INTRODUCTION TO TODAY'S ULTRAHIGH-STRENGTH STRUCTURAL STEELS

Issued Under the Auspices of
AMERICAN SOCIETY FOR TESTING AND MATERIALS
and
THE DEFENSE METALS INFORMATION CENTER

Prepared by
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AN INTRODUCTION TO TODAY'S ULTRAHIGH-STRENGTH STRUCTURAL STEELS

A. M. Hall*

ABSTRACT

The features that distinguish the "ultrahigh-strength" steels from the other classes of high-strength constructional steel are described. The various families of ultrahigh-strength steel are discussed in terms of composition, mechanical properties, forms available, forming characteristics, and weldability. Recent developments in the technology are described, and illustrative applications are given. The families of ultrahigh-strength steel discussed include medium-carbon low-alloy hardenable, medium- and high-alloy hardenable, high-nickel maraging, hardenable stainless, and cold-rolled stainless.

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INTRODUCTION

In old but dynamic technologies, confusion surrounding terminology is fairly common. Metallurgy indeed is no exception. One culprit in the metallurgical lexicon that is responsible for a particularly large degree of confusion is the term "high-strength steel". This term is applied quite frequently to any structural steel capable of being used at strength levels higher than those for which structural carbon steels were developed, i.e., higher than 33,000 to 36,000 psi minimum yield point. When thought of in this sense, a high-strength steel may possess a yield strength capability ranging all the way from some 42,000 psi to more than 350,000 psi--so wide a spread in strength as to rob the term of its meaning.

Most probably, this state of affairs can be attributed to the rapid advance of steel technology during the past 40 years, which has made available a steadily increasing number of steels usable at higher and higher strengths. Yesterday's ultimate in strength is topped by today's achievements which, in turn, will be surpassed by tomorrow's developments. As a result of this sequence of events, the term "high strength" has become applied to all sorts of steels.

Indeed, the confusion has been compounded by specification writing bodies. These organizations began quite logically to refer to steels with minimum yield points of 42,000 to 50,000 psi as high-strength steels and later, in the same vein, classified a series of steels with minimum yield points of 30,000 psi to 38,000 psi as being of intermediate strength. At the same time, they referred to a steel with a minimum yield point of 37,500 psi, and a tensile strength-to-yield point ratio slightly higher than called for in other specifications, as a high-tensile-strength steel. In addition, they have used both "quenched and tempered" and "high-strength quenched and tempered" to describe steels that are both in the same strength range, i.e., 85,000 to 100,000 psi minimum yield strength. However, in defense of specification writers, it must be said that they often are hard pressed to find acceptable descriptors for the many varieties of materials with which they are obliged to deal.

A simple and useful classification scheme in shown in Table 1.[1] This scheme has the advantage of being based not only on attainable strength but also on the condition in which the steel usually is supplied to the customer, i.e., the condition in which it usually is formed and joined.

TABLE 1. CLASSIFICATION OF HIGH-STRENGTH CONSTRUCTIONAL STEELS[1]

Class	Yield Strength Range Available, ksi	Condition in Which the Steel Usually is Supplied
High Strength	42-70	Hot rolled[a]
Extra-High Strength	60-110	Quenched and tempered[b]
Ultrahigh Strength	130-350	Soft[c]

(a) Cold-rolled sheet and strip are available; some steels with yield strengths of 65-70 ksi are supplied as stress relieved, depending on their composition (such steels experience moderate increases in strength during stress relieving because they are mildly precipitation-hardenable).[2]

(b) Bar stock and semifinished forgings are supplied unheat treated; also, the composition of some steels in this class is such that they develop the desired strength on controlled cooling from the hot-rolling temperature, without the necessity for subsequent hardening and tempering.[3]

(c) Annealed or normalized, except severely cold-rolled austenitic stainless steels, 5Ni-Cr-Mo-V steel plate which is supplied quenched and tempered, and abrasion-resistant plate which is supplied quenched and tempered to the desired final hardness.

In Table 1, a yield strength range of 130,000 to 350,000 psi has been assigned to the ultrahigh-strength class. As to the upper limit, when account is taken of such materials as heat-treated razor blade strip, cold-drawn plow steel and music wire, hard-drawn and aged semiaustenitic stainless steel wire, and hard-drawn austenitic stainless and improved carbon-steel wire, the maximum strength level achievable in reality is upwards of 600,000 psi. However, because these materials are special in form, limited in dimensions, and used only in highly specialized structural applications, they are not brought under discussion in this report.

As indicated in Table 1, the ultrahigh-strength steels generally are supplied to the customer in the soft condition. Usual practice is to form and join these steels in the soft condition and then heat treat them to high strength. This procedure is dictated, of course, by the tremendous difficulty encountered in machining these steels or in forming them into anything but the simplest shapes, with extremely generous radii of curvature, after they have been fully hardened. Thus, in addition to their extraordinary strength, the ultrahigh-strength steels are distinguished by the fact that they usually must be heat treated by the fabricator rather than the producer, or by a heat-treating shop, after fabrication. In either case, the heat treater must have a high degree of technical competence and the best equipment.

The ultrahigh-strength class of constructional steel is extremely broad and includes a number of distinctly different families of steels. The steels in this category are medium-carbon low-alloy hardenable, medium-alloy hardenable, high-alloy hardenable, low-carbon high-nickel maraging, martensitic and martensitic precipitation-hardenable stainless, semiaustenitic precipitation-hardenable stainless, and cold-rolled austenitic stainless steel.

MEDIUM-CARBON LOW-ALLOY HARDENABLE STEELS

General Characteristics

The medium-carbon low-alloy steels constitute the earliest family of ultrahigh-strength structural steels. They made their start well before World War II with AISI 4130, which was followed soon by the higher strength AISI 4140 and then the higher strength, deeper hardening AISI 4340. The family has served well and is still the most frequently used in the ultrahigh-strength class.

These steels generally are quenched to a fully martensitic structure which is tempered to improve ductility and toughness as well as to adjust the strength to the required level. Their carbon content usually is in the range of 0.35 to 0.45 percent, which is sufficient to permit these steels to be hardened to great strength. Their alloy content gives them some extra solid-solution strength together with the requisite through-hardening capability.

In the years since these steels were introduced, modifications have been developed. In some cases, the silicon content has been increased to avoid embrittlement when the steel is tempered at the low temperatures required for extremely high strength. Vanadium has been added to promote toughness by refining the grain size. Sulfur and phosphorus contents have been reduced to improve toughness and transverse ductility. Because martensite becomes increasingly brittle and refractory with increasing carbon content, the practice has been established of using the lowest amount of carbon in the steel needed to attain the desired strength level. In this way, welding characteristics, toughness, and formability are optimized. The compositions of a few typical low-alloy ultrahigh strength steels are given in Table 2.

No distinctly new or different steels have been added to the family in recent years. Rather, the thrust of recent developmental effort has been toward reduction in the content and size of nonmetallic inclusions, the content of elemental impurities, and the number and severity of surface and internal defects in mill products. Toward these ends, several routes have been taken, i.e., use of high-grade, low-impurity melting stock; advanced melting methods such as vacuum-arc remelting, double vacuum melting, carbon deoxidation in conjunction with vacuum-arc remelting and vacuum degassing; improved mill processing procedures including appropriate amounts of cross rolling of flat-rolled products, and effective amounts of upset forging in the production of forged products, forged billets, and preforms; close process control; and thorough inspection. The result has been increased reproducibility of properties from heat to heat and lot to lot, increased toughness and ductility especially in the transverse directions, and improved reliability in service.

The ultrahigh-strength low-alloy steels can be obtained in a variety of forms including billets, bars, bar shapes, and tubing. They also can be obtained in the form of sheets, strip, and plate. Occasionally, some of these steels are used in the form of castings.

Properties

As suggested in the foregoing section, the mechanical properties of a low-alloy hardenable steel are controlled largely by the carbon content of the steel, whether it is in the annealed condition or has been given a hardening heat treatment. The effect of carbon content on the tensile properties of annealed AISI 4300-type steels, in the form of 1-inch-round bars, is illustrated in Table 3.[4] Similar properties are obtained in the other low-alloy hardenable steels in the annealed condition for similar carbon contents.

By varying the hardening temperature, the quenching rate, and the tempering temperature, a wide range of mechanical properties is obtainable from these steels in the quenched and tempered condition. The effect on tensile properties that is produced by varying the tempering temperature is illustrated in Figure 1 for AISI 4340 and 300M.[5] Also shown in the figure is the way in which the higher silicon content of 300M influences the Charpy V-notch impact properties of the steel compared with those of AISI 4340.

In these steels, the mechanical properties vary not only with carbon and alloy content and heat-treating schedule, but also with section size. Again, the extent to which section size influences mechanical properties depends on the hardenability of the steel, which, in turn, is a function of the alloy content. Most ultrastrong low-alloy steels are sufficiently alloyed that section thickness up to 1/2-inch or so has little effect, but the properties change noticeably as the section gets larger. The influence of section size is illustrated by the data in Table 4.[6]

Forming, Heat Treating, and Joining

The ultrahigh-strength low-alloy steels are cut, sheared, punched, and cold formed in the annealed condition. Cutting is commonly done with the saw or the abrasive disk. Coolants should be employed in this operation. When flame cut, most of these steels are preheated to about 600 F; then, because the cut edge is hard, they are annealed before the next operation. In cold working operations, the yield strength of the annealed steel can be used as a guide in estimating the sturdiness required of the equipment,

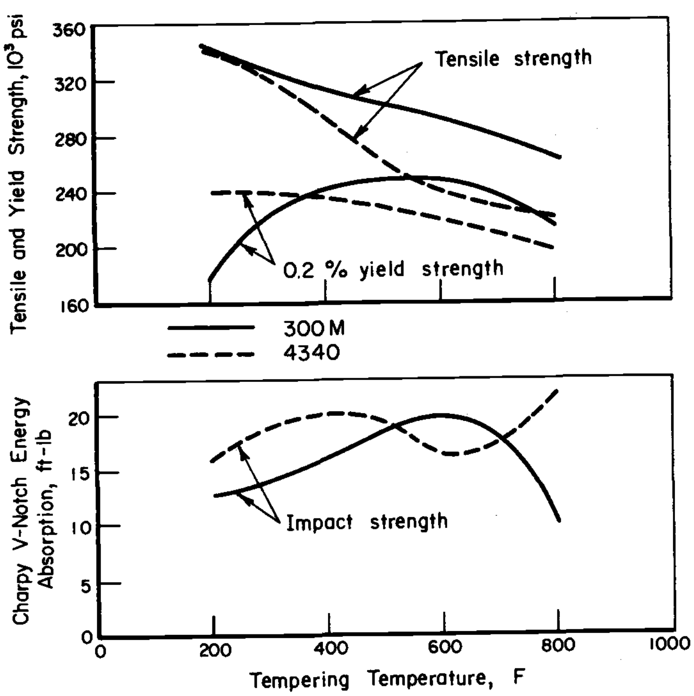

FIGURE 1. EFFECTS OF TEMPERING TEMPERATURE ON THE TENSILE AND IMPACT PROPERTIES OF 1-INCH-ROUND BARS OF TWO MEDIUM-CARBON LOW-ALLOY STEELS OIL QUENCHED FROM 1575 F[5]

TABLE 2. COMPOSITIONS OF TYPICAL ULTRAHIGH-STRENGTH LOW-ALLOY STEELS

Designation	Composition, weight percent						
	C	Mn	Si	Cr	Ni	Mo	V
AISI 4130[a]	0.28/0.33	0.40/0.60	0.20/0.35	0.80/1.10	--	0.15/0.25	--
AISI 4140[a]	0.38/0.43	0.75/1.0	0.20/0.35	0.80/1.10	--	0.15/0.25	--
AISI 4340[a]	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[b]	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
Ladish D6AC[c]	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
300M[c]	0.41/0.46	0.65/0.90	1.45/1.80	0.70/0.95	1.65/2.00	0.30/0.45	0.05 min

(a) Designation of the American Iron and Steel Institute.
(b) Designation of Aerospace Material Specification.
(c) Trade name.

TABLE 3. INFLUENCE OF CARBON ON THE TENSILE PROPERTIES OF AISI 4300-TYPE STEELS AS ANNEALED[a][4]

Carbon Content, percent	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction of Area, percent
0.10	87	70	28	58
0.20	95	77	23	52
0.30	108	88	20	45
0.40	120	100	17	43
0.50	128	108	15	38

(a) The series containing nominally 1.75 percent nickel, 0.70 percent chromium, and 0.25 percent molybdenum. The last two digits in a 4-digit designation refer to carbon content, e.g., 4340 steel contains 0.40 percent carbon. Annealed in the form of 1-inch round bars.

TABLE 4. INFLUENCE OF SECTION SIZE ON THE TENSILE PROPERTIES OF AISI 4340 STEEL OIL QUENCHED FROM 1550 F AND TEMPERED AT 800 F[6]

Diameter, inches	Tensile Strength, ksi	Yield Strength 0.2 Percent Offset, ksi	Reduction of Area, percent	Elongation in 2 Inches, percent
1/2	212	200	51	13
1-1/2	210	198	45	11
3	206	192	38	10

power requirements, minimum bend radii, and spring-back allowances. Generally, a minimum bend radius of 3t is used. The figure for yield strength is approximately three times that of structural carbon steel.

These steels are readily hot forged, usually in the range of 1950 to 2250 F; to avoid cracking as a result of their air-hardening characteristics, preheating and furnace cooling after forging are recommended.(7-9) Preparatory to machining, usual practice is to normalize at 1600 to 1700 F and temper at 1200 to 1250 F, or to anneal at 1500 to 1550 F and furnace cool to about 1000 F if the steel is appreciably air hardening. These treatments give the steel a structure of moderate hardness that is composed of medium to fine pearlite lamellae. When the steel is in this condition, its machinability rating is about half that of AISI B1112 screw stock. A very soft structure composed of coalesced or spheroidized carbides in a ferrite matrix usually is not wanted for machining. With such a structure, the steel tends to tear, the chips break away with difficulty, and metal tends to build up on the machining tool. However, for cold spinning, deep drawing, and other severe cold working operations, the soft, ductile spheroidized structure may be preferable to the pearlitic one. A number of schedules can be used to obtain the spheroidized structure. An effective procedure is to heat the steel at a temperature somewhat above that at which transformation to austenite starts, Ae_1, and then to cool it and hold it at a temperature slightly below Ae_1.(10) One schedule that is used to spheroidize AISI 4340 is to preheat to 1275 F for 2 hours, raise the temperature to 1375 F, cool to 1200 F and hold 6 hours, furnace cool to 1100 F and then air cool.(6)

For hardening, austenitizing temperatures range from about 1475 F to some 1650 F, the work usually being surrounded by a protective atmosphere or other medium that will neither decarburize nor carburize the steel.(6-10) Quenching in warm oil or molten salt is common. The tempering range for these steels is very broad, usually 300 to 1200 F. The particular tempering temperature chosen depends on the strength desired. Double tempering is recommended.

The ultrastrong low-alloy steels are welded preferably in the annealed or normalized condition and then heat treated to the desired strength. They are welded by such processes as inert-gas tungsten-arc, shielded metal-arc, inert-gas metal-arc, submerged arc, pressure, and flash welding. Filler wire compositions are designed to produce a deposit that responds to subsequent heat treatment in approximately the same manner as the base metal. To avoid brittleness and crack formation in the joining process, preheating and interpass heating are used; for the same reasons, complex structures are tempered or otherwise heat treated immediately after welding.

MEDIUM-ALLOY STEELS

Types

During the 1950's, the aircraft industry pioneered application of the H-11 and H-13 types of 5Cr-Mo-V hot-work die steel for ultrahigh-strength structural applications. These steels are still in use. However, they are not so popular today as they once were because several other steels in the same cost bracket have been found to possess substantially greater fracture toughness at the same high strength levels. Nevertheless, they have a number of attractive features: by virtue of their secondary hardening capability, they maintain an unusually high strength-to-weight ratio to at least 1000 F; for the same reason, they can be tempered at comparatively high temperatures, which permits a substantial measure of stress relief to occur during the tempering treatment; also, they are air hardened, which is a procedure that promotes less distortion than does the much more drastic process of oil or water quenching often required for the low-alloy steels. The chromium, molybdenum and vanadium contents provide secondary hardening capability, while the chromium and molybdenum account for the air hardening capability of these steels.

Interest in these steels by the aircraft and missile industry stimulated standardization on an aircraft-quality grade which has become known as "5Cr-Mo-V aircraft steel" with the composition shown in Table 5. Many proprietary steels of this type have been developed for, or adapted to, structural applications. These steels are obtainable in the form of forging billets, bar, sheet, strip, plate, and wire.

In recent years, another medium-alloy quenched and tempered steel with considerably different properties from those of the 5Cr-Mo-V steels has been developed for the U.S. Navy by the U.S. Steel Corporation.(11) Known as 5Ni-Cr-Mo-V steel as well as HY 130/150, it has been designed for hydrospace, aerospace and general pressure containment applications requiring plate as the starting

TABLE 5. COMPOSITIONS OF BASIC 5Cr-Mo-V STEELS

Designation	Composition, weight percent					
	C	Mn	Si	Cr	Mo	V
5Cr-Mo-V aircraft steel	0.37/0.43	0.20/0.40	0.80/1.20	4.75/5.25	1.20/1.40	0.4/0.6
H-11[a]	0.30/0.40	0.20/0.40	0.80/1.20	4.75/5.50	1.25/1.75	0.30/0.50
H-13[a]	0.30/0.40	0.20/0.40	0.80/1.20	4.75/5.50	1.25/1.75	0.80/1.20

(a) Designation of the American Iron and Steel Institute.

material. Plate produced from this steel is available in thicknesses up through 4 inches. The nominal composition is 0.10C, 0.75Mn, 0.25Si, 5.00Ni, 0.55Cr, 0.55Mo, 0.07V with sulfur, phosphorus, and nitrogen maintained as low as is practical.

A number of considerations were taken into account in developing this steel: Sufficient hardenability was desired to permit achieving the target mechanical properties at the midthickness of a 4-inch-thick plate; the steel was to be readily weldable with a minimum tendency toward heat-affected-zone cracking; the ductile-to-brittle transition of the steel was to be such that the operating temperature of the structure would be above that at which there would be any tendency toward brittle behavior. For hydrospace applications, the last named consideration was taken to mean that the steel was to behave in a thoroughly tough manner at temperatures down to 0 F or below.

Achievement of the desired minimum tendency for heat-affected-zone cracking required that the carbon content of the steel be restricted to about 0.10 percent. Thus, it would be necessary to accept the yield strength attainable in a 0.10 percent carbon steel containing sufficient amounts of selected alloying elements to develop the desired hardenability. As shown in Figure 2, the corresponding yield strength is in the range of 130 to 150 ksi.

Figure 2 also shows the influence of carbon content on toughness as measured by the energy absorbed in the Charpy V-notch test at 0 F. Note that, at the level of 0.10 percent carbon, the toughness is very good. The nickel content has contributed significantly to the toughness of the steel. Also, the manganese and chromium contents have been restricted because these elements detract from toughness. In addition, the steel can be tempered at the relatively high temperatures that promote toughness, without losing strength. This desirable characteristic results from the secondary hardening capability imparted to the steel by its chromium, molybdenum, and vanadium contents.

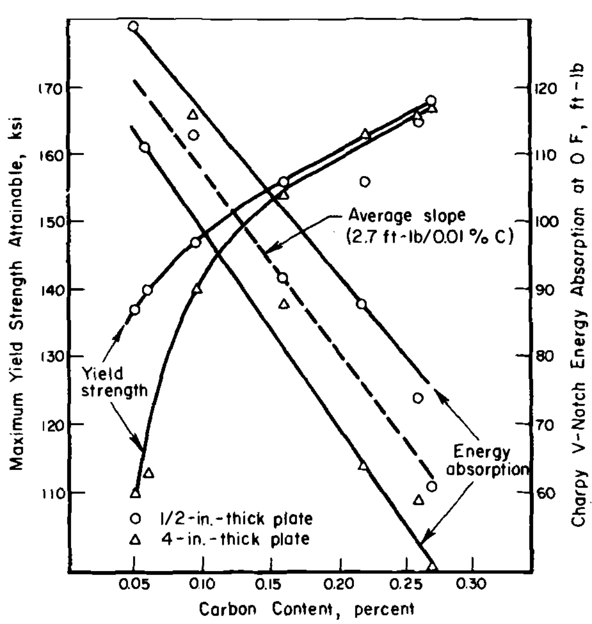

FIGURE 2. EFFECT OF CARBON CONTENT ON MAXIMUM YIELD STRENGTH AND NOTCH TOUGHNESS OF 5Ni-Cr-Mo-V STEEL[11]

Properties and Fabrication

5Cr-Mo-V Steels

The mechanical properties of the H-11 and H-13 types of 5Cr-Mo-V steel are controlled by the same factors as those that control the properties of low-alloy and other quenched and tempered steels, i.e., carbon content, alloy content, heat-treating condition, and section size. In the annealed condition, the steels exhibit tensile properties of the order of 90,000 to 125,000 psi ultimate strength, 65,000 to 100,000 psi yield strength, and 16 to 19 percent elongation. Air cooling from the hardening temperature, followed by tempering, produces a range of tensile properties depending on the tempering conditions. The practical maximum tensile strength is of the order of 310,000 psi, the corresponding yield strength being about 245,000 psi with about 5 percent elongation in 2 inches. The effect of tempering temperature on the tensile properties of H-11 is illustrated by the data in Figure 3. Because they are sufficiently alloyed to be air hardening, the 5Cr-Mo-V steels are not so sensitive to section thickness as are the low-alloy hardenable steels discussed in the foregoing section.

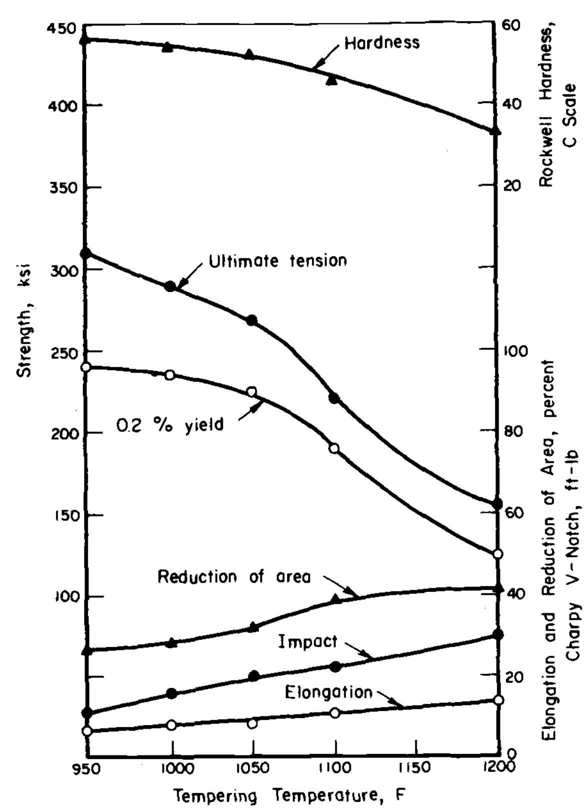

FIGURE 3. TENSILE AND IMPACT PROPERTIES OF AN H-11 TYPE STEEL AIR COOLED FROM 1850 F AND TRIPLE TEMPERED AT THE INDICATED TEMPERATURES[12]

The form of the material was 1/2-inch-diameter rounds.

The procedures and equipment for forming the 5Cr-Mo-V steels are similar to those used in forming the medium-carbon low-alloy hardenable steels. Because these steels are strongly air hardening, they should be preheated to perhaps 600 F before flame cutting and then annealed immediately afterward. Otherwise, a brittle layer that is susceptible to cracking will form at the cut faces.

Forging should be started at 2000 F and stopped when the temperature of the work has dropped to 1600 F; cooling should be carried out in the furnace or in an insulating medium. Hardening is accomplished by preheating at 1450 F, holding 20 to 30 minutes at 1800 to 1900 F in a protective atmosphere, then air cooling to room temperature. The usual tempering range is 950 to 1200 F; double tempering is recommended.(13, 14)

Fusion welding of these steels is carried out preferably in the annealed condition, and generally is accomplished with inert-gas-shielded 5Cr-Mo-V wire or with coated electrodes of the same composition as the base metal. Parts to be welded should be preheated to about 1000 F and then welded while maintaining the temperature above 600 F. After welding, the work can be post-heated sufficiently for retarded cooling to 150 - 200 F, or furnace cooled, or cooled in an insulating medium. The part is then annealed or stress relieved at 1250 to 1350 F for 2 hours and air cooled, to obtain a fully tempered microstructure suitable for straightening or storing. Full annealing before the final heat treatment is recommended.(13, 14)

5Ni-Cr-Mo-V (HY 130/150) Steel

As is the case with other quenched and tempered steels, the mechanical properties of the 5Ni-Cr-Mo-V steel are influenced by section size and heat treating schedule. An example of the influence of section size is given in Table 6, for steel water quenched from 1500 F and tempered at 1120 F. The influence of tempering temperature on the mechanical properties of 1/2-inch-thick plate produced from a typical 80-ton heat is illustrated in Figure 4. The steel had been water quenched from 1500 F. As the data show, the HY 130/150 steel displays a high degree of toughness. In addition, the steel retains its strength and toughness for long periods of time at temperatures up to 600 F.

The steel can be cold formed successfully and can be welded by such processes as gas-tungsten arc, gas-metal arc, coated electrode, electron beam, and plasma arc. Tensile properties obtainable in welded joints of 5/16-inch-thick plate are illustrated in Table 7. Joint properties are seen to approximate those of the base metal very well.

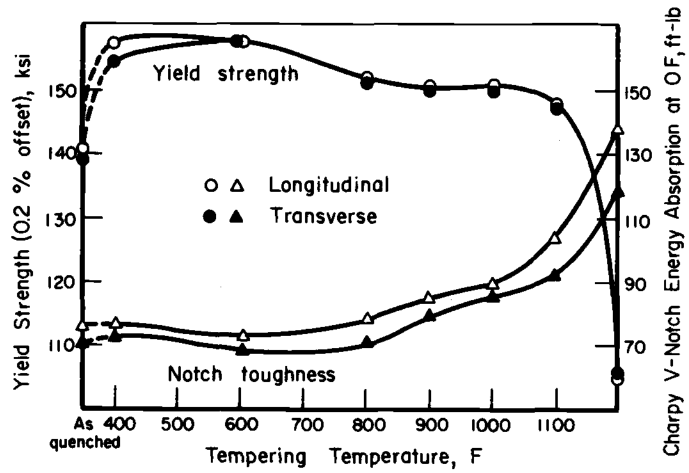

FIGURE 4. TEMPERING CHARACTERISTICS OF 1/2-INCH-THICK 5Ni-Cr-Mo-V (HY 130/150) STEEL PLATE(11)

TABLE 6. INFLUENCE OF PLATE THICKNESS ON THE MECHANICAL PROPERTIES(a) OF 5Ni-Cr-Mo-V (HY 130/150) STEEL(15)

(Water Quenched From 1500 F and Tempered at 1120 F)

Plate Thickness, inches	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Value at 0 F: Energy Absorption, ft-lb	Charpy V-Notch Value at 0 F: Shear Fracture, %
1/2	Longitudinal	149	155	20.0	71.4	101	100
	Transverse	151	156	19.5	69.9	91	100
1	Longitudinal	148	155	19.0	69.1	99	100
	Transverse	148	156	18.5	67.7	86	100
2	Longitudinal	150	160	18.0	66.9	81	90
	Transverse	150	160	19.0	66.8	71	85
4	Longitudinal	137	145	19.5	63.7	77	95
	Transverse	137	150	19.5	63.0	74	90

(a) Midthickness properties.

TABLE 7. PROPERTIES OF WELDED JOINTS MADE IN 5/16-INCH-THICK 5Ni-Cr-Mo-V (HY 130/150) PLATE[16]

Weld Type	Condition	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, percent
Base metal	Heat treated[a]	147	153-155	18
Tungsten arc	As welded	138-140	154	13
Electron beam	As welded	146-149	153-154	15.5-16.0
Plasma arc	As welded	145	149-150	13-14

(a) Water quenched from 1500 F, tempered at 1120 F, and water quenched.

HIGH-ALLOY STEELS

Types

Two types of highly alloyed steels are represented on the list of ultrahigh-strength steels. One type develops its high strength by the standard thermal treatment of hardening and tempering. The other type is a high-nickel low-carbon steel that obtains its high strength from a single thermal treatment called "maraging", which is carried out in the vicinity of 900 F. The high-nickel maraging steels were developed by The International Nickel Company, Inc.

HP 9-4 Steels*

Representing the quenched and tempered type of high-alloy steel are two steels developed by Republic Steel Corporation. Known as HP 9-4-20 and HP 9-4-30 (Cr, Mo), these steels have the compositions shown in Table 8.

HP 9-4-20 was developed originally as a plate steel for use in the hulls of deep submersibles.[19] As such, the steel was designed to possess a high degree of toughness, good weldability, and relatively high strength in the range of 180 ksi yield strength. The basic concept used to achieve these goals was to employ the minimum carbon content capable of developing the desired strength.[17] Assuming the structure of the hardened steel to be virtually all martensite, this carbon content is about 0.20 percent. In this way, the detrimental effect of carbon on toughness and weldability is held to a minimum. Because of the low carbon content and the high cobalt content of the steel, the temperature at which the martensite transformation starts (M_s) is high enough (about 595 F) to permit considerable self tempering of the martensite as it cools through the transformation range to room temperature. The self tempering characteristic results in an as-quenched martensite that is strong and tough, i.e., a yield strength of about 155 ksi and a room-temperature Charpy V-notch value of about 50 ft-lbs. This self tempering property also is reported to be the key to the high strength and toughness observed in as-deposited welds of HP 9-4-20.

*Sometimes called the 9Ni-4Co steels.

On tempering, the yield strength is increased substantially as a result of secondary hardening brought about by the precipitation of alloy carbides.[17] However, the amount of the alloy carbide formers, chromium and molybdenum, that is used is so adjusted as to give a fairly flat tempering response curve, while avoiding a pronounced secondary hardening peak and the attendant loss in toughness.

The other steel, HP 9-4-30 (Cr, Mo), is looked upon primarily as a forging steel.[19] This steel was designed to develop a tensile strength in the range of 220 to 240 ksi, to retain its properties on long exposure at temperatures up to 800 F with excursions as high as 1000 F, and to possess reasonably high toughness.[18] To meet the strength requirement, it was necessary to increase the carbon content substantially above that used in HP 9-4-20, as shown in Table 8. Of course, in so doing, some toughness and weldability were sacrificed. In addition, it was not possible to fully transform the structure to martensite by a simple oil quench from the austenitizing temperature. Normalizing before austenitizing, and refrigerating at -100 F after oil quenching, was found to overcome this problem and to result in the best combination of strength and toughness on subsequent tempering. Response to tempering in the range of 900 to 1050 F is fairly constant as a result of a moderate amount of secondary hardening.

TABLE 8. NOMINAL COMPOSITIONS OF HP 9-4 STEELS[17,18]

Designation	C	Mn	Si[a]	S[a]	P[a]	Ni	Cr	Mo	V	Co
HP 9-4-20	0.20	0.30	0.10	0.01	0.01	9.0	0.75	0.75	0.10	4.50
HP 9-4-30 (Cr, Mo)	0.30	0.20	0.10	0.01	0.01	7.5	1.00	1.00	0.10	4.50

(a) Maximum.

Maraging Steels

During the past decade, a series of high-nickel maraging steels has been developed. The compositions of those members of the series that have come into substantial use are given in Table 9. At the outset, this type of steel evoked tremendous interest, especially in the aerospace world, because it offered an extraordinary combination of ultrahigh strength and fracture toughness in a material that was, at the same time, formable, weldable, and easy to heat treat. The high-nickel maraging steels are available in the form of plate, sheet, forging billets, bar stock, strip, and wire. Several members of the series also are available as tubing.

In these steels, the equilibrium structure at elevated temperatures is austenite, while at ambient temperatures it is ferrite and austenite. However, equilibrium, which is brought about by diffusion processes, is extremely difficult to achieve in these alloys at intermediate and low temperatures; instead, on cooling, the austenitic structure transforms to a body-centered-cubic martensite by shearing, even when the cooling rate is very low. The maraging steels are so alloyed that, on cooling to room temperature, no untransformed austenite remains and the martensite that forms is the very tough massive type rather than the less tough twinned variety. In addition, the only transformation product is martensite; no intermediate or alternative austenite decomposition products form. Thus, cooling rate in the usual sense, and hence section size, are not factors in martensite formation and the concept of hardenability, which dominates the technology of quenched and tempered steels, is not applicable to the maraging steels.[20,21] However, attention should be called to one effect of cooling rate. On cooling very slowly from the austenitizing temperature, severe embrittlement may be encountered.

A further implication of the fact that martensite is the only austenite transformation product is that, under normal conditions, the transformation is reversible. As a consequence the grain size does not change on passing up and down through the phase transition, the structure merely shearing back and forth between the original austenite and the descendant martensite. To refine the grain size of this type of alloy requires the development of plastic strain in the material prior to, or during, the austenitizing treatment, so that recrystallization of the austenite can be brought about. Of course, the greater the degree of straining, the greater will be the number of nuclei activated during the thermal treatment and the finer will be the resulting grain size.[20]

In contrast, the ferritic grain size of standard plain carbon and alloy steels is subject to alteration when these steels pass through the ferrite-austenite transition, as in normalizing and various kinds of annealing treatments. This transformation provides an opportunity for grain finement by thermal treatment because it is an irreversible nucleation and growth process, and the nucleation and growth factors can be controlled.

When the maraging steels are heated to moderate temperatures, but below the temperature range of rapid reversion to austenite, their hardness and strength increase markedly. For example, a maraging steel with a yield strength of 100,000 psi in the martensitic or annealed condition, on being aged three hours at 900 F may reach a yield strength of 250,000 psi. Because these steels derive their strength on being aged while in the martensitic condition, they have become known as "maraging" steels.

The mechanism whereby these steels achieve their ultrahigh strength on aging at moderate temperatures has been the subject of considerable research. Some discrepancies exist in the substantial amount of data that has been accumulated and some differences of opinion prevail as to the interpretation of the data. However, a fair amount of agreement seems to be emerging to the effect that the strengthening occurring on aging results from the early formation of zones or clusters based on an Ni_3Mo grouping containing iron [i.e., $(Ni,Fe)_3Mo$] which, at higher aging temperatures, may give way or evolve into a precipitate of Fe_2Mo. At the lower aging temperatures and the longer holding times, the clusters may perhaps be supplemented by the Fe_2Mo precipitate. It is also hypothesized that a third precipitate containing titanium forms in the promotion of age hardening in these steels. Quite possibly, this precipitate is FeTi sigma phase.

When the maraging steels are heated for long periods of time at the higher aging temperatures, or at temperatures between the aging range and the annealing range, the matrix tends to revert to austenite. The presence of reverted austenite in the steel is highly undesirable because it is unacceptably soft and generally is too stable

TABLE 9. NOMINAL COMPOSITIONS OF MARAGING STEELS

Designation[a]	C[b]	Mn[b]	Si[b]	S[b]	P[b]	Ni	Co	Mo	Ti	Al
18Ni (200)	0.03	0.10	0.10	0.01	0.01	18.0	8.5	3.25	0.20	0.10
18Ni (250)	0.03	0.10	0.10	0.01	0.01	18.0	8.0	4.90	0.40	0.10
18Ni (300)	0.03	0.10	0.10	0.01	0.01	18.5	9.0	4.90	0.65	0.10
18Ni (350)	0.01	0.10	0.10	0.01	0.01	17.5	12.5	3.75	1.80	0.15

(a) The numbers in parentheses indicate the nominal yield strength, in ksi, to which it is possible to heat treat the steel.

(b) Maximum.

to retransform to martensite on subsequent cooling. Thus, overaging is avoided and process or intermediate annealing is not practiced. However, in welding, a narrow region in which austenite reversion occurs inevitably develops in heat-affected zones. On the other hand, the harmful effect of this zone can be greatly diminished by holding the heat input to the minimum and encouraging fast cooling.[20]

Properties and Fabrication

HP 9-4 Steels

Currently, HP 9-4-20 is available in the form of sheets, strip, billets, bars and rods, in addition to plate. Typical tensile properties of the steel in the form of 1-inch-thick plate as water quenched from 1500 F and tempered at 1025 F are reported to be as follows:[17]

Tensile Strength, ksi	195/215
Yield Strength, 0.2% offset, ksi	180/195
Elongation in 2 Inches, %	14/19
Reduction of Area, %	55/65
Charpy V-Notch at Room Temperature, ft-lb	45/60

Minimum mechanical properties offered by the producer are given in Table 10.

HP 9-4-20 can be hot and cold formed, and, in fact, is reported to be capable of being bent, rolled, and shear spun in the heat-treated condition.[17] For hardening, the practice recommended by the producer is to normalize prior to austenitizing. In this way, maximum Charpy V-notch toughness is developed. Normalizing is carried out at 1650 F, heating one hour per inch of thickness; the austenitizing temperature is 1500 F, the steel being water quenched from this temperature; the recommended tempering temperature is 1025 F, the holding time being 4 to 8 hours.[17]

HP 9-4-20 is weldable in the quenched and tempered condition by the gas tungsten-arc process, no post-heat being required. A reduced-section transverse tension test from a double-U butt joint, made in a 2-inch-thick plate, gave the following tensile properties:[17]

Tensile Strength, ksi	200
Yield Strength, 0.2% offset, ksi	185
Reduction of Area, %	58

Illustrative mechanical properties of HP 9-4-30 (Cr, Mo) in the form of 1-inch-thick plate in one of the preferred conditions of heat treatment, namely, normalized at 1700 F, reheated to 1525 F, refrigerated at -100 F, and double tempered at 1000 F, are as follows:[18]

Tensile Strength, ksi	231
Yield Strength, 0.2% offset, ksi	210
Elongation in 1 Inch, %	16
Reduction of Area, %	62
Charpy V-Notch at Room Temperature, ft-lb	34
Chappy V-Notch at 0 F, ft-lb	32

Maraging Steels

In the soft condition, which is the condition in which these steels usually are supplied by the producer, the high-nickel maraging steels display tensile properties somewhat similar to those of annealed medium-carbon ultrahigh-strength steels. Illustrative properties are shown in Table 11. Depending on the steel's composition, an increase in yield strength of as much as 200,000 psi can be obtained when the steel is given the aging treatment. An aging temperature of 900 F generally is preferred, the usual time at temperature being 3 hours. Illustrative tensile properties for aged rounds from vacuum-arc remelted steel are given in Table 12, while tensile properties obtained on flat-rolled products are shown in Table 13.

TABLE 10. MINIMUM ROOM-TEMPERATURE MECHANICAL PROPERTIES FOR HP 9-4-20 STEEL[17]

	Tensile Ultimate, ksi	Tensile Yield, ksi	Elongation, percent	Reduction of Area, percent	Charpy V-Notch[a] ft-lb
Plate					
Less than 2 inches	195	180	14	55	45
Over 2 inches to 4 inches	195	175	14	55	40
Billet					
25-square-inch reforge	195	180	14	55	50

(a) Average values for tests at 0 F. Minimum individual result shall not be below the average required by more than 5 ft-lb.

TABLE 11. TENSILE PROPERTIES OF 18Ni MARAGING STEELS IN THE SOFT CONDITION[22]

Grade	Tensile Strength, ksi	Yield Strength 0.2% Offset, ksi	Elongation in 4D, percent	Reduction of Area, percent
200	140	110	18	72
250	140	100	19	78
300	150	100	18	72
350	165	120	18	70

TABLE 12. TYPICAL ROOM-TEMPERATURE TENSILE PROPERTIES OF AGED ROUNDS PRODUCED FROM VACUUM-ARC REMELTED 18Ni MARAGING STEEL[22]

Grade	Tensile Strength, ksi	Yield Strength 0.2% Offset, ksi	Elongation in 4D, percent	Reduction of Area, percent
200[a]	210	203	11	50
250[a]	257	250	8	42
300[a]	278	273	9	48
350[b]	357	354	6	32

(a) 4-inch round, midradius.
(b) 2-1/2-inch round, center.

TABLE 13. ILLUSTRATIVE ROOM-TEMPERATURE TENSILE PROPERTIES OF 18Ni MARAGING STEEL FLAT-ROLLED PRODUCTS[22]

Grade	Thickness, inch	Tensile Strength, ksi	Yield Strength 0.2% Offset, ksi	Elongation in 2 Inches, percent
200	0 500	209	204	13[a]
200	0.320	208	202	14[a]
200	0.080	215	213	4
200	0.060	216	207	4
250[b]	0.070	263	258	3
300	0.250	321	315	5
300	0.125	317	314	3
300	0.090	313	308	3
300	0.065	307	301	3
300	0.045	295	292	2
300	0.025	296	294	1

(a) Elongation in 1 inch.
(b) Data for this grade are from Reference 23.

The maraging steels are cut, sheared, and cold formed in the annealed condition. They can be torch cut; plasma arc is preferred because of its efficient heat input.[24] Sawing can be done either with circular or with power hack saws manufactured from high speed steel. These steels can be roll formed, spun, and deep drawn successfully as annealed. The high-nickel maraging steels work harden only to a moderate extent, as demonstrated by the fact that they can be cold rolled up to 80 percent between anneals.[25,26] This is an advantage in some cold forming operations. However, ductility is somewhat limited, especially uniform elongation in tension; consequently, frequent intermediate annealing is required when maraging steel sheet is cold worked extensively by processes in which the stresses are predominantly tensile.[20]

The maraging steels can be hot worked readily by standard rolling and forging procedures.[24] The work should be soaked at 2300 F. Finishing operations should be carried out at a low temperature, i.e., as low as 1500 F.

The high-nickel maraging steels are readily machined as annealed; limited machining can be done in the hardened condition.[25,26] As annealed, the steels are gummy and susceptible to tearing. Better finishes are obtained on hardened material. These steels are weldable by the inert-gas-shielded tungsten-arc process, the inert-gas-shielded metal-arc process, and the shielded metal-arc process; the submerged-arc method also can be used. No preheat or post-heat is required. Subsequent aging results in joints of extremely high strength.

Some additional characteristics of maraging steels should be mentioned. Because these steels do not have the hardenability limitations of the quenched and tempered steels, they are capable of developing their ultrahigh strength even in extremely thick sections. Another attribute is their extremely high compressive yield strength which often is substantially greater than the tensile yield strength. A third characteristic is the fact that they undergo very little distortion or dimensional change during aging. Thus, in the manufacture of precision components, they can be finish machined essentially in the soft condition, with only minor dressing operations required after aging.

STAINLESS STEELS

Martensitic Types

Early in the history of stainless steels a hardenable straight chromium type emerged which ultimately found widespread application in tablewear, cutlery, surgical instruments, and the like. This steel, containing 12 to 14 percent chromium and up to 0.35 percent carbon, combined stainlessness with very considerable strength. With the development of the turbo supercharger just before World War II and the arrival of the turbojet engine during that war, this steel, modified by additions of such elements as molybdenum, columbium, vanadium, and tungsten, became a compressor-blade and turbine-blade material for use at moderately elevated temperatures. Since World War II, numerous proprietary modifications of the basic hardenable straight-chromium stainless steel have been developed. At the same time, usage of this type of steel has been extended into applications requiring a material having moderate corrosion resistance combined with ultrahigh strength.

The father of this steel family carries the designation AISI 420. Its composition is given in Table 14, along with those of several recent proprietary modifications. Most of the additional alloying elements are incorporated in the composition to enhance strength at room or elevated temperatures. All the steels are hardened by quenching and tempering in a manner similar to that of other quench-hardening steels. However, in many cases, additional strengthening occurs by means of an aging mechanism that is operative during the tempering treatment. Examples of age-hardening martensitic stainless steels include 17-4PH, PH13-8Mo, and Custom 455.

TABLE 14. NOMINAL COMPOSITIONS OF SOME MARTENSITIC STAINLESS STEELS

Designation	C	Mn	Si	Cr	Ni	Mo	Cu	Other	Originator
AISI 420[a]	0.15[b]	1.0[c]	1.0[c]	13	-	-	-	-	--
AISI 431[a]	0.20[c]	1.0[c]	1.0[c]	16	2.0	-	-	-	--
12MoV[d]	0.25	0.5	0.5	12	0.5	1.0	-	0.3V	U.S. Steel
17-4PH[d]	0.07[c]	1.0[c]	1.0[c]	16.5	4.0	-	4.0	0.3Cb	Armco Steel
PH13-8Mo[d]	0.05[c]	0.1[c]	0.1[c]	12.5	8.0	2.5	-	1.1Al	Armco Steel
Pyromet X-15[d]	0.03[c]	0.1[c]	0.1[c]	15	-	2.9	-	20.0Co	Carpenter
Custom 455[d]	0.05[c]	0.5[c]	0.5[c]	12	8.5	0.5[c]	2.0	0.3Cb, 1.1Ti	Carpenter
AFC 77[d]	0.15	-	-	14.5	-	5.0	4.0	13.5Co, 0.5V, 0.05N	Crucible Steel

(a) Designation of the American Iron and Steel Institute.
(b) Minimum.
(c) Maximum.
(d) Trade name.

The martensitic stainless steels are most commonly available in the form of billets, bar stock, and bar shapes. They also can be obtained as plate, sheet, strip, tubing, and wire. Some, like 17-4PH, are frequently used in the form of castings.

In general, the effect of heat treatment on the mechanical properties of these stainless steels is analogous to that on other quenched and tempered ultrahigh-strength steels. In the annealed condition, their tensile properties run 95,000 to 160,000 psi ultimate strength, 50,000 to 150,000 psi yield strength, and 6 to 25 percent elongation in 2 inches, depending on the specific alloy and the mill product form. By quenching and tempering, some of the martensitic stainless steels can be strengthened to as much as 260,000 psi tensile strength and 250,000 psi yield strength with 3 to 6 percent elongation in 2 inches.[27] Table 15 offers an indication of the range of mechanical properties available in these steels and of the tremendous influence of the heat treating schedule on the mechanical properties.

The martensitic stainless steels can be cut with abrasive disks and with various types of hack saw. Coolants should be used in both kinds of cutting. The friction saw also can be used. These stainless steels can be flame cut by the methods which have been developed for stainless steels in general, i.e., flux injection, powder cutting, oxy-arc, or arc-air.[28] They should be flame cut in the annealed condition; some of them should be heated to 500 to 700 F ahead of the cut and then, because they are air hardening, they require heat treatment after cutting to restore softness and ductility.

These stainless steels can be sheared, slit, nibbled, and punched quite readily when they are in the annealed condition. The equipment should be rigid, knives must be sharp, and hold-down must be firm. A considerable variety of cold-forming operations can be employed with these steels when they are in the soft condition. They can be bent, stretch bent, bent in press brakes, roll formed, deep drawn, flared, and spun. In general, their cold-forming behavior is similar to that of a carbon steel of the same strength and ductility.

Hot forging can be carried out in the range of 2200 to about 1600 F, depending on the specific alloy. To minimize the severity of thermal stresses, obtain uniformity of temperature in the workpiece, and reduce scaling, heating in two stages for forging is recommended. Slow heating to about 1500 F, soaking at that temperature, followed by rapid heating to, and a short soak at, the forging temperature is suggested. Because they air harden intensely, these steels should be annealed immediately on completion of hot-working operations. Some fabricating jobs may be done at temperatures up to about 1400 F; the work may then be stress relieved at this temperature. Other forming operations may require temperatures of 1500 to 1600 F; the work should then be given a full anneal immediately thereafter.

These stainless steels can be machined in the annealed cold-worked, or age-hardened conditions. They are amenable to all the usual machining operations, provided the cutting tools, procedures, and lubricants that have been developed for them are faithfully employed. In the solution-annealed condition, their machinability is similar to that of AISI Types 302 and 304 austenitic chromium-nickel stainless steels.[23] In the aged condition, their machinability improves as the aging temperature is increased.

The martensitic stainless steels can be welded in either the annealed or fully hardened conditions, usually

TABLE 15. TYPICAL MECHANICAL PROPERTIES OF PH13-8Mo BARS[28]

	Condition[a]													
	RH 950		H 950		H 1000		H 1050		H 1100		H 1150		H 1150-M	
	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans
Ultimate Tensile Strength, ksi	235	-	225	225	215	215	190	190	160	160	145	145	130	130
0.2% Yield Strength, ksi	215	-	210	210	205	205	180	180	150	150	105	105	85	85
Elongation in 2 In. or 4D, %	12	-	12	12	13	13	15.0	15.0	18.0	18.0	20.0	20.0	22.0	22.0
Reduction of Area, %	45	-	50	40	55	50	55.0	55.0	60.0	60.0	63.0	63.0	70.0	70.0
Hardness, Rc	48	-	47	47	45	45	43	43	35	35	33	33	28	28
Impact Charpy V-Notch, ft-lb	20	-	20	-	30	-	50	-	60	-	80	-	120	-

(a) All material was solution annealed at 1700 F and air or oil cooled below 60 F, followed by reheating 4 hours at the temperature indicated.

RH material was held 2 hours at -100 F before being reheated at the indicated temperature.

H 1150-M material was reheated 2 hours at 1400 F and air cooled after the solution anneal, and then heated 4 hours at 1150 F.

without preheat or post-heat.[28] These steels can be welded by resistance butt welding, resistance spot welding, or the inert-gas-shielding processes. High strength is obtainable simply by tempering after welding. In this way, distortion of the weldment often can be minimized. However, for optimum strength and ductility, the joint should be annealed before being tempered. In small sections, 100 percent joint efficiency after tempering is possible; in large sections, the joint efficiency may be somewhat less.[27]

Semiaustenitic Types

In 1948, the Armco Steel Corporation introduced a chromium-nickel stainless steel that was soft and ductile when annealed at temperatures in the region of 1950 F but could be hardened to great strength by appropriate thermal treatment. In the soft condition, it was austenitic and could be fabricated readily. By thermal treatment, the austenite could be induced to transform to martensite and, subsequently, a precipitate could be caused to form in the martensite. The steel achieved outstanding strength by the combination of these two hardening processes. Armco's steel was called 17-7PH. In 1954, Allegheny Ludlum introduced AM 350, a steel with somewhat similar characteristics. Because these unique stainless steels could be made either austenitic and soft, or martensitic and strong, at will, the term "semiaustenitic" was coined to distinguish them from other stainless steels. These semiaustenitic stainless steels quickly aroused great interest. Their considerable corrosion resistance, their capability to be formed and joined, and their outstanding strength constitute an extremely attractive combination of qualities. As a consequence, the number of steels of this type has grown. The nominal compositions of some of them are listed in Table 16.

Briefly, the composition of this type of steel is so adjusted as to achieve a particular balance between the effect of those elements that promote austenite formation and those that oppose it.[31] Included in the former group are carbon, nitrogen, nickel, copper, and manganese; in the latter group are such elements as silicon, chromium, molybdenum, tungsten, titanium, and aluminum. The composition balance desired is such that, when the steel is cooled to room temperature after being annealed at a high temperature (i.e., 1825 to 1950 F) where all the elements are completely dissolved, the structure is austenite; however, when the steel is reheated to an intermediate temperature (i.e., 1700 to 1750 F) where some of the dissolved carbon can be removed by precipitation as a chromium carbide, or is refrigerated, or is severely cold worked, the austenitic matrix becomes sufficiently unstable to transform to martensite. Final properties are then realized by a tempering or aging treatment carried out in the range of 850 to 1100 F.

In general, these stainless steels were developed for use in the form of sheet, strip, and foil. Some like AM 355, were intended to be used primarily as bar stock. 17-7PH and PH15-7Mo are available as billet, bar, rod, wire, plate, sheet, strip, foil, tubing, and specialty products.

Illustrative tensile properties of alloys originated at Armco are given in Table 17; tensile properties for Allegheny-Ludlum alloys are shown in Table 18. Note that in the annealed condition, the alloys display considerable ductility and low yield strength which make them readily formable. However, by means of the appropriate heat treatments, it is possible to increase their strength tremendously.

Cutting, shearing, punching, and cold-forming operations in general are carried out on the semiaustenitic stainless steels in the soft condition achieved by full annealing. These steels can be sawed, abrasive disk cut, sheared, slit, and friction sawed; sturdy equipment in good condition is required because, like other austenitic stainless steels, these steels are tough and tend to be gummy. They can be bent, stretch formed, spun, deep drawn, roll formed, expanded, flared, and cold hammered. These stainless steels can be hot forged and subjected to other hot-forming operations with success. Working temperature ranges are similar to those for other austenitic stainless steels, i.e., about 2200 to 1600 F. Likewise, working practices are similar to those used on other austenitic stainless steels.[33]

These steels can be machined in all conditions from fully annealed to fully hardened. When hardened stock is machined, speeds and feeds must be reduced, and tool life is shortened. When fully annealed material is machined,

TABLE 16. NOMINAL COMPOSITIONS OF SOME SEMIAUSTENITIC ULTRAHIGH-STRENGTH STAINLESS STEELS[29,30,31]

Designation[a]	C	Mn	Si	Cr	Ni	Mo	Al	N	Originator
17-7PH	0.09[b]	1.0[b]	1.0[b]	17.0	7.0	-	1.0	--	Armco Steel
PH15-7Mo	0.09[b]	1.0[b]	1.0[b]	15.0	7.0	2.5	1.0	--	Armco Steel
PH14-8Mo	0.05[b]	0.1[b]	0.1[b]	15.0	8.5	2.5	1.1	--	Armco Steel
AM 350	0.12[b]	0.90	0.5[b]	16.5	4.5	3.0	-	0.10	Allegheny Ludlum
AM 355	0.15[b]	0.95	0.5[b]	15.5	4.5	3.0	-	0.09	Allegheny Ludlum

(a) For each steel listed, the designation used is a trade name.
(b) Maximum.

TABLE 17. TYPICAL TRANSVERSE ROOM-TEMPERATURE TENSILE PROPERTIES FOR SEMIAUSTENITIC STAINLESS STEELS IN THE FORM OF SHEET[29,30]

Designation	Condition	Tensile Strength, ksi	Yield Strength 0.2% Offset, ksi	Elongation in 2 Inches, percent
17-7PH	Annealed	130	40	35
	RH 950[a]	230	217	6
	TH 1050[b]	200	185	9
	CH 900[c]	265	260	2
PH15-7Mo	Annealed	130	55	30
	RH 950[a]	240	225	6
	TH 1050[b]	210	200	7
	CH 900[c]	265	260	2
PH14-8Mo	Annealed	125	55	25
	RH 950[a]	230	215	6
	RH 1050[d]	210	200	6

(a) Heated at 1750 F, refrigerated at -100 F, tempered at 950 F.
(b) Heated at 1400 F, cooled to 55 F, tempered at 1050 F.
(c) Cold rolled, tempered at 900 F.
(d) Heated at 1750 F, refrigerated at -100 F, tempered at 1050 F.

TABLE 18. ILLUSTRATIVE ROOM-TEMPERATURE TENSILE PROPERTIES OF AM 350 AND AM 355 STAINLESS STEELS[32]

Condition	Designation	Tensile Strength, ksi	Yield Strength 0.2% Offset, ksi	Elongation in 2 Inches, percent
Solution annealed at 1950 F	AM 350	149	63	39
Solution annealed at 1875 F	AM 355	187	56	29
Heated 3 hours at 850 F after refrigeration	AM 350	201	172	13
	AM 355	216	181	11
Heated at 1710 F, reheated at 1375 F, and tempered 3 hours at 850 F	AM 350	195	155	11
	AM 355	195	155	10
Cold rolled and tempered 30 minutes at 850 F	AM 350	225	195	13
	AM 355	235	200	16
Refrigerated at -100 F, cold rolled, and tempered	AM 355	290	280	2

allowance must be made for the dimensional changes that occur on heat treatment.

The semiaustenitic stainless steels are weldable by the conventional fusion and resistance processes normally used for austenitic stainless steels. However, in the case of the aluminum-containing alloys (see Table 16), covered electrodes are not recommended because the flux coating does not give adequate protection to the aluminum in the steel.[30] No preheat or post-heat is required. For optimum properties, the weldment should be annealed and heat treated.

Cold-Rolled Austenitic Stainless Steels

Certain austenitic stainless steels, such as AISI 301 and 201, the compositions of which are shown in Table 19, are designed to be used as cold rolled. They are the one type of ultrahigh-strength steel that is hardened first and formed afterward. A considerable range of mechanical properties is available in these steels, depending on the degree of cold reduction used. In the soft condition, the tensile properties of these steels run 40 to 50 ksi yield strength, 100 to 115 ksi tensile strength, and 55 to 60 percent elongation in 2 inches. On the other hand, in the extra-hard rolled condition, they can attain yield strengths of 250 ksi and above. Illustrative tensile properties are shown in Tables 20 and 21. Necessarily, the available forms are limited to sheet, strip, and foil.

When these steels are heated above about 800 F, they begin to lose the strength that they had acquired from cold rolling. Therefore, in forming and shaping these steels, only cold-working operations are used. Thus, these steels are sawed or disk cut, rather than flame cut. Of course because of their great strength and low ductility, they are subjected only to the mildest forming operatings involving very generous bend radii. A common operation is roll forming. These steels can be machined; a frequent operation is drilling which can be done by using relatively slow speeds and heavy feeds with appropriate lubricants.

Limitations are inevitably placed on the welding of these steels by the forms in which they are produced and by the fact that they have been severely work hardened. Thus, only welding processes adapted to sheet and strip are used. In addition, any joint expected to have high efficiency must be so designed as to be reinforced in some way, in order to compensate for the loss in strength that unavoidably accompanies the heating produced by the welding operation. A common joint in cold-rolled austenitic stainless steel sheet is an inert-gas-shielded arc butt weld backed up with a doubler that has been attached by spot welding. Frequently used processes include inert-gas-shielded tungsten arc, inert-gas-shielded metal arc, spot welding, and seam welding.

RELIABILITY

One of the predominant themes that has pervaded the development of the ultrahigh-strength steels in recent

TABLE 19. HIGH-STRENGTH COLD-ROLLED AUSTENITIC STAINLESS STEELS

Type	Designation	C	Mn	Si	Cr	Ni
17Cr-7Ni	AISI 301[a]	0.08/0.20	2.00 max	1.00 max	16.0/18.0	6.0/8.0
Cr-Ni-Mn	AISI 201[a]	0.15 max	5.5/7.5	1.00 max	16.0/18.0	3.5/5.5

(a) Designation of the American Iron and Steel Institute.

TABLE 20. TENSILE PROPERTIES OF EXTRA-HARD TYPE 301 STEEL IN THE FORM OF 0.020-INCH SHEET[34]

	Longitudinal Direction			Transverse Direction		
Condition	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2 Inches, percent
Cold rolled 65 percent	260	244	1.5	279	241	3.8
Cold rolled 65 percent and stress relieved 8 hr at 750 F	275	265	-	300	274	-

TABLE 21. LONGITUDINAL TENSILE PROPERTIES OF FULL-HARD TYPE 201 SHEET[34]

Condition	Tensile Strength, ksi	Yield Strength, ksi	Elongation in 2 Inches, percent
As rolled	195	173	10.5
As stress relieved	215	180	7

years is the concept of reliability, i.e., the degree to which the steel performs in service in the manner expected of it and without unanticipated or premature failure. This concept, quite evidently, is vitally important in the bulk of the applications that make use of ultrahigh-strength steels.

Several factors influence reliability. One of them is the degree of reproducibility of mechanical properties from lot to lot and heat to heat of a given steel. Because the capability to reproduce such properties is far from perfect, they cannot be defined as single values but inevitably must be described in terms of a scatter band. Clearly, the narrower the scatter band the greater is the degree of reliability. In this regard, the direction of developmental effort has been toward elevating the curve delineating the scatter band's lower limit. Toward this end, producers are melting to ever narrower composition ranges using high-grade, low-impurity melting stock, and increasingly more rapid and accurate methods of analyzing the steel while it is in the process of being melted and refined.

For the same reason, they are improving the chemical homogeneity of the material. Thereby, phenomena that promote low ductility and poor toughness (such as freckles and banding) are less likely to occur. Likewise, property variations from ingot to ingot, as well as from the bottom to the top of individual ingots, are minimized. Chemical homogeneity can be influenced by ingot-making practices, homogenizing heat treatments, and ingot conversion procedures such as the use of upset forging in making forged products and cross rolling in producing flat-rolled products.

Another factor is the frequency and severity of surface and internal stress raisers in mill products. In this category are such items as nonmetallic inclusions, porosity, pipe, delaminations, splits, cracks, seams, scabs, and laps. Their presence can greatly impair, if not completely destroy, the reliability of the material. The producers are taking increasingly effective steps to reduce the number and severity of such defects and discontinuities.

The composition, size, shape, and number of nonmetallic inclusions are influenced by the quality of the charge materials, the melting and deoxidation practices, the ladle and ingot-making practices, and the ingot breakdown procedures. The presence of surface defects is strongly influenced by the procedures used to condition ingots and intermediate mill products such as blooms, slabs, and billets. Equally important are in-process and final inspection practices and equipment.

A tremendously important factor influencing reliability is toughness, i.e. the ability to absorb energy and deform plastically before fracturing. An important approach toward increasing toughness is through judicious use of alloying elements, and the employment of minimum amounts of carbon commensurate with the strengthening mechanism and the strength level desired. Another approach is through drastic reduction or elimination of detrimental elements including sulfur, phosphorus, hydrogen, oxygen, and nitrogen by using high-purity melting stock, advanced melting methods and advanced melting equipment.

For quenched and tempered steels with yield strengths up to perhaps 170 ksi or so, a commonly used criterion for toughness is the ductile-to-brittle transition temperature curve obtained by making a series of Charpy V-notch tests over the appropriate temperature range. An example of such a curve is shown in Figure 5. The material is expected to behave in a tough manner and hence with optimum reliability, in the temperature range corresponding to the upper plateau of the curve. As temperature is decreased below the range of the plateau, the behavior will be mixed or uncertain and, finally, it will be uniformly brittle. This change in behavior with temperature serves to emphasize the importance of taking service temperature into account in designing structures and selecting materials of construction.

At higher strength levels, the upper plateau of the ductile-to-brittle transition curve shifts to lower and lower values of absorbed energy until a transition is no longer discernible. In effect then, at very high strength levels, with the exact strength depending on the toughness of the particular steel, the Charpy test does not discriminate among different degrees of toughness. Under these circumstances, use is made of fracture-mechanics concepts and the basic toughness criterion that has emerged from fracture mechanics is the critical plane-strain stress-intensity factor or K_{Ic} value. This value is obtained by loading specimens containing extremely sharp notches, usually cracks intentionally produced in the specimen. Figure 6 contains some K_{Ic} data for several steels plotted as a function of yield strength.

Measurement of toughness becomes increasingly important as the strength of the steel increases, because the steel becomes increasingly sensitive to defects and discontinuities. In other words, the higher the strength of the steel, other things equal, the smaller will be the flaw required to initiate brittle fracture. In this regard, the K_{Ic} value can be used to calculate critical crack (flaw) sizes. Further information on plane-strain fracture toughness can be obtained from such reports as Reference 36.

Reliability has an additional aspect. The commentary up to this point has been directed at the reliability of the material. However, the real concern is toward the reliability of the item, the assembly, the structure, made from the material. In this regard, it is mandatory that proper design be used and proper fabrication procedures be followed in order that the reliability developed in the material of construction be realized in the completed structure. Achievement of optimum reliability in structures composed of ultrahigh-strength steels places a great deal of responsibility upon the designer, the process engineer, and the quality assurance personnel.

APPLICATIONS

From the foregoing discussion, it is clear that a host of steels has been developed that are capable of attaining ultrahigh strengths and, at the same time, are commercial materials in every sense of the word. These steels are readily produced in a variety of mill products; can be formed, joined, and heat treated by following the appropriate procedures; and are in daily use at yield strengths as high as 350 ksi.

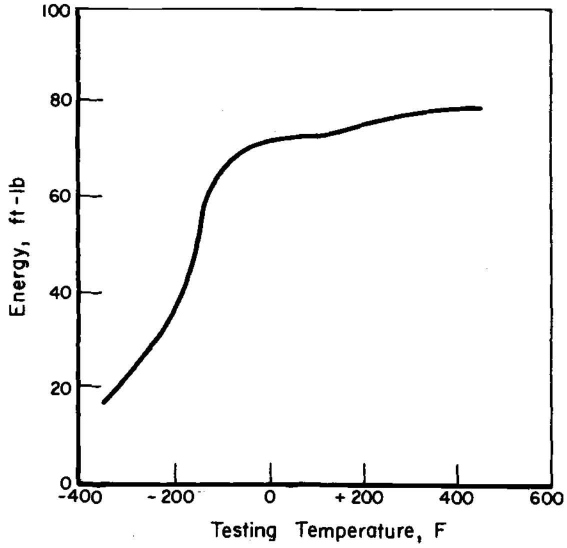

FIGURE 5. NOTCH TOUGHNESS OF FULLY MARTENSITIC AISI 4340 STEEL QUENCHED AND TEMPERED TO A YIELD STRENGTH OF 130 KSI[35]

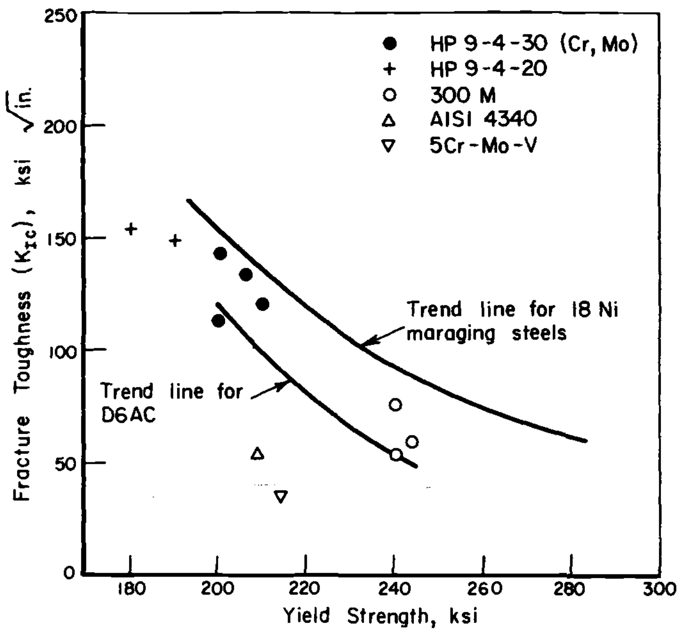

FIGURE 6. MISCELLANEOUS FRACTURE TOUGHNESS DATA FOR SOME ULTRAHIGH-STRENGTH STEELS[36]

It is axiomatic that the ultrahigh-strength steels are used where extreme strength is required or where there is an extraordinary premium on strength-to-weight ratio. The low-alloy hardenable and 5Cr-Mo-V types are used where corrosion is not a great problem, or where adequate means to protect the materials are available. Examples of such applications are solid-propellant rocket-motor cases, landing-gear components, and aircraft structural components. The 5Ni-Cr-Mo-V steel is designed for applications requiring plate that is strong, weldable, and extremely tough; illustrative applications include hulls for deep submersibles, pressure vessels, and thick-walled cylinders.

A high degree of toughness and good weldability are featured in the high-alloy steels, the maraging steels having the added advantage of a simple single-step hardening treatment that causes almost no distortion or dimensional change. Examples of applications for these steels are rocket-motor cases and pressure vessels. Applications taking advantage of the minimal dimensional changes accompanying the hardening of the maraging steels include flexible shafts, pivots, and components of equipment for precision machining. Because of their tremendous strength in compression, the maraging steels also are being used in such applications as extrusion dies, die holders, dummy blocks, and extrusion rams.

Needless to say, the stainless types are used where some inherent corrosion or oxidation resistance is desirable or needed. Generally, improvement in corrosion resistance entails some sacrifice in strength. On the other hand, when the semiaustenitic stainless steels are employed, there may be a great additional gain in ease of fabrication. Major characteristics and illustrative applications for the stainless as well as the other types of ultrahigh-strength steel are summarized in Table 22.

TABLE 22. APPLICATIONS FOR ULTRAHIGH-STRENGTH STEELS

Characteristics	Applications
Low Alloy	
Well known, moderate cost, high hardenability, fabricable and weldable.	Solid-propellant rocket-motor cases; gun tubes and breech blacks; bolts, pins, fittings and structural components far aircraft; arresting hooks for naval aircraft; axles, gears and shafts; gas storage bottles.
5Cr-Mo-V	
Air hardening, which minimizes buildup of residual stress in heat treatment; strength retained to 1000 F; high tempering temperature, which provides substantial stress relief.	Actuating cylinders; arresting gear; aircraft engine mounts and landing-gear components; shafting, bolts, pins, springs, pump camponents; fuselage frames, longerans, cargo lug supports and other structural components of aircraft.
5Ni-Cr-Mo-V	
Strong, weldable, extremely tough plate steel.	Hulls for deep submersibles; nuclear reactor components; large turbine disks; pressure vessels; thick-walled cylinders.
HP 9-4	
High degree of toughness; good weldability.	Hulls for deep submersibles; rocket-motor cases; pressure vessels; armor.
18Ni Maraging	
Can be hardened after fabrication by a single-step heat treatment that causes virtually no distortion or dimensional change; weldable; excellent fracture toughness; develops high strength even in very thick sections. High compressive strength.	Solid-propellant rocket-motor cases; forging and extrusion dies; flexible shafts; aircraft landing-gear components; die holders, dummy blocks and extrusion rams. Precision machine components.
Martensitic Stainless	
Moderate corrosion resistance; can be hardened after fabrication by a single heat treatment at moderate temperature.	Brackets, clamps, high shear rivets and bolts for aircraft; forgings and sheet metal components; engine mounts; parts for pumps and valves; camponents of papermaking machinery.
Semiaustenitic Stainless	
Corrosion resistant and readily fabricated.	Stiffeners, interior frames, bulkheads and longerons for aircraft; sandwich and honeycomb structures, skins, tanks, and ducts for aircraft; boat shafts; nuclear reactor components; skins far spacecraft; compressor disks.
Cold-Rolled Austenitic Stainless	
Moderately resistant to general-corrosion and stress-corrosion cracking; available anly as sheet, strip and fail; limited capability far fabrication and joining.	Skin for liquid fueled missiles; tanks far fuel and oxidizers; equipment for hauling food and chemicals.

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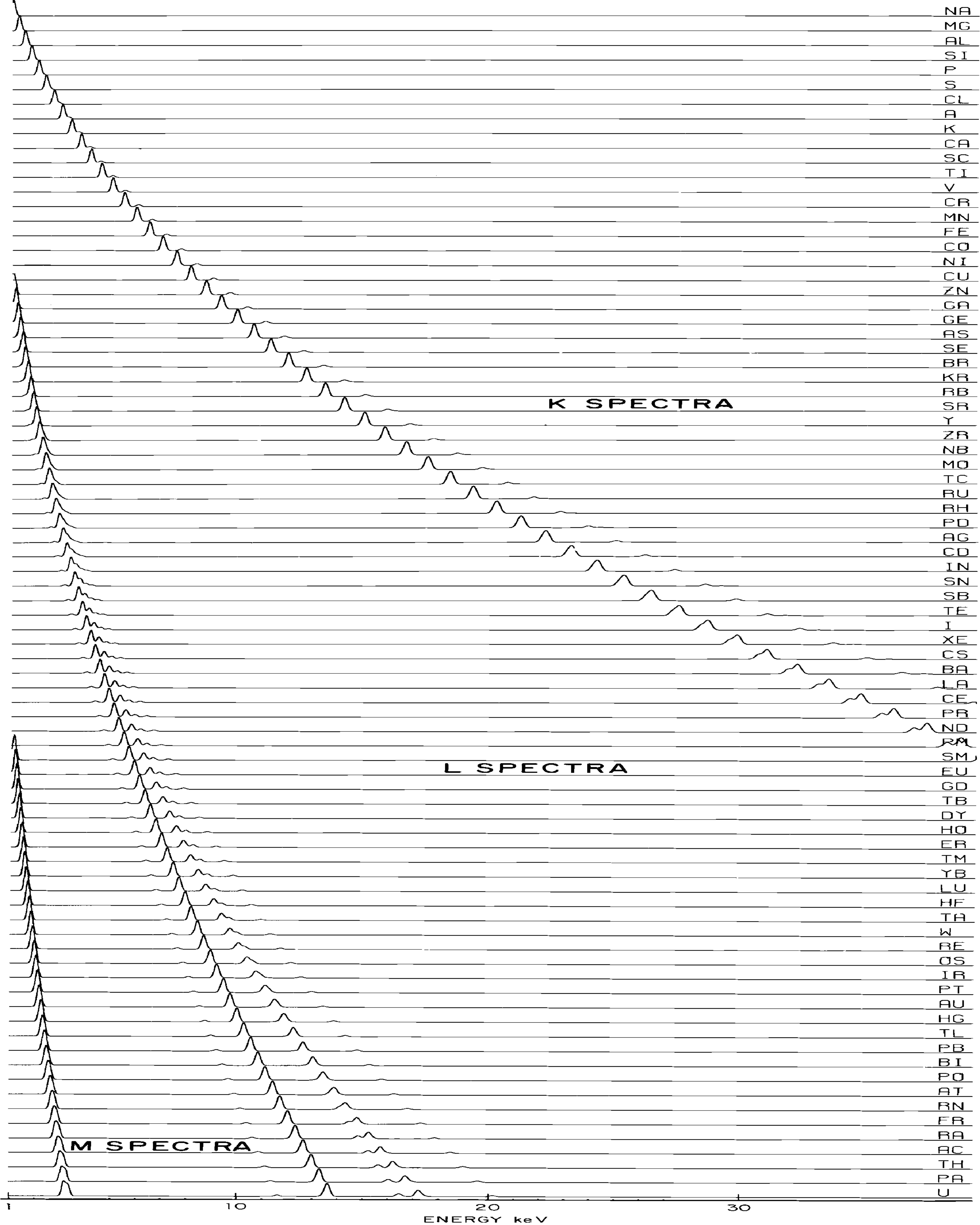

STP 485X Figure 11 — Fitzgerald