

Metallurgy and Steel Properties

Introduction

The development of our modern society is closely related to the development of metallic and non-metallic materials. In fact, materials like **steel** have been at the centre of most major industrial breakthroughs. The mechanical and chemical properties of steel allowed researchers to create new applications in various modern industries. As a metal, steel is strong, abundant and can be produced at affordable costs.

Steel or more precisely its predecessor, **iron**, has been used by man since 3000 B.C. It was discovered that when a very small amount of carbon is added to iron, its properties change dramatically - so much that it was given a new name; steel. This little bit of carbon is what makes steel so popular. It increases the strength and hardness of the material and allows us to change these properties through heat treatments. Even though several metals have been discovered since, steel is still by far the most popular metal.

During the Iron Age, man had only forging as a process to transform and shape metal. Since then steel making has been refined. It is now possible to produce stronger steels, using alloying elements that can be assembled by various methods. Welding is one method widely used in the metalworking industry.

In order to properly understand what happens when a weld is made, it is important to learn the basic principles of the science that lies at the root of all materials development. This science is called metallurgy.

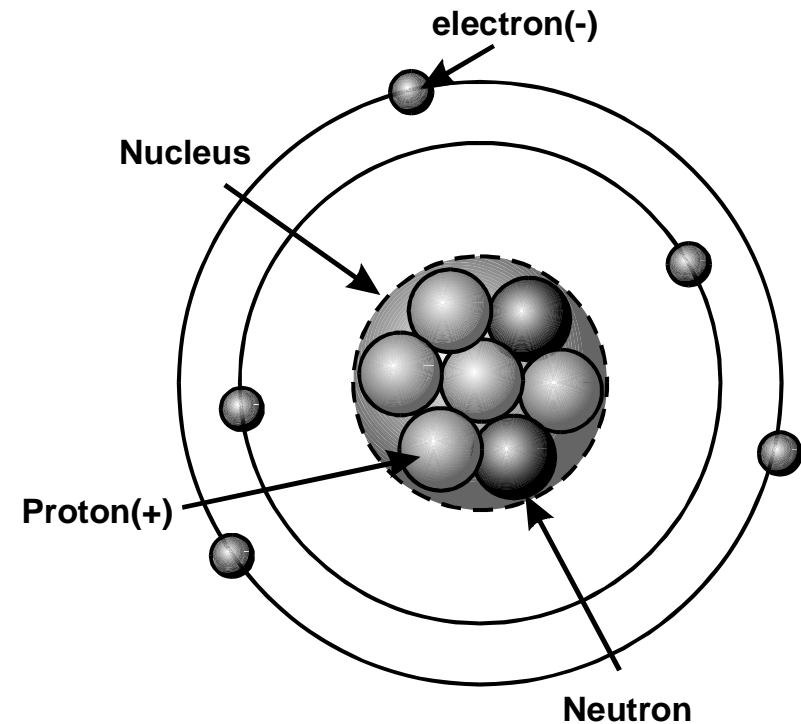
Webster's dictionary states that a metal is:

"a name given to certain substances of which gold, silver, iron, lead, are examples, having a luster and generally fusible by heat"

Metallurgy is the science that extracts metals from the earth and transforms them into physical forms such as plates, bars, beams or angles. Welding Metallurgy applies this science to welding.

Metals are delivered with specific mechanical and chemical properties. During the manufacturing process and especially during welding, mechanical properties

are affected. In the following we will see how steel is produced and how welding affects its properties. We will also look at some techniques that help retain or restore the properties of the metal after welding.

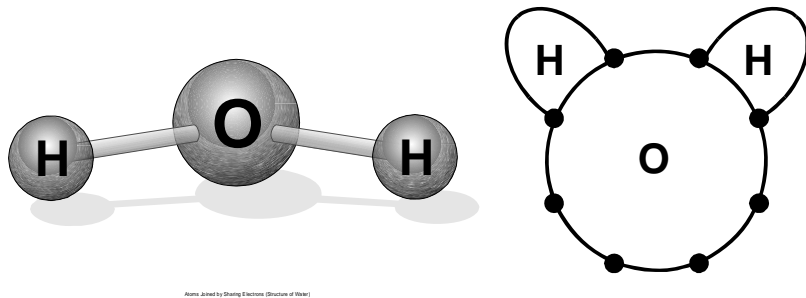


☒ Structure of the atom

Before discussing the properties of iron and steels it is important to understand the building blocks of matter. People normally consider matter as something, which can be divided into small identical pieces. This, however, is not true. Several decades ago, scientists were able to determine that all matter could be understood as being large amounts of "atoms". The atom was supposed to be the smallest unit of matter but we learned since that this also was not true. In fact the atom can be divided into smaller particles.

An **atom** is composed of two parts: the nucleus which contains the protons (+) and neutrons, and a cloud of electrons (-) that circle around the nucleus. Atoms

combine to form compounds and materials by either sharing or exchanging these electrons.



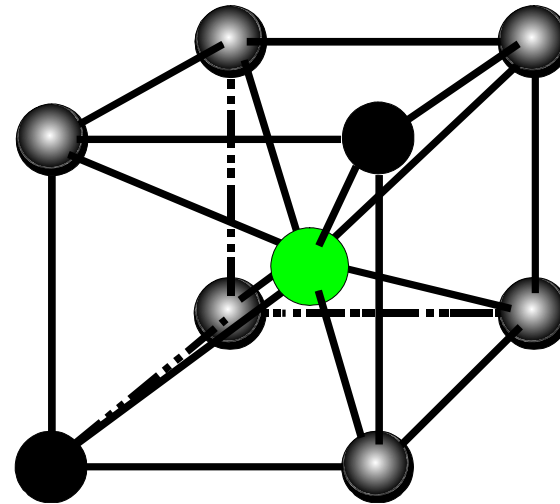
▣ Atoms joined by sharing electrons

An atom is not electrically charged because the number of electrons (-) equals the number of protons (+) and these positive and negative charges are balanced. Studies of the atomic structure shown that there are 103 known different atoms. Each one has specific physical and chemical properties. Since it is not easy to refer to matter as atoms, scientists decided that a substance made only of one type of atom would be called an element. The atoms of each element are different in size and weight, which gives them each different properties. For example carbon (C) can be found as coal, graphite, coke or diamond but it is still only carbon whatever form it assumes.

Elements such as carbon, oxygen, iron or copper have distinctive properties like:

- atomic weight
- atomic diameter
- density
- melting point
- boiling point

In order to create solid structures like metals, atoms have to be joined together. In fact, atoms in metals are joined together in specific patterns. Iron arranges its atoms in a cube as shown in the next figure. This basic arrangement is a cube with one atom on each corner and one in the middle of the cube. This cubic arrangement is the basic cell or building block of steel.



▣ Body-Centered-Cubic arrangement of iron atoms (BCC)

Atoms are bonded together by strong or weak electrical forces that influence their properties. As a general rule, strong bonding will result in high melting temperatures (ex: carbon) because the atoms need a lot of heat to free themselves from the others. Similarly, weak bonding will result in low melting temperatures (ex: lead).

Elements are not normally found as pure substances in nature. Gold is one of the well-known exceptions. When we combine elements to make a material of certain properties the new material is called an 'alloy'. Alloys have properties that may differ greatly from the parent elements. As already discussed, steel is not composed of only one element. In the introduction we discussed adding carbon to iron to change its properties, thereby making a **new material from the two elements - steel**.

We will talk about states of matter in the next section however it is important to realize that matter can be normally found in three states depending on the energy contained in the atoms. When energy levels are low, matter is solid. As energy, or temperature, is gradually increased matter will transform from solid to liquid and finally to gas. During welding all three states of matter occur. Metals to be welded are first in the solid state. The heat generated by welding

will melt the metal and gases will be produced. Metallurgy is a science that studies these changes of states in metals.

Since welding is primarily concerned with solid matter, we will concentrate our efforts on elements that can be worked with in the solid state. Changes can occur to a material in the solid state. Metals are particularly useful in this regard. The properties of steel can be changed while it is solid. One of the best ways we have is through the heating and cooling of the material. Welding metallurgy not only studies the weld metal, but also it is also used to predict changes in the base metal that happen due to the welding heat. This is why welding metallurgy is so important. Welding locally heat treats the parts being joined. Welding Metallurgy attempts to predict the effect of this heat treatment on the structure and properties of the material.

Steel

Steel is one of **most widely used materials for welded construction**. Its use can be seen in bridges and buildings, offshore structures and ships, nuclear reactors and pressure vessels, railway equipment, trucks and automobiles, mining and pulp and paper equipment, machinery components, etc. The environments in which these steel structures and components function vary widely, for example, low temperatures in winter or in arctic regions, seawater, high temperatures, and corrosive chemicals.

Any one standard "Steel" is not and cannot be expected to perform satisfactorily for all the applications and environments listed above. Instead, based on research performed over the last fifty years, metallurgists have developed a **variety of steels**, each having superior characteristics / properties appropriate to individual applications.

What is Steel?

Steel is an **alloy of iron** (Fe) and carbon (C). In steels meant to be welded, the carbon content is usually less than 0.5 wt%. Depending on the desired steel properties (and the intended steel application), one or more of other **alloying elements** are also added to the steel. The important ones are:

manganese (Mn),
silicon (Si),

aluminum (Al),
nickel (Ni),
chromium (Cr),
molybdenum (Mo),
copper (Cu),
vanadium (V),
niobium (Nb),
titanium (Ti) and
boron (B).

The elements V, Nb and Ti are called micro-alloying elements because they are usually present in small amounts only - typically less than 0.05 wt% and sometimes less than 0.01 wt% for Ti. Vanadium on the other hand may be present in amounts up to 0.2 wt% in certain steels. In addition to the above elements, small amounts of sulfur (S), phosphorous (P), nitrogen (N) and oxygen (O) are invariably present in steel as impurities, which are not easily removed from the steels. In steels to be welded, these impurities are removed as much as possible in light of the steel cost and application. Once again exceptions exist, for example, classes of steels may have intentionally added nitrogen (up to 0.02 wt%) in high vanadium steels, or sulfur in free machining steels.

How is Steel Produced?

With the exception of gold, elements are normally mixed into complex compounds called **ores**. These are mixtures of various elements that can be grouped according to the main element.

Types of ores:

Oxides (oxygen)
Sulfides (sulphur)
Carbonates (calcium / carbon / oxygen)
Chlorides (chlorine)

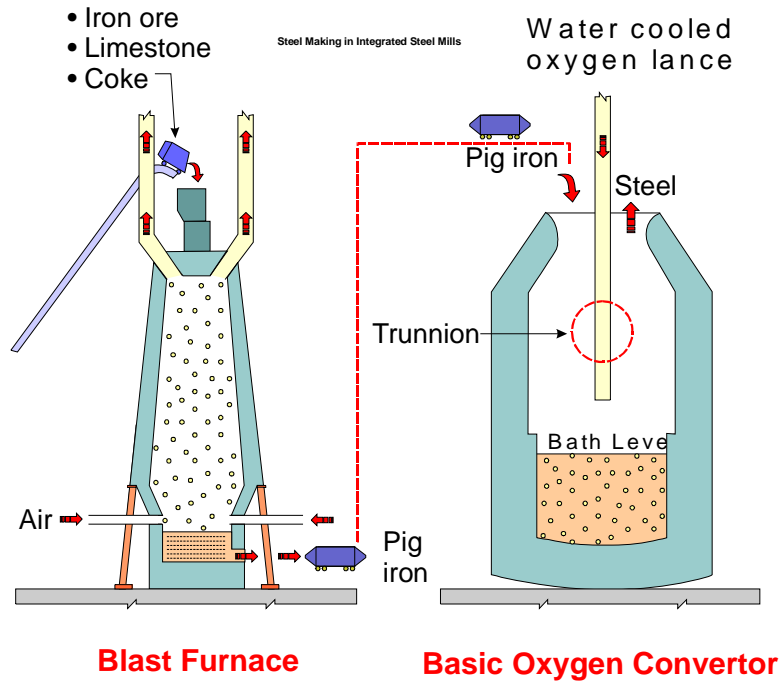
Most metals are found either as oxides or sulfides. Iron ores are one of the most common ores, easily extracted from open-pit or underground mines.

In their initial state, ores are not very useful - the metal must be separated from the ore. In order to extract the metal from the ores, chemical compounds have to go through several mechanical, chemical and heat treatments.

The **ore transformation process** can be broken into five main steps extending from the mine to the final product. These are:

- Mining
- Crushing
- Melting
- Refining
- Shaping into solid forms

The way steel is produced can affect its properties as well as some other characteristics that can make the difference between a sound weld and one with flaws. It is, therefore, useful to briefly review how steels are produced.



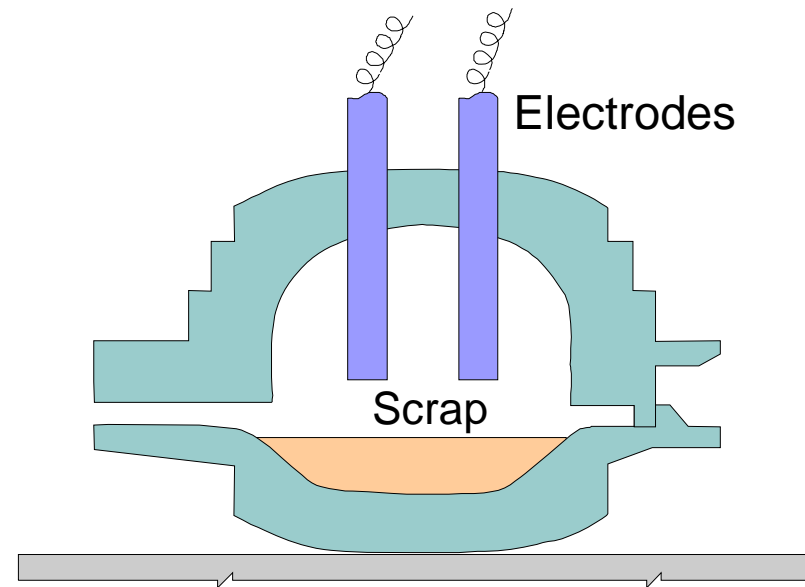
■ Steel making in integrated steel mills

Melting the Steel

In integrated steel mills, molten pig iron is first produced in a blast furnace from iron ore, coke and limestone.

The pig iron contains impurities like sulfur and phosphorous, and a high carbon content; about 3 to 4%. The molten pig iron is charged into a basic oxygen converter. In the converter, the carbon content and impurities are first reduced to the desired level by oxidation and the molten metal in the converter can now be called steel. The steel can then be tapped into a ladle for casting. For higher quality steels however, a **deoxidant** (usually **ferrosilicon**) is added to reduce the amount of oxygen present in the steel and then, either before or during tapping into a ladle, various alloying elements added so that the desired steel composition is achieved.

In other steel plants called mini-mills, the steel is produced and composition finalized in an electric arc furnace where the raw material is carefully selected steel scrap.

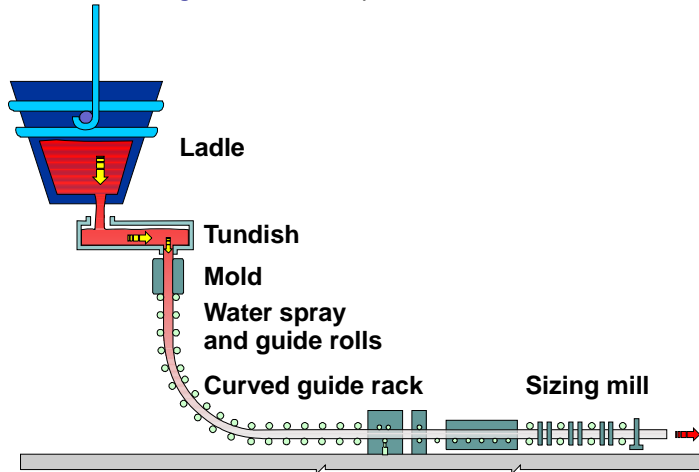


■ Electric arc furnace steel making

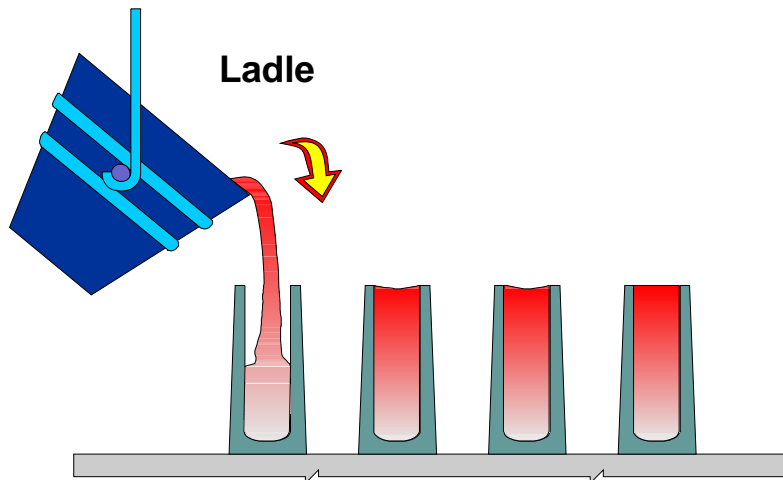
For high quality steels, certain additional treatments can be performed in the ladle such as removal of sulfur, hydrogen and oxygen.

Casting the Steel

The molten steel, tapped from the basic or the electric arc furnace into a **ladle**, is then cast either into individual **ingots** or continuously cast into slabs or billets.



Continuous casting

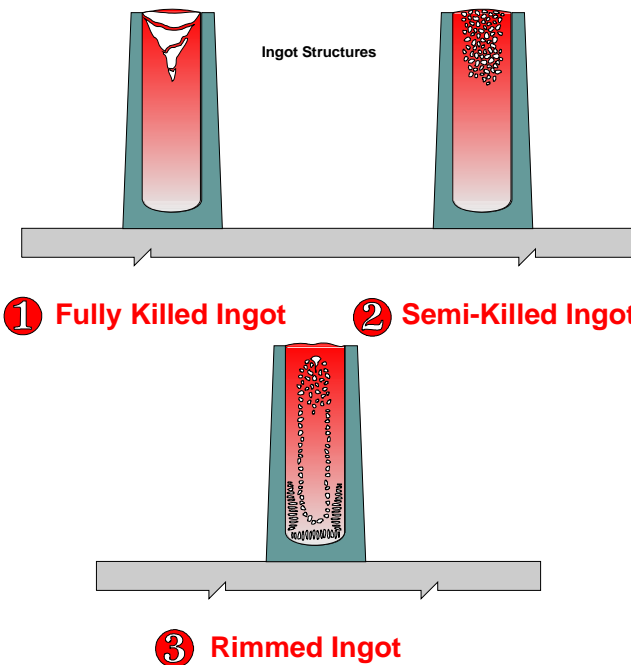


Ingot casting

The solidification behaviour of the ingots depends on the extent to which the oxygen has been removed from the molten steel in the previous step. When no deoxidants have been added, the oxygen and carbon in the steel react to cause considerable gas evolution during solidification, and the steel is called rimmed steel. There is no **shrinkage cavity** formed at the top of the ingot. Instead, there are blowholes present in the body of the ingot, and the outer rim of the ingot is purer (less carbon content and impurities) than the interior. Such steels usually have less than 0.25 wt% carbon.

When sufficient deoxidants have been added so that insufficient oxygen is present for reaction with carbon, then no gas evolution occurs, and a cavity is formed at the top centre of the ingot due to steel contraction during solidification. Such steels are fully killed steels. In between are the semi-killed steels where only a part of the oxygen is removed so that gas evolution just compensates for the shrinkage cavity that would have formed otherwise. The steels which are cast into slabs using the continuous casting process are semi-killed or fully killed types.

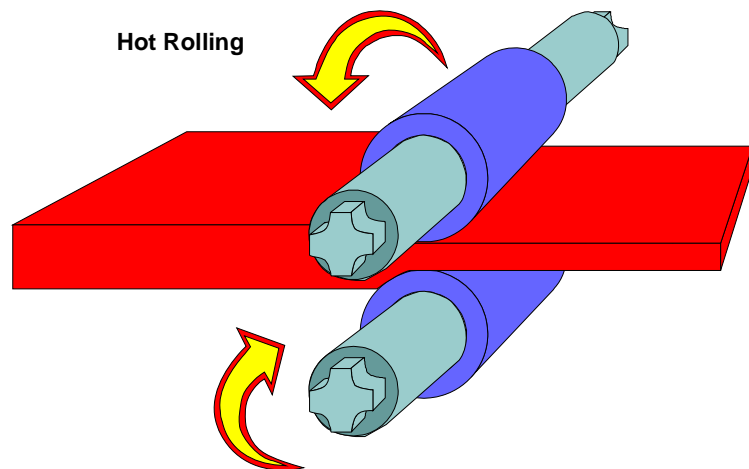
It should be noted, however, that in all types of steels there is some possibility of segregation of elements like carbon, manganese, phosphorous, etc. at the centre of the ingot or the slab. Also, depending on the sulfur and oxygen content, there invariably are some **non-metallic inclusions** present in the steel.



Ingot structures

Rolling the Steel

The cast ingots and slabs are usually **reheated** (typically to 1100°C) and then passed through a **series of rolls** that progressively reduce the thickness for plate products and for other product applications (bars, rods, channel or H beam sections) shape the steel also.



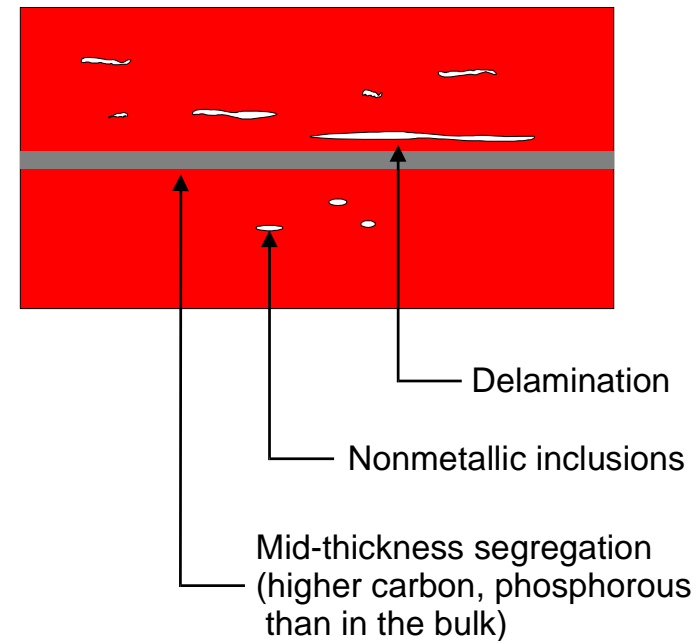
Hot rolling

When the rolling is finished, the steel temperature can be anywhere from 1000°C (**hot rolling**) to room temperature (**cold rolling**), depending on the product and the desired properties. For plate steels, the finish rolling temperature varies from 1000°C to about 800°C, depending on steel composition. Lower finishing temperatures help increase the strength and notch toughness of the steel, and are called control rolled steels.

Some of the **effects** of the steel melting, casting and rolling variables on steel plate welding are as follows:

- rimmed steels can generate gases during welding causing porosity in the weld metal.

- if the shrinkage cavity in fully killed steel ingots is not completely removed, it will present itself as a delamination in the rolled product.



Deoxidation practice and weldability

- there can be segregation of elements at the plate mid-thickness location, which can cause local cracking or porosity.
 - too many inclusions in the steel plate can lead to lamellar tearing in restrained T or cruciform joints. The inclusions can also cause interpretation difficulties in ultrasonic examination of welds.
- fully killed steels generally have better toughness than semi-killed or rimmed steels.

Heat Treating the Steel

Steel products can be used in the as-rolled condition, or they may be heat treated to improve some of their properties. The two most commonly used heat treatments are **normalizing** and **quenching** and tempering.

The **primary objective** of **normalizing** is to **increase the low temperature toughness of the steel** and these steels are usually fully killed and treated with aluminum or microalloying elements. **Quenching** and tempering treatment is used to **increase the strength of the steel**.

These steels are also usually fully killed and contain alloying elements such as nickel, chromium, molybdenum, etc.

In order to understand what these heat treatments do and how the weld heat affects the steel, we need to understand the changes in steel structure when it is heated and cooled at different rates.

Classification of Steel

There are several codes that classify steels according to their chemical composition, their applications and/or their mechanical properties.

The most common numbering systems used in Canada have been developed by the following organizations:

Canadian Standards Association (**CSA G40.21**)
 Society of Automotive Engineers (**SAE**)
 American Iron and Steel Institute (**AISI**)
 American Society for Testing and Materials (**ASTM**)

CSA G20.1

Canadian Standards Association - CSA G40.21

This specification normally refers to structural steels. There are eight different types of steels produced under this classification.

Types Of Steel

G	General construction steel	
W	Weldable steel	
WT	Weldable notch toughness steel	
R	Atmospheric corrosion resistant steel	
A	Atmospheric corrosion resistant weldable steel	
AT	Atmospheric corrosion resistant weldable notch toughness steel	
Q	Quenched and tempered low alloy steel	
QT	Quenched and tempered low alloy notch toughness steel	

The eight types and seven strength levels have been combined into twenty-two grades:

Type	Yield Strength, MPa (Ksi)						
	230(33)	260(38)	300(44)	350(50)	400(60)	480(70)	700(100)
G	230G	-	-	350G	400G	-	-
W	-	260W	300W	350W	400W	480W	-
WT	-	260WT	300WT	350WT	400WT	480WT	-
R	-	-	-	350R	-	-	-
A	-	-	-	350A	400A	480A	-
AT	-	-	-	350AT	400AT	480AT	-
Q	-	-	-	-	-	-	700Q
QT	-	-	-	-	-	-	700QT

SAE AISI

**SAE (Society of Automotive Engineers)-
AISI (American Iron and Steel Institute)**

The **SAE-AISI numbering system** normally consists of four digits. The first two digits (ex: 86) provide information about the elements used as alloys. The last two digits refer to the percentage of carbon in the steel in hundredths of one percent. (ex: 20 means 0.20%C).

AISI **Composition**
or
SAE
Number

10xx	Plain carbon steels
11xx	Plain carbon (resulfurized for machinability)
13xx	Manganese (1.5-2.0%)
23xx	Nickel (3.25-3.75%)
25xx	Nickel (*4.75-5.25%)
31xx	Nickel (1.10-1.40%), chromium (0.55-0.90%)
33xx	Nickel (3.25-3.75%), chromium (1.40-1.75%)
40xx	Molybdenum (0.20-0.30%)
41xx	Chromium (0.40-1.20%), molybdenum (0.08-0.25%)
43xx	Nickel (1.65-2.00%), chromium (0.40-0.90%), molybdenum (0.20-0.30%)
46xx	Nickel (1.40-2.00%), molybdenum (0.15-0.30%)
48xx	Nickel (3.25-3.75%), molybdenum (0.20-0.30%)
51xx	Chromium (0.70-1.20%)
61xx	Chromium (0.70-1.10%), vanadium ((0.10%)
81xx	Nickel (0.20-0.40%), chromium (0.30-0.55%), molybdenum (0.08-0.15%)
86xx	Nickel (0.30-0.70%), chromium (0.40-0.85%), molybdenum (0.08-0.25%)
87xx	Nickel (0.40-0.70%), chromium (0.40-0.60%), molybdenum (0.20-0.30%)
92xx	Silicon (1.80-2.20%)
xx:	carbon content, 0.xx%
Mn:	All steels contain 0,50% ± manganese
B:	Prefixed to show Bessemer steel
C:	Prefixed to show open-hearth steel
E:	Prefixed to show electric furnace steel

ASTM

ASTM - American Society for Testing and Materials

The **ASTM classification** is widely used for structural and pressure vessels steels. In this classification, steels are given a reference number. For example: ASTM A-36, A-285, A-516, A-572.

The number refers to a set combination of chemical composition and mechanical properties. **Some ASTM steels are comparable to Canadian steels.** For instance, Grade 300W can be used as a substitute for ASTM A-36. The ASTM number is sometimes followed by a grade number (ex: ASTM A-572 grade 42 or 50). In the above case, different Canadian grades have to be selected. Grade 300W can be considered as being equivalent to ASTM A-572 grade 42 and Grade 350W will be used as an equivalent to ASTM A-572 grade 50.

With this diversity of steels it is necessary to always know the type of steel to be welded. The alloy content of the steel drastically affects the resulting weld.

Summary

- Canadian Standards Association Technical Committee on Structural Steel, G40
- CAN/CSA G40.20-M, “General requirements for Rolled or Welded Structural Quality Steel”
- CAN/CSA G40.21-M, “Structural Quality Steels”
- 8 types covered in CAN/CSA G40.21-M:
 - (a) Type G – General Construction Steel
 - (b) Type W – Weldable Steel
 - (c) Type WT – Weldable Notch Tough Steel
 - (d) Type R – Atmospheric Corrosion-Resistant Steel.
 - (e) Type A – Atmospheric Corrosion-Resistant Weldable Steel
 - (f) Type AT – Atmospheric Corrosion-Resistant Weldable Notch Tough Steel.
 - (g) Type Q – Quenched and Tempered Low Alloy Steel Plate
 - (h) Type QT – Quenched and Tempered Low Alloy Notch Tough Steel Plate
- a specified product may not always be available in the tonnage and time frame contemplated
- about steel covered by ASTM standards should be consulted when appropriate

- unidentified structural steel, Clause 5.2.2 of CAN/CSA-S16-01 requires F_y be taken as 210 MPa and F_u as 380 Mpa
- older steel material: see “Iron and Steel Beams 1873 to 1952”, by the American Institute of Steel Construction (first date listed for both ASTM A7 and A9 is the year 1900)

General

Canadian structural steels are covered by two sets of standards prepared by the Canadian Standards Association Technical Committee on Structural Steel, G40. Currently, these are the SI metric version, CAN/CSA G40.20-M92 and CAN/CSA G40.21-M92, and the imperial version, CAN/CSA G40.20-92 and CAN/CSA G40.21-92. Information provided in this section is based on the SI metric version in keeping with Canadian design standards.

CAN/CSA G40.20-M, “General requirements for Rolled or Welded Structural Quality Steel” sets out the general requirements governing the delivery of structural quality steels. These requirements include: *Definitions, Chemical Composition, Variations in dimensions, Methods of Testing, Frequency of Testing, Heat Treatment, Repairs of defects, Marking, etc.*

CAN/CSA G40.21-M, “Structural Quality Steels” governs the chemical and mechanical properties of 8 types and 8 strength levels of structural steels for general construction and engineering purposes. All strength levels are not available in all types, and selection of the proper grade (type and strength level) is important for a particular application. CAN/CSA G40.21-M 300W is the standard weldable steel normally specified for building construction, while CAN/CSA G40.21-M 350A and CAN/CSA G40.21-M 350AT are atmospheric corrosion resistant steels normally used in bridge construction. CAN/CSA G40.21-M 350W is the normal steel used for HSS sections.

The 8 types covered in CAN/CSA G40.21-M are:

(a) Type G – General Construction Steel. Steels of this type meet specified strength requirements; however, the chemical control is not such that all of these steels may be welded satisfactorily under normal field conditions. These steels are primarily designed for applications involving bolted connections or for welding under carefully controlled shop conditions.

(b) Type W – Weldable Steel. Steels of this type meet specified strength requirements and are suitable for general welded construction where notch toughness at low temperature is not a design requirement. Applications may include buildings, compression members of bridges, etc.

(c) Type WT – Weldable Notch Tough Steel. Steels of this type meet specified strength and Charpy V-Notch impact requirements and are suitable for welded construction where notch toughness at low temperature is a design requirement. The purchaser, in addition to specifying the grade, must specify the category of steel required that establishes the Charpy V-Notch test temperature and energy level. Applications may include primary tension members in bridges and similar elements.

(d) Type R – Atmospheric Corrosion-Resistant Steel. Steels of this type meet specified strength requirements and display an atmospheric corrosion-resistance approximately four times that of plain carbon steels (Copper content not exceeding 0.02%). These steels may be readily welded up to the maximum thickness covered by this standard. Applications include unpainted siding, unpainted light structural members, etc., where notch toughness at low temperature is not a design requirement.

(e) Type A – Atmospheric Corrosion-Resistant Weldable Steel. Steels of this type meet specified strength requirements and display an atmospheric corrosion-resistance approximately four times that of plain carbon steels*. These steels are suitable for welded construction where notch toughness at low temperature is not a design requirement and are often used in structures in the unpainted condition. Applications are similar to those for type W.

(f) Type AT – Atmospheric Corrosion-Resistant Weldable Notch Tough Steel. Steels of this type meet specified strength and Charpy V-Notch impact requirements and display an atmospheric corrosion-resistance of approximately four times that of plain carbon steels (Copper content not exceeding 0.02%). These steels are suitable for welded construction where notch toughness at low temperature is a design requirement and are often used in structures in the unpainted condition. The purchaser, in addition to specifying the grade, must specify the category of steel required that establishes the Charpy V-Notch test temperature and energy level. Applications may include primary tension members in bridges and similar elements.

(g) Type Q – Quenched and Tempered Low Alloy Steel Plate. Steels of this type meet specified strength requirements. While these steels may be readily welded, the welding and fabrication techniques are of fundamental importance and must not adversely affect the properties of the plate, especially the heat-affected zone. Applications may include bridges and similar structures.

(h) Type QT – Quenched and Tempered Low Alloy Notch Tough Steel Plate. Steels of this type meet specified strength and Charpy V-Notch impact requirements. They provide good resistance to brittle fracture and are suitable for structures where notch toughness at low temperature is a design requirement. The purchaser, in addition to specifying the grade, must specify the category of steel required that establishes the Charpy V-Notch test temperature and energy level. While these steels may be readily welded, the welding and fabrication techniques are of fundamental importance and must not adversely affect the properties of the plate, especially the heat-affected zone. Applications may include primary tension members in bridges and similar elements.

Comments

Availability of any grade and shape combination should be kept in mind when designing to ensure overall economy, since a specified product may not always be available in the tonnage and time frame contemplated. Local availability should always be checked.

Steel is identified at the mill as to type and grade according to the requirements of the G40.21-M standard by a colour code. Normally one end of each piece is marked with the appropriate colour code, however, where products are bundled or are shipped as secured lifts only the top or an outside piece may be marked, or a substantial tag may be used.

The particular standards, CAN/CSA G40.20-M and CAN/CSA G40.21-M should be consulted for more detail. Similar information about steel covered by ASTM standards should be consulted when appropriate.

Historical Remarks

When confronted with an unidentified structural steel, Clause 5.2.2 of CAN/CSA-S16-01 requires F_y be taken as 210 Mpa and F_u as 380 Mpa. This provides a minimum in lieu of more precise information, such as coupon testing. For more information on ASTM specifications and properties and dimensions of iron and steel beams previously produced in the U.S.A., consult "Iron and Steel Beams 1873 to 1952", and published by the American Institute of Steel Construction. In that publication, the first date listed for both ASTM A7 and A9 is the year 1900. Between 1900 and 1909, medium steel in A7 and A9 had a tensile strength 5 ksi higher than that adopted in 1914. For CSA standards, consult original documents.

STANDARDS AND IDENTIFICATION

The design requirements contained in S16-01 have been developed on the assumption that the materials and products, which will be used, are those listed in Clause 5. These materials and products are all covered by standards prepared by the Canadian Standards Association (CSA) or the American Society for Testing and Materials (ASTM).

The standards listed provide controls over manufacture and delivery of the materials and products, which are necessary to ensure that the materials and products will have the characteristics assumed when the design provisions of S16-01 were prepared. The use of materials and products other than those listed is permitted, provided that approval, based on published specifications, is obtained. In this case, the designer should assure himself that the materials and products have the characteristics required to perform satisfactorily in the structure. In particular, ductility is often as important as the strength of the material. Weldability and toughness may also be required in many structures. The values for yield and tensile strength reported on mill test reports are not to be used for design. Only the specified minimum values published in product standards and specifications may be used. This has always been implicit in the requirements of the Standard by definition of the terms F_y and F_u but is now explicitly stated. Furthermore, when tests are done to identify steel, the *specified minimum* values of the steel, once classified, shall be used as the basis for design.

When, however, sufficient representative tests are done on the steel of an existing structure to be statistically significant, those statistical data on the variation of the material and geometric properties may be combined with that for test/predicted ratios available in the literature to develop appropriate resistance factors. This is by no means equivalent, for example, to substituting a new mean yield stress for a specified minimum value as the new reference value and the bias coefficient must be established. It could well be that, although a higher mean value of the yield stress is established, the bias coefficient, depending as it does on the reference value, would be less. It would be expected that the coefficient of variation for the material properties in particular, derived for the steel in a single structure, would be less than for steel in general.