

INTRODUCTION TO PRECIOUS METALS

METALLURGY FOR JEWELERS & SILVERSMITHS



Mark Grimwade



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Metallurgy for Jewelers and Silversmiths
by Mark Grimwade

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Foreword

If you work with precious metal, you need to read this book. If you make jewelry and haven't studied metallurgy, reading this book will be like an awakening into a new world of understanding and possibilities that you never imagined.

My father was a master goldsmith who learned his skill through an Old World style apprenticeship, in St. Louis, Missouri with his European-trained uncle. By refining, alloying, and milling metals, he learned the nature of metals at their most basic level. Before an apprentice could work with precious metals, he learned about annealing, hardening, and tempering, always under the watchful care of a master intent on passing on his craft. In my father's case, the apprenticeship required a nine-year commitment.

For better or worse, that kind of hands-on practical education is not part of the modern world. While we can argue that much has been lost in giving up the apprenticeship system, we can also acknowledge that the conservatism it fostered stifled innovation.

What has taken its place, fortunately for us, is a science that is broader, richer, and far more precise than it was in my father's time. The last century saw the development of the electron microscope, lasers, and perhaps more fundamentally, an international scientific community with unprecedented ability to share information. The precise measurements, mathematics, and nomenclature of science allow us to replace trial and error with research. The need to connect an apprentice to a master has been replaced by a network of universities and polytechnics with the result of huge leaps forward in our understanding of the world around us.

A genuine understanding of materials and the physics and chemistry related to them not only allows, but fosters innovation. Among the many examples that come to mind, I think of the well-known jewelry artist Steven Kretchmer who invented and patented a platinum alloy with steel-like spring qualities for tension set stones. In an inspiring merger of technology, art, and innovation, Kretchmer harnessed the best of all three to create something radically new for the field of jewelry.

What remains, then, is the need for a guide to lead artists and manufacturers into the fascinating world of metallurgy. I can think of no one I'd rather follow than Mark Grimwade. Mark has a rare gift as an educator. He presents complex metallurgical concepts in ways that goldsmiths can understand and apply. During the 15 years that his lectures opened the Santa Fe Symposium on Jewelry Manufacturing Technology, the room was always packed. It is a

tribute to Mark that the metallurgists attending the symposium (some with PhDs) never missed his lectures, and jewelers like me who listened to him year after year always learned something useful. After his lectures the comments I heard usually mentioned a new sense of empowerment, and also regret about not studying metallurgy at the start of a career.

Since his *Introduction to Precious Metals* was published in 1985, Mark has refined and expanded the content, making the information even more useful to people who work with precious metals. Since that book went out of print, several of his friends, me included, have urged him to update his work and make it available again. Nothing like it is available for jewelers, and his clear writing style makes him uniquely qualified for the job. The book you hold in your hands is exactly what we had in mind—all the features of the original book and now about a third larger with even more information. This is a reference book you will use often. If you're like me, you'll turn to it for the answer to a specific problem and soon find yourself reading further than you intended, probing the inner structures of metals.

— Eddie Bell,
*Technical Director, Rio Grande and Neutec/USA
and Founder of The Santa Fe Symposium*

Preface

In 1970, I was asked by Peter Gainsbury, then Director of Design and Technology for the Worshipful Company of Goldsmiths in the UK, to give a series of lectures on Basic Metallurgy for Silversmiths and Jewelers for people in the trade and college students in the London area. This exposed me to the world of the artist/craftsperson and manufacturers of jewelry and precious metalware of which I knew little but which was to be my good fortune. The challenge was and remains the task of explaining to those with little scientific background the underlying physical, chemical, and metallurgical principles and accompanying technology for the materials and processes they were familiar with. Eventually, this led to the publication in 1985 of a book called *Introduction to Precious Metals*.

Since then, I have witnessed a revolution in the manufacture of jewelry and decorative metalware. First, an industry that hitherto had been somewhat secretive became more open to sharing knowledge and ideas. At the forefront has been the Santa Fe Symposia on Jewelry Manufacturing Technology, co-founded by Eddie Bell and Dave Schneller in 1987. This has been the major forum for the dissemination of knowledge about the industry for over twenty years. Secondly, advances in process technology and equipment have enabled both manufacturers and craftspersons to explore new fabrication techniques, e.g. rapid prototyping, electroforming, precious metal clays, etc.

This book is a revision and enlargement of the original book and is intended specifically for jewelers and metalsmiths. The opening chapters are devoted to the properties of the precious metals and their occurrence and extraction and these are followed by chapters on the metallurgical principles underlying melting, solidification, working, annealing, and alloying behavior. The precious metals and their alloys in relation to their use for jewelry and decorative metalware are discussed. The remaining seven chapters are concerned with processing technology, assaying and hallmarking.

I have deliberately avoided the use of specific references throughout the text as it is not always easy to track down original sources. Instead, I have adopted the policy of including 'Further Reading' sections where appropriate at the end of chapters and a Bibliography at the end of the book. However, my task would have been impossible without the information that I have gained from the many contributors to the Santa Fe Symposia and to those I have met on my travels around the World on behalf of the World Gold Council. They are too numerous to mention by name but my heartfelt thanks go to all of them.

In particular, I am indebted to Eddie Bell for inviting me to speak at many Santa Fe Symposia and for his friendship, to Robert Owen and Dr Christopher Corti, both formerly of the World Gold Council, for asking me to be one of their consultants, notably in the developing gold markets in the World, to the Worshipful Company of Goldsmiths for the experience I have gained in acting as their metallurgical consultant for over 21 years, to Dr. John Wright for helpful discussions, and to the many friends and colleagues I have met in the forty years I have been associated with jewelry and precious metalware. My special thanks must go to Tim McCreight, not only for his very generous review of the original book, but for giving me the impetus to produce a new book and agreeing to publish it.

I dedicate the book to my wife Pamela for her love, support and encouragement during fifty years of marriage. It was she who sat me down one evening and told me in no uncertain terms that I had to get on with it.

– Mark Grimwade

Introduction

Gold, silver, and platinum are all regarded as precious metals. In particular, gold and silver have been highly prized by mankind for thousands of years. Early civilizations associated the yellow color of gold with the sun, and for the Egyptians, gold was the symbol of their sun god Ra. Just as gold was associated with the fire of the sun, so the brilliant white color of silver was related to the moon. The original Latin name for silver was *luna* meaning “moon,” although this was changed later to *argentum* meaning “white and shining.”

Throughout the ages, fabulous treasures have been made by artists and craftsmen exploiting the natural beauty of these metals. Alchemists spent their lives in search of the Philosopher’s Stone which was said to possess the property of converting base metals, i.e., the non-precious metals, to gold, and although their efforts proved to be fruitless in that direction, they were instrumental in laying the foundations of the science of chemistry. Indeed, it was the discovery of the precious metals and copper 7000–9000 years ago and the craft skills developed by the early civilizations, such as the Egyptians, that can be said to have laid the foundations of metallurgy.

The discovery of platinum and the other platinum group metals (PGMs) is

much more recent. Although platinum was used by the Pre-Columbian Indians of South America to make small ornaments, it was not until the 18th century that its true worth was recognized. The other PGMs are palladium, now used as a jewelry metal in its own right, rhodium, iridium, ruthenium, and osmium.

But what is it that makes these metals so precious? First, they have a remarkable resistance to attack by their environment. Whereas the base metals readily combine with other substances to form oxides, sulfides, silicates and other minerals, the precious metals, or “noble metals” as they are sometimes called, can occur naturally in the uncombined state as lode deposits in rocks, or as placer deposits in the gravel beds of rivers and streams and in alluvial sands.

Secondly, gold and silver, although not platinum, were widely distributed throughout the world, which explains why so many different civilizations discovered these naturally occurring “native” metals. It was relatively easy to extract the gold and silver and the early metalworkers soon discerned another important property, namely the ease with which they could be fabricated into shapes for decorative purposes and their inherent aesthetic beauty. Nevertheless, such deposits were

rare, and accordingly, gold and to a lesser extent, silver attained a great value and became a symbol of wealth. Unfortunately, these deposits have been largely exhausted including those found during the great gold rushes in Canada, the USA, and Australia in the 19th century. Consequently, mining for the precious metals is now a large commercial undertaking.

Apart from their use for jewelry and decorative metalware, gold and silver soon assumed a monetary role because their indestructibility and rarity made them suitable for trading and accumulating wealth. This monetary usage persisted for over 2000 years, culminating in the Gold Standard in the 19th and early 20th centuries. Today, the price of gold is allowed to fluctuate depending on market forces but the central banks of many countries still hold reserves of gold. Further discussion on this aspect is outside the scope of this book but an insight into the marketing and financial dealings in gold may be found in *The Gold Companion* (see Further Reading).

People in Europe, North America, and Japan now tend to buy jewelry for adornment, whereas in many other countries, such as the Middle East and India, jewelry is purchased also as an investment.

Gold has inspired artists and craftspersons throughout the ages to produce jewelry, ornaments, and priceless works of art. One has only to think of the tomb of Tutankhamen, the riches of the Ancient Greeks, Etruscans and Thracians among many others, to realize the skills that these early metalworkers possessed. At a later period in the world's history, but separated from that of the Mediterranean World, the Mexican civilizations, e.g., the Aztecs, and the Mohica, Chimu, and Inca cultures of Peru were equally adept in working gold.

Silver has also been used for centuries

for artistic purposes. The Romans were excellent silversmiths as is shown by a visit to the British Museum to see the Mildenhall and Water Newton hoards dating from the Roman occupation of Britain in the 1st-4th centuries AD.

Today, we find that beautiful works of art in gold, silver, and platinum are being made not only using the traditional skills of the goldsmith, but also incorporating modern technology in their manufacture.

In addition to their use in the decorative arts and for monetary and investment purposes, there is an ever-expanding need for the precious metals in industry and medicine. These applications will not be discussed further in this book except to note here that since the 1950s, gold has played an important role in the electronics industry. The manufacture of high-grade optical glass, and control of atmospheric pollution from automobiles and industrial plants would be impossible without platinum. Also, the photographic industry has depended on silver although the use of digital cameras has made a difference in recent years; the standard of dentistry has benefited greatly from the use of all the major precious metals; and drugs based on gold, silver, and platinum compounds are widely used in medicine.

Figure A shows the usage of gold in 2006 in various fields of activity. Note the very high proportion used for karat gold jewelry, investment coins, and bullion bars. Figures B, C, and D show the consumption of silver, platinum, and palladium in the various categories, respectively. Although platinum and palladium are important jewelry metals, by far, the major usage is as catalysts in the automobile and petroleum industries.

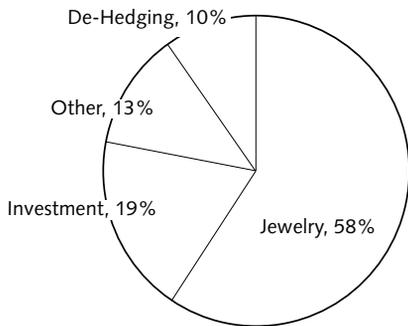


Figure A Gold usage in various activities in 2006.

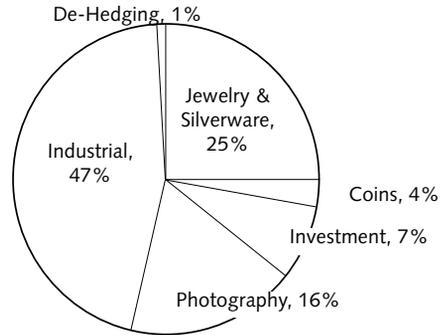


Figure B Silver usage in various activities in 2006.

N.B. De-hedging is a strategy to protect grantors of options on buying and selling gold.

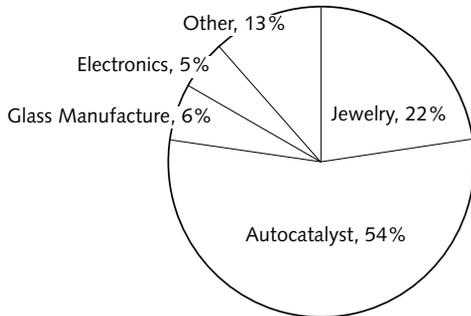


Figure C Platinum usage in various activities in 2006.

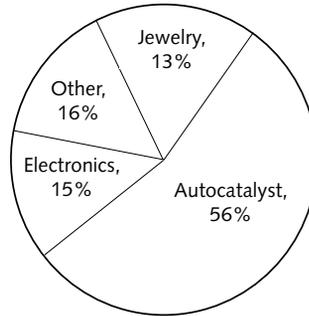


Figure D Palladium usage in various activities in 2006.

Aims and Objectives

The purpose of this book is to:

- Assist jewelers and goldsmiths to develop an awareness of the physical, chemical, and metallurgical nature of the metals and alloys with which they are working. The term “goldsmith” includes those who work also with other precious metals.
- Promote an appreciation of what is happening when metals and alloys are cast and/or worked and annealed.
- Help in understanding why alloying affects the properties of pure metals such as their strength, ductility (malleability), resistance to chemical attack, color, etc.
- Enable jewelers and goldsmiths to recognize the causes of some of the defects and failures that can occur during processing, so that when they do arise, it is easier to prevent their occurrence, or to determine a remedy, or at least to know when advice should be sought on metallurgical questions.

Since this book is written primarily for jewelers and goldsmiths, it will concentrate on the precious metals and their alloys and on the process technology used in the production of jewelry and decorative metalware.

The scientific approach to an understanding of the nature of metals and alloys and of their physical, chemical, and metallurgical properties is of relatively recent origin. It is only about 150 years ago that the metallurgical microscope was developed enabling humans to explore the microstructure of metals and so to discover the effects of alloying on microstructure and mechanical properties. Also, it is only within the 20th century that the advent of X-Ray diffraction analysis and the development of the electron microscope have permitted

us to discover the arrangement of atoms in a crystal lattice and to understand the way in which metal crystals are deformed during mechanical working processes, such as the production of sheet, wire or tube, or raising a bowl in the studio. Sophisticated instruments capable of measuring a wide range of physical and mechanical characteristics of metals are also of relatively recent origin.

The contemporary metalsmith can rightly claim that in a practical sense, his or her profession has been highly regarded from as early as about 4000 BC as outlined by the examples given above coupled with the writings of people like the 12th century monk Theophilus and the great Italian goldsmith Benvenuto Cellini. The metalsmith then may ask quite reasonably “With all this wealth of knowledge and expertise that has been passed down to us through the centuries, why should it be necessary or advantageous to study the basic metallurgical principles underlying the use of the precious metals and their alloys?”

Practical experience in working with metals is undoubtedly the best teacher, but it is when things go wrong that the exact nature of the problem may not be easily understood without some knowledge of metallurgy and process technology. For example, when castings have unacceptable levels of porosity, or fracture has occurred either when working the metal or even after sale to a customer. I am reminded of a motto that hung on the wall at the back of a large hall in a polytechnic in Chennai (South India) that had a jewelry school. It read:

“Theory without practice is fruitless, but practice without theory is rootless.”

This may be particularly true when one considers the impact of modern technology

on the jewelry trade. For example, even in small-scale manufacturing companies, investment casting machines are producing a hundred or more ring shanks or other small objects in one cast, furnaces with protective gas atmospheres are used for heat treating and soldering large numbers of items, and mechanical processes are used in the manufacture of semi-finished products such as sheet, strip, rod, and wire. In these circumstances, it is imperative for economic reasons that any problems are rapidly dealt with. Similar arguments can be applied equally to the metalsmith working at the bench on an item that has been commissioned.

It is not the intention of the author to expect every jeweler and goldsmith to become a fully-fledged metallurgist but simply to provide some understanding of the principles underlying the materials and processes they use to make jewelry and silverware. They may not always have an answer to all the problems they meet, but if they recognize that they are likely to have a

metallurgical origin, then they are in a better position to ask an expert for help.

This book is roughly in three parts. The opening chapters are concerned with the physical, chemical, and mechanical characteristics of metals and their alloying behavior. The second part deals specifically with the precious metals and their alloys and their relevance to jewelry and decorative metalware. The third part concentrates on the practical aspects of manufacture and process technology.

Throughout this book the values for weight, length, strength, etc. are generally given in SI (scientific international) units unless stated otherwise, i.e., tonnes or grams, millimeters or meters, newtons per square millimeter, etc. However, the weight of a precious metal is often expressed in troy ounces, which is traditional and persists to the present. This is different from the imperial system with which many may be familiar, namely, "avoirdupois." A troy ounce is equivalent to 31.1035 grams and one metric ton (tonne) contains 32150.72 troy ounces.

Further Reading

T. Green, *The Gold Companion*, Published by MKA Finance S.A., Geneva, Switzerland, Revised Edition 1997.

Chapter One

Physical Properties of the Precious Metals

The eight individual pure precious metals are chemical elements, i.e., they cannot be split up into simpler substances. All the atoms of an element have a similar structure but are different to atoms of another element. There are 92 elements naturally occurring in the earth's crust and atmosphere ranging from the gas hydrogen (H), with atomic no. 1, to the metal uranium (atomic no. 92). In addition, there are a number of man-made elements produced in atomic reactors having atomic numbers greater than 92 but they need not concern us here.

The Periodic Table of Elements

In 1869, the Russian chemist Dmitri Mendeleev published the Periodic Law that states "the properties of elements are in periodic dependence on their atomic weights." Many physical and chemical properties of elements obey this law and it was possible for Mendeleev to arrange the known elements in the form of a table, a modern version of which is shown in Figure 1.1.

Vertical columns, known as Groups contain elements that show a strong family resemblance with regards to their physical and chemical characteristics. For example, Group 1b consists of the elements copper (Cu), silver (Ag), and gold (Au), and

although copper is regarded as a base metal, as distinct from the precious metals silver and gold, its behavior is similar in many respects and, as will be seen in Chapter 5, it only just misses out on being a precious or noble metal.

Horizontal rows, known as Periods, also have important features in common. Note, particularly that the six platinum-group metals (PGMs) form a block in the center of the table together with iron (Fe), cobalt (Co), and nickel (Ni). This block is referred to a Group VIII.

Each element is numbered in ascending order from top to bottom and from left to right. This is the atomic number, mentioned above, and it tells us something about the nature of the atoms of each element. An atom consists of a nucleus made up of electrically-positive charged particles called protons and electrically-neutral particles called neutrons, together, with electrically-negative charged particles called electrons. For simplicity, the electrons can be considered to orbit the nucleus in a series of layers or shells. Since the atom is electrically neutral overall, the number of protons is equal to the number of electrons, and this number is the atomic number. Hence, for example, gold with atomic number 79 will have atoms with 79 protons in their nuclei and 79 electrons in

Group	I a	II a	III a	IV a	V a	VI a	VII a	VIII										I b	II b	III b	IV b	V b	VI b	VII B	0
Period 1																				1 H	2 He				
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne							
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar							
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Ni	28 Co	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr							
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe							
6	55 Cs	56 Ba	57-71 *R.E.	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn							
7	87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	Transuranic Elements																		

Figure 1.1 - The Periodic Table of Elements

* Rare Earth Metals

a series of shells around each nucleus. The atoms of one element, therefore, differ from those of another and, because many physical and chemical properties such as color, chemical reactivity, and reflectivity depend on the atomic structure, these characteristics vary from one element to another. The periodicity discovered by Mendeleev and others arises from the fact that similarities in electron orbit configuration periodically reoccur with ascending atomic number, hence, the similarities in certain properties in elements within a group.

The elements are assigned chemical symbols. Metals that have been known before Roman times have symbols relating to their Latin names. For example, the symbol for copper is Cu from the Latin word *cuprum*, gold is shortened to Au from *aurum*, and silver is shortened to Ag from *argentum*. The same is true for iron (Fe) and lead (Pb). About $\frac{3}{4}$ of the 92 elements are metals and they are characterized by their ability to give up their outermost electrons and the way their atoms bond together. The remaining elements are gases and non-metals.

It is interesting to note that when Mendeleev constructed his Periodic Table there were a number of gaps due to undiscovered elements. The publication of the Table and Law enabled researchers to predict and find many of these elements, germanium (Ge) being a case in point.

It will be apparent that there should be an increase in the weight of each atom (atomic weight) with atomic number since the number of protons, electrons, and incidentally, neutrons are increasing almost without exception. The atomic weight of an atom is almost entirely made up from the nucleus, i.e., the weights of the protons and the neutrons. This is because the weight of an electron is only about $\frac{1}{1800}$ of that of the electrically equivalent proton. A neutron has about the same weight as a proton. Atomic weight is on a comparative scale using the standard of 12 as the weight of a carbon atom, which has 6 protons and 6 neutrons in its nucleus. Table 1.1 gives the atomic numbers and weights of the precious metals with their atomic sizes assuming the atoms are spheres of a certain radius. The

Element	Chemical Symbol	Atomic Number	Atomic Weight	Atomic Radius(nm)*
Silver	Ag	47	107.87	0.1443
Gold	Au	79	196.97	0.1442
Ruthenium	Ru	44	101.07	0.1340
Rhodium	Rh	45	102.91	0.1369
Palladium	Pd	46	106.40	0.1347
Osmium	Os	76	190.20	0.1337
Iridium	Ir	77	192.20	0.1356
Platinum	Pt	78	195.09	0.1386

Table 1.1 Atomic characteristics of the precious metals.

*One nanometer = 10^{-9} meters.

alloying behavior of metallic elements is partly determined by the atomic radii and the atomic size mismatch of the elements present in the alloy. These factors also influence the strength of the alloy.

Crystal Structure

For our purposes, we can consider atoms to be very small spheres, the radii of which depend on the individual element. Obviously, to make a lump of metal that can be handled, a very large number of atoms must be brought together and bonded in some way.

Before going on to discuss bonding and crystal structure it is important to distinguish between atoms and molecules. Too often, I hear jewelers and metalsmiths refer to the molecules of a metal when they should be talking about atoms. Metals do not exist in molecular form in the way that gases such as oxygen and hydrogen or substances like water and certain chemical compounds do. Molecules are generally specific combinations of atoms e.g., oxygen gas consists of molecules each containing two atoms of oxygen; ozone gas has molecules of three atoms of

oxygen; the water molecule is two atoms of hydrogen to one atom of oxygen. Water coming out of a tap will consist of a very large collection of those molecules. A solid chemical compound can be considered to be molecular in the sense that they exist in certain atom combinations. For example, the compound calcium sulphate hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$), better known as gypsum (an important constituent of lost wax investment powder) has the combination of one atom of calcium to one atom of sulfur and four atoms of oxygen with half a molecule of water. Even so, it will have a crystal structure as all true solids do. On the other hand, pure metals and most alloys exist as a collection of atoms and not as specific combinations of atoms. The only exception is in the case of intermetallic compounds (see later in Chapter 6) where it is true that the compound has a fixed, or nearly-fixed, ratio of atoms of one metal to another.

Let us now return to the subject of crystal structure of metals and alloys. At very high temperatures, a metal will vaporize. Its atoms will be far apart and will not take up any structural form. As the

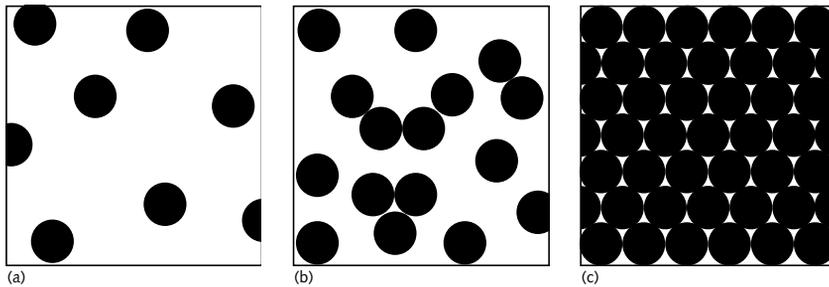


Figure 1.2 Atomic arrangement of a) Gases, b) Liquids, and c) Solids; the three states of matter.

temperature is lowered, the vapor condenses to a liquid in the same way that water vapor condenses to steam (minute water droplets) and liquid water. In a quantity of liquid, the atoms are loosely held together in a random fashion. There is a rudimentary structure of small clusters of atoms that are continually breaking up and the atoms move relatively easily to form new clusters. As the temperature drops still further, the liquid freezes to form a solid and all the atoms take up positions in a regular geometric array known as a “lattice” to form a crystal structure characteristic of that particular substance. A two-dimensional representation is shown in Figure 1.2.

All true solids have a regular crystal structure whether they are metals or non-metals. The main factor that distinguishes metals from non-metals is the manner in which their atoms are bonded in the lattice. Metals have a special form of bonding known as “metallic bonding” in which the atoms are not so tightly held as in chemical compounds (ionic bonding) or as in carbon in the form of diamonds (covalent bonding). With metallic bonding, the outermost electrons of the atoms float throughout the lattice as an electron cloud. It is this type of bonding that is responsible for the characteristics of ductility (malleability), toughness and good electrical and thermal conductivity. Solids

that are ionic- or covalent-bonded may be strong and hard but they are not ductile and will shatter if subjected to a sufficiently high force as in a hammer blow.

There are fourteen ways in which spheres can be packed together to form a regular geometric array. The vast majority of metals fall into one of three categories. The precious metals, with the exceptions of osmium and ruthenium, have a lattice in which the unit cell or basic building block is known as face-centered cubic (f.c.c.). This structure has an atom at each corner of the cube and one in the center of each face (Figure 1.3). If other similar cells are added on in all three directions ad infinitum, a single metal crystal can be built up that is sufficiently large enough to handle (Figure 1.4). It will be noticed that the corner and face atoms are shared between adjacent cells.

Apart from gold (Au), silver (Ag), platinum (Pt), palladium (Pd), iridium (Ir) and rhodium (Rh), other f.c.c. metals include aluminium (Al), copper (Cu), nickel (Ni) and lead (Pb). For reasons that are too complex to discuss in this book, the f.c.c. metals have very good malleability and ductility as will be recognized from the above list. Osmium (Os) and ruthenium (Ru) are exceptions in that their lattice is close-packed hexagonal (c.p.h.). The c.p.h.

lattice (Figure 1.5) often displays limited ductility. Indeed, osmium and ruthenium are notoriously difficult to fabricate and, consequently, their industrial uses are somewhat limited. Other examples of c.p.h. metals are zinc (Zn), cadmium (Cd) and magnesium (Mg).

A third common occurrence category is the body-centered cubic lattice (b.c.c.). Again, the unit cell is a cube with an atom at each corner but with an atom also at the center of the cube instead of in each face (Figure 1.6). Examples of b.c.c. metals are chromium (Cr), tungsten (W) and molybdenum (Mo).

A few metals can display more than one type of crystal structure. The most notable examples are iron (Fe) and titanium (Ti). Iron is b.c.c. (ferritic) up to 910°C (1670°F) where it changes to f.c.c. (austenitic) simply by the atoms moving positions in the solid

state. At approximately 1400°C (2552°F) it changes back again to the b.c.c. form and remains so up to the melting point of 1535°C (2795°F). It is the ferrite to austenite change that is responsible for the fact that steels, which are alloys of iron, can be heat treated and hardened. Titanium is c.p.h. up to 885°C (1625°F) where it changes to b.c.c.. These metals are said to undergo an “allotropic transformation.”

However, it is the precious metals and their f.c.c. crystal structures that mainly concern us. What then is the difference between their f.c.c. lattices? Because the sizes of their atoms vary from one metal to another, the dimensions of the unit cell will also vary. The length of a cube edge for gold for instance, will be different from that of platinum or silver. Crystallographers can measure the cell dimensions by X-Ray diffraction analysis and refer to the dimensions as the “lattice parameters” for the particular metal. It is only necessary to quote the cube edge parameter “a” for the f.c.c. and b.c.c. metals whereas the c.p.h. metals have the parameter “a” for the length of the side of the hexagon and the “c” parameter for the height of the cell (Table 1.2).

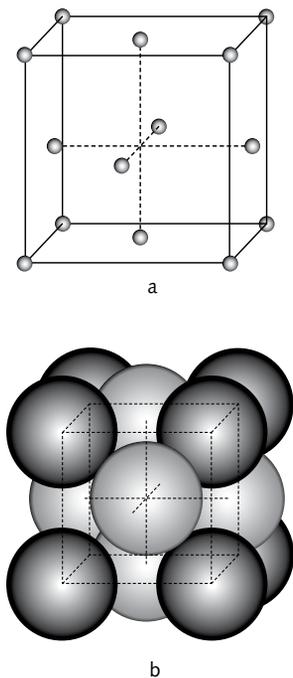


Figure 1.3 The face-centered cubic (f.c.c.) cell represented by a) points and b) spheres where each face-centered atom touches its nearest corner atoms.

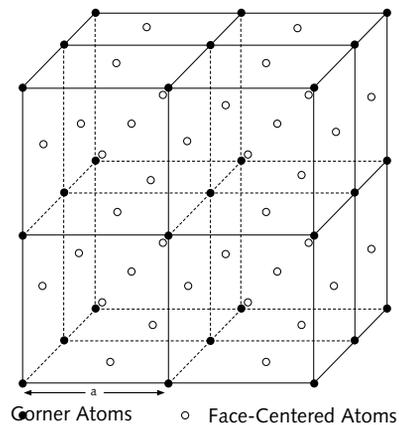


Figure 1.4 A block of eight face-centered cubic cells illustrating the way a crystal is built up.

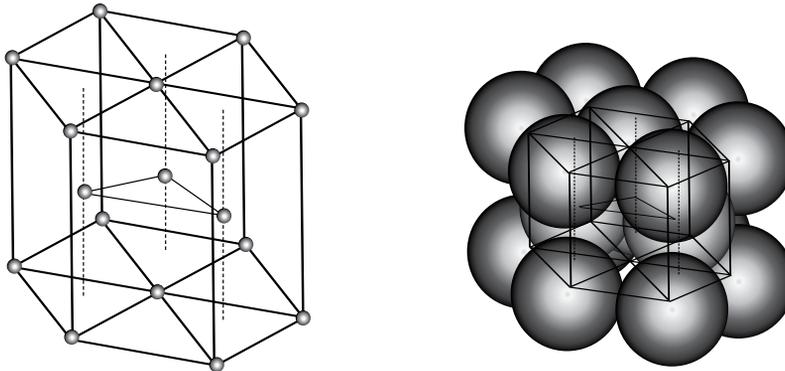


Figure 1.5 The close packed hexagonal (c.p.h.) cell. All atoms on the base and the top planes are in contact with each other on that plane and the atoms on the intermediate plane nest on three of the six niches so formed.

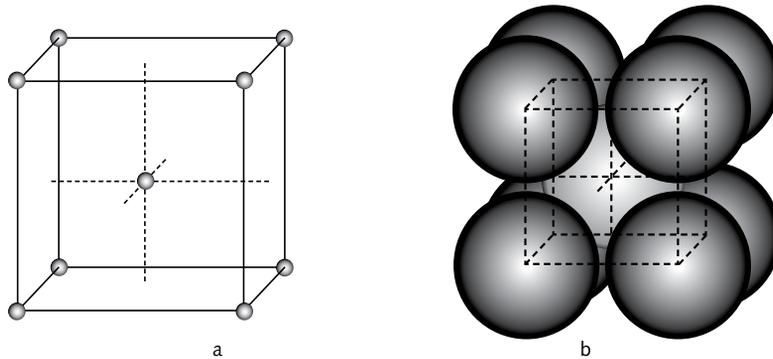


Figure 1.6 The Body Centered Cubic (b.c.c.) Cell. The center atom touches each corner atom, but these do not touch each other.

Density

The density of a substance is defined as its weight per unit volume and it is usually expressed in grams per cubic centimeter (gcm^{-3}) although the preferred International System of Units (SI unit) is kg m^{-3} . Density is a function of both atomic weight and crystal structure. Therefore, elements with high atomic weights usually have high densities, particularly if their atoms are closely packed together in the lattice. Both the f.c.c. and the c.p.h. structures represent the closest form of atomic packing of all types of lattice. Consequently, it is not surprising to find

that gold, osmium, iridium, and platinum are regarded as heavy metals (Table 1.3). Temperature also affects the density value because the crystal structure expands on heating. Density values are usually quoted for measurements taken at 0°C or 20°C (32°F to 68°F) on fully annealed metal.

To put the importance of density into context, consider an item of jewelry made in either sterling silver or 22 karat gold. Each contains almost identical amounts of silver or gold at $\sim 92.5\%$. The density of gold is nearly twice that of silver, hence the item

Metal	Structure	Lattice parameter (nm)	
Gold	f.c.c.	0.40786	
Silver	f.c.c.	0.40862	
Platinum	f.c.c.	0.39229	
Palladium	f.c.c.	0.38029	
Rhodium	f.c.c.	0.38906	
Iridium	f.c.c.	0.38392	
		a	c
Osmium	c.p.h.	0.27340	0.43194
Ruthenium	c.p.h.	0.27056	0.42816

Table 1.2 Crystal structure and lattice parameters.

* The close packed hexagonal (c.p.h.) cell has two characteristic dimensions and hence two parameters must be stated. The parameter for the f.c.c. cell is the length of the cube edge.

will weigh almost twice as much in 22k gold as in silver. Similarly, a platinum ring of 950 fineness will be heavier than an 18k gold ring of the same design and dimensions. It is also an important consideration when costing items for manufacture and sale as precious metal content, density, and price per troy ounce have to be taken into account.

Metal	Density (g cm ⁻³)
Gold	19.32
Silver	10.49
Platinum	21.45
Palladium	12.02
Rhodium	12.41
Iridium	22.65
Osmium	22.61
Ruthenium	12.45

Table 1.3 Density values for the precious metals at 20°C.

Melting and Boiling Points

The melting (freezing) temperatures of silver, gold, palladium, and platinum are of special interest and of great practical importance because they are used as primary and secondary fixed points on the International Practical Temperature Scale from which all temperature-measuring devices are calibrated. This scale is periodically revised, the latest being in 1990, as standards of purity and measuring techniques are improved. The precious metals are chosen as reference points because they are produced to a high degree of purity and are free from contamination by oxidation.

Boiling points are more difficult to determine and a wide variation in values has been reported in the technical literature over the years. The values quoted in Table 1.4 are the currently accepted values. However, boiling points are of little interest to metalsmiths.

Metal	Melting Point (°C)	Boiling Point (°C)
Gold	1064	2807
Silver	961	2212
Platinum	1772	3827
Palladium	1552	2927
Rhodium	1966	3727
Iridium	2410	4527
Osmium	3045	5027
Ruthenium	2250	3900

Table 1.4 Melting and boiling points of the precious metals.

Optical Properties

Much of the fascination of gold throughout the ages has been due to its beautiful yellow color and the high luster or reflectivity that can be retained indefinitely because of its resistance to corrosive attack by the environment. Copper is the only metal besides gold with a characteristic color, but unfortunately it lacks the corrosion resistance of gold. Similarly, the aesthetic appeal of silver largely arises from its brilliant white color and very high reflectivity. It has the highest reflectivity of all metals. Unfortunately, the tarnishing behavior of silver limits its usefulness as a reflector.

The colors of gold and copper result from a sharp increase in reflectivity within a narrow band of increasing wavelength of incident light falling on the surface of the metal. Reflectivity (R) is low at the blue end of the visible light spectrum, (wavelength less than 500 nanometers (nm)) but rises dramatically at the yellow-red-infrared end of the spectrum (500–1200 nm). This change in reflectivity is associated with the nature of the electron configurations in the atomic structures of gold and copper but a detailed discussion is beyond the scope of this book.

Figure 1.7 shows the relationship between R (on scale 0 to 1, where one equals 100%, and wavelength for gold, silver, rhodium, and platinum. Silver has a high R value over the entire visible light spectrum which accounts for its brilliant white luster. Of the PGMs, rhodium has the highest reflectivity, with a mean value of about 80%. That, coupled with a lack of tarnishing behavior, makes it eminently suitable as an electroplated finish for silver and the so-called white golds.

The optical properties of gold are profoundly altered by alloying and this is of considerable importance to the jeweler

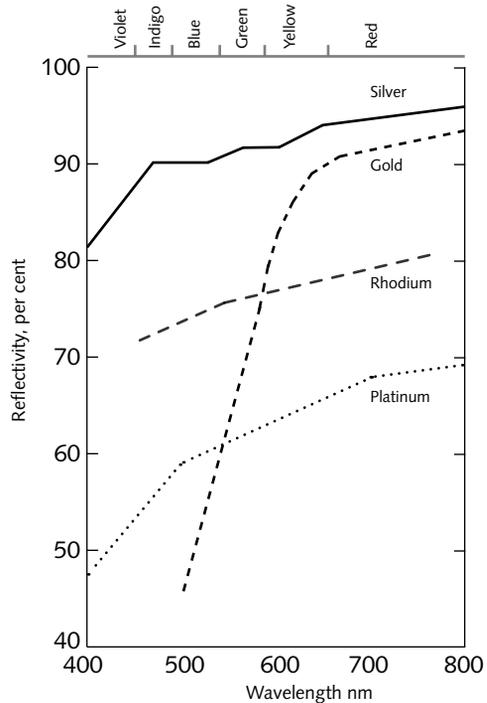


Figure 1.7 Reflectivity in precious metals.

and goldsmith. The effect of alloying on the color of the karat gold alloys will be discussed more fully in Chapter 9. Much interest has been shown in standardizing colors for gold alloys. The European watch industry adopted a coding system particularly for electroplated watchcases although it has also been applied for wrought alloys (Table 1.5). In recent years, a quantitative system of color measurement has been developed that enables alloy manufacturers and jewelers to give a better definition of the color of their products. It is the CIELAB system which measures color in terms of space coordinates L^* , a^* and b^* using a color spectrophotometer. L^* measures the black (0) – white (100) coordinate. Metals with a high reflectivity or whiteness will have values approaching 100. The a^* coordinate goes from $-a^*$ values representing a green