10 incl	■	◐					

This table is for Normalized, 0.025 percent maximum sulfur.

CONTINUED

Standard specification for pressure vessel plates, carbon steel, for moderate and lower temperature service

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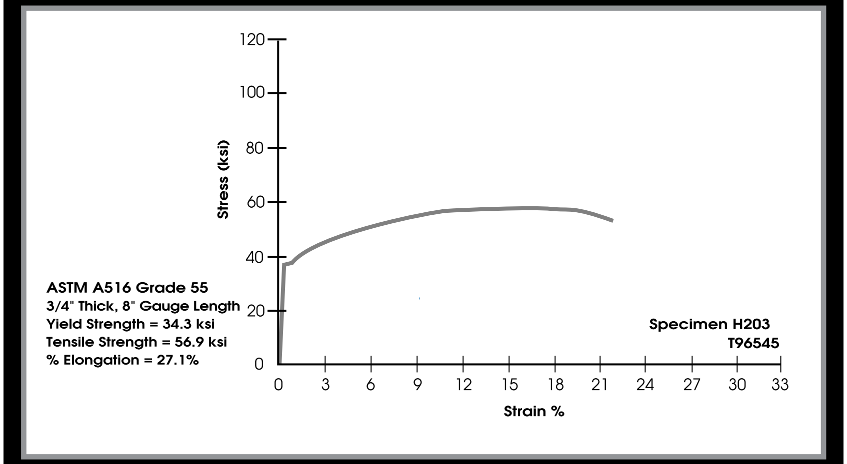
Stress vs. strain curve—tensile coupon



Description
Specification covers high-strength quenched and tempered alloy steel plates intended for use in fusion welded boilers and other pressure vessels. This specification has been approved by the Department of Defense for listing in the DOD Index of Specifications and Standards. The structural version of this specification is A514.

Year introduced
1964

Special features
Of the 13 compositions permitted, ArcelorMittal USA produces Grades A, B, E, F, H, P and Q. The steels are made using a fine austenitic grain size practice.

Normal uses
Excellent for fusion welded boilers and other pressure vessels. The chemistries of the A517 grades are often used to produce abrasion resistant grades to minimum Brinell requirements. Welding information is also provided for them.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
Because of its critical alloy content and specialized properties, welding procedures are of fundamental importance especially in the heat affected zone.

This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Grades A, E, P — Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Grades B, F, H, Q — It is important to note this grade of steel may be susceptible to cracking in the heat-affected zone of welds during post-weld heat treatment (stress relief). Therefore, ArcelorMittal USA recommends careful consideration be given to this phenomenon by competent welding engineers before stress relieving is applied to weldments of this grade. Also, it is not recommended for service at temperatures lower than -50°F or higher than 800°F.

Standard specification for pressure vessel plates, alloy steel, high strength, quenched and tempered

(ArcelorMittal USA makes only A514 Grades A, B, E, F, H, P and Q.)

Welding data
Suggested welding consumables for arc welding processes[1]

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc	Notes
Up to 20.5 incl	E11015-x, E11016-x, E11018-x	F11xx-Exx-xx	ER110S-x	E11xTx-x	See Special notes section for concerns about post-weld heat treatment.
Over 20.5	E10015-x, E10016-x, E10018-x	F10xx-Exx-xx	ER100S-x	E10xTx-x	

1 Deposited weld metal shall have a minimum impact strength of 20 ft-lb (27.1J) at 0°F (-18°C) when Charpy V-Notch specimens are required.

Suggested minimum preheat and interpass temperatures for welding

Thickness (inches)	Produced to A517 tensile properties	Produced to minimum Brinell hardness requirements for abrasion resistant applications
Up to ¾ incl	50°F	100°F
Over ¾ to 10.5 incl	125°F	150°F
Over 10.5 to 20.5 incl	175°F	200°F
Over 20.5	225°F	250°F

A preheat or interpass temperature above the minimum shown may be required for highly restrained welds—preheat or interpass temperatures should not exceed 400°F for thickness up to 1.5 inch.

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A	Up to 1.25	0.45 to 0.55
B	Up to 1.25	0.40 to 0.53
E	Up to 6	0.70 to 0.80
F	Up to 2.25	0.50 to 0.60
H	Up to 2	0.50 to 0.60
P	Up to 4	0.60 to 0.70
Q	Up to 6	0.75 to 0.85

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Transverse test coupon.

Grade	Thickness (inches)	Lowest test temp. °F	Impact values (ft-lb)
All	All	Testing temperature as specified by the customer, but no higher than 32°F	None specified by ASTM A20 (Lateral expansion requirements below)

Lateral expansion requirements: 0.015 in. minimum lateral expansion required using a full size transverse test coupon.

Standard specification for pressure vessel plates, alloy steel, quenched and tempered, manganese-molybdenum and manganese-molybdenum-nickel

Welding data
Suggested welding consumables for arc welding processes

Class	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
1	E80xx-x	F8xx-Exx-xx	ER80S-x	E8xTx-x
2	E90xx-x	F9xx-Exx-xx	ER90S-x	E9xTx-x
3	E100xx-x	F10xx-Exx-xx	ER100S-x	E100T1-K3, E100T5-K3

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B, C, D	Up to 1 incl 1 to 2 incl Over 2	200°F 300°F 400°F	200°F 300°F 400°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Grade	Thickness (inches)	Typical carbon equivalent values
A, B, C, D	Up to 12	0.48 to 0.67

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Description
Specification covers manganese-molybdenum and manganese-molybdenum-nickel alloy plate steel for use in the quenched and tempered condition for the construction of welded pressure vessels.

Year introduced
1965

Special features
This specification is available in four types of chemical analysis and three classes of different strength levels.

Normal uses
Often used in the beltline region of nuclear reactor vessels where the properties may be affected by high levels of radiation.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This alloy plate steel in the as-rolled condition is sensitive to cracking during transit and handling, particularly in the thicknesses over 1 in. or 2 in. It should be shipped in the as-rolled condition only with the mutual agreement of the manufacturer and fabricator.

This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description
Specification covers heat treated carbon-manganese-silicon plate steel intended for fusion welded pressure vessels and structures.

Year introduced
1965

Special features
This grade is available in three classes, Class 1 normalized and Class 2 and 3 quenched and tempered. The steel is made using a fine austenitic grain size practice.

Normal uses
Welded pressure vessels.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Standard specification for pressure vessel plates, heat-treated carbon-manganese-silicon steel

Welding data
Suggested welding consumables for arc welding processes

Class	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
1	E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS
2, 3	E8015-x, E8016-x	F8xx-Exx-xx	ER80S-x	E8xTx-x

Notes: If deposited weld metal should have a minimum impact strength, see the appropriate AWS specification for impact requirements of specific welding consumable designations.

Suggested minimum preheat and interpass temperature for arc welding

Class	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
1, 2, 3	Up to 1 incl	70°F	70°F
	Over 1 to 10.5 incl	100°F	100°F
	Over 10.5 to 20.5 incl	150°F	150°F
	Over 20.5 to 6 incl	225°F	225°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Class	Thickness (inches)	Typical carbon equivalent values
1	Up to 4	0.39 to 0.54
2, 3	Up to 6	0.40 to 0.55

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon

			Impact Values (ft-lb)	
Class	Thickness (inches)	Lowest test temp. °F	Avg. 3 specimens	Minimum for one specimen
1	Up to 1 incl	-80	15	12
	Over 1 to 20.5 incl	-75	15	12
	Over 20.5 to 3 incl	-75	13	10
	Over 3 to 4 incl	-50	13	10
2, 3	Up to 1 incl	-90	20	15
	Over 1 to 20.5 incl	-90	20	15
	Over 20.5 to 3 incl	-75	15	12
	Over 3 to 4 incl	-50	15	12

CONTINUED

Standard specification for pressure vessel plates, heat-treated carbon-manganese-silicon steel

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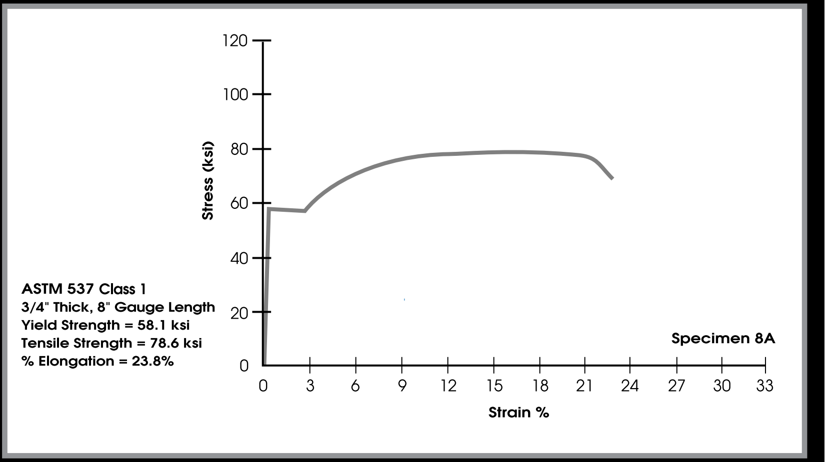
Stress vs. strain curve—tensile coupon



Description
Specification covers killed carbon-manganese-silicon plate steel intended for welded pressure vessels in service at moderate and lower temperatures.

Year introduced
1970

Special features
This steel is killed and made using a fine austenitic grain size practice.

Normal uses
Welded pressure vessels requiring moderate or lower temperatures, particularly railway tank cars.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Standard specification for pressure vessel plates, carbon steel, high strength, for moderate and lower temperature service

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
All	E80xx-x, E90xx-x	F8xx-Exx-xx, F9xx-Exx-xx	ER80S-x, ER90S-x	E8xTx-x, E9xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
All	Up to 0.5 incl	100°F	100°F
	Over 0.5 to 1 incl	150°F	150°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

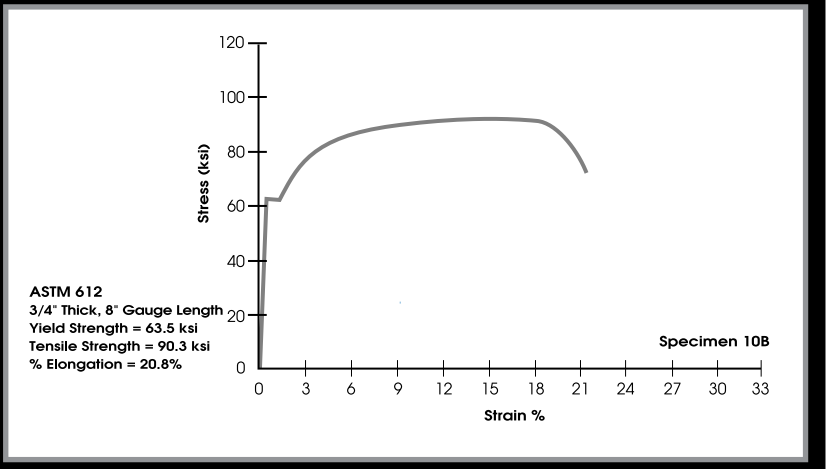
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Thickness (inches)	Typical carbon equivalent values
Up to 1	0.44 to 0.52

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon

Grade	Thickness (inches)	Lowest test temp. °F	Impact Values (ft-lb) Avg. 3 specimens	Impact Values (ft-lb) Minimum for one specimen
All	Up to 1	-50	20	15

Stress vs. strain curve—tensile coupon



Standard specification for pressure vessel plates, carbon-manganese-silicon steel for moderate and lower temperature service

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A, B, C	E70xx, E70xx-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B, C	Up to 1 incl Over 1 to 2 incl	50°F 100°F	50°F 100°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A, B, C	Up to 2	0.37 to 0.48

Charpy V-Notch test minimum available requirements per ASTM A20, Table A1.15, using Type "A" (full size specimens). Longitudinal test coupon

Grade	Thickness (inches)	Lowest test temp. °F	Impact Values (ft-lb) Avg. 3 specimens	Impact Values (ft-lb) Minimum for one specimen
A	Up to 2	-75	13	10
B	Up to 2	-60	13	10
C	Up to 2	-50	15	12

Description
Specification covers carbon-manganese plate steel intended primarily for service in welded pressure vessels where improved low temperature notch toughness is important.

Year introduced
1972

Special features
This material is available in three grades having different strength levels. The steel is made using a fine austenitic grain size practice.

Normal uses
Welded pressure vessels where low temperature notch toughness is important.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes
This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description

Specification covers high-strength and low-alloy plate steel for service in welded pressure vessels and piping components. The structural version of this specification is A633.

Year introduced

1976

Special features

This specification is available in two different strength levels. The steel is made using a fine austenitic grain size practice.

Normal uses

Used for piping and pressure vessel applications where high strength and improved toughness are required.

Impact toughness

Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. ArcelorMittal USA can furnish the Charpy values shown on this sheet at extra charge. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties.

Special notes

Because of its critical alloy content and specialized properties, welding procedures are of fundamental importance, especially in the heat affected zone.

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels.

Standard specification for pressure vessel plates, high-strength, low-alloy steel

Welding data
Suggested welding consumables for arc welding processes

Grade	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
B	E70xx, E70xx-x	F7xx-Exxx	ER70S-x	E7xT-x
C	E80xx-x	F8xx-Exx-xx	ER80S-x	E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
B, C	Up to ¾ incl	50°F	50°F
	Over ¾ to 1 incl	100°F	100°F
	Over 1 to 10.5 incl	150°F	150°F
	Over 10.5 to 2 incl	200°F	200°F
	Over 2	250°F	250°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Grade	Thickness (inches)	Typical carbon equivalent values
B	Up to 4	0.38 to 0.46
C	Up to 4	0.45 to 0.57

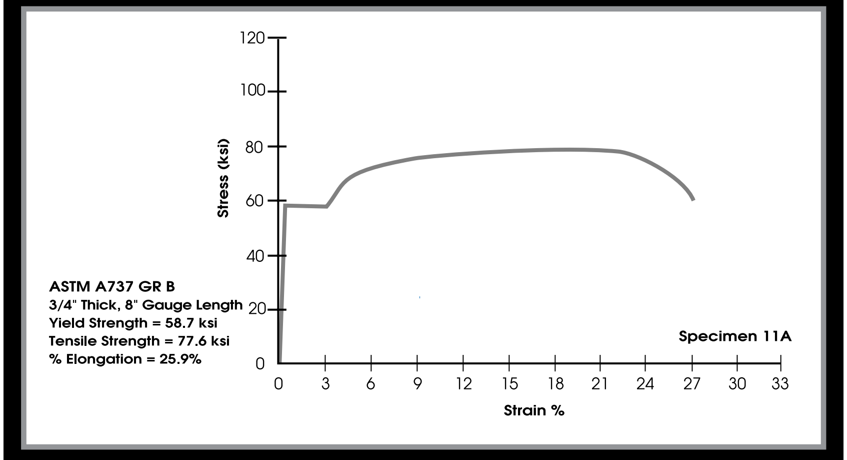
The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Shaded area denotes availability of A737 Grade B and C plate with Charpy 15 ft-lb longitudinal impact toughness at various temperatures

Grade	Thickness (inches) / Temp.	+70°F	+40°F	+0°F	-20°F	-40°F	-60°F	-80°F
B	Up to 4	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
C	Up to 3 incl	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
C	Over 3 to 6 incl	Shaded	Shaded	Shaded	Shaded			

This table is for Normalized, 0.010 percent maximum sulfur.

Stress vs. strain curve—tensile coupon



Standard specification for pressure vessel plates, heat-treated, carbon-manganese-silicon steel, for moderate and lower temperature service

Welding data
Suggested welding consumables for arc welding processes

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
A	All	E80xx-x	F8xx-Exxx, F8xx-Exx-xx	ER80S-x	E8xTx-x
B	All	E90xx-x	F9xx-Exx-xx	ER90S-x	E9xTx-x
C	Up to 20.5 incl Over 20.5	E90xx-x E80xx-x	F9xx-Exx-xx F8xx-Exx-xx	ER90S-x ER80S-x	E9xTx-x E8xTx-x

Suggested minimum preheat and interpass temperature for arc welding

Grade	Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc
A, B, C	Up to 0.5 incl Over 0.5 to 1 incl Over 1 to 2 incl Over 2	100°F 150°F 200°F 250°F	100°F 150°F 200°F 250°F

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Grade	Thickness (inches)	Typical carbon equivalent values
A, B	Up to 6	0.46 to 0.54

Description
Specification covers heat treated carbon-manganese-silicon plate steel intended for use in welded pressure vessels at moderate and lower temperature service.

Year introduced
1976

Special features
This specification is available in three grades with different strength levels.

Normal uses
Used for welded pressure vessels requiring moderate and lower temperature service.

Impact toughness
Impact toughness requirements are not included in the basic specification, but can be added as a supplementary requirement. Additional requirements such as deoxidation practice, modified chemistry, special rolling or heat treatment may be necessary to achieve the properties. The impact toughness of this specification is strongly influenced by chemistry, heat treatment and required post-weld heat treatment. Contact ArcelorMittal USA with your specific requirements.

Special notes
Grade A is the material that, prior to 1984, was covered by specification A738 without a grade designation.

This grade is available with Integra® or Fineline™ quality to achieve improved properties.

Description

Specification covers plate steel produced by the thermo-mechanical-control-process (TMCP) (see Chapter 4). The plates are intended primarily for use in welded pressure vessels.

Year introduced

1985

Special features

This specification is available in two strength levels.

Normal uses

Used for welded pressure vessels.

Impact toughness

Impact toughness requirements are a part of the basic specification. Test results of 10 mm x 10 mm specimens shall meet an average minimum value of 15 ft-lb at -40°F. Tests per ASTM A20.

Special notes

This grade is available with Integra® or Fineline™ quality to achieve improved properties. Post-weld heat treatment may degrade heat-affected zone strength and toughness. Pretesting of specific welding and post-weld heat treating procedures is recommended to assure optimization of final property levels. The TMCP heating and rolling practices are defined in Fig. X1.1 of specification A841.

Standard specification for plate steel for pressure vessels produced by thermo-mechanical-control-process (TMCP)

Welding data
Suggested welding consumables for arc welding processes

Manual shielded Metal-arc Low hydrogen	Submerged-arc	Gas metal-arc	Flux cored-arc
E7015-x, E7016-x, E7018-x, E7028-x	F7xx-Exxx, F7xx-Exx-xx	ER70S-x	E7xT-x except -2, -3, -10, -GS

Suggested minimum preheat and interpass temperature for arc welding

Thickness (inches)	Manual shielded Metal-arc Low hydrogen	Submerged-arc Gas metal-arc Flux cored-arc	Notes
Up to ¾ incl	None*	None*	* When the base metal temperature is under 32°F, preheat the base metal to at least 70°F and maintain this temperature during welding.
Over ¾ to 10.5 incl	70°F	70°F	
Over 10.5 to 20.5 incl	150°F	150°F	
Over 20.5 to 4 incl	225°F	225°F	

Preheat and interpass temperatures to prevent hydrogen-assisted cracking depend on specific welding conditions and restraint level associated with joint configuration. This table should only be used as a guide for preheat and interpass temperatures. In general, the listed temperatures are similar to those published in the AWS Structural Welding Code, D1.1.

Welding carbon equivalent =

$$C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The carbon equivalent range shown in the table is based on heat analysis. It is the range most commonly produced for plates by ArcelorMittal USA. Individual plates or heats may have carbon equivalents beyond the range in the table. See Chapter 10, page 38, regarding the significance of carbon equivalent.

Thickness (inches)	Typical carbon equivalent values
Up to 20.5 incl	0.30 to 0.35
Over 20.5 to 4 incl	0.35 to 0.40

Physical properties of plate steel

Physical Properties of Plate Steel

Item	English Units	Metric Units
Specific gravity	7.9	7.9
Density	490 lb/ft^3	7850 kg/m^3
Melting point	2370°F–2640°F	1300°C–1450°C
Specific heat	0.12 $\frac{Btu}{(lb)\ (°F)}$	0.12 $\frac{(Cal)}{(gr)\ (°C)}$
Linear coefficient of thermal expansion	$6.5 \times 10^{-6} \frac{1}{F}$	$(11.7) \times 10^{-6} \frac{1}{C}$
Volumetric coefficient of thermal expansion	$19.5 \times 10^{-6} \frac{1}{F}$	$(35.1) \times 10^{-6} \frac{1}{C}$
Thermal conductivity at 60°F	$\frac{34\ (Btu)}{(hr)\ (ft)\ (°F)}$	$\frac{0.14\ (Cal)}{(sec)\ (cm)\ (°C)}$
Electrical resistivity at 60°F		17×10^{-8} (ohm-meters)
Speed of sound through steel	18,000 ft/sec	5490 m/sec
Young's modulus of elasticity	29,000,000 $\frac{lb}{(in)^2}$	207,000 MPa
Poisson's ratio, 0.3 in the elastic range and 0.5 in the plastic range		
Bulk modulus	23,000,000 $\frac{lb}{(in)^2}$	159,000 MPa
Shear modulus	12,000,000 $\frac{lb}{(in)^2}$	83,000 MPa
Emissivity of polished metal surface	.07 at 100°F .10 at 500°F .14 at 1000°F	.07 at 38°C .10 at 260°C .14 at 540°C
Emissivity of oxidized plate steel at 60°F	0.80	0.80

The properties listed above vary with the chemistry of the plate steel.
The values shown are typical for non-alloy plate grades.
If more accuracy is required, refer to a physics handbook.

Glossary

Accelerated cooling. Cooling the plate with water immediately following the final rolling operation. Generally the plate is water cooled from about 1400°F to approximately 1100°F.

Aging. A time-dependent change in the properties of certain steels that occurs at ambient or moderately elevated temperatures after hot-working, after a thermal treatment (quench aging), or after a cold-working operation (strain aging).

Allow steel. Steel is considered to be an alloy steel when either (1) the maximum of the range given for the content of alloying elements exceeds one or more of the following percentages: manganese 1.65 percent, silicon 0.60 percent, copper 0.60 percent; or (2) a definite range or definite minimum quantity of those elements considered alloys is specified. For example, chromium, molybdenum and nickel.

Annealing. A thermal cycle involving heating to, and holding at, a suitable temperature and then cooling at a suitable rate, for such purposes as reducing hardness, improving machinability, facilitating cold-working, producing a desired microstructure, or obtaining desired mechanical or other properties.

Austenitizing. The process of forming the austenite phase by heating a ferrous alloy into the transformation range (partial austenitizing above the lower critical temperature) or above this range (complete austenitizing above the upper critical temperature).

Bainite. A decomposition product of austenite consisting of an aggregate of ferrite and carbide. In general, it forms at temperatures lower than those where very fine pearlite forms, and higher than those where martensite begins to form on cooling.

Brinell Hardness Number (HB). A measure of hardness determined by the Brinell hardness test, in which a hard steel ball under a specific load is forced into the surface of the test material. The number is derived by dividing the applied load by the surface area of the resulting impression.

Camber. As it relates to plates, camber is the horizontal edge curvature in the length, measured over the entire length of the plate.

Carbon steel. By common custom, steel is considered to be carbon steel when no minimum content is specified or required for aluminum, boron, chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium or any other element added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40 percent; or when the maximum content specified for any of the following elements does not exceed the percentages: manganese 1.65 percent, silicon 0.60 percent, copper 0.60 percent. Small amounts of alloying elements may be present and are considered incidental.

Carburizing. A process in which an austenitized ferrous material is brought into contact with a carbonaceous atmosphere or medium of sufficient carbon potential as to cause absorption of carbon at the surface and, by diffusion, create a concentration gradient. Hardening by quenching follows.

Cold cracking. Develops in a weldment after solidification. It forms within hours or days after welding, depending on steel grade, residual stresses and hydrogen content. Proper processing will prevent this problem.

Continuous casting. The most popular technique for solidifying steel. Involves pouring steel into an intermediate tundish before entering a water-cooled, copper mold. A solidifying steel strand is drawn through a machine where it continues to cool before exiting the machine.

Controlled cooling. A process by which steel is cooled from an elevated temperature in a predetermined manner to avoid hardening, cracking or internal damage, or to produce desired microstructure or mechanical properties.

Controlled-rolling. A rolling practice that improves mechanical properties by controlling the related parameters of time-temperature and deformation.

Corrosion. The gradual degradation of steel caused by atmosphere, moisture or other agents. Can also lead to cracking of various forms, e.g., stress corrosion cracking, hydrogen induced cracking and sulfide stress cracking.

Creep. A time-dependent deformation of steel occurring under conditions of elevated temperature accompanied by stress intensities well within the apparent elastic limit for the temperature involved.

Critical range (Temperatures). Synonymous with "transformation range," which is the preferred term. (See Austenitizing)

Decarburization. The loss of carbon from the surface of steel as a result of heating in a medium that reacts with the carbon.

Deoxidation. A process used during melting and refining of steel to remove and/or chemically combine oxygen from the molten steel to prevent porosity in the steel when it is solidified.

Ductility. The ability of a material to deform plastically without fracturing, usually measured by elongation or reduction of area in a tension test, or, for flat products such as sheet, by height of cupping in an Erichsen test.

Elastic limit. The greatest stress a steel can see without permanent deformation.

Elongation. A measure of ductility, determined by the amount of permanent extension achieved by a tension test specimen, and expressed as a percentage of that specimen's original gauge length (as: 25 percent in 2 in.).

End-quench hardenability test (Jominy test). A method for determining the hardenability of steel by water-quenching one end of an austenitized cylindrical test specimen and measuring the resulting hardness at specified distances from the quench end.

Endurance limit. The maximum cyclic stress, usually expressed in pounds per square inch, to which a metal can be subjected for indefinitely long periods without damage or failure.

Extensometer. An instrument capable of measuring small magnitudes of strain occurring in a specimen during a tension test, conventionally used when a stress-strain diagram is to be plotted.

Ferrite. The room temperature form of alpha iron, one of the two major constituents of steel (with cementite) in which it acts as the solvent to form solid solutions with such elements as manganese, nickel, silicon and, to a small degree, carbon.

Flame hardening. A hardening process in which the surface is heated by direct flame impingement and then quenched.

Grain size number. An arbitrary number calculated from the average number of individual crystals, or grains, that appear on the etched surface of a specimen.

Hardenability. The property of steel that determines the depth and distribution of hardness induced on cooling after austenitizing.

Hardness. The resistance of a material to plastic deformation. Usually measured in steels by the Brinell, Rockwell or Vickers indentation-hardness test methods.

Heat affected zone. Portion of the base plate, that was heated during a thermal cutting or welding operation.

High-strength, low-alloy steels. A specific group of steels with chemical compositions especially developed to impart higher mechanical properties and, in certain instances, improved atmospheric corrosion resistance relative to conventional carbon steel. It is not considered to be an alloy steel as previously described, even though use of any intentionally added alloy content would technically qualify it as such. Typical grades are A572 and A588.

Ingot casting. A technique for solidifying molten steel by pouring it into cast iron ingot molds.

Impact test. A test for determining the ability of a steel to withstand high-velocity loading, as measured by the energy (in ft-lb) that a notched-bar specimen absorbs upon fracturing.

Martensite. A microconstituent or structure in hardened steel, characterized by an acicular or needle-like pattern, and having the maximum hardness of any of the decomposition products of an austenite.

Mechanical properties. Properties that reveal the reactions, elastic and inelastic, of a material to applied forces. Sometimes defined erroneously as "physical properties."

Microstructure. The metallurgical structure for a steel determined by polishing and etching samples and examining them at high magnifications using light or electron optical methods. Examples include ferrite, pearlite, bainite and martensite.

Modulus of elasticity (Young's modulus). A measure of stiffness, or rigidity, expressed in pounds per square inch. Developed from the ratio of the stress, as applied to a tension test specimen, to the corresponding strain or elongation of the specimen. Applicable for tensile loads below the elastic limit of the material.

Notch (impact) toughness. An indication of a steel's capacity to absorb energy when a stress concentrator or notch is present. Examples are Charpy V-Notch, dynamic tear, drop-weight and drop-weight tear tests.

Normalizing. A thermal treatment consisting of heating to a suitable temperature above the transformation range and then cooling in still air. Usually employed to improve toughness or machinability, or as a preparation for further heat treatment.

Pearlite. A microconstituent of iron and steel consisting of a lamellar aggregate of ferrite and cementite (a compound of iron and carbon—Fe_3C).

Physical properties. Properties pertaining to the physics of a material, such as density, electrical conductivity and coefficient of thermal expansion. Not to be confused with mechanical properties.

Post-weld heat treatment (PWHT). Also referred to as stress relieving, this process is used to soften the heat affected zones and relieve residual stresses created during welding.

Preheating. A process to heat plate prior to thermal cutting or welding to prevent hard areas or cracking.

Proportional limit. The maximum stress at which strain remains directly proportional to stress.

Quench cracking. Occurs in medium carbon and alloy steels during quenching and tempering heat treatment. Proper part design, heat treating and quenching practices will prevent this problem.

Quenching and tempering. A thermal process used to increase the hardness and strength of steel. It consists of austenitizing, then cooling at a rate sufficient to achieve partial or complete transformation to martensite. Tempering involves reheating to a temperature below the transformation range and then cooling at any rate desired. Tempering improves ductility and toughness, but reduces the quenched hardness by an amount determined by the tempering temperature and time.

Reduction of area. A measure of ductility determined by the difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross-section at the point of fracture. Expressed as a percentage of the original area.

Rockwell hardness (HRB OR HRC). A measure of hardness determined by the Rockwell hardness tester, by which a diamond spheroconical penetrator (Rockwell C scale) or a hard steel ball (Rockwell B scale) is forced into the surface of the test material under sequential minor and major loads. The difference between the depths of impressions from the two loads is read directly on the arbitrarily calibrated dial as the Rockwell hardness value.

Spherodized annealing. A prolonged heating of the steel in a controlled-atmosphere furnace at or near the lower critical point, followed by retarded cooling in the furnaces, to produce a lower hardness than can be obtained by regular annealing.

Steckel mill. A rolling mill design with heated coiling furnaces on each side to allow efficient rolling of thin plate products.

Stress-cracking. Occurs during the thermal cutting of high carbon and alloy steels at the cut edges. Proper processing, which may include preheating, will prevent this problem.

Stress relieving. A thermal cycle involving heating to a suitable temperature, usually 1000°F to 1200°F, holding long enough to reduce residual stresses from either cold deformation or thermal treatment, and then cooling slowly enough to minimize the development of new residual stresses.

Temper embrittlement. Brittleness that results when certain steels are held within, or are cooled slowly through, a specific range of temperatures below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

Tempering. See Quenching and tempering.

Tensile strength. The maximum tensile stress in pounds per square inch that a material is capable of sustaining, as developed by a tension test.

Tension test. A test in which a machined or full-section specimen is subjected to a measured axial load sufficient to cause fracture. The usual information derived includes the elastic properties, ultimate tensile strength, and elongation and reduction of area.

Thermal cutting. A process for cutting plate steel to size using an oxy-fuel, plasma or laser heat source. Oxidation or burning of steel is initiated by melting with the heat source and then a stream of high purity oxygen continues the reaction.

Thermo-mechanical-controlled-processing (TMCP). A term referring to special rolling practices that use controlled-rolling and/or accelerated cooling.

Thermal treatment. Any operation involving the heating and cooling of a metal or alloy in the solid state to obtain the desired microstructure or mechanical properties.

Tool steel. Steel with a higher carbon and alloy content. Used to make tools for cutting, forming or otherwise shaping a material into a part or component for a definite use.

Toughness. An indication of a steel's capacity to absorb energy, particularly in the presence of a notch or a crack.

Transformation ranges. Those ranges of temperatures within which austenite forms during heating and transforms during cooling.

Transformation temperatures. The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range.

Yield point. The minimum stress at which a marked increase in strain occurs without an increase in stress, as indicated by a sharp knee in the stress-strain curve.

Yield strength. The stress at which a material exhibits a specified deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain, and in the offset method, usually a strain of 0.2 percent is specified.

Young's modulus. See Modulus of elasticity.

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9/17 Printed in the U.S.

GCC/IBT 565