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CHROME DYES. See Azo dyes; Dyes—Application and evaluation.

CHROMIUM AND CHROMIUM ALLOYS

Chromium [*7440-47-3*] is the 21st element in the earth's crust in relative abundance, ranking with **V,** Zn, Ni, Cu, and W. With atomic number 24, it belongs to Group VIB of the periodic table whose other members are molybdenum and tungsten. Its neighbors are vanadium and manganese.

Chromium was first isolated and indentified as a metal by the French chemist, Vauquelin, in 1798 working with a rare mineral, Siberian red lead (crocoite, $PbCrO_4$). He chose to name it chromium, from the Greek word chroma meaning color, because of the wide variety of brilliant colors displayed by compounds of the new metal. An early application of chromium compounds was as pigments, particularly chrome yellow, $PbCrO_4$; basic chromium sulfate was used for tanning of hides where the reaction of chromium with collagen raises the hydrothermal stability of the leather and also renders it resistant to bacterial attack (see Leather). The most important application of chromium, namely its use as an alloying element, was gradually developed during the 19th century, mainly in France, and led to chromium steels (1–2). Their first major structural application was in the famous Eads Bridge across the Mississippi (1867–1874). Further technological developments included improved oxidation resistance and hardenability, and the superior corrosion resistance of a ferritic 12.8% chromium–iron and of austenitic alloys of 18 Cr–8 Ni variety. Chromite was employed as a furnace refractory as early as 1879 (see Chromium compounds; Pigments, inorganic; Steel).

Occurrence and Mining

The only commercial ore, chromite, has the ideal composition $FeO.Cr_2O_3$, ie 68% Cr_2O_3, 32% FeO or ca 46% chromium. Actually the Cr/Fe ratio varies considerably and the ores are better represented as $(Fe,Mg)O.(Cr,Fe,Al)_2O_3$. Table 1 gives the classification of chromite ores.

Chromite deposits occur in olivine and pyroxene type rocks and their derivatives. Geologically they appear in stratiform deposits several feet thick covering a very wide area and are usually mined by underground methods. Podiform deposits, ie, isolated lenticular, tabular, or pod-shaped bodies ranging in size from a kilogram to several million tons are mined by both surface and underground methods, depending on size and occurrence. Most chrome ores are rich enough for hand sorting. However, fines or lower-grade ores can be effectively concentrated by gravity separation methods yielding products as high as 50% Cr_2O_3 with the Cr/Fe ratio of the original ore usually unchanged (see Gravity concentration). Decreasing world supplies **(3)** of high-grade lumpy ore and increasing availability of high-grade fines and concentrates has increased the use of three agglomeration methods, *(a)* briquetting with a binder, *(b)* production of an oxide pellet by kiln firing, and *(c)* production of a prereduced pellet by furnace treatment. (For analysis, see Chromium compounds.)

Properties

The valence states of chromium are **+2, +3,** and +6, the latter two being the most common. The +2 and +3 states are basic, whereas the +6 is acidic, forming ions of the type $(CrO_4)^{2-}$ (chromates) and $(Cr_2O_7)^{2-}$ (dichromates). The blue-white metal is refractory and very hard. Its properties are listed in Table 2 (4–9).

Oxidation tests in oxygen at atmospheric pressure on a chromium specimen containing 0.04% carbon showed the formation of an oxide film 0.15 μm thick in 2 h at 700°C and **2.4** μm thick in 1 h at 900°C (7).

Chromium is highly acid resistant and is only attacked by hydrochloric, hydrofluoric, and sulfuric acids.

Mechanical Properties. Perhaps more so than any other common metal, the mechanical properties of chromium (6,7,9) depend on purity, history, grain size, strain rate, and surface condition. Most reported mechanical properties for chromium are thus those of an ill-defined dilute alloy of unique history and metallurgical condition and hence of little value for handbook quotation. More meaningful data are those reported for swaged iodide chromium as shown in Table **3.** Not only is the ductile-

Table 1. Composition of Chromite Ores[a]

Grade	Composition	Ratio Cr:Fe
metallurgical, high Cr	46% Cr_2O_3 min	>2:1[b]
chemical, high Fe	40 to 46% Cr_2O_3	1.5 to **2:1**
refractory, high Al	>20% Al_2O_3	
	>60% $Al_2O_3 + Cr_2O_3$	

[a] Ref. 2.
[b] Some South African ore of a ratio ca 1.5:1 is also used for ferrochromium production,

Table 2. Physical Properties of Chromium

Property	Value
atomic weight	51.996
isotopes, %	
50	4.31
52	83.76
53	9.55
54	2.38
crystal structure	bcc
a_0, nm	0.2844–0.2848
density at 20°C, g/cm^3	7.19
melting point, °C	1875
boiling point, °C	2680
vapor pressure, 130 Pa[a], °C	1610
heat of fusion, kJ/mol[b]	13.4–14.6
latent heat of vaporization at bp, kJ/mol[b]	320.6
specific heat at 25°C, kJ/(mol·K)[b]	23.9 (0.46 kJ/(kg·K))
linear coefficient of thermal expansion at 20°C	6.2×10^{-6}
thermal conductivity at 20°C, W/(m·K)	91
electrical resistivity at 20°C, μΩ·m	0.129
specific magnetic susceptibility at 20°C	3.6×10^{-6}
total emissivity at 100°C, nonoxidizing atm	0.08
reflectivity, R	
A, nm	300 500 1000 4000
%	67 70 63 88
refractive index	
a	1.64–3.28
A	2,5704,080
standard electrode potential, valence 0 to 3+, V	0.71
ionization potential, V	
1st	6.74
2nd	16.6
half-life of ^{51}Cr isotope, days	27.8
thermal neutron scattering cross section, m^2	6.1×10^{-28}
elastic modulus, GPa[c]	250
compressibility[a,d] at 10–60 TPa	70×10^{-3}

[a] To convert Pa to mm Hg, multiply by 0.0075.
[b] To convert J to cal, divide by 4.184.
[c] To convert GPa to psi, multiply by 145,000.
[d] 99% Cr; to convert TPa to megabars, multiply by 10.

to-brittle transition temperature (DBTT) dependent on the several variables cited above, but the potential utility of the metal is impaired by the fact that the ductility below this transition is essentially nil. To achieve measurable ductility, impurity contents should be below the following limits: O, 2000 ppm; N, 100 ppm; C, 100 ppm; H, 20 ppm; Si, 1500 ppm; S, 150 ppm.

Production

An overview of the production processes (2,4–8,10) leading to chromium metal and the various chromium compounds is shown in the simplified flow sheet of Figure 1. Very little chromite, of course, is processed all the way to ductile chromium, since

Table 3. Mechanical Properties of Room Temperature Swaged Iodide Chromium[a]

Condition	Yield strength, 0.2% offset, MPa[b]	Ultimate strength, MPa[b]	Elongation, %[c]	Reduction of area, %
wrought	362	413	44	78
recrystallized		282	0	0

[a] Pure chromium made by the iodide process.
[b] To convert MPa to psi, multiply by 145.
[c] Percent elongation in a 6 mm gage length.

most can be used in the various intermediate forms. For example, the chromite ore itself, mixed with small amounts of lime or magnesia, is made into refractory brick; ferrochrome is used directly in steel making; chrome alum is used as a mordant and in tanning leather; pigments, metal finishing agents, wood preservatives, etc, are made from sodium dichromate; and chromic acid, in addition to being the main source of chromium for electroplating, is also used for metal finishing, organic syntheses, and in the manufacture of catalysts (see Catalysis; Electroplating; Metal surface treatment).

Ferrochrome. Ferrochrome is usually made by reduction of chromite with coke in a three-phase electric submerged arc furnace. This process leads inevitably to a high-carbon ferrochrome [*11114-46-8*] whose use was formerly restricted to high-carbon steels. With increasing use of argon-oxygen decarburization (AOD) and similar processing of alloy and stainless steels, this limitation is less severe (10). Care is taken to keep sulfur low as it embrittles both Cr metal and the Fe–Ni and Ni-base alloys to which Cr is added.

Low-carbon ferrochromes cannot be made by carbonaceous reduction unless accompanied by top blowing with oxygen. Aluminum, or especially silicon, is frequently used as the reducing agent. When silicon is employed, high-silicon ferrochrome, practically carbon-free, is first produced in a submerged arc furnace, and then treated in an open arc-type furnace with a synthetic slag containing Cr_2O_3. A ferrochromium of very low carbon content (0.01%) is produced in a solid-state process by heating high-carbon ferrochrome with oxidized ferrochrome in a high vacuum with the carbon removed as carbon monoxide (Simplex process). In the other smelting processes the molten ferrochrome is tapped from the furnace, cast into chills, broken into lumps, and graded.

The compositions of several different grades of ferrochrome are given in Table 4.

Chromium Metal by Pyrometallurgical Reduction. The principal pyrometallurgical process for commercial chromium metal is the reduction of Cr_2O_3 by aluminum.

$$Cr_2O_3 + 2\,Al = 2\,Cr + Al_2O_3$$

The chromium oxide is mixed with aluminum powder and placed in a refractory-lined vessel and ignited with barium peroxide and magnesium powder. The reaction is exothermic and self-sustaining. Chromium metal of 97–99% purity is obtained, the chief impurities being aluminum, iron, and silicon (carbon, sulfur, and nitrogen are about 0.03, 0.02, and 0.045%, respectively).

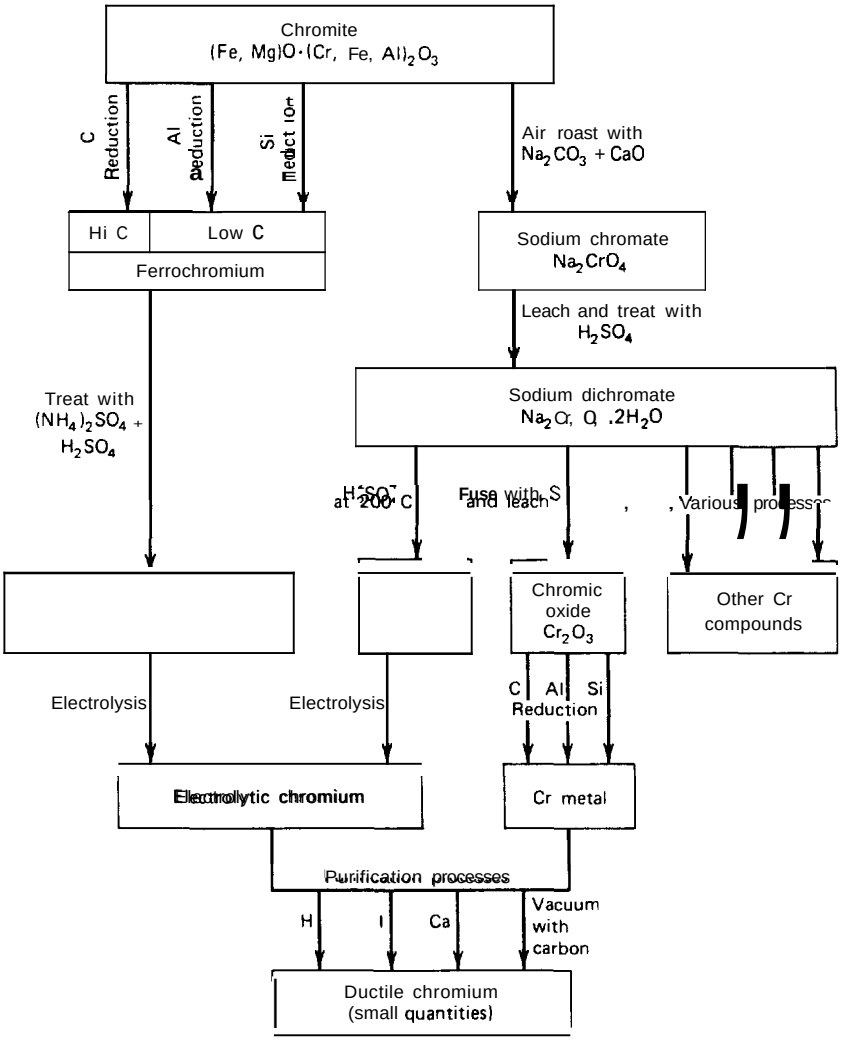

Figure 1. Simplified **flow** chart for the production of metallic chromium and chromium compounds **from** chromite.

Commercial chromium metal may also be produced from the oxide by reduction with silicon in an electric arc furnace.

$$2\,Cr_2O_3 + 3\,Si = 4\,Cr + 3\,SiO_2$$

The product is similar to that obtained by the aluminothermic process; however, the aluminum content is lower and silicon may run as high as 0.8%.

The oxide may also be reduced with carbon at low pressure.

$$Cr_2O_3 + 3\,C = 2\,Cr + 3\,CO$$

Briquets of mixed, finely divided oxide and carbon are heated to 1275–1400°C in a refractory container. The minimum pressure is about 40 Pa **(0.3** mm Hg) for reduction at 1400°C. Lower pressures or higher temperatures cause excessive volatilization of

Table 4. Composition of Typical Ferrochromium Alloys and Chromium Metal,[a] Percent of Principal Constituent[b]

Grade	Chromium	Silicon	Carbon	Sulfur[c]	Phosphorus[c]	Other
ferrochromium						
high-carbon	66–70	1–2	5–6.5	0.04	0.03	
high-carbon, high-silicon						
blocking chrome	55–63	8–12	4–6	0.03		
exothermic ferrochrome	41–51	9–14	3.6–6.4	0.03		
foundry ferrochrome	55–63	8–12	4–6			
refined chrome	53–63	2.5[c]	3–5	0.03		
SM ferrochrome	60–65	4–6	4–6			4–6 manganese
charge chromium						
50–55 percent chromium	50–56	3–6	6–8	0.04	0.03	
66–70 percent chromium	66–70	3[c]	5–6.5	0.04	0.03	
low-carbon:						
0.025 percent carbon	67–75	1[c]	0.025[c]	0.025	0.03	
0.05 percent carbon	67–75	1[c]	0.05[c]	0.025	0.03	
Simplex	63–71	2.0[c]	0.01 or 0.025			
ferrochromium–silicon:						
36/40 grade	35–37	39–41	0.05[c]			
40/43 grade	39–41	42–45	0.05[c]			
chromium metal						
electrolytic	99.3[d]	0.01[c]	0.02[c]	0.03		0.5 oxygen[c] 0.05 nitrogen[c]
aluminothermic	99.3[d]	0.15[c]	0.05[c]	0.015	0.01	0.2 oxygen[c] 0.3 aluminum[c]

[a] Ref. 2.
[b] Difference between sum of percentages shown and 100 percent is chiefly iron content.
[c] Maximum.
[d] Minimum.

chromium. The product contains about 0.02% silicon, less than 0.03% iron, and 0.015% carbon, 0.001% nitrogen, and 0.04% oxygen.

Electrowinning of Chromium. ***Chrome Alum Electrolysis.*** The Union Carbide Corporation's Metals Division Plant at Marietta, Ohio, is a typical chrome–alum plant with a capacity of 2000 net metric tons per year.

In this process (see Fig. 2), high-carbon ferrochromium is leached with a hot solution of reduced anolyte plus chrome alum mother liquor and makeup sulfuric acid. The slurry is then cooled to 80°C by the addition of cold mother liquor from the ferrous ammonium sulfate circuit, and the undissolved solids, mostly silica, are separated by filtration. The chromium in the filtrate is then converted to the nonalum form by several hours' conditioning treatment at elevated temperature.

Ammonium chrome alum, $NH_4Cr(SO_4)_2.12H_2O$, exists in a violet and a green modification. Their properties are quite different with regard to conductivity, solubility, and ionization. Above 50°C, the green complex is more stable; at room temperature it changes slowly to the violet form with a change in pH. In solutions of ammonium chromium alum, the chromium **(111)** ion can exist in a variety of forms, depending on time, temperature and past conditions. At higher temperatures, a variety of green nonalum ions such as $[Cr(H_2O)_5\text{–}SO_4]^+$, $[Cr(H_2O)_5(OH)]^{2+}$, and $[(SO_4)\text{-}(H_2O)_4Cr\text{–}O\text{–}Cr(H_2O)_5]^{2+}$ form, whereas the violet hexaquo ion $[Cr(H_2O)_6]^{3+}$ predominates in cool, dilute solutions of moderate acidity. It is only the latter which permits crystallization of the desired ammonium chromium alum.

Once the green, "non-alum" forms of the chromium ion have formed, their revision to the hexaquo form on cooling is sufficiently slow that on chilling to 5°C, a crude ferrous ammonium sulfate can be crystallized, removing nearly all the iron from the system. This crude iron salt is treated with makeup ammonium sulfate, heated again to retain the chromium impurities in the green noncrystallizable form, and then cooled to separate the bulk of the iron as a technical ferrous ammonium sulfate which is sold for fertilizer and other purposes. The mother liquor from this crystallization is returned to the filtration step.

The mother liquor from the crude ferrous sulfate crystallization contains nearly all the chromium. It is clarified and aged with agitation at **30°C** for a considerable period to reverse the reactions of the conditioning step. Hydrolysis reactions are being reversed; therefore, the pH increases. Also, sulfate ions are released from complexes and the chromium is converted largely to the hexaquo ion, $[Cr(H_2O)_6]^{3+}$. Ammonium chrome alum precipitates as a fine crystal slurry. It is filtered and washed and the filtrate sent to the leach circuit; the chrome alum is dissolved in hot water, and the solution is used as cell feed.

The principal electrolytic cell reactions are shown in Figure **3.** A diaphragm-type cell prevents the sulfuric acid and chromic acid formed at the anode from mixing with the catholyte and oxidizing the divalent chromium. Electrolyte is continuously fed to the cells to maintain the proper chromium concentration. The catholyte pH of each is controlled by adjusting the amount that flows through the diaphragms into the anolyte compartments. Control of the pH between narrow limits governs the successful electrodeposition of chromium as well **as** the preservation of divalent chromium at the cathode.

The analyses of the solutions in the electrolytic circuit and cell operating data are given in Tables 5 and 6, respectively. The current efficiency of **45%** shown in Table **6** includes low efficiencies that always prevail during the startup of a reconditioned

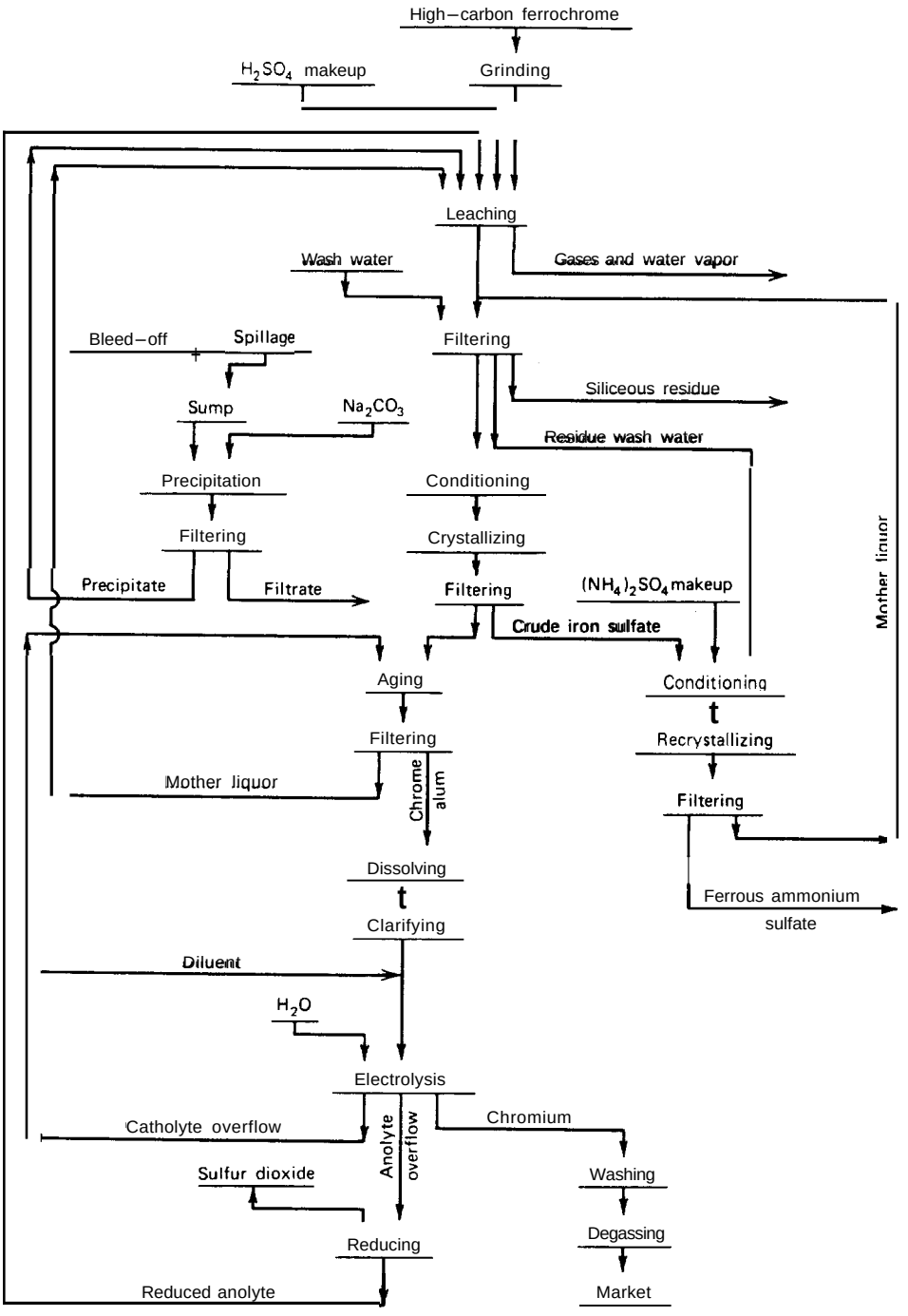

Figure 2. **Flow** sheet for production **of** electrolytic chromium **by** the chrome alum process. Marietta Plant, Union Carbide Corporation, Marietta, Ohio.

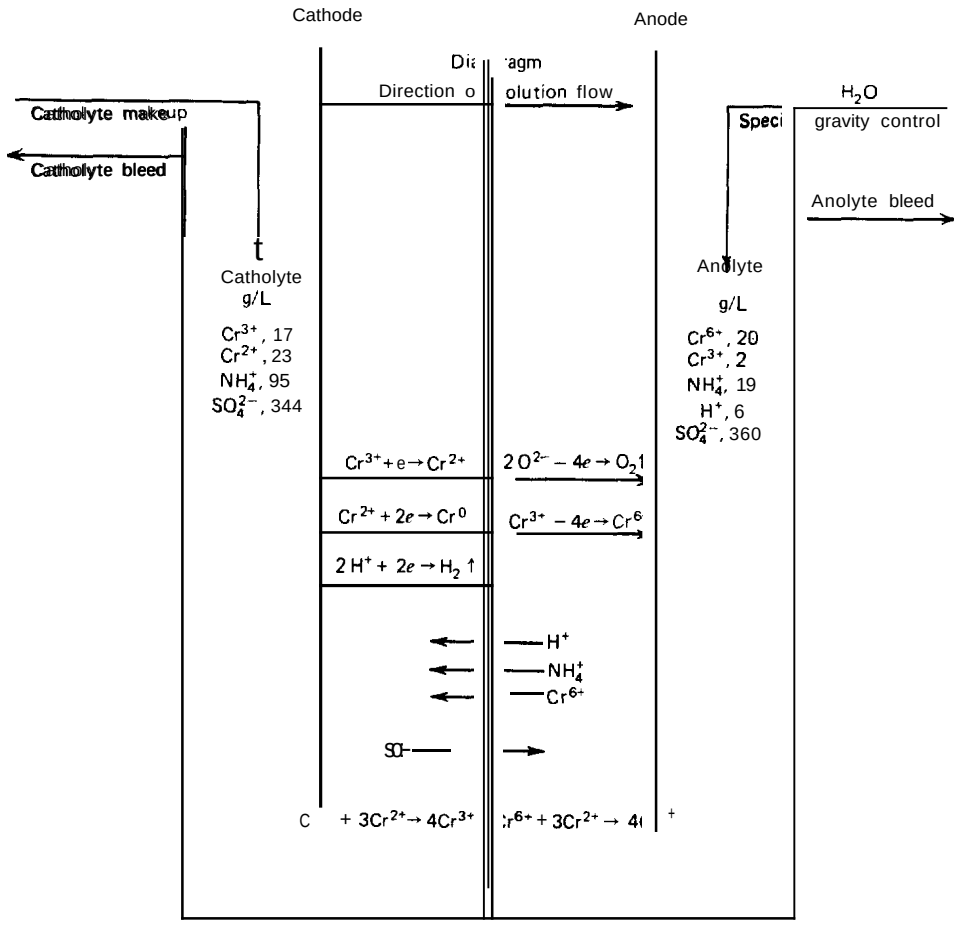

Figure 3. Principal electrolytic cell reactions in chromium production by the chrome alum process.

Table 5. Typical Analyses of Solutions in Electrolysis of Chrome Alum, g/L

	Total Cr	Cr^{6+}	Cr^{3+}	Cr^{2+}	Fe	NH_3	H_2SO_4
cell feed	130	0	130	0	0.2	43	3
circulating mixture	65	0	63	2	0.1	68	1
catholyte	24	0	11.5	12.5	0.035	84	
anolyte	15	13	2	0	0.023	24	280

cell. The 2.1–2.4 pH range used in the plant also results in a somewhat lower current efficiency but provides a safe operating latitude.

At the end of the 72-h cycle, the cathodes are removed from the cells, washed in hot water, and the brittle deposit (3-6 mm thick) is stripped by a series of air hammers. The metal is then crushed by rolls to 50 mm size and again washed in hot water. The metal contains about 0.034% hydrogen and, after drying, is dehydrogenated by heating

Table 6. Operating Data for Electrowinning of Chromium from Chrome Alum

cathode current density, A/m^2	753
cell potential, V	4.2
current efficiency, %	45
electrical consumption, MJ/kg[a]	67
pH of catholyte	2.1–2.4
catholyte temperature, °C	53 ± 1
deposition time, h	72
cathode material	Type 316 stainless steel
anode material, wt %	1–99 Ag–Pb

[a] To convert J to cal, divide by 4.184.

to at least 400°C in stainless steel cans. A typical product composition is shown below:

chromium	99.8%	sulfur	0.025%	oxygen	0.50%	silicon	0
iron	**0.14%**	copper	0.01%	hydrogen	0.004%	phosphorus	0
carbon	0.01%	lead	0.002%	nitrogen	0.01%	manganese	0
						aluminum	0

Chromic Acid Electrolysis. The chromic acid, CrO_3, is obtained from sodium dichromate (see Chromium compounds). Small amounts of an ionic catalyst, specifically sulfate, chloride, or fluoride, are essential. Fluoride and complex fluoride catalyzed baths have become especially important in recent years. The cell conditions for the chromic acid process are given in Table 7.

The low current efficiency of this process is due to the evolution of hydrogen at the cathode; this occurs because the hydrogen deposition overvoltage on chromium is significantly more positive than that at which chromous ion deposition would be expected to commence. This hydrogen evolution at the cathode surface also increases the pH of the catholyte beyond 4 which may result in the precipitation of $Cr(OH)_3$ and $Cr(OH)_2$, causing a partial passivation of the cathode and a reduction in current efficiency. The latter is also inherently low, as six electrons are required to reduce hexavalent ions to chromium metal.

Plating variables for this process may be summarized as follows: Higher operating temperatures (87°C) enable the oxygen content of the metal to be reduced to 0.01%; The ratio CrO_3:SO_4 should be below 100 to obtain low-oxygen metal; Current efficiencies greater than 8% are associated with high oxygen contents; Better current efficiencies are obtained at low current densities.

The metal obtained by this process contains less iron and oxygen than that from

Table 7. Cell Conditions for Chromic Acid Process for Electrowinning of Chromium[a]

bath composition, g/L	300 CrO_3, 4 sulfate ion
temperature, °C	84–87
current density, A/m^2	9500
current efficiency, %	6–7
plating time, h	80–90
production rate, g/week	1000

[a] From Ref. 6.

the chrome alum electrolyte. The gas content is 0.02% O, 0.0025% N, and 0.009% H. If desired, the hydrogen content can be still further lowered by a dehydrogenation treatment.

Purification. The metal obtained from both electrolytic processes contains considerable oxygen, which is believed to cause brittleness at room temperature. For most purposes the metal as plated is satisfactory. However, if ductile metal is desired, the oxygen can be removed by hydrogen reduction, the iodide process, calcium refining, or melting in a vacuum in the presence of a small amount of carbon.

In the hydrogen reduction process the electrolytic metal is heated to about 1500°C in a closed-circuit stream of dry, pure hydrogen. Although this process reduces the oxygen content considerably and the nitrogen content somewhat less so, it has little effect on the other impurities. A typical product from this process might contain 0.005 wt % oxygen and 0.001 wt % nitrogen.

In the iodide purification process (Van Arkel process) the impure chromium and iodine are sealed in an evacuated bulb containing an electrically heated wire. The bulb is heated to the temperature of formation of chromium(III) iodide. This chromic iodide reacts with more of the impure metal to form chromium(II) iodide which diffuses to the hot wire where it decomposes and deposits chromium. The freed iodine forms additional chromous iodide, and the process continues (cyclic process). Iodination at 900°C and decomposition at 1000–1300°C may also be carried out separately (straight-flow process), but with lower efficiency. The analyses of metal treated by iodide purification showed 0.0008% oxygen, 0.003% nitrogen, 0.00008% hydrogen, and 0.001% carbon; the other impurities were very low. This metal is produced by the Chromalloy Corporation under the trade name Iochrome.

In the calcium refining process the chromium reacts with calcium vapor at about 1000°C in a titanium-lined bomb which is first evacuated and then heated to the proper temperature. A pressure of about 2.7 Pa (20 μm Hg) is maintained during heating until the calcium vapor reaches the cold end of the bomb and condenses. This allows the calcium vapor to pass up through the chromium metal where it reacts with the oxygen. Metal obtained by this process contained 0.027% oxygen, 0.0018% nitrogen, 0.008% carbon, 0.012% sulfur, and 0.015% iron.

Carbon purification is accomplished by addition to the melt or to the solid charge before melting. Melting is carried out in vacuum and completion of the deoxidation process is observed by a rapid pressure drop indicating when the evolution of CO is complete.

The vacuum melting process can upgrade chromium at a modest cost; the other purification processes are very expensive. Thus iodide chromium is about 100 times as expensive as the electrolytic chromium and, therefore, is used only for laboratory purposes or special biomedical applications.

Consolidation and Fabrication. Chromium metal may be consolidated by powder metallurgy techniques or by arc melting in an inert atmosphere (5,7,11–12).

For powder metal consolidation the metal is first ball-milled using chromium-plated balls. The powder is then pressed at 300–500 MPa (3000–5000 atm) with or without a binder such as a wax; the binder is then removed by heating to about 300°C before sintering. The sintering operation which follows is carried out at high temperatures, 1450–1500°C, in a slow stream of purified hydrogen, helium, or argon. Sometimes sintering and purification *can* be combined, and in this case a large volume of purified hydrogen is needed to ensure adequate oxygen removal.

In a chemical vapor deposition (CVD) variant of conventional powder metallurgy processing, fine chromium powder is obtained by hydrogen reduction of CrI_2 and simultaneously combined with fine ThO_2 particles (see under Chromium-based alloys). This product is isostatically pressed to 70 MPa (700 atm) and 1100°C for 2 h. Compacts are steel clad and hot rolled to sheets (11).

Vacuum melting of chromium must take place in highly refractory crucibles such as pure zirconia, beryllia, or alumina lined with thoria. Under proper conditions, the nitrogen content of chromium-base alloys can be lowered to 0.01% or less, and carbon can be used as a deoxidizer to obtain alloys with 0.01% carbon and oxygen. Volatilization of some chromium is a drawback in this process. Arc melting into a water-cooled copper mold in an inert atmosphere has been successfully used for chromium and has the advantage that no refractory material comes in contact with the molten metal. The chromium must be given an oxygen purification before melting if low-oxygen material is required. It is claimed that addition of a small amount of yttrium or other rare earth element during melting to act as a scavenger improves the workability and mechanical properties.

The initial cast structure of arc melted ingots must be carefully broken down by hot working in order to permit subsequent warm working. Forging, swaging, and extrusion are all possible, with ease of working increasing from forging to extrusion, and particularly with hydrostatic extrusion. Hot working usually takes place in a steel or stainless sheath to protect the metal from contamination and this sheath is later removed by acid dissolution on completion of the working. The working process seems to make the material more ductile over and above benefits resulting from break-up of the as-cast structure (12). Electropolishing is often used to further improve the apparent ductility of sheet and wire samples. Elimination of the surface layer in this way removes any air-contaminated layer of chromium and also minimizes the effects of any notches.

Electroplating, Chromizing, and other Chromium-Surfacing Processes

Electroplating of chromium (13,1617) on various substrates is practiced in order to realize a more decorative and corrosion or wear-resistant surface. About 80% of the chromium employed in metal treatment is used for chromium plating; over 50% is for decorative chromium plating. Hard chromium plating differs from decorative plating mostly in terms of thickness. Hard chromium plate may be 10 to several 100 μm thick, whereas the chromium layers in a decorative plate may be as little as 0.25 μm or about 2 g Cr/m^2 of surface. Hard plating is noted for its excellent hardness, wear resistance, and low coefficient of friction. Decorative chromium plating retains its brilliance because air exposure immediately forms a thin, invisible protective oxide film. The chromium is not applied directly to the surface of the metal but rather over a nickel plate which in turn is laid over a copper plate. Since the chromium plate is not free of cracks, pores, and similar imperfections, the intermediate nickel layer must provide the basic protection. Indeed, optimum performance is obtained when a controlled but high density of microcracks in the chromium is achieved (40–80 microcrack intersections per linear millimeter) leading to reduced local galvanic current density at the imperfections and increased cathode polarization. Modern practice uses a duplex nickel layer containing a small amount of sulfur. In addition to the familar applications of chromium plate in the automotive and plumbing fields, it has recently been introduced

as a substitute for tin plate on steel for canning purposes. Since 1926, commercial chromium plating has used **a** chromic acid bath (Cr^{6+}) to which various catalyzing anions have been added. Currently much attention is being given the development of trivalent plating baths (see Electroplating).

Chromizing (16) is the other principal method of obtaining a chromium-rich surface on steel. The material to be treated is embedded in a mixture of ferrochrome powder, a chromium halide, alumina, and sometimes NH_4Cl. The chromium is diffused in by a furnace treatment at about 1100°C to produce an effective stainless steel surface whose mean composition is about 18%Cr and whose thickness is controlled by the time of treatment. This is an economical process improving the corrosion resistance of steel parts where cut edges and appearance are not important considerations, eg, automotive exhausts, heat exchangers, and silos.

Other surface processes (16) using chromium include sputtering, ion implantation, chemical vapor deposition, metal spraying, cladding, and weld overlayment. Only the latter two have commercial significance. Stainless clad steel (single- or double-faced) has been prepared, for more than 40 years, by hot rolling a duplex or triplex metal sandwich. It is an attractive means of conserving expensive stainless steel. Weld overlayment is used where clad is not available or unreliable or where wear resistance is an important consideration. Flame and arc welding are both practiced. The most popular alloys deposited are the Co–Cr based Stellites and similar compositions, but chromium carbides and oxides can also be deposited (see Metal surface treatments).

Economic Aspects

During much of the 19th century, the U.S. was the principal world producer of chromite when deposits in Maryland, Pennsylvania, and Virginia were exploited. However, today the United States is completely dependent on imports from the USSR, South Africa, Turkey, and Rhodesia.

The general features of the supply and demand relationships for the U.S. are shown in Figure **4.** It does not, however, show that in the past **5** to 10 years the import to the U.S. (as well as to other highly developed countries) has shifted from chromite to ferrochrome as countries with low-cost energy and natural resources have installed the furnace capacity to convert the ore to ferrochrome. Since supply routes from the eastern hemisphere sources are long and world political problems pose a constant threat of interruption of supply, chromium consuming industries have been forced to maintain large stocks.

The distribution of chromium consumption in the U.S. by physical form is shown in Table 8 and detailed breakdown of consumption areas in Table 9. Growth has been modest over the past two decades with few changes in the consumption pattern. A recent study (2) has projected a **3.4%** growth in U.S. chromium consumption leading to a total U.S. primary chromium demand in the year 2000 of 1,000,000 metric tons. Stainless steels dominate all other classes of chromium use since chromium is absolutely essential to the production of stainless steel. It is unlikely that research will lead to the development of a chromium-free stainless steel. In view of the importance of stainless steel to today's industrial economy and the fact that substitute materials increase cost or impair performance, U.S. vulnerability resulting from the near monopoly control of chromite by Soviet and African sources is extreme. The price of Soviet

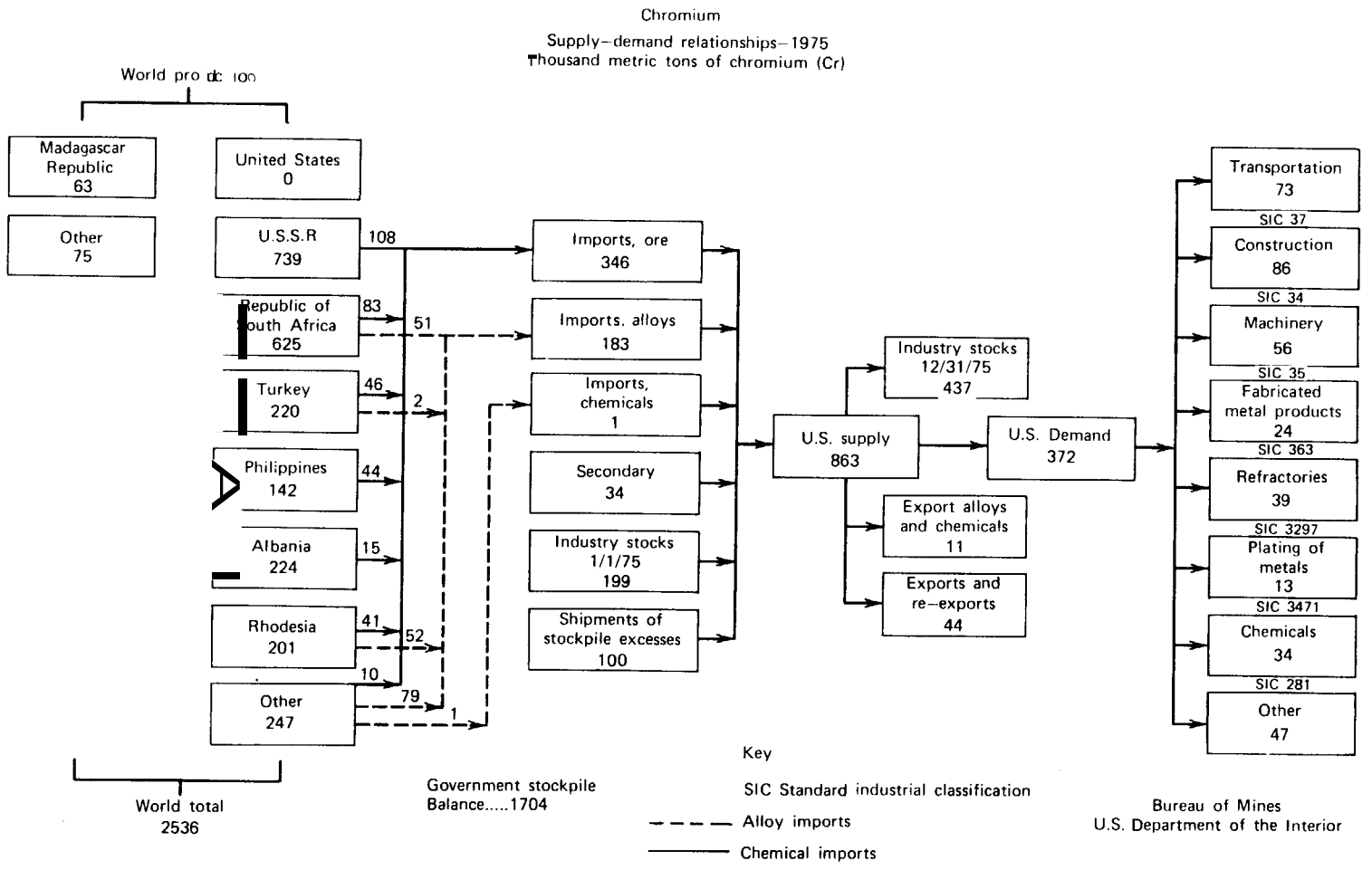

Figure 4. Supply and demand relationships for chromium in the United States in 1975 (2).

Table 8. Chromium Consumption in the United States[a]

	Contained chromium, 1000 metric tons		% of total[b]	
	1964	1976	1964	1976
metal production				
high-carbon ferrochrorne	75	144	21	44
low-carbon ferrochrorne	94	49	27	15
ferrochrome silicon	29	24	8	7
other	9	a	3	2
Total	*207*	*225*	*59*	68
refractories	103	44	29	13
chemicals	41	58	12	18
Grand total	*351*	*327*	*100*	*100*

[a] From ***Minerals Yearbook,*** 1964 and 1976.
[b] Totals may not add due to rounding.

chromite approximately tripled between 1974 and 1977 after having been virtually constant for many years.

Prices for ferrochromium depend on both size and chromium and carbon content. In the United States requirements for air pollution controls have increased costs. It has been estimated that during the 1970–1974 period, **60%** of new investment dollars in the domestic ferroalloy industry was spent on pollution control equipment rather than for increased capacity of new furnaces (2,10).

CHROMIUM ALLOYS

In addition to inorganic compounds of chromium, important as pigments and tanning agents, and certain organic compounds used in greases, catalysts and plastic compounding agents, there are a number of metallic compounds of chromium significant either in their own right or as metallurgical constituents in Cr-bearing alloys. The carbide Cr_3C_2 is important as a wear-resistant gage material, CrB for oil-well drilling, and $Cr_xMn_{2x}Sb$ as a magnetic material with unique characteristics. The intermetallic compounds Cr_3Al, Cr_3Si, and Cr_2Ti are encountered in developmental oxidation-resistant coatings. $Cr_{23}C_6$, Cr_7C_3, CrFe (a phase), and $Cr_{12}Fe_{36}Mo_{10}$ (χ phase) are found as constituents in many alloy steels and $CrAl_7$ and CoCr in aluminum and cobalt-based alloys. The chromium-rich interstitial compounds (Cr_2H, Cr_2N, $Cr_{23}C_6$) play an important role in the effect of trace impurities on the properties of unalloyed chromium. The intermetallic and the interstitial compounds of chromium are stabilized by electronic and/or spatial factors and are not to be regarded as simple ionic or covalent compounds.

Chromium-Based Alloys

Alloying has not solved the problem of resistance to gaseous embrittlement. Alloying with yttrium improves the resistance to embrittlement by high-temperature exposure to oxygen but not to nitrogen-bearing atmospheres, and a barrier coating approach must be used. Furthermore, although solid solution additions can improve high temperature strength by three- to four-fold over unalloyed chromium, these have

Table 9. U.S. Chromium Consumption Pattern in 1977

	Quantity consumed[a], (thousand metric tons)	Fraction of U.S. consumption*, %
metallurgical		
wrought stainless and heat resisting steels	210	51.3
tool steels	5	1.3
wrought alloy steels	39	9.5
cast alloy steels	13	3.1
alloy cast irons	7	1.8
nonferrous alloys	13	3.1
other	5	1.3
Total	*292*	*71.5*
refractories		
chrome and chrome-magnesite	9	2.2
magnesite-chrome brick	13	3.1
granular chrome-bearing	24	6.0
granular chromite	9	2.2
Total	55	*13.5*
chemicals		
pigments	16	4.0
metal finishing	14	3.3
leather tanning	10	2.4
drilling muds	3	0.7
wood treatment	4	0.9
water treatment	4	0.9
chemical manufacture	5	1.1
textiles	2	0.4
catalysts	<1	<0.3
other	5	1.1
Total	*64*	*15.0*
Grand total	*411*	*100*

[a] Exclusive of scrap.
[b] Totals may not add due to rounding.

also resulted in increases in the ductile-to-brittle transition temperature (DBTT). A better combination of properties has been achieved through precipitation or dispersion hardening. The second phases may be oxides, carbides, or borides.

It appears that nitrogen embrittlement is the result of dislocation pinning by the presence of small Cr_2N particles on certain crystallographic planes rather than by elemental nitrogen retained in solid solution. On the other hand, the improvement of ductility experienced with oxide, carbide, or boride particles is apparently achieved through the generation and multiplication of free dislocations by one of several hypothesized mechanisms. Chromium–thorium oxide dispersions prepared by CVD (see under Consolidation and Fabrication) have been found not only to lower the DBTT relative to unalloyed chromium but largely to preserve this improvement even after a 1 hour anneal at 1200°C (11). Silicides (9), rare earths (Y and Y + La) (9), and a Cu–30Pd alloy (18) seem to improve protection against nitrogen embrittlement (100–200h at 1150°C). The leading developmental chromium-based alloys are shown in Table 10. Creep rupture results indicate a temperature advantage of 110–140°C

Table 10. Leading Developmental Chromium Based Alloys

Country	Common name	Composition, wt %
United States	c-207	Cr–7.5W–0.8Zr–0.2Ti–0.1C–0.15Y
	CI-41	Cr–7.1Mo–2Ta–0.09C–0.1(Y + La)
	IM-15	Cr–1.7Ta–0.1B–0.1Y
	Chrome-30	Cr–6MgO–0.5Ti
	Chrome-90	Cr–3MgO–2.5V–0.5Si
	Chrome-90S	Cr–3MgO–2.5V–1Si–0.5Ti–2Ta–0.5C
	CVD-Cr	Cr–3ThO_2
Australia	Alloy E	Cr–2Ta–0.5Si–0.1Ti
	Alloy H	Cr–2Ta–0.5Si–0.5RE
	Alloy J	Cr–2Ta–0.5Si
Soviet Union	VKh-1I	Cr–(0.3–1.0Y)–0.02C
	VKh-2	Cr–(0.1–0.35)V–0.02C
	VKh-2I	Cr–(0.3–1.0)Y–(0.1–0.35)V–(0.1–0.2Ti)–0.02C
	VKh-4	Cr–32Ni–1.5W–0.3V–0.2Ti–0.08C

over the strongest superalloys with 100-h stress-rupture strengths as high as 140 MPa (20,300 psi) at 1150°C. Further improvements in low-temperature toughness and high-temperature nitridation resistance are still needed.

Stainless Steels (1,5,20–21,23–27)

The stainless quality is conferred on steels if they contain enough chromium to form a protective surface film. About 12 wt % chromium is required for protection in mild atmospheres or in steam. With 18–20 wt % chromium, sufficient protection is achieved for satisfactory performance in a wide variety of more destructive environments, including those occurring in the chemical, petrochemical, and the power-generating industries. Stainless grades with 25 wt % chromium or more and containing other alloying elements such as molybdenum provide even higher corrosion resistance. In certain stainless steels, chromium depresses martensite transformation below room temperature; by thus stabilizing austenite it permits achievement of desired mechanical properties without loss of corrosion resistance (see Steel).

Stainless steels are classified in terms of their microstructures as austenitic, martensitic, ferritic, duplex (austenite + ferrite), and precipitation hardening (PH). The microstructure type is determined by base composition and heat treatment and, in turn, dictates the properties, especially strength, toughness, and corrosion resistance. The compositions of the leading stainless steels are shown in Tables 11–17 and the major groupings are illustrated diagramatically in Figure 5. Since most stainless steels are based on the Fe–Cr–Ni system, their relationships are conveniently interpreted in reference to the metastable phase diagram for such alloys with a carbon content of 0.1%, rapidly cooled from 1000°C as shown in Figure 6. Table 18 shows the relative production of the various stainless grades (19).

The *austenitic* stainless steels have won wide favor because of their outstanding corrosion and oxidation resistance coupled with good formability. They cannot, however, be hardened by heat treatment which, in certain types, may impair corrosion resistance by allowing precipitation of chromium carbide near the grain boundaries (sensitization) and hence local impoverishment in chromium. Variants of the basic

Table 11. Austenitic Grades of Stainless Steels

UNS[a] no.	AISI[b] type	Max C, %	Max Mn, %	Max Si, %	Cr, %	Ni, %	Other[c], %
S20100	201	0.15	7.50	1.00	16.0–18.0	3.5–5.5	0.25 max N
S20200	202	0.15	10.00	1.00	17.0–19.0	4.0–6.0	0.25 max N
S30100	301	0.15	2.00	1.00	16.0–18.0	6.0–8.0	
S30200	302	0.15	2.00	1.00	17–19	8–10	
S30215	302B	0.45	2.00	3.00	17–19	8–10	
S30300	303	0.15	2.00	1.00	17–19	8–10	0.15 min S
S30323	303Se	0.15	2.00	1.00	17–19	8–10	0.15 min Se 0.20 max P, 0.060 max S
S30400	304	0.08	2.00	1.00	18–20	8–12	
S30403	304L	0.03	2.00	1.00	18–20	8–12	
S30500	305	0.12	2.00	1.00	17–19	10–13	
S30800	308	0.08	2.00	1.00	19–21	10–12	
S30900	309	0.20	2.00	1.00	22–24	12–15	
S30908	309S	0.08	2.00	1.00	22–24	12–15	
S31000	310	0.25	2.00	1.50	24–26	19–22	
S31008	310S	0.08	2.00	1.50	24–26	19–22	
S31400	314	0.25	2.00	3.00	23–26	19–22	
S31600	316	0.08	2.00	1.00	16–18	10–14	2.0–3.0 Mo
S31603	316L	0.03	2.00	1.00	16–18	10–14	2.0–3.0 Mo
S31700	317	0.08	2.00	1.00	18–20	11–15	3.0–4.0 Mo
S32100	321	0.08	2.00	1.00	17–19	9–12	5XC min Ti
S34700	347	0.08	2.00	1.00	17–19	9–13	10XC min Nb + Ta
S34800	348	0.08	2.00	1.00	17–19	9–13	10XC min Nb + Ta; 0.10 max Ta

[a] Unified Numbering System (22).
[b] American Iron and Steel Institute.
[c] Except as noted all have 0.045 max P; 0.030 max S.

Table 12. New Proprietary Mn–N-Rich Austenitic Stainless Steels

o	(former)	Typical Composition, %					
		C	Mn	Cr	Ni		
S24000	Nitronic 33 (18–3 Mn)	0.03	12.0	18.0	3.2	0.32	
S21904	Nitronic 40 (21–6–9)	0.03	9.0	21.0	7.0	0.30	
S20910	Nitronic 50 (22–13–5)	0.04	5.0	21.2	12.5	0.30	2.2 Mo, 0.2 Cb, 0.2 V
S21400	USS Tenelon (XM–31)	0.10	15.0	18.0		0.40	
S21460	Cryogenic Tenelon (XM–14)	0.10	15.1	17.5	5.5	0.42	
S21600	AL 216 (XM–17)	0.06	8.3	20.0	6.0	[illegible]	[illegible]

Table 13. Martensitic or Hardenable Grades of Stainless Steel

no.	type	C, %	Max Mn, %	Max Si, %	Cr, %	Ni; %	Other[a], %
S40300	403	0.15 max	1.00	0.50	11.5–13.0		
S40500	405	0.08 max	1.00	1.00	11.5–14.5		0.10 to 0.30 Al
S41000	410	0.15 max	1.00	1.00	11.5–13.5		
S41400	414	0.15 max	1.00	1.00	11.5–13.5	1.25–2.5	
S41600	416	0.15 max	1.25	1.00	12.0–14.0		0.15 min S, 0.060 P max
S42000	420	0.15 min	1.00	1.00	12.0–14.0		
S42200	422	0.20–0.25	1.00	0.75	11.0–13.0	0.50–1.0	0.75–1.25 Mo 0.15–0.30 V, 0.75–1.25 W
S43100	431	0.20 max	1.00	1.00	15.0–17.0	1.25–2.50	0.025 P max, 0.025 S max
S44002	440A	0.60–0.75	1.00	1.00	16.0–18.0		
S44003	440B	0.75–0.95	1.00	1.00	16.0–18.0		0.75 max Mo
S44004	440C	0.95–1.25	1.00	1.00	16.0–18.0		0.75 max Mo 0.75 max Mo

[a] 0.040 max P and 0.030 max S unless otherwise noted.

Table 14. Ferritic or Nonhardenable Grades of Stainless Steel

UNS no.	AISI type	Max C, %	Max Mn, %	Max Si, %	Cr, %	Mo, %	Ni, %	Other[a], %
S40900	409	0.08	1.00	1.00	10.5–11.75		0.5 max	(6 × C, .75 max) Ti; 0.045 P max, 0.045 S max
S42900	429	0.12	1.00	1.00	14.0–16.0			
S43000	430	0.12	1.00	1.00	14.0–18.0			
S43020	430F	0.12	1.25	1.00	14.0–18.0			0.15 min S, 0.060 max P, 0.60 Mo (optional)
S43400	434	0.12	1.00	1.00	14.0–18.0	1.0		
S43600	436	0.12	1.00	1.00	16.0–18.0	0.75–1.25		(Cb + Ti) = 5 × C min −0.70 max
S44200	442	0.20	1.00	1.00	18.0–23.0			
S44600	446	0.20	1.50	1.00	23.0–27.0			0.24 max N

[a] 0.040 max P, 0.030 max S unless otherwise noted.

Table 15. Super-ferritic Grades

UNS no.	Common name	Max C, %	Max Mn, %	Max Si, %	Cr, %	Mo, %	Ni, %	Other[a], %
S44400	18-2-Ti	0.025	1.00	1.00	17.5–19.5	1.75–2.50	1.0 max	0.025 max N, C + N <0.030 desirable Ti + Cb = 0.20 + 0.4 (C + N) min = 0.80 max
S44626	26-1-Ti	0.060	0.75	0.75	25.0–27.0	0.75–1.50	0.50 max	0.040 max N, 0.2 to 1.0 Ti typical [7 × (C + N) min] C + N = 0.050 typical, Cu = 0.20 max, S = 0.020 max
	26-1-Cb	0.005	1.00	1.00	25.5–27.5	0.6–1.4		Cb = 13–29 × N %
	28-2-4-Cb	0.015	1.00	1.00	26.0–30.0	1.75–2.25	3.6–4.4	0.035 max N, C + N ≤0.040 with Cb ≥0.2 + 12 (C + N)%
S44700	29-4	0.010	0.30	0.20	28.0–30.0	3.5–4.2		0.020 max N, C + N ≤0.025, 0.15 max Cu[b]
S44800	29-4-2	0.010	0.30	0.20	28.0–30.0	3.5–4.2		0.020 max N, C + N ≤0.025, 0.15 max Cu[b]

[a] 0.040 max P, 0.030 max S unless otherwise noted.
[b] 0.025 max P, 0.020 max S.

Table 16. Duplex (Ferrite + Austenite) Grades of Stainless Steel

UNS no.	AISI type	Max C, %	Max Mn, %	Max Si, %	Cr, %	Ni, %	Others[a], %
S31500		0.030	1.20–2.00	1.4–2.0	18.0–19.0	4.25–5.25	2.5–3.0 Mo, 0.030 max P
	327	0.10	1.00	1.00	25.0–26.0	4.8	
S32900	329	0.10	2.00	0.75	25.0–30.0	3.0–6.0	1.0–2.0 Mo

[a] 0.040 max P, 0.030 max S unless otherwise noted.

Table 17. Precipitation Hardenable Stainless Steels

UNS no.	Common name	Typical composition, %							
		C	Mn	Si	Cr	Ni	Mo	Al	Others[a]
S15800	PH 15–8 Mo	0.05 max	0.10 max	0.10 max	12.25–13.25	7.5–8.5	2.0–2.5	0.90–1.35	0.010 N 0.01 max P 0.008 max S
S15500	15-5 PH	0.07 max	1.00 max	1.00 max	14.5–15.5	3.5–5.5			2.4–4.5 Cu, Cb + Ta = 0.15–0.45
S17400	17-4 PH	0.07 max	1.00 max	1.00 max	15.5–17.5	3.0–5.0			3.0–5.0 Cu, Cb + Ta = 0.15–0.45
S17700	17-7 PH	0.09 max	1.0 max	1.0 max	16.0–18.0	6.5–7.75		0.75–1.5	0.040 max S
	PH 15-7 Mo	0.09 max	1.0 max	1.0 max	14.0–16.0	6.5–7.75	2.0–3.0	0.75–1.5	

[a] 0.040 max P, 0.030 max S unless otherwise noted.

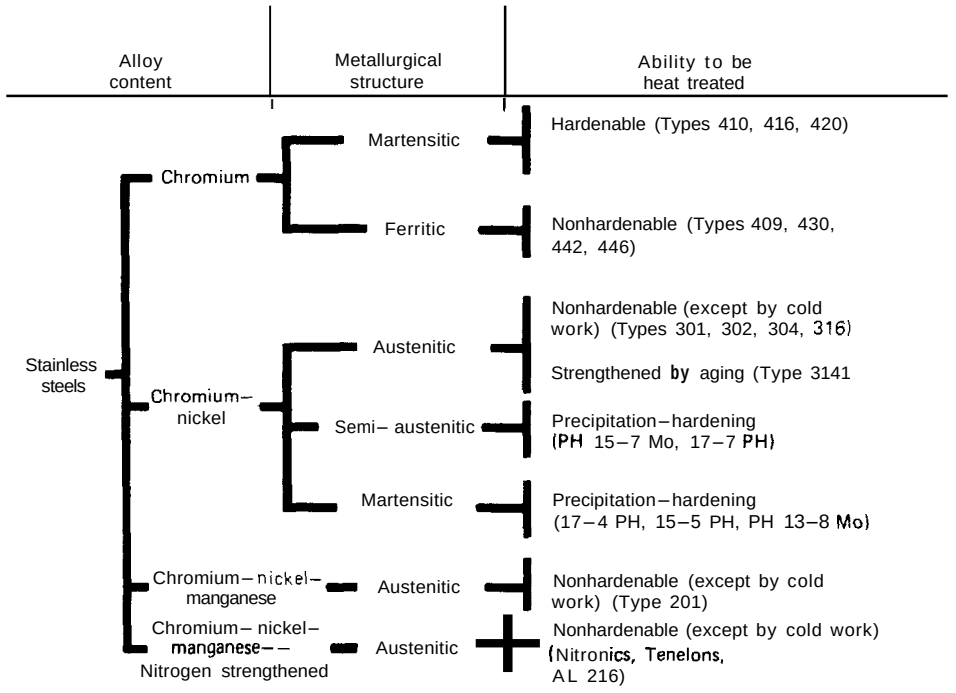

Figure 5. Diagramatic illustration of major classes of stainless steels (20).

Table 18. Relative Production of Major Stainless and Heat-Resistant Steel Grades, 1975

Grades	Percent
304	27.4
301	8.7
316	5.2
410	5.1
304L	4.6
316L	4.0
430	4.0
201[a], 202[a]	2.8
300 series[a], all other	7.3
400 series[b], all other	6.7
other chromium nickel stainless steels	5.9
501[b], 502[b], and all other high chromium heat resistant steels	3.3
all others	15.0

[a] The principal alloy elements are chromium and nickel.
[b] The principal alloy element is chromium.

18 Cr–8 Ni composition contain Mo for improved resistance to sulfuric acid or Ti or Cb to prevent the undesirable precipitation of chromium carbide at grain boundaries. Sulfur or selenium additions improve machinability. Recent additions to the austenitic class are the nitrogen strengthened Cr–Mn proprietary alloys, leading grades of which are shown in Table 12. They have higher strength at both room and elevated tem-

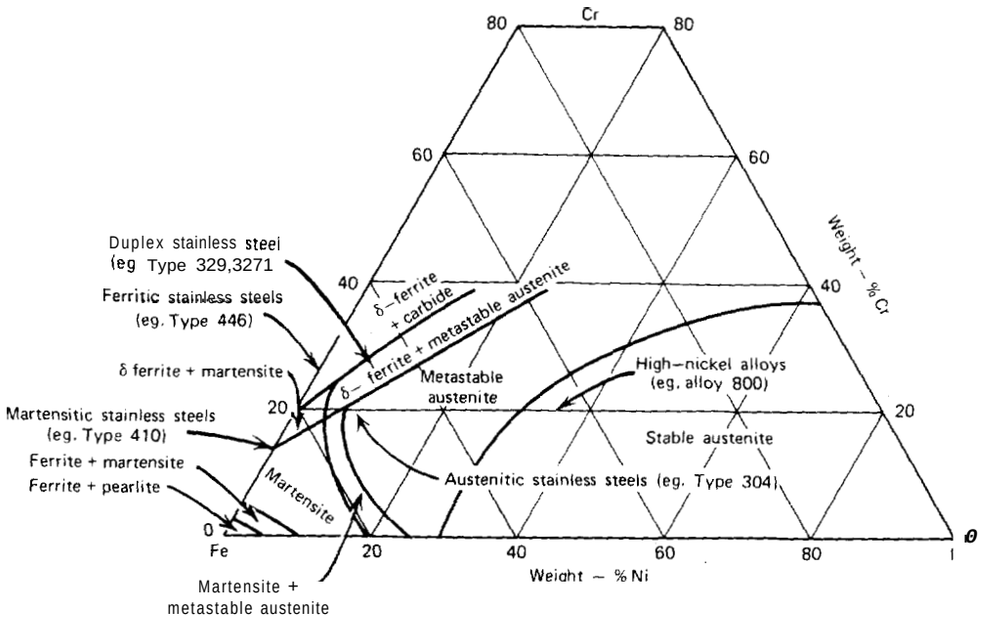

Figure 6. Metastable Fe–Ni–Cr "ternary" phase diagram with C = 0.1% and for alloys cooled rapidly **from** 1000°C showing the locations of austenitic, duplex, ferritic and martensitic stainless steels with respect to the metastable phase boundaries. For **higher** carbon contents than **0.1%** martensite lines occur at lower alloy contents (21).

peratures than standard **300** grades as well as improved corrosion resistance and low temperature toughness.

Ferritic stainless steels with low carbon and high chromium can be heated to the melting point without transformation to the austenitic structure as shown in Figure 7. This fact ensures their freedom from quench hardening, thereby facilitating fabrication, but eliminates the possibility of grain refinement by heat treatment. Such steels are widely used for architectural work, automotive trim, and equipment in the chemical and food industries. Types **430** and **446** are especially resistant to oxidation and hence are favored for furnace **parts,** heat exchangers, and other high temperature equipment. Recently some new grades in this class have appeared, the so-called super-ferritics, (see Table **15).** They offer superior toughness, weldability, and stress corrosion cracking resistance at strength levels comparable to those of conventional ferritics.

Martensitic stainless steels have somewhat higher carbon contents than the ferritic grades for the equivalent chromium level. They are therefore subject to the austenite–martensite transformation on heating **and** quenching and **can** be hardened significantly. The higher-carbon martensitic types, eg 420 and **440** are typical cutlery compositions, whereas the lower-carbon grades are used for special tools, dies, and machine parts and equipment subject to combined abrasion and mild corrosion.

Leading grades of the so-called precipitation hardening (PH) types are shown in Table 17. Hardened by precipitating a nickel-rich intermetallic compound in a martensite matrix, they are shipped either in the martensitic or austenitic condition. The austenite is transformed to martensite before the precipitation-aging heat treatment. Compared to standard stainless steels, especially the martensitic grades,

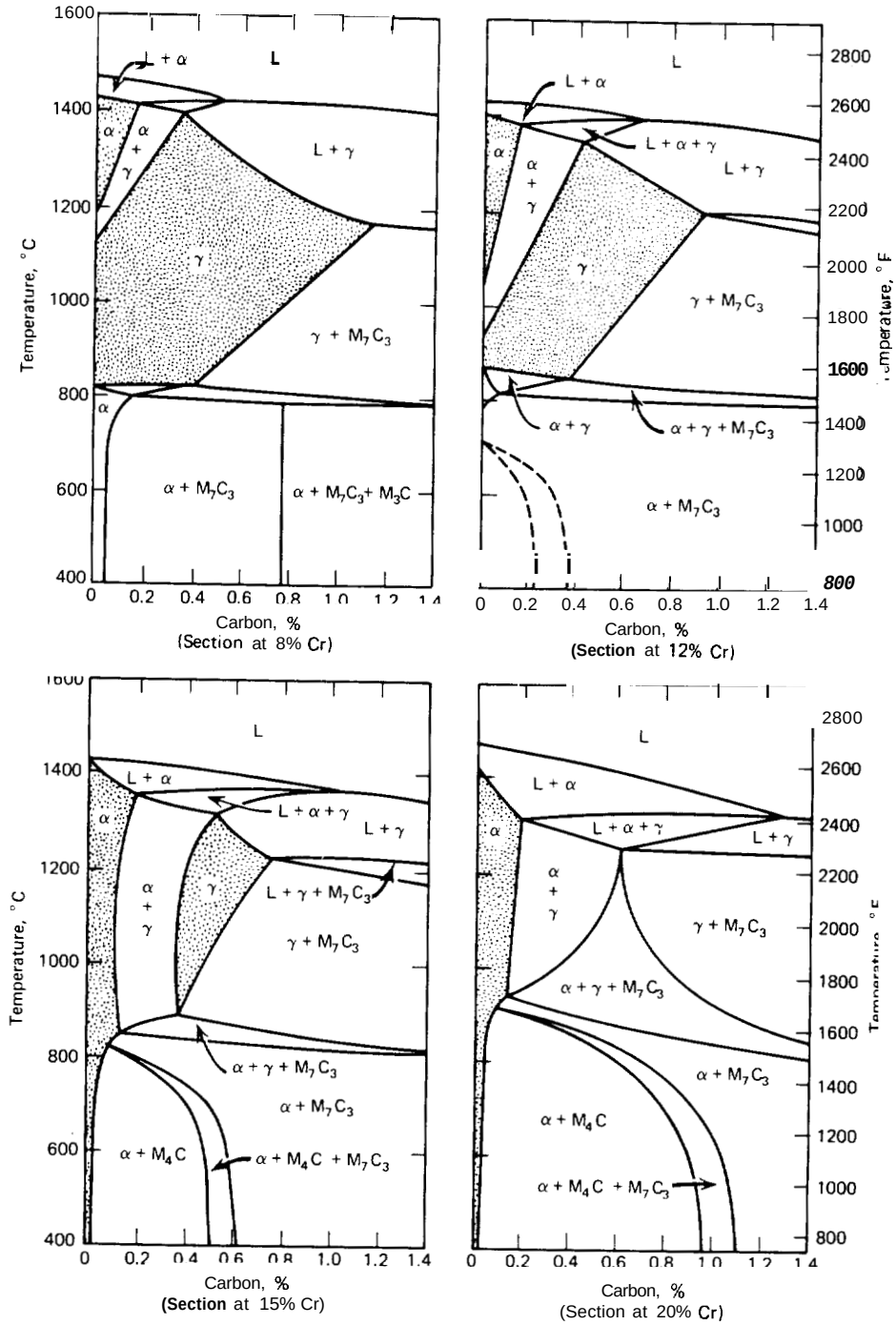

Figure 7. Fe–Cr–C vertical sections at constant chromium content **(23–24).**

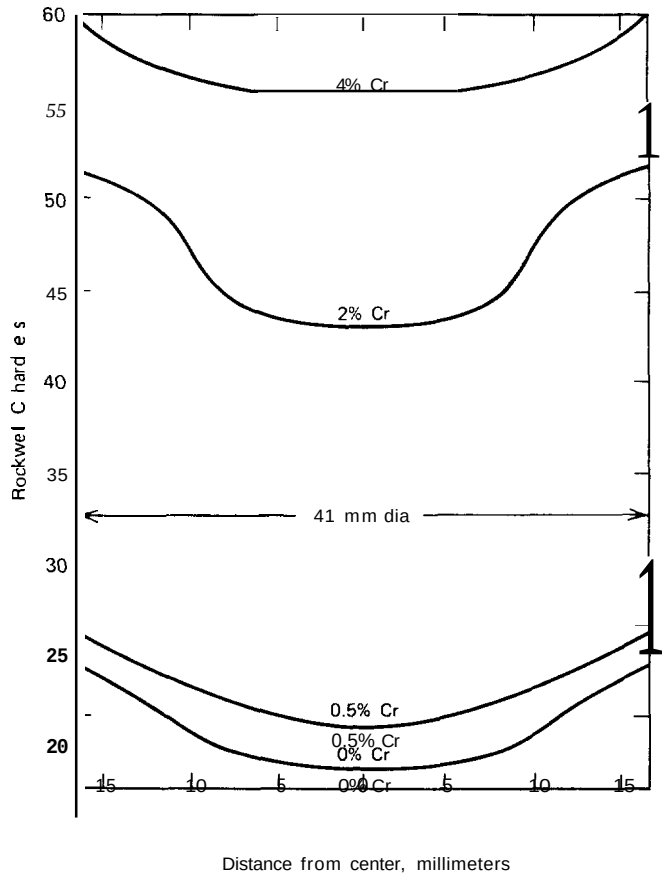

Figure 8. Effect of chromium on hardenability of steel as indicated by hardness distribution across 41 mm rounds of oil-quenched 0.35%C steel (25).

the PH stainless steels offer high yield strength—someeven above 1400MPa (203,000 psi),—good ductility, and corrosion resistance.

Other Alloy Steels (5,25)

In low-alloy steels chromium contributes more to hardenability, tempering resistance, and toughness than to solid-solution hardening or oxidation resistance. In the high-chromium tool steel compositions chromium carbides improve the high hot hardness. The marked effect of small additions of chromium on hardenability is shown in Figure 8. Other alloying elements show a similar or greater effect, but chromium is one of the cheapest. The effect of chromium on resistance to tempering is shown in Figure 9.

Wrought alloy steels, alloyed cast irons and steels, and tool steels account for 20–25% of the annual U.S. consumption of chromium. The largest category are the wrought alloy steels classified as shown in Table 19. In terms of chromium consumption, the most important classes are the CrMo, NiCrMo, and Cr steels (in that order). They may be further subdivided into carburizing and through-hardening grades. Such

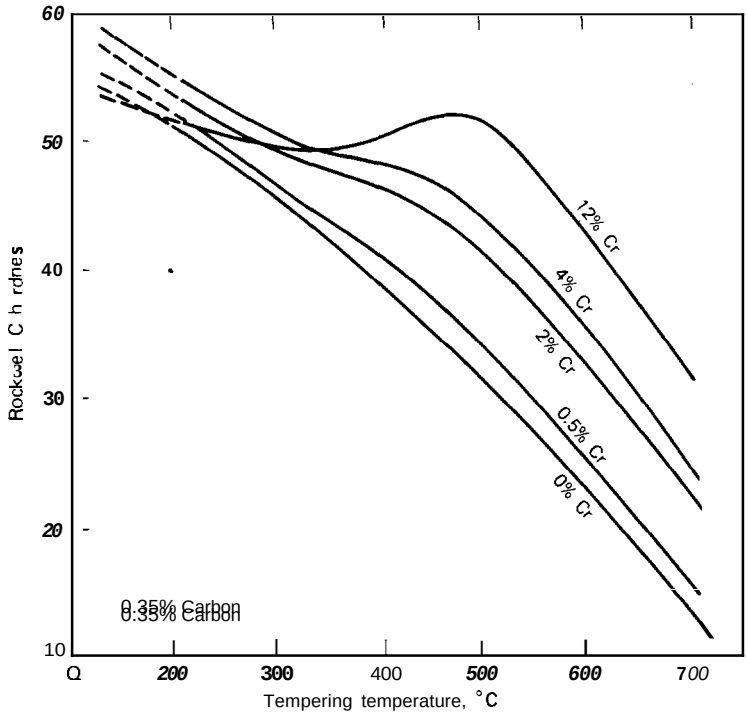

Figure 9. Effect of chromium on tempering resistance of **quenched 0.35%**C **steel** (25).

steels are extensively used in machinery, construction, and other structural work, and in machine parts such as bearings, gears, rolls, springs, and shafting. The AISI 500 series steels shown in Table 20 with their higher chromium content find application in the oil industry where their resistance to corrosion and oxidation is especially important.

Nonferrous Alloys

Nonferrous alloys account for only about 2% of the total chromium used in the United States. Nonetheless, some of these applications are unique and constitute a vital role for chromium. For example, chromium confers corrosion and oxidation resistance on the nickel-base superalloys used in jet engines; the familiar electrical resistance heating elements are made of a Ni–Cr alloy; and a variety of Fe–Ni and Ni-based alloys used in a diverse array of applications (especially in the nuclear reactor field) depend on chromium for oxidation and corrosion resistance.

Recovery and Reuse

At the present time only about 15% of chromium consumed in the United States is recycled and this largely from stainless steel scrap. Today because of environmental considerations much of the chromium formerly lost from plating operations is recovered. However this does not amount to a significant tonnage. Furthermore, steps are now being taken to improve recovery of the substantial chromium losses incurred

Table 19. Basic Numbering System for Chromium-Bearing low-Alloy Steels

Alloy	AISI/SAE designation[a]	UNS[b] no.
nickel–chromium steels		
Ni 1.25; Cr 0.65	31XX	G31XXZ
Ni 3.50; Cr 1.57	33xx	G33XXZ
chromium–molybdenum steels		
Cr 0.50 and 0.95; Mo 0.25, 0.20, and 0.12	41XX	G41XXZ
nickel–chromium–molybdenum steels		
Ni 1.82; Cr 0.50 and 0.80; Mo 0.25	43xx	G43XXZ
Ni 1.05; Cr 0.45; Mo 0.20	47xx	G47XXZ
Ni 0.55; Cr 0.50 and 0.65; Mo 0.20	86XX	G86XXZ
Ni 0.55; Cr 0.50; Mo 0.25	87XX	G87XXZ
Ni 3.25; Cr 1.20; Mo 0.12	93xx	G93XXZ
Ni 1.00; Cr 0.80; Mo 0.25	98XX	G98XXZ
chromium steels		
Cr 0.27, 0.40, and 0.50	50XX	G50XXZ
Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05	51XX	G51XXZ
Cr 0.50	501XX	G509ZZ
Cr 1.02	511XX	G519ZZ
Cr 1.45	521XX	G529ZZ
chromium–vanadium steels		
Cr 0.80 and 0.95; V 0.10 and 0.15 (min)	61XX	G61XXZ
boron-treated chromium steels	XXBXX[c]	various

[a] The XX after the designation is left open for carbon content; thus, 3110 equals a 0.10% carbon, nickel–chromium steel, and in this case XX = 0.10.
[b] The XX after the designation follows the AISI/SAE system and hence indicates carbon content; the Z is either an arbitrary number or 0. For a fuller description and tabulations of this new numbering system see Ref 22.
[c] The XX before the B is for the type numbers and after the B for carbon content.

Table 20. Composition of Heat-Resisting Chromium Steels

UNS no.	AISI type	C, %	Mn[a], %	Si[a], %	P[a], %	S[a], %	Cr, %	Mo, %
S50100	501	over 0.10	1.00	1.00	0.04	0.03	4.0–6.0	0.40–0.65
S50200	502	0.10 (max)	1.00	1.00	0.04	0.03	4.0–6.0	0.40–0.65
S50300	503	0.15 (max)	1.00	1.00	0.04	0.04	6.0–8.0	0.45–0.65
S50400	504	0.15 (max)	1.00	1.00	0.04	0.04	8.0–10.0	0.90–1.10

[a] Maximum.

in the past from refractory and foundry applications of chromite grain (see Recycling).

Future Trends

World political problems and the unique and vital industrial role of chromium are stimulating research and development to create new economically feasible sources of chromium and to achieve a more conservative use of chromium. Thus we can expect to see process developments permitting the recovery of chromium from lower-grade

ores, and the replacement of chromium-containing materials by other materials, development of low chromium grades, especially in stainless steels, and extended and improved recycling. Further research may lead to practical chromium plating processes based on Cr^{3+} rather than Cr^{6+} and to Cr-based alloys of acceptable ductility that can effectively exploit chromium's potential as a high-temperature material.

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