Quenched and Tempered Low-Alloy Steel

Alloy steels are defined as those steels that:

1. contain manganese, silicon, or copper in quantities greater than the maximum limits (1.65% Mn, 0.60% Si, and 0.60% Cu) of carbon steel; or
2. that have specified ranges or minima for one or more other alloying additions.

The low-alloy steels are those steels containing alloy elements, including carbon, up to a total alloy content of about 8.0%. Low-alloy steels with suitable alloy compositions have greater hardenability than structural carbon steel and, thus, can provide high strength and good toughness in thicker sections by heat treatment. Their alloy contents may also provide improved heat and corrosion resistance.

Except for plain carbon steels that are micro alloyed with just vanadium, niobium, and/or titanium, most low-alloy steels are suitable as engineering quenched and tempered steels and are generally heat treated for engineering use.

Low-alloy steels with suitable alloy compositions have greater hardenability than structural carbon steel and, thus, can provide high strength and good toughness in thicker sections by heat treatment. Their alloy contents may also provide improved heat and corrosion resistance. Effect of manganese on precipitation strengthening is greater than its effect in niobium steels. However, the absolute strength of niobium steel with 1.2% Mn is only about 50 MPa less than that of vanadium steel but at a much lower alloy level (that is, 0.06% Nb versus 0.14% V).

Another factor affecting the strength of vanadium steels is the ferrite grain size produced after cooling from the austenitizing temperature. Finer ferrite grain sizes can be produced by either lower austenite-to-ferrite transformation temperatures or by the formation of finer austenite grain sizes prior to transformation.

The austenite grain size of hot-rolled steels is determined by the recrystallization and grain growth of austenite during rolling. Vanadium hot-rolled steels usually undergo
conventional rolling but are also produced by recrystallization controlled rolling. With conventional rolling, vanadium steels provide moderate precipitation strengthening and relatively little strengthening from grain refinement. The maximum yield strength of conventionally hot-rolled vanadium steels with 0.25% C and 0.08% V is about 450 MPa. The practical limit of yield strengths for hot-rolled vanadium-microalloyed steel is about 415 MPa.

**Niobium Microalloyed Steels.** Like vanadium, niobium increases yield strength by precipitation hardening; the magnitude of the increase depends on the size and amount of precipitated niobium carbides. However, niobium is also a more effective grain refiner than vanadium. Thus, the combined effect of precipitation strengthening and ferrite grain refinement makes niobium a more effective strengthening agent than vanadium. The usual niobium addition is 0.02 to 0.04%, which is about one-third the optimum vanadium addition. Strengthening by niobium is 35 to 40 MPa per 0.01% addition.

Niobium steels are produced by controlled rolling, recrystallization controlled rolling, accelerating cooling, and direct quenching. The recrystallization controlled rolling of niobium steel can be effective without titanium, while recrystallization rolling of vanadium steels requires titanium for grain refinement.

**Vanadium-Niobium Microalloyed Steels.** Steels microalloyed with both niobium and vanadium provide higher yield strength in the conventionally hot-rolled condition than that achievable with either element alone. As conventionally hot rolled, the niobium-vanadium steels derive almost all of their increased strength from precipitation strengthening and therefore have high ductile-brittle transition temperatures. If the steel is controlled rolled, the addition of both niobium and vanadium together is especially advantageous for increasing the yield strength and lowering ductile-brittle transition temperatures by grain refinement.

Usually niobium-vanadium steels are made with relatively low carbon contents. This reduces the amount of pearlite and improves toughness, ductility, and weldability. These steels are frequently referred to as pearlite-reduced steels.

**Niobium-Molybdenum Microalloyed Steels.** Steels microalloyed with niobium and molybdenum may have either a ferrite-pearlite microstructure or an acicular ferrite microstructure. In ferrite-pearlite niobium steels, the addition of molybdenum increases the yield strength and tensile strength by about 20 MPa and 30 MPa, respectively, per 0.1% Mo, over a range of 0% to 0.27% Mo.

The principal effect of molybdenum on the microstructure is to alter the morphology of the pearlite and to introduce upper bainite as a partial replacement for pearlite. However, because the individual strength values of pearlite and bainite are somewhat similar, it has been proposed that the strength increase is due to solid-solution strengthening and enhanced precipitation strengthening caused by a molybdenum-niobium synergism.

**Vanadium-Nitrogen Microalloyed Steels.** Vanadium combines more strongly with nitrogen than niobium does, and forms VN precipitates in vanadium-nitrogen steel. Nitrogen additions to high-strength steels containing vanadium have become
Some producers use nitrogen additions to assist in the precipitation strengthening of controlled-cooled sheet and plate with thicknesses above 9.5 mm. In one case, hot-rolled plates with vanadium and 0.018 to 0.022% N have been produced by controlled cooling in thicknesses up to 16 mm with yield strengths of 550 MPa. However, delayed cracking is a major problem in these steels. The use of nitrogen is not recommended for steels that will be welded because of its detrimental effect on notch toughness in the heat-affected zone.

Titanium-Microalloyed Steels. Titanium in low-carbon steels forms into a number of compounds that provide grain refinement, precipitation strengthening, and sulfide shape control. However, because titanium is also a strong deoxidizer, titanium can be used only in fully killed (aluminum deoxidized) steels so that titanium is available for forming into compounds other than titanium oxide. Commercially, steels precipitation strengthened with titanium are produced in thicknesses up to 9.5 mm in the minimum yield strength range from 345 to 550 MPa with controlled rolling required to maximize strengthening and improve toughness.

Like niobium and/or vanadium steels, titanium microalloyed steels are strengthened by mechanisms that involve a combination of grain refinement and precipitation strengthening; the combination depends on the amount of alloy additions and processing methods. In reheated or continuously cast steels, small amounts of titanium (<0.025% Ti) are effective grain refiners because austenite grain growth is retarded by titanium nitride.

Titanium-Niobium Microalloyed Steels. Although precipitation-strengthened titanium steels have limitations in terms of toughness and variability of mechanical properties, research has shown that an addition of titanium to low-carbon niobium steels results in an overall improvement in properties. Titanium increases the efficiency of niobium because it combines with the nitrogen-forming titanium nitrides, thus preventing the formation of niobium nitrides.

Acicular Ferrite (Low-Carbon Bainite) Steels. Another approach to the development of HSLA steels is to obtain a very fine, high-strength acicular ferrite microstructure, instead of the usual polygonal ferrite microstructure during the cooling transformation of ultra-low carbon (<0.08% C) steels with sufficient hardenability (by additions of manganese, molybdenum, and/ or boron). Niobium can also be used for precipitation strengthening and grain refinement. The principal difference between the structure of acicular ferrite (which is also referred to as low-carbon bainite) and that of polygonal ferrite is that the former is characterized by a high dislocation density and fine, highly elongated grains that are not exhibited in polygonal ferrite.

Acicular ferrite steels can be obtained by quenching or, preferably, by air-cooling with suitable alloys for hardenability. The principal advantage of this type of HSLA steel is the unusual combination of high yield strengths (415 to 690 MPa), high toughness, and good weldability. A major application of these steels is line pipe in arctic conditions.