Ultrahigh-Strength Steels

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STRUCTURAL STEELS with very high strength levels are often referred to as ultrahigh-strength steels. The designation ultrahigh-strength is arbitrary because no universally accepted strength level for the term has been established. Also, as structural steels with greater and greater strength have been developed, the strength range for which the term is applied has gradually increased. This article describes those commercial structural steels capable of a minimum yield strength of 1380 MPa (200 ksi).

In addition to the steels discussed in this article, many other proprietary and standard steels are used for essentially the same types of applications, but at strength levels slightly below the arbitrary, lower limit of 1380 MPa (200 ksi) established above for the ultrahigh-strength class of constructional steels. Medium-alloy steels such as 4330V and 4335V (vanadium-modified versions of the corresponding AISI standard steels) are among the more widely used steels for yield strengths of 1240 to 1380 MPa (180 to 200 ksi). Certain proprietary steels such as Hy Tuf (a silicon-modified steel similar to 300M) exhibit excellent toughness at strengths up to or slightly above 1380 MPa. The toughness of Hy Tuf is about the same as a maraging steel in this strength range. For properties and other information on steels and strength ranges not discussed here, the reader is referred to sources such as *Aerospace Structural Metals Handbook* (Ref 1) and to producer data sheets.

The ultrahigh-strength class of constructional steels is quite broad and includes several distinctly different families of steels. This article covers only medium-carbon low-alloy steels, medium-alloy air-hardening steels, and high fracture toughness steels. It does not cover 18Ni maraging steels, which are described in the article "Maraging Steels" in this Volume. Ultrahigh-strength steels of the stainless type (martensitic, martensitic precipitation hardenable, semiaustenitic precipitation hardenable, and cold-rolled austenitic steels) are covered in the Section "Specialty Steels and Heat-Resistant Alloys" in this Volume.

The effects of thermomechanical treatments such as ausforming and hot-cold working on the properties of many ultrahigh-strength steels have been investigated extensively. With adequate deformation while the steel is in a metastable condition, strength levels not attainable by standard quench and temper treatments have been obtained, quite often with higher ductility and fracture toughness than those normally expected at these very high strength levels. However, such thermomechanical treatments are not widely used commercially, presumably because of practical difficulties in adapting experimental techniques to actual production. Therefore, thermomechanical treatments and the properties that result from them are also excluded from this article.

Medium-Carbon Low-Alloy Steels

The medium-carbon low-alloy family of ultrahigh-strength steels includes AISI/SAE 4130, the higher-strength 4140, and the deeper hardening, higher-strength 4340. Several modifications of the basic 4340 steel have been developed. In one modification (300M), silicon content is increased to prevent embrittlement when the steel is tempered at the low temperatures required for very high strength. In AMS 6434, vanadium is added as a grain refiner to increase toughness, and the carbon is slightly reduced to promote weldability. Ladish D-6ac contains the grain refiner vanadium; slightly higher carbon, chromium, and molybdenum than 4340; and slightly lower nickel. Other less widely used steels that may be included in this family are 6150 and 8640. Chemical compositions are given in Table 1.

No new or distinctly different commercial steels have been added to this class of steels in recent years. Rather, developmental efforts have been primarily aimed at increasing ductility and toughness by improving melting and processing techniques and by using stricter process control and inspection. Steels with fewer and smaller nonmetallic inclusions and mill products with fewer internal and surface imperfections are produced by the use of selected raw materials as the melting charge and the employment of advanced melting techniques such as vacuum carbon deoxidation, vacuum degassing, electroslag remelting (ESR), vacuum arc remelting (VAR), and double vacuum melting (vacuum induction melting followed by vacuum arc remelting). These techniques yield less variation in properties from heat to heat and lot to lot; greater ductility and toughness, especially in the transverse direction; and greater in-service reliability.

Medium-carbon low-alloy ultrahigh-strength steels are readily hot forged, usually at temperatures ranging from 1065 to 1230 °C (1950 to 2250 °F). Specific forging temperatures are described in the subsequent sections for the various steels. To avoid stress cracks resulting from air hardening, the forged part should be slowly cooled in a furnace or embedded in lime, ashes, or other insulating material. Prior to machining, the usual practice is to normalize at 870 to 925 °C (1600 to 1700 °F) and temper at 650 to 675 °C (1200 to 1250 °F), or to anneal by furnace cooling from 815 to 845 °C (1500 to 1550 °F) to about 540 °C (1000 °F) if the steel is a deep air-hardening grade. These treatments impart moderately hard structures consisting of medium-to-fine pearlite. In this condition, the steel has a machinability rating of about one-half that of B1112. A very soft structure consisting of spheroidized carbides in a matrix of ferrite can be obtained by full annealing. Such a structure is not as well suited for machining as a normalized structure: The steel tends to tear, chips break away with difficulty, and metal tends to build up on the machining tool. However, the soft and ductile spheroidized structure is preferred for severe cold-forming operations such as spinning and deep drawing.

Medium-carbon low-alloy steels are cut, sheared, punched, and cold formed in the annealed condition. Cutting is commonly done with a saw or abrasive disk; if these steels are flame cut, most of them are preheated to about 315 °C (600 °F). After flame cutting, because the cut edge is hard, blanks

Table 1 Compositions of the ultrahigh-strength steels described in text

Designation or trade name	Composition, wt%(a) C	Mn	Si	Cr	Ni	Mo	V	Co
Medium-carbon low-alloy steels								
4130	0.28–0.33	0.40–0.60	0.20–0.35	0.80–1.10	...	0.15–0.25	...	...
4140	0.38–0.43	0.75–1.00	0.20–0.35	0.80–1.10	...	0.15–0.25	...	...
4340	0.38–0.43	0.60–0.80	0.20–0.35	0.70–0.90	1.65–2.00	0.20–0.30	...	...
AMS 6434	0.31–0.38	0.60–0.80	0.20–0.35	0.65–0.90	1.65–2.00	0.30–0.40	0.17–0.23	...
300M	0.40–0.46	0.65–0.90	1.45–1.80	0.70–0.95	1.65–2.00	0.30–0.45	0.05 min	...
D-6a	0.42–0.48	0.60–0.90	0.15–0.30	0.90–1.20	0.40–0.70	0.90–1.10	0.05–0.10	...
6150	0.48–0.53	0.70–0.90	0.20–0.35	0.80–1.10	...	...	0.15–0.25	...
8640	0.38–0.43	0.75–1.00	0.20–0.35	0.40–0.60	0.40–0.70	0.15–0.25	...	...
Medium-alloy air-hardening steels								
H11 mod	0.37–0.43	0.20–0.40	0.80–1.00	4.75–5.25	...	1.20–1.40	0.40–0.60	...
H13	0.32–0.45	0.20–0.50	0.80–1.20	4.75–5.50	...	1.10–1.75	0.80–1.20	...
High fracture toughness steels								
AF1410(b)	0.13–0.17	0.10 max	0.10 max	1.80–2.20	9.50–10.50	0.90–1.10	...	13.50–14.50
HP 9-4-30(c)	0.29–0.34	0.10–0.35	0.20 max	0.90–1.10	7.0–8.0	0.90–1.10	0.06–0.12	4.25–4.75

(a) P and S contents may vary with steelmaking practice. Usually, these steels contain no more than 0.035 P and 0.040 S. (b) AF1410 is specified to have 0.008P and 0.005S composition. Ranges utilized by some producers are narrower. (c) 9Ni-4Co steels and premium quality, vacuum arc remelted steels typically is specified to have 0.10 max P and 0.10 max S. Ranges utilized by some producers are narrower.

are annealed before being formed or machined.

Preferably, medium-carbon low-alloy steels are welded in the annealed or normalized condition and then heat treated to the desired strength. Such processes as inert-gas tungsten-arc, shielded metal-arc, inert-gas metal-arc, and pressure processes, as well as flash welding, can be used. Filler wire having the same composition as the base metal is preferred, but if such is not available, the filler wire should at least be of a composition that will produce a deposit that responds to heat treatment in approximately the same manner as the base metal. To avoid brittleness and cracking, preheating and interpass heating are used, and complex structures are stress relieved or hardened and tempered immediately after welding.

4130 Steel

AISI/SAE 4130 is a water-hardening alloy steel of low-to-intermediate hardenability. It retains good tensile, fatigue, and impact properties up to about 370 °C (700 °F); however, it has poor impact properties at cryogenic temperatures. This steel is not subject to temper embrittlement and can be nitrided. It usually is forged at 1100 to 1200 °C (2000 to 2200 °F); finishing temperature should never fall below 980 °C (1800 °F).

Available as billet, bar, rod, forgings, sheet, plate, tubing, and castings, 4130 steel is used to make automotive connecting rods, engine mounting lugs, shafts, fittings, bushings, gears, bolts, axles, gas cylinders, airframe components, hydraulic lines, and nitrided machinery parts.

Heat Treatments. The standard heat treatments that apply to 4130 steel are:

- *Normalize*: Heat to 870 to 925 °C (1600 to 1700 °F) and hold for a time period that depends on section thickness; air cool. Tempering at 480 °C (900 °F) or above is often done after normalizing to increase yield strength
- *Anneal*: Heat to 830 to 860 °C (1525 to 1575 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool
- *Harden*: Heat to 845 to 870 °C (1550 to 1600 °F) and hold, then water quench; or heat to 860 to 885 °C (1575 to 1625 °F); hold and then oil quench. Holding time depends on section thickness
- *Temper*: Hold at least ½ h at 200 to 700 °C (400 to 1300 °F); air cool or water quench. Tempering temperature and time at temperature depend mainly on desired hardness or strength level
- *Spheroidize*: Heat to 760 to 775 °C (1400 to 1425 °F) and hold 6 to 12 h; cool slowly

Properties. Table 2 summarizes the typical properties obtained by tempering water-quenched and oil-quenched 4130 steel bars

Table 2 Typical mechanical properties of heat-treated 4130 steel

Tempering temperature °C	°F	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Izod impact energy J	ft · lbf
Water quenched and tempered(a)										
205	400	1765	256	1520	220	10.0	33.0	475	18	13
260	500	1670	242	1430	208	11.5	37.0	455	14	10
315	600	1570	228	1340	195	13.0	41.0	425	14	10
370	700	1475	214	1250	182	15.0	45.0	400	20	15
425	800	1380	200	1170	170	16.5	49.0	375	34	25
540	1000	1170	170	1000	145	20.0	56.0	325	81	60
650	1200	965	140	830	120	22.0	63.0	270	135	100
Oil quenched and tempered(b)										
205	400	1550	225	1340	195	11.0	38.0	450	...	...
260	500	1500	218	1275	185	11.5	40.0	440	...	...
315	600	1420	206	1210	175	12.5	43.0	418	...	...
370	700	1320	192	1120	162	14.5	48.0	385	...	...
425	800	1230	178	1030	150	16.5	54.0	360	...	...
540	1000	1030	150	840	122	20.0	60.0	305	...	...
650	1200	830	120	670	97	24.0	67.0	250	...	...

(a) 25 mm (1 in.) diam round bars quenched from 845 to 870 °C (1550 to 1600 °F). (b) 25 mm (1 in.) diam round bars quenched from 860 °C (1575 °F)

Table 3 Effects of mass on typical properties of heat-treated 4130 steel
Round bars oil quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F)

Bar size(a) mm	in.	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Surface hardness, HB
25	1	1040	151	880	128	18.0	55.0	307
50	2	740	107	570	83	20.0	58.0	223
75	3	710	103	540	78	22.0	60.0	217

(a) 12.83 mm (0.505 in.) diam tensile specimens were cut from center of 25 mm diam bar and from midradius of 50 and 75 mm diam bars.

at various temperatures. Because 4130 steel has low hardenability, section thickness must be considered when heat treating to high strength (see Table 3).

4140 Steel

AISI/SAE 4140 is similar in composition to 4130 except for a higher carbon content. It is used in applications requiring a combination of moderate hardenability and good strength and toughness, but in which service conditions are only moderately severe. Because of its higher carbon content, 4140 steel has greater hardenability and strength than does 4130, but with some sacrifice in formability and weldability. Tensile strengths of up to 1650 MPa (240 ksi) are readily achieved in 4140 through conventional quench and temper heat treatments. This steel can be used at temperatures as high as 480 °C (900 °F), above which its strength decreases rapidly with increasing temperature. The material can be readily nitrided. Like other martensitic and ferritic steels, 4140 undergoes a transition from ductile to brittle behavior at low temperatures, the transition temperature varying with heat treatment and stress concentration. When 4140 is heat treated to high strength levels, it is subject to hydrogen embrittlement, such as that resulting from acid pickling or from cadmium or chromium electroplating. Ductility can be restored by baking for 2 to 4 h at 190 °C (375 °F).

The forging of 4140 steel can be done readily, usually at 1100 to 1200 °C (2000 to 2200 °F); the finishing temperature should not be below 980 °C (1800 °F). Parts should be cooled slowly after hot forming. This steel has good weldability using any of the standard welding methods. For welding, preheating at 150 to 260 °C (300 to 500 °F) and postheating at 600 to 675 °C (1100 to 1250 °F), followed by slow cooling, are recommended. Cold drawn 4140 has a machinability rating of 62% (B1112, 100%).

The steel 4140 is available as bar, rod, forgings, sheet, plate, strip, and castings. It is used for many high-strength machine parts (some of them nitrided) such as connecting rods, crankshafts, steering knuckles, axles, oil well drilling bits, piston rods, pump parts, high-pressure tubing, large industrial gears, flanges, collets, machine tool parts, wrenches, tong jaws, sprockets, and studs.

Heat Treatments. The standard heat treatments that apply to 4140 steel are:

- *Normalize*: Heat to 845 to 900 °C (1550 to 1650 °F) and hold for a time period that depends on section thickness; air cool
- *Anneal*: Heat to 845 to 870 °C (1550 to 1600 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool
- *Harden*: Heat to 830 to 870 °C (1525 to 1600 °F) and hold; then oil quench. (For water quenching, which is rarely used, hardening temperatures are 815 to 845 °C, or 1500 to 1550 °F.) Holding time depends on section thickness
- *Temper*: Hold at least ½ h at 175 to 230 °C (350 to 450 °F) or 370 to 675 °C (700 to 1250 °F); air cool or water quench. Tempering temperature and time at temperature depend mainly on desired hardness. To avoid blue brittleness, 4140 is usually not tempered between 230 and 370 °C (450 and 700 °F); 4140 is not subject to temper embrittlement
- *Spheroidize*: Heat to 760 to 775 °C (1400 to 1425 °F) and hold 6 to 12 h; cool slowly

Properties. Table 4 summarizes the mechanical properties obtained by tempering oil-quenched 4140 steel at various temperatures. Because 4140 is not a deep-hardening steel, section size should be considered when specifying heat treatment, especially for high strength levels. The effects of mass on hardness and tensile properties are given in Table 5. As expected, 4140 steel has low impact strength at cryogenic temperatures.

Table 4 Typical mechanical properties of heat-treated 4140 steel
Round bars of 13 mm (½ in.) diameter, oil quenched from 845 °C (1550 °F)

Tempering temperature, °C	Tempering temperature, °F	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Izod impact energy, J	Izod impact energy, ft · lbf
205	400	1965	285	1740	252	11.0	42	578	15	11
260	500	1860	270	1650	240	11.0	44	534	11	8
315	600	1720	250	1570	228	11.5	46	495	9	7
370	700	1590	231	1460	212	12.5	48	461	15	11
425	800	1450	210	1340	195	15.0	50	429	28	21
480	900	1300	188	1210	175	16.0	52	388	46	34
540	1000	1150	167	1050	152	17.5	55	341	65	48
595	1100	1020	148	910	132	19.0	58	311	93	69
650	1200	900	130	790	114	21.0	61	277	112	83
705	1300	810	117	690	100	23.0	65	235	136	100

Table 5 Effects of mass on typical properties of heat-treated 4140 steel

Diameter of bar(a), mm	Diameter of bar(a), in.	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Surface hardness, HB
25	1	1140	165	985	143	15	50	335
50	2	920	133	750	109	18	55	302
75	3	860	125	655	95	19	55	293

(a) Round bars oil quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F). 12.83 mm (0.505 in.) diam tensile specimens were cut from center of 25 mm (1 in.) diam bars and from midradius of 50 and 75 mm (2 and 3 in.) diam bars.

Table 6 Effects of mass on the mechanical properties of 4340 steel

Section diameter, mm	Section diameter, in.	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB
Oil quenched and tempered(a)								
13	½	1460	212	1380	200	13	51	...
38	1½	1450	210	1365	198	11	45	...
75	3	1420	206	1325	192	10	38	...
Water quenched and tempered(b)								
75	3	1055	153	930	135	18	52	340
100	4	1035	150	895	130	17	50	330
150	6	1000	145	850	123	16	44	322

(a) Austenitized at 845 °C (1550 °F); tempered at 425 °C (800 °F). (b) 75 mm (3 in.) diam bar austenitized at 800 °C (1475 °F); 100 and 150 mm (4 and 6 in.) diam bars austenitized at 815 °C (1500 °F). All sizes tempered at 650 °C (1200 °F). Test specimens taken at midradius. Source: Ref 2

4340 Steel

AISI/SAE 4340 steel is considered the standard by which other ultrahigh-strength steels are compared. It combines deep hardenability with high ductility, toughness, and strength. It has high fatigue and creep resistance. It is often used where severe service conditions exist and where high strength in heavy sections is required. In thin sections, this steel is air hardening; in practice, it is usually oil quenched. It is especially immune to temper embrittlement. It does not soften readily at elevated temperatures; that is, it exhibits good retention of strength. Hydrogen embrittlement is a problem for 4340 heat treated to tensile strengths greater than about 1400 MPa (200 ksi). Parts exposed to hydrogen, such as during pickling and plating, should be baked subsequently. This steel exhibits extremely poor resis-

Table 7 Typical mechanical properties of 4340 steel
Oil quenched from 845 °C (1550 °F) and tempered at various temperatures

Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness HB	Hardness HRC	Izod impact energy J	Izod impact energy ft · lbf
205	400	1980	287	1860	270	11	39	520	53	20	15
315	600	1760	255	1620	235	12	44	490	49.5	14	10
425	800	1500	217	1365	198	14	48	440	46	16	12
540	1000	1240	180	1160	168	17	53	360	39	47	35
650	1200	1020	148	860	125	20	60	290	31	100	74
705	1300	860	125	740	108	23	63	250	24	102	75

Table 8 Notch toughness, fracture toughness, and K_{Iscc} for 4340 steel tempered to different hardnesses

Hardness, HB	Equivalent tensile strength(a) MPa	Equivalent tensile strength(a) ksi	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf	Plane-strain fracture toughness (K_{Ic}) MPa$\sqrt{m}$	Plane-strain fracture toughness (K_{Ic}) ksi$\sqrt{in.}$	K_{Iscc} in seawater MPa$\sqrt{m}$	K_{Iscc} in seawater ksi$\sqrt{in.}$
550	2040	296	19	14	53	48	8	7
430	1520	220	30	22	75	68	30	27
380	1290	187	42	31	110	100	33	30

(a) Estimated from hardness

tance to stress-corrosion cracking when tempered to tensile strengths of 1500 to 1950 MPa (220 to 280 ksi). It can be readily nitrided, which often improves fatigue life.

The 4340 steel is usually forged at 1065 to 1230 °C (1950 to 2250 °F); after forging, parts may be air cooled in a dry place or, preferably, furnace cooled. The machinability rating of 4340 is 55% for cold-drawn material, and 45% for annealed material (cold-rolled B1112, 100%). A partly spheroidized structure obtained by normalizing and then tempering at 650 °C (1200 °F) is best for optimum machinability. The 4340 steel has good welding characteristics. It can be readily gas or arc welded, but welding rods of the same composition should be used. Because 4340 is air hardening, welded parts should be either annealed or normalized and tempered shortly after welding.

The steel 4340 is widely and readily available as billet, bar, rod, forgings, sheet, tubing, and welding wire. It is also produced as light plate and castings. Typical applications include bolts, screws, and other fasteners; gears, pinions, shafts, and similar machinery components; crankshafts and piston rods for engines; and landing gear and other critical structural members for aircraft.

Heat Treatments. The standard heat treatments that apply to 4340 steel are:

- *Normalize*: Heat to 845 to 900 °C (1550 to 1650 °F) and hold for a time period that depends on section thickness; air cool
- *Anneal*: Heat to 830 to 860 °C (1525 to 1575 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool
- *Harden*: Heat to 800 to 845 °C (1475 to 1550 °F) and hold 15 min for each 25 mm (1 in.) of thickness (15 min, minimum); oil quench to below 65 °C (150 °F), or quench in fused salt at 200 to 210 °C (390 to 410 °F), hold 10 min, and then air cool to below 65 °C (150 °F)
- *Temper*: Hold at least ½ h at 200 to 650 °C (400 to 1200 °F); air cool. Temperature and time at temperature depend mainly on desired final hardness
- *Spheroidize*: The preferred schedule is to preheat to 690 °C (1275 °F) and hold 2 h, increase the temperature to 745 °C (1375 °F) and hold 2 h, cool to 650 °C (1200 °F) and hold 6 h, furnace cool to about 600 °C (1100 °F), and finally air cool to room temperature. An alternative schedule is to heat to 730 to 745 °C (1350 to 1375 °F), hold several hours, and then furnace cool to room temperature
- *Stress relieve*: After straightening, forming, or machining, parts may be stress relieved at 650 to 675 °C (1200 to 1250 °F)
- *Bake*: To avoid hydrogen embrittlement, plated parts must be baked at least 8 h at 185 to 195 °C (365 to 385 °F) as soon after plating as possible

Properties. Through-hardening of 4340 steel can be done by oil quenching, for round sections up to 75 mm (3 in.) in diameter, and by water quenching, for larger sections (up to the limit of hardenability). The influence of section size on tensile properties of oil-quenched and water-quenched 4340 is indicated in Table 6.

Variation in hardness of 4340 with the tempering temperature is shown in Fig. 1. Typical mechanical properties of oil-quenched 4340 are given in Table 7. Additional data on mechanical properties (impact strength, fracture toughness, and threshold stress intensity for stress-corrosion cracking) are given in Table 8.

Variations in tensile properties with test temperature are plotted in Fig. 2 and 3; low-temperature impact properties are plotted in Fig. 4.

Consumable electrode vacuum melting (commonly known as vacuum arc remelting, or VAR) and electroslag remelting

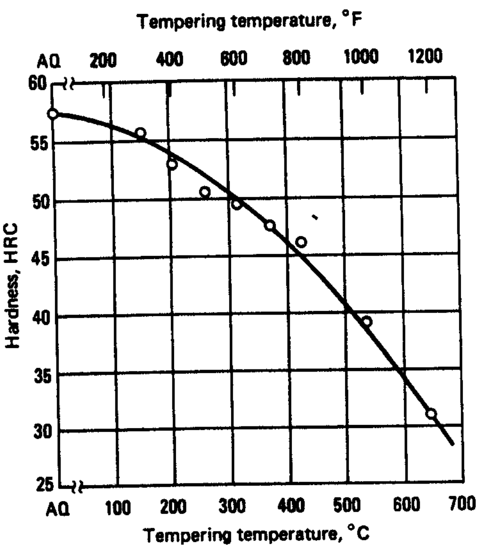


Fig. 1 Variation in hardness with tempering temperature for 4340 steel. All specimens oil quenched from 845 °C (1550 °F) and tempered 2 h at temperature. AQ, as quenched

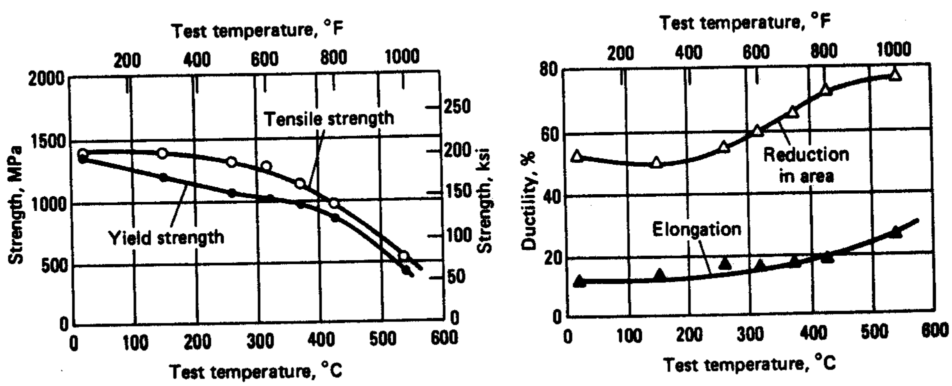
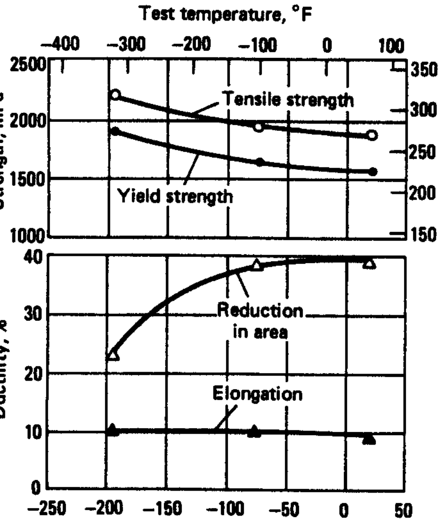


Fig. 2 Variation in tensile properties with temperature for 4340 steel. Properties determined using specimens heat treated to a room-temperature tensile strength of 1380 MPa (200 ksi). Source: Ref 1, 3



ig. 3 Low-temperature tensile properties of 4340 steel. Properties determined for specimens l quenched from 860 °C (1575 °F) and double tem-ered at 230 °C (450 °F). Source: Ref 1, 4

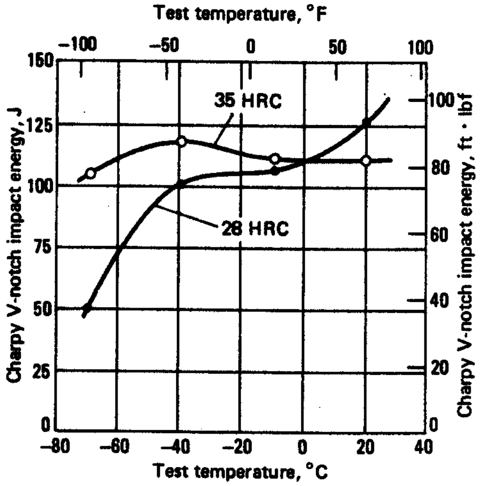


Fig. 4 Low-temperature toughness of 4340 steel. Determined for material heat treated to room-temperature hardnesses of 28 and 35 HRC

ESR) have resulted in substantial improve-ıents in the properties of 4340 steel be-ause of significant reductions in gas con-ent and in the size and number of onmetallic inclusions. Typical average gas ontents of air-melted 4340 are 1.4 ppm H_2, 25 ppm O_2, and 100 ppm N_2; these can be reduced to about 0.9 ppm H_2, 4 ppm O_2, and 53 ppm N_2 by vacuum arc remelting. The remelted steels are more homogeneous than are the air-melted products. Table 9 compares average transverse tensile properties obtained on several heats of air melted and vacuum arc remelted 4340 steel tempered to different strength levels. Longitudinal and transverse mechanical properties, including R.R. Moore fatigue data and plane-strain fracture toughness data, of air-melted and vacuum arc remelted 4340 are compared in Table 10. Mechanical properties are significantly improved by VAR processing, especially in the transverse direction, although for plane-strain fracture toughness there appear to be no significant differences between longitudinal and transverse values for the same heat. Table 11 compares longitudinal properties of VAR- and ESR-processed 4340 bars. No significant differences in properties between VAR and ESR steels are evident; the two processes appear to give roughly equivalent improvements over air melting.

able 9 Transverse tensile properties of air-melted and vacuum arc remelted 4340 steels
roperties listed are averages of several heats from the same producer; billet size and amount of ɔt reduction were not available.

empering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
C	°F	MPa	ksi	MPa	ksi		
r melted							
0	450	1945	282	1585	230	6.0	14.0
0	900	1380	200	1190	173	8.0	16.0
0	1000	1240	180	1125	163	10.0	22.0
cuum arc remelted							
0	450	1930	280	1635	237	6.5	17.0
0	900	1380	200	1210	175	9.0	20.0
0	1000	1240	180	1100	160	10.5	24.0

ble 10 Average mechanical properties of air-melted and vacuum arc remelted heats 4340 steel
ɔt reduced about 98% to round billets 100 to 115 mm (4 to 4½ in.) in diameter. Specimens were ɔrmalized at 900 °C (1650 °F), oil quenched from 845 °C (1550 °F), refrigerated, and tempered 2 h 205 °C (400 °F).

ecimen direction	Tensile strength		Yield strength		Reduction in area, %	Plane-strain fracture toughness (K_{Ic})		Fatigue limit(a)	
	MPa	ksi	MPa	ksi		MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa	ksi
r melted									
ngitudinal	2005	291	1660	241	47.5	44.5	40.5	795	115
ansverse	2000	290	1655	240	8.9	45.8(b) 48.8(c)	41.7(b) 44.4(c)	540	78
cuum arc remelted									
ngitudinal	2035	295	1660	241	49.2	60.4	55.0	965	140
ansverse	2015	292	1650	239	40.2	61.5(b) 59.7(c)	56.0(b) 54.3(c)	715	104

At 10^7 cycles. (b) WR orientation. (c) WW orientation. Source: Ref 5

300M Steel

Alloy 300M is basically a silicon-modified (1.6% Si) 4340 steel, but it has slightly higher carbon and molybdenum contents and also contains vanadium. This steel exhibits deep hardenability and has ductility and toughness at tensile strengths of 1860 to 2070 MPa (270 to 300 ksi). Many of the properties of this steel are similar to those of 4340 steel, except that the increased silicon content provides deeper hardenability, increased solid-solution strengthening, and better resistance to softening at elevated temperatures. Compared to 4340 of similar strength, 300M can be tempered at a higher temperature, which provides greater relief of quenching stresses. The so-called 260 °C (500 °F) embrittlement is displaced to higher temperatures. Because of the high silicon and molybdenum contents, 300M is particularly prone to decarburization. During thermal processing, care should be exercised to avoid decarburization, or the decarburized layer should be removed after processing. When heat treated to strength levels higher than 1380 MPa (200 ksi), 300M is susceptible to hydrogen embrittlement. If the steel is properly baked after plating, the resulting improvement in properties is better than that for 4340 or D-6ac steel of equal strength.

The steel 300M is forged at 1065 to 1095 °C (1950 to 2000 °F). Forging should not be continued below 925 °C (1700 °F). After forging, it is preferred that parts be slowly cooled in a furnace, but they may be allowed to cool in air in a dry place. Although 300M can be readily gas or arc welded, welding is generally not recommended; welding rod of the same composition should be used. Because 300M is an air-hardening steel, parts should be either annealed or normalized and tempered after welding. The machinability rating of annealed 300M is about 45% (B1112, 100%). A partially spheroidized structure, obtained by normalizing and then tempering at 650 to 675 °C (1200 to 1250 °F), gives optimum machinability.

Table 11 Longitudinal mechanical properties of bar stock made from remelted 4340 steel

Bars were normalized at 900 °C (1650 °F), oil quenched from 845 °C (1550 °F), and tempered 2 h at 541 °C (1005 °F). All specimens taken from midradius

Melting method	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 4D, %	Reduction in area, %	Charpy V-notch impact energy at −12 °C (10 °F) J	Charpy V-notch impact energy at −12 °C (10 °F) ft · lbf	Hardness, HRC
Vacuum arc remelted(a)..........	1210	175	1120	163	16.4	61.2	65	48	37
Electroslag remelted(b)..........	1185	171	1090	158	16.1	59.0	64	47	37

(a) 91.9 mm (3.62 in.) round. (b) 117.4 mm (4.625 in.) round

Table 12 Typical mechanical properties of 300M steel

Round bars, 25 mm (1 in.) in diameter, oil quenched from 860 °C (1575 °F) and tempered at various temperatures

Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf	Hardness, HRC
90	200.........	2340	340	1240	180	6.0	10.0	17.6	13.0	56.0
205	400.........	2140	310	1650	240	7.0	27.0	21.7	16.0	54.5
260	500.........	2050	297	1670	242	8.0	32.0	24.4	18.0	54.0
315	600.........	1990	289	1690	245	9.5	34.0	29.8	22.0	53.0
370	700.........	1930	280	1620	235	9.0	32.0	23.7	17.5	51.0
425	800.........	1790	260	1480	215	8.5	23.0	13.6	10.0	45.5

Table 13 Effects of mass on tensile and impact properties of 300M steel

Round bars, normalized at 900 °C (1650 °F), oil quenched from 860 °C (1575 °F), and tempered at 315 °C (600 °F)

Bar diameter mm	Bar diameter in.	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.),%	Reduction in area, %	Charpy V-notch impact energy when tested at 21 °C (70 °F) J	21 °C (70 °F) ft · lbf	−46 °C (−50 °F) J	−46 °C (−50 °F) ft · lbf	−73 °C (−100 °F) J	−73 °C (−100 °F) ft · lbf
25	1.......	1990	289	1690	245	9.5	34.1	30	22	26	19	24	18
75	3.......	1940	281	1630	236	9.5	35.0	26	19	19	14	12	9
145	5¾.....	2120	308	1800	261	7.3	22.3	12	9	9	7	7	5

Table 14 Transverse tensile properties of air-melted and vacuum arc remelted 300M steel

Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %
Air melted							
315	600	1960	284	1620	235	5.0	11
425	800	1760	255	1540	223	7.0	14
540	1000	1585	230	1480	215	9.0	22
Vacuum arc remelted							
260	500	2020	293	1620	235	7.0	25
425	800	1760	255	1550	225	10.0	34
540	1000	1585	230	1480	215	11.0	35

Typical applications of 300M, which is available as bar, sheet, plate, wire, tubing, forgings, and castings, are aircraft landing gear, airframe parts, fasteners, and pressure vessels.

Heat Treatments. The standard heat treatments that apply to 300M steel are:

- *Normalize*: Heat to 915 to 940 °C (1675 to 1725 °F) and hold for a time period that depends on section thickness; air cool. If normalizing to enhance machinability, charge into a tempering furnace at 650 to 675 °C (1200 to 1250 °F) before the steel reaches room temperature
- *Harden*: Austenitize at 860 to 885 °C (1575 to 1625 °F). Oil quench to below 70 °C (160 °F) or quench in salt at 200 to 210 °C (390 to 410 °F), hold 10 min, and then air cool to 70 °C (160 °F) or below
- *Temper*: Hold at 2 to 4 h at 260 to 315 °C (500 to 600 °F). Double tempering is recommended. This tempering procedure produces the best combination of high yield strength and high impact properties. Tempering outside this temperature range results in severe deterioration of properties
- *Spheroidize*: Heat to about 775 °C (1430 °F) and hold for a time period that depends on section thickness or furnace load. Cool to 650 °C (1200 °F) at a rate no faster than 5.5 °C/h (10 °F/h); then cool to 480 °C (900 °F) no faster than 10 °C/h (20 °F/h); finally, air cool to room temperature. The same schedule is recommended for annealing

Properties. Variations in hardness and mechanical properties of 300M with tempering temperature are presented in Table 12. Because 300M has deep hardenability, heat-treated bars 75 mm (3 in.) in diameter have essentially the same tensile properties as do bars 25 mm (1 in.) in diameter. Reductions in tensile ductility and impact strength, however, are observed in heat-treated bars 145 mm (5¾ in.) in diameter. Variations in properties of 300M (including impact strength at room and low temperatures) with section size are presented in Table 13.

In R.R. Moore fatigue tests of polished specimens, endurance limits of about 800 MPa (116 ksi) and 585 MPa (85 ksi) were found for longitudinal and transverse specimens, respectively, of air-melted 300M heat treated to a tensile strength of about 2025 MPa (294 ksi) by oil quenching from 870 °C (1600 °F) and tempering at 290 °C (550 °F). Vacuum arc remelting and electroslag remelting improve transverse ductility and impact strength by producing a cleaner microstructure. Transverse tensile properties of air-melted and vacuum arc remelted 300M are compared in Table 14. The data are average values from several heats.

In another study, transverse tensile properties were determined for specimens of 300M taken from 40 billets, each 125 mm (5 in.) square, representing seven vacuum arc remelted heats. Specimens were normalized for 1 h at 925 °C (1700 °F), reheated 1 h at 870 °C (1600 °F), oil quenched, and tempered 4 h at 315 °C (600 °F). Average properties were as follows: tensile strength, 1978 MPa (286.9 ksi); yield strength, 1671 MPa (242.4 ksi); elongation, 9.3%; and reduction in area, 36.6%. Property ranges were: tensile strength, 1896 to 2039 MPa (275.0 to 295.7 ksi); yield strength, 1581 to 1752 MPa (229.3 to 254.1 ksi); elongation, 9 to 10%; and reduction in area, 31.7 to 45.0%.

Samples from two heats of VAR 300M steel heat treated to an average tensile strength of 2025 MPa (294 ksi), average yield strength of 1710 MPa (248 ksi), average elongation of 11.5%, average reduction in area of 45.6%, and average Charpy V-notch impact value of 27 J (20 ft · lbf) showed an average K_{Ic} value of 60.2 MPa$\sqrt{m}$ (54.8 ksi$\sqrt{in.}$) and an average K_{Iscc} value of 15.9 MPa$\sqrt{m}$ (14.5 ksi$\sqrt{in.}$) in a 3.5% NaCl solution (Ref 6). Table 15 presents longitudinal and transverse tensile and plane-strain fracture toughness data for both air-melted and vacuum arc remelted 300M steel. R.R. Moore fatigue test results on transverse specimens indicate fatigue

Table 15 Average mechanical properties of air-melted and vacuum arc remelted heats of 300M steel

Hot reduced 96 to 98% to round-cornered square billets, about 100 × 100 mm (4 × 4 in.). Specimens were normalized at 925 °C (1700 °F), oil quenched from 870 °C (1600 °F), refrigerated, and double tempered, 2 + 2 h at 315 °C (600 °F).

Specimen direction	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Reduction in area, %	Plane-strain fracture toughness (K_{Ic}) MPa$\sqrt{m}$	Plane-strain fracture toughness (K_{Ic}) ksi$\sqrt{in.}$
Air melted							
Longitudinal	2095	304	1805	262	44.8	49.3	44.9
Transverse	2035	295	1750	254	23.6	58.7(a)	53.4(a)
						61.4(b)	55.9(b)
Vacuum arc remelted							
Longitudinal	2080	302	1785	259	47.8	57.4	52.2
Transverse	2015	292	1760	255	33.6	64.1(a)	58.3(a)
						61.4(b)	55.9(b)

(a) WR orientation. (b) WW orientation

limits of about 580 MPa (84 ksi) for air-melted 300M and about 675 MPa (98 ksi) for VAR 300M; the latter represents an improvement of about 17% over air-melted 300M. In the same study, there was no significant difference in transverse fatigue limit between VAR 300M and ESR 300M that had been hot reduced only 75% from the ingot. In all these studies, remelted steels (whether VAR or ESR) had better ductility and toughness, particularly in the transverse direction, although there did not appear to be any significant difference between longitudinal and transverse plane-strain fracture toughness values.

D-6a and D-6ac Steel

Ladish D-6a is a low-alloy ultrahigh-strength steel developed for aircraft and missile structural applications. It is designed primarily for use at room-temperature tensile strengths of 1800 to 2000 MPa (260 to 290 ksi). The steel D-6a maintains a very high ratio of yield strength to tensile strength up to a tensile strength of 1930 MPa (280 ksi), combined with good ductility. It has good notch toughness, which results in high resistance to impact loading. It is deeper hardening than 4340 and does not exhibit temper embrittlement. It retains high strength at elevated temperature. Susceptibility of D-6a to stress-corrosion cracking and corrosion fatigue in moist and aqueous environments is comparable to that of 300M steel at the same strength level. The alloy is called D-6a when produced by air melting in an electric furnace and D-6ac when produced by air melting followed by vacuum arc remelting. The mechanical properties of D-6a and D-6ac differ somewhat as a result of the differences in melting practices. Other characteristics of the two steels, including processing behavior, are identical.

D-6a and D-6ac are available as bar, rod, billet, and forgings and can be made as flat-rolled products (sheet and plate) as well. These forms are used in landing gear and critical structural components for aircraft, motor cases for solid-fuel rockets, shafts, gears, springs, dies, dummy blocks, and backer blocks.

Processing. To forge D-6a, it should be heated to a maximum temperature of 1230 °C (2250 °F); forging should be finished above 980 °C (1800 °F). Finished forgings should be cooled slowly, either in a furnace or embedded in a suitable insulating medium such as ashes or lime. For maximum machinability, the parts should be charged into a 650 °C (1200 °F) furnace immediately after forging and held for 12 h; temperature should be increased to 900 °C (1650 °F) and held for a time period that depends on section size; parts should be cooled to 650 °C (1200 °F), held 10 h, and finally air cooled to room temperature.

The material D-6a, even in heavy sections, can be welded provided that the techniques and controls normally employed for welding medium-carbon, high hardenability alloy steels are used. Welding rod of the same composition should be used. For critical applications, gas tungsten arc welding is preferred; filler metal wire should be of vacuum-melted stock containing less carbon than is in the base metal and minimum amounts of phosphorus, sulfur, and dissolved gases. Welds made in this manner will have higher toughness than that of the base metal, but slightly lower strength. Preheat and interpass temperatures of 230 to 290 °C (450 to 550 °F) are recommended. Highly restrained weldments should be postheated 1½ h at 300 to 330 °C (575 to 625 °F) and cooled in still air. When the weldments reach 150 °C (300 °F), they should be charged immediately into a furnace for stress relieving at 650 to 700 °C (1200 to 1300 °F).

Annealed D-6a has a machinability rating of 50 to 55% (B1112, 100%). When the steel is to be severely cold formed, it is usually normalized and then spheroidized before working.

Heat Treatments. The standard heat treatments that apply to D-6a and D-6ac steels are:

- *Normalize*: Heat to 870 to 955 °C (1600 to 1750 °F) and hold for a time period that depends on section thickness; air cool
- *Anneal*: Heat to 815 to 845 °C (1500 to 1550 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool to 540 °C (1000 °F) at a rate no greater than 28 °C/h (50 °F/h); and then air cool to room temperature
- *Harden*: Austenitize at 845 to 900 °C (1550 to 1650 °F) for ½ to 2 h. Sections no thicker than 25 mm (1 in.) may be air cooled. Sections thicker than 25 mm (1 in.) may be oil quenched to 65 °C (150 °F) or salt quenched to 205 °C (400 °F) and then air cooled. For optimum dimensional stability, "aus-bay" quench in a furnace at 525 °C (975 °F), equalize the temperature, and then quench in an oil bath held at 60 °C (140 °F) or quench in 205 °C (400 °F) salt and air cool. The cooling rate during quenching significantly affects fracture toughness. For high fracture toughness, especially in heavy sections, austenitize at 925 °C (1700 °F), aus-bay quench to 525 °C (975 °F), equalize, and oil quench to 60 °C (140 °F)
- *Temper*: Immediately after hardening, hold 2 to 4 h in the range of 200 to 700 °C (400 to 1300 °F), depending on desired strength or hardness
- *Spheroidize*: Heat to 730 °C (1350 °F) and hold 5 h; increase temperature to 760 °C (1400 °F) and hold 1 h; furnace cool to 690 °C (1275 °F) and hold 10 h; furnace cool to 650 °C (1200 °F) and hold 8 h; air cool to room temperature
- *Stress relieve*: Heat to an appropriate temperature in the range of 540 to 675 °C (1000 to 1250 °F) and hold for 1 to 2 h; air cool

Properties. The effect of tempering temperature on typical room-temperature hardness of D-6a steel bar is shown in Fig. 5; other mechanical properties of D-6a bar are given in Table 16. Tensile properties of heat-treated D-6ac billet material are given in Table 17. D-6a maintains impact resistance to very low temperatures (Fig. 6). Typical elevated-temperature tensile properties of D-6a are presented in Table 18, and in Table 19 room-temperature tensile properties after 10 h and 100 h exposures at 540 °C (1000 °F) are compared with properties of unexposed material. Data on stress-rupture life at 480 and 540 °C (900 and 1000 °F) are presented in Fig. 7. The effects of tempering temperature on smooth-bar and notched-bar tensile strengths are plotted in Fig. 8. As mentioned in the section on heat treatment, the rate of cooling during quenching has a significant effect on fracture toughness. When the steel is heat treated for high fracture toughness (as outlined above), a K_{Ic} value of 99 to 104 MPa$\sqrt{m}$ (90 to 95 ksi$\sqrt{in.}$) can be obtained at a tensile strength of about 1650 MPa (240 ksi) (Ref 7).

Table 16 Typical mechanical properties of D-6a steel bar

Normalized at 900 °C (1650 °F), oil quenched from 845 °C (1550 °F), and tempered at various temperatures

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Charpy V-notch impact energy	
°C	°F	MPa	ksi	MPa	ksi			J	ft · lbf
150	300	2060	299	1450	211	8.5	19.0	14	10
205	400	2000	290	1620	235	8.9	25.7	15	11
315	600	1840	267	1700	247	8.1	30.0	16	12
425	800	1630	236	1570	228	9.6	36.8	16	12
540	1000	1450	210	1410	204	13.0	45.5	26	19
650	1200	1030	150	970	141	18.4	60.8	41	30

Table 17 Tensile properties of double-tempered D-6ac billet material

Austenitized 1 h at 900 °C (1650 °F), quenched in fused salt at 205 °C (400 °F) for 5 min, then air cooled to room temperature. Tempered 1 h at 205 °C; second temper, 4 h at indicated temperature

Second tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
°C	°F	MPa	ksi	MPa	ksi		
480	900	1686.5	244.6	1540.3	223.4	11.1	40.0
510	950	1652.7	239.7	1519.7	220.4	13.2	44.1
540	1000	1613.4	234.0	1483.8	215.2	13.7	47.2

Table 18 Tensile properties of D-6a steel at elevated temperatures

Normalized at 900 °C (1650 °F), oil quenched from 845 °C (1550 °F), and tempered 28 °C (50 °F) above indicated test temperature

Test temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
°C	°F	MPa	ksi	MPa	ksi		
260	500	1839.6	266.8	1294.9	187.8	15.2	55.0
315	600	1629.3	236.3	1256.3	182.2	15.8	57.4
370	700	1430.0	207.4	1164.6	168.9	14.7	55.0
425	800	1277.6	185.3	1096.3	159.0	15.2	55.0
480	900	1158.4	168.0	976.3	141.6	16.2	57.5
540	1000	957.7	138.9	831.5	120.6	19.8	64.5
595	1100	497.1	72.1	395.8	57.4	41.7	86.5

The alloy is susceptible to stress-corrosion cracking; the K_{Iscc} value, in both water and 3.5% NaCl solution, appears to be less than 16 MPa $\sqrt{m}$ (15 ksi $\sqrt{in.}$). The steel has high fatigue strength; Table 20 presents data for both D-6a and D-6ac derived from rotating-beam fatigue tests, and Table 21 gives data for rapid-cycle (about 186 kHz) tension-tension and tension-compression fatigue tests at room and elevated temperatures.

6150 Steel

AISI/SAE 6150 is a tough, shock-resisting, shallow-hardening chromium-vanadium steel with high fatigue and impact resistance in the heat-treated condition. It can be nitrided for maximum surface hardness and abrasion resistance; nitriding characteristics are similar to those of 4140 and 4340 steels. The steel 6150 may be forged from temperatures up to 1200 °C (2200 °F), but the usual temperature range is 1175 to 950 °C (2150 to 1750 °F). Parts made of 6150 steel can readily be welded using any of the standard welding methods. After welding, parts should be normalized and then hardened and tempered to the desired hardness.

For best machinability, 6150 should be in the annealed condition. Machinability rating is about 55% (B1112, 100%). As with other low-alloy steels of about the same carbon content, the optimum microstructure for machining is coarse lamellar pearlite and/or coarse spheroidite. Chips are continuous and springy, which can make the steel difficult to machine.

Available as bar, rod, plate, sheet, strip, wire, and tubing, 6150 steel may be forged

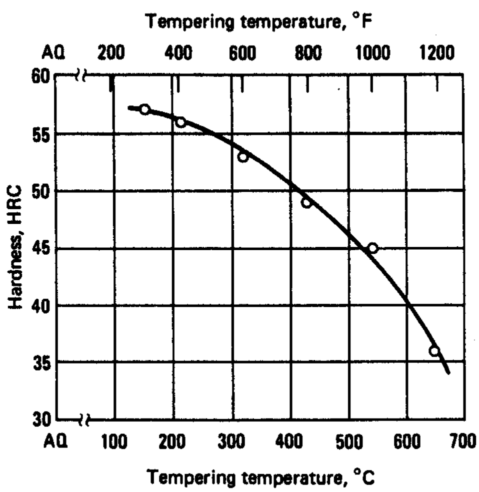


Fig. 5 Variation of hardness with tempering temperature for D-6a steel. All specimens oil quenched from 845 °C (1550 °F) and tempered 2 h at temperature. AQ, as quenched

Table 19 Room-temperature properties of D-6a steel after various times at 540 °C (1000 °F)

Steel normalized at 900 °C (1650 °F), oil quenched from 845 °C (1550 °F), and tempered at 565 °C (1050 °F)

Time at 540 °C (1000 °F), h	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
	MPa	ksi	MPa	ksi		
0	1410	204	1340	195	14.8	50.5
10	1410	204	1330	193	14.5	52.0
100	1330	193	1260	183	14.8	51.0

Table 20 Typical fatigue limits for D-6a and D-6ac steel

Steel	Tempering temperature		Hardness, HRC	Fatigue limit(a)	
	°C	°F		MPa	ksi
D-6a(b)	540	1000	45.0	760	110
			46.0	750	108
			45.0	740	107
D-6ac(b)	575	1075	42.0	780	113
			42.5	795	115
			41.5	760	110
			43.5	750	108
D-6a(c)	315	600	50.0	740	107

(a) At 10^6 stress cycles in rotating-beam tests using polished specimens. (b) 1520 MPa (220 ksi) tensile strength. (c) 1790 MPa (260 ksi) tensile strength

Table 21 Room-temperature and elevated-temperature fatigue limits for D-6ac steel

Smooth specimens heat treated to a tensile strength of 1860 MPa (270 ksi); test speed, 186 kHz

Test temperature		Tension-tension(a)		Tension-compression(b)	
°C	°F	MPa	ksi	MPa	ksi
24	75	1035	150	690	100
232	450	930	135	550	80
288	550	930	135	575	75

(a) Mean stress equal to alternating stress ($R = 0$). (b) Mean stress equal to zero ($R = -1$)

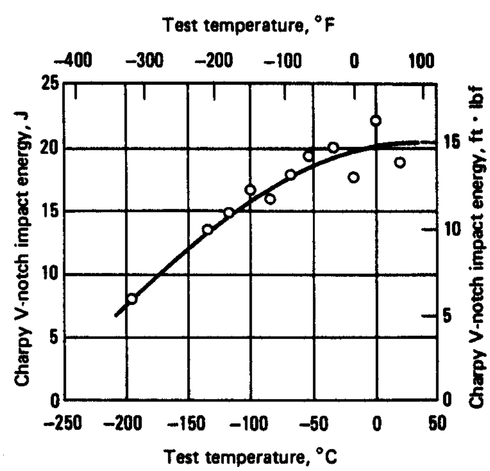


Fig. 6 Low-temperature toughness of a D-6a steel. All specimens heat treated to a room-temperature tensile strength of 1790 to 1860 MPa (260 to 270 ksi). Each data point is the average of three tests.

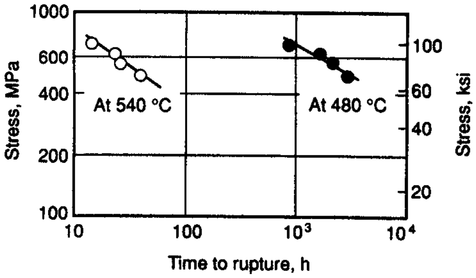


Fig. 7 Stress-rupture life for a D-6a steel. Determined for material heat treated to a room-temperature tensile strength of 1380 to 1520 MPa (200 to 220 ksi)

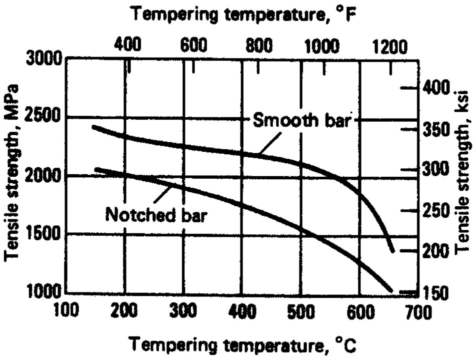


Fig. 8 Variation in smooth-bar and notched-bar tensile strengths with tempering temperature for D-6a steel. Specimens oil quenched from 845 °C (1550 °F) and tempered 2 h at temperature. Notched bars had a stress-concentration factor, K_t, of 4.2.

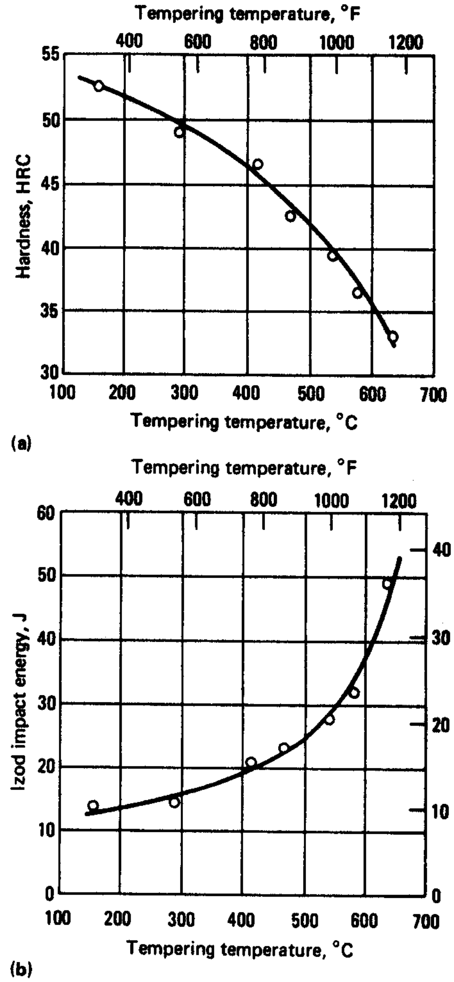


Fig. 9 Variation in (a) hardness and (b) impact energy with tempering temperature for 6150 steel. Specimens oil quenched from 885 °C (1625 °F) and tempered 2 h at temperature

or cast into shapes. Typical applications include gears, pinions, springs (both coiled and flat), shafts, axles, heavy duty pins, bolts, and machinery parts.

Heat Treatments. The heat treatments that apply to 6150 steel are:

- *Normalize*: Heat to 870 to 955 °C (1600 to 1750 °F) and hold for a time period that depends on section thickness; air cool
- *Anneal*: Heat to 845 to 900 °C (1550 to 1650 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool
- *Harden*: Austenitize at 845 to 900 °C (1550 to 1650 °F); oil quench
- *Temper*: Hold at least ½ h at 200 to 650 °C (400 to 1200 °F). Tempering temperature and time at temperature primarily depend on desired final hardness
- *Austemper*: Austenitize in a salt bath at 845 to 900 °C (1550 to 1650 °F); quench in a salt bath at 230 to 315 °C (450 to 600 °F), hold 20 to 30 min, and quench or air cool to room temperature
- *Martemper*: Austenitize in a salt bath at 845 to 870 °C (1550 to 1600 °F); quench in a salt bath at 230 to 260 °C (450 to 500 °F), equalize, and then air cool or quench to room temperature. Temper to desired hardness
- *Spheroidize*: Heat to 800 to 830 °C (1475 to 1525 °F), hold until heated through, furnace cool to 650 °C (1200 °F), and hold several hours; then cool slowly to room temperature

Properties. Typical properties of small-diameter round sections of 6150 tempered at various temperatures are given in Table 22. Variations in hardness and Izod impact energy with tempering temperature are plotted in Fig. 9. The effects of section size on tensile properties and hardness are presented in Table 23.

8640 Steel

AISI/SAE 8640 was especially designed to provide the maximum hardenability and best combination of properties possible with minimum alloying additions. The material 8640 is an oil-hardening steel, but may be water hardened if precautions are taken to prevent cracking. It exhibits properties similar to those of 4340, except that its strength in large sections is not as high.

This steel is available as billets, bars, rods, forgings and castings. It is used to make gears, pinions, shafts, axles, studs, fasteners, machinery parts, and forged hand tools.

Processing. The 8640 steel may be forged at temperatures up to 1200 °C (2200 °F), but is usually forged in the range from 1175 to 950 °C (2150 to 1750 °F). Forged parts are cooled slowly from the forging temperature, then annealed prior to machining.

This steel can be welded by any of the standard welding methods. Because 8640 has some air-hardening tendencies, preheating to 150 to 260 °C (300 to 500 °F) before welding and postheating after welding are recommended. Stress relieving at 600 to 650 °C (1100 to 1200 °F) is quite satisfactory for most welded parts.

Cold-drawn 8640 has a machinability rating of 64% (B1112, 100%). Annealing prior to cold drawing can improve machinability by about 10%.

Table 22 Room-temperature tensile properties of heat-treated 6150 steel

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lbf
Round bars, 14 mm (0.55 in.) in diameter(a)										
205	400	2050	298	1810	263	1	5	610	...	...
260	500	2070	300	1810	263	4	12	570	...	...
315	600	1950	283	1720	250	7	27	540	...	...
370	700	1770	257	1620	235	10	37	505	9	7
425	800	1585	230	1490	216	11	42	470	14	10
480	900	1410	204	1340	195	12	44	420	16	12
540	1000	1250	182	1210	175	13	46	380	20	15
595	1100	1150	167	1080	157	16	47	350	28	21
Round bars, 25 mm (1 in.) in diameter(b)										
425	800	1570	228	1450	210	10	37	461	...	...
480	900	1360	197	1210	175	11	41	401	...	...
540	1000	1180	171	1030	150	12	45	341	...	...
595	1100	1030	150	875	127	15	50	302	...	...
650	1200	920	133	760	110	19	55	262	...	...
705	1300	810	118	660	96	23	61	235	...	...

(a) Normalized at 870 °C (1600 °F), oil quenched from 860 °C (1575 °F), and tempered at various temperatures. (b) Oil quenched from 860 °C and tempered at various temperatures

Table 23 Effects of mass on properties of heat-treated 6150 steel

Specimen size(a) mm	in.	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB
25	1	1185	172	1040	151	14	45	341
50	2	1170	170	1030	149	13	48	341
75	3	1090	158	950	138	13	47	331

(a) Round bars, oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F); 12.83 mm (0.505 in.) diam tensile specimens taken from center of 25 mm (1 in.) bars and from midradius of 50 and 75 mm (2 and 3 in.) diam bars

Heat Treatments. The heat treatments that apply to 8640 steel are:

- *Normalize*: Heat to 870 to 925 °C (1600 to 1700 °F) and hold for a time period that depends on section thickness; air cool
- *Anneal*: Heat to 845 to 870 °C (1550 to 1600 °F) and hold for a time period that depends on section thickness or furnace load; furnace cool
- *Harden*: Austenitize at 815 to 845 °C (1500 to 1550 °F); quench in oil or water
- *Temper*: Hold at least ½ h at 200 to 650 °C (400 to 1200 °F)
- *Spheroidize*: Heat to 705 to 720 °C (1300 to 1325 °F) and hold several hours; furnace cool

Properties. Variations in properties of heat-treated round sections of 8640 with tempering temperature are given in Table 24. Variations in properties with section size (mass effect) are given in Table 25. Impact behavior is illustrated in Fig. 10.

Medium-Alloy Air-Hardening Steels

The ultrahigh-strength steels H11 modified (H11 mod) and H13, which are popularly known as 5% Cr hot-work die steels, are discussed in this section. Besides being extensively used in dies, these steels are widely used for structural applications, but not as widely as they once were, primarily because of the development of several other steels at essentially the same cost but with substantially greater fracture toughness at equivalent strength. Nonetheless, H11 mod and H13 possess some attractive features. Both can be hardened through in large sections by air cooling. The chemical compositions of these steels are given in Table 1.

H11 Modified

This steel is a modification of the martensitic hot-work die steel AISI H11, the significant difference being a slightly higher carbon content. The H11 mod steel can be heat treated to strengths exceeding 2070 MPa (300 ksi). It is air hardened, which results in minimal residual stress after hardening. Because H11 mod is a secondary hardening steel, it develops optimum properties when tempered at temperatures above 510 °C (950 °F). The high tempering temperatures used for this steel provide substantial stress relief and stabilization of properties so that the material can be used to advantage at elevated temperatures. This also enables heat-treated parts to be warm worked at temperatures as much as 55 °C (100 °F) below the prior tempering temperature or to be preheated for welding. At high strength levels (those exceeding 1800 MPa, or 260 ksi), H11 mod has good ductility, impact strength, notch toughness, and fatigue life, as well as high creep and rupture strength, at temperatures up to about 650 °C (1200 °F). It is used for parts requiring maximum levels of strength, ductility, toughness, fatigue resistance, and thermal stability at temperatures between −75 and 540 °C (−100 and 1000 °F). At elevated temperatures, parts should be protected from corrosion (oxidation) by an appropriate surface treatment. The material H11 mod has good formability in the annealed condition and is readily welded. It is subject to hydrogen embrittlement. Its fracture toughness is rather low; if it is used in critical applications at yield strengths above 1380 MPa (200 ksi), care should be taken to eliminate small discontinuities.

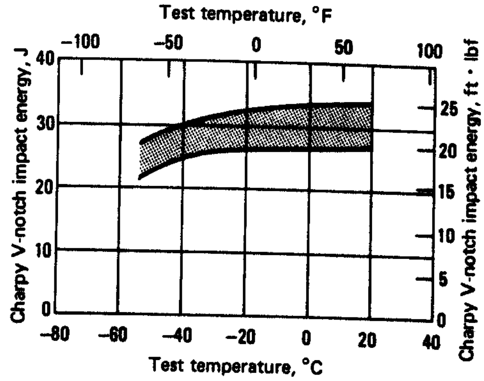


Fig. 10 Low-temperature toughness of 8640 steel. Determined for material oil quenched and tempered to room-temperature hardness of 401 to 415 HB

Table 24 Typical room-temperature mechanical properties of 8640 steel

Tempering temperature °C	°F	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Impact energy J	ft · lbf	Hardness HB	HRC
Round bars, 13.5 mm (0.53 in.) in diameter(a)											
205	400	1810	263	1670	242	8.0	25.8	11.5(b)	8.5(b)	555	55
315	600	1585	230	1430	208	9.0	37.3	15.6(b)	11.5(b)	461	48
425	800	1380	200	1230	179	10.5	46.3	27.8(b)	20.5(b)	415	44
540	1000	1170	170	1050	152	14.0	53.3	56.3(b)	41.5(b)	341	37
650	1200	870	126	760	110	20.5	61.0	96.9(b)	71.5(b)	269	28
Round bars, 25 mm (1 in.) in diameter(a)											
425	800	1382	200.5	1230	179	10	46	27(c)	20(c)	415	44
480	900	1250	181	1120	162	13	51	41(c)	30(c)	388	42
540	1000	1070	155	940	137	17	56	54(c)	40(c)	331	36
595	1100	1020	148	910	132	16	57	73(c)	54(c)	302	32
650	1200	865	125.5	760	110.5	20	61	83(c)	61(c)	269	28

(a) Oil quenched from 830 °C (1525 °F) and tempered at indicated temperature. (b) Izod. (c) Charpy V-notch

Table 25 Effects of mass on properties of heat-treated 8640 steel

Bar size(a) mm	in.	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Surface hardness, HB
25	1	1070	155	940	137	17	56	331
50	2	910	132	770	112	18	57	293
75	3	860	125	710	103	19	58	277

(a) Oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F)

The H11 mod steel is available as bar, billet, rod, wire, plate, sheet, strip, forgings, and extrusions. It is used for parts requiring high strength combined with either strength retention at elevated temperatures or moderate corrosion resistance. Typical applications include aircraft landing gear components, airframe components, internal parts for steam and gas turbines, fasteners, springs, and hot-work dies.

Parts to be used at elevated temperatures are commonly protected by nickel-cadmium plating. If such plating is done, baking to avoid hydrogen-induced delayed cracking is recommended. Alternatively, part surfaces may be protected from oxidation by hot dipping in aluminum or by applying a heat-resistant paint.

Processing. The material H11 mod is readily forged from 1120 to 1150 °C (2050 to 2100 °F). Preferably, stock should be preheated at 790 to 815 °C (1450 to 1500 °F) and then heated uniformly to the forging tem-

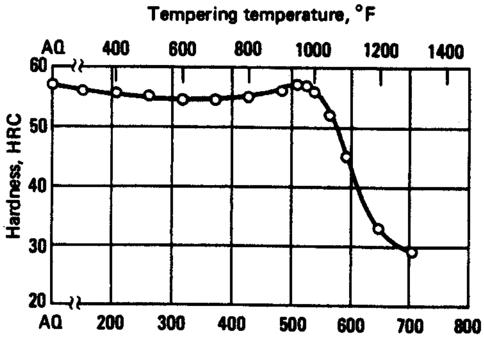


Fig. 11 Variation in hardness with tempering temperature for H11 mod steel. All specimens air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at temperature. AQ, as quenched

Table 26 Typical longitudinal mechanical properties of H11 mod steel
Air cooled from 1010 °C (1850 °F); double tempered, 2 + 2 h at indicated temperature

Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf	Hardness, HRC
510	950	2120	308	1710	248	5.9	29.5	13.6	10.0	56.5
540	1000	2005	291	1675	243	9.6	30.6	21.0	15.5	56.0
565	1050	1855	269	1565	227	11.0	34.5	26.4	19.5	52.0
595	1100	1540	223	1320	192	13.1	39.3	31.2	23.0	45.0
650	1200	1060	154	855	124	14.1	41.2	40.0	29.5	33.0
705	1300	940	136	700	101	16.4	42.2	90.6	66.8	29.0

Table 27 Typical short-time elevated-temperature properties of H11 mod steel
Longitudinal specimens taken from bar stock air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated tempering temperature

Test temperature °C	Test temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf
Tempered at 540 °C (1000 °F)									
260	500	1860	270	1520	220	9.9	33.2	...	...
315	600	1840	267	1490	216	10.3	34.5	...	...
425	800	1670	242	1440	209	12.0	42.6	...	...
480	900	1580	229	1365	198	12.3	46.1	...	...
540	1000	1480	215	1255	182	13.7	48.2	...	...
650	1200	610	88	583	84.5	24.8	95.2	...	...
Tempered at 565 °C (1050 °F)									
Room	Room	1810	262	1480	215	9.8	35.4	...	...
150	300	1700	246	1365	198	10.1	36.1	29.4	21.7
260	500	1610	233	1340	195	10.2	35.8	41.2	30.4
315	600	1600	231.5	1330	193	10.3	36.0	42.7	31.5
425	800	1500	217	1270	184	11.4	38.8	40.0	29.5
480	900	1420	206	1140	166	12.2	39.3	39.7	29.3
540	1000	1240	180	970	141	12.2	41.3	41.4	30.5
595	1100	980	142	720	105	12.8	46.8	45.0	33.2
650	1200	590	85	440	64	19.0	66.8	80.0	59.0
Tempered at 595 °C (1100 °F)									
260	500	1340	195	1130	164	10.0	45.0	44	33
315	600	1310	190	1100	160	10.0	48.1	...	...
425	800	1230	178	1010	146	12.4	52.2	41	30
480	900	1130	164	900	131	13.5	56.0	...	...
540	1000	980	142	790	115	15.5	62.0	...	...

perature. Forging should not be continued below 925 °C (1700 °F). Stock may be reheated as often as necessary. Because H11 mod is air hardening, it must be cooled slowly after forging to prevent stress cracks. After forging, the part should be charged into a furnace at about 790 °C (1450 °F); soaked until the temperature is uniform; and then slowly cooled, either while retained in the furnace or buried in an insulating medium such as lime, mica, or a siliceous filler material such as silocel. When the forging has cooled, it should be annealed.

The steel H11 mod, even in heavy sections, is readily welded. Fusion welding generally is accomplished with an inert-gas process or with coated electrodes. Filler metal should be of the same general composition. Preheating at about 540 °C (1000 °F) is recommended, and during welding the temperature should be maintained above 315 °C (600 °F). Thin sheet can be welded without preheating, but should be postheated at about 760 °C (1400 °F). Weldments, especially heavy-section weldments, should be cooled slowly in a furnace or an insulating medium. All weldments should be fully annealed after welding. Weldments of H11 mod have shown weld metal strength and ductility equal to or greater than those of the base metal. The machinability rating for H11 mod is about 60% of the rating for 1% C steel, or about 45% of that for B1112.

Heat Treatments. The standard heat treatments that apply to H11 mod steel are:

- *Normalize*: Generally not necessary. For effective homogenization, heat to about 1065 °C (1950 °F), soak 1 h for each 25 mm (1 in.) of thickness; air cool. Anneal immediately after the part reaches room temperature. Note: There is a possibility that H11 mod may crack during this treatment
- *Anneal*: Heat to 845 to 885 °C (1550 to 1625 °F) and hold to equalize temperature; cool very slowly in the furnace to about 480 °C (900 °F) and then more rapidly to room temperature. This treatment should produce a fully spheroidized microstructure free of grain boundary carbide networks
- *Harden*: Preheat to 760 to 815 °C (1400 to 1500 °F) and then raise the temperature to 995 to 1025 °C (1825 to 1875 °F) and hold 20 min plus 5 min for each 25 mm (1 in.) of thickness; air cool. For a few applications, oil quenching from the low end of the hardening temperature range may be done. Air cooling, which produces less distortion than oil quenching, is more commonly employed
- *Temper*: Heat at the secondary hardening temperature of about 510 °C (950 °F) for maximum hardness and strength, or above the secondary hardening peak to temper back to a lower hardness or strength. A minimum of 1 h at temperature should be allowed, but preferably parts should be double tempered: Hold 2 h at temperature, cool to room temperature, and then hold 2 h more at temperature. Triple tempering is more desirable, especially for critical parts. For high-temperature applications, parts should be tempered at a temperature above the maximum service temperature to guard against unwanted changes in properties during service
- *Stress relieve*: Heat to 650 to 675 °C (1200 to 1250 °F); cool slowly to room temperature. This treatment is often used to achieve greater dimensional accuracy in heat-treated parts by stress relieving rough-machined parts, then finish machining, and finally heat treating to the desired hardness
- *Nitride*: Finish-machined and heat-treated parts should be gas or liquid nitrided at temperatures of about 525 °C (980 °F). The depth of the nitrided case depends on time at temperature. For example, gas nitriding in 20 to 30% dissociated ammonia for 8 to 48 h normally produces a case depth of about 0.2 to 0.35 mm (0.008 to 0.014 in.)

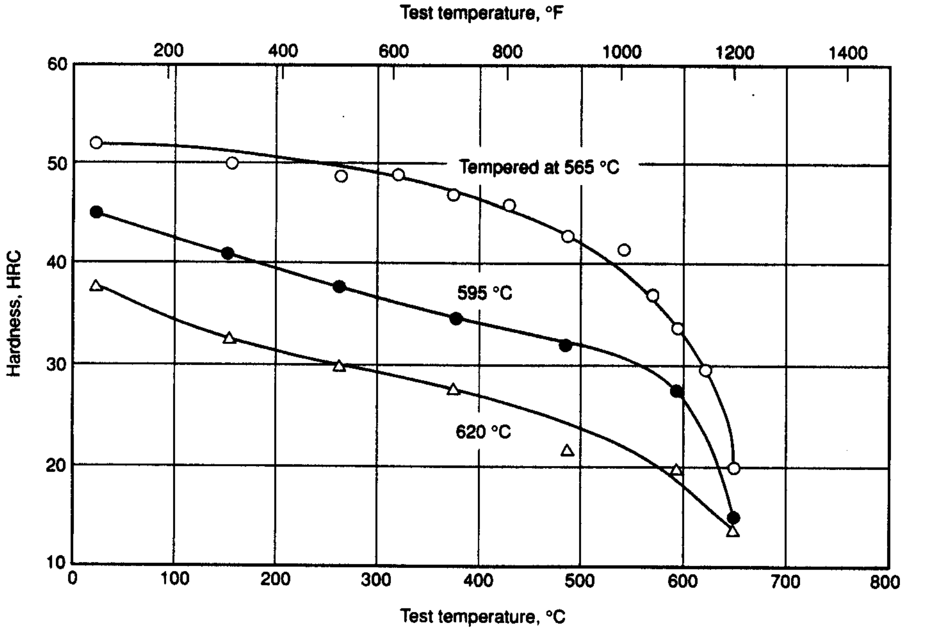


Fig. 12 Typical hot hardness of H11 mod steel. Specimens air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated tempering temperature. Rockwell hardness converted from microhardness values

Table 28 Longitudinal room-temperature tensile properties of H11 mod steel after exposure to elevated temperature for 10 or 100 h
Air cooled from 1010 °C (1850 °F); double tempered

Exposure temperature °C	°F	Exposure time, h	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %
510(a)	950(a)	100	1790	260	1760	255	11.5	42.8
540(b)	1000(b)	10	1650	239	1410	204	12.4	49.9
		100	1450	210	1300	188	13.7	52.9
540(c)	1000(c)	10	1385	201	1190	173	14.1	52.4
		100	1300	189	1100	160	15.2	58.2

(a) Tempered 2 + 2 h at 540 °C (1000 °F). (b) Tempered 2 + 2 h at 565 °C (1050 °F). (c) Tempered 2 + 2 h at 595 °C (1100 °F)

Table 29 Typical stress-rupture properties of H11 mod steel
Air cooled from 1010 °C (1850 °F) and tempered 1 h at temperature

Test temperature °C	°F	Stress MPa	ksi	Rupture life, h	Elongation(a), %	Reduction in area(a), %
Tempered at 565 °C (1050 °F)						
480	900	1380	200	10.4	9.9	33.7
		1170	170	257.3	5.7	33.7
540	1000	1070	155	11.1	9.9	20.9
		760	110	58.0	12.4	24.9
		520	75	254.0	13.3	30.3
		480	70	318.0	17.3	35.4
Tempered at 650 °C (1200 °F)						
540	1000	655	95	6.9	24.5	32.3
		480	70	31.4	25.4	46.7
		275	40	435.4	31.3	68.7
595	1100	410	60	3.3	25.7	60.4
		205	30	73.1	49.3	64.6
		140	20	444.3	55.2	71.3
650	1200	205	30	2.3	28.1	75.0
		100	15	70.5	69.9	84.8

(a) At rupture

- *Bake*: After plating in an acid bath, or after other processing that might introduce hydrogen into the metal, parts should be baked 24 h or longer at 190 °C (375 °F) or above

Properties. Variations in hardness of H11 mod with tempering temperature are plotted in Fig. 11. Variations in typical room-temperature longitudinal mechanical properties with tempering temperature are given in Table 26. This steel is quite notch tough; the ratio of notched-bar tensile strength (K_t = 3.3) to smooth-bar tensile strength at room temperature is about 1.4 at a smooth-bar tensile strength of 1380 MPa (200 ksi) and about 1.15 at 1930 MPa (280 ksi).

Because of secondary hardening characteristics, H11 mod has good temper resistance, which results in high hardness and strength at elevated temperatures. Hot hardness of H11 mod tempered to three room-temperature hardness levels is plotted in Fig. 12. Regardless of the initial room-temperature hardness, the hot hardness drops precipitously to levels corresponding to the annealed state at temperatures above about 620 °C (1150 °F). Short-time elevated-temperature tensile properties of bar stock tempered at 540, 565, and 595 °C (1000, 1050, and 1100 °F) are given in Table 27. The high temper resistance of H11 mod is indicated in Table 28, which gives room-temperature tensile properties after prolonged exposure to elevated temperatures. This material has fairly good stress-rupture properties at temperatures below 650 °C (1200 °F), as shown in Table 29.

The steel H11 mod has comparatively low fracture toughness, but has good resistance to stress-corrosion cracking compared to other ultrahigh-strength steels heat treated to the same strength. In a four-point bend test, plate 13 mm (½ in.) thick heat treated to 1295 MPa (188 ksi) yield strength by tempering at 595 °C (1100 °F) had a room-temperature K_{Ic} value of 59 MPa$\sqrt{m}$ (54 ksi$\sqrt{in.}$). The K_{Iscc} value in 3.5% NaCl solution was 33 MPa$\sqrt{m}$ (30 ksi$\sqrt{in.}$). In another bend test (Ref 8), 12.7 mm plate with a yield strength of about 1450 MPa (210 ksi) resulting from tempering at 580 °C (1080 °F) had K_{Ic} values of 37 MPa$\sqrt{m}$ (34 ksi$\sqrt{in.}$) at room temperature and 60 MPa$\sqrt{m}$ (55 ksi$\sqrt{in.}$) at 93 °C (200 °F).

Significant improvements in H11 mod properties such as transverse ductility and toughness, particularly in large sections, can be achieved by vacuum arc remelting and electroslag remelting, both of which result in greater homogeneity and cleanliness of the steel. A comparison of midradius transverse tensile properties of air-melted and vacuum arc remelted billets is presented in Table 30. Each value is the average of four tests, two from the top of the ingot, and two from the bottom.

H13 Steel

AISI H13 is a 5% Cr ultrahigh-strength steel similar to H11 mod in composition, heat treatment, and many properties. The main difference in composition is the higher vanadium content of H13 (see Table 1); this leads to a greater dispersion of hard vanadium carbides, which results in higher wear resistance. Also, H13 has a slightly wider

Table 30 Effect of billet size and melting method on transverse strength and ductility of H11 mod steel
Air cooled from 1010 °C (1850 °F); triple tempered, 2 + 2 + 2 h at 540 °C (1000 °F)

Billet size	Melting method	Tensile strength MPa	Tensile strength ksi	Reduction in area, %
150 × 150 mm (6 × 6 in.)	Air	1965	285	16.1
	VAR	1985	288	25.7
300 × 300 mm (12 × 12 in.)	Air	1972	286	7.2
	VAR	2013	292	19.7

Table 31 Typical longitudinal room-temperature mechanical properties of H13 steel
Round bars, oil quenched from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated temperature

Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 4D gage length, %	Reduction in area, %	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf	Hardness, HRC
527	980	1960	284	1570	228	13.0	46.2	16	12	52
555	1030	1835	266	1530	222	13.1	50.1	24	18	50
575	1065	1730	251	1470	213	13.5	52.4	27	20	48
593	1100	1580	229	1365	198	14.4	53.7	28.5	21	46
605	1120	1495	217	1290	187	15.4	54.0	30	22	44

Table 32 Longitudinal short-time tensile properties of H13 steel bar
Oil quenched from 1010 °C (1850 °F) and double tempered to indicated hardness

Room-temperature hardness, HRC	Test temperature °C	Test temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 4D gage length, %	Reduction in area, %
52(a)	425	800	1620	235	1240	180	13.7	50.6
	540	1000	1305	189	1000	145	13.9	54.0
	595	1100	1020	148	825	120	17.5	65.4
	650	1200	450	65	340	49	28.9	88.9
48(b)	425	800	1400	203	1150	167	15.0	59.9
	540	1000	1160	168	960	139	17.1	62.4
	595	1100	940	136	750	109	18.0	68.5
	650	1200	455	66	350	51	33.6	89.0
44(c)	425	800	1200	174	1005	146	17.0	64.1
	540	1000	995	144	820	119	20.6	70.0
	595	1100	827	120	690	100	22.6	74.0
	650	1200	450	65	350	51	28.4	87.6

(a) Tempered 2 + 2 h at 527 °C (980 °F). (b) Tempered 2 + 2 h at 575 °C (1065 °F). (c) Tempered 2 + 2 h at 605 °C (1120 °F)

range of carbon content than does H11 mod. Depending on the producer, the carbon content of H13 may be near the high or low side of the accepted range, with a corresponding variation in strength and ductility for a given heat treatment.

Like H11 mod, H13 is a secondary hardening steel. It has good temper resistance and maintains high hardness and strength at elevated temperatures. It is deep hardening, which allows large sections to be hardened by air cooling. H13 steel can be heat treated to strengths exceeding 2070 MPa (300 ksi); like H11 mod, it has good ductility and impact strength. With standard heat treatment, the fracture toughness of H13 appears to be even lower than that of H11 mod.

The material H13 has good resistance to thermal fatigue. Hot-work tooling made of H13 can be safely water cooled between hot-working operations. Its resistance to thermal fatigue, erosion, and wear has made it a preferred die material for aluminum and magnesium die casting, as well as for many other hot-work applications. However, H13 is subject to hydrogen embrittlement. It can be nitrided for additional wear resistance.

Although H13 has not been used as widely as H11 mod as an ultrahigh-strength constructional steel, the similarities in properties make H13 equally attractive for such applications. This is particularly true in noncritical service in which slightly higher wear resistance is an advantage.

The H13 steel is available as bar, rod, billet, and forgings. Typical hot-work applications include die casting dies, inserts, cores, ejector pins, plungers, sleeves, slides, forging dies, extrusion dies, dummy blocks, and mandrels. Other tooling and structural applications include punches, shafts, beams, torsion bars, shrouds, and ratchets.

Processing. For forging, H13 steel is heated slowly and uniformly to a temperature of 1090 to 1150 °C (2000 to 2100 °F), preferably after preheating at 760 to 815 °C (1400 to 1500 °F). The steel should be thoroughly heated before forging. Forging should not be done below 900 °C (1650 °F), but the parts may be reheated as often as necessary. Because H13 is air hardening, parts should be cooled slowly after forging. Simple forgings may be cooled in an insulating medium such as dry ashes, lime, or expanded mica. The best practice for large forgings is to place in a heated furnace at about 790 °C (1450 °F), soak until the temperature is uniform, shut off the furnace, and let cool slowly. Parts should then be given a full spheroidizing anneal.

When annealed H13 is welded, it should be preheated to 540 °C (1000 °F), or to as high a temperature as is practical, preferably in a furnace to ensure uniform, stress-free preheating. Uncoated rod, preferably of the same general composition, should be used, with shielded-arc equipment. The temperature of the part should be kept above 315 °C (600 °F), and the part reheated if necessary, until welding has been completed. After welding, the part should be cooled slowly in an insulating medium and given a full anneal. A heat-treated part such as a die can be welded using the same procedure, preferably preheating the part in a furnace to a temperature about 55 °C (100 °F) below the original tempering temperature. After welding, the part should be placed in a furnace at the preheating temperature and cooled slowly to room temperature. It is recommended that the part then be reheated to just below the original tempering temperature and air cooled. This helps to relieve welding stresses and blend the hardness of the weld area into that of the base metal. Regardless of the situation, adequate preheating and slow cooling are essential to minimize the risk of cracking during welding.

Fully annealed H13 has a machinability rating that is about 70% of the rating for 1% C tool steel, or about 45% of that for B1112.

Heat Treatments. The heat treatments that apply to H13 steel are:

- *Normalize*: Not recommended for H13. Some improvement in homogeneity can be obtained by preheating to about 790 °C (1450 °F), heating slowly and uniformly to 1040 to 1065 °C (1900 to 1950 °F), holding 1 h for each 25 mm (1 in.) of thickness, and then air cooling. Just before the part reaches room temperature, it should be recharged into a furnace and given a full anneal. Note: There is a risk of cracking during this treatment, especially if done in a furnace in which the atmosphere is not controlled to prevent surface decarburization
- *Anneal*: Heat uniformly to 860 to 900 °C (1575 to 1650 °F) in a furnace with controlled atmosphere, or with the part packed in a neutral compound, so that decarburization is prevented. Cool very slowly in the furnace to about 480 °C (900 °F); then cool more rapidly to room temperature. This treatment results in a fully spheroidized microstructure

Table 33 Longitudinal impact properties of H13 bar tempered at different temperatures

Tempering temperature(a) °C	Tempering temperature(a) °F	Hardness(b), HRC	Charpy V-notch impact energy at test temperature of −73 °C (−100 °F), J	ft · lbf	21 °C (70 °F), J	ft · lbf	260 °C (500 °F), J	ft · lbf	540 °C (1000 °F), J	ft · lbf	595 °C (1100 °F), J	ft · lbf
524	975	54	7	5	14	10	27	20	31	23	...	...
565	1050	52	7	5	14	10	30	22	34	25	34(c)	25(c)
607	1125	47	8	6	24	18	41	30	45	33	43	32
615	1140	43	9.5	7	24	18	52	38	60	44	57	42

(a) Air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated temperature. (b) At room temperature. (c) At 565 °C (1050 °F)

- *Harden*: Heat slowly and uniformly to 995 to 1025 °C (1825 to 1875 °F) and soak 20 min plus 5 min for each 25 mm (1 in.) of thickness; preheating at 790 to 815 °C (1450 to 1500 °F) is usually recommended for thick parts. Air cool in still air. Air cooling is usually done from the high side of the hardening temperature range. For a few applications, H13 may be oil quenched from the low side of the hardening temperature, but at the risk of distortion or cracking
- *Temper*: Heat at the secondary hardening peak of about 510 °C (950 °F) for maximum hardness and strength, or at higher temperatures to temper back to a lower level of hardness or strength. Double tempering, that is, 2 h at temperature, air cooling, then 2 h more at temperature, is recommended. Occasionally, triple tempering may be desirable
- *Stress relieve*: Heat to 650 to 675 °C (1200 to 1250 °F) and soak 1 h or more; cool slowly to room temperature. This treatment is often used to achieve greater dimensional accuracy in heat-treated parts by stress relieving rough-machined parts, then finish machining, and finally heat treating to the desired hardness
- *Nitride*: Finish-machined and heat-treated parts may be nitrided to produce a highly wear-resistant surface. Because it is carried out at the normal tempering temperature, nitriding can serve as the second temper in a double-tempering treatment. The depth of the nitrided case depends on the time at temperature. For example, gas nitriding at 510 °C (950 °F) for 10 to 12 h produces a case depth of 0.10 to 0.13 mm (0.004 to 0.005 in.) and for 40 to 50 h produces a case depth of about 0.3 to 0.4 mm (0.012 to 0.016 in.). Parts that have been deep nitrided are usually lapped or gently surface ground to remove the thin, brittle white layer. Selective nitriding is sometimes done to produce a nitrided case only where it is needed. Copper plating is preferred for stopping off areas that are not to be nitrided; stop-offs containing lead should be avoided, because lead embrittles H13 steel

Properties. The properties presented in this section are for H13 with a carbon content in the middle of the composition range (for composition, see Table 1). Somewhat different properties should be expected when the carbon content is near either the high end or the low end of the range.

The variation in hardness of H13 with tempering temperature is plotted in Fig. 13. Room-temperature longitudinal mechanical properties of bars tempered to different hardness levels are given in Table 31. Because it is a secondary hardening steel, H13 maintains high hardness and strength at elevated temperatures. Values of hot hardness for specimens tempered to three different hardness levels are presented in Fig. 14. Typical short-time tensile properties of H13 bar tempered to different hardness levels are listed in Table 32 for various service (test) temperatures. Regardless of initial room-temperature hardness, H13 attains essentially the same low properties at 650 °C (1200 °F). Like H11 mod, H13 has good

Table 34 Longitudinal fracture toughness of H13 steel

Air cooled from 1050 °C (1920 °F) and tempered 2 h at temperature

Tempering temperature °C	Tempering temperature °F	Plane-strain fracture toughness(a)(K_{Ic}) MPa$\sqrt{m}$	ksi$\sqrt{in.}$
400	750	47.7	43.4
475	885	33.0	30.0
500	930	27.4	24.9
530	985	24.3	22.1
550	1020	23.1	21.0
600	1110	33.2	30.2
625	1155	52.4	47.7
650	1200	77.7	70.7

(a) Values should not be used for design purposes because they represent material that was not heat treated in the usual manner, but was cooled from an austenitizing temperature higher than normal. Source: Ref 9

Table 35 Comparison of transverse mechanical properties of air-melted and electroslag-remelted H13 steel

Specimen property(a)	Air melted(b)	Electroslag remelted(c)
Tensile strength, MPa (ksi)	1615 (234)	1650 (239)
Yield strength, MPa (ksi)	1395 (202)	1425 (207)
Elongation in 4D gage length, %	2.9	5.6
Reduction in area, %	5.7	12.8
Charpy V-notch impact energy, J (ft · lbf)	5 (4)	7 (5)

(a) Specimens taken from midradius of round bar; oil quenched from 1010 °C (1850 °F); and double tempered, 2 + 2 h at 588 °C (1090 °F). Final hardness, 48 HRC. (b) Round section, 355 mm (14 in.) in diameter. (c) Round section, 457 mm (18 in.) in diameter

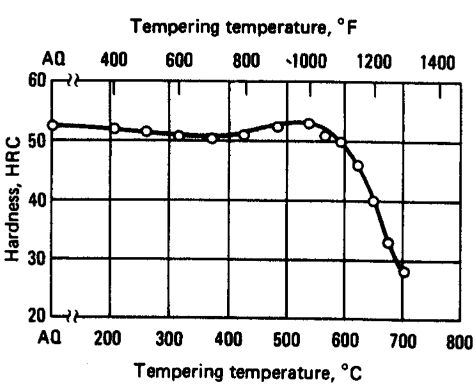


Fig. 13 Variation in hardness with tempering temperature for H13 steel. All specimens air cooled from 1025 °C (1875 °F) and tempered 2 h at temperature. AQ, as quenched

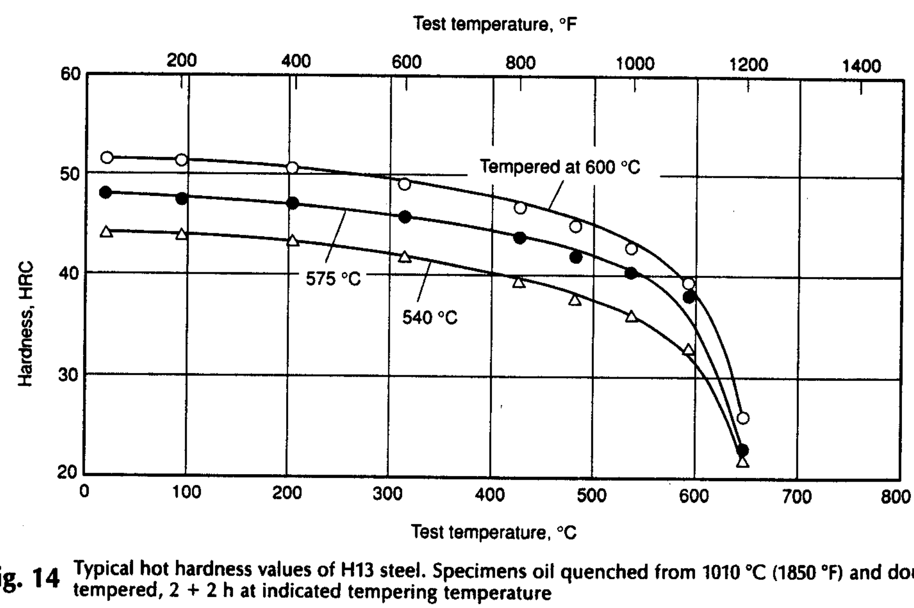


Fig. 14 Typical hot hardness values of H13 steel. Specimens oil quenched from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated tempering temperature

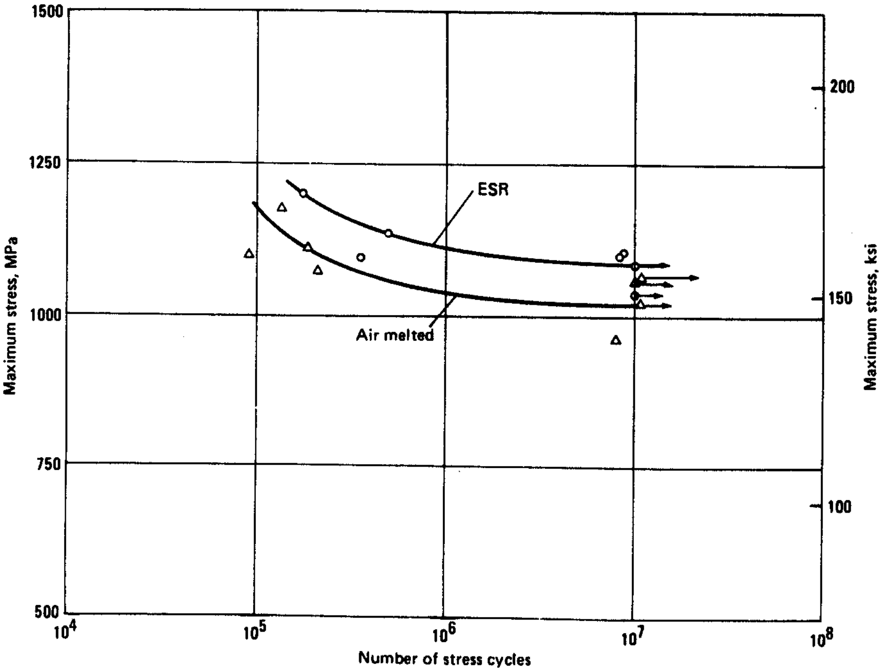


Fig. 15 Tension-tension fatigue curves for longitudinal specimens of air-melted and electroslag-remelted heats of H13 steel. Axial fatigue tests performed in an Ivy machine at a frequency of 60 Hz; the alternating stress was 67% of the mean stress for all tests (R = 0.2). Arrows signify tests terminated without any sign of fatigue cracking.

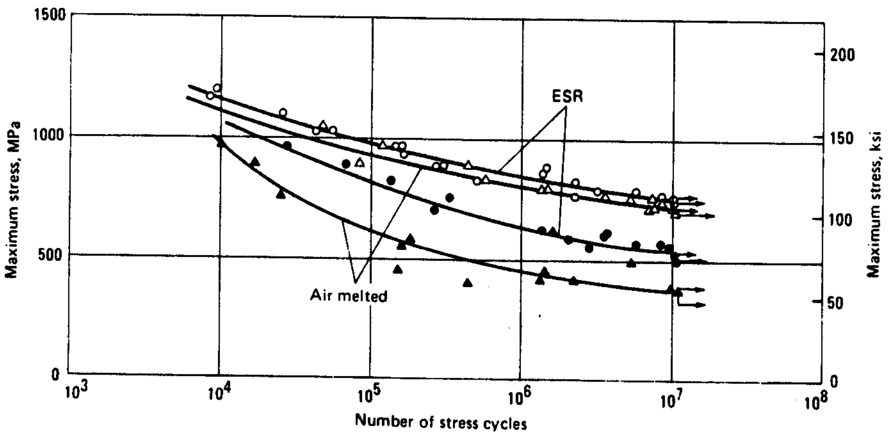


Fig. 16 Tension-compression fatigue curves for air-melted and electroslag-remelted heats of H13 steel. Axial fatigue tests performed in an Ivy machine at a frequency of 60 Hz; the stresses were fully reversed for all tests (R = −1). Open symbols indicate longitudinal fatigue data; filled symbols indicate transverse data. Arrows signify tests terminated without any sign of fatigue cracking. Source: Ref 10

Table 36 Room-temperature mechanical properties of HP 9-4-30 steel

Property	Typical value for hardness of 49–53 HRC(a)	Typical value for hardness of 44–48 HRC(b)	Minimum value(c)
Tensile strength, MPa (ksi)	1650–1790 (240–260)	1520–1650 (220–240)	1520 (220)
Yield strength, MPa (ksi)	1380–1450 (200–210)	1310–1380 (190–200)	1310 (190)
Elongation in 4D gage length, %	8–12	12–16	10
Reduction in area, %	25–35	35–50	35
Charpy V-notch impact energy, J (ft · lbf)	20–27 (15–20)	24–34 (18–25)	24 (18)
Fracture toughness (K_{Ic}), MPa$\sqrt{m}$ (ksi$\sqrt{in.}$)	66–99 (60–90)	99–115 (90–105)	. . .

(a) Oil quenched from 845 °C (1550 °F), refrigerated to −73 °C (−100 °F) and double tempered at 205 °C (400 °F). (b) Same heat treatment as (a) except double tempered at 550 °C (1025 °F). (c) For sections forged to 75 mm (3 in.) or less in thickness (or to less than 0.016 m², or 25 in.², in total cross-sectional area), quenched to martensite and double tempered at 540 °C (1000 °F)

impact properties at temperatures up to 540 °C (1000 °F). Charpy V-notch impact energies at subzero, room, and elevated temperatures are compared in Table 33.

Little work has been done to determine the fracture toughness of H13. It appears that with the standard heat treatment H13 has slightly lower fracture toughness than H11 mod. Available data on fracture toughness of H13 are given in Table 34.

Vacuum arc remelted (VAR) and electroslag remelted (ESR) H13 have better cleanliness and homogeneity than air melted H13. The VAR and ESR processes are used to produce steels with superior ductility, impact strength, and fatigue resistance, especially in the transverse direction, and particularly in large section sizes. Table 35 compares room-temperature transverse mechanical properties of air-melted and ESR H13 in large section sizes.

In axial (tension-tension) fatigue tests, the life of ESR H13 was superior to that of air-melted H13 (Fig. 15). When both were fatigue tested under fully reversed stresses, there was no significant difference in the life of longitudinal specimens. However, for transverse specimens, the life of ESR H13 was significantly better (Fig. 16).

High Fracture Toughness Steels

High-strength, high fracture toughness steels as described in this article are commercial structural steels capable of a yield strength of 1380 MPa (200 ksi) and a K_{Ic} of 100 MPa$\sqrt{m}$ (91 ksi$\sqrt{in.}$). (These steels also exhibit stress corrosion cracking resistance.) A number of developmental steels that are not fully commercial alloys are excluded from this discussion. The HP-9-4-30 and AF1410 steels, however, are discussed below.

Both these alloys are of the Ni-Co-Fe type and have a number of similar characteristics. Both are weldable, and the melt practice requires a minimum of VAR. Control of residual elements to low levels is required for optimum toughness. The machining practices used for 4340 steel are generally satisfactory; however, Ni-Co-Fe alloys are considered more difficult to machine than are alloy steels.

HP-9-4-30 Steel

During the 1960s, Republic Steel Corporation introduced a family of four weldable steels, all of which had high fracture toughness when heat treated to medium/high strength levels. Only HP-9-4-30 has been produced in significant quantities and is comparable to the high-strength, high fracture toughness steels of this article. The chemical composition is given in Table 1. The HP-9-4-30 steel is usually electric arc melted and then vacuum arc remelted. Forging temperatures should not exceed

Table 37 Mechanical properties of HP 9-4-30 steel at three test temperatures
All specimens normalized at 900 °C (1650 °F); oil quenched from 845 °C (1550 °F); and double tempered, 2 + 2 h at 550 °C (1025 °F)

Test temperature °C	Test temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 4D gage length, %	Plane-strain fracture toughness(a)(K_{Ic}) MPa$\sqrt{m}$	Plane-strain fracture toughness(a)(K_{Ic}) ksi$\sqrt{in.}$
24	75	1530	222	1275	185	16	109.3	99.5
260	500	1380	200	1215	176	16	106.3	96.7
345	650	1325	192	1110	161	17	103.8	94.5

(a) WR orientation; average of two tests at each temperature. Source: Ref 11

Table 38 Room-temperature mechanical properties of HP 9-4-30 steel after 1000 h at various elevated temperatures
All specimens austenitized, quenched to martensite, and tempered at 540 °C (1000 °F)

Temperature of exposure °C	Temperature of exposure °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 25 mm (1 in.), %	Reduction in area, %	Charpy V-notch impact energy J	Charpy V-notch impact energy ft · lbf
Not exposed		1650	239	1350	196	14	52	39	29
205	400	1585	230	1405	204	16	60	41	30
345	650	1585	230	1440	209	15	56	38	28
425	800	1650	239	1400	203	14	50	34	25
480	900	1565	227	1395	202	15	51	26	19

Table 39 Effect of various heat treatments on mechanical properties of a cobalt-nickel steel (VIM/VAR plate of AF1410 steel)

Heat treatment(a)(b)	Ultimate strength MPa	Ultimate strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %	Reduction in area, %	Charpy V-notch J	Charpy V-notch ft · lbf
Plate of 15 mm (⅝ in.) thickness								
X+ water quench per (c) + Z	1580	229	1515	220	16	60	91	67
X + refrigeration treatment per (d) + Z	1650	239	1550	225	17	69	83	61
X + vermiculite cool and refrigeration per (e) + Z	1620	235	1490	216	17	70	84	62
X + reaustenitization and refrigeration per (f) + Z	1660	241	1525	221	17	73	113	83
Average for several heats								
Heat treatment per (g)	1675	243	1590	231	...	...	92	68
Plate of 75 mm (3 in.) thickness								
Y + water quench per (c) + Z	1585	230	1540	223	16	66	65	48
Y + refrigeration treatment per (d) + Z	1680	244	1540	223	17	70	81	60
Y + vermiculite cool and refrigeration per (c) + Z	1480	215	1380	200	18	68	58	43
Y + reaustenitization, air cool, and refrigeration per (f) + Z	1670	242	1540	223	17	69	95	70

(a) Time at 900 °C (1650 °F) or 815 °C (1500 °F) is as follows: 1 h for the 15 mm (⅝ in.) plate or 3 h for the 75 mm (3 in.) plate. (b) Initial and final heat treatments: X = 900 °C (1650 °F) for 1 h with air cooling and 675 °C (1250 °F) for 8 h with air cooling; Y = 900 °C (1650 °F) for 3 h with air cooling and 675 °C (1250 °F) for 8 h with air cooling; Z = 510 °C (950 °F) for 5 h with air cooling. (c) 815 °C (1500 °F) for the time per (a) and water quenching. (d) 815 °C (1500 °F) for the time per (a) with air cooling and a refrigeration treatment of −73 °C (−100 °F). (e) 815 °C (1500 °F) for the time per (a) with vermiculite cool and a refrigeration treatment of −73 °C (−100 °F). (f) 900 °C (1650 °F) for time per (a) with air cooling, 815 °C (1500 °F) for time per (a) with air cooling, and refrigeration at −73 °C (−100 °F). (g) 900 °C (1650 °F) for time per (a) with water quench, 815 °C (1500 °F) for time per (a) with water quench, 815 °C (1500 °F) for time per (a) with water quench, and 510 °C (950 °F) for 5 h with air cooling. Source: Ref 1

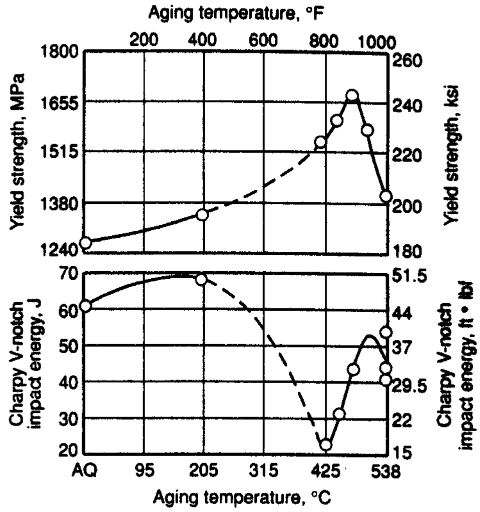


Fig. 17 Effect of aging temperature on impact energy (bottom) and yield strength (top) of AF1410 steel (VIM/VAR plate 15 mm, or ⅝ in., thick). Heat treatments: Heat at 900 °C (1650 °F) for ½ h and water quench; heat at 815 °C (1500 °F) for ½ h and water quench; age for 5 h at indicated temperatures and air cool. AQ, as quenched. Source: Ref 1

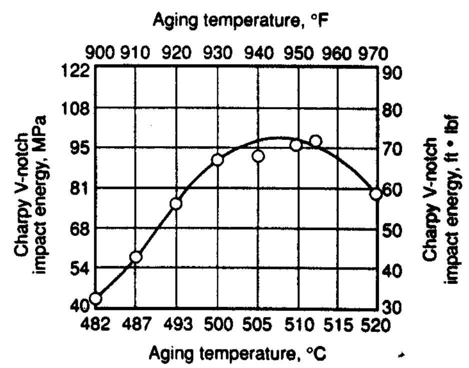


Fig. 18 Effect of aging temperature on impact energy of AF1410 steel (VIM/VAR plate 15 mm, or ⅝ in., thick). Heat treatments: See Fig. 17.

1120 °C (2050 °F). The HP-9-4-30 steel is capable of developing a tensile strength of 1520 to 1650 MPa (220 to 240 ksi) with a plain-strain fracture toughness of 100 MPa$\sqrt{m}$ (91 ksi$\sqrt{in.}$). This steel has deep hardenability and can be fully hardened to martensite in sections up to 150 mm (6 in.) thick. The HP-9-4-30 steel in the heat-treated condition can be formed by bending, rolling, or shear spinning. Heat-treated parts can readily be welded. Tungsten arc welding under inert-gas shielding is the preferred welding process. Neither postheating nor postweld heat treating is required. After welding, parts may be stress relieved at about 540 °C (1000 °F) for 24 h. This is a stress-relieving treatment and has no adverse effect on the strength or toughness of either the weld metal or the base metal. The HP-9-4-30 steel is available as billet, bar, rod, plate, sheet, and strip. It has been used for aircraft structural components, pressure vessels, rotor shafts for metal forming equipment, drop hammer rods, and high-strength shock-absorbing automotive parts.

Heat Treatments. The heat treatments that apply to HP 9-4-30 steel are:

- *Normalize*: Heat to 870 to 925 °C (1600 to 1700 °F) and hold 1 h for each 25 mm (1 in.) of thickness (1 h minimum); air cool
- *Anneal*: Heat to 620 °C (1150 °F) and hold 24 h; air cool
- *Harden*: Austenitize at 830 to 860 °C (1525 to 1575 °F) and hold 1 h for each 25 mm (1 in.) of thickness (1 h minimum); water or oil quench. Complete the martensitic transformation by refrigerating at least 1 h at −87 to −60 °C (−125 to −75 °F); allow to warm to room temperature
- *Temper*: Hold at 200 to 600 °C (400 to 1100 °F), depending on desired final strength; double tempering is preferred. The most widely used tempering treatment is double tempering, that is, 2 h at temperature, air cooling, and then 2 h more at temperature, at a temperature ranging from 540 to 580 °C (1000 to 1075 °F)
- *Stress relieve*: Usually required only after welding restrained sections. Heat to 540

°C (1000 °F) and hold 24 h; air cool to room temperature

Properties. Table 36 presents room-tem- erature mechanical properties of HP 9-4-30 ouble tempered at three different temper- tures. The data for material double tem- ered at 540 °C (1000 °F) represent mini- num mechanical properties for this ondition: properties listed for the other onditions may be considered typical. Smooth-bar fatigue strengths at 10^7 cycles f 830 MPa (120 ksi) have been reported for naterial double tempered at 540 °C (1000 F); the corresponding notched-bar fatigue trength was 380 MPa (55 ksi).

The HP 9-4-30 steels have good thermal tability, which makes them suitable for ong-term service at temperatures up to at east 370 °C (700 °F). Table 37 gives short- ime tensile properties and fracture tough- ess values for 25 mm (1 in.) plate tested at oom temperature and at 260 and 345 °C 500 and 650 °F). In the same study, it was eported that the fatigue crack propagation ate was not affected by temperatures up to 345 °C (650 °F). Room-temperature mechan- cal properties of material exposed to ele- vated temperature for 1000 h are given in Table 38. Stresses to cause rupture in 100 h have been reported as 860 MPa (125 ksi) at 480 °C (900 °F) and 380 MPa (55 ksi) at 540 °C (1000 °F) for material double tempered at 540 °C (1000 °F). Corresponding values for 1000 h life are 585 MPa (85 ksi) at 480 °C 900 °F) and 195 MPa (28 ksi) at 540 °C (1000 °F).

AF1410 Steel

The steel AF1410 was an outgrowth of the U.S. Air Force sponsorship of the ad- vanced submarine hull steels, the result of which was the development of the low- carbon Fe-Ni-Co type alloys. These alloys had significant stress corrosion cracking resistance. By raising the cobalt and carbon content, the ultimate tensile strength was increased to a typical 1615 MPa (235 ksi). This increase in strength was obtained while maintaining a K_{Ic} value of 154 MPa$\sqrt{m}$ (140 ksi$\sqrt{in.}$). This combination of strength and toughness exceeds that of other commer- cially available steels, and the alloy has been considered as a replacement for titani- um in certain aircraft parts. The AF1410 material (see Table 1 for composition) is air hardenable in sections up to 75 mm (3 in.) thick. The preferred melting practice is presently vacuum induction melting fol- lowed by vacuum arc remelting (VIM/ VAR). However, initially VIM and VIM/ ESR practices were used. Melting practice requires that impurity elements be kept at very low levels to ensure high fracture toughness. Although forgeable to 1120 °C (2050 °F), at least a 40% reduction must be obtained below 900 °C (1650 °F) to attain maximum properties. Weldability is good using a continuous wave (CW)-gas tungsten arc welding (GTAW) process, provided that high-purity wire is used and oxygen con- tamination is avoided. Information on stress-corrosion cracking is incomplete; however, it has been determined that at 52 HRC AF1410 has a K_{Iscc} of 66 MPa$\sqrt{m}$ (60 ksi$\sqrt{in.}$). Obtainable as bar, billet, rod, plate, sheet, and strip, AF1410 has been used for aircraft structural components.

Table 40 Mechanical properties of a cobalt-nickel steel (AF1410) in various quenching media

Test specimens were 50 mm (2 in.) plate from VIM/VAR melt with the heat treatment: 675 °C (1250 °F) for 8 h with air cooling, 900 °C (1650 °F) for 1 h, quenching, 830 °C (1525 °F) for 1 h, quenching, refrigeration at −73 °C (−100 °F) for 1 h, 510 °C (950 °F) for 5 h, and air cooling. Source: Ref 1

Quench medium	Ultimate strength		Yield strength		Elongation, %	Reduction in area, %	Charpy V-notch		Plane-strain fracture toughness (K_{Ic})	
	MPa	ksi	MPa	ksi			J	ft · lbf	MPa$\sqrt{m}$	ksi$\sqrt{in.}$
Air	1680	244	1475	214	16	69	69	51	174	158
Oil	1750	254	1545	224	16	69	65	48	154	140
Water	1710	248	1570	228	16	70	65	48	160	146

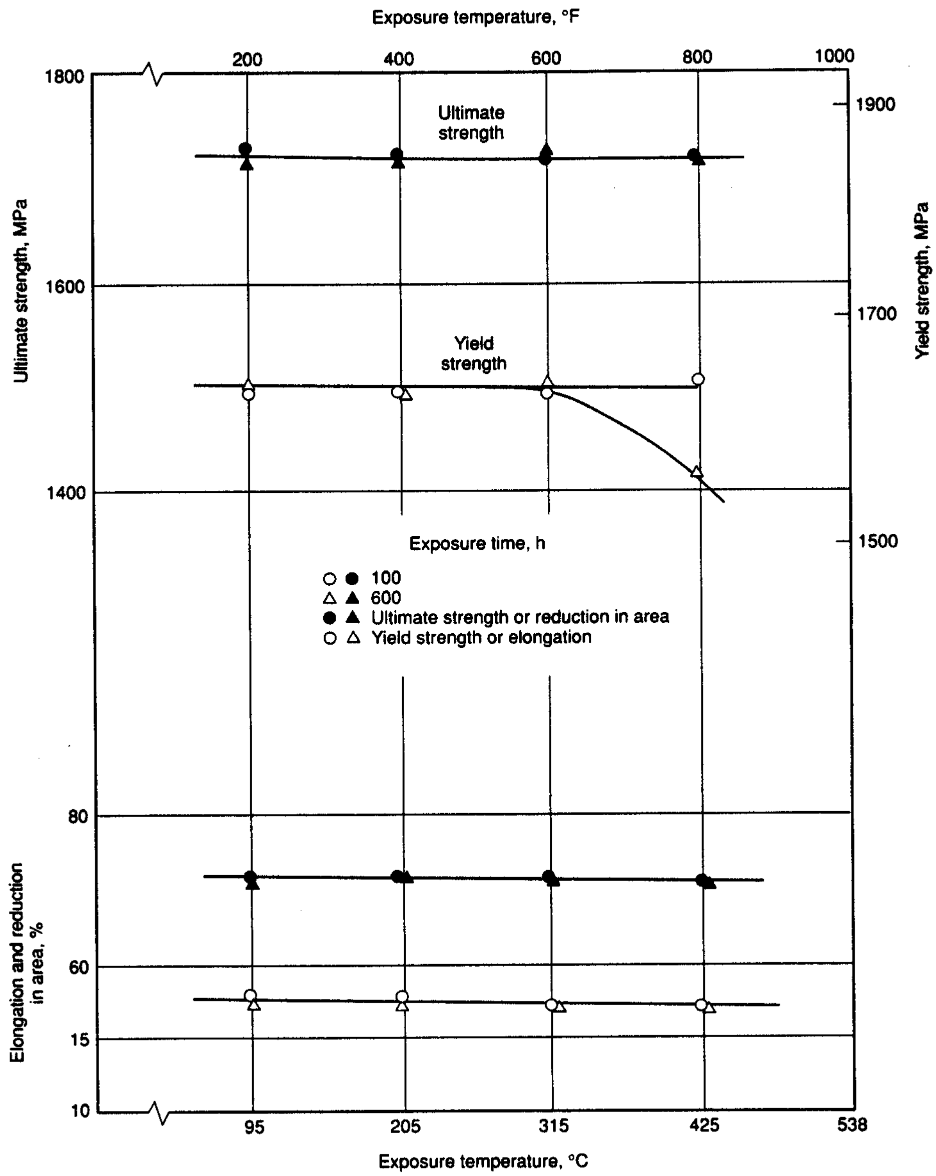


Fig. 19 Effect of exposure to elevated temperature on room-temperature tensile properties of AF1410 steel (VIM/VAR plate 30 mm, or 1¼ in., thick). Heat treatment: Heat at 900 °C (1650 °F) for ½ h and water quench, heat at 815 °C (1500 °F) for ½ h and water quench, and then heat at 510 °C (950 °F) for 5 h and air cool. Source: Ref 1

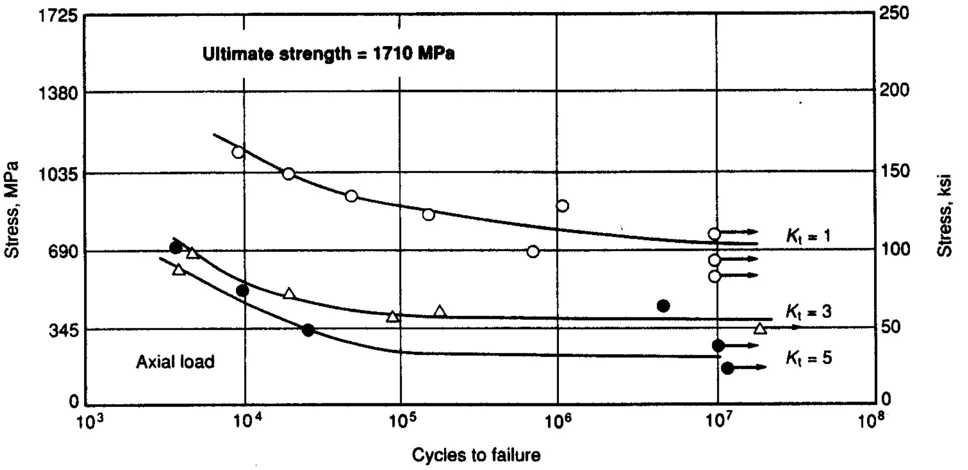


Fig. 20 *S-N* curves at room temperature for AF1410 steel (VIM/VAR plate with 20 mm, or ¾ in., thickness) tested in transverse direction at several stress concentrations for $R = -1$. Heat treatment: Heat at 900 °C (1650 °F) for 1 h and water quench, heat at 815 °C (1500 °F) for 1 h and water quench, and then heat at 510 °C (950 °F) for 5 h and air cool. Source: Ref 1

The microstructure of AF1410 consists of Fe-Ni lath martensite, precipitation on which produces the strengthening mechanism. Quenching from the austenitizing temperature produces a highly dislocated lath martensite that has a high toughness, as measured by the Charpy V-notch impact test (Fig. 17). Aging produces a complex series of changes in carbide structure. At approximately 425 °C (800 °F), Fe_3C is precipitated. At 455 °C (850 °F), Fe-Cr-Mo M_2C carbide is obtained, which at 480 °C (900 °F) will begin to produce a pure Mo-Cr M_2C carbide. By raising the temperature to 510 °C (950 °F), the M_2C will begin to coarsen; at 540 °C (1000 °F) M_2C will begin to be replaced by M_6C, which has little strengthening effect. The steel is normally austenitized and aged. The secondary hardening, which is due to the aging, produces a maximum tensile strength when aged at 480 °C (900 °F) using a 5 h aging time and a minimum impact energy when aged at 425 °C (800 °F), as shown in Fig. 17. When aged in the temperature range between 425 °C (800 °F) and 540 °C (1000 °F), the impact energy exhibits a maximum at about 508 °C (947 °F), as shown in Fig. 18. At aging temperatures above 540 °C (1000 °F), both the tensile strength and the impact energy decrease rather rapidly.

The steel is subject to austenite reversion during aging. At normal aging temperatures, the retained austenite is generally less than 1% by volume. However, 540 °C (1000 °F) or higher will produce large amounts of austenite, and these will weaken the matrix of the steel. The best combination of strength and ductility results from a 510 °C (950 °F) age.

Heat Treatment. The heat treatments that apply to AF1410 steel are:

- *Normalized and Overaged*: This is the condition the material is normally supplied for best machinability. Heat between 880 °C (1620 °F) and 900 °C (1650 °F), hold 1 h for each 25 mm (1 in.) of thickness; air cool and over age at 675 °C (1250 °F) for 5 h minimum
- *Anneal*: Usually, normalizing and overaging (above) are used to soften and stress relieve the product. A stress relief of 675 °C (1250 °F) may be applied to relieve mechanical stress
- *Harden*: Double austenitize, first at 870 to 900 °C (1600 to 1650 °F), hold 1 h for each 25 mm (1 in.) of thickness; oil, water, or air cool depending on section size; reaustenitize at 800 to 815 °C (1475 to 1500 °F); oil, water, or air cool. An alternative is to single austenitize at 800 to 815 °C (1475 to 1500 °F), hold 1 h for each 25 mm (1 in.) of thickness; oil, water, or air cool depending on section size
- *Quench*: Air cooling from the austenitizing temperature will produce tensile strength, toughness, and fatigue strength essentially equal to oil or water quenching in section sizes up to 75 mm (3 in.). Refrigeration treatment of −73 °C (−100 °F) is optional. The aim is to reduce the amount of retained austenite. There is no real evidence that such a treatment has any substantial effect on the material or the mechanical properties
- *Aging*: Age at 480 to 510 °C (900 to 950 °F) 5 to 8 h. Air cooling is normally employed

Properties. Tensile strength properties and impact energy for VIM/VAR melted plate quenched in air, water, or vermiculite and cooled following austenitizing are shown in Table 39. The heat treatments showed some effect on the tensile and impact properties for both 15 mm (⅝ in.) and 75 mm (3 in.) VIM/VAR melted plate.

Room-temperature tensile properties after exposure to long-term elevated temperatures show some degradation after 500 h (Fig. 19). Fracture toughness, tensile properties, and impact energy of VIM/VAR melted 50 mm (2 in.) plate quenched and aged at 510 °C (950 °F) (a premachining heat treatment had been applied) are shown after quenching in different media (Table 40). Axial load fatigue data are provided in Fig. 20. Maximum stress for 10^7 cycles is approximately 690 MPa (100 ksi) for $K_t = 1$. Comparison of fatigue crack growth rate in low-humidity air (Fig. 21) and in 3½% saltwater solution (Fig. 22) indicates the relative insensitivity of AF1410 to saltwater exposure.

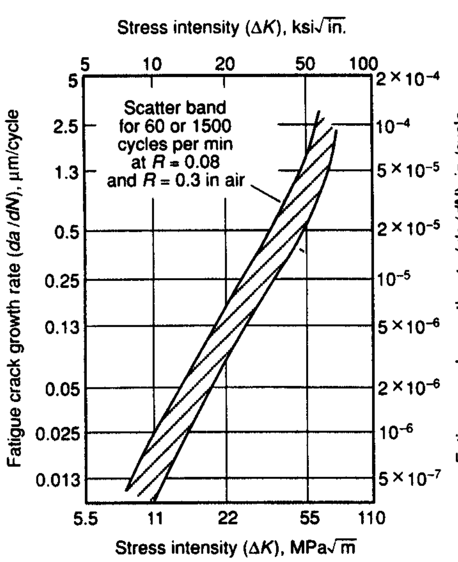


Fig. 21 Fatigue crack growth rate at two frequencies and two *R* ratios for AF1410 steel (VIM/VAR plate 25 mm, or 1 in., thick) at room temperature in low-humidity air. Heat treatment same as in Fig. 20. Source: Ref 1

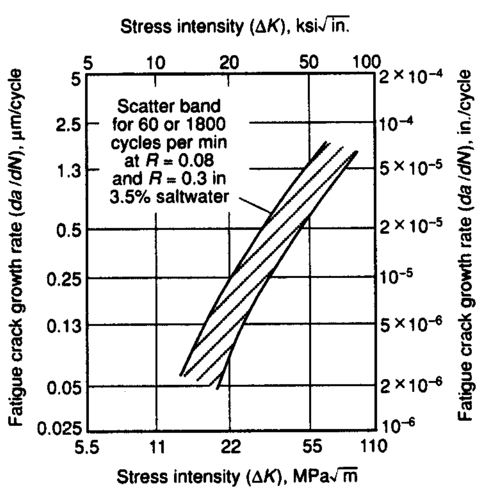


Fig. 22 Fatigue crack growth rate at two frequencies and two *R* ratios for AF1410 steel (VIM-VAR plate 25 mm, or 1 in., thick) at room temperature in 3½% saltwater. Heat treatment same as in Fig. 20. Source: Ref 1

REFERENCES

1. W.F. Brown, Jr., *Aerospace Structural Metals Handbook*, Code 1224, Metals and Ceramics Information Center, 1989, p 1-30
2. A.M. Hall, Sr., *Introduction to Today's Ultrahigh-Strength Structural Steels*, STP 498, American Society for Testing and Materials, 1971
3. G. Sachs, "Survey of Low-Alloy Aircraft Steels Heat Treated to High Strength Levels," WADC TR 53-254, Part 4, Wright Air Development Center, Dec 1953
4. R.L. McGee, J.E. Campbell, L.R. Carlson, and G.K. Manning, "The Mechanical Properties of Certain Aircraft Structural Metals at Very Low Temperature," WADC TR 58-386, Wright Air Development Center, Nov 1958
5. J.J. Hauser and M.G.H. Wells, The Effect of Inclusions on Fatigue Properties in High-Strength Steels, Mechanical Working and Steel Processing, in Vol 14, Iron and Steel Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers, 1976, p 314-348
6. G.M. Waid, "Stress Corrosion and Hydrogen Embrittlement Studies of Ultrahigh-Strength Steels (HP 310, 4340, 300M)," Research Report, Republic Steel Corporation, Sept 1976
7. L. Peterman and R.L. Jones, Effects of Quenching Variables on Fracture Toughness of D-6ac Steel Aerospace Structures, *Met. Eng. Q.*, Vol 15 (No. 2), May 1975, p 59
8. "Plane Strain Fracture Toughness (K_{Ic}) Data Handbook for Metals," Army Materials and Mechanics Research Center, Dec 1973
9. K. Firth and R.D. Gargood, Fractography and Fracture Toughness of 5% Cr-Mo-V Ultrahigh-Strength Steels, "Fracture Toughness of High-Strength Materials: Theory and Practice," Publication 120, The Iron and Steel Institute, 1970, p 81
10. T.V. Philip, ESR: A Means of Improving Transverse Mechanical Properties in Tool and Die Steels, *Met. Technol.*, Dec 1975, p 554
11. H.I. McHenry, "Fatigue Crack Propagation in Steel Alloys at Elevated Temperature," Report EER-EW-1029, Convair Aerospace Division, General Dynamics Corporation, Sept 1970