High-Strength Structural and High-Strength Low-Alloy Steels

HIGH-STRENGTH carbon and low-alloy steels have yield strengths greater than 275 MPa (40 ksi) and can be more or less divided into four classifications:

- As-rolled carbon-manganese steels
- As-rolled high-strength low-alloy (HSLA) steels (which are also known as microalloyed steels)
- Heat-treated (normalized or quenched and tempered) carbon steels
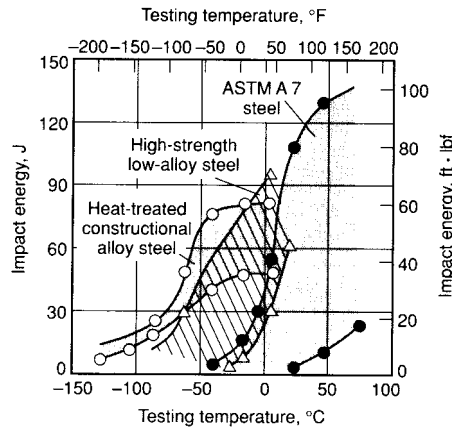- Heat-treated low-alloy steels

These four types of steels have higher yield strengths than mild carbon steel in the as-hot-rolled condition (Table 1). The heat-treated low-alloy steels and the as-rolled HSLA steels also provide lower ductile-to-brittle transition temperatures than do carbon steels (Fig. 1).

Table 1 General comparison of mild (low-carbon) steel with various high-strength steels

Steel	C (max)	Chemical composition, %(a)			Minimum yield strength		Minimum tensile strength		Minimum ductility (elongation in 50 mm, or 2 in.), %
		Mn	Si	Other	MPa	ksi	MPa	ksi	
Low-carbon steel	0.29	0.60–1.35	0.15–0.40	(b)	170–250	25–36	310–415	45–60	23–30
As-hot rolled carbon-manganese steel	0.40	1.00–1.65	0.15–0.40	...	250–400	36–58	415–690	60–100	15–20
HSLA steel	0.08	1.30 max	0.15–0.40	0.20 Nb or 0.05 V	275–450	40–65	415–550	60–80	18–24
Heat-treated carbon steel									
ÃNormalized(b)	0.36	0.90 max	0.15–0.40	...	200	29	415	60	24
ÃQuenched and tempered	0.20	1.50 max	0.15–0.30	0.0005 B min	550–690	80–100	660–760	95–110	18
Quenched and tempered low-alloy steel	0.21	0.45–0.70	0.20–0.35	0.45–0.65 Mo, 0.001–0.005 B	620–690	90–100	720–800	105–115	17–18

(a) Typical compositions include 0.04% P (max) and 0.05% S (max). (b) If copper is specified, the minimum is 0.20%.

Fig. 1 General comparison of Charpy V-notch toughness for a mild-carbon steel (ASTM A 7, now ASTM A 283, grade D), an HSLA steel, and a heat-treated constructional alloy steel

These four types of high-strength steels have some basic differences in mechanical properties and available product forms. In terms of mechanical properties, the heat-treated (quenched and tempered) low-alloy steels offer the best combination of strength (Table 1) and toughness (Fig. 1). However, these steels are available primarily as bar and plate products and only occasionally as sheet and structural shapes. In particular, structural shapes (I-beams, channels, wide-flanged beams, or special sections) can be difficult to produce in the quenched and tempered condition because shape warpage can occur during quenching. Heat treating steels is also a more involved process than the production of as-rolled steels, which is one reason the as-rolled HSLA steels are an attractive alternative. The as-rolled HSLA steels are also commonly available in all the standard wrought product forms (sheet, strip, bar, plate, and structural shapes).

This article considers four types of high-strength structural steel (which is defined here as those steels with yield strengths greater than 275 MPa, or 40 ksi): high-strength carbon steel, carbon-manganese steel, quenched and tempered low-alloy steel, and HSLA steel. Particular emphasis is placed on HSLA steels, which are an attractive alternative in structural applications because of their competitive price-per-yield strength ratios (generally, HSLA steels are priced from the base price of carbon steels but have higher yield strengths than as-rolled carbon steels). High-strength steels are used to reduce section sizes for a given design load, which allows weight savings. Reductions in section size may also be beneficial in obtaining the desired strength level during the production of structural steel. Whether steels are furnished in the as-hot-rolled or heat-treated condition, the strength levels tend to decrease as section size increases. In as-hot-rolled or normalized steel, this results from the coarser microstructure (larger grains and coarser pearlite) that develops from the slower cooling rates on the rolling mill for the thicker sections. In quenched and tempered steels, the lower strengths result because the transformation temperature increases as section thickness increases and the amount of martensite (the strongest microstructural constituent) progressively decreases. Thus, as the section size increases, it becomes more difficult to obtain the strength levels characteristic of a particular alloy.

Structural Carbon Steels

Structural carbon steels include mild steels, hot-rolled carbon-manganese steels, and heat-treated carbon steels. Mild steels and carbon-manganese steels are available in all the standard wrought forms: sheet, strip, plate, structural shapes, bar, bar-size shapes, and special sections. The heat-treated grades are available as plate, bar, and, occasionally, sheet and structural shapes.

Mild (low-carbon) steels are normally considered to have carbon contents up to 0.25% C with about 0.4 to 0.7% Mn, 0.1 to 0.5% Si, and some residuals of sulfur, phosphorus, and other elements. These steels are not deliberately strengthened by alloying elements other than carbon; they contain some manganese for sulfur stabilization and silicon for deoxidation. Mild steels are mostly used in the as-rolled, forged, or annealed condition and are seldom quenched and tempered.

The largest category of mild steels is the low-carbon (<0.08% C, with ≤0.4% Mn) mild steels used for forming and packaging. Mild steels with higher carbon and manganese contents have also been used for structural products such as plate, sheet, bar, and structural sections. Typical examples include:

| Steel	Minimum yield strength	
	MPa	ksi
Hot-rolled SAE 1010 steel sheet	207	30
ASTM A 283, grade D	228	33
ASTM A 36	250	36

Before the advent of HSLA steels, these mild steels were commonly used for the structural parts of automobiles, bridges, and buildings. In automotive applications, for example, hot-rolled SAE 1010 sheet has long been used as a structural steel. However, as lighter weight automobiles became more desirable during the energy crisis, there was a trend to reduce weight by using higher-strength steels with suitable ductility for forming operations.

The trend for structural steels used in the construction of bridges and buildings has also been away from mild steels and toward HSLA steels. For many years, ASTM A 7 (now ASTM A 283, grade D) was widely used as structural steel. In about 1960,

improved steelmaking methods resulted in the introduction of ASTM A 36, with improved weldability and slightly higher yield strength. Now, however, HSLA steels often provide a superior substitute for ASTM A 36, because HSLA steels provide higher yield strengths without adverse effects on weldability. Weathering HSLA steels also provide better atmospheric corrosion resistance than carbon steel.

Hot-Rolled Carbon-Manganese Structural Steels. For rolled structural plate and sections, one of the earliest approaches in achieving higher strengths involved the use of higher manganese contents. Manganese is a mild solid-solution strengthener in ferrite and is the principal strengthening element when it is present in amounts over 1% in rolled low-carbon (<0.20% C) steels. Manganese can also improve toughness properties (Fig. 2 b).

Fig. 2 Effect of (a) normalizing and (b) manganese content on the Charpy V-notch impact energy of normalized carbon steels. (a) Impact energy and transition temperature of 1040 steel pipe, deoxidized with aluminum and silicon. (b) Charpy V-notch impact energy for normalized 0.30% C steels containing various amounts of manganese

(a)

(b)
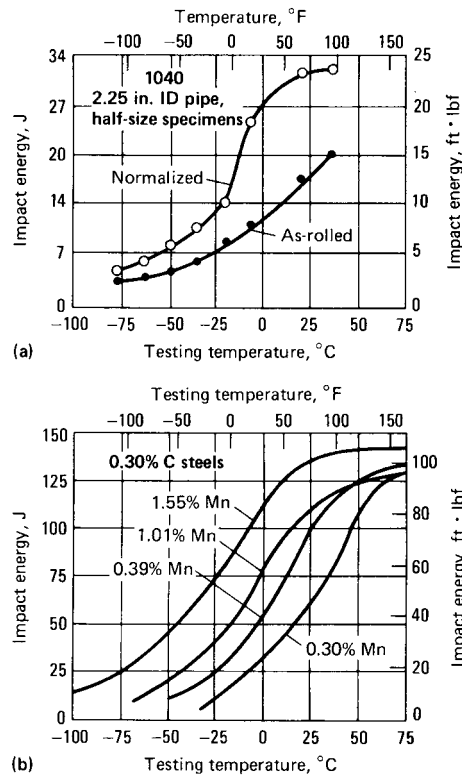
Before World War II, strength in hot-rolled structural steels was achieved by the addition of carbon up to 0.4% and manganese up to 1.5%, giving yield strengths of the order of 350 to 400 MPa (50 to 58 ksi). The strengthening of these steels relies primarily on the increase in carbon content, which results in greater amounts of pearlite in the microstructure and thus higher tensile strengths. However, the high carbon contents of these steels greatly reduces notch toughness and weldability. Moreover, the increase of pearlite contents in hot-rolled carbon and alloy steels has little effect on yield strength, which, rather than tensile strength, has increasingly become the main strength criterion in structural design.

Nevertheless, carbon-manganese steels with suitable carbon contents are used in a variety of applications. Table 2 lists some high-strength carbon-manganese structural steels in the as-hot-rolled condition. If structural plate or shapes with improved toughness are required, small amounts of aluminum are added for grain refinement. Carbon-manganese steels are also used for stampings, forgings, seamless tubes, and boiler plates. Some of these steels are described according to product form in previous articles of this Volume.

Table 2 Typical compositions, tensile properties, and product sizes of high-strength structural carbon steels

Specification and grade or class	Product form	Product thickness(a)		Heat analysis composition, % (b)				Yield strength		Tensile strength		Elongation in 200 mm (8 in.), %
		mm	in.	Carbon	Manganese	Silicon	Copper	MPa	ksi	MPa	ksi	
As-hot-rolled carbon-manganese steels												
ASTM A 529	Bar, plate, and shapes	13	$\frac{1}{2}$	0.27	1.20	...	0.20(c)	290	42	415–585	60–85	19

Specification	Product form			C	Mn	P	S	MPa	ksi	MPa	ksi	El, %
ASTM A 612	Plate	13	$\frac{1}{2}$	0.25	1.00–1.35	0.15–0.40	0.35	345	50	570–725	83–165	16
		20	$\frac{3}{4}$	0.25	1.00–1.35	0.15–0.40	0.35	345	50	560–695	81–101	16
		20–25	$\frac{3}{4}$–1	0.25	1.00–1.50	0.15–0.50	0.35	345	50	560–695	81–101	16
ASTM A 570 grades 45, 50, 55	Sheet	6	0.229	0.25	1.35	...	0.20(c)	310–380	45–55	415–480	60–70	14–10
ASTM A 662, grade B	Plate	40	$1\frac{1}{2}$	0.19	0.85–1.50	0.15–0.40	...	275	40	450–585	65–85	20
ASTM A 662, grade C	Plate	40	$1\frac{1}{2}$	0.20	1.00–1.60	0.15–0.50	...	295	43	485–620	70–90	18
SAE J410, grade 945C	Sheet and strip	...	...	0.23	1.40	...	...	310	45	415	60	...
	Plate, bar, and shapes	13	$\frac{1}{2}$	0.23	1.40	...	...	310	45	450	65	18
	Plate, bar, and shapes	13–40	$\frac{1}{2}$–$1\frac{1}{2}$	0.23	1.40	...	...	290	42	427	62	19
	Plate, bar, and shapes	40–75	$1\frac{1}{2}$–3	0.23	1.40	...	...	275	40	427	62	19
SAE J410, grade 950C	Sheet and strip	...	...	0.25	1.60	...	...	345	50	483	70	...
	Plate, bar, and shapes	13	$\frac{1}{2}$	0.25	1.60	...	...	345	50	483	70	18
	Plate, bar, and shapes	13–40	$\frac{1}{2}$–$1\frac{1}{2}$	0.25	1.60	...	...	310	45	462	67	19
	Plate, bar, and shapes	40–75	$1\frac{1}{2}$–3	0.25	1.60	...	...	290	42	434	63	19
Normalized structural carbon-manganese steels												
ASTM A 537, class 1	Plate	40	$1\frac{1}{2}$	0.24	0.70–1.35	0.15–0.50	0.35	345	50	485–620	70–90	18
	Plate	40–65	$1\frac{1}{2}$–$2\frac{1}{2}$	0.24	1.00–1.60	0.15–0.50	0.35	345	50	485–620	70–90	18
	Plate	65–100	$2\frac{1}{2}$–4	0.24	1.0–1.60	0.15–0.50	0.35	310	45	450–585	65–85	18
ASTM A 612	Plate	Same as ASTM A 612 in the as-rolled condition, but can be normalized for improved impact toughness										
ASTM A 633, grade A	Plate	100	4	0.18	1.00–1.35	0.15–0.50	...	290	42	430–570	63–83	18
ASTM A 662, grade A	Plate	40–50	$1\frac{1}{2}$–2	0.14	0.90–1.35	0.15–0.40	...	275	40	400–540	58–78	20
ASTM A 662, grade B	Plate	40–50	$1\frac{1}{2}$–2	0.19	0.85–1.50	0.15–0.40	...	275	40	450–585	65–85	20
ASTM A 662, grade C	Plate	40–50	$1\frac{1}{2}$–2	0.20	1.00–1.60	0.15–0.50	...	295	43	485–620	70–90	18
ASTM A 738, grade A	Plate	65(d)	2.5(d)	0.24	1.50(d)	0.15–0.50	0.35	310	45	515–655	75–95	20(e)
ASTM A 737, grade B	Plate	100	4	0.20	1.15–1.50	0.15–0.50	...	345	50	485–620	70–90	18
Quenched and tempered structural carbon-manganese steels												
SAE J 368, grade Q980	Plate	20	$\frac{3}{4}$	0.20	1.35	...	...	550	80	655–795	95–115	18(e)
ASTM A 537, class 2	Plate	40	$1\frac{1}{2}$	0.24	0.70–1.35	0.15–0.50	0.35	415	60	550–690	80–100	22(e)
		40–65	$1\frac{1}{2}$–$2\frac{1}{2}$	0.24	1.00–1.60	0.15–0.50	0.35	415	60	550–690	80–100	22(e)
		65–10	$2\frac{1}{2}$–	0.24	1.00–1.60	0.15–0.	0.35	380	55	515–65	75–95	22(e)

		0	4			50				5		
		100–150	4–6	0.24	1.00–1.60	0.15–0.50	0.35	315	46	485–620	70–90	22(e)
ASTM A 678, grade A	Plate	40	1½	0.16	0.90–1.50	0.15–0.50	0.20(c)	345	50	485–620	70–90	22(e)
ASTM A 678, grade B	Plate	40	1½	0.20	0.70–1.35	0.15–0.50	0.20(c)	415	60	550–690	80–100	22(e)
		40–65	1½–2½	0.20	1.00–1.60	0.15–0.50	0.20(c)	415	60	550–690	80–100	22(e)
ASTM A 678, grade C	Plate	20	¾	0.22	1.00–1.60	0.20–0.50	0.20(c)	515	75	655–790	95–115	19(e)
		20–40	¾–1½	0.22	1.00–1.60	0.20–0.50	0.20(c)	485	70	620–760	90–110	19(e)
		40–50	1½–2	0.22	1.00–1.60	0.20–0.50	0.20(c)	450	65	585–720	85–105	19(e)
ASTM A 738, grade B	Plate	65	2.5	0.20	0.90–1.50	0.15–0.50	0.35	415	60	585–705	85–102	20(e)
ASTM A 738, grade C	Plate	65	2.5	0.20	1.50	0.15–0.50	0.35	415	60	550–690	80–100	22(e)
		65–100	2.5–4	0.20	1.62	0.15–0.50	0.35	380	55	515–655	75–95	22(e)
		100–150	4–6	0.20	1.62	0.15–0.50	0.35	315	46	485–620	70–90	20(e)

(a) Product thicknesses are a maximum unless a range is given. (b) Compositions are a maximum unless a range is given or if otherwise specified in footnotes. Residual amounts of sulfur and phosphorus are limited in all grades and have specified maximums of 0.035 to 0.04% P (max) and 0.04 to 0.05% S (max), depending on the specifications. (c) Minimum amount of copper if specified. (d) Over 65 mm (2.5 in.), ASTM A 738 grade A requires quenching and tempering and 1.62% Mn (max) to achieve the specified strength levels. (e) Elongation in 50 mm (2 in.).

High-strength structural carbon steels have yield strengths greater than 275 MPa (40 ksi) and are available in various product forms:

- Cold-rolled structural sheet
- Hot-rolled carbon-manganese steels in the form of sheet, plate, bar, and structural shapes
- Heat-treated (normalized or quenched and tempered) carbon steels in the form of plate, bar, and occasionally, sheet and structural shapes

This section focuses on the heat-treated carbon structural steels, which typically attain yield strengths of 290 to 690 MPa (42 to 100 ksi). Cold-rolled carbon steel sheet with yield strengths greater than 275 MPa (40 ksi) are discussed in the article "Carbon and Low-Alloy Steel Sheet and Strip" in this Volume. High-strength carbon-manganese steels in the as-hot-rolled condition are discussed in the previous section of this article.

The heat treatment of carbon steels consists of either normalizing or quenching and tempering. These heat treatments can be used to improve the mechanical properties of structural plate, bar, and occasionally, structural shapes. Structural shapes (such as I-beams, channels, wide-flange beams, and special sections) are primarily used in the as-hot-rolled condition because warpage is difficult to prevent during heat treatment. Nevertheless, some normalized or quenched and tempered structural sections can be produced in a limited number of section sizes by some manufacturers.

Normalizing involves air cooling from austenitizing temperatures and produces essentially the same ferrite-pearlite microstructure as that of hot-rolled carbon steel, except that the heat treatment produces a finer grain size. This grain refinement makes the steel stronger, tougher, and more uniform throughout. Typical product forms and tensile properties of normalized carbon structural steels are given in Table 2 . Charpy V-notch impact energies at various temperatures are given in Fig. 2 (b) for a normalized carbon steel with varying manganese contents.

Quenching and tempering, that is, heating to about 900 °C (1650 °F), water quenching, and tempering at temperatures of 480 to 600 °C (900 to 1100 °F) or higher, can provide a tempered martensitic or bainitic microstructure that results in better combinations of strength and toughness. An increase in the carbon content to about 0.5%, usually accompanied by an increase in manganese, allows the steels to be used in the quenched and tempered condition. For quenched and tempered carbon-manganese steels with carbon contents up to about 0.25% (Table 2), low hardenability restricts the section sizes to about 150 mm (6 in.).

The yield strength of quenched and tempered carbon-manganese steel plate varies from 315 to 550 MPa (46 to 80 ksi), depending on section thickness (Table 2). Minimum Charpy V-notch impact toughness may be as high as 27 to 34 J (20 to 25 ft · lbf) at temperatures as low as −68 °C (−90 °F) for quenched and tempered carbon steel having yield strengths of 345 MPa (50

ksi). However, for quenched and tempered carbon steel with 690 MPa (100 ksi) yield strengths (Table 1), the impact values are lower, normally about 20 J (15 ft · lbf) at −60 °C (−75 °F). All grades can be grain refined with aluminum to improve toughness.

In addition to high-strength plate applications, quenched and tempered carbon-manganese steels are used for shafts and couplings. Steels with 0.40 to 0.60% C are used for railway wheels, tires, and axles, while those with higher carbon contents can be used as high-strength wire laminated spring materials, often with silicon-manganese or chromium-vanadium additions. The higher-carbon steels are also used for rails (0.7% C) and, over a range of carbon contents (typically, 0.20−0.50% C), for reinforcing bar.

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 minimums 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%.

Except for plain carbon steels that are microalloyed with just vanadium, niobium, and/or titanium (see the section "Microalloyed Quenched and Tempered Grades" in this article), 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. However, as the alloy contents increase, alloy steels become more expensive and more difficult to weld. Quenched and tempered structural steels are primarily available in the form of plate or bar products.

Alloying Elements and Their Effect on Hardenability and Tempering. Quenched and tempered steels have carbon contents in the range of 0.10 to 0.45%, with alloy contents, either singly or in combination, of up to 1.5% Mn, 5% Ni, 3% Cr, 1% Mo, 0.5% V, 0.10% Nb; in some cases they contain small additions of titanium, zirconium and/or boron. Generally the higher the alloy content, the greater the hardenability, and the higher the carbon content, the greater the available strength. Some typical compositions of quenched and tempered low-alloy steel plate are shown in Table 3 . The response to heat treatment is the most important function of the alloying elements in these steels.

Table 3 Typical compositions of quenched and tempered low-alloy steel plate

Additional grades can be found in the article "Carbon and Low-Alloy Steel Plate" in this Volume.

Specification or common designation	Grade, type, or class	Compositions, % (a)									
		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Others
SAE J368a	Q980B	0.20	1.50	0.04	0.05	...	...	...	...	...	0.0005 B, min
	Q990B	0.20	1.50	0.04	0.05	...	...	...	...	...	0.0005 B, min
	Q9100B	0.20	1.50	0.04	0.05	...	...	...	...	...	0.005 B, min
ASTM A 514 or A 517	A	0.15−0.21	0.80−1.10	0.035	0.04	0.40−0.80	0.50−0.80	...	0.18−0.28	...	0.05−0.15 Zr, 0.0025 B
	B	0.12−0.21	0.70−1.00	0.035	0.04	0.20−0.35	0.40−0.65	...	0.15−0.25	...	0.03−0.08 V, 0.01−0.03 Ti, 0.0005−0.005 B
	C	0.10−0.20	1.10−1.50	0.035	0.04	0.15−0.30	...	...	0.20−0.30	...	0.001−0.005 B
	E	0.12−0.20	0.40−0.70	0.035	0.04	0.20−0.35	1.40−2.00	...	0.40−0.60	0.20−0.40	0.04−0.10 Ti(b), 0.0015−0.005 B
	F	0.10−0.20	0.60−1.00	0.035	0.04	0.15−0.35	0.40−0.65	0.70−1.00	0.40−0.60	0.15−0.50	0.03−0.08 V
ASTM A 533	A	0.25	1.15−1.50	0.035	0.040	0.15−0.30	...	...	0.45−0.60	...	...
	B	0.25	1.15−1.50	0.035	0.040	0.15−0.30	...	0.40−0.70	0.45−0.60	...	...
	C	0.25	1.15−1.50	0.035	0.040	0.15−0.30	...	0.70−1.00	0.45−0.60	...	...
	D	0.25	1.15−1.	0.035	0.040	0.15−0.30	...	0.20−0.40	0.45−0.60	...	...

			50								
ASTM A 543	B	0.23	0.40	0.020	0.020	0.20–0.40	1.50–2.00	2.60–4.00 (c)	0.45–0.60	...	0.03 V
	C	0.23	0.40	0.020	0.020	0.20–0.40	1.20–1.50	2.25–3.50	0.45–0.60	...	0.03 V
ASTM A 678	D	0.22	1.15–1.50	0.04	0.05	0.15–0.50	...	...	...	0.20(d)	0.04–0.11 V(e)
ASTM A 709	70W	0.19	0.80–1.35	0.04	0.05	0.20–0.65	0.40–0.70	0.50	...	0.25–0.40	0.02–0.10 V
ASTM A 709, grades 100 and 100W, Type	A	0.15–0.21	0.80–1.10	0.035	0.04	0.40–0.80	0.50–0.80	...	0.18–0.28	...	0.05–0.15 Zr, 0.0025 B (min)
	B	0.12–0.21	0.70–1.00	0.035	0.04	0.20–0.35	0.40–0.65	...	0.15–0.25	...	0.03–0.08 V, 0.01–0.03 Ti
	C	0.10–0.20	1.10–1.50	0.035	0.04	0.15–0.30	...	...	0.20–0.30	...	0.0005–0.005 B 0.001–0.005 B
	E	0.12–0.20	0.40–0.70	0.035	0.04	0.20–0.40	1.40–2.00	...	0.40–0.60	...	0.04–0.10 Ti(b), 0.001–0.005 B
	F	0.10–0.20	0.60–1.00	0.035	0.04	0.15–0.35	0.40–0.65	0.70–1.00	0.40–0.60	0.15–0.50	0.03–0.08 V, 0.0005–0.006 B
	H	0.12–0.21	0.95–1.30	0.035	0.04	0.20–0.35	0.40–0.65	0.30–0.70	0.20–0.30	...	0.03–0.08 V, 0.0005–0.005 B
	J	0.12–0.21	0.45–0.70	0.035	0.04	0.04–0.20	...	...	0.50–0.65	...	0.001–0.005 B
	M	0.12–0.21	0.45–0.70	0.035	0.04	0.04–0.20	...	1.20–1.50	0.45–0.65	...	0.001–0.005 B
	P	0.12–0.21	0.45–0.70	0.035	0.04	0.04–0.20	0.85–1.20	1.20–1.50	0.45–0.65	...	0.001–0.005 B
HY-80	...	0.12–0.18	0.10–0.40	0.025	0.025	0.15–0.35	1.00–1.80	2.00–3.25	0.20–0.60	0.25	0.03 V, 0.02 Ti
HY-100	...	0.12–0.20	0.10–0.40	0.025	0.025	0.15–0.35	1.00–1.80	2.25–3.50	0.20–0.60	0.25	0.03 V, 0.02 Ti
HY-130	...	0.12	0.60–0.90	0.010	0.015	0.15–0.35	0.40–0.70	4.75–5.25	0.30–0.65	...	0.05–0.10 V

(a) When a single value is shown, it is a maximum limit. (b) Vanadium may be substituted for part or all of the titanium content on a one-for-one basis. (c) Limiting values vary with plate thickness. (d) Minimum when specified. (e) Niobium may be present in ASTM A 678, grade D, in the amount of 0.01 to 0.05%.

Steel on Hardenability. The hardenability of a steel is the property that determines the depth and distribution of martensite induced by quenching. It is usually the single most important criterion for selecting a low-alloy steel. To ensure adequate hardenability, the alloys must be in solution in austenite so that they retard the diffusion-controlled transformation of austenite to ferrite-pearlite. This allows the slower cooling of a piece or the quenching of a larger piece in a given medium without subsequent transformation of austenite to undesirable ferrite-pearlite transformation products.

Hardenability is measured in terms of an ideal diameter (D_I), which facilitates the comparison of the hardening response of different steels to the same quenching medium. The ideal diameter, D_I, is affected by austenite grain size, carbon content, and alloy content; an increase in any of these factors reduces or eliminates diffusion-controlled transformations, thereby encouraging the formation of martensite. Carbon is the most potent alloy for increasing hardenability, but it can be undesirable in structural steels because of its adverse effects on weldability and toughness. The other two factors, grain size and alloy elements, are considered below and in the article "Hardenability of Carbon and Low-Alloy Steels" in this Volume.

Austenite grain size influences not only hardenability but also strength and toughness. Increases in austenite grain size reduce the strength of a given transformation product (see Fig. 3(b) for martensitic transformation products, for example), but these increases do allow hardening to a greater depth than fine-grained steels, all other factors being equal. For steels in which pearlite (or ferrite) limits the hardenability of the steel, a useful diagram relating grain size (ASTM grain size number) to ideal critical diameter (D_I) in steels was developed by Grossmann in 1952 and is shown in Fig. 3(a) . For such steels, the influence of grain size can be considered independent of the steel composition. For alloy steels in which bainite, rather than pearlite, is the dominant structure limiting full hardening, the effect of austenitic grain size is not the same. Low-carbon (0.06%) bainites may not be greatly affected by prior-austenite grain size. Although a larger grain size improves hardenability, increases in grain size increase the possibility of quench cracking. The small effect of prior-austenite grain size on the strength of martensite is shown in Fig. 3(b) for two alloy steels. Larger grain size can also degrade toughness, although avoiding proeutectoid ferrite is the overriding

concern in the maintenance of notch toughness.

Fig. 3(a) Diagram showing direct relationship between ASTM grain size number and hardenability. For a grain size increment of one ASTM grain size number, multiply by 1.083. For a grain size increase of two ASTM size numbers, multiply by 1.172. For an increased grain size of three ASTM size numbers, multiply by 1.270. Source: Ref 1
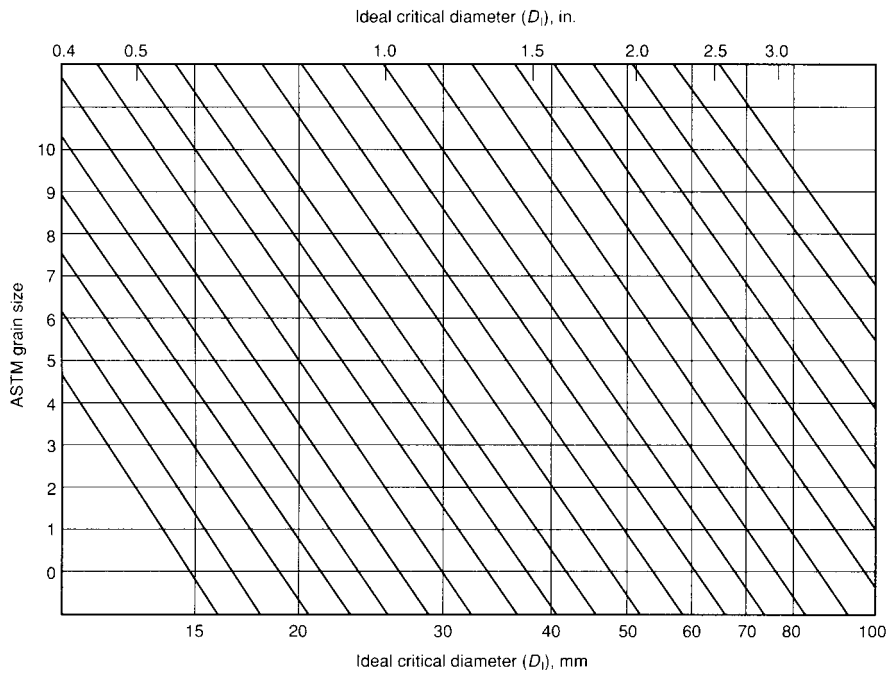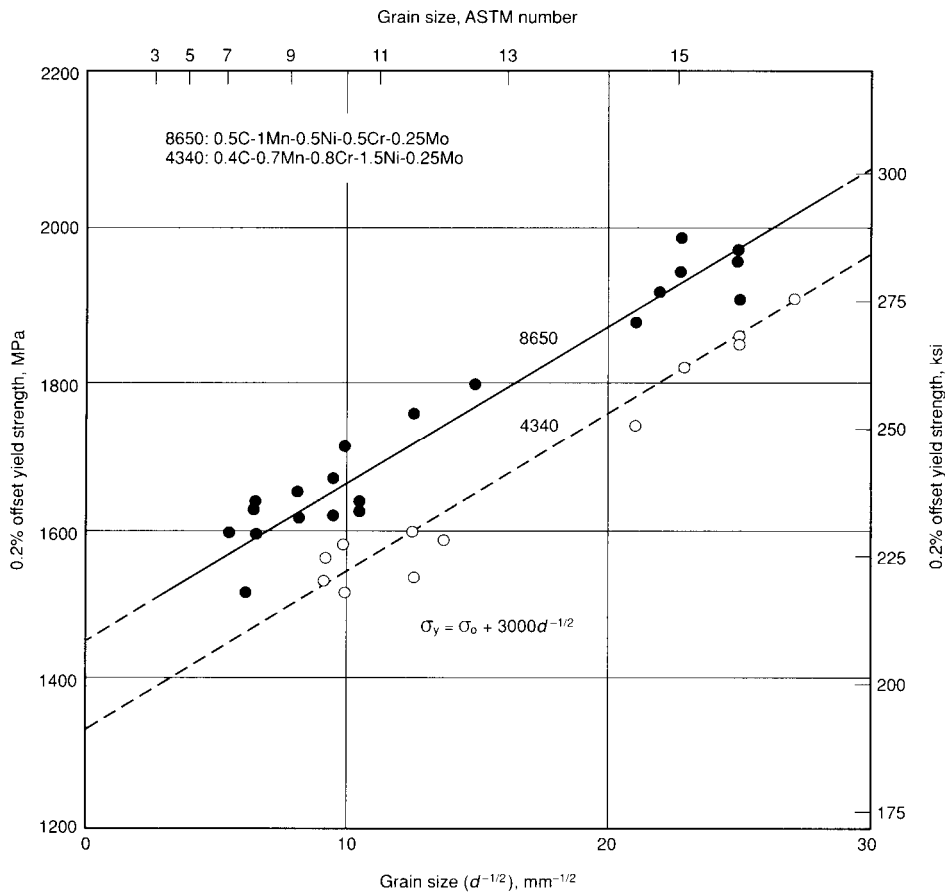

Fig. 3(b) Effect of prior-austenite grain size on the strength of martensite. Source: Ref 2

8650: 0.5C-1Mn-0.5Ni-0.5Cr-0.25Mo
4340: 0.4C-0.7Mn-0.8Cr-1.5Ni-0.25Mo

$$\sigma_y = \sigma_o + 3000 d^{-1/2}$$

The effect of alloying elements on hardenability was shown by Grossmann in 1942 to be a multiplicative effect rather than an additive effect. During subsequent research, multiplying factors were developed with the realization that at times interaction effects occured (that is, the multiplying factor for a given percentage of an element was not the same when added in conjunction with another element as it was when the element was used alone). For example, the multiplying factor for molybdenum varies with nickel content (Fig. 4). Also, there is a different set of multiplying factors for low-carbon alloys than for medium-carbon alloys. Because of this, Fig. 4 provides multiplying factors for steels having carbon contents similar to those shown in Table 3 .

Fig. 4 Average multiplying factors for several elements in alloy steels containing 0.15 to 0.25% C. Source: Ref 1
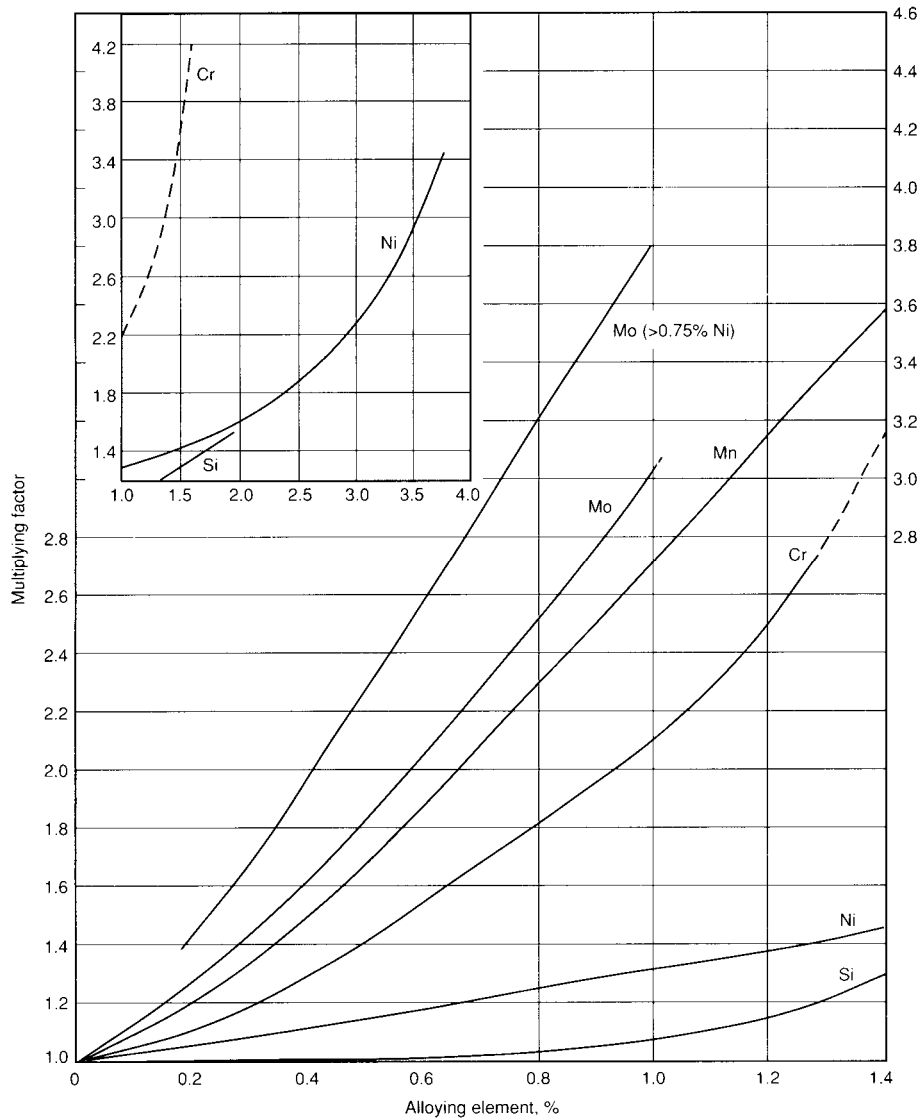
Some other interaction effects of alloying elements on hardenability are shown in Table 4 . In general, alloying elements can be separated according to whether they are austenite stabilizers, such as manganese, nickel, and copper, or ferrite stabilizers (for example, γ-loop formers), such as molybdenum, silicon, titanium, vanadium, zirconium, tungsten, and niobium (Ref 4). Ferrite stabilizers require a much lower alloying addition than the austenite stabilizers for an equivalent increase in hardenability. However, with many of these ferrite stabilizers the competing process of carbide precipitation in the austenite depletes the austenite of both carbon and alloy addition, thus lowering hardenability. The precipitates also produce grain refinement, which further decreases hardenability.

Table 4 Effects of alloy elements on the heat treatment of quenched and tempered alloy steels

Effect of alloy on hardenability during quenching	Effect of alloy on tempering
Manganese contributes markedly to hardenability, especially in amounts greater than 0.8%. The effect of manganese up to 1.0% is stronger in low- and high-carbon steels than in medium-carbon steels.	Manganese increases the hardness of tempered martensite by retarding the coalescence of carbides, which prevent grain growth in the ferrite matrix. These effects cause a substantial increase in the hardness of tempered martensite as the percentage of manganese in the steel increases.

|	
Nickel is similar to manganese at low alloy additions, but is less potent at the high alloy levels. Nickel is also affected by carbon content, the medium-carbon steels having the greatest effect. There is an alloy interaction between manganese and nickel that must be taken into account at lower austenitizing temperatures.	Nickel has a relatively small effect on the hardness of tempered martensite, which is essentially the same at all tempering temperatures. Because nickel is not a carbide former, its influence is considered to be due to a weak solid-solution strengthening.
Copper is usually added to alloy steels for its contribution to atmospheric-corrosion resistance and at higher levels for precipitation hardening. The effect of copper on hardenability is similar to that of nickel, and in hardenability calculations it has been suggested that the sum of copper plus nickel be used with the appropriate multiplying factor of nickel.	Copper is precipitated out when steel is heated to about 425–650 °C (800–1200 °F) and thus can provide a degree of precipitation hardening.
Silicon is more effective than manganese at low alloy levels and has a strengthening effect on low-alloy steels. However, at levels greater than 1% this element is much less effective than manganese. The effect of silicon also varies considerably with carbon content and other alloys present. Silicon is relatively ineffective in low-carbon steel but is very effective in high-carbon steels.	Silicon increases the hardness of tempered martensite at all tempering temperatures. Silicon also has a substantial retarding effect on softening at 316 °C (600 °F), and has been attributed to the inhibiting effect of silicon on the conversion of ε-carbide to cementite(a).
Molybdenum is most effective in improving hardenability. Molybdenum has a much greater effect in high-carbon steels than in medium-carbon steels. The presence of chromium decreases the multiplying factor, whereas the presence of nickel enhances the hardenability effect of molybdenum(b).	Molybdenum retards the softening of martensite at all tempering temperatures. Above 540 °C (1000 °F), molybdenum partitions to the carbide phase and thus keeps the carbide particles small and numerous. In addition, molybdenum reduces susceptibility to tempering embrittlement.
Chromium behaves much like molybdenum and has its greatest effect in medium-carbon steels. In low-carbon steel and carburized steel, the effect is less than in medium-carbon steels, but is still significant. As a result of the stability of chromium carbide at lower austenitizing temperatures, chromium becomes less effective.	Chromium, like molybdenum, is a strong carbide-forming element that can be expected to retard the softening of martensite at all temperatures. Also, by substituting chromium for some of the iron in cementite, the coalescence of carbides is retarded.
Vanadium is usually not added for hardenability in quenched and tempered structural steels (such as ASTM A 678, grade D) but is added to provide secondary hardening during tempering. Vanadium is a strong carbide former, and the steel must be austenitized at a sufficiently high temperature and for a sufficient length of time to ensure that the vanadium is in solution and thus able to contribute to hardenability. Moreover, solution is possible only if small amounts of vanadium are added (c).	Vanadium is a stronger carbide former than molybdenum and chromium and can therefore be expected to have a much more potent effect at equivalent alloy levels. The strong effect of vanadium is probably due to the formation of an alloy carbide that replaces cementite-type carbides at high tempering temperatures and persists as a fine dispersion up to the A_1 temperature.
Tungsten has been found to be more effective in high-carbon steels than in steels of low carbon content (less than 0.5%). Alloy interaction is important in tungsten-containing steels, with manganese-molybdenum-chromium having a greater effect on the multiplying factors than silicon or nickel additions.	Tungsten is also a carbide former and behaves like molybdenum in simple steels. Tungsten has been proposed as a substitute for molybdenum in reduced-activation ferritic steels for nuclear applications(d).
Titanium, niobium, and zirconium are all strong carbide formers and are usually not added to enhance hardenability for the same reasons given for vanadium. In addition, titanium and zirconium are strong nitride formers, a characteristic that affects their solubility in austenite and hence their contribution to hardenability.	Titanium, niobium, and zirconium should behave like vanadium because they are strong carbide formers.
Boron can considerably improve hardenability, the effect varying notably with the carbon content of the steel. The full effect of boron on hardenability is obtained only in fully deoxidized (aluminum-killed) steels.	Boron has no effect on the tempering characteristics of martensite, but a detrimental effect on toughness can result from the transformation to nonmartensitic products.

(a) Ref 3. (b) Fig. 4 (c) See the section "Microalloyed Quenched and Tempered Grades" in this article. (d) See the article "Elevated-Temperature Properties of Ferritic Steels" in this Volume. Source:Ref 2, 4

Effects of Tempering. Because the hard martensite produced after quenching is also extremely brittle, virtually all hardened steels undergo a subcritical heat treatment referred to as tempering. Tempering improves the toughness of the as-quenched martensite, but also softens the steel, thus causing a decrease in strength and an increase in ductility. This softening is largely due to the rapid coarsening of cementite (Fe_3C) with increasing tempering temperature and a reduction in dislocation density.

Alloying elements can help retard the degree of softening during tempering, and certain elements are more effective than others. The alloys that act as solid-solution strengtheners (nickel, silicon, aluminum, and manganese) remain dissolved in the martensite and do not significantly retard the softening effect, although silicon (Table 4) does retard softening by inhibiting the coarsening of iron carbide (Fe_3C). The most effective elements in retarding the rate of softening during tempering are the strong carbide-forming elements such as molybdenum, chromium, vanadium, niobium, and titanium (Table 4). The metal carbides produced from these elements are harder than martensite (Fig. 5) and have a fine dispersion because the diffusion of the carbide-forming elements is more sluggish than the diffusion of carbon. The lower diffusion rate of the carbide-forming elements inhibits the coarsening of Fe_3C and thus retards the rate of softening at elevated temperatures.

Fig. 5 Hardness of martensite and various carbides in an M2 tool steel. Representative analyses of carbide compositions
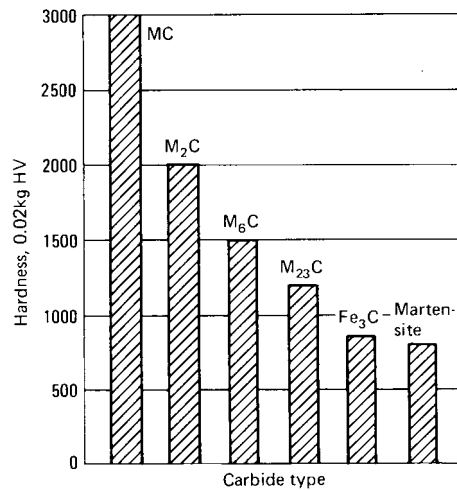
Carbide type	Alloying element	Composition, %
MC	C	13.0
	Fe	4.0
	W	23.0
	Mo	14.0
	V	43.0
	Cr	4.5
M_2C	C	6.0
	Fe	7.0
	W	41.0
	Mo	28.0
	V	11.0
	Cr	8.0
M_3C	C	6.7
	Fe	76.0
	W	5.0
	Mo	4.0
	V	2.0
	Cr	8.0
$M_{23}C_6$	C	4.0
	Fe	45.0
	W	25.0
	Mo	18.0
	V	4.0
	Cr	5.0
M_6C	C	3.0
	Fe	35.0
	W	35.0
	Mo	19.0
	V	3.3
	Cr	3.3

The formation of carbides, which is a diffusion-controlled process dependent upon the migration of the carbide-forming elements, can reduce the rate of softening at all tempering temperatures. The degree of softening also depends on the quantity of the carbide-forming element. **Figure 6**, for example, shows reductions in softening at all tempering temperatures with various

amounts of molybdenum. Similar effects occur for other carbide-forming elements, with the retardation in softening depending upon the type of carbide formed. In Fig. 5 , for example, the maximum hardness obtainable in martensite is compared with the range of hardness for metal carbides (MC, M_2C, M_6C, M_3C and $M_{23}C$), with representative analyses of carbide compositions shown in the table accompanying Fig. 5 . In this case, the hardest carbide in steel, MC, is predominately a carbide of vanadium. The M_2C is a carbide of tungsten and molybdenum, and some vanadium.

Fig. 6 Retardation of softening and secondary hardening during the tempering of a 0.35% C steel with various additions of molybdenum. Source: Ref 6
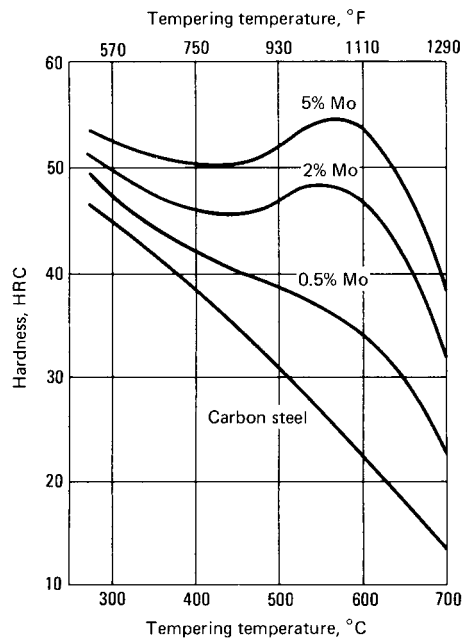
If the carbide-forming elements are present in sufficient quantity, the metal carbides not only reduce softening but also produce a hardness increase at the higher tempering temperature (Fig. 6). This hardness increase is frequently referred to as secondary hardening. Given a sufficient level of carbide-forming elements, secondary hardening depends on a high enough temperature to allow a sufficient diffusion rate of the carbide-forming elements. Moreover, because the diffusion of the carbide formers is a more sluggish process than carbon diffusion, the metal carbides formed have a fine dispersion and are very resistant to coarsening. The latter characteristic of the fine metal carbides provides good creep resistance and is used to advantage in steels that must not soften during elevated-temperature. exposure. See the articles "Wrought Tool Steels" and "Elevated-Temperature Properties of Ferritic Steels" in this Volume for additional information on secondary hardening steels with additions of molybdenum, vanadium, chromium, tungsten, and/or other carbide-forming elements.

Microalloyed Quenched and Tempered Grades. Although fittings with 0.6% Mn and induction bends use quenching and tempering as a standard practice, mild steels (plain, low-carbon steels with less than 0.7% Mn) with microalloying additions of vanadium, niobium, or titanium are seldom used as quenched and tempered steels. However, elements such as boron and vanadium are considered as substitutes for other elements that enhance hardenability. For example, the high cost of molybdenum in the late 1970s prompted considerable research in an effort to partially or completely replace molybdenum with microadditions of vanadium or of vanadium plus titanium (Ref 7, 8, 9, 10). The titanium was added in order to form titanium nitride, thereby retaining an increased amount of vanadium in solution. This provided for a more efficient use of vanadium as a hardenability agent.

In terms of hardenability, the basic difficulty with vanadium (and other strong carbide formers such as titanium, niobium, and zirconium) is that the hardenability of steel can be increased only if small amounts are added and if the steel is austenitized at a high enough temperature and for a long enough time to ensure that the vanadium (or other strong carbide former) is in solution. Opinions vary as to the practical maximum amount of vanadium that can be added while still avoiding the nucleating effect of undissolved vanadium carbides, which would reduce hardenability. Complete solubility of vanadium during austenitization may not be the only factor in raising hardenability (Ref 11). The interaction of vanadium with other elements and the stabilization of nitrogen (with titanium) also influence hardenability. For example, Sandberg *et al*. (Ref 9, 10) investigated completely V-substituted variants of 4140-base series (0.4C-1Cr) with titanium additions, as well as partially V-substituted variants with and without titanium additions. The study concluded that:

- Complete substitution of molybdenum by vanadium does not increase the hardenability over standard 4140 (0.20% Mo) even when all the vanadium is dissolved during austenitization
- Steels containing 0.1 to 0.2% V and 0.04% Ti are characterized by significantly increased hardenability (10 to 25% in D_I) over standard 4140

- Microalloy combinations of V + Mo + Ti (~0.06-0.06-0.04%) provide very high hardenability, with D_I being up to 60% greater than the D_I in standard 4140 with 0.20% Mo. This effect is completely absent in a partially substituted steel without titanium (or aluminum as discussed below)

With regard to the third observation, however, Manganon (Ref 7, 8) has reported that for 4330-base steel (0.3C-0.5Cr-1.9Ni), 0.15% V (without titanium) can be substituted for 0.3% Mo without detriment to hardenability (although at present, complete substitution is more expensive because the price of molybdenum is much lower than that of vanadium). Nevertheless, there also exists a synergism between molybdenum and vanadium such that the hardenability of a steel containing 0.15% V and 0.10% Mo is considerably superior to that of standard 4330 with 0.3% Mo. Additions of titanium to this partially substituted steel produced a further marginal increase in hardenability. Niobium also produces a niobium-molybdenum synergy in quenched and tempered steels; niobium can be present in amounts up to about 0.04% Nb without a decrease in the hardenability of carbon steels.

The pronounced effect on hardenability of molybdenum-vanadium combinations without titanium as observed by Manganon (Ref 7, 8) in 4330 steels, can probably be reconciled with the third result of Sandberg *et al.*, in that the latter studied steels containing 0.06% Al, which would be expected to remove nitrogen to about the same extent as 0.04% Ti. Because small amounts of dissolved nitrogen promote the formation of VN (which removes vanadium from solution and thus detracts from the effectiveness of vanadium as a hardenability raiser), dissolved nitrogen must be limited via the presence of titanium or excess aluminum. By tying up the nitrogen as TiN or AlN, the vanadium can be in solution and thus increase hardenability.

Mechanical Properties. Quenched and tempered alloy steels can offer a combination of high strength and good toughness. Table 5 lists some typical tensile properties of the low-alloy plate steels given in Table 3. Figure 1 compares the low-temperature impact toughness of a heat-treated alloy steel with the impact toughness of a mild steel (ASTM A 7, which is now ASTM A 283, grade D) and an HSLA steel.

Table 5 Minimum tensile properties and maximum plate thickness for the quenched and tempered low-alloy steels listed in Table 3

Specification or common designation	Grade, type, or class	Plate thickness(a)		Minimum yield strength		Tensile strength		Minimum elongation in 50 mm (2 in.), %
		mm	in.	MPa	ksi	MPa	ksi	
SAE J368a	Q980B	32	$1\frac{1}{4}$	550	80	655–795	95–115	18
	Q990B	40	$1\frac{1}{2}$	620	90	690–895	100–130	18
	Q9100B	25	1	690	100	760 (min)	110 (min)	18
ASTM A 514 or A 517	A, B, C	32	$1\frac{1}{4}$	690	100	760–895	110–130	18
	E, F	65	$2\frac{1}{2}$	690	100	760–895	110–130	18
	E	65–150	$2\frac{1}{2}$–6	620	90	690–895	100–130	16
ASTM A 533	Class 1 (type A, B, or C)	300	12	345	50	550–690	80–100	18
	Class 2 (type A, B, or C)	300	12	485	70	620–795	90–115	16
	Class 3 (type A, B, or C)	65	$2\frac{1}{2}$	570	83	690–860	100–125	16
ASTM A 543	B, C	(b)	(b)	485–585	70–85	620–930	90–135	14–16
ASTM A 678	D	75	3	515	75	620–760	90–110	18
ASTM A 709	70W	100	4	425	70	620–760	90–110	19
	100, 100W	65	$2\frac{1}{2}$	690	100	760–895	110–130	18
	100, 100W	65–100	$2\frac{1}{2}$–4	620	90	690–895	100–130	16
HY-80		20	$\frac{3}{4}$	550–690	80–100	...	...	19
		20–200	$\frac{3}{4}$–8	550–685	80–100	...	...	20
HY-100		20	$\frac{3}{4}$	690–825	100–120	...	...	17
		20–150	$\frac{3}{4}$–6	690–790	100–115	...	...	18
HY-130		9.5–14	$\frac{3}{8}$–$\frac{9}{16}$	895–1030	130–150	...	...	14
		14–100	$\frac{9}{16}$–4	895–1000	130–145	...	...	15

(a) Maximum plate thickness for the specified mechanical properties when a single value is shown. (b) Maximum plate thickness is not defined in ASTM A 543; plates in ASTM A 543 are intended for applications requiring plate thicknesses of 50 mm (2 in.) or more.

In addition, quenched and tempered alloy steel plate is available with ultrahigh strengths and enhanced toughness. Ultrahigh-strength steels with yield strengths above 1380 MPa (200 ksi) are described in the article "Ultrahigh-Strength Steels" in this Volume. Also within the category of ultrahigh-strength quenched and tempered steels is ball and roller bearing steel (see the article "Bearing Steels" in this Volume).

Enhanced toughness and high strength are achieved in the nickel-chromium-molybdenum alloys, which include steels such as ASTM A 543, HY-80, HY-100, and HY-130 (Table 3). These steels use nickel to improve toughness. The Charpy V-notch impact energies of the HY-80 and HY-100 grades are shown in Table 6 . Figure 7 shows the Charpy V-notch impact energies of HY-130 at various temperatures.

Table 6 Charpy V-notch impact strengths of two nickel-chromium-molybdenum steels

Alloy	Plate thickness		Transverse impact strength at −85 °C (0 °F)		Transverse impact strength at −85 °C (−120 °F)		Longitudinal impact strength at −85 °C (−120 °F)	
	mm	in.	J	ft · lbf	J	ft · lbf	J	ft · lbf
HY-80	<50	<2	81	60	47	35	68	50
	>50	>2	81	60	34	25	40	30
HY-100	<50	<2	75	55	40	30	68	50
	>50	>2	75	55	34	25	40	30

Fig. 7 Typical Charpy V-notch impact strengths of a 5% Ni low-alloy steel. Longitudinal specimens from 25 mm (1 in.) HY-130 steel plate were used.
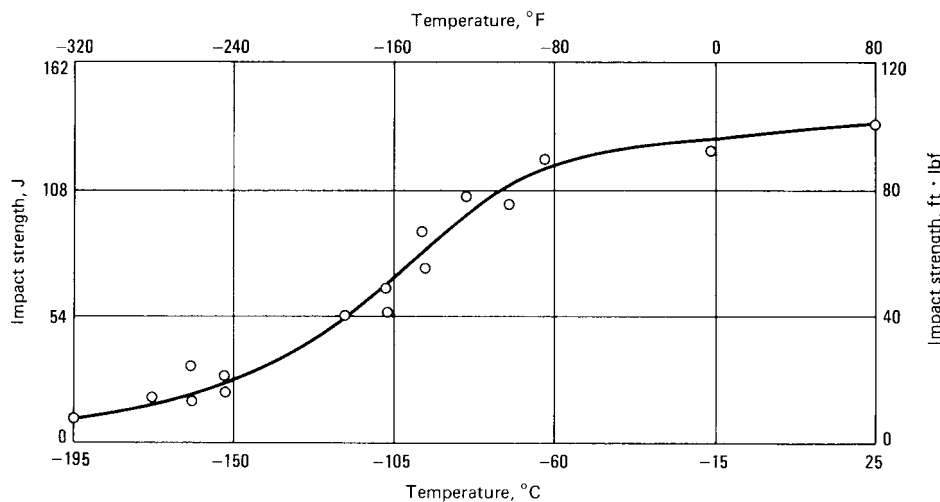
High-Nickel Steels for Low-Temperature Service. For applications involving exposure to temperatures from 0 to −195 °C (32 to −320 °F), the ferritic steels with high nickel contents are typically used. Such applications include storage tanks for liquefied hydrocarbon gases and structures and machinery designed for use in cold regions. Properties of steels at low temperatures are discussed in the article "Low-Temperature Properties of Structural Steels" in this Volume.

The steels considered for the above applications also include the HY-130 steel in Table 3 and the various steels shown in Table 7 . These steels utilize the effect of nickel content in reducing the impact transition temperature, thereby improving toughness at low temperatures. Carbon and alloy steel castings for subzero-temperature service are covered by ASTM standard specification A 757.

Table 7 Compositions of ferritic nickel steel plate for use at subzero temperatures

ASTM specification	Compositions of plates <50 mm (2 in.) thick, %(a)							
	C	Mn	P	S	Si	Ni	Mo	Others
A 203 A	0.17	0.70	0.035	0.040	0.15–0.30	2.10–2.50	...	...
A 203 B	0.21	0.70	0.035	0.040	0.15–0.30	2.10–2.50	...	...
A 203 C	0.17	0.70	0.035	0.040	0.15–0.30	3.25–3.75	...	...
A 203 D	0.20	0.70	0.035	0.040	0.15–0.30	3.25–3.75	...	...
A 645	0.13	0.30–0.60	0.025	0.025	0.20–0.35	4.75–5.25	0.20–0.35	0.02–0.12 Al, 0.020 N
A 353	0.13	0.90	0.035	0.040	0.15–0.30	8.5–9.5	...	...
A 553 I	0.13	0.90	0.035	0.040	0.15–0.30	8.5–9.5	...	...
A 553 II	0.13	0.90	0.035	0.040	0.15–0.30	7.5–8.5	...	...

(a) Single values are maximum limits.

The 5% Ni alloys for low-temperature service include HY-130 in Table 3 and ASTM A 645 in Table 7 . Typical Charpy V-notch impact energies of HY-130 at low temperatures are shown in Fig. 7 . For steel purchased according to ASTM A 645, minimum Charpy V-notch impact requirements for 25 mm (1 in.) plate are designated at −170 °C (−275 °F) for hardened, tempered, and reversion-annealed plate. Minimum impact energies at this temperature range from 5 J (4 ft · lbf) for a 10 × 2.50 mm (0.4 × 0.1 in.) transverse specimen to 22 J (16 ft · lbf) for a 10 × 10 mm (0.4 × 0.4 in.) transverse specimen.

Double normalized and tempered 9% nickel steel is covered by ASTM A 353, and quenched and tempered 8% and 9% nickel steels are covered by ASTM A 553 (types I and II). For quenched and tempered material, the minimum lateral expansion in Charpy V-notch impact tests is 0.38 mm (0.015 in.). Charpy tests on 9% Ni steel (type I) are conducted at −195 °C (−320 °F); tests on 8% Ni steel (type II) are conducted at −170 °C (−275 °F). The transverse Charpy V-notch impact energies must not be less than 27 J (20 ft · lbf) at the specified temperature. Each impact test value must constitute the average value of three specimens, with not more than one value being below the specified minimum value of 27 J (20 ft · lbf) and no value being below 20 J (15 ft · lbf) for full-size specimens. Longitudinal Charpy impact properties must not be less than 34 J (25 ft · lbf) at the specified temperatures.

Typical tensile properties of 5% and 9% Ni steels at room temperature and at subzero temperatures are presented in Table 8 . Yield and tensile strengths increase as testing temperature is decreased. These steels remain ductile at the lowest testing temperatures.

Table 8 Typical tensile properties of ferritic nickel steels at low temperatures

Temperature		Tensile strength		Yield strength		Elongation, %	Reduction in area, %
°C	°F	MPa	ksi	MPa	ksi		
A 645 plate, longitudinal orientation(a)							
24	75	715	104	530	76.8	32	72
−168	−270	930	135	570	82.9	28	68
−196	−320	1130	164	765	111	30	62
A 353 plate, longitudinal orientation(b)							
24	75	780	113	680	98.6	28	70
−151	−240	1030	149	850	123	17	61
−196	−320	1190	172	950	138	25	58
−253	−423	1430	208	1320	192	18	43
−269	−452	1590	231	1430	208	21	59
A 553-I plate, longitudinal orientation(c)							
24	75	770	112	695	101	27	69
−151	−240	995	144	885	128	18	42
−196	−320	1150	167	960	139	27	38

(a) Quenched and tempered, and reversion annealed. (b) Double normalized and tempered: held at 900 °C (1650 °F) 1 h for each 25 mm (1 in.) of thickness, air cooled; 790 °C (1450 °F) 1 h for each 25 mm (1 in.) of thickness, air cooled; held at 570 °C (1050 °F) for 1 h for each 25 mm (1 in.) of thickness, air cooled or water quenched. (c) Quenched and tempered: 800 °C (1475 °F), water quenched; 570 °C (1050 °F) for 30 min for each 25 mm (1 in.) of thickness, air cooled or water quenched. Source: Ref 12, 13, 14, 15, 16, 17, 18

Ferritic nickel steels are too tough at room temperature for valid fracture toughness (K_{Ic}) data to be obtained on specimens of reasonable size, but limited fracture toughness data have been obtained on these steels at subzero temperatures by the J-integral method. Results of these tests are presented in Table 9 . The 5% Ni steel retains relatively high fracture toughness at −162 °C (−260 °F), and the 9% Ni steel retains relatively high fracture toughness at −196 °C (−320 °F). These temperatures approximate the minimum temperatures at which these steels may be used.

Table 9 Fracture toughness of 5% and 9% Ni steel plate for compact tension specimens in transverse or longitudinal orientation

Alloy and condition	Yield strength(a)		Fracture toughness (K_{Ic}), J(b), at					
			−162 °C (−260 °F)		−196 °C (−320 °F)		−269 °C (−452 °F)	
	MPa	ksi	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$
5% Ni steel (A 645) quenched, tempered, and reversion annealed	534	77.5	196	178	87.1	79.3	58.4	53.2
9% Ni steel (A 553, type I) quenched and tempered	689	99.9	...	...	184	167	...	...

(a) At room temperature. (b) Fracture toughness determined from the J-integral method. Source: Ref 15, 16, 17, 18, 19, 20
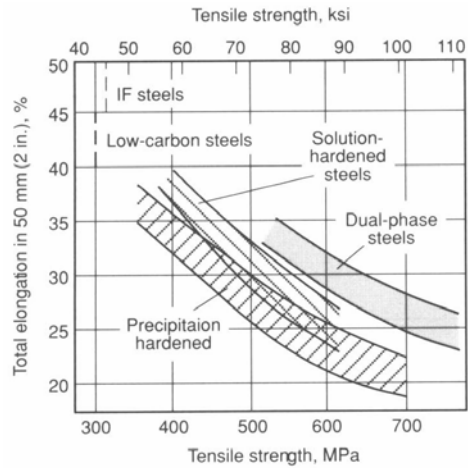
HSLA Steels

High-strength low-alloy (HSLA) steels are a group of low-carbon steels that utilize small amounts of alloying elements to attain yield strengths greater than 275 MPa (40 ksi) in the as-rolled or normalized condition. These steels have better mechanical properties and sometimes better corrosion resistance than as-rolled carbon steels. Moreover, because the higher strength of HSLA steels can be obtained at lower carbon contents, the weldability of many HSLA steels is comparable to or better than that of mild steel (Ref 21).

High-strength low-alloy steels are primarily hot-rolled into the usual wrought product forms (sheet, strip, bar, plate, and structural sections) and are commonly furnished in the as-hot-rolled condition. However, the production of hot-rolled HSLA products may also involve special hot-mill processing that further improves the mechanical properties of some HSLA steels and product forms. These processing methods include:

- *The controlled rolling* of precipitation-strengthened HSLA steels to obtain fine austenite grains and/or highly deformed (pancaked) austenite grains, which during cooling transform into fine ferrite grains that greatly enhance toughness while improving yield strength
- *The accelerated cooling* of, preferably, controlled-rolled HSLA steels to produce fine ferrite grains during the transformation of austenite. These cooling rates cannot be rapid enough to form acicular ferrite, nor can they be slow enough so that high coiling temperatures result and thereby causing the overaging of precipitates
- *The quenching or accelerated air or water cooling* of low-carbon steels (≤0.08% C) that possess adequate hardenability to transform into low-carbon bainite (acicular ferrite). This microstructure offers an excellent combination of high yield strengths (275 to 690 MPa, or 60 to 100 ksi), excellent weldability and formability, and high toughness (controlled rolling is necessary for low ductile-brittle transition temperatures)
- *The normalizing* of vanadium-containing HSLA steels to refine grain size, thereby improving toughness and yield strength
- *The intercritical annealing* of HSLA steels (and also carbon-manganese steels with low carbon contents) to obtain a dual-phase microstructure (martensite islands dispersed in a ferrite matrix). This microstructure exhibits a lower yield strength but, because of rapid work-hardening capability, provides a better combination of ductility and tensile strength than conventional HSLA steels (Fig. 8) and improved formability

The usefulness and cost effectiveness of these processing methods are highly dependent on product form and alloy content, which are considered in more detail in the following sections.
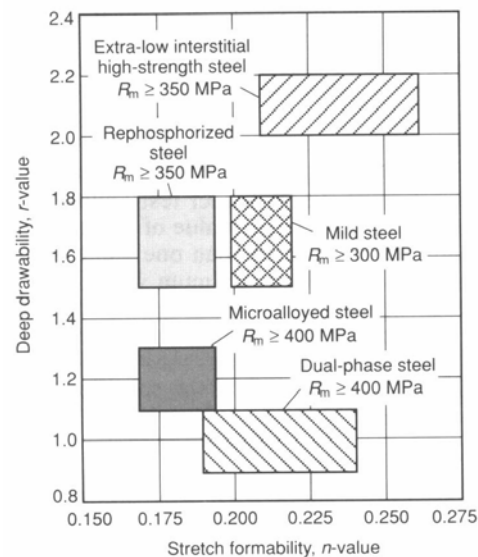
Fig. 8 Tensile and forming properties of dual-phase steels and interstitial-free (IF) steels. (a) Strength-elongation relationships for various hot-rolled sheet steels. (b) Strength-elongation relationships for various cold-rolled sheet steels. (c) Deep-drawing properties of steel sheet grades. Source: Ref 21

Tensile strength, ksi

(a)

Tensile strength, ksi
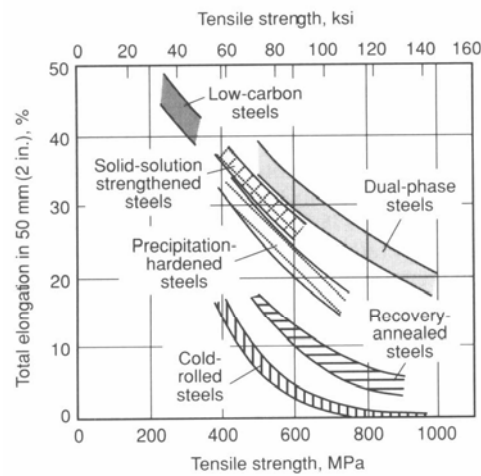
(b)

(c)

In addition to hot-rolled products, HSLA steels are also furnished as cold-rolled sheet and forgings. Cold-rolled HSLA sheet and HSLA forgings are discussed in the section "Applications of HSLA Steels" in this article. HSLA forgings are also covered in the article"High-Strength Low-Alloy Steel Forgings" in this Volume. The main advantage of HSLA forgings (like as-hot-rolled HSLA products) is that yield strengths in the range of 275 to 485 MPa (40 to 70 ksi) or perhaps higher can be achieved without heat treatment. Base compositions of these microalloyed ferrite-pearlite forgings are typically 0.3–0.50% C and 1.4−1.6% Mn.

Low-carbon bainitic HSLA steel forgings have also been developed.

HSLA Steel Categories and Specifications

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 judicious (small) addition of alloys and, perhaps, special processing techniques such as controlled rolling. 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.

Although HSLA steels are available in numerous standard and proprietary grades (see, for example, the listing of over 600 HSLA steels in Ref 23), 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
- *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 (<0.08% C) steels with an excellent combination of high yield strengths, 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 (Fig. 8)
- *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 are changed from elongated stringers to small, dispersed, almost spherical globules
- *Hydrogen-induced cracking resistant steels* with low carbon, low sulfur, inclusion shape control, and limited manganese segregation, plus copper contents greater than 0.26%

These seven categories are not necessarily distinct groupings, in that 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. A separate category might also be considered for the HSLA 80 (Navy) nickel-copper-niobium steel (0.04% C, 1.5% Mn, 0.03% Nb, 1.0% Ni, 1.0% Cu, and 0.7% Cr). Table 10 describes some typical HSLA steels, their available mill forms, and their intended applications.

Table 10 Summary of characteristics and intended uses of HSLA steels described in ASTM specifications

| ASTM specifications(a)	Title	Alloying elements(b)	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 constructions
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 mainly bolted or riveted 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	Not specified	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion resistance twice that of carbon steel (type 2) or four times that of carbon steel (type 4)	Structural and miscellaneous purposes for which weight savings or added

					resistance
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 ≥ –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 ($\frac{5}{8}$ in.) in thickness	Yield strength of 552 MPa (80 ksi)	Truck frames, brackets, crane booms, rail cars, and other applications 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 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 ($\frac{1}{2}$ 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 A 606 and A 607; yield strengths of 345 to 550 MPa (50 to 80 ksi) in four grades	Structural and miscellaneous applications for which high strength, weight savings, 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 ($2\frac{1}{2}$ in.) in thickness	Charpy V-notch impact energies of 40–60 J (30–45 ft · lbf) at –45 °C (–50 °F)	Railway tank cars
A 812	High-strength low-alloy steels	V, 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 ($1\frac{3}{8}$ in.) in thickness | Atmospheric-corrosion resistance four times that of carbon structural steel | Tubular structures and poles |

(a) For   and mechanical properties, see Table 16 . (b) 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 13 . (c) Obtained by

composition

Weathering Steels. The first HSLA steels developed were the weathering steels. These steels contain copper and other elements that enhance corrosion resistance, solid-solution strengthening, and some grain refinement of the ferritic microstructure. The solid-solution strengthening effect of several alloying elements is shown in Fig. 9 . Of these, copper, phosphorus, and silicon provide corrosion resistance in addition to solid-solution strengthening.

Fig. 9 Solid-solution strengthening of ferrite. Source: Ref 24
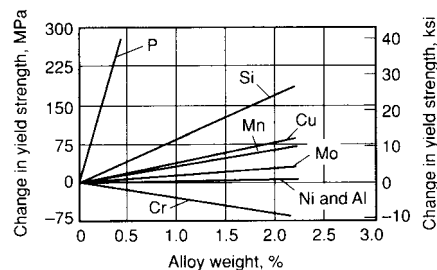

Several of the ASTM specifications listed in Table 10 cover weathering steels with enhanced atmospheric-corrosion resistance. The original architectural grade of weathering steel is covered by ASTM A 242, and the heavier structural grade is covered by ASTM A 588. These two steels reduce corrosion by forming their own protective oxide surface film. Although these steels initially corrode at the same rate as plain carbon steel, they soon exhibit a decreasing corrosion rate, and after a few years, continuation of corrosion is practically nonexistent. The protective oxide coating is fine textured, tightly adherent, and a barrier to moisture and oxygen, effectively preventing further corrosion. Plain carbon steel, on the other hand, forms a coarse-textured flaky oxide that does not prevent moisture or oxygen from reaching the underlying noncorroded steel base. Steels conforming to ASTM A 242 and A 588 are not recommended for exposure to highly concentrated industrial fumes or severe marine conditions, nor are they recommended for applications in which they will be buried or submerged. In these environments, the highly protective oxide does not form properly, and corrosion is similar to that for plain carbon steel.

The numerous grades of HSLA weathering steels can be classified into two groups:

- Weathering steels with normal low-phosphorus contents and multiple-alloy additions for solid-solution strengthening and enhanced corrosion resistance
- Proprietary weathering steels with high phosphorus contents (0.05 to 0.15%) for strengthening and corrosion resistance, together with multiple-alloy additions similar to those of the low-phosphorus weathering steels

The atmospheric-corrosion resistance of the low-phosphorus weathering steels (Ref 23) is two to six times that of carbon structural steel, while the proprietary weathering steels may have higher corrosion resistance. For example, an early (circa 1933) proprietary weathering steel, Cor-Ten A produced by United States Steel Corporation, has an atmospheric-corrosion resistance of five to eight times greater than that of carbon steel (Fig. 10), depending on the environment. This high-phosphorus weathering steel has a minimum yield strength of 345 MPa (50 ksi) in section thicknesses up to 13 mm ($\frac{1}{2}$ in.).

Fig. 10 Atmospheric-corrosion resistance of a proprietary high-phosphorus HSLA weathering steel (Cor-Ten A). Composition of weathering steel: 0.12% C (max), 0.20 to 0.50% Mn, 0.07 to 0.15% P, 0.05% S (max), 0.25 to 0.75% Si, 0.25 to 0.75% Cu, 0.30 to 1.25% Cr, and 0.65% Ni (max)
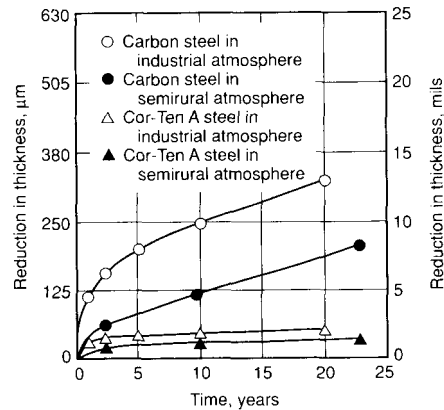
Microalloying with vanadium and/or niobium can improve the yield strength of weathering steels; the addition of niobium also improves toughness. Normalizing or controlled rolling-cooling can also refine the grain size (and thus improve toughness and yield strength). However, if normalizing or accelerated cooling is used to refine grain size, the effect of carbon content and alloy additions on hardenability and the potential for undesirable transformations to upper bainite and Widmanstätten ferrite must be considered.

Microalloyed ferrite-pearlite steels 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) (Ref 25). 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

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).

Some specifications of microalloyed HSLA steels do not specify the range of microalloying additions needed to achieve the desired strength level. These steels are often specified in terms of mechanical properties, with the amounts of microalloying elements left to the discretion of the steel producer. For example, SAE specification J410 covers various HSLA steels with varying carbon and manganese limits for sheet, strip, plate, bar, and shapes (Table 11). This specification limits only carbon and manganese contents (besides impurities such as sulfur), with the amounts of microalloying elements depending on the desired mechanical properties and corrosion resistance. Similar specifications based on mechanical properties without specific microalloying amounts also are given in SAE J1392 (hot- and cold-rolled HSLA sheet), SAE J1442 (hot-rolled HSLA plate), and some of the ASTM specifications in Table 10 (ASTM A 242, A 606, and A 715). The other ASTM specifications in Table 10 define specific ranges for microalloying additions.

Table 11 Compositions, mill forms, and characteristics of HSLA steels describe in SAE J410c

See Table 17 for mechanical properties.

| Grade(a)	C (max)	Mn (max)	P (max)	Other elements(c)	Available mill forms	Special characteristics
		Heat compositional limits, %(b)				
942X 0.21		1.35	0.04	Nb, V	Plate, bar, and shapes ≤ 100 mm (4 in.) in thickness	Similar to 945X and 945C except for better weldability and formability
945A 0.15		1.00	0.04	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Excellent weldability, formability, and notch toughness
945C 0.23		1.40	0.04	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Similar to 950C except that lower carbon and manganese content improve weldability, formability, and notch toughness
945X 0.22		1.35	0.04	Nb, V	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Similar to 945C except for better weldability and formability
950A 0.15		1.30	0.04	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Good weldability, notch toughness, and formability
950B 0.22		1.30	0.04	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Fairly good notch toughness and formability
950C 0.25		1.60	0.04	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Fair formability and toughness
950D 0.15		1.00	0.15	· · ·	Sheet, strip, plate, bar, and shapes ≤ 75 mm (3 in.) in thickness	Good weldability and formability; phosphorus should be considered in conjunction with other elements
950X 0.23		1.35	0.04	Nb, V	Sheet, strip, plate, bar, and shapes ≤ 40 mm (1.5 in.) in thickness	Similar to 950C except for better weldability
955X 0.25		1.35	0.04	Nb, V, N	Sheet, strip, plate, bar, and shapes ≤ 40 mm (1.5 in.) in thickness	Similar to 945X and 950X except that progressively higher strengths are obtained by increasing the carbon and manganese contents, or by adding nitrogen ≤ 0.015%; formability and weldability generally decrease with increased strength; toughness varies with composition and mill practice
960X 0.26		1.45	0.04	Nb, V, N	Sheet, strip, plate, bar, and shapes ≤ 40 mm (1.5 in.) in thickness	
965X 0.26		1.45	0.04	Nb, V, N	Sheet, strip, plate, bar, and shapes ≤ 20 mm (0.75 in.) in thickness	
970X 0.26		1.65	0.04	Nb, V, N	Sheet, strip, plate, bar, and shapes ≤ 20 mm (0.75 in.) in thickness	
980X 0.26		1.65	0.04	Nb, V, N	Sheet, strip, plate, bar, and shapes ≤ 10 mm (0.38 in.) in thickness	

(a) Fully killed steel made to fine grain practice may be specified by adding a second suffix, K, for instance, 945XK. Steels made to K practice are normally specified only for applications requiring better toughness at low temperatures than steels made to normal semikilled practice. (b) 0.05% P (max) and 0.90 % Si (max), all grades. (c) Elements normally added singly or in combination to produce specified mechanical properties and other characteristics. Other alloying elements such as copper, chromium, and nickel may be added to enhance atmospheric-corrosion resistance.

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 (Ref 26), 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. 11 . An optimum level of precipitation strengthening occurs at a cooling rate of about 170 °C/min (306 °F/min) (Fig. 11). 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 the temperature results in larger austenite grain sizes, while decreasing the temperature makes rolling more difficult.

Fig. 11 Effect of cooling rate on the increase in yield strength due to precipitation strengthening in a 0.15% V steel. Source: Ref 26
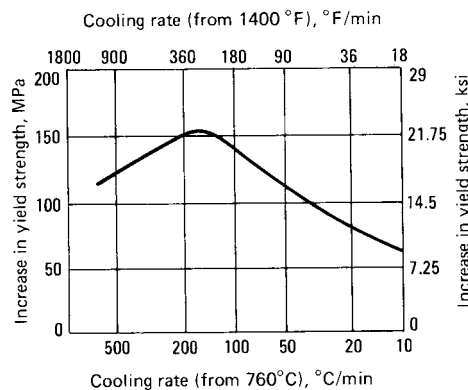
Manganese content and ferrite grain size also affect the strengthening of vanadium microalloyed steels. The effect of manganese on a hot-rolled vanadium steel is shown in Table 12 . The 0.9% increase in manganese content increased the strength

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).

Table 12 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

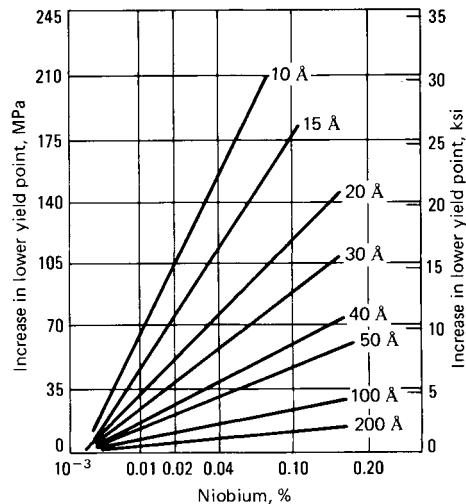| Vanadium content, %	Yield strength		Change in yield strength	
	MPa	ksi	MPa	ksi
0.3% Mn				
0.00	297	43	0	0
0.08	352	51	55	8
0.14	380	55	83	12
1.2% Mn				
0.00	331	48	0	0
0.08	462	67	131	19
0.14	552	80	221	32

Source: Ref 23, 27

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 (see the section "Controlled Rolling" in this article). 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), 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. 12). 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.

Fig. 12 Effect of niobium carbide on yield strength for various sizes of niobium carbide particles

245 — 35
210 — 30
175 — 25
140 — 20
105 — 15
70 — 10
35 — 5
0 — 0

Increase in lower yield point, MPa

Increase in lower yield point, ksi

10 Å
15 Å
20 Å
30 Å
40 Å
50 Å
100 Å
200 Å

10^{-3} 0.01 0.02 0.04 0.10 0.20

Niobium, %

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 recrystallization controlled rolling of niobium steel can be effective without titanium, while recrystallization rolling of vanadium steels requires titanium for grain refinement. Also, much less niobium is needed, and niobium-titanium steels can be recrystallization controlled rolled at higher temperatures. At present, offshore platform steels up to 75 mm (3 in.) thick with yield strengths of 345 to 415 MPa (50 to 60 ksi) are routinely produced.

Vanadium-Niobium Microalloyed Steels. Steels microalloyed with both niobium and vanadium provide a 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 (<0.10% C). 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 may have either a ferrite-pearlite microstructure or an acicular ferrite microstructure. Steels with the latter microstructure are discussed in the section "Acicular Ferrite (Low-Carbon Bainite) Steels" in this article.

In ferrite-pearlite niobium steels, the addition of molybdenum increases the yield strength and tensile strength by about 20 MPa (3 ksi) and 30 MPa (4.5 ksi), respectively, per 0.1% Mo, over an investigated range of 0% to 0.27% Mo (Ref 28). 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 Nb(CN) precipitation strengthening caused by a molybdenum-niobium synergism. The interaction between molybdenum and niobium (or vanadium) has been proposed as an explanation for the increase in precipitation strengthening by the addition of molybdenum. This effect has been attributed to the reduced precipitation in austenite from an increase in solubility arising from a decrease in carbon activity brought about by molybdenum (Ref 28). With less precipitation in austenite, more precipitates could form in the ferrite, resulting in enhanced strength. Also, molybdenum has been identified in the precipitates themselves; its presence may increase their strengthening effectiveness by increasing coherency strains and/or by increasing the volume fraction of precipitation (Ref 28). These metallurgical factors, when considered in conjunction with the effectiveness of controlled rolling to temperatures just below the Ar_3 temperature, have led to the development of a more economical X-70 molybdenum-niobium linepipe steel (Ref 28).

Vanadium-Nitrogen Microalloyed Steels. Vanadium combines more strongly with nitrogen than does niobium and forms VN precipitates in vanadium-nitrogen steel. Nitrogen additions to high-strength steels containing vanadium have become commercially important because the additions enhance precipitation hardening. Precipitation hardening may be accompanied by a drop in notch toughness, but this can often be overcome by lowering the carbon content. The precipitation of vanadium nitride also acts as a grain refiner.

Some producers use nitrogen additions to assist in the precipitation strengthening of controlled-cooled sheet and plate with thicknesses above 9.5 mm (0.375 in.). In one case (Ref 23), hot-rolled plates with vanadium and 0.018 to 0.022% N have been produced by controlled cooling in thicknesses up to 16 mm (0.625 in.) with yield strengths of 550 MPa (80 ksi). 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 (0.375 in.) in the minimum yield strength range from 345 to 550 MPa (50 to 80 ksi), 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 (Fig. 13(a)) by titanium nitride. Small amounts of titanium are also effective in recrystallization controlled rolling because titanium nitride retards the grain growth of recrystallized austenite. In conventional controlled rolling, however, titanium is a moderate grain refiner, causing less refinement than niobium but more than vanadium.

Fig. 13(a) Austenite grain coarsening during reheating and after hot rolling for a holding time of 30 min. Titanium contents were between 0.008 and 0.022% Ti. Source: Ref 25
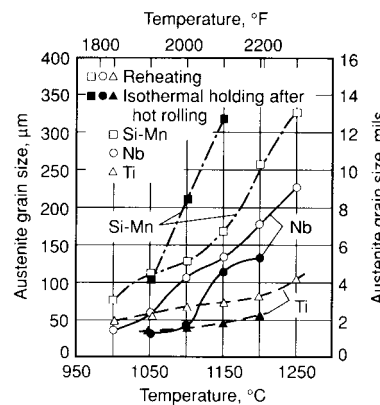
In terms of precipitation strengthening (Fig. 13(b)), a sufficient amount of titanium is required to form titanium carbide. Small percentages of titanium (<0.025% Ti) form mainly into TiN, which has an effect on austenite grain growth but little effect on precipitation strengthening because the precipitates formed in the liquid are too coarse. Increasing the titanium content leads to the formation first of titanium-containing manganese sulfide inclusions (Mn, Ti)S, and then of globular carbosulfides, $Ti_4C_2S_2$ (which provide sulfide shape control). The formation of $Ti_4C_2S_2$ is accompanied by and followed by titanium carbide (TiC) formation, which can be used for the precipitation strengthening of low-carbon steels. To determine the amount of titanium that is available for precipitation strengthening, the total titanium content must be adjusted for the formation of the coarse, insoluble titanium nitride and carbosulfides that do not participate in precipitation strengthening.

Fig. 13(b) The dependence of precipitation strengthening on average precipitate size (x̄) and fraction according to theory and experimental observations for given microalloying additions. Source: Ref 22
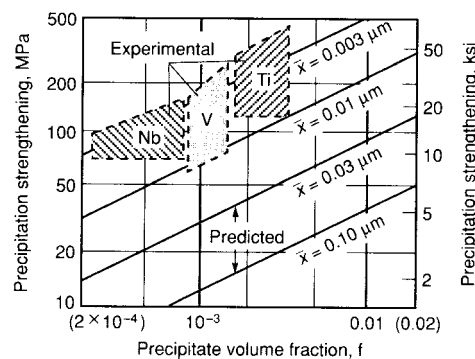
Experimentally observed strength increases from TiC precipitation have ranged up to 440 MPa (64 ksi) for very fine particles (less than 30 Å) and a relatively large fraction of precipitate (Fig. 13(b)). If sufficient amounts of titanium are used, titanium carbide can provide more precipitation strengthening than either niobium or vanadium. However, because higher levels of precipitation strengthening are generally associated with reduced toughness, grain refinement would be necessary to improve toughness. Titanium is a moderate grain refiner (compared to niobium and vanadium in hot-rolled steels), and the high levels of precipitation strengthening of titanium microalloyed steels result in a severe penalty in toughness. Using only titanium as a strengthener in high-strength hot-rolled strip has also resulted in unacceptable variability in mechanical properties (see the paper "Restricted Yield Strength Variation in High Strength Low Alloy Steels" by E.G. Hamburg in Ref 11).

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 (see, for example, the article "Recent Developments in Automotive Hot-Rolled Strip Steels" by G. Tither in Ref 25). Titanium increases the efficiency of niobium because it combines with the nitrogen-forming titanium nitrides, thus preventing the formation of niobium nitrides. This allows for increased solubility of niobium in the austenite resulting in subsequent increased precipitation of Nb(C,N) particles in the ferrite. The addition of 0.04% titanium to steel strip containing various amounts of niobium consistently produced a yield strength increase of about 105 MPa (15 ksi) for a coiling temperature of 675 °C (1250 °F). Hot-rolled niobium-titanium steel strip is effective in achieving yield strengths of 550 MPa (80 ksi) in ferrite-pearlite steels. An addition of either vanadium or molybdenum can raise yield strengths to 690 MPa (100 ksi).

As-rolled pearlitic structural steels are a specific group of steels in which enhanced mechanical properties (and, in some cases, resistance to atmospheric corrosion) are obtained by the addition of moderate amounts of one or more alloying elements other than carbon. Some of these steels are carbon-manganese steels and differ from ordinary carbon steels only in having a greater manganese content. Other pearlitic structural steels contain small amounts of alloying elements, which are added to enhance weldability, formability, toughness, and strength.

The as-rolled pearlitic structural steels are characterized by as-rolled yield strengths in the range of 290 to 345 MPa (42 to 50 ksi). They are not intended for quenching and tempering and should not be subjected to such treatment. For certain applications, they may be annealed, normalized, or stress relieved, processes which may alter mechanical properties.

When these steels are used in welded structures, care must be exercised in grade selection and in the specification of the welding process details. Certain grades may be welded without preheating or postheating. The basic disadvantages of these steels is that the pearlitic microstructure raises the ductile-brittle transition temperature but does not improve yield strengths. In addition, the high carbon content (relative to other HSLA steels) reduces weldability.

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 ultralow 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, or 60 to 100 ksi), high toughness (Fig. 14), and good weldability. A major application of these steels is linepipe in arctic conditions.

Fig. 14 Impact toughness and yield strengths of 25 mm (1 in.) thick, controlled-rolled, ultralow-carbon bainitic steel plate. In addition to the molybdenum contents shown, nominal contents of other alloying elements included 0.024 to 0.027% C, 0.92 to 1.00% Mn, 3.54 to 3.63% Ni, and 0.050 to 0.055% Nb. Source: Ref 29
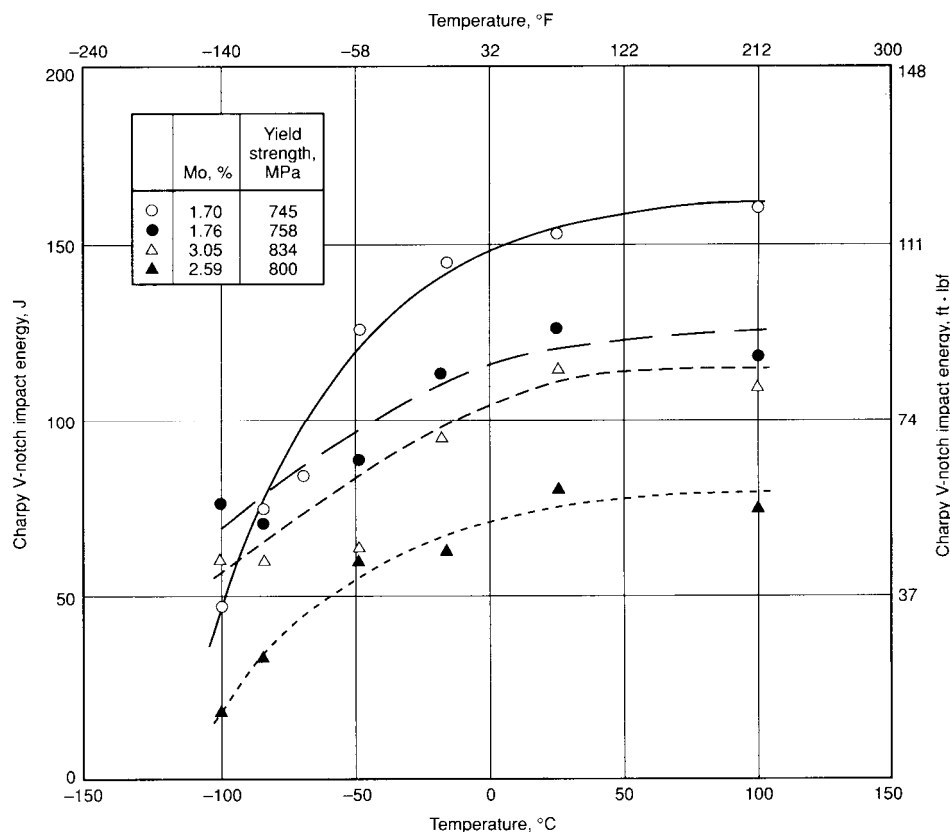
Typical properties of conventionally rolled, air-cooled 13 mm (0.5 in.) plate are (Ref 24):

- Yield strength: 470 to 530 MPa (68 to 77 ksi)
- Charpy V-notch 50% shear area fracture appearance transition temperature: −23 to 10 °C (−10 to 50 °F)
- Charpy V-notch ductile-shelf energy: greater than 136 J (100 ft · lbf)

Properties of a controlled-rolled acicular ferrite steel are summarized in Fig. 14 .

The major application of acicular ferrite steel involves oil pipelines in arctic conditions. This application requires a combination of high strength, superior toughness, excellent resistance to hydrogen-induced cracking, and first-rate field weldability. In answer to these needs, Nippon Kokan K.K. developed a tough acicular ferrite steel for linepipe through the optimization of carbon and niobium content, the addition of boron, and/or the application of on-line accelerated cooling.

In this pipe, optimum carbon content ranges from 0.01 to 0.05%. Below 0.01% carbon, grain boundaries in the heat-affected zone (HAZ) are embrittled, resulting in intergranular, hydrogen-induced cracking and loss of toughness in the HAZ. The addition of boron and/or the application of on-line accelerated cooling ensures both high strength and superior toughness, along with desirable welding properties.

Three grades for arctic service are available: X-65, X-70, and X-80. An X-70 composition includes 0.03% C, 0.25% Si, 1.91% Mn, 0.008% P, 0.001% S, 0.048% N, plus titanium, boron, and calcium. Work at Bethlehem Steel Corporation to improve the properties of X-70 linepipe through the optimization of composition and processing parameters found that:

- An X-70 strength requirement, along with a 68 J (50 ft · lbf) minimum Charpy energy at 0 °C (32 °F) can be met with a controlled-rolled, low-carbon, low-sulfur vanadium-niobium composition. Full-curve Charpy data for the 10.9 mm (0.429 in.) wall linepipe indicate that with the chemistry and processing used, a 68 J (50 ft · lbf) Charpy requirement could also be met at −18 °C (0 °F) at this wall thickness
- There is a positive shift in both yield and tensile strength during pipe forming that is related to the amount of expansion and the corresponding stress-strain characteristics, such as work hardening and Lüders extension. As the percentage of expansion increases, the shift in yield strength rises continuously, but the shift in tensile strength levels off at about 27 to 35 MPa (4 to 5 ksi) after about 1.4% expansion
- Various Linde wire and flux combinations produce excellent toughness in the pipe body and HAZ, but only the Linde wire 83 and Linde flux 101 combinations provide excellent Charpy absorbed energies in the weld metal, such that the pipe body, heat-affected zone, and weld metal satisfy a 68 J (50 ft · lbf) requirement at 0 °C (32 °F)

Dual-phase steels have a microstructure with 80 to 90% polygonal ferrite and 10 to 20% martensite islands dispersed throughout the ferrite matrix. These steels have a low yield strength and continuous yielding behavior; therefore they form just like low-strength steel, but they can also provide high strength in the finished component because of their rapid work-hardening rate. Figure 8 compares the ductility and tensile strength of dual-phase steels with other HSLA steels. Typical as-shipped yield strength is 310 to 345 MPa (45 to 50 ksi).

Dual-phase steels can be produced from low-carbon steels in three ways (Ref 30):

- Intercritical austenitization of carbon-manganese steels followed by rapid cooling
- Hot rolling with ferrite formers such as silicon and transformation-delaying elements such as chromium, manganese, and/or molybdenum
- Continuous annealing of cold-rolled carbon-manganese steel followed by quenching and tempering

Additional information on dual-phase steels is contained in the article "Dual-Phase Steels" in this Volume.

Interstitial-Free (IF) Steels. Steels with very low interstitial contents exhibit excellent formability with low yield strength, high elongation, and good deep drawability (Fig. 8 c). With the addition of carbonitride-forming elements, the deep drawability and the non-aging properties are further improved. The effect of niobium, unlike that of other microalloyed elements, is to improve the planar anisotropy, reducing earing. This is due to the finer grain size already in the hot strip material prior to cold rolling. Titanium is also added to improve the effectiveness of niobium (see the section "Titanium-Niobium Microalloyed Steels" in this article). Information on the processing and steelmaking of IF steels is given in the articles "Steel Processing Technology" and "Microstructures, Processing, and Properties of Steels" in this Volume.

Inclusion Shape Controlled Grades. An important development in microalloyed HSLA steels is the use of inclusion shape control. Sulfide inclusions, which are plastic at rolling temperatures and thus elongate and flatten during rolling, adversely affect ductility in the short transverse (through thickness) direction. The main objective of inclusion shape control is to produce sulfide inclusions with negligible plasticity at even the highest rolling temperatures.

The preferred method for sulfide shape control involves calcium-silicon ladle additions. However, sulfide shape control is also performed with small additions of rare-earth elements, zirconium, or titanium that change the shape of the sulfide inclusions from elongated stringers to small, dispersed, almost spherical globules. This change in the shape of sulfide inclusions substantially increases transverse impact energy and improves formability. Inclusion shape control was introduced with the advent of hot-rolled sheet and light plate having a yield strength of 550 MPa (80 ksi) in the as-rolled condition. This technology has also been extended to include grades with lower yield strengths ranging from 310 to 550 MPa (45 to 80 ksi). The improved

formability of these grades is recognized in ASTM A 715. Inclusion shape control with rare-earth elements is seldom used because rare-earth elements produce relatively dirty steel.

Sulfide inclusion shape control performs several important roles in HSLA steels. It improves transverse impact energy, and it can minimize lamellar tearing in welded structures by improving through-thickness properties that are critical in constrained weldments.

Control of HSLA Steel Properties

Most HSLA steels are furnished in the as-hot-rolled condition with ferritic-pearlitic microstructure. The exceptions are the controlled-rolled steels with an acicular ferrite microstructure and the dual-phase steels with martensite dispersed in a matrix of polygonal ferrite. These two types of HSLA steels use the formation of eutectoid structures for strengthening, while the ferritic-pearlitic HSLA steels generally require strengthening of the ferrite. Pearlite is generally an undesirable strengthening agent in structural steels because it reduces impact toughness and requires higher carbon contents. Moreover, yield strength is largely unaffected by a higher pearlite content.

Strengthening Mechanisms in Ferrite. The ferrite in HSLA steels is typically strengthened by grain refinement, precipitation hardening, and, to a lesser extent, solid-solution strengthening. Grain refinement is the most desirable strengthening mechanism because it improves not only strength but also toughness.

Grain refinement is influenced by the complex effects of alloy design and processing methods. For example, the various methods of grain refinement used in the three different stages of hot rolling (that is, reheating, hot rolling, and cooling) include:

- The addition of titanium (Fig. 13(a)) or aluminum to retard austenite grain growth when the steel is reheated for hot deformation or subsequent heat treatment
- The controlled rolling of microalloyed steels to condition the austenite so that it transforms into fine-grain ferrite
- The use of alloy additions and/or faster cooling rates to lower the austenite-to-ferrite transformation temperature

The use of higher cooling rates for grain refinement may require consideration of its effect on precipitation strengthening and the possibility of undesirable transformation products.

Precipitation strengthening occurs from the formation of finely dispersed carbonitrides developed during heating and cooling. Because precipitation strengthening is generally associated with a reduction in toughness, grain refinement is often used in conjunction with precipitation strengthening to improve toughness.

Precipitation strengthening is influenced by the type of carbonitride, its grain size, and, of course, the number of carbonitrides precipitated. The formation of MC is the most effective metal carbide in the precipitation strengthening of microalloyed niobium, vanadium, and/or titanium steels. The number of fine MC particles formed during heating and cooling depends on the solubility of the carbides in austenite and on cooling rates (Fig. 11). Figure 13(b) shows the dependence of precipitation strengthening on precipitate size and volume fraction.

Steelmaking. Precise steelmaking operations are also essential in controlling the properties and chemistry of HSLA steels. Optimum property levels depend on such factors as the control of significant alloying elements and the reduction of impurities and nonmetallic inclusions.

Developments in secondary steelmaking such as desulfurization, vacuum degassing, and argon shrouding have enabled better control of steel chemistry and the effective use of microalloyed elements. In particular, the use of vacuum degassing equipment allows the production of interstitial-free (IF) steels. The IF steels exhibit excellent formability, high elongation, and good deep drawability (Fig. 8).

Compositions and Alloying Elements. Chemical compositions for the HSLA steels specified by ASTM standards (Table 10) are listed in Table 13 . The principal function of alloying elements in these ferrite-pearlite HSLA steels, other than corrosion resistance, is strengthening of the ferrite by grain refinement, precipitation strengthening, and solid-solution strengthening. Solid-solution strengthening is closely related to alloy contents (Fig. 9), while grain refinement and precipitation strengthening depend on the complex effects of alloy design and thermomechanical treatment.

Table 13 Compositional limits for HSLA steel grades described in ASTM specifications

ASTM specification (a)	Type or grade	UNS designation	Heat compositional limits, %(b)									
			C	Mn	P	S	Si	Cr	Ni	Cu	V	Other
A 242	Type 1	K11510	0.15	1.00	0.45	0.05	...	...	...	0.20 min	...	...
A 572	Grade 42	...	0.21	1.35(c)	0.04	0.05	0.30(c)	...	...	0.20 min(d)	...	(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	...	0.23(c	1.65(c)	0.04	0.05	0.30	...	...	0.20 min(d)	...	(e)

	65		)									
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 Ia	...	0.15	1.00	0.15	0.05	...	...	...	0.20 min	...	...
	Grade Ib	...	0.20	1.35	0.04	0.05	...	...	...	0.20 min(f)	...	...
	Grade II	K12609	0.22	0.85–1.25	0.04	0.05	0.30	...	...	...	0.02 min	...
	Grade III	K12700	0.23	1.35	0.04	0.05	0.30	...	...	...	0.02 min	0.005 Nb min(g)
A 633	Grade A	K01802	0.18	1.00–1.35	0.04	0.05	0.15–0.30	...	...	...	...	0.05 Nb
	Grade C	K12000	0.20	1.15–1.50	0.04	0.05	0.15–0.50	...	...	...	...	0.01–0.05 Nb
	Grade D	K02003	0.20	0.70–1.60 (c)	0.04	0.05	0.15–0.50	0.25	0.25	0.35	...	0.08 Mo
	Grade E	K12202	0.22	1.15–1.50	0.04	0.05	0.15–0.50	...	...	...	0.04–0.11	0.01–0.05 Nb(d), 0.01–0.03 N
A 656	Type 3	...	0.18	1.65	0.025	0.035	0.60	...	...	...	0.08	0.020 N, 0.005–0.15 Nb
	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 690	...	K12249	0.22	0.60–0.90	0.08–0.15	0.05	0.10	...	0.40–0.75	0.50 min	...	...
A 709	Grade 50, type 1	...	0.23	1.35	0.04	0.05	0.40	...	...	...	...	0.005–0.05 Nb
	Grade 50, type 2	...	0.23	1.35	0.04	0.05	0.40	...	...	...	0.01–0.15	...
	Grade 50, type 3	...	0.23	1.35	0.04	0.05	0.40	...	...	...	(h)	0.05 Nb max
	Grade	...	0.23	1.35	0.04	0.05	0.40	...	...	...	(i)	0.015 N max

	50, type 4											
A 715	...	...	0.15	1.65	0.025	0.035	...	...	...	...	V, Ti Nb added as 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 10 ; for mechanical properties, see Table 16 . (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 ≥ 4 N). (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 over 40 mm (1 to 5 in.), ASTM A 841 specifies manganese contents of 1.00 to 1.60%.

Alloying elements are also selected to influence transformation temperatures so that the transformation of austenite to ferrite and pearlite occurs at a lower temperature during air cooling. This lowering of the transformation temperature produces a finer-grain transformation product, which is a major source of strengthening. At the low carbon levels typical of HSLA steels, elements such as silicon, copper, nickel, and phosphorus are particularly effective for producing fine pearlite. Elements such as manganese and chromium, which are present in both the cementite and ferrite, also strengthen the ferrite by solid-solution strengthening in proportion to the amount dissolved in the ferrite.
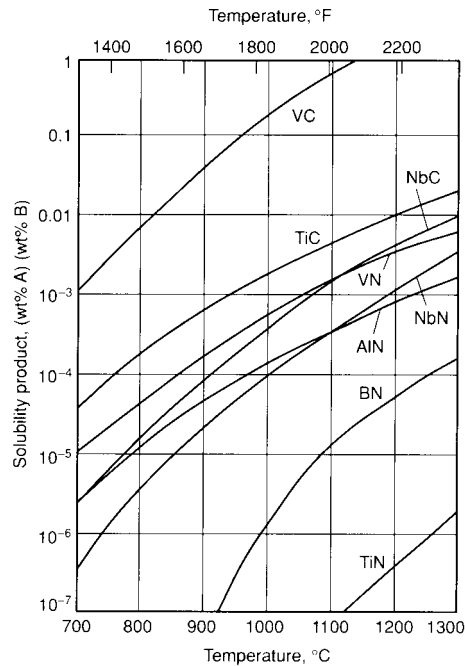
Carbon markedly increases the amount of pearlite in the microstructure and is one of the more potent, as well as economical, strengthening elements. However, higher carbon contents reduce weldability and the impact toughness of steel. Increases in pearlite content are also ineffective in improving yield strength, which is often the main strength criterion in structural applications.

In the presence of alloying elements, the practical maximum carbon content at which HSLA steels can be used in the as-rolled condition is approximately 0.20%. Higher levels of carbon tend to form martensite or bainite in the microstructure of as-rolled steels, although some of the higher-strength low-alloy steels have carbon contents that approach 0.30%. Many of the proprietary microalloyed HSLA steels have carbon contents of 0.06% or even lower, yet are still able to develop yield strengths of 345 to 620 MPa (50 to 90 ksi). Carbon levels as low as 0.03% are utilized in some alloy designs. The required strength is developed by the combined effect of:

- Fine grain size developed during controlled hot rolling and enhanced by microalloyed elements (especially niobium)
- Precipitation strengthening caused by the presence of vanadium, niobium, and titanium in the composition

Nitrogen in amounts up to about 0.02% has been used to obtain strengths typical of HSLA steels and at reasonable cost. For carbon and carbon-manganese steels, such a practice is limited to light-gage products because the increase in strength is accompanied by a drop in notch toughness. In some applications, nitrogen contents are limited to 0.005%. Nitrogen additions to high-strength steels containing vanadium have become commercially important because such additions enhance precipitation hardening. The precipitation of vanadium nitride in vanadium-nitrogen steels also improves grain refinement because it has a lower solubility in austenite than vanadium carbide (Fig. 15). The total effect of nitrogen on yield strength is discussed in the section "Tensile Properties" in this article.

Fig. 15 Solubility product versus temperature for eight carbonitride compounds in austenite

Temperature, °F

1400   1600   1800   2000   2200

Solubility product, (wt% A) (wt% B)

VC
NbC
TiC
VN
NbN
AlN
BN
TiN

700 800 900 1000 1100 1200 1300
Temperature, °C

Manganese is the principal strengthening element in plain carbon high-strength structural steels when it is present in amounts over 1%. It functions mainly as a mild solid-solution strengthener in ferrite, but it also provides a marked decrease in the austenite-to-ferrite transformation temperature. In addition, manganese can enhance the precipitation strengthening of vanadium steels (Table 12) and, to a lesser extent, niobium steels.

Silicon. One of the most important applications of silicon is its use as a deoxidizer in molten steel. It is usually present in fully deoxidized structural steels in amounts up to 0.35%, which ensures the production of sound, dense ingots. Silicon has a strengthening effect in low-alloy structural steels. In larger amounts, it increases resistance to scaling at elevated temperatures. Silicon has a significant effect on yield strength enhancement by solid-solution strengthening (Fig. 9) and is widely used in HSLA steels for riveted or bolted structures. It can be used up to 0.30% in weldable steels; higher amounts produce a deterioration in notch toughness and weldability (Ref 23).

Copper. Approximately 0.20% copper is used to provide resistance to atmospheric corrosion. Its effect on resistance to corrosion is enhanced when phosphorus is present in amounts greater than about 0.05%.

Copper in levels in excess of 0.50% also increases the strength of both low- and medium-carbon steels by virtue of ferrite strengthening, which is accompanied by only slight decreases in ductility. In amounts over about 0.60%, copper can precipitate as ε-copper, which precipitation strengthens the ferrite. Copper can be retained in solid solution even at the slow rate of cooling obtained when large sections are normalized, but it is precipitated out when the steel is reheated to about 510 to 605 °C (950 to 1125 °F). At about 1% copper, the yield strength is increased by about 70 to 140 MPa (10 to 20 ksi), regardless of the effects of other alloying elements. Copper in amounts up to 0.75% is considered to have only minor adverse effects on notch toughness or weldability.

Copper precipitation hardening gives the steel the ability to be formed extensively (while still low in strength) and then precipitation hardened as a complex shape or welded assembly. This avoids the distortion or difficulty encountered by quenching compared with components made from conventionally heat-treated alloy steel.

Steels containing more than 0.50% Cu can exhibit hot shortness, with the result that cracks and a rough surface may develop during hot working. Careful control of oxidation during heating and prevention of overheating can minimize these conditions. The addition of nickel in amounts equal to at least one-half the copper content is very beneficial to the surface quality of copper-bearing steels. Copper is also added in amounts between 0.25−0.35% to improve resistance to hydrogen-induced cracking in aqueous environments and H_2S environments.

Phosphorus is an effective solid-solution strengthener in ferrite (Fig. 9). It also enhances corrosion resistance but causes a decrease in ductility. Phosphorus at low levels (<0.05% P) can also cause embrittlement through segregation to the prior-austenite grain boundaries.

The atmospheric-corrosion resistance of steel is increased appreciably by the addition of phosphorus, and when small amounts of copper are present in the steel, the effect of the phosphorus is greatly enhanced. When both phosphorus and copper are present, there is a greater beneficial effect on corrosion resistance than the sum of the effects of the individual elements.

Chromium is often added with copper to obtain improved atmospheric-corrosion resistance. Upon exposure to the atmosphere, a steel composition with about 0.12% P, 0.85% Cr, and 0.40 Cu% develops a particularly adherent, dense oxide coating that is characteristic of weathering steels.

Nickel can be added in amounts up to about 1% in several HSLA steels and in amounts up to 5% for high-strength heat-treated alloy grades. It moderately increases strength by solution hardening of the ferrite. In HSLA steels, it enhances

atmospheric-corrosion resistance and, when present in combination with copper and/or phosphorus, increases the seawater corrosion resistance of steels. Nickel is often added to copper-bearing steels to minimize hot shortness.

Molybdenum in hot-rolled HSLA steels is used primarily to improve hardenability when transformation products other than ferrite-pearlite are desired. For example, molybdenum is an essential ingredient for producing as-rolled acicular ferrite steels. In addition, it effectively enhances elevated-temperature properties.

Molybdenum (0.15 to 0.30%) in microalloyed steels also increases the solubility of niobium in austenite, thereby enhancing the precipitation of NbC(N) in the ferrite. This increases the precipitation-strengthening effect of Nb(C,N). Molybdenum has also been shown to join the Nb(C,N) precipitates, which further raises the yield strength.

Niobium. Small additions (0.03 to 0.05% Nb) of niobium increase yield strength by a combination of precipitation strengthening (Fig. 12) and grain refinement. Niobium is a more effective grain-refining element than vanadium because niobium carbide is more stable in austenite than vanadium carbide at typical rolling temperatures. The lower solubility of niobium carbide in austenite (Fig. 15) provides more stable precipitate particles, which pin the austenite grain boundaries and thus retard austenite grain growth.

Aluminum is widely used as a deoxidizer and was the first element used to control austenite grain growth during reheating. During controlled rolling, niobium and titanium are more effective grain refiners than aluminum. Titanium (Fig. 13(a)), niobium, zirconium, and vanadium are also effective grain growth inhibitors during reheating. However, for steels that are heat treated (quenched and tempered), these four elements may have adverse effects on hardenability because their carbides are quite stable and difficult to dissolve in austenite prior to quenching.

Vanadium strengthens HSLA steels by both precipitation hardening the ferrite and refining the ferrite grain size. The precipitation of vanadium carbonitride in ferrite can develop a significant increase in strength that depends not only on the rolling process used, but also on the base composition. Carbon contents above 0.13 to 0.15% and manganese content of 1% or more enhances the precipitation hardening, particularly when the nitrogen content is at least 0.01%. Grain size refinement depends on thermal processing (hot rolling) variables, as well as vanadium content.

Titanium is unique among common alloying elements in that it provides both precipitation strengthening and sulfide shape control. Small amounts of titanium (<0.025%) are also useful in limiting austenite grain growth (Fig. 13(a)). However, it is useful only in fully killed (aluminum deoxidized) steels because of its strong deoxidizing effects. The versatility of titanium is limited because variations in oxygen, nitrogen, and sulfur affect the contribution of titanium as a carbide strengthener.

Zirconium can also be added to killed high-strength low-alloy steels to improve inclusion characteristics, particularly in the case of sulfide inclusions, for which changes in inclusion shape improve ductility in transverse bending.

Boron has no effect on the strength of normal hot-rolled steel but can considerably improve hardenability when transformation products such as acicular ferrite are desired in low-carbon hot-rolled plate. Its full effect on hardenability is obtained only in fully deoxidized (aluminum-killed) steels.

Rare-earth elements, principally cerium, lanthanum, and praseodymium, can be used to provide shape control of sulfide inclusions. Sulfide inclusions, which are plastic at rolling temperatures and thus elongate and flatten during rolling, adversely affect ductility in the short transverse (through-thickness) direction. The chief role of rare-earth additives is to produce rare-earth sulfide and oxysulfide inclusions, which have negligible plasticity at even the highest rolling temperatures. Excessive amounts of cerium (>0.02%) and other rare-earth elements lead to oxide or oxysulfide stringers that may affect directionality. Treatment with rare-earth elements is seldom used because they produce relatively dirty steels. Treatment with calcium is preferred for sulfide inclusion shape control.

Controlled Rolling. The hot-rolling process has gradually become a much more closely controlled operation, and controlled rolling is now being increasingly applied to microalloyed steels with compositions carefully chosen to provide optimum mechanical properties at room temperature. Controlled rolling is a procedure whereby the various stages of rolling are temperature controlled, with the amount of reduction in each pass predetermined and the finishing temperature precisely defined. This processing is widely used to obtain reliable mechanical properties in steels for pipelines, bridges, offshore platforms, and many other engineering applications. The use of controlled rolling has resulted in improved combinations of strength and toughness and further reductions in the carbon content of microalloyed HSLA steels. This reduction in carbon content improves not only toughness but also weldability.

The basic objective of controlled rolling is to refine and/or deform austenite grains during the rolling process so that fine ferrite grains are produced during cooling. Controlled rolling can be performed on carbon steels but is most beneficial in steels with vanadium and/or niobium additions. During hot rolling, the undissolved carbonitrides of vanadium and niobium pin austenite grain boundaries and thus retard austenite grain growth. In carbon steels, however, the temperatures involved in hot rolling lead to marked austenite grain growth, which basically limits any benefit of grain refinement by controlled rolling. Controlled rolling is performed on strip, plate, and bar mills but not on continuous hot strip mills. On a hot strip mill, the water cooling on the runout table ensures a fine grain size.

The three methods of controlled rolling are:

- Conventional controlled rolling
- Recrystallization controlled rolling
- Dynamic recrystallization controlled rolling

These three methods use different techniques for grain refinement, but they are all preceded by a roughing operation to refine grain size by repeated recrystallization. In the roughing stage, stable carbonitride precipitates are desirable because they pin the
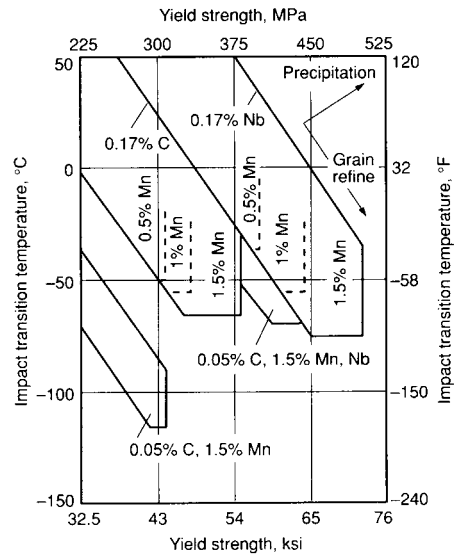
grain boundaries of the recrystallized austenite and thus prevent their growth. Niobium is more effective than vanadium in preventing austenite grain growth during rolling because niobium forms precipitates that are less soluble than vanadium carbide in austenite (Fig. 15). Roughing can achieve austenite grain sizes on the order of 20 μm (0.8 mil). The austenite grains are then either deformed or further refined by controlled rolling during finishing operations.

Conventional controlled rolling is based on the deformation, or flattening (pancaking), of austenite grains so that a large number of nucleation sites exist on the deformed austenite grain boundaries and on the deformation bands with the austenite grains. These nucleation sites allow the formation of very fine-grain ferrite during transformation cooling. This process requires a total reduction of up to 80% in a temperature range where the austenite deforms but does not recrystallize.
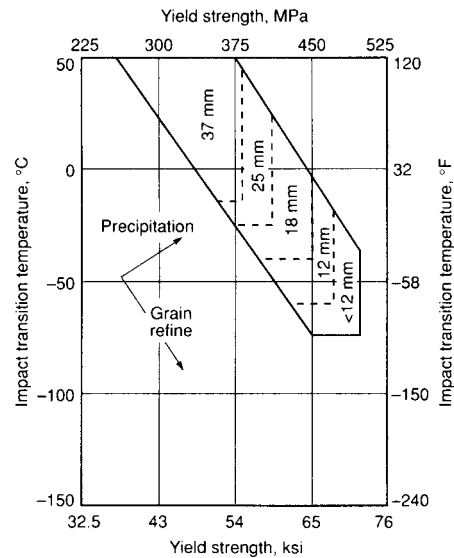
Niobium is the most effective alloying element for grain refinement by conventional controlled rolling. During the rolling reductions at temperatures below 1040 °C (1900 °F), the niobium in solution suppresses recrystallization by solute drag or by strain-induced Nb(C,N) precipitation on the deformed austenite and slip planes. The strain-induced precipitates are too large to affect precipitation strengthening but are beneficial for two reasons: They allow additional suppression of recrystallization by preventing migration of austenite grain sub-boundaries, and they provide a large number of nuclei in the deformed austenite for the formation of fine ferrite particles during cooling. The strain-induced precipitates in the austenite detract from the precipitation-hardening potential of the ferrite by removing the available niobium from austenite solid solution. Nevertheless, a useful measure of precipitation strengthening is possible in controlled-rolled niobium steels.

The controlled rolling of niobium steels can lead to ferrite grain sizes in the range of 5 to 10 μm (ASTM grain size numbers 10 to 12). General combinations of yield strength and ductile-brittle transition temperatures for niobium steel with various compositions and section sizes are shown in Fig. 16 . Because the precipitation of Nb(CN) in the austenite during hot rolling retards recrystallization and raises the temperature at which recrystallization of austenite ceases (the recrystallization stop temperature), a broader temperature range is possible for hot working the steel to produce highly deformed austenite. The optimum amount of niobium to suppress recrystallization between passes can be as little as 0.02%. Titanium, zirconium, and vanadium are not as effective as niobium in raising the recrystallization stop temperature. Titanium and zirconium nitride formed during solidification and upon cooling of the slab do not readily dissolve upon reheating to hot-rolling temperatures. Although these nitrides may prevent grain coarsening upon reheating, they are not effective in preventing recrystallization, because insufficient titanium or zirconium remains in solution at the rolling temperature to precipitate on deformed austenite during boundaries during hot-rolling and thus suppress austenite recrystallization. Vanadium, on the other hand, is so soluble that precipitation does not readily occur in the austenite at normal hot-rolling temperatures. The concentrations of niobium, titanium, vanadium, carbon, and nitrogen; the degree of strain; the time between passes; the strain rate; and the temperature of deformation all influence recrystallization during hot working.

Fig. 16 General combinations of yield stress and impact transition temperatures available in controlled-rolled steels of various (a) compositions and (b) section sizes. Source: Ref 24

(a)

Yield strength, MPa

225 300 375 450 525

Precipitation

0.17% Nb

0.17% C

Grain refine

0.5% Mn

1% Mn

1.5% Mn

0.5% Mn

1% Mn

1.5% Mn

0.05% C, 1.5% Mn, Nb

0.05% C, 1.5% Mn

Impact transition temperature, °C: 50, 0, −50, −100, −150

Impact transition temperature, °F: 120, 32, −58, −150, −240

Yield strength, ksi: 32.5 43 54 65 76

(b)

Yield strength, MPa

225 300 375 450 525

37 mm

25 mm

18 mm

12 mm

<12 mm

Precipitation

Grain refine

Impact transition temperature, °C: 50, 0, −50, −100, −150

Impact transition temperature, °F: 120, 32, −58, −150, −240

Yield strength, ksi: 32.5 43 54 65 76

Recrystallization Controlled Rolling. Although conventional controlled rolling can lead to very fine ferrite grain sizes, the low finishing temperature (750 to 900 °C, or 1400 to 1650 °F) of this method leads to increased rolling loads for heavy plate and thick-walled seamless tube. For thicker sections, recrystallization controlled rolling is used to refine austenite grain size. This process can result in ferrite grain sizes on the order of 8 to 10 μm (0.3 to 0.4 mil).

Recrystallization controlled rolling involves the recrystallization of austenite at successively lower temperatures below roughing temperatures but still above 900 °C (1650 °F). Recrystallization should not be sluggish for this method to succeed, and thus vanadium can be beneficial because vanadium carbide is readily dissolved at rolling temperature and therefore unavailable for suppressing recrystallization. However, vanadium steels require stable carbonitrides, such as titanium nitride, to retard grain growth after recrystallization. Niobium steels, on the other hand, can undergo recrystallization controlled rolling at higher temperatures with Nb(C,N) precipitates eventually forming. This precipitation of Nb(C,N) will restrict austenite grain growth and may preclude the need for a titanium addition.

Dynamic recrystallization controlled rolling is used when there is insufficient time for recrystallization between rolling passes. This process initiates recrystallization during deformation and requires appreciable reductions (for example, 100%) to achieve an austenite grain size of 10 μm (0.4 mil). With low-temperature finishing, dynamic recrystallization can result in ferrite grain as fine as 3 to 6 μm (0.12 to 0.24 mil).

Interpass Cooling in Controlled Rolling. One of the major drawbacks with conventional controlled rolling is excessive processing time, especially on single-stand mills lacking facilities for removing plates off line during the hold period. Therefore, some investigations have examined the possibility of reducing processing time by the application of accelerated cooling both during the delay period and between individual roughing and finishing passes. In general, it would appear that the process time can be shortened by 30 to 40%, depending on exactly when forced cooling is applied in the rolling schedule. The as-rolled microstructure is not affected very much by intermittent cooling between passes but prolonged exposure to water during the hold

period causes the temperature of the surface layers of the plate to fall below Ar$_3$. On resumption of rolling, this surface shell is reaustenitized by heat conduction from the interior of the plate; the surface austenite grain size is thereby considerably finer than that in the rest of the material, and this difference persists, of course, in the microstructure after rolling. Such nonuniformity of microstructure and properties in the through-thickness direction is hardly desirable, but it is unlikely to be directly detrimental to any particular bulk property of the plate (with the possible exception of bendability). Plates processed with shorter rolling times by the application of accelerated cooling between passes and/or under holding appear to exhibit equivalent strength and toughness properties to those controlled rolled in the conventional manner (Ref 11).

Normalizing. As with carbon steels, normalizing can be used to refine the ferrite-pearlite grain size in HSLA steels. However, because microalloyed HSLA steels may involve some strengthening by precipitation hardening, normalizing may cause a reduction in precipitation strengthening when stable carbonitride precipitates coarsen at typical austenitizing temperatures for normalizing. For example, normalizing a conventionally hot-rolled niobium steel reduces the yield strength considerably so that much of the precipitation strengthening increment that is due to niobium in the as-rolled condition is lost (Ref 23, 31). At the usual austenitizing temperatures for normalizing, most of the niobium has not been taken into solution and is present as relatively coarse precipitates. Thus, niobium inhibits grain coarsening, but provides little or no precipitation strengthening when the steel is normalized. However, the grain refining accounts for the improved low-temperature impact properties and most of the small increase in strength, compared to a niobium-free steel (Ref 23). Normalized niobium steels thus provide a fairly good combination of yield strength and ductile-brittle impact transition temperatures, even in semikilled steels (which contain free nitrogen that is detrimental to impact toughness). Niobium steels, along with titanium and vanadium steels, in the form of normalized, heavy-gage plate find important applications in offshore and general construction, shipbuilding, and pressure vessels in Europe. Normalized steels of this type are always fully aluminum killed (Ref 23). A typical example of a normalized niobium steel in the United States is the grade C steel in ASTM A 633 (Table 13). Minimum yield strengths of this steel range from 345 MPa (50 ksi) for plate thicknesses under 65 mm (2.5 in.) to 315 MPa (46 ksi) for plate thicknesses of 65 to 100 mm (2.5 to 4 in.). Charpy V-notch impact energies for the normalized steels in ASTM A 633 range from 41 J (30 ft · lbf) for transverse specimens at 0 °C (32 °F) to 20 J (15 ft · lbf) for transverse specimens at −50 °C (−60 °F).

Although normalized niobium steels have a finer ferrite grain size than do normalized carbon-manganese steels, when strength is of paramount importance, controlled rolling of niobium steels is preferred over normalizing because controlled rolling also provides a measure of precipitation strengthening. Vanadium, on the other hand, causes marked precipitation strengthening with limited grain refinement upon normalizing because practically all of the vanadium is in solution at usual normalizing temperatures. The strengthening with vanadium in normalized steels is far greater than can be obtained in normalized niobium steels (Ref 23). In the normalized condition, vanadium semikilled structural steels also have impact properties superior to those of the semikilled niobium steels because vanadium combines with part of the nitrogen, thereby reducing the free-nitrogen content.

Table 14 lists some typical impact toughness values and yield strengths of aluminum-killed European vanadium steels in the normalized condition (see Table 15 for chemical compositions). In the United States, a typical example of a normalized vanadium steel is the grade E steel in ASTM A 633 (Table 13). Minimum yield strengths for this steel range from 415 MPa (60 ksi) for plate thicknesses under 100 mm (4 in.) to 380 MPa (55 ksi) for plate thicknesses of 100 to 150 mm (4 to 6 in.). Charpy V-notch impact energies are the same as for ASTM A 633, grade C, mentioned in the previous paragraph.

Table 14 Mechanical properties of a representative sample of normalized HSLA steels produced in Europe

Steel	Minimum yield strength, MPa (ksi), for a plate thickness of		Minimum ultimate tensile strength, MPa (ksi), for a plate thickness of		Minimum Charpy V-notch impact energy, J (ft · lbf) at				
					0 °C (32 °F)		−50 °C (−60 °F)	
	≤16 mm (≤0.63 in.)	50 <t≤80 mm (2<t≤3 in.)	≤16 mm (≤0.63 in.)	50 <t≤80 mm (2<t≤3 in.)	Longitudinal	Transverse	Longitudinal	Transverse
Usiten 420-II	420 (61)	...	550 (80)	...	56 (41)	44 (32)	28 (21)	21 (15)
Usiten 460-I	460 (67)	...	590 (85)	...	48 (35)	36 (27)	...	...
Usiten 460-II	...	420 (61)	...	570 (82)	48 (35)	36 (27)	28 (21)	16 (12)
FG 43 T	420 (61)	...	530 (77)	...	...	...	27 (20)	27 (20)(a)
FG 47 CT	460 (67)	...	560 (81)	...	...	...	27 (20)	27 (20)(a)
FG 51 T	500 (72)	...	610 (88)	...	...	31 (23)	27 (20)(b)	...
Dillinal 55/43E	420 (61)	380 (55)	530 (77)	530 (77)	90 (66)	70 (52)	30 (22)	27 (20)
Dillinal 58/47E	460 (67)	420 (61)	560 (81)	560 (81)	90 (66)	70 (52)	30 (22)	27 (20)
Hyplus 29	450 (65)	400 (58)(d)	570 (82)	570 (82)	54 (40)	...	27 (20)(c)	...
BS 4360:55E	450 (65)	415 (60)(d)	550 (80)	550 (80)	...	61 (45)(a)	...	27 (20)
WSTE 500	480 (70)	450 (65)	610 (88)	610 (88)	≥44 (≥32)(a)	...	...	...

(a) −20 °C (−4 °F). (b) −40 °C (−40 °F) (c) −30 °C (−22 °F) (d) For plate thicknesses of 40 to 63 mm (1.5 to 2.5 in.)

Table 15 Chemical composition of a representative sample of normalized HSLA steels produced in Europe

Steel	Producer	Composition, %										
		C max	Mn max	Si max	P max	S max	Nb max	V	Ni	Cr max	Mo max	Cu
Usiten 420-II	Usinor	0.22	1.6	0.55	0.035	0.030	...	...	0.5–0.7	0.2	0.1	0.3 max
Usiten 460-I	Usinor	0.20	1.7	0.50	0.035	0.030	0.045	0.07–0.13	≤0.2	0.2	0.1	0.3 max
Usiten 460-II	Usinor	0.18	1.7	0.40	0.035	0.030	0.045	0.09–0.15	0.5–0.7	0.2	0.1	0.3 max
FG 43 T	Thyssen	0.18	1.7	0.5	0.030	0.030	...	0.10–0.18	0.7 max	...	...	...
FG 47 CT	Thyssen	0.15	1.5	0.5	0.030	0.030	...	0.08–0.18	0.5–0.7	...	...	0.5–0.7
FG 51 T	Thyssen	0.21	1.7	0.5	0.030	0.030	...	0.10–0.20	0.4–0.7	...	...	...
Dillinal 55/43E	Dillinger	0.18	1.7	0.5	0.025	0.015	...	0.10–0.18	0.7 max	...	...	...
Dillinal 58/47E	Dillinger	0.20	1.7	0.5	0.025	0.015	...	0.10–0.20	0.7 max	...	...	...
Hyplus 29	BSC	0.22	1.6	0.5	0.05	0.03	...	0.20 max	...	...	...	...
BS 4360:55E	BSC	0.22	1.6	0.6	0.04	0.04	0.10	0.20 max	...	...	...	...
WSTE 500	Creusot-Loire	0.18	1.6	...	0.015	0.010	...	0.10 max	0.3–0.7	...	...	...

Precipitation Strengthening With Copper. Steels with about 0.6% or more copper can be precipitation strengthened by aging in a temperature range from about 425 to 650 °C (800 to 1200 °F). When reheated to 510 to 607 °C (950 to 1125 °F) after rolling, precipitation-hardened copper-bearing steels with more than 0.75% Cu have typical mechanical properties:

Tensile strength, MPa (ksi)	540 (78)
Yield strength, MPa (ksi)	485 (70)
Elongation in 50 mm (2 in.), %	20
Reduction of area, %	60

Mechanical Properties of Hot-Rolled HSLA Steels

The three major types of HSLA steel microstructures are dual-phase microstructures, acicular ferrite microstructures, and ferrite-pearlite microstructures. Typical tensile properties of dual-phase HSLA steels are summarized in Fig. 8 of this article and are discussed in more detail in the article "Dual-Phase Steels" in this Volume. Some limited yield strength and impact toughness values of various controlled-rolled acicular ferrite HSLA steels are given in Fig. 14 .

Hot-rolled steels with ferrite-pearlite microstructures are the most common HSLA steels and are the primary focus of this section. Commercially available HSLA steels with ferrite-pearlite microstructures have yield strengths ranging up to 700 MPa (100 ksi), which is almost a fourfold increase over the 200 MPa (30 ksi) yield strength of conventional hot-rolled plain carbon steel. The increased strengths are developed by variations in composition and processing, but compositions having similar strengths are produced in different ways by different producers. There are three principal microalloying additions: niobium, vanadium, and titanium. Other additions can be made, depending on processing capabilities (particularly the cooling facilities) and on property requirements for the finished steel. In order to achieve good transverse properties, calcium-silicon ladle additions (or, less often, additions of rare-earth elements) are used in niobium- or vanadium-containing steels to control the shape of sulfide inclusions. For HSLA compositions containing titanium, ladle treatments for sulfide shape control are not required; titanium itself has the desired effect on the shape of sulfide inclusions. In recent years, calcium treatment has replaced rare-earth elements in sulfide inclusion shape control.

Tensile properties of some hot-rolled ferrite-pearlite HSLA steels are summarized in Tables 16 and 17 . These properties are influenced by alloying elements and production methods.

Table 16 Tensile properties of HSLA steel grades specified in ASTM standards

ASTM specification (a)	Type, grade, or condition	Product thickness(b)		Minimum tensile strength(c)		Minimum yield strength(c)		Minimum elongation, % (c)		Bend radius (c)	
		mm	in.	MPa	ksi	MPa	ksi	in 200 mm (8 in.)	in 50 mm (2 in.)	Longitudinal	Transverse
A 242	Type 1	20	3/4	480	70	345	50	18	...	...	...
		20–40	3/4–1 1/2	460	67	315	46	18	21	...	...
		40–100	1 1/2–4	435	63	290	42	18	21	...	...

A 572	Grade 42	150	6	415	60	290	42	20	24	(d)	...
	Grade 50	100	4	450	65	345	50	18	21	(d)	...
	Grade 60	32	$1\frac{1}{4}$	520	75	415	60	16	18	(d)	...
	Grade 65	32	$1\frac{1}{4}$	550	80	450	65	15	17	(d)	...
A 588	Grades A-K	100	4	485	70	345	50	18	21	(d)	...
		100–125	4–5	460	67	315	46	...	21	(d)	...
		125–200	5–8	435	63	290	42	...	21	(d)	...
A 606	Hot rolled	Sheet		480	70	345	50	...	22	t	$2t$–$3t$
	Hot rolled and annealed or normalized	Sheet		450	65	310	45	...	22	t	$2t$–$3t$
	Cold rolled	Sheet		450	65	310	45	...	22	t	$2t$–$3t$
A 607	Grade 45	Sheet		410	60	310	45	...	22–25	t	$1.5t$
	Grade 50	Sheet		450	65	345	50	...	20–22	t	$1.5t$
	Grade 55	Sheet		480	70	380	55	...	18–20	$1.5t$	$2t$
	Grade 60	Sheet		520	75	415	60	...	16–18	$2t$	$3t$
	Grade 65	Sheet		550	80	450	65	...	15–16	$2.5t$	$3.5t$
	Grade 70	Sheet		590	85	485	70	...	14	$3t$	$4t$
A 618	Ia, Ib, II	19	$\frac{3}{4}$	485	70	345	50	19	22	t–$2t$	...
	Ia, Ib, II, III	19–38	$\frac{3}{4}$–$1\frac{1}{2}$	460	67	315	46	18	22	t–$2t$	...
A 633	A	100	4	430–570	63–83	290	42	18	23	(d)	...
	C, D	65	2.5	485–620	70–90	345	50	18	23	(d)	...
	C, D	65–100	2.5–4	450–590	65–85	315	46	18	23	(d)	...
	E	100	4	550–690	80–100	415	60	18	23	(d)	...
	E	100–150	4–6	515–655	75–95	380	55	18	23	(d)	...
A 656	50	50	2	415	60	345	50	20	...	(d)	...
	60	40	$1\frac{1}{2}$	485	70	415	60	17	...	(d)	...
	70	25	1	550	80	485	70	14	...	(d)	...
	80	20	$\frac{3}{4}$	620	90	550	80	12	...	(d)	...
A 690	...	100	4	485	70	345	50	18	...	$2t$	...
A 709	50	100	4	450	65	345	50	18	21	...	...
	50W	100	4	485	70	345	50	18	21	...	...
A 715	Grade 50	Sheet		415	60	345	50	...	22–24	0	t
	Grade 60	Sheet		485	70	415	60	...	20–22	0	t
	Grade 70	Sheet		550	80	485	70	...	18–20	t	$1.5t$
	Grade 80	Sheet		620	90	550	80	...	16–18	t	$1.5t$
A 808	...	40	$1\frac{1}{2}$	450	65	345	50	18	22	...	...
		40–50	$1\frac{1}{2}$–2	450	65	315	46	18	22	...	...
		50–65	2–$2\frac{1}{2}$	415	60	290	42	18	22	...	...
A 812	65	Sheet		585	85	450	65	...	13–15	...	...
	80	Sheet		690	100	550	80	...	11–13	...	...
A 841	...	65	2.5	485–620	70–90	345	50	18	22	...	...
		65–100	2.5–4	450–585	65–85	310	45	18	22	...	...
A 871	60, as-hot-rolled	5–35	$\frac{3}{16}$–$1\frac{3}{8}$	520	75	415	60	16	18	...	...
	65, as-hot-rolled	5–20	$\frac{3}{16}$–$\frac{3}{4}$	550	80	450	65	15	17	...	...

(a) For characteristics and intended uses, see Table 10 ; for specified compositional limits, see Table 13 . (b) Maximum product thickness

except when a range is given. No thicknesses are specified for sheet products. (c) May vary with product size and mill form. (d) Optional supplementary requirement given in ASTM A 6

Table 17 Mechanical properties of HSLA steel grades described in SAE J410

Grade(a)	Minimum tensile strength(b)		Minimum yield strength(b), (c)		Minimum elongation, %(b)		Bend diameter(b), (d)
	MPa	ksi	MPa	ksi	in 200 mm (8 in.)	in 50 mm (2 in.)	
942X	415	60	290	42	20	24	$t–3t$
945A	415–450	60–65	275–310	40–45	18–19	22–24	$t–3t$
945C	415–450	60–65	275–310	40–45	18–19	22–24	$t–3t$
945X	415	60	310	45	19	22–25	$t–2.5t$
950A	430–483	63–70	290–345	42–50	18–19	22–24	$t–3t$
950B	430–483	63–70	290–345	42–50	18–19	22–24	$t–3t$
950C	430–483	63–70	290–345	42–50	18–19	22–24	$t–3t$
950D	430–483	63–70	290–345	42–50	18–19	22–24	$t–3t$
950X	450	65	345	50	18	22	$t–3t$
955X	483	70	380	55	17	20	$t–3.5t$
960X	520	75	415	60	16	18	$1.5t–3t$
965X	550	80	450	65	15	16	$2t–3t$
970X	590	85	485	70	14	14	$3t$
980X	655	95	550	80	10	12	$3t$

(a) For compositions, available mill forms, and special characteristics of these steels, see Table 11 . (b) May vary with product size and mill form; for specific limits, refer to SAE J410. (c) 0.2% offset. (d) 180° bend test at room temperature. Used for mill acceptance purposes only; not to be used as a basis for specifying fabricating procedures.

In vanadium-microalloyed HSLA steels, yield strengths are influenced by manganese content (Table 12), nitrogen content (Fig. 17), and cooling rates (Fig. 11). The cooling rate, which determines the level of precipitation strengthening in vanadium steels, depends on the temperature, the product thickness, and the cooling medium. For thin products, temperature is the primary factor influencing cooling rates. For example, the strength of vanadium steel sheet is shown in Fig. 17 as a function of coiling temperature.

Fig. 17 Effect of coiling temperature and total nitrogen content on the yield strength of a vanadium microalloyed steel (0.13% C, 1.4% Mn, 0.5% Si, 0.12% V). Yield strengths are for a 6.3 mm (0.25 in.) thick sheet, finished at 900 °C (1650 °F) and then cooled at 17 °C/s (30 °F/s). Source: Ref 5
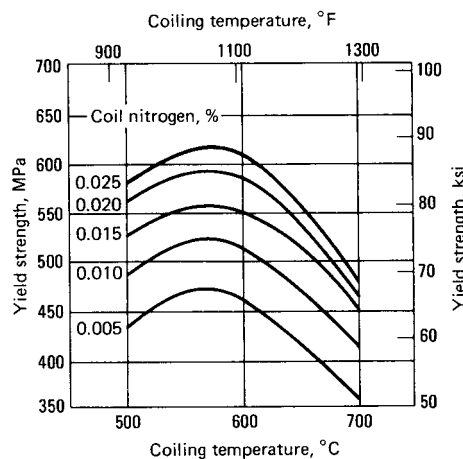
Yield strengths in niobium steels are also affected by rolling procedures and cooling rates. Figure 18 shows the effect of finishing temperature on the yield strength of a niobium-manganese steel after finish-rolling reductions of 75 and 66%. The range of yield strengths for controlled-rolled niobium steels of various compositions and section thicknesses is shown in Fig. 16 . A typical controlled-rolled and accelerated-cooled HSLA steel is specified in ASTM A 841.

Fig. 18 Effect of finishing temperatures and reductions during finishing on the yield strength of a niobium-manganese steel (0.1% C, 1.25% Mn, 0.027% Nb, 0.2% Si, 0.03% Al). The reheat temperature was 1080 °C (1975 °F), with a cooling

rate of 10 °C/s (18 °F/s) and a cooling temperature of 600 °C (1110 °F). Source: Ref 32
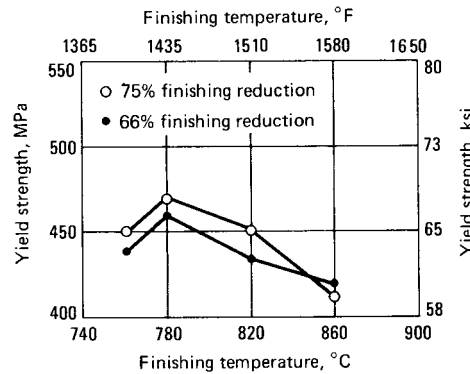
The notch toughness of microalloyed structural steels, as evaluated by Charpy-impact or drop-weight tests, is generally superior to that of structural carbon steels. The transition temperatures of the former also are lower. Figure 1 compares Charpy V-notch impact values for structural carbon steel (ASTM A 7), an HSLA steel, and a heat-treated constructional alloy steel. In the presence of a stress raiser, brittle failure is less likely to occur at subnormal temperatures in steels with lower transition temperatures. The transition temperatures of proprietary grades in the as-rolled or normalized conditions are controlled principally by chemical composition (particularly carbon) and ferrite grain size.

Notch toughness is reduced when the ferrite-pearlite HSLA steels are strengthened by precipitation hardening. The notch toughness of vanadium steels can be improved by normalizing or recrystallization controlled rolling. The notch toughess of niobium steels is normally improved by conventional controlled rolling, although the effects of recrystallization controlled rolling are under study. Figure 16 shows the range in notch toughness for controlled-rolled niobium steels, as evaluated by ductile-brittle transition temperatures.

Brittle Fracture. Most structural steels exhibit a transition in fracture behavior from ductile to brittle when the temperature is lowered to some critical temperature known as the nil-ductility transition temperature (NDTT). This temperature is defined as the temperature at which steel loses its ability to flow plastically in the presence of a sharp, cracklike discontinuity. At and below the NDTT, a brittle cleavage fracture will initiate from this discontinuity when stresses approaching the yield strength are reached in the volume of material surrounding the discontinuity. Once initiated, brittle fracture can propagate easily through regions of the structure that are subjected only to low levels of applied stress. In some steels, the transition from ductile to brittle fracture can occur at relatively high temperatures if a mechanical or metallurgical notch is present. If no sharp notch or crack is present, temperatures as low as −75 °C (−100 °F) are necessary to produce brittle fracture.

For welded structures, it is assumed that sharp notches are present; this makes brittle fracture at normal operating temperatures an important concern. Most structural members remain within elastic loadings, except for corners, cutouts, and similar locations where slight yielding may occur. For this type of service, brittle fracture is possible when certain conditions exist:

- The temperature is below the characteristic NDTT value for the steel being used
- A cracklike notch is present
- Load values are sufficiently large to raise the nominal stress level in the area of the notch to values close to or exceeding the yield strength

At and below the NDTT, the effects of residual stress may be considered. Weldments can contain residual stresses as high as 80% of the original yield strength. In these cases, an applied stress of only 20% of the yield strength would be sufficient to initiate brittle fracture. All three factors, high stress, low temperature, and cracklike flaws, must be present for brittle fracture to initiate. However, as flaw size increases, the stress required for crack initiation decreases. With larger flaw sizes, the levels can be well below the yield strength, and residual stresses will play an increasingly important role.

At temperatures slightly above or below the NDTT, localized plastic deformation is required to initiate brittle fracture, and residual stresses are less harmful. At temperatures well below the NDTT, design is critical; the nominal stress (the sum of applied stress and residual stress) must not exceed the yield strength at the locations of cracklike flaws. In general, the lower the temperature below NDTT, the less severe the notch must be to initiate brittle fracture. For very thin sections, stresses act in a manner that makes brittle fracture considerations less critical.

Each type of high-strength low-alloy steel has a range of NDTT values that depends on chemical composition, as-rolled ferritic grain size, and other variables; a range of 35 °C (60 °F) is not uncommon. On the basis of limited test data, expected NDTT ranges are estimated in Table 18 . Grain coarsening may occur in different products because of rolling practice, which will increase the NDTT to above the maximum values shown in Table 18 .

Table 18 Typical nil-ductility transition temperature ranges for several HSLA steels

	Nil-ductility transition temperature	
Type of steel	°C	°F

345 MPa (50 ksi) minimum yield strength; fully killed	−70 to −30	−90 to −25
345 and 550 MPa (50 and 80 ksi) minimum yield strength; fully killed; microalloyed, with low-carbon content and inclusion shape control	−70 to −30	−90 to −25
310 MPa (45 ksi) minimum yield strength; fully killed	−50 to −18	−60 to 0
310 MPa (45 ksi) minimum yield strength; silicon killed	−40 to −7	−40 to 20
290–450 MPa (42–65 ksi) minimum yield strength; semikilled	−25 to 10	−10 to 50

Directionality of Properties. In microalloyed HSLA steels, the changes in mechanical properties resulting from the use of niobium and vanadium, together with controlled rolling, result in improved yield strength, weldability, and toughness. The ferrite grain size is reduced, with an attendant increase in yield strength. Because of this increase, any reduction in toughness due to precipitation strengthening can generally be tolerated. The remaining properties, however, are typical only of samples tested in the direction of rolling. In the transverse direction, toughness is reduced considerably, and formability is inadequate because of the characteristic shape of nonmetallic inclusions which, during rolling, become elongated in the rolling direction. The effect of elongated inclusions on notch toughness is shown in Fig. 19 . For the data presented, the impact energy for 100% shear fracture (upper-shelf energy) exceeds 55 J (40 ft · lbf) in the longitudinal direction, but is only 20 J (15 ft · lbf) in the transverse direction. For aluminum-killed steels, the low-shelf energy in the transverse direction is caused primarily by elongated sulfide inclusions. Reducing the sulfur content to 0.010% is not sufficient to eliminate directionality.

Fig. 19 Typical transition behavior for HSLA steel without inclusion shape control. Data determined on half-size Charpy V-notch test specimens
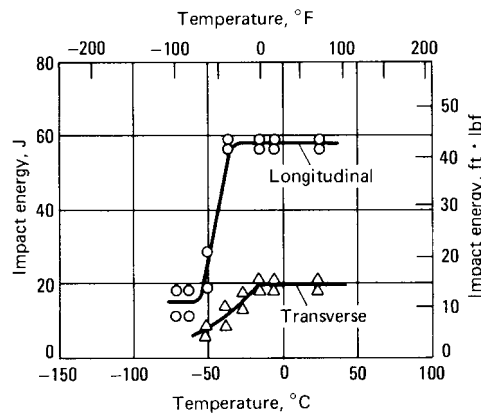
To prevent the sulfides from becoming excessively elongated during hot rolling, it is necessary to alter their composition. This can be done by adding elements such as zirconium, titanium, calcium, or rare earths, which form sulfides having high melting points. Sulfides with high melting points are less plastic at hot rolling temperatures and cannot be deformed readily. As indicated in Fig. 20 , rare-earth additions can effectively enhance transverse toughness so that when the cerium-to-sulfur ratio is between 1.5 and 2.0, the transverse upper-shelf energy approaches that of the longitudinal direction. Of the elements mentioned above, calcium and rare earths are the most frequently used for improving transverse or through-thickness properties.

Fig. 20 Effect of cerium-to-sulfur ratio on upper-shelf impact energy for HSLA steel. Circles, steel treated with mischmetal; squares, steel treated with rare-earth silicides
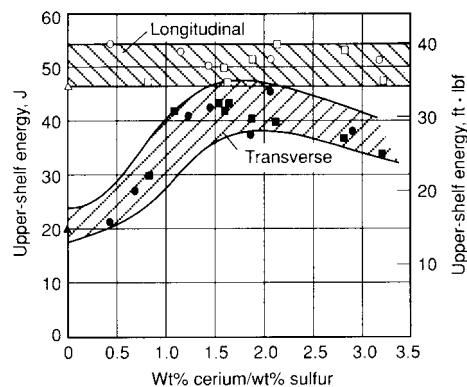
Fatigue Characteristics of HSLA Steels. Many structural applications for HSLA steels involve cyclic loading. The fatigue behavior of these steels therefore becomes important. In listing below, some of the fatigue characteristics of HSLA steels are compared to similar characteristics of hot-rolled low-carbon steels:

- HSLA steels have fatigue properties equivalent or superior to those of hot-rolled low-carbon steel. Microalloyed HSLA steels of the three major compositional approaches (vanadium, niobium, and titanium) have similar properties
- Although the notch sensitivity is somewhat greater, HSLA steels have greater notch fatigue resistance than hot-rolled low-carbon steels
- Large plastic prestrains tend to impair the fatigue life of both HSLA and hot-rolled low-carbon steels, particularly the response of HSLA steels to cyclic loading at high-strain amplitudes. Tensile prestrains are more detrimental to fatigue resistance than are compressive prestrains for both classes of material
- Most of the gains in monotonic strength achieved by work hardening are not retained under cyclic loading for either HSLA or hot-rolled low-carbon steel

Forming of HSLA Steels

High-strength low-alloy steels are generally formed at room temperature using conventional equipment. Cold forming should not be done at temperatures below 10 °C (50 °F). As a class, high-strength steels are inherently less formable than low-carbon steels because of their greater strength and lower ductility. This reduces their ability to distribute strain. The greater strength makes it necessary to use greater forming pressure and to allow for more springback compared to low-carbon steels. However, high-strength steels have good formability, and straight bends can be made to relatively tight bend radii, especially with the grades having lower strengths and greater ductility. Further, high-strength steels can be stamped to relatively severe shapes such as automotive bumper facings, wheel spiders, and engine-mounting brackets. Table 19 ranks the formability of the various HSLA steels specified in SAE J410 (Table 11).

Table 19 Listing of SAE J410 grades in approximate order of decreasing toughness, formability, and weldability

Toughness	Formability	Weldability
945A	945A	945A
950A	950A	950A
950B	945C, 945X	950D
950D	950B, 950X, 942X	945X
945X, 950X	950D	950B, 950X
945C, 950C, 942X	950C	945C
955X	955X	955X, 950C, 942X
960X	960X	960X
965X	965X	965X
970X	970X	970X
980X	980X	980X

With the advent of inclusion shape control, cold formability has been substantially improved. Any grade produced with inclusion shape control can be more severely formed than a grade of the same strength level produced without inclusion shape control. Inclusion shape control enables the steel to be formed to nearly the same extent in both the longitudinal and transverse directions and is responsible for the moderately good formability of the higher-strength HSLA steels such as the grades having 550 MPa (80 ksi) yield strengths.

As with any metal, the bendability of HSLA steels is inversely proportional to strength and thickness, as shown by the suggested minimum bend radii in Table 20 . These minimum bend radii are generally conservative, especially for inclusion shape controlled grades, as indicated by the bend test radii given in Table 21 . The minimum radii in Table 20 represent safe production practice for parts made from HSLA steels without inclusion shape control; more liberal bend radii than those shown in Table 21 may be allowed for production of parts made from the inclusion shape controlled grades.

Table 20 Suggested minimum inside bend radii for SAE J410 steels of various strengths and thicknesses

Grade	Minimum bend radius for thickness of		
	<4.6 mm (0.180 in.)	4.6–6.4 mm (0.180–0.250 in.)	6.4–12.7 mm (0.250–0.500 in.)
942X	...	*t*	2*t*
945A, 945C	*t*	2*t*	2.5*t*
945X	*t*	*t*	2*t*
950A, 950B, 950C, 950D	*t*	2*t*	3*t*
950X	1.5*t*	2.5*t*	2.5*t*
955X	2*t*	3*t*	3*t*

960X	2.5t	3.5t	3.5t
965X	3t	4t	4t
970X	3.5t	4.5t	4.5t
980X(a)	3.5t	4.5t	4.5t

(a) Available only in thicknesses to 9.5 mm (0.375 in.)

Table 21 Specified bend test radii for inclusion shape controlled ASTM A 715 steel sheet

	Bend test radius for	
Grade	**Transverse bends(a)**	**Longitudinal bends(a)**
50	0.5t	0
60	0.5t	0
70	0.75t	0.5t
80	0.75t	0.5t

(a) For sheet thicknesses up to 5.84 mm (0.2299 in.)

High-strength low-alloy steels can be hot formed. However, hot forming usually alters mechanical properties, and a particular problem that arises in many applications is that some of the more recent thermomechanical processing techniques (such as controlled rolling) used for plates in particular are not suitable where hot forming is used during fabrication. The kind of property deterioration obtained is shown in Fig. 21 for a thermomechanically treated steel. Similar effects can be predicted for accelerated-cooled steels. This problem can be circumvented by the use of a rolling finishing temperature that coincides with the hot-forming temperature (900 to 930 °C, or 1650 to 1700 °F. Subsequent hot forming therefore simply repeats this operation, and deterioration in properties is then small or even absent provided that grain growth does not occur.

Fig. 21 Mechanical properties of a thermomechanically treated HSLA steel after reheating at different temperatures. (a) Yield and tensile strength. (b) Charpy V-notch impact toughness at –40 °C (–40 °F)
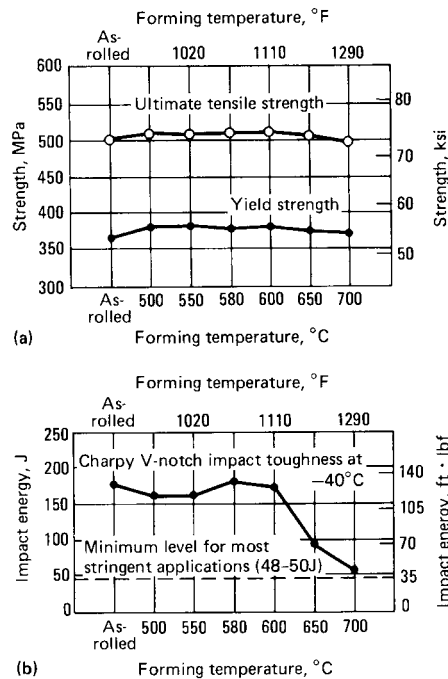
Producers should be consulted for recommendations of specific hot-forming temperatures and for comments on their effects on mechanical properties. According to one producer, satisfactory results can be obtained with certain grades by forming at temperatures between 815 and 900 °C (1500 and 1600 °F) without appreciable hardening after cooling. However, hot forming at these temperatures may result in material with mechanical properties equivalent to those of annealed or normalized material. Most producers advise against hot forming at temperatures below 650 °C (1200 °F). In the case of HSLA linepipe steels, hot bends are manufactured by induction heating followed by forming and (optional) quenching and tempering. The heating time is short (2 to 4 min), and limited grain growth occurs. Thus bending temperatures in the range of 850 to 1040 °C (1560 to 1900 °F) have been used successfully.

Welding of HSLA Steels

High-strength low-alloy steels are readily welded by any of the welding processes used for plain carbon structural steels, including shielded metal arc, submerged arc, flux-cored arc, gas metal arc, and electrical resistance methods. Welding can usually be performed without the need for preheat or postheat. Because the carbon content of HSLA steels is low, these steels exhibit hardening characteristics (in the HAZ) similar to those of plain carbon steels of similar low-carbon content. They do not exhibit the severe hardening in the HAZ that characterizes some plain carbon steels (those with sufficient carbon contents to attain yield and tensile strengths comparable to those of HSLA steels). Weldability generally decreases with increasing carbon content. For shielded metal arc welding, both mild steel covered electrodes and low-hydrogen electrodes can be used. Use of the latter is often recommended in order to preclude the need for preheating except when welding thick, highly restrained sections.

Submerged arc welding is often preferred because of the high production rates that can be attained. However, notch toughness of the weld metal in submerged arc welds can vary because of such factors as base metal composition, filler metal composition, type of welding flux, welding speed, current, voltage, and joint preparation. The choice of a particular steel is often greatly influenced by its ability to be used in welded construction, with less attention being given to the influence of steel composition on weld metal composition. In a submerged arc weld, the base metal may sometimes account for as much as 50 to 75% of the total weld metal. Base metal composition, therefore, can have an important effect on weld microstructure.

With constructional HSLA plate steels, the use of low-hydrogen electrodes and other precautions to minimize hydrogen pickup is advised. Various electrodes are available to match base metal strength and toughness. Preheating is generally required for all thicknesses over 25 mm (1 in.) and for highly restrained joints. Specific preheating temperatures depend largely on the grade, thickness, and welding process used and usually range from 40 to 200 °C (100 to 400 °F). Depending on design strength requirements for welded joints in heat-treated alloy grades, low-hydrogen electrodes E70 (485 MPa, or 70 ksi, minimum tensile strength) through E120 (830 MPa, or 120 ksi, minimum tensile strength) are used. In applications involving low stress levels (as when high-strength steel is used chiefly for its wear-resisting properties), E70 class electrodes are preferred. For joints requiring maximum strength, E120 class electrodes can be used. Electrodes containing vanadium must be avoided for any weldments that are to be subsequently stress relieved because reheating at temperatures below the critical temperature causes precipitation of vanadium carbides and raises the transition temperature of the weld metal.

The ductility and toughness of high-strength heat-treated steels depend on a tempered martensitic type of microstructure. Therefore, welding heat and preheat must be controlled so that the weld zone is cooled rapidly enough to retain a martensitic microstructure rather than the upper transformation products such as pearlite and ferrite that would result from unrestricted high-heat inputs and and slow cooling. For this reason, the high heat usually generated by submerged arc and gas-shielded metal arc welding makes these processes unsuitable when maximum joint efficiency is required in high-strength heat-treated materials less than 13 mm ($\frac{1}{2}$ in.) thick. Many electrode-flux combinations have been developed to produce acceptable welds with a yield strength over 620 MPa (90 ksi) and an NDTT of about −100 °C (−150 °F) in both the as-welded and stress-relieved conditions. The best electrodes are based on either boron-molybdenum-titanium alloying or, more conventionally, nickel alloying.

Applications of HSLA Steels

High-strength low-alloy steels gained their first use as structural shapes and plates in the early 1960s because of their ability to be welded with ease. By the early 1970s, they were also used in pipelines in both elevated-temperature and severe arctic conditions. Later in the 1970s, concurrent with the energy crisis, another dominant application involved the use of HSLA steels to reduce the weight of parts and assemblies in automobiles and trucks. In the 1980s, bars, forgings, and castings have emerged as applications of particular interest. For example, weldable and nonweldable reinforcing bars are available, and high-strength forgings in the as-forged condition are being used to replace quenched and tempered steels. Shapes such as elbows and fittings for pipelines are also being cast out of microalloyed steel. A chronology of some of the important trends and developments in HSLA technology (as of 1984) is presented in Table 22 .

Table 22 Chronology of trends and developments in HSLA steels

Period	Focus	Advances in technology
1939–1960	Discovery	Microalloying elements were used in a minor way in plate and in structural shapes to ensure the attainment of minimum yield strength
1960–1965	Research and experimentation on strengthening mechanisms	Development of a physical metallurgical basis. Hot-rolled semikilled or fully killed steels. Emphasis on replacing heat-treated steel
1965–1972	Toughening; experimentation on grain refinement and desulfurization	Hot-rolled steel, plate, pipeline steels, and structural shapes. Development of controlled rolling
1970–1976	Weldability; formability	Emphasis on lowering carbon and carbon equivalent, reduction of sulfur content, and control of inclusion shape. Improved bendability and stretchability
1972 to present	Secondary properties and steelmaking	Emphasis on brittle and ductile fracture control in pipelines and offshore structures, fatigue, resistance to H_2S corrosion, yielding behavior, formability of sheet steel, and development of continuous casting technology

1979 to present	Reformulation and reconstitution	Changes in availability of alloying elements such as molybdenum reawakened alloy developers. Previously inaccessible avenues opened by improvements in steelmaking. Focus on environmental degradation
1980 to present	Diffusion of technology	Cross-fertilization using development from other product areas
Future	Maturity; trend to higher strengths	Emphasis on reducing alloying costs and processing steps. Reconstitution of the steels to reflect direct hot-rolling and plate mill water-cooling technology

High-strength low-alloy steels are used in a wide variety of applications, and properties can be tailored to specific applications by the combination of composition and structures obtained in processing at the mill. For example, low-carbon and closely controlled carbon equivalent values provide good toughness and weldability. Good yield strength and fracture toughness are the products of fine grain size. The effects of microalloying elements (mainly niobium, vanadium, and titanium, but also aluminum and, to a lesser degree, nitrogen) are fully exploited by such mill finishing processes as controlled rolling and accelerated cooling. The scope of HSLA applications and different product forms used at the international level are implied by the production statistics for 1986 in Table 23 . A more complete listing of structural applications includes bridges, buildings, electricity pylons, pressure vessels, penstocks, steel piling, railway tracks, trucks, trailers, earthmoving equipment, mining equipment, tanks, and reinforcing bars. The numbers in Table 23 show percentages of use in various applications by country. In some applications use by country varies markedly; in some instances, the explanation is found in local conditions or requirements. Japan, for example, is the major user of HSLA for shipbuilding, while Europe is the leader in plate and section applications in offshore construction for the harsh material requirements of oil and gas production platforms on the European continental shelf.

Table 23 Proportion of product forms made with HSLA steel (1986)

| Product form | Proportion made with HSLA steel, % | | |
	Europe	North America	Japan
Linepipe	95	95	95
Shipbuilding	40	20	75
Offshore steels			
ÃPlate	90	30	70
ÃSections	70	20	10
Pressure vessels	30	25	85
Structural			
ÃSections	30	20	10
ÃSections, automotive	70	70	30
ÃSections, ships	15–30	20	10
ÃSheet piling	25	15	100
ÃRebar	100	>50	100
ÃPlate	25	20	10–30
Sheet and coil (including galvanized)			
ÃAutomotive	20	10	20
ÃBuilding (not rebar)	95	80	70

Selection Guidelines. As a rule, it is necessary to look beyond comparative material costs to justify the use of HSLA steel. These steels almost always cost more than carbon steel and sometimes the alloy steel they compete with in a given application. High-strength low-alloy steels typically have an edge over other materials when their unique properties allow:

- Weight reductions
- New or more efficient designs with improved performance
- Attractive reductions in fabrication/ manufacturing costs
- Reduced transportation costs from weight reductions

These benefits may come in combinations, depending on the application. In automobiles, for example, the initial advantage in substituting an HSLA grade for a mild steel part is in weight reduction. The gage of the metal can be reduced because HSLA steel is stronger. This weight reduction not only provides improved gas mileage but can also have multiplying effects in the design when lightening one component leads to a series of weight reductions in associated parts and assemblies. In some situations, however, it is possible to justify the specification of HSLA steel on the basis of comparative material costs alone. The

technique, called cost-effective weight reduction, is shown in Fig. 22 . The replacement of a mild steel part with HSLA steel is said to be cost effective when full advantage can be taken of its higher strength. The amount of weight savings needed to make HSLA steel cost competitive in terms of material costs is indicated in Fig. 23 . Data based on substituting a grade with a yield strength of 340 to 550 MPa (50 to 80 ksi) for a mild steel indicate that a savings in weight of about 30% is needed to reduce material costs. Of course, the savings in a given application depends on relative material costs.

Fig. 22 Material cost ratio as a function of weight reduction potential for various materials compared to mild steel as the base. Solid line is break-even line for materials cost.
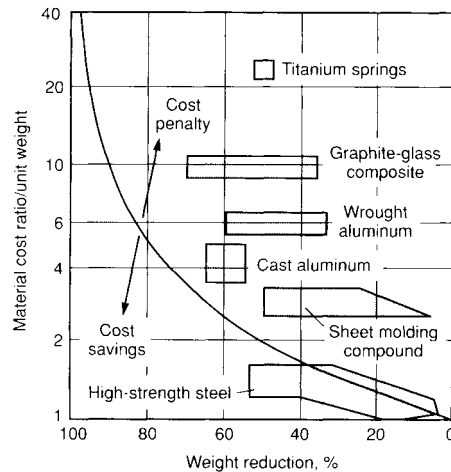
Fig. 23 Weight savings required to break even when substituting 340 to 550 MPa (50 to 80 ksi) yield strength HSLA steels for mild steel
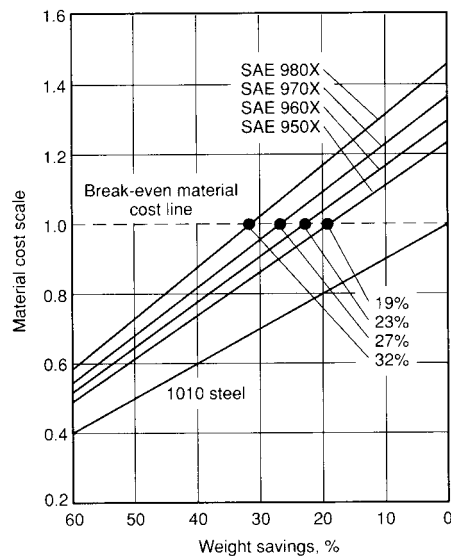
Another type of benefit involves the elimination of fabrication/manufacturing operations, such as those associated with the heat treating of quenched and tempered medium-carbon steels. For example, HSLA steels allow the production of high-strength forgings without any subsequent heat treatment (Fig. 24). By using a microalloyed steel in the as-forged condition, it is possible to eliminate quenching, tempering, straightening, and stress-relieving operations. In applications such as the forging of crankshafts or connecting rods, final savings in part costs of the order of 10% have been gained. Another example of reducing manufacturing steps with HSLA steel involves the production of cold-headed automotive fasteners (Fig. 25). Microalloyed steel wire rod replaced heat-treated medium-carbon wire. Benefits were realized before drawing and cold heading (elimination of spheroidize annealing) and after these operations (elimination of quenching and tempering).

Fig. 24 Required manufacturing steps for producing crankshafts from quenched and tempered and microalloyed medium-carbon steels
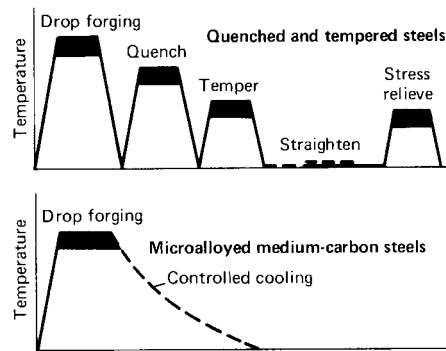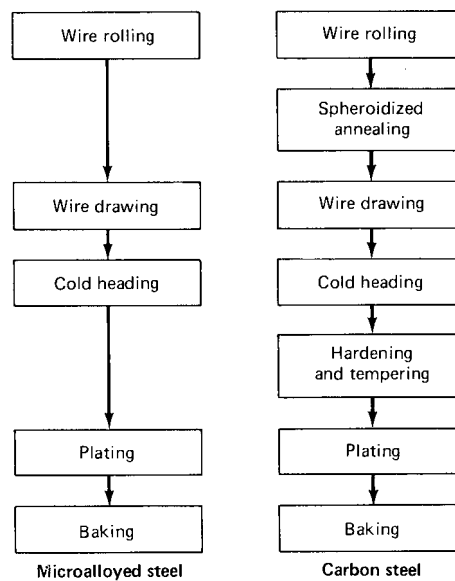
Fig. 25 Manufacturing sequence for class 8.8 automotive bolts from microalloyed and carbon steels

Other factors to consider in the selection of HSLA steel include:

- *Formability*: Limitations of microalloying technology in a given application may be overcome through part redesign and minor modifications in processing procedures
- *Notch toughness*: Microalloying in combination with controlled rolling generally provides better toughness properties than those of hot-rolled steel
- *Fatigue properties*: Adequate in most cases, with the possible exception being in the area of a welded joint
- *Weldability*: No longer considered a barrier to usage
- *Machinability*: At least similar and sometimes better than that of quenched and tempered steels. Control of alumina formation with calcium additions and substitutions of aluminum grain refinement by niobium have also been introduced. Free-machining grades (with added sulfur) are also available
- *Corrosion resistance*: Weathering HSLA steels can provide atmospheric-corrosion resistance four to eight times that of carbon steel, depending on the environment
- *Hydrogen-induced cracking and stress-corrosion cracking resistance*: Linepipe and pressure vessel steels have been developed with superior resistance to H_2S degradation

Oil and gas pipelines are a classic application of HSLA steel, and one of the first applications involved the use of acicular ferrite steel for pipelines in the Arctic Circle; see the section "Acicular Ferrite (Low-Carbon Bainite) Steels" in this article. The development of high-strength linepipe grades has permitted the use of large-diameter pipe operating at high pressure in excess of 11 MPa (1600 psi). Grades with minimum yield strengths up to 483 MPa (70 ksi) in thicknesses up to 25 mm (1 in.) are readily available. While tensile strength is a key requirement in linepipe, other properties are no less critical to the fabrication and operation of oil and gas pipelines. They include weldability, fracture toughness, and resistance to sour gas attack. In addition to higher strengths in greater thicknesses, HSLA steels can provide excellent toughness, good field weldability, resistance to ductile crack propagation, and, in some cases, resistance to sour gas and oil.

The girth weld is the main joining problem because it is a low heat input operation (HAZ cracking is not a problem at high

welding temperature) that is carried out at high speed. The problem is alleviated by taking maximum advantage of the lowest possible carbon equivalent steels made possible by advanced thermomechanical rolling or accelerated cooling.

Fracture toughness is another major requirement. The approach to avoiding brittle fracture involves a combination of lower carbon content and fine grain size by microalloying along with thermomechanical rolling or accelerated cooling.

The common technique being used to prevent the propagation of ductile cracks through a gas pipeline is to lower sulfur content to less than 0.005%. Low sulfur content, in this instance about 0.002%, also reduces reactions with sour gas and oil transported in pipelines, and calcium treatment is used to ensure that residual sulfide inclusions are of the modified round type rather than the elongated type. Also important are the elimination of all other nonmetallic inclusions, particularly oxides, and the reduction or elimination of segregation by a combination of modified casting practices at the mill and a reduction in the content of the main segregating elements, carbon, manganese, and phosphorus.

Automotive Applications. High-strength low-alloy steels used by the United States automobile industry fall into four major groups:

- *Structural grades*: These materials are produced by a combination of phosphorus and microalloying elements (mainly niobium) to develop yield strengths between 255 and 345 MPa (37 and 50 ksi). They have a cost advantage over other HSLA grades with equivalent strength and are available in the hot- or cold-rolled condition. Drawing characteristics are rated superior to those of other HSLA steels
- *Formable grades*: Alloying elements commonly used to obtain high strength are niobium, vanadium, titanium, or zirconium. Transverse ductility is improved with zirconium, calcium, or rare-earth additions by changing the morphology of sulfide inclusions. Strength levels for automotive applications vary from 275 to 550 MPa (40 to 80 ksi). Fully killed grades are used most frequently, but semikilled grades are also used
- *Dual-phase grades*: These steels are used because of their superior formability over equivalent-strength microalloyed steels. Their duplex structure (ferrite and martensite) gives them a high strain hardening capability. Yield strengths range from 275 to 550 MPa (40 to 80 ksi)
- *Ultrahigh-strength grades*: In this instance, yield strengths of 550 MPa (80 ksi) are obtained by recovery-annealing cold-rolled HSLA grades. The most common strength levels used are 690, 825, and 965 MPa (100, 120, and 140 ksi). Low ductility has limited their applications

Experience in the application of cold- and hot-rolled HSLA sheet in automotive applications indicates the importance of additional requirements with respect of stiffness, crash behavior, fatigue life, corrosion resistance, acoustic properties, and, of course, formability and weldability. For one manufacturer (Ref 33), the substitution of HSLA for unalloyed steel requires a gage reduction of at least one-third to avoid an increase in manufacturing costs. This manufacturer (Opel in Germany), found certain limitations of HSLA sheet in automotive applications (Ref 33):

- Limited formability must be taken into consideration
- Fatigue strength of electric resistance welded joints is not much better than that of mild steel
- Increased notch sensitivity, which means higher cut edge sensitivity, must be taken into consideration
- With the use of thinner gages, reduced rigidity, susceptibility to corrosion, and noise behavior must be taken into consideration

The function of the automotive part is also important in determining whether or not the application of HSLA steels is feasible. For applications in which yield strength is the major consideration, as in door beams and bumper beams, the efficient use of HSLA can be made, and weight savings of 40 to 60% are possible when substituting, for example, higher-strength grades, such as 340 to 550 MPa (50 to 80 ksi) grades for mild steel. However, for other parts, such as outer body panels, which are also subjected to bending and/or buckling, stiffness is more important than yield strength. Part geometry and modulus of elasticity, the latter of which is the same for mild steel and HSLA steel, are the key factors. In such instances, an economic case cannot be made for using HSLA steel. However, through component redesign, such as adding beads or ribs to upgrade stiffness properties, the performance of the part may be improved and allow the efficient use of a higher-strength HSLA grade.

In addition to improvements in gas mileage through weight reduction, benefits may be found in increasing payloads without a change in fuel consumption. Candidate applications here include trucks, rail cars, off-highway vehicles, and ships. Ship applications of HSLA, however, are also limited by buckling and stiffness considerations.

Offshore Applications. The essential characteristics of steels for these applications include:

- Yield strength in the region of 350 of 415 MPa (50 to 60 ksi)
- Good weldability
- High resistance to lamellar tearing
- Lean composition to minimize preheating requirements
- High toughness in the weld heat-affected zone
- Good fracture toughness at the designated operating temperatures

Some of these goals have been realized through a reduction in impurities such as sulfur, nitrogen, and phosphorus in the steelmaking process for conventional steels. A major challenge, however, was to reduce carbon equivalents to improve weldability while still maintaining strength. This trend toward lower carbon equivalents and adequate strengths is shown in Table 24 . Controlled rolling and accelerated cooling of niobium steels has also allowed reductions in carbon contents, which can be further reduced when accelerated cooling is employed.

Table 24 Comparison of typical 1972 and 1986 chemical composition of offshore structural steel

Element	Typical, 1972(a)	Typical, 1986(b)	
		U.S. mill	Foreign mill
Carbon	0.17	0.15	0.12
Manganese	1.30	1.34	1.44
Phosphorus	0.025	0.015	0.009
Sulfur	0.02	0.006	0.001
Silicon	0.40	0.30	0.38
Niobium	0.05	0.05	0.20
Aluminum, total	0.03	0.040	0.035
Nickel	...	0.17	0.18
Chromium	...	0.08	0.009
Molybdenum	...	0.056	0.001
Vanadium	...	0.002	0.001
Copper	...	0.032	0.16
Arsenic	...	...	0.003
Tin	...	...	0.001
Antimony	...	...	0.000
Carbon equivalent, max(c)	0.41	0.40	0.38

(a) Minimum yield strength of 290 MPa (42 ksi). (b) Minimum yield strength of 345 MPa (50 ksi). (c) Carbon equivalent (CE) = C + (Mn/6) + [(Cr + Mo + V)/5] + [(Ni + Cu)/15]

Most offshore structures have been built using normalized carbon-manganese-niobium steel. Advances in computer control and rolling capability have led to the development of thermomechanically controlled processes that produce steels with higher strength, high fracture toughness, improved weldability, and lower cost. Thermomechanically controlled processes combine controlled rolling and accelerated cooling (with controlled water sprays) or direct quenching to room temperature. Very fine-grain steel (ASTM grain size numbers 10 to 12) is produced. These steels are characterized by low-carbon content (usually less than 0.10% C), which makes them less susceptible to increases in hardness caused by rapid cooling rates between 425 to 260 °C (800 to 500 °F) during welding. Potentially, these steels can be welded with little or no preheat.

Two approaches have been taken to eliminate lamellar tearing. One is to reduce sulfur to levels below 0.008%, while the other involves modification of the sulfide shape. The latter relies on the addition of calcium or rare-earth metals to form spheroidal calcium or rare-earth sulfides. This approach usually results in both the elimination of lamellar tearing and an improvement in transverse impact properties. Both sulfur reduction and sulfide shape control are often used to eliminate lamellar tearing. Calcium treatment is preferred for sulfide inclusion shape control.

In using continuously cast steels, centerline segregation is also a concern. The approach favored by users is to minimize segregation through steelmaking practice and to minimize the use of elements (carbon, manganese, sulfur, and phosphorus) known to segregate easily during solidification. Soft, in-line reduction practices have been introduced. Users also specify minimum slab soaking time and temperature to control centerline segregation.

Cold-Forming Strip. The attraction of HSLA in this instance, particularly in automotive applications, is to make lighter parts by reducing gage requirements. Formability is a problem that is dealt with in several ways; welding is not as much of a problem with strip as it is with plate. Generally, welding problems are dealt with through the process itself or with surface treatments, rather than with modification of the fundamental characteristics of the steels themselves.

A tabulation of the cold-forming strip steels presently being used (along with their yield and tensile properties, ranges of carbon content, and alloying additions) are listed in Table 25 . This tabulation includes the important category for interstitial-free steels, which have excellent deep-drawing characteristics (Fig. 8 c).

Table 25 Cold-forming strip steels

		Range of minimum strength		Composition, %	
		Yield strength	Tensile strength		

Steel type	Processing	MPa (ksi)	MPa (ksi)	Carbon	Alloying element
Precipitation strengthened and grain refined	Hot rolled	280–600 (40–87)	400–700 (58–100)	0.05–0.15	≤1.5% Mn max plus Ti, Nb, or V
	Cold rolled	240–440 (35–64)	340–550 (49–80)	0.05–0.15	≤1.5% Mn max plus Ti, Nb, or V
Solid-solution strengthened	Hot or cold rolled C Mn	230–338 (33–49)	370–520 (54–75)	0.10–0.20	≤1.5% Mn max
	Cold rolled Al killed	220–300 (32–43)	340–435 (49–63)	<0.05	≤0.01% P
	Cold rolled, interstitial free	220–300 (32–43)	300–400 (43–58)	<0.005	≤0.1% P plus Ti, Nb, or B
Bake hardening	Cold rolled Al killed	200–230 max (29–33 max)	310–380 (45–55)	0.01–0.02	≤0.1% max, possibly Si
		240–300(a) (35–43)(a)			
	Cold rolled Nb	210 max (30 max)	360–380 (52–55)	<0.005	≤0.1% P plus Nb
		240(a) (35)(a)			
Dual phase	Hot and cold rolled	200–900 (29–130)	350–1300 (50–190)	0.02–0.15	≤1.5% Mn
Transformation strengthened	Hot and cold rolled	≤1400 (200)	≤1500 (215)	≤0.20	Mn ≤ 1.5% Mn
Cold-work strengthened	Cold rolled	≤1000 (145)	≤1100 (160)	≤0.20	≤1.5% Mn, with Ti, Nb, and V possible

(a) After baking

The larger tonnage of cold-rolled steels have yield strengths less than 345 MPa (50 ksi). The microalloyed grades derive their higher yield strength from a combination of grain refinement and precipitation strengthening. They are normally produced in the hot-rolled or cold-rolled and annealed condition. Because of their limited formability, they are typically used for structures and reinforcement parts for automobiles, buildings, and various forms of domestic equipment. Forming properties are summarized in Table 26 .

Table 26 Forming properties of various steel types

Primary strengthening mechanism	Stretchability	Drawability	Strength range
Cold worked	Very poor	Poor	Large
Recovery annealed	Poor	Poor	Large
Transformation strengthened	Moderate	Moderate	Large
HSLA precipitation grain refined	Moderate	Moderate	Fairly large
Solid-solution aluminum killed	Good	Good	Limited
Bake hardenable	Good	Good	Limited
Dual phase	Good	Moderate	Large

Solid-solution strengthened grades have better formability than precipitation-strengthened grades. The most common alloying elements in this instance are manganese, silicon, and phosphorus. When phosphorus is above 0.10%, it tends to present problems in electric resistance welding. Solution-strengthened steels can be used in automotive body panels. These steels can be further strengthened by the addition of a small percentage of niobium (Table 25).

Bake-hardened grades are of interest because they are formed at a low strength level and subsequently strengthened during the paint-baking operation, at about 170 °C (340 °F). Advantage is taken of the quench aging mechanism. Carbon is quenched into solution at the cooling rates obtained after batch or continuous annealing and is later precipitated during the paint-baking operation.

Transformation-strengthened HSLA steels include dual-phase alloys in which the second phase may be martensite, bainite, or pearlite, depending on the strength requirements. These steels have good formability and weldability. They are used extensively in rolled form.

The highest strength strip with yield strengths up to 1600 MPa (230 ksi) are alloyed to ensure transformation to martensite.

Applications include door impact beams and rear bumper supports. The formability of these grades is limited.

Corrosion protection is of concern because the corrosion resistance of nonweathering HSLA steel may not be significantly different from that of other steels. In this case, a number of coatings that inhibit corrosion and enhance the appearance of automobiles and buildings are available. They include zinc galvanized and aluminized coatings, which are applied by hot dip or continuous processes. A variety of colored organic coatings are available.

Structural Steels. Niobium, vanadium, and titanium microalloy additions are used, and chromium and molybdenum are added for elevated-temperature service. Processes used include controlled rolling, normalizing, quenching and tempering. For rolled shapes, direct accelerated cooling from the rolling temperature is a recent innovation. Steel frames for buildings are expected to be competitive with other building construction materials, including prestressed concrete. Benefits include an increase in the load bearing capacity of columns, weight savings, and gains in space. Composite construction (HSLA rolled sections and reinforcing bar bonded together with concrete) also appears to have potential. These composites offer great strength in compression, high building strength, and good resistance to fire.

Shipbuilding. Ship applications are limited by buckling and stiffness considerations. Growth in usage of hull plate is apparently held back by the fact that because HSLA and mild steel have the same elastic modulus, reducing thickness can lower elastic rigidity. This has caused concern regarding potential problems with hull rigidity.

One of the main challenges in this application area has been to reduce the need for welding preheat in the most common hull plate thicknesses. Some exceptions to this are reported. The Japanese are using readily welded hull structures employing HSLA grades that are processed by accelerated cooling and have yield strengths up to 400 MPa (58 ksi).

Crane and vehicle applications include trucks tankers, mobile cranes, dumper trucks, and heavy-duty material-handling equipment. Important properties include strength and toughness, resistance to brittle fracture, fatigue strength, weldability, and formability. In crane construction, high minimum yield strengths are needed to obtain high load-bearing capacities to handle dead loads. For example, a quenched and tempered grade with a minimum yield strength of 960 MPa (140 ksi) offers both technical and economic advantages, especially with cranes subjected to lifting heavy loads. Acceptable brittle fracture properties are obtained, for example, with acicular ferrite steel.

Resistance to cyclic loading is extremely important; in particular the fatigue strength of welded joints which is typically not as strong as that of the base metal because of microstructural changes due to the heat from welding. Improvements can be realized through postweld treatments. In using controlled rolled grades, heat input must be limited because of the likelihood of softening in the HAZ during welding.

Microalloyed HSLA steels used in commercial vehicles are typically cold formed. Good forming properties in the longitudinal and transverse directions are required when thermomechanically rolled steels are used. The desired result is obtained by optimizing sulfide shape control by the addition of calcium and cerium.

Railway Tank Car Applications. Three improved grades of high-strength steel for railway tank cars are defined by the ASTM specifications below. All the specified to a minimum yield strength of 345 MPa (50 ksi) and a tensile strength of 485 MPa (70 ksi).

- ASTM A 633D is a lower-carbon version of the presently used ASTM A 612 (TC-128B) steel (carbon-manganese steel with nickel, chromium, molybdenum, and vanadium additions). It is produced as a normalized grade
- ASTM A 737B (LC) is representative of the first generation of niobium microalloyed steels, which is produced as a normalized steel because equivalent properties cannot be developed by controlled rolling
- ASTM A 808 is representative of second-generation (controlled-rolled) niobium-vanadium microalloyed steels. For low-temperature service, sulfur should be limited to 0.010% (max)

These grades were compared by preliminary weldability analysis and fracture analysis (Ref 34). General conclusions indicate that:

- ASTM A 633D and A 737B (LC) are expected to satisfy near-term requirements, but they require postweld heat treatment to meet objectives
- ASTM A 808 (CR) with 0.010% (max) is expected to satisfy long-term requirements. Postweld heat treatment is not needed because a ductile HAZ is developed as-welded, a distinct advantage in making field repairs

Bars, forgings, and castings have emerged as the latest area of opportunity for microalloyed HSLA steels, and there has been rapid assimilation of the technology developed in other product areas. In particular, the search for higher strengths, elimination or reduction of heat treatments, simplified cold finishing or machining operations, and improved toughness have been combined with a simultaneous concern for other end-use properties such as toughness, machinability, and weldability. The result has been an integrated approach, including the proper selection of microstructure and transformation conditions, the application of thermomechanical processing and control of deoxidation and solidification practices (Ref 35).

The range of available steel types and compositions is indicated in Table 27 . Carbon contents range from 0.05% in weldable castings and acicular ferrite bar used in cold heading to 0.60% for spring steels and high-strength wire. Tensile strengths range from 600 to 2000 MPa (87 to 290 ksi) and higher.

Table 27 Summary of microalloyed bar products, castings, and forgings

Steel product	Typical composition, %						Applications
	C	Mn	Si	Nb	V	Other	
Hot-rolled bar							
ÃHigh carbon	0.58	0.80	0.30	0.04	...	...	Drawn wire having residual-deformation capability
ÃMedium carbon							
ÃÃRebar	0.38	1.20	0.20	0.03 (or V)	...	...	Standard reinforcing bar
ÃÃStructural	0.35	1.00	0.25	0.02–0.10	...	...	Machined automotive parts, or forged vanadium steel
ÃÃEngineering	0.40	0.80	0.20	...	0.09 (or Nb)	...	Replaces quenched and tempered steel
ÃÃMachined bar	0.30	1.20	0.30	0.03	...	Al free	Machined bar in automotive and engineering equipment
ÃLow carbon	0.10–0.20	1.65	0.15	0.04	...	...	Weldable reinforcing bar, Arctic concrete structures, cryogenic storage tanks
ÃVery low carbon	0.10	1.70	0	0.08	...	Boron	Cold-headed parts
Heat-treated bar							
ÃConcast billets	0.25	1.30	0.20	0.03	...	...	Heat-treated parts for tractors, and so forth
ÃEngineering	0.60	0.85	0.80	...	0.11	...	High-strength drawn wire
ÃRebar	0.18	0.60	0.05	...	0.05	...	Concrete structures
ÃHigh carbon	0.58	0.85	2.10	0.15	0.12	...	
Forgings							
ÃAs-forged bar	0.30–0.40	0.80	0.20	...	0.09 (or Nb and 0.50 Cr)	...	Automotive components, universal couplings, stabilizer bars, wheel hubs, knuckle arms, connecting rods
ÃCrankshafts	0.53	0.80	0.40	0.06 (or 0.10V)	...	...	Lightweight German automobiles
ÃSmall forgings	0.12	1.45	0.35	0.07	0.07 (or 0.015)	...	Automobile and off-highway equipment
Castings							
ÃNodes	0.15	1.40	0.30	0.03	0.07	0.48 CE max	Offshore platforms
ÃFittings	0.18	1.50	0.20	0.03	0.05	...	Pipeline elbows and fittings, and so on
ÃSmall castings	0.05	1.60	0.10	0.06	...	0.40 Mo	Small engineering castings, brake parts, compressors, and so on

Microalloying is used to satisfy a wide variety of metallurgical and manufacturing objectives, such as the substitution of as-rolled or as-forged steels for parts that required heat treatment for the improvement of toughness, fatigue behavior, machinability, or response to cold rolling. Examples of how microalloying is used in combination with processing to develop of improve specific properties follow.

Vanadium is generally used when it is necessary to develop hardening in conjunction with low austenitizing temperatures, but it is often necessary to add titanium, which prevents grain growth during high-temperature forging applications. For normal high-temperature rolling conditions, higher levels of precipitation strengthening in vanadium (and/or niobium) steels may have a detrimental effect on toughness. When controlled rolling is used in combination with niobium (0.03 to 0.08%) or extralow carbon content, toughness improved dramatically, and the properties of niobium steels are superior to those obtained in vanadium steels.

Niobium is added to improve the toughness of as-forged components. Such steels are widely used in Europe for automobile components. Niobium-containing steels are accepted for safety related parts such as steering knuckles and suspension components.

Niobium or vanadium are also added to hot-rolled carbon-manganese steel bars to effect grain refinement and improve toughness. Steel grades include 1020 through 1090. Niobium and/or vanadium are also added to the 4100 series for the same reason.

Medium- and Low-Carbon Microalloyed Bars. Vanadium and niobium act as precipitation strengtheners in medium-carbon 0.40%) steels are used widely in concrete-reinforcing bars. If enhanced toughness is needed for low-temperature service conditions or if weldability is a problem, carbon is reduced to the 0.10 to 0.20% range, maximizing the contribution of microalloying, rather than pearlite, in the strengthening process. Further improvements are available through controlled rolling.

However, low-carbon bainitic microalloyed steels appear to have better potential for replacing high strength-high toughness quenched and tempered steels than do medium-carbon microalloyed steels (Ref 36). Medium-carbon microalloyed steels are not ideal candidates for using the benefits of microalloying technology because their carbon contents and precipitation-strengthening effects contribute to poor notch toughness. Low-carbon steels microalloyed with ferrite-bainite microstructures exhibit a better

combination of strength and toughness properties (Ref 36).

Solute niobium is used to eliminate the quenching and tempering of forged crankshafts (Table 27). Forging is followed by high-temperature (1225 °C, or 2240 °F) induction heating and controlled air cooling, which results in a desirable microstructure consisting of 80% pearlite and 20% ferrite.

Microalloying of carbon-manganese steel bars can increase the strength of steel bars (0.35 to 0.45% C) used to reinforce concrete. Recent applications call for improvements in bendability, weldability, and toughness for low ambient service temperatures or for low-temperature structures, such as refrigerated warehouses, liquid natural gas storage facilities, foundations for nuclear power stations, and construction in seismic-prone areas. For these conditions, carbon content is lowered, and the strengthening properties of niobium and vanadium are used singly or in combination.

Microalloying elements as a substitute for aluminum in grain refinement can facilitate the production of desired inclusion compositions for applications in which machining or surface treatments such as carburizing or nitriding are involved. Such steels are designed to decrease the abrasive tool wear caused by hard alumina inclusions. Deoxidation practice produces soft, glassy inclusions that are relatively plastic at hot working temperatures. The elimination of aluminum requires the use of another strong deoxidant such as calcium and the addition of niobium or other suitable grain refiner.

Niobium or vanadium containing castings have applications that are given in Table 27 . Large castings, for example, are used in offshore construction. Built-in reinforcements improve performance under cyclic loading conditions. Many low-carbon steels have inherently high ductility and can tolerate the presence of some potentially injurious second-phase particles such as carbide eutectics. Niobium and niobium-vanadium microalloyed low-carbon steels with manganese and molybdenum have been developed and applied in Europe. Castings are used in either the as-cast or as-quenched and tempered condition. In either case, weldability is reported to be excellent. A development for the future are low-carbon (0.02%) manganese-niobium-boron-titanium steels, originally developed as high heat input filler (weld) metals.

Cold-Rolled HSLA Steel. Although most HSLA steel is hot rolled, large tonnages of cold-rolled HSLA sheet and strip are produced. However, because many applications of cold-rolled steel already involve thin product forms, substituting a thinner, stronger steel for weight savings may not be feasible because of stiffness and deflection considerations.

The general types of cold-rolled HSLA steels utilize precipitation strengthening, solid-solution strengthening, or strengthening from a dual-phase (martensite in ferrite) microstructure. These types of cold-rolled HSLA steel are compared in Fig. 8 (b) in terms of ductility and tensile strength. the cold-rolled solution-hardened steels have superior elongation and stretchability compared with cold-rolled precipitation-strengthened steels of the same tensile strength, but are limited to a tensile strength of about 600 MPa (87 ksi). The cold-rolled precipitation-strengthened steels allow higher tensile strengths compared with solution-strengthened steels, but these have less ductility at a given tensile strength (Fig. 8 b). Because titanium provides sulfide shape control and precipitation strengthening, titanium steels have plastic-strain ratios up to 1.4 at tensile strengths of 550 to 650 MPa (80 to 95 ksi) (Ref 23).

Dual-phase steels offer improved ductility at higher tensile strengths (Fig. 8 b). Sheets of dual-phase steel have very low yield strengths without sharp yield points (that is, continuous yielding), but the yield strengths are increased substantially during forming or by a tempering or aging treatment at 300 to 400 °C (570 to 750 °F) for about 5 min after air cooling. The formability (in terms of plastic-strain ratios and strain-hardening exponents) of a dual-phase steel is compared with other cold-rolled automotive sheet steels in Table 28 and Fig. 8 (c). Although many of the high-strength cold-rolled steels have rather low plastic-strain ratios and, hence, are not deep drawn as readily, their drawability can be improved by a suitable precoating lubricant (Ref 23, 37). Interstitial-free steels offer the best deep-drawing properties (Fig. 8 c).

Table 28 Mechanical properties of cold-rolled, high-strength steels

| Steel grade | Yield strength | | Tensile strength | | Elongation, % | Formability factors | |
	MPa	ksi	MPa	ksi		Strain-hardening exponent (*n*)	Plastic-strain ratio (*r*)
Low carbon, killed	172	25	275	40	40	0.23	1.4
Structural grade, high strength	275	40	380	55	35	0.22	1.4
Formable grade, high strength	345	50	415	60	30	0.20	1.1
	550	80	620	90	18	0.14	0.8
Dual phase, high strength	345	50	550	80	25	0.24	0.8
Ultrahigh strength	825	120	860	125	8	...	...
	965	140	1000	145	4	...	...

Selection and Application Example. The following describes the use of structural and HSLA steels in an architectural application.

Example : Design and Construction of Retractable SkyDome Roof. Toronto, Canada's SkyDome, completed in June 1989, is a multipurpose structure that seats 54,000 for baseball, 55,000 for football, and up to 70,000 for special events (Ref 38). The SkyDome incorporates a patented rigid frame structural steel retractable roof. Within a span of 20 min, the movable roof transforms the SkyDome from an open-air stadium into an enclosed air-conditioned or heated domed stadium.

Roof Dimensions. The roof consists of four panels, three of which are movable, that stack and interlock on top of each other to provide a closed, sealed, and weather-tight structure (Fig. 26). Utilization of four parabolic arch panels in this arrangement exposes 91% of the seats in the open-air section and stacks all four panels within the building footprint (Ref 39). The roof covers 32,275 m^2 (347,420 ft^2, or 8 acres); it rises to a maximum height of 86 m (282 ft), which is high enough to accommodate a 31-story skyscraper within its confines. The roof has a steel dead weight of 69,000 kN (7760 tonf) (Ref 39, 40). The movable panels have the following dimensions:

Panel	Depth		Span	
	m	ft	m	ft
1	50	165	175	575
2	50	165	206	675
3	50	165	190	625

Source: Ref 38

Fig. 26 Location and progressive movement of the three movable roof panels of the SkyDome as it is converted from an open-air facility into an enclosed environmentally controlled dome. (a) All four panels stacked at the north end of the SkyDome in the open position. Panel 4 remains stationary. (b) Panel 1 is first to move as it begins its circular motion. (c) All three movable panels are in motion as panels 2 and 3 begin their straight-line motion while panel 1 continues in its circular path. (d) Within 20 min, panel movement is complete and the structure is in its closed position. Source: Adapted from *Sports Illustrated*, 12 June 1989
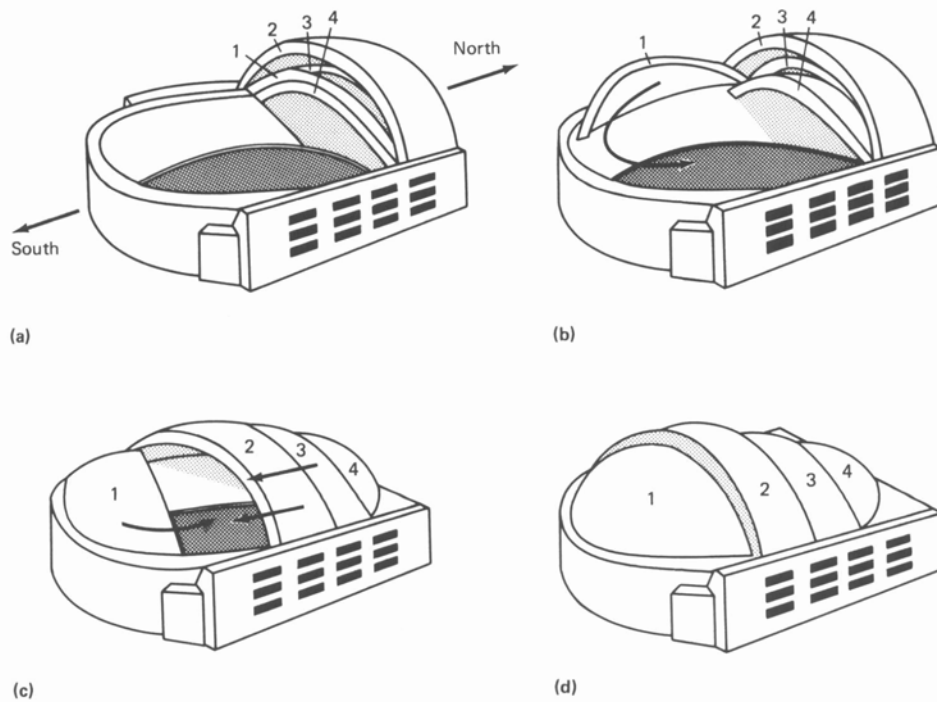
Roof Opening Procedure (Ref 41). The roof of the SkyDome is closed most of the time. Panel 4 is fixed in place at the north end and has the configuration of a segment of a spherical shell or quarterdome. Panel 1 has a similar shape but is slightly larger. When the roof is in the closed position, panel 1 is located at the south end, directly opposite panel 4. As the roof opens, panel 1 travels along a 310 m (1020 ft) circular 4-rail track, carried by 22 steel-wheeled bogies (10 of which are fitted with two 7.5-kW, or 10-hp, dc electric-drive units), and parks itself directly above panel 4. Some of these roof-carrying bogies weigh up to 36 tonnes (40 tons) per unit.

Panels 2 and 3 sit adjacent to each other when the roof is closed. A total of 16 bogies are used to move panels 2 and 3. Eight of the bogies on panel 2 and six of the bogies on panel 3 are equipped with drive units. Panel 2 is slightly higher and larger than panel 3. Both move linearly northward when the roof is opening. Panel 2 initially moves along the parallel tracks and passes directly over panel 3, which then also starts its travel to the north end of the stadium.

All three movable panels are simultaneously in motion for a short portion of the 20-min operation when panel 1 begins its journey around the circular track. Panel 1 eventually comes to rest approximately 180° from its original position. When the SkyDome roof is open, panel 1 nests above the similarly shaped panel 4 but below panel 3, while panel 2 sits atop the other three panels (Fig. 26).

Structural Components. Figure 27 shows the SkyDome in its final stages of construction. Construction of the geometrically complex SkyDome roof involved the fabrication and erection of 7575 tonnes (8330 tons) of structural steel components, 975

tonnes (1070 tons) of bogies, and 930 tonnes (1025 tons) of rails, all to a high degree of precision ([Ref 41](#)).

Fig. 27 SkyDome construction nearing completion. Courtesy of Jane Welowszky, SkyDome Stadium Corporation of Ontario

The 7575 tonnes (8330 tons) of zinc-coated structural steels used in the roof structure are employed in a linear system of parallel arches with transverse trusses of hollow structural steel (HSS). These HSS trusses conform to Canadian Standards Association (CSA) specification CAN 3-G40.21-M81, which closely approximates ASTM A 572. CSA grade 300 W is equivalent to ASTM grade 42, while CSA grade 300 W is equivalent to ASTM grade 50. CSA type W steels are suitable for general welded construction where notch toughness at low temperatures is not a design requirement ([Ref 42](#)).

Grade 300 W, with a minimum yield strength of 300 MPa (44 ksi), is a standard general-purpose weldable hot-rolled structural steel with 130 to 170 HB hardness. In addition to being used for the joint connections and plates in the structural framework of the SkyDome, grade 300 W structural plate was used extensively in the construction of the bogies that move the roof panels.

Grade 350 W, with a minimum yield strength of 350 MPa (50 ksi), is a cold-rolled and stress-relieved HSLA weldable structural steel with 130 to 180 HB hardness. Grade 350 W structural steel was seam welded to form a hollow square tube which serves as a roof tubular support. These HSS square tubes range in size from 150 × 150 mm (6 × 6 in.), with a thickness of 6.4 mm ($\frac{1}{4}$in.), to 300 × 300 mm (12 × 12 in.), with a thickness of 12 mm ($\frac{1}{2}$in.). The use of standard structural steel hollow tubes has resulted in a roof that has great strength and stiffness characteristics and yet is relatively lightweight and has a depth relative to the large span, which is close to 206 m (675 ft) wide.

Trusses for the four panels were shop-fabricated in large sections and then bolted on-site using 140,000 ASTM A 325 galvanized 25 mm (1 in.) diam bolts and corresponding ASTM A 194 nuts. Both fastener types were made from quenched and tempered medium-carbon high-strength structural steels.

Acoustic Roof Deck. The actual roof covering consists of an acoustic steel roof deck weighing 500 tonnes (550 tons). The galvanized corrugated square-profile steel panels conform to ASTM A 446 grades B (255 MPa, or 37 ksi, minimum yield strength; 310 MPa, or 45 ksi, minimum tensile strength) and C (275 MPa, or 40 ksi, minimum yield strength; 380 MPa or 55 ksi minimum tensile strength); ([Ref 42](#)). The thickness of the steel strip and sheet used to fabricate the panels varies from 0.813 to 1.27 mm (0.032 to 0.050 in.) depending on location and load requirements.

The corrugated panels are fluted, perforated ([Fig. 28](#)), and provided with interlocking J-hook ends ([Fig. 29](#)) to provide a baffle that contains crowd noise within the confines of the structure when it is closed. Fabricated in lengths up to 6 m (20 ft), the corrugated panels have square profiles of 450 mm (18 in.) or 600 mm (24 in.). Both the inner and the outer exposed sections of the corrugated panels contain acoustic pads to absorb sound ([Fig. 30](#)). In addition, the roof sandwich also includes thermal insulation and a 1 mm (0.04 in.) thick single-ply polyvinyl chloride membrane.

Fig. 28 Profiles of the fluted and perforated interlocking galvanized steel corrugated roof panels. All dimensions are given in millimeters. (a) D-200 roof panel, 600 mm (24 in.) wide coverage. (b) D-150 roof panel, 450 mm (18 in.) wide coverage
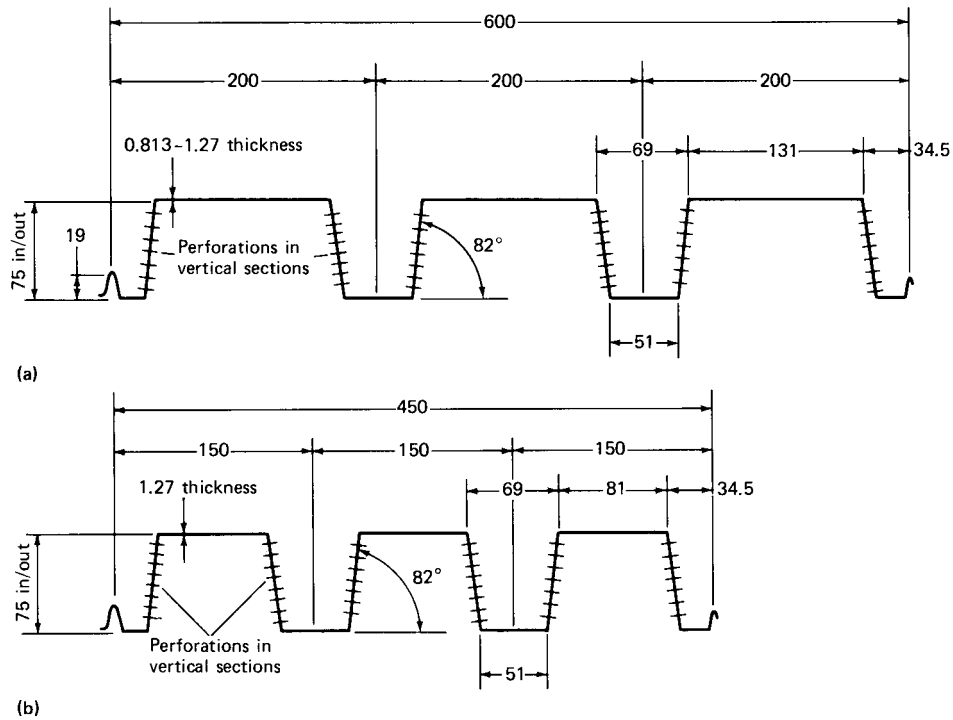
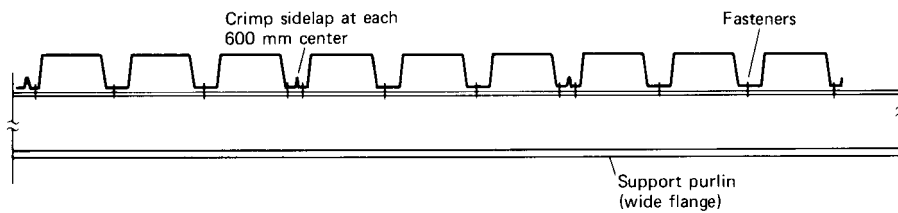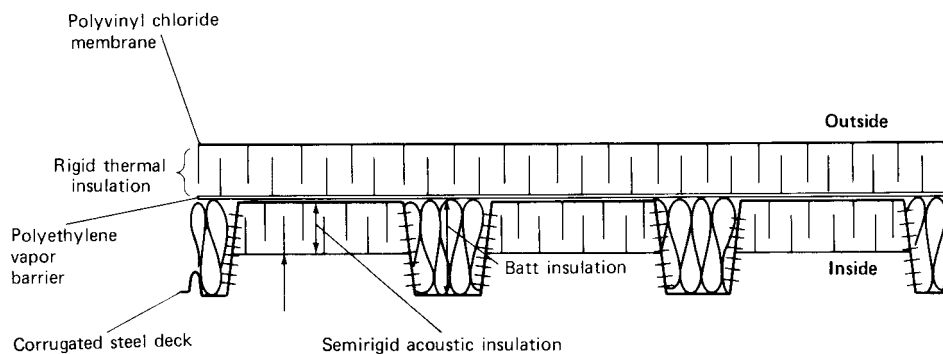**Fig. 29 Interlocking ends of corrugated roof panels**

Fig. 30 Cross section of acoustic roof deck components used for the SkyDome. Setup shown is for the D-200 (600 mm, or 24 in., wide) corrugated steel panel; an identical setup is used for the D-150 (450 mm, or 18 in., wide) panel.

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