MATERIAL OF CONSTRUCTION IN ASME CODE PRESSURE VESSELS

Pressure vessel components are normally fabricated from ferrous alloys and/or nonferrous alloys. The type of material selected for construction depends mostly on the type of service and the construction code being used. Most pressure vessels operating above 15 psi (100 kPa) internal pressure are required to be built in accordance with ASME Section VIII code. Specifications for ferrous alloys in the US are designated by ASTM with a letter "A" such as S-516 material, while the specifications for nonferrous alloys are designate by a letter "B" such as B-168 material. The ASME pressure vessel code adds a letter "S" to the specification such as SA-516 and SB-168 to indicate that the material is approved by ASME for use in pressure vessel construction.

FERROUS ALLOYS

Ferrous alloys used in pressure vessel construction are divided into three categories:

Carbon Steel (CS)

Carbon steel is the most commonly used engineering material. It is cheap, is available in wide range of standard forms and sizes and can be easily worked and welded. Carbon steels are magnetic, and their average density is about 0.284 lb/in^3. Carbon steels generally contain maximum 0.3% carbon. Vessels constructed of carbon steel normally operate at temperatures of up to around 650^{o}F (345^{o}C). Above this temperature, their strength drops rapidly. However, carbon steel has limited corrosion resistance and low creep strength and is normally not advised for use in the creep range that is for temperatures more than 750^{o}F (400^{o}C).

The chemical composition of carbon steel consists of iron with small amounts of a few added elements such as carbon, manganese and silicon for enhanced strength and workability. Phosphorus and sulfur are also controlled.

Carbon: Added to increase the strength of steel. However, toughness of steel tends to decrease with an increase in the carbon content.

Manganese: Increases the toughness of steel by lowering the transition temperature.

Phosphorus: Added to increase the strength and hardness of steel but is controlled to avoid embrittlement that occurs at higher levels.

Silicon: Used as deoxidizer and to produce more uniform grain distribution and it improves toughness.

Sulfur: Increases the machinability of steel but tends to reduce toughness.

Low Alloy Steel (LAS)

Low alloy steels contain, in addition to the elements listed for low carbon steels, chromium, molybdenum and nickel to enhance strength at elevated temperatures. Their density is essentially the same as that of carbon steels. The percentage of alloying elements is generally kept below 10%. Low alloy steels are typically selected for elevated temperatures when corrosion is not a major consideration. Their higher cost is justified by their ability to withstand higher temperatures.

Objects of main alloying elements are given below:

Chromium: Improves resistance to oxidation and improves resistance, abrasion resistance, high-temperature strength, and resistance to high-pressure hydrogen.

Molybdenum: Improves strength at elevated temperature, creep strength, and resistance to pitting.

Vanadium: Improves wear resistance, high-temperature strength, and resistance to high-pressure hydrogen.

Nickel: Improves toughness, low temperature properties, and corrosion resistance.

Common products are 1.25Cr-0.5Mo, 2.25Cr-1Mo, and 9Cr-1Mo.

Commercially produced steels are supplied in the annealed condition, the normalized-tempered, or the quenched-and-tempered conditions. Since chromium and molybdenum increase the strength at elevated temperatures, give better toughness, and improve corrosion resistance, these steels are often used in pressure vessels operating in the range of 750°F (400°C) to 1200°F (650°C). The complexity of Cr-Mo steels requires the mill to specify additional parameters such as annealing, normalizing, tempering and quenching to produce a product with the appropriate properties.

Annealing (solution annealing): Consists of heating the steel and then furnace cooling down to room temperature. The slow cooling process results in a refined grain structure and soft material. The annealing temperature depends on the type of steel. Carbon and low alloy steels are usually annealed at about 1380°F (750°C), while high alloy stainless steels are solution annealed at 1900°F (1040°C).

Normalizing: Consists of heating the steel to about 1430°F (775°C) and then air cooling it to room temperature. The purpose of normalizing is to increase the strength and hardness of steel. It also refines the grain and homogenizes the structure.

Quenching: Is a rapid cooling of steel, usually in water or oil, to increase hardness.

Tempering: Consists of additional heating of the product to reduce hardness of normalized or quenched steels and to increase toughness.

<u>High Alloy Steels (Stainless Steel)</u>

The stainless steels are most frequently used corrosion resistant materials in the industry. To impart corrosion resistance, the chromium content must be above 12%, and higher the chromium content, the more resistant is the alloy to corrosion in the oxidizing conditions. Nickel is added to improve the corrosion resistance in non-oxidizing environments. High alloy steels are used for both elevated temperatures and for corrosive environments.

There are three varieties of stainless steels: austenitic, martensitic, and ferritic.

- *Austenitic* is corrosion resistant, tough, ductile, and easy to form and weld. These steels are suitable for low service temperature in the range of -110°F to 480°F (-80°C to 250°C) as well as high service temperature in the range of 750°F to 930°F (400°C to 500°C). Some special grades such as 304H, 316H, and 321H are suitable for very high service temperatures in the range of 930°F to 1500°F (500°C to 816°C). They contain 18 to 20% chromium and greater than 7% nickel.

  The uniform FCC structure of Austenite is the desired structure for corrosion resistance, and it is these grades that are widely used in the chemical industry. The composition of main grades of austenitic steels are shown in the table below:

Grade	C (max)	Si (max)	Mn (max)	Cr (range)	Ni (range)	Mo (range)	Ti	Nb
304	0.08	---	2.00	17.5 - 20.0	8.0 – 11.0	---	---	---
304L	0.03	1.00	2.00	17.5 - 20.0	10 min	---	---	---
321	0.12	1.00	2.00	17.0 – 20.0	7.5 min	---	4 x C	---
347	0.08	1.00	2.00	17.0 – 20.0	9 min	---	---	---
316	0.08	1.00	2.00	16.5 – 18.5	10 min	2.25 – 3.00	---	---

  S and P: 0.045% all grades.

Type 304: This is so-called 18-8 stainless steel and most generally used. It contains minimum Cr and Ni that give it a stable austenitic structure. The carbon content is low enough for heat treatment not to be normally needed with thin sections to prevent weld decay.

Type 304L: This is low carbon version of Type 304 where C content is less than 0.03%. It is used for thicker welded sections where carbide precipitation would occur with Type 304.

Type 321: This is a stabilized version of Type 304, stabilized with titanium to prevent carbide precipitation during welding. It has slightly higher strength than Type 304L and is more suitable for high temperature use.

Type 347: This is stabilized with niobium.

Type 316: In this alloy, molybdenum is added to improve the corrosion resistance in reducing conditions such as in dilute sulphuric acid and particularly to solutions containing chlorides.

Type 316L: This is low carbon version of Type 316 which should be specified if welding or heat treatment is liable to cause carbide precipitation in Type 316.

Type 309/310: These are alloys with high Cr content to give greater resistance to oxidation at high temperatures. Alloys with greater than 25% Cr are susceptible to embrittlement due to sigma phase formation at temperatures above 930^{o}F (500^{o}C).

Austenitic stainless steels have greater strength than plain carbon steels, particularly at elevated temperatures. Unlike the plain carbon steel, these steels also do not become brittle at low temperatures. Thermal conductivity of austenitic stainless steel is significantly lower than that of carbon steel and they are non-magnetic in annealed condition.

The higher the alloying content, the better is the corrosion resistance over a wide range of conditions, but the cost is higher.

- *Martensitic* contains 1 to 14% chromium. Type 409, 410, and 410S are commonly used for non-cooled and non-pressure parts required for high-temperature service. They contain 10 to 12% chromium, 0.2 to 0.4% carbon and up to 2% nickel.
- *Ferritic* contains 13 to 20% chromium, less than 0.1% carbon and no nickel. Type 429, 430, and 439 belong to this category. These grades are corrosion-resistant and suitable for higher service temperatures up to 1200^{o}F (650^{o}C) and up to 1470^{o}F (800^{o}C) for non-cooled and non-pressure parts.

Intergranular corrosion (weld decay) and stress corrosion cracking are problems associated with the use of stainless steels and must be considered when selecting types suitable for use in a particular environment. Stress corrosion cracking in stainless steels can be caused by a few ppm of chloride ions. In general, stainless steels are used for corrosion resistance when oxidizing conditions exist. Special types, or other high nickel alloys, should be specified if reducing conditions are likely to occur.

HIGH ALLOY CONTENT STAINLESS STEELS

Super austenitic, high nickel, stainless steels, containing between 29 to 30% nickel and 20% chromium, have a good resistance to acids and acid chlorides. They are more expensive than the lower alloy content.

Duplex, and super-duplex stainless steels, contain high percentages of chromium. They are called duplex because their structure is a mixture of the austenitic and ferritic phases. They have a better corrosion resistance than the austenitic stainless steels and are less susceptible to stress corrosion cracking. The Cr content of duplex stainless steels is around 20% and around 25% in super-duplex grades. The cost of duplex grades is comparable with Type 316 steels. Super-duplex is around fifty percent higher than the cost of duplex.

NONFERROUS ALLOYS

ASME Code lists alloys of five nonferrous metals: aluminium, copper, nickel, titanium and zirconium.

- *Aluminium*: Aluminium alloys are nonmagnetic. Their average density is about 0.10 lb/in^3 which is about one-third of steel. Aluminium alloys generally develop a passive oxide layer on the surface, and do not oxidize further in air at room temperature. The maximum design temperature for aluminium alloys listed by the ASME code is typically 400^{o}F (205^{o}C) or less. Aluminium can be alloyed with various elements to increase strength and corrosion resistance.

- *Copper*: Copper alloys are nonmagnetic, and their average density is 0.324 lb/in^3, about 14% heavier than steel. Most copper alloys oxidize in air at room temperature – exceptions are copper nickel alloys that tend to keep their original color in air. The most common alloys of copper are as follows:

  1) Brass – alloy of copper and zinc
  2) Bronze – alloy of copper and tin
  3) Copper nickel – alloy of copper and up to 49.9% nickel

  The maximum design temperature for most copper alloys listed by ASME code is about 400^{o}F (205^{o}C), but it can go as high as 700^{o}F (370^{o}C) for copper nickel alloys.

- *Nickel*: Nickel is highly magnetic, but some nickel alloys are nonmagnetic. The average density of nickel alloys is about 0.306 lb/in^3, slightly denser than steel. Nickel alloys do not oxidize in air at room temperature. They are used extensively in high temperature applications with corrosive environments. The table below show some commonly used nickel alloys and their generic composition and provides a cross reference between commercial name, alloy designation, UNS number, and major composition.

Commercial Name	Alloy Designation	UNS	Major Composition	ASME Spec Number	Max Temp.
Nickel 200	200	N02200	Ni	SB-160, 161, 162, 163, 366	600^{o}F (315^{o}C)
Nickel 201	201	N02201	Ni–low C	SB-160, 161, 162, 163, 366	600^{o}F–1200^{o}F (315^{o}C–650^{o}C)
Monel 400	400	N04400	Ni-Cu	SB-1276, 163, 164, 165, 366, 564	500^{o}F–900^{o}F (260^{o}C–480^{o}C)
Monel 405	405	N04405	Ni-Cu	SB-164	900^{o}F (480^{o}C)
Inconel 600	600	N06600	Ni-Cr-Fe	SB-163, 166, 167, 168, 516, 517, 564	1200^{o}F (650^{o}C)
Inconel 625	625	N06625	Ni-Cr-Mo-Cb	SB-366, 443, 444, 446, 564, 704, 705	1200^{o}F–1600^{o}F (650^{o}C–870^{o}C)
Inconel 690	690	N06690	Ni-Cr-Fe	SB-166, 167, 168	850^{o}F (455^{o}C)
Incoloy 800	800	N08800	Ni-Fe-Cr	SB-163, 366, 407, 408, 409, 514, 515, 564	1500^{o}F (815^{o}C)
Incoloy 800H	800H	N08810	Ni-Fe-Cr	SB-163, 407, 408, 409, 514, 515, 564	1650^{o}F–1800^{o}F (900^{o}C–980^{o}C)
Incoloy 825	825	N08825	Ni-Fe-Cr-Mo-Cu	SB-163, 366, 423, 424, 425, 564, 704, 705	1000^{o}F (540^{o}C)
Hastelloy B2	B2	N10665	Ni-Mo-Fe	SB-333, 335, 366, 462, 564, 619, 622, 626	800^{o}F (425^{o}C)

Hastelloy B3	B3	N10675	Ni-Mo-Fe	SB-333, 335, 366, 462, 564, 619, 622, 626	800°F (425°C)
Hastelloy C4	C4	N06445	Ni-Mo-Cr	SB-366, 574, 575, 619, 622, 626	800°F (425°C)
Hastelloy C276	C276	N10276	Ni-Mo-Cr	SB-574, 575, 619, 622, 626	1250°F (675°C)
Hastelloy G	G	N06007	Ni Cr-Fe-Mo	SB-366, 581, 582, 619, 622, 626	1000°F (540°C)
Hastelloy G2	G2	N06975	Ni-Cr-Fe-Mo	SB-582, 619, 622, 626	800°F (425°C)
Hastelloy G3	G3	N06985	Ni-Cr-Fe-Mo	SB-366, 581, 582, 619, 622, 626	800°F (425°C)
Hastelloy G30	G30	N06030	Ni-Cr-Fe-Mo	SB-366, 462, 581, 582, 619, 622, 626	800°F (425°C)
Hastelloy G35	G35	N06035	Ni-Cr-Mo	SB-366, 462, 564, 574, 575, 619, 622, 626	800°F (425°C)
Carpenter 20	20Cb	N08020	Ni-Fe-Cr-Cb	SB-366, 462, 463, 464, 468, 473, 729	800°F (425°C)
Rolled Alloy 330	330	N08330	Ni-Cr-Si	SB-366, 511, 535, 536, 710	1650°F (900°C)
Alloy 904L	904L	N08904	Fe-Ni-Cr-Mo	SA-182, 240, 249, 312, 403, SB-649, 677	700°F (370°C)

- *Titanium*: Titanium alloys are reactive, combining readily with oxygen at elevated temperatures. Hence, they pose challenges in welding and cutting during the fabrication process. They are nonmagnetic and their average density is about 0.163 lb/in^3, or a little less than 60% that of mild steel. Titanium alloys do not oxidize in air at room temperature. Their strength-to-weight ratio makes them excellent material for pressure vessels in severe environments where corrosion is a problem. The disadvantages of using titanium alloys are their cost and the temperature limit of around 600°F (315°C).
- *Zirconium*: Zirconium alloys are nonmagnetic, reactive at elevated temperatures, and have their average density of about 0.240 lb/in^3. Zirconium alloys do not oxidize in air at room temperature. The maximum design temperature for zirconium listed by the ASME code is about 700°F (370°C). They are used for pressure vessels under many severely corrosive environments. Their excellent radioactive neutron absorption property makes them ideal as isotope supports in nuclear components.

TANTALUM ALLOYS

Tantalum alloys are nonmagnetic, reactive at elevated temperatures, and have their average density of about 0.602 lb/in^3. Tantalum alloys do not oxidize in air at room temperature. They are not listed in the ASME code as a material of construction but are used as liners for pressure vessels with severely corrosive contents such as nitric and sulfuric acids, as substitute for glass-lined vessels. Their density is about 50% greater than that of lead. Their low yield strength and high elongation makes them easy to form during fabrication. Their corrosion resistance is similar to that of silver and their cost is about the same.

UNIFORM NUMBERING SYSTEM

All ASTM materials used in pressure vessel construction are also designated by a Uniform Numbering System (UNS) number. The UNS number consists of a prefix and a five-digit number. The UNS prefix designations for commonly used materials and alloys in pressure vessels are given in Table 1.

Table 1: Unified Numbering System (UNS) Designations

UNS Designation	Alloy Type
A00001 to A99999	Aluminium and aluminium alloys
C00001 to C99999	Copper and copper alloys
F00001 to F99999	Cast irons
G00001 to G99999	AISC and SAE carbon and alloy steels
J00001 to J99999	Cast steels
K00001 to K99999	Miscellaneous steels and ferrous alloys
N00001 to N99999	Nickel alloys
R00001 to R99999	Reactive metals and alloys R05xxx – tantalum alloys R5xxxx – titanium alloys R6xxxx – zirconium alloys
S00001 to S99999	Stainless steels
W00001 to W99999	Welding filler metals

Hence, carbon steel plate SA-516 Grade 70 is designated as UNS K02700 and nickel alloy plate SB-575 type Hastelloy C-276 as UNSN10276.

MECHANICAL PROPERTIES

Typical mechanical properties of more common materials used in the design and construction of pressure vessels are as follows:

<u>Tensile Strength</u>

The tensile strength (also called ultimate tensile strength) is a measure of basic strength of a material. It is the maximum stress that the material will withstand, measures by a standard tensile test. The maximum allowable stress for a material, a value used in design calculations, is based on the tensile strength or on the yield strength.

<u>Stiffness</u>

Stiffness is the ability to resist bending and buckling. It is a function of the elastic modulus of the material and the shape of the cross section of the member (the second moment of area).

<u>Toughness</u>

Toughness is associated with tensile strength and is a measure of the material's resistance to crack propagation. The crystal structure of ductile materials, such as steel, aluminium and copper, is such that they stop the propagation of a crack by local yielding at the crack tip. In other materials, such as cast irons and glass, the structure is such that local yielding does not occur and the materials are brittle. Brittle materials are weak in tension but strong in compression. Under compression, any incipient cracks present are closed up.

<u>Hardness</u>

The surface hardness, as measured in a standard test, is an indication of a material's ability to resist wear. This will be an important property if the equipment is being designed to handle abrasive solids, or liquids containing suspended solids which are likely to cause erosion.

Fatigue

Fatigue failure is likely to occur in equipment subject to cyclic loading; for example, rotating equipment, such as pumps and compressors, and equipment subject to pressure cycling.

Creep

Creep is the gradual extension of a material under a steady tensile stress, over a prolonged period of time. It is usually only important at high temperatures, for instance, with steam and gas turbine blades. The creep strength of a material is usually reported as the stress to cause rupture in 100,000 hours, at the test temperature.

MATERIAL COSTS

An indication of the relative cost of some commonly used materials (relative to carbon steel) is given in the table to the right.

The relative cost of pressure vessel made from different materials will depend on the cost of fabrication, as well as the basic cost of material. Unless a particular material requires special fabrication techniques, the relative cost of the finished pressure vessel will be lower than the relative bare material cost. For example, the purchased cost of a stainless-steel pressure vessel will be 2 to 3 times the cost of the same pressure vessel in carbon steel material, even though the relative cost of the materials is between 5 and 8.

Carbon steel	1
Low alloy steel (Cr-Mo)	1.3 to 2.3
Nickel steel (9%)	2.6
Austenitic stainless steels:	
304	5.3
321	5.6
316	8.0
310	10.0
High Ni	20.0
Copper alloys	6.0
Aluminium alloys	5.0
Nickel alloys	16.0-50.0
Monel	8.6
Titanium alloys	55.0
Zirconium alloys	65.0
Tantalum alloys	330.0

Reference:

ASME Boiler and Pressure Vessel Code, Section VIII and Section II.
Fabrication of Metallic Pressure Vessels *by* Owen R. Greulich and Maan H. Jawad
Design of Pressure Vessels *by* Subhash Reddy Gaddam
Coulson & Richardson's Chemical Engineering *by* R.K. Sinnott