METALLURGY

1. Introduction

The early foundations of metallurgy can be traced to the late Stone Age (ca 8000 BC) when copper (qv) was first used as a substitute for stone. The Metallic Age, when copper was melted and casted into tools, utensils, and weapons, followed. The Mesopotamians, the metallurgists of the ancient world, made exquisitely formed gold and bronze objects that have been dated to around 3000 BC. The Industrial

Revolution of the eighteenth and nineteenth centuries was driven to a large degree by metallurgy and the use of basic materials such as iron (qv), steel (qv), and copper. Certainly, the large-scale generation and delivery of electrical energy would not have been possible without copper (see POWER GENERATION). Going into the twenty-first century, numerous advanced materials utilized in contemporary society depend on specialty metals often requiring novel processing techniques as well as a detailed knowledge of chemistry and atomic structure (see ABLATIVE MATERIALS; GLASSY METALS; HIGH TEMPERATURE ALLOYS; SHAPE-MEMORY ALLOYS). Clearly, metallurgy is both an ancient art and a modern science.

The first authoritative cataloging of metallurgical knowledge, by Georgius Agricola in *De Re Metallica* (1556) (1), reflected an early appreciation for metallurgy as encompassing many disciplines. Metal production was known to be achieved by many diverse processes. Early sources define metallurgy as the process of extracting metal from ores. For many metals, the primary source materials as of the 1990s are still crude metalliferous ores. For some metals however, recycled materials contribute significantly to total metal production. For example, in the United States the recycling (qv) rate of all-aluminum used beverage cans is over 50%. For an energy-intensive metal such as aluminum, this represents a substantial energy saving. Recycled aluminum requires only 5% of the energy needed to make aluminum from bauxite ore (see ALUMINUM AND ALUMINUM ALLOYS; RECYCLING, NONFERROUS METALS).

Metallurgy includes not only the treatment of crude ore and scrap, but also the processing of intermediates, ie, concentrates, and wastes, such as, slags, tailings, etc, for contained metal values. The various areas and subdisciplines comprising metallurgy may be summarized as follows:

Extractive metallurgy			
Mineral processing	Chemical metallurgy	Process metallurgy	Physical metallurgy
comminution classification flotation	hydrometallurgy pyrometallurgy electrometallurgy corrosion	alloying casting deformation processes heat treatment powder metallurgy nuclear metallurgy	structure–property relationships failure analysis corrosion

Extractive metallurgy, the initial phase of winning metals from a given raw material, involves both physical and chemical processes. Those steps consisting of physical operations are termed mineral processing or mineral beneficiation, sometimes referred to as ore dressing. Physical operations are often required to liberate and concentrate metal values contained in an ore so that subsequent chemical processing can be performed at higher efficiencies (see also MINERAL RECOVERY AND PROCESSING). Processes involving some form of chemical change, required to free a given metal from associated impurities, embody the field of chemical metallurgy. Chemical metallurgy in turn is conveniently divided into pyrometallurgy, hydrometallurgy, and electrometallurgy.

Process metallurgy, the next phase in the metals cycle, is the procedure or sequence of procedures whereby metals are worked or shaped. There are five main methods of working and shaping metals including casting, hot and cold working, machining, electroforming, and powder metallurgy. Powder metallurgy is especially important in working with high melting point metals. Examples are tungsten, mp = 3410°C, rhenium, mp = 3180°C, tantalum, mp = 2996°C, and platinum, mp = 1774°C. Powder processing is vital to the manufacture of products from refractory metals and alloys (see REFACTORIES).

Metallurgy also embraces the scientific study of the structure, properties, and behavior of metals and metal alloys. This branch of metallurgy is referred to as physical metallurgy. The two areas that commonly characterize physical metallurgy are structure–property relationships and failure analysis.

Both powder and nuclear metallurgy have attained a certain status and prominence and, in certain respects, represent main areas within the field of metallurgy (see METALLURGY, POWDER METALLURGY). Nuclear metallurgy involves all the main disciplines in metallurgy as related to the production of fuels, fabrication of fuels, and the fabrication of cladding materials and moderators (see NUCLEAR REACTORS). Corrosion is a discipline which bridges aspects of both chemical and physical metallurgy (see CORROSION AND CORROSION CONTROL).

2. Definitions

The field of metallurgy has a unique and frequently very specialized vocabulary. Understanding this language helps to clarify certain concepts and processing steps. A complete dictionary of mining, mineral, and related terms has been compiled (2). The definitions and explanations of key terms follow.

2.1. Concentrate. An action to intensify in strength or purity by the removal of valueless or unneeded constituents, ie separation of ore or metal from its containing rock or earth. The concentration of ores always proceeds by steps or stages. Liberation of mineral values is often the initial step. Concentrate also means a product of concentration, ie, enriched ore after removal of waste in a beneficiation mill.

2.2. Electrometallurgy. A term covering the various electrical processes for the working of metals, eg, electrodeposition, electrorefining and electrowinning, and operations in electric furnaces.

2.3. Flotation. The method of mineral separation in which a froth created in water by a variety of reagents floats some finely crushed minerals, whereas other minerals sink.

2.4. Gangue. Undesired minerals associated with ore, mostly nonmetallic. Gangue represents the portion of ore rejected as tailings in a separating process. It is usually valueless, but may have some secondary commercial use.

2.5. Hydrometallurgy. The treatment of ores, concentrates, and other metal-bearing materials by wet processes, usually involving the solution of some component, and its subsequent recovery from solution.

2.6. Leaching. Extracting a soluble metallic compound from an ore by selectively dissolving it in a suitable solvent. The solvent is usually recovered by precipitation of the metal or by other methods.

2.7. Mineral. An inorganic substance occurring in nature, though not necessarily of inorganic origin, which has (*1*) a definite chemical composition, or more commonly, a characteristic range of chemical composition, and (*2*) distinctive physical properties or molecular structure. In a broad sense, mineral should embrace both inorganic and organic substances, eg, fuel minerals such as coal (qv), oil (see PETROLEUM), and natural gas (see GAS, NATURAL). Ore is often classified as containing ore minerals, valuable constituents, and gangue minerals, ie, waste.

2.8. Mineral Dressing. Physical and chemical concentration of raw ore into a product from which a metal can be recovered at a profit.

2.9. Ore. A mineral or aggregate of minerals from which a valuable constituent, especially a metal, can be profitably extracted.

2.10. Pyrometallurgy. Metallurgy involved in winning and refining metals where heat is used, as in roasting and smelting. Pyrometallurgy is the oldest extractive process and is probably the most important.

2.11. Roast. The heating of solids, frequently to promote a reaction with a gaseous constituent in the furnace atmosphere.

2.12. Smelt/Smelting. Any metallurgical operation in which metal is separated by fusion from those impurities with which it may be chemically combined or physically mixed, such as in ores.

3. Ore

The metal content of an ore is typically called the ore grade and is usually expressed as weight percent for most metals. For precious metals, however, grade is usually expressed in g/t (oz/short ton). Because the definition of ore is established by economic considerations, there is no upper limit to grade, ie, the richer, the better. There is frequently a lower limit or cutoff grade, however, based on process efficiency and economics. Table 1 shows the average grade of various metalliferous ores that can be processed economically. Also shown is an estimate of the world total reserve base for each metal. For many metals, ore grade depletion has been a serious problem. This is illustrated for copper by the decline in average copper yield for U.S. copper ores during the 1900s (Fig. 1). The ability of the copper industry to remain competitive while faced with this problem has been a challenge. Technical developments in leaching, and improvements in solution concentration, purification, and metal reduction (solvent extraction and electrowinning), have turned this problem into an opportunity for additional metal production. Leaching of large tonnages of low grade material accounts for about 35% of the U.S. primary copper production.

Modern heap leaching practice has also made possible the treatment of extremely lean (ca 1 g/t) gold ores, which had been considered uneconomic as late as the early 1980s. In addition, changing technology and process innovations have contributed to the extraction of nickel from low grade lateritic ores and to the potential recovery of aluminum from nonbauxitic aluminum resources.

Some metals are produced primarily as a by-product from the mining and refining of other metals. For example, approximately one-half of the world's

Table 1. **Grade of Ore for Economic Processing and Estimated World Reserves**

Ore	Grade, wt%	World reserves, t
aluminum	27–29	
chromium	27–34	6,778,000,000[a]
cobalt	1–11	8,340,000
copper	0.5–2	574,000,000
gold	0.0001–0.001	48,600
iron	30–60	230,000,000,000
lead	5–10	120,000,000
manganese	45–55	3,540,000,000
molybdenum	0.6–1.8	13,000,000
nickel	1.5–3	109,000,000
platinum	0.001	100,000[b]
silver	0.04–0.08	420,000
tin	1–5	6,050,000
titanium	2.5–25	
uranium	0.1–0.9	
vanadium	1.6–4.5	16,330,000
zinc	10–30	295,000,000

[a] As chromite [53293-42-8].
[b] Reserves of the platinum group metals (qv), ie Pt, Pd, Rh, Ru, Ir, and Os, together equal 1×10^8 t.

cobalt supply is produced as a by-product from copper operations in Zaire and Zambia. Also, significant quantities of cobalt are produced as a by-product of nickel. Molybdenum is found in small (0.005–0.15% Mo) quantities in porphyry copper ores, and for many years high grade molybdenite, MoS_2, concentrates have been produced as part of copper-milling operations. Other important by-products associated with copper ores are nickel, cobalt, silver, gold, platinum, lead, and zinc.

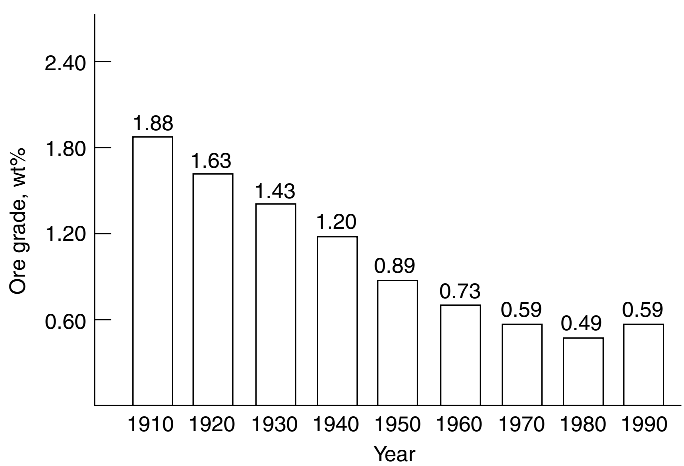

Fig. 1. Average yield of copper ores mined in the United States.

4. Product Specifications

Impurities in crude metal can occur as other metals or nonmetals, either dissolved or in some occluded form. Normally, impurities are detrimental, making the metal less useful and less valuable. Sometimes, as in the case of copper, extremely small impurity concentrations, eg, arsenic, can impart a harmful effect on a given physical property, eg, electrical conductivity. On the other hand, impurities may have commercial value. For example, gold, silver, platinum, and palladium, associated with copper, each has value. In the latter situation, the purity of the metal is usually improved by some refining technique, thereby achieving some value-added and by-product credit.

Refined metals, as traded on the open market, vary considerably in composition. However, there are strict specifications for certain impurity elements for a number of metals. The degree of purity of common industrial metals obtained from modern metallurgical practices is shown in Table 2 (3).

5. Economic Aspects

Metals have influenced and have served as the unit of monetary exchange throughout many parts of the world for millennia. Metal price has a very significant influence on production patterns. Price drives metal exploration and development of new resources, and is the main factor in determining materials substitution. High metal prices stimulate exploration activities and new mine development, which in turn increase supply. High metal prices also encourage the search for substitutes, decreasing demand. The prices in constant 1987 dollars of selected metals are plotted in Figure 2 (4). Metal price fluctuations and cycles are controlled by

Table 2. **Analyses of Refined Metals,[a] wt%**

Metal	Copper[b]	Nickel[c]	Lead[d]	Zinc[e]	Silver
Cu	99.99	0.02	0.0010	0.002	0.01
Ni	0.001	99.8	0.0002		
Pb	0.0005	0.005	99.97	0.003	0.001
Zn	0.0001	0.005	0.0005	99.990	
Ag	0.0025		0.0025		99.99
Sb	0.0004	0.005	0.0005		
As	0.0005	0.005	0.0005		
Fe	0.001	0.02	0.001	0.003	0.001
O	0.0005				
P	0.0003	0.005			
Se	0.0003				0.0005
S	0.0015	0.01			
Sn	0.0002	0.005	0.0005	0.001	

[a] Values are minimum for the primary metal and maximum for impurity concentrations.
[b] Oxygen-free electrolytic copper containing 0.0001 wt% Bi and Cd and 0.00005 wt% Mn.
[c] Refined nickel primarily produced from ore or matte or similar material.
[d] Pure lead for lead–acid battery application.
[e] Special high grade containing only 0.003 wt% Cd and 0.002 wt% Al.

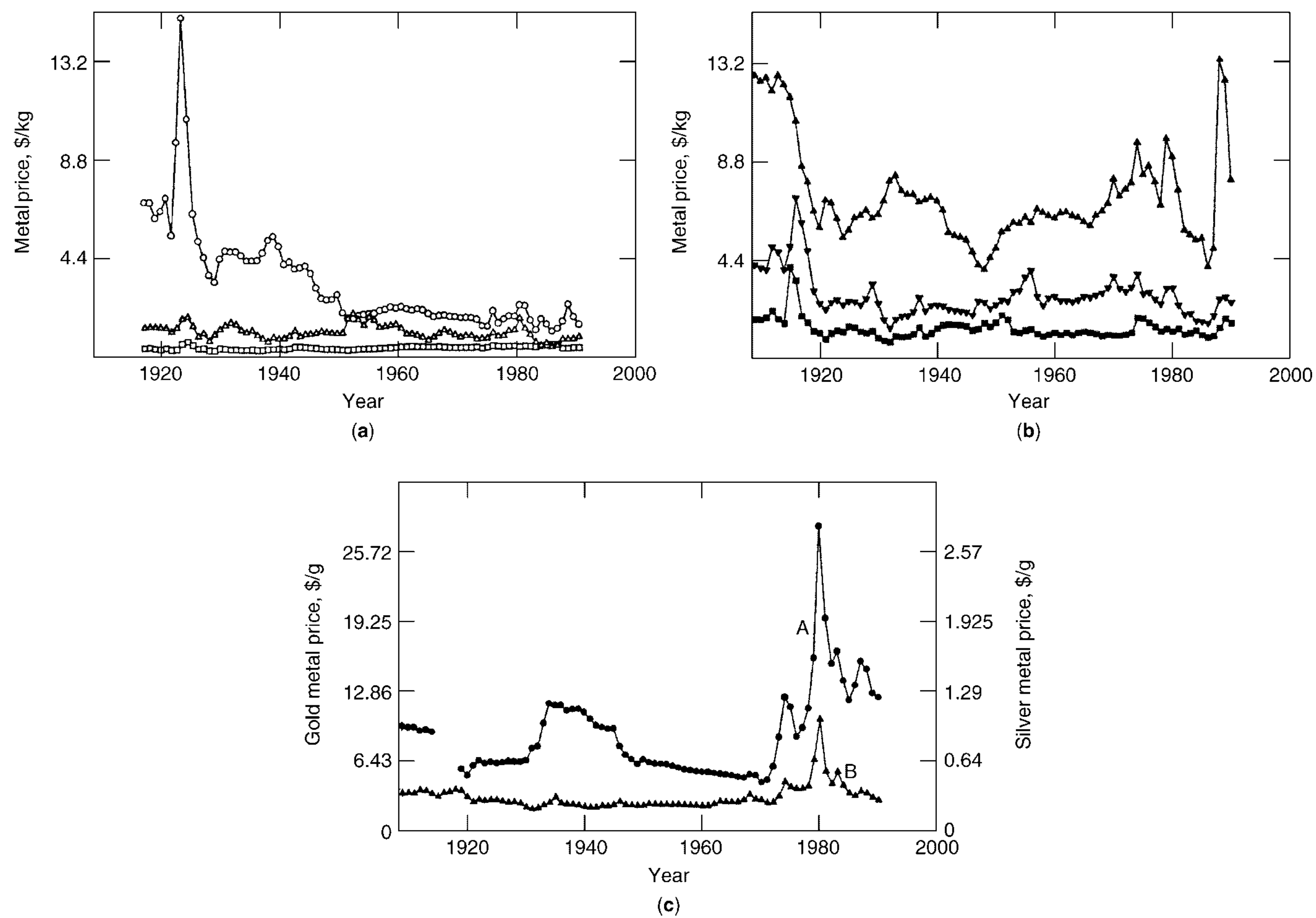

Fig. 2. Metal price in constant 1987 dollars since 1909 for (**a**) (□) iron (hot-rolled steel bars), (○) aluminum, and (△) lead; (**b**) (▼) copper, (■) zinc, and (▲) nickel; and (**c**) A, gold and B, silver (4). To convert \$/g to \$/troy oz, multiply by 31.10.

numerous factors. For example, the price of aluminum (Fig. 2**a**) indicates supply shortages and a relatively high price during World War I, and a general price decrease following this period. This decreasing trend reflects, in part, improved metallurgical efficiencies and process innovations. The decrease in copper, zinc, and nickel prices (Fig. 2**b**) after 1920 indicates the successful and widespread application of sulfide ore flotation and advances in electrolytic processing. Swings in gold and silver price (Fig. 2**c**) since the early 1970s indicate free-market forces and global political and economic effects following suspension of governmental price controls.

There is a general relationship between metal price and terrestrial concentration. Metals present at relatively high concentrations, in the earth's crust, such as iron and aluminum, are the least expensive; rare metals such as gold and platinum are the most valuable. This situation has existed for gold and silver valuation for centuries. The amount of silver in the earth's crust is approximately 20 times that of gold, and the historical price ratio for gold and silver varied between 10 and 16 for over 3000 years. Since 1970 that price ratio has been strongly affected by market forces and investor speculation.

Metal demand has an important influence on price. Both lead and gallium occur in the earth at about 0.0015 wt%. The demand for gallium (1990 U.S. consumption was 10,000 kg) is limited to optoelectronic devices and high performance microelectronics. There appears to be no need to expand supply, which would reduce price. On the other hand, reported 1990 consumption of lead in the United States was 1.25×10^6 t. Lead (qv) production is carried out on a large scale by relatively simple and efficient processes.

Approximately three-quarters of the elements in the Periodic Table are metals. The winning, refining, and fabrication of these metals for commercial use together represent the complex and diverse field of metallurgy. Metallurgy has played a vital role in society for thousands of years, yet it continues to advance and to have increasing importance in many areas of science and technology.

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Brent Hiskey
University of Arizona