
High-Strength Low-Alloy Steels

Introduction and Overview

High-strength low-alloy (HSLA) steels, or microalloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition (HSLA steels have yield strengths greater than 275 MPa, or 40 ksi). The chemical composition of a specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements. The HSLA steels in sheet or plate form have low carbon content (0.05 to –0.25% C) in order to produce adequate formability and weldability, and they have manganese content up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are used in various combinations.

HSLA Steel Categories. High-strength low-alloy steels include many standard and proprietary grades designed to provide specific desirable combinations of properties such as strength, toughness, formability, weldability, and atmospheric corrosion resistance. These steels are not considered alloy steels, even though their desired properties are achieved by the use of small alloy additions. Instead, HSLA steels are classified as a separate steel category, which is similar to as-rolled mild-carbon steel with enhanced mechanical properties obtained by the addition of small amounts of alloys and, perhaps, special processing techniques such as controlled rolling and accelerated cooling methods. This separate product recognition of HSLA steels is reflected by the fact that HSLA steels are generally priced from the base price for carbon steels, not from the base price for alloy steels. Moreover, HSLA steels are often sold on the basis

of minimum mechanical properties, with the specific alloy content left to the discretion of the steel producer.

HSLA steels can be divided into six categories:

- *Weathering steels*, which contain small amounts of alloying elements such as copper and phosphorus for improved atmospheric corrosion resistance and solid-solution strengthening (see the article “Carbon and Alloy Steels”).
- *Microalloyed ferrite-pearlite steels*, which contain very small (generally, less than 0.10%) additions of strong carbide or carbonitride-forming elements such as niobium, vanadium, and/or titanium for precipitation strengthening, grain refinement, and possibly transformation temperature control
- *As-rolled pearlitic steels*, which may include carbon-manganese steels but which may also have small additions of other alloying elements to enhance strength, toughness, formability, and weldability
- *Acicular ferrite (low-carbon bainite) steels*, which are low-carbon (less than 0.05% C) steels with an excellent combination of high yield strengths, (as high as 690 MPa, or 100 ksi) weldability, formability, and good toughness
- *Dual-phase steels*, which have a microstructure of martensite dispersed in a ferritic matrix and provide a good combination of ductility and high tensile strength
- *Inclusion-shape-controlled steels*, which provide improved ductility and through-thickness toughness by the small additions of calcium, zirconium, or titanium, or perhaps rare earth elements so that the shape of the sulfide inclusions is changed from elongated stringers to small, dispersed, almost spherical globules

These categories are not necessarily distinct groupings, as an HSLA steel may have characteristics from more than one grouping. For example, all the above types of steels can be inclusion shape controlled. Microalloyed ferrite-pearlite steel may also have additional alloys for corrosion resistance and solid-solution strengthening. Table 1 lists compositions of some HSLA steels covered in ASTM specifications.

Applications of HSLA steels include oil and gas pipelines, heavy-duty highway and off-road vehicles, construction and farm machinery, industrial equipment, storage tanks, mine and railroad cars, barges and dredges, snowmobiles, lawn mowers, and passenger car components. Bridges, offshore structures, power transmission towers, light poles, and building beams and panels are additional uses of these steels.

The choice of a specific high-strength steel depends on a number of application requirements including thickness reduction, corrosion resistance, formability, and weldability. For many applications, the most important factor in the steel selection process is the favorable strength-to-weight

Table 1 Compositional limits for HSLA steel grades described in ASTM specifications

ASTM specification(a)	Type or grade	UNS designation	Heat computational limits, % (b)											Other			
			C	Mn	P	S	Si	Cr	Ni	Cu	V						
A 242	Type 1	K11510	0.15	1.00	0.45	0.05	...	...	...	...	...	...	...	...	...	...	...
A 572	Grade 42	...	0.21	1.35(c)	0.04	0.05	0.30(c)	...	...	...	...	0.20 min	...	...	...	...	(e)
	Grade 50	...	0.23	1.35(c)	0.04	0.05	0.30(c)	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 60	...	0.26	1.35(c)	0.04	0.05	0.30	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 65	...	0.23(c)	1.65(c)	0.04	0.05	0.30	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
A 588	Grade A	K11430	0.10-0.19	0.90-1.25	0.04	0.05	0.15-0.30	0.40-0.65	...	...	...	0.25-0.40	0.02-0.10	...	...	...	...
	Grade B	K12043	0.20	0.75-1.25	0.04	0.05	0.15-0.30	0.40-0.70	0.25-0.50	...	...	0.20-0.40	0.01-0.10	...	...	...	...
	Grade C	K11538	0.15	0.80-1.35	0.04	0.05	0.15-0.30	0.30-0.50	0.25-0.50	...	...	0.20-0.50	0.01-0.10	...	...	...	...
	Grade D	K11552	0.10-0.20	0.75-1.25	0.04	0.05	0.50-0.90	0.50-0.90	...	...	...	0.30	...	...	...	...	0.04 Nb, 0.05-0.15 Zr
	Grade K	...	0.17	0.5-1.20	0.04	0.05	0.25-0.50	0.40-0.70	0.40	...	...	0.30-0.50	...	...	...	...	0.10 Mo, 0.005-0.05 Nb
A 606	...	...	0.22	1.25	...	0.05	...	...	...	...	...	...	...	...	...	...	...
A 607	Grade 45	...	0.22	1.35	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 50	...	0.23	1.35	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 55	...	0.25	1.35	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 60	...	0.26	1.50	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 65	...	0.26	1.50	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
	Grade 70	...	0.26	1.65	0.04	0.05	...	...	...	...	...	0.20 min(d)	...	...	...	...	(e)
A 618	Grade 1a	...	0.15	1.00	0.15	0.05	...	...	...	...	...	0.20 min	...	...	...	...	(e)
	Grade 1b	...	0.20	1.35	0.04	0.05	...	...	...	...	...	0.20 min(f)	...	...	...	...	(e)
	Grade 2	K12609	0.22	0.85-1.25	0.04	0.05	0.30	...	...	...	...	...	0.02 min	...	...	...	0.005 Nb min(g)
	Grade 3	K12700	0.23	1.35	0.04	0.05	0.30	...	...	...	...	...	0.02 min	...	...	...	0.05 Nb
A 633	Grade A	K01802	0.18	1.00-1.35	0.04	0.05	0.15-0.30	...	...	...	...	...	...	...	...	...	0.01-0.05 Nb
	Grade C	K12000	0.20	1.15-1.50	0.04	0.05	0.15-0.50	...	...	...	...	...	...	...	...	...	0.08 Mo
	Grade D	K02003	0.20	0.70-1.60(c)	0.04	0.05	0.15-0.50	0.25	0.25	0.25	0.35	...	...	...	...	...	0.01-0.05 Nb(d), 0.01-0.03 N
	Grade E	K12202	0.22	1.15-1.50	0.04	0.05	0.15-0.50	...	...	...	...	...	0.04-0.11	...	...	...	...

(continued)

(a) For characteristics and intended uses, see Table 2. (b) If a single value is shown, it is a maximum unless otherwise stated. (c) Values may vary, or minimum value may exist, depending on product size and mill form. (d) Optional or when specified. (e) May be purchased as type 1 (0.005-0.05 Nb), type 2 (0.01-0.15 V), type 3 (0.05 Nb, max, plus 0.02-0.15 V) or type 4 (0.015 N, max, plus V \geq 4N). (f) If chromium and silicon are each 0.50% min, the copper minimum does not apply. (g) May be substituted for all or part of V. (h) Niobium plus vanadium, 0.02 to 0.15%. (i) Nitrogen with vanadium content of 0.015% (max) with a minimum vanadium-to-nitrogen ratio of 4:1. (j) When silicon-killed steel is specified. (k) For plate under 40 mm (1.5 in.), manganese contents are 0.70 to 1.35% or up to 1.60% if carbon equivalents do not exceed 0.47%. For plate thicker than 40 mm (1 to 5 in.), ASTM A 841 specifies manganese contents of 1.00 to 1.60%.

Table 1 (continued)

ASTM specification(a)	Type or grade	UNS designation	Heat computational limits, % (b)											Other
			C	Mn	P	S	Si	Cr	Ni	Cu	V			
A 656	Type 3	...	0.18	1.65	0.025	0.035	0.60	...	...	...	0.08	0.020 N, 0.005-0.15 Nb
A 690	Type 7	...	0.18	1.65	0.025	0.035	0.60	...	...	...	0.005-0.15	0.020 N, 0.005-0.10 Nb
A 709	...	K12249	0.22	0.60-0.90	0.08-0.15	0.05	0.10	...	0.40-0.75	...	...	...
	Grade 50, type 1	...	0.23	1.35	0.04	0.05	0.40	...	...	...	0.01-0.15	0.005-0.05 Nb
	Grade 50, type 2	...	0.23	1.35	0.04	0.05	0.40	...	...	...	(h)	0.05 Nb max
	Grade 50, type 3	...	0.23	1.35	0.04	0.05	0.40	...	...	...	(i)	0.015 N max
	Grade 50, type 4	...	0.23	1.35	0.04	0.05	0.40	...	...	...	Added as necessary	Ti, Nb added as necessary
A 715	...	...	0.15	1.65	0.025	0.035	...	...	...	...	necessary	...
A 808	...	...	0.12	1.65	0.04	0.05 max or 0.010 max	0.15-0.50	...	...	...	0.10	0.02-0.10 Nb, V + Nb = 0.15 max
A 812	65	...	0.23	1.40	0.035	0.04	0.15-0.50(j)	...	...	...	V + Nb = 0.02-0.15	0.05 Nb max
	80	...	0.23	1.50	0.035	0.04	0.15-0.50	0.35	...	...	V + Nb = 0.02-0.15	0.05 Nb max
A 841	...	...	0.20	(k)	0.030	0.030	0.15-0.50	0.25	0.25	0.35	0.06	0.08 Mo, 0.03 Nb, 0.02 Al total
A 871	...	...	0.20	1.50	0.04	0.05	0.90	0.90	1.25	1.00	0.10	0.25 Mo, 0.15 Zr, 0.05 Nb, 0.05 Ti

(a) For characteristics and intended uses, see Table 2. (b) If a single value is shown, it is a maximum unless otherwise stated. (c) Values may vary, or minimum value may exist, depending on product size and mill form. (d) Optional or when specified. (e) May be purchased as type 1 (0.005-0.05 Nb), type 2 (0.01-0.15 V), type 3 (0.05 Nb, max, plus 0.02-0.15 V) or type 4 (0.015 N, max, plus V ≥ 4N). (f) If chromium and silicon are each 0.50% min, the copper minimum does not apply. (g) May be substituted for all or part of V. (h) Niobium plus vanadium, 0.02 to 0.15%. (i) Nitrogen with vanadium content of 0.015% (max) with a minimum vanadium-to-nitrogen ratio of 4:1. (j) When silicon-killed steel is specified. (k) For plate under 40 mm (1.5 in.), manganese contents are 0.70 to 1.35% or up to 1.60% if carbon equivalents do not exceed 0.47%. For plate thicker than 40 mm (1 to 5 in.), ASTM A 841 specifies manganese contents of 1.00 to 1.60%.

ratio of HSLA steels compared with conventional low-carbon steels. This characteristic of HSLA steels has led to their increased use in automobile components. Table 2 describes mill forms, characteristics, and applications for selected HSLA steels.

Effects of Microalloying Additions

Emphasis in this section is placed on microalloyed ferrite-pearlite steels, which use additions of alloying elements such as niobium and vanadium to increase strength (and thereby increase load-carrying ability) of hot-rolled steel without increasing carbon and/or manganese contents. Extensive studies during the 1960s on the effects of niobium and vanadium on the properties of structural-grade materials resulted in the discovery that very small amounts of niobium and vanadium (<0.10% each) strengthen the standard carbon-manganese steels without interfering with subsequent processing. Carbon content thus could be reduced to improve both weldability and toughness because the strengthening effects of niobium and vanadium compensated for the reduction in strength due to the reduction in carbon content.

The mechanical properties of microalloyed HSLA steels result, however, from more than just the mere presence of microalloying elements. Austenite conditioning, which depends on the complex effects of alloy design and rolling techniques, is also an important factor in the grain refinement of hot-rolled HSLA steels. Grain refinement by austenite conditioning with controlled rolling methods has resulted in improved toughness and high yield strengths in the range of 345 to 620 MPa (50 to 90 ksi). This development of controlled-rolling processes coupled with alloy design has produced increasing yield strength levels accompanied by a gradual lowering of the carbon content. Many of the proprietary microalloyed HSLA steels have carbon contents as low as 0.06% or even lower, yet are still able to develop yield strengths of 485 MPa (70 ksi). The high yield strength is achieved by the combined effects of fine grain size developed during controlled hot rolling and precipitation strengthening that is due to the presence of vanadium, niobium, and titanium.

The various types of microalloyed ferrite-pearlite steels include:

- Vanadium-microalloyed steels
- Niobium-microalloyed steels
- Niobium-molybdenum steels
- Vanadium-niobium microalloyed steels
- Vanadium-nitrogen microalloyed steels
- Titanium-microalloyed steels
- Niobium-titanium microalloyed steels
- Vanadium-titanium microalloyed steels

Table 2 Summary of characteristics and intended uses of HSLA steels described in ASTM specifications

ASTM specification	Title	Alloying elements ^(a)	Available mill forms	Special characteristics	Intended uses
A 242	High-strength low-alloy structural steel	Cr, Cu, N, Ni, Si, Ti, V, Zr	Plate, bar, and shapes ≤100 mm (4 in.) in thickness	Atmospheric-corrosion resistance four times that of carbon steel	Structural members in welded, bolted, or riveted construction
A 572	High-strength low-alloy niobium-vanadium steels of structural quality	Nb, V, N	Plate, bar, shapes, and sheet piling ≤150 mm (6 in.) in thickness	Yield strengths of 290 to 450 MPa (42 to 65 ksi) in six grades	Welded, bolted, or riveted structures, but primarily welded bridges and buildings
A 588	High-strength low-alloy structural steel with 345 MPa (50 ksi) minimum yield point ≤100 mm (4 in.) in thickness	Nb, V, Cr, Ni, Mo, Cu, Si, Ti, Zr	Plate, bar, and shapes ≤200 mm (8 in.) in thickness	Atmospheric-corrosion resistance four times that of carbon steel; nine grades of similar strength	Welded, bolted, or riveted structures, but primarily welded bridges and buildings in which weight savings or added durability is important
A 606	Steel sheet and strip, hot-rolled and cold-rolled, high-strength low-alloy with improved corrosion resistance	Not specified	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion resistance twice that of carbon steel (type 2) or fourtimes that of carbon steel (type 4)	Structural and miscellaneous purposes for which weight savings or added durability is important
A 607	Steel sheet and strip, hot-rolled and cold-rolled, high strength low-alloy niobium and/or vanadium	Nb, V, N, Cu	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion resistance twice that of carbon steel, but only when copper content is specified; yield strengths of 310 to 485 MPa (45 to 70 ksi) in six grades	Structural and miscellaneous purposes for which greater strength or weight savings is important
A 618	Hot-formed welded and seamless high-strength low-alloy structural tubing	Nb, V, Si, Cu	Square, rectangular, round, and special-shape structural welded or seamless tubing	Three grades of similar yield strength; may be purchased with atmospheric-corrosion resistance twice that of carbon steel	General structural purposes, included welded, bolted, or riveted bridges and buildings
A 633	Normalized high-strength low-alloy structural steel	Nb, V, Cr, Ni, Mo, Cu, N, Si	Plate, bar, and shapes ≤150 mm (6 in.) in thickness	Enhanced notch toughness; yield strengths of 290 to 415 MPa (42 to 60 ksi) in five grades	Welded, bolted, or riveted structures for service at temperatures at or above -45 °C (-50 °F)
A 656	High-strength, low-alloy, hot-rolled structural vanadium-aluminum-nitrogen and titanium-aluminum steels	V, Al, N, Ti, Si	Plate, normally ≤16 mm (5/8 in.) in thickness	Yield strength of 552 MPa (80 ksi)	Truck frames, brackets, crane booms, rail cars, and other application for which weight savings is important
A 690	High-strength low-alloy steel H-piles and sheet piling	Ni, Cu, Si	Structural-quality H-piles and sheet piling	Corrosion resistance two to three times greater than that of carbon steel in the splash zone of marine structures	Dock walls, sea walls, bulkheads, excavations, and similar structures exposed to seawater

(a) In addition to carbon, manganese, phosphorus, and sulfur. A given grade may contain one or more of the listed elements, but not necessarily all of them; for specified compositional limits, see Table 1. (b) Obtained by producing killed steel, made to fine grain practice, and with microalloying elements such as niobium, vanadium, titanium, and zirconium in the composition

Table 2 (continued)

ASTM specification	Title	Alloying elements ^(a)	Available mill forms	Special characteristics	Intended uses
A 709, grade 50 and 50W	Structural steel	V, Nb, N, Cr, Ni, Mo	All structural-shape groups and plate ≤100 mm (4 in.) in thickness	Minimum yield strength of 345 MPa (50 ksi). Grade 50W is a weathering steel	Bridges
A 714	High-strength low-alloy welded and seamless steel pipe	V, Ni, Cr, Mo, Cu, Nb	Pipe with nominal pipe size diameters of 13 to 660 mm (1/2 to 26 in.)	Minimum yield strengths ≤345 MPa (50 ksi) and corrosion resistance two to four times that of carbon steel	Piping
A 715	Steel sheet and strip, hot-rolled, high-strength low-alloy with improved formability	Nb, V, Cr, Mo, N, Si, Ti, Zr, B	Hot-rolled sheet and strip	Improved formability(c) compared to A606 and A607; yield strengths of 345 to 550 MPa (50 to 80 ksi) in four grades	Structural and miscellaneous applications for which high strength, weight saving, improved formability, and good weldability are important
A 808	High-strength low-alloy steel with improved notch toughness	V, Nb	Hot-rolled steel plate ≤65 mm (2 1/2 in.) in thickness	Charpy V-notch impact energies of 40–60 J (30–45 ft.-lb) at –45 °C (–50 °F)	Railway tank cars
A 812	High-strength low-alloy steels	Y, Nb	Steel sheet in coil form	Yields strengths of 450–550 MPa (65–85 ksi)	Welded layered pressure vessels
A 841	Plate produced by thermomechanical controlled processes	V, Nb, Cr, Mo, Ni	Plates ≤100 mm (4 in.) in thickness	Yield strengths of 310–345 MPa (45–50 ksi)	Welded pressure vessels
A 847	Cold-formed welded and seamless high-strength low-alloy structural tubing with improved atmospheric-corrosion resistance	Cu, Cr, Ni, Si, V, Ti, Zr, Nb	Welded tubing with maximum periphery of 1625 mm (64 in.) and wall thickness of 16 mm (0.625 in.) or seamless tubing with maximum periphery of 810 mm (32 in.) and wall thickness of 13 mm (0.50 in.)	Minimum yield strengths ≤345 MPa (50 ksi) with atmospheric-corrosion resistance twice that of carbon	Round, square, or specially shaped structural tubing for welded, riveted, or bolted construction of bridges and buildings
A 860	High-strength butt-welding fittings of wrought high-strength low-alloy steel	Cu, Cr, Ni, Mo, V, Nb, Ti	Normalized or quenched-and-tempered wrought fittings	Minimum yield strengths ≤485 MPa (70 ksi)	High-pressure gas and oil transmission lines
A 871	High-strength low-alloy steel with atmospheric corrosion resistance	V, Nb, Ti, Cu, Mo, Cr	As-rolled plate ≤35 mm (1 3/8 in.) in thickness	Atmospheric-corrosion resistance four times that of carbon structural steel	Tubular structures and poles

(a) In addition to carbon, manganese, phosphorus, and sulfur. A given grade may contain one or more of the listed elements, but not necessarily all of them; for specified compositional limits, see Table 1. (b) Obtained by producing killed steel, made to fine grain practice, and with microalloying elements such as niobium, vanadium, titanium, and zirconium in the composition

These steels may also include other elements for improved corrosion resistance and solid-solution strengthening, or enhanced hardenability (if transformation products other than ferrite-pearlite are desired).

Vanadium Microalloyed Steels. The development of vanadium-containing steels occurred shortly after the development of weathering steels, and flat-rolled products with up to 0.10% V are widely used in the hot-rolled condition. Vanadium-containing steels are also used in the controlled-rolled, normalized, or quenched and tempered condition.

Vanadium contributes to strengthening by forming fine precipitate particles (5 to 100 nm in diameter) of V(CN) in ferrite during cooling after hot rolling. These vanadium precipitates, which are not as stable as niobium precipitates, are in solution at all normal rolling temperatures and thus are very dependent on the cooling rate for their formation. Niobium precipitates, however, are stable at higher temperatures, which is beneficial for achieving fine-grain ferrite (see the section “Niobium Microalloyed Steels” in this article).

The strengthening from vanadium averages between 5 and 15 MPa (0.7 and 2 ksi) per 0.01 wt% V, depending on carbon content and rate of cooling from hot rolling (and thus section thickness). The cooling rate, which is determined by the hot-rolling temperature and the section thickness, affects the level of precipitation strengthening in a 0.15% V steel, as shown in Fig. 1. An optimum level of precipitation strengthening occurs at a cooling rate of about 170 °C/min (306 °F/min) (Fig. 1). At cooling rates lower than 170 °C/min (306 °F/min), the V(CN) precipitates coarsen and are less effective for strengthening. At higher cooling rates, more V(CN) remains in solution, and thus a smaller fraction of V(CN) particles precipitate and strengthening is reduced. For a given section thickness and cooling medium, cooling rates can be increased or decreased by increasing or decreasing, respectively, the temperature before cooling. Increasing

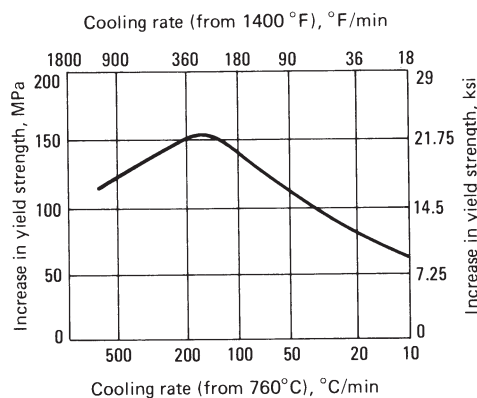


Fig. 1 Effect of cooling rate on the increase in yield strength due to precipitation strengthening in a 0.15% V steel

the temperature results in larger austenite grain sizes, while decreasing the temperature makes rolling more difficult.

Manganese content also affects the strengthening of vanadium microalloyed steels. The effect of manganese on a hot-rolled vanadium steel is shown in Table 3. The 0.9% increase in manganese content increased the strength of the matrix by 34 MPa (5 ksi) because of solid-solution strengthening. The precipitation strengthening by vanadium was also enhanced because manganese lowered the austenite-to-ferrite transformation temperature, thereby resulting in a finer precipitate dispersion. This effect of manganese on precipitation strengthening is greater than its effect in niobium steels. However, the absolute strength in a niobium steel with 1.2% Mn is only about 50 MPa (7 ksi) less than that of vanadium steel but at a much lower alloy level (that is, 0.06% Nb versus 0.14% V).

The third factor affecting the strength of vanadium steels is the ferrite grain size produced after cooling from the austenitizing temperature. Finer ferrite grain sizes (which result in not only higher yield strengths but also improved toughness and ductility) can be produced by either lower austenite-to-ferrite transformation temperatures or by the formation of finer austenite grain sizes prior to transformation. Lowering the transformation temperature, which affects the level of precipitation strengthening as mentioned above, can be achieved by alloy additions and/or increased cooling rates. For a given cooling rate, further refinement of ferrite grain size is achieved by the refinement of the austenite grain size during rolling.

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 (65 ksi). The practical limit of yield strengths for hot-rolled vanadium-microalloyed steel is about 415 MPa (60 ksi),

Table 3 Effect of manganese content on the precipitation strengthening of a vanadium-microalloyed steel with a base composition of 0.08% C and 0.30% Si

Vanadium content, %	Yield strength		Change in yield strength	
	MPa	ksi	MPa	ksi
0.3% Mn				
0.00	297	43	0	0
0.08	352	51	55	8
0.14	380	55	83	12
1.2% Mn				
0.00	331	48	0	0
0.08	462	67	131	19
0.14	552	80	221	32

even when controlled rolling techniques are used. Vanadium steels subjected to recrystallization controlled rolling require a titanium addition so that a fine precipitate of TiN is formed that restricts austenite grain growth after recrystallization. Yield strengths from conventional controlled rolling are limited to a practical limit of about 415 MPa (60 ksi) because of the lack of retardation of recrystallization. When both strength and impact toughness are important factors, controlled-rolled low-carbon niobium steel (such as X-60 hydrogen-induced cracking resistant plate) is preferable.

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 (Fig. 2). 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 (5 to 6 ksi) per 0.01% addition. This strengthening was accompanied by a considerable impairment of notch toughness until special rolling procedures were developed and carbon contents were lowered to avoid formation of upper bainite. In general, high finishing temperatures and light deformation passes should be avoided with niobium steels because that may result in mixed grain sizes or Widmanstätten ferrite, which impair toughness.

Niobium steels are produced by controlled rolling, recrystallization controlled rolling, accelerating cooling, and direct quenching. The recrystal-

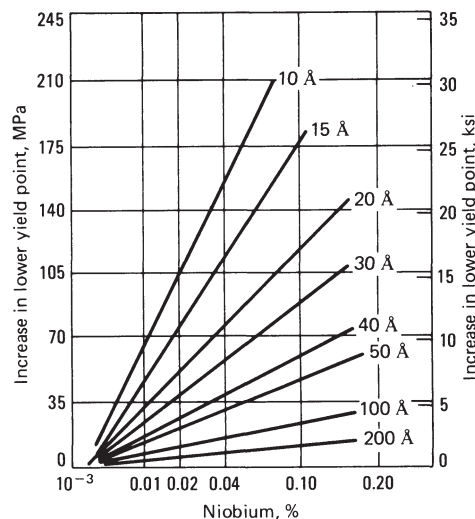


Fig. 2 Effect of niobium carbide on yield strength for various sizes of niobium carbide particles



ASM International is the society for materials engineers and scientists, a worldwide network dedicated to advancing industry, technology, and applications of metals and materials.

ASM International, Materials Park, Ohio, USA
www.asminternational.org

This publication is copyright © ASM International®. All rights reserved.

Publication title	Product code
Alloying: Understanding the Basics	#06117G

To order products from ASM International:

Online Visit www.asminternational.org/bookstore

Telephone 1-800-336-5152 (US) or 1-440-338-5151 (Outside US)

Fax 1-440-338-4634

Mail Customer Service, ASM International
9639 Kinsman Rd, Materials Park, Ohio 44073-0002, USA

Email CustomerService@asminternational.org

In Europe American Technical Publishers Ltd.
27-29 Knowl Piece, Wilbury Way, Hitchin Hertfordshire SG4 0SX,
United Kingdom
Telephone: 01462 437933 (account holders), 01462 431525 (credit card)
www.ameritech.co.uk

In Japan Neutrino Inc.
Takahashi Bldg., 44-3 Fuda 1-chome, Chofu-Shi, Tokyo 182 Japan
Telephone: 81 (0) 424 84 5550

Terms of Use. This publication is being made available in PDF format as a benefit to members and customers of ASM International. You may download and print a copy of this publication for your personal use only. Other use and distribution is prohibited without the express written permission of ASM International.

No warranties, express or implied, including, without limitation, warranties of merchantability or fitness for a particular purpose, are given in connection with this publication. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this publication shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this publication shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.