Explainer: Alloys

In this explainer, we will learn how to describe the formation and the applications of alloys and the effect of alloying on the properties of metals.

Humans have been knowingly combining different elements to produce more desirable alloys for several thousands of years. The ancient Sumerians were producing bronze alloys as early as five and a half thousand years ago, and some archaeologists have found bronze artifacts in Neolithic Majiayao culture sites. Humans have been continuously alloying different pure metal elements for what seems to be all of recorded history because alloying is a relatively simple process that can transform a relatively unuseful metal into a much more useful metallic composite substance.

Alloys always contain at least one metal element and another element that can be a metal or a nonmetal substance. Alloys are sometimes described as being metallic solid solutions. This is partly because they are a solid composite material that contains at least two different chemical elements. It is also because the different types of alloy atoms are arranged somewhat similarly to atoms in a liquid solution. The atoms of at least one chemical element are dispersed throughout the lattice of another metal element.

Definition: Alloys

Alloys are metallic solid solutions that contain at least two different types of elements.

Example 1: Describing Alloys

Which of the following is the best description of an alloy?

A. A solid solution of one or more elements within a pure metal
B. A mixture of two or more nonmetals
C. A pure metal
D. The product of smelting
E. A material made by alternating layers of different materials

Answer

Alloys always contain at least one metal element and another element that can be a metal or a nonmetal substance. Alloys are sometimes described as being metallic solid solutions. This is partly because they are a solid composite material that contains at least two different chemical elements. It is also because the different types of alloy atoms are arranged somewhat similarly to atoms in a liquid solution. The atoms of at least one chemical element are dispersed throughout the lattice of another metal element. These statements can be used to determine that A is the correct answer for this question.

It is generally accepted that bronze is the first alloy produced by humans. Prehistoric societies produced bronze alloys from unrefined copper ore. They would initially heat the copper ore to drive off undesirable impurities, and they would then combine the refined copper product with other metal elements such as tin and arsenic. This process was used to make bronze blocks. Masons would take those bronze blocks and they would reshape them to produce sculptures and weapons.

Bronze has a characteristic reddish-brown color, and it tends to be much harder than pure copper metal. It also tends to be much less ductile and much less malleable as well. Bronze is highly resistant to most forms of corrosion, and it is currently used to make the components of ships and other types of seafaring vehicles. The alloy has a unique set of mechanical properties that make it suitable for many maritime and seafaring applications.

Definition: Ductile Materials

Ductile materials are ones that can be drawn out into long and thin wires without breaking.

Bronze has an unusually low friction parameter. It is ideally suited for designing certain components of automotive vehicles. The substance is used to make sleeves of metals that can be placed next to axles. The sleeves have a low friction parameter, and they help adjacent axles rotate smoothly. Some forms of bronze have been designated names like bearing bronze because they are used so frequently to make mechanical bearing components.

Example 2: Identifying the Alloying Element in Bronze

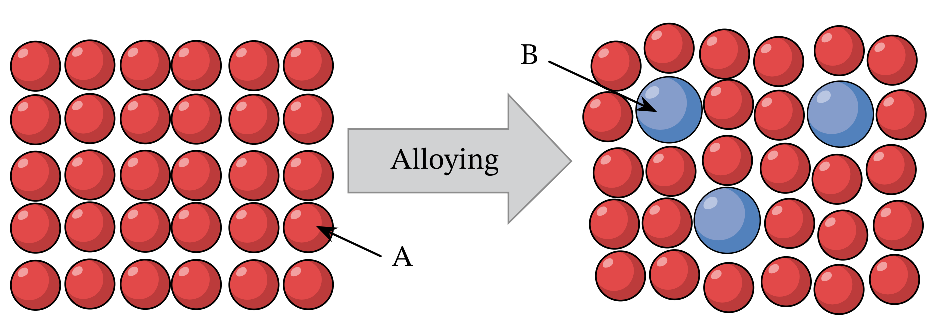
Fill in the blank: Bronze is an alloy of copper and ______.

A. lead
B. zinc
C. tin
D. iron
E. nickel

Answer

Bronze is a reddish-brown alloy that can be made by mixing copper with other metals such as tin or arsenic. The list does not include the arsenic element, but it does include the tin element. The correct answer must be tin because the other metals cannot be combined with copper to make bronze. C must be the correct answer for this question.

Pure metal elements are usually described as being malleable and ductile because they are made up of atoms that are all essentially the same size. The similarly sized atoms are arranged into a relatively simple three-dimensional lattice, and it is easy for one layer of pure metal atoms to slide over another layer of pure metal atoms. Alloys are usually described as being much less malleable and ductile because they are made up of at least two different types of atoms and the alloy atoms are not arranged into one simple lattice. Each layer of alloy atoms can have its own unique structure that differs from every other layer, and it is much more challenging to push one layer of alloy atoms over another layer of alloy atoms. The irregular arrangement of atoms in alloys also explains why they are usually stronger and harder than pure metals. The following figure shows how the simple lattice structure of one metal element (A) can be disrupted if it is mixed with a second altogether different metal element (B).

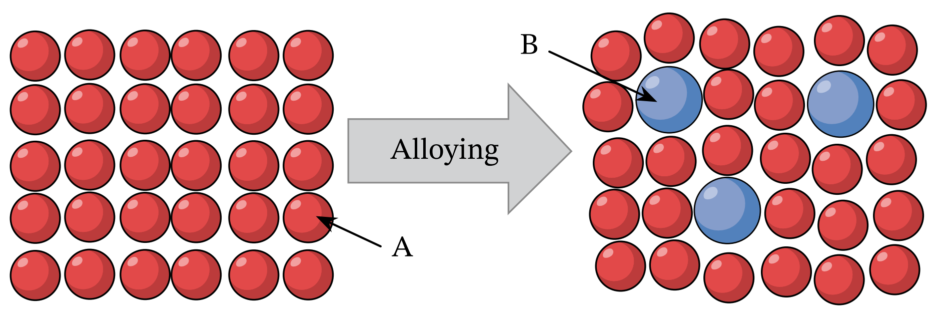


Definition: Malleable Materials

Malleable materials are ones that can be hammered or pressed into different shapes and thin sheets without breaking or cracking.

Example 3: Effect of Alloying on Malleability

Illustrated in the diagram is the alloying of a metal A with small amounts of element B. The malleability of the alloy differs from that of pure metal A.



1. Which of the following is the best definition of malleability?
    A. Ability to be hammered or rolled into sheets
    B. Ability to be drawn into thin wires
    C. Resistance to stretching and compression
    D. Resistance to breaking under an applied force
    E. Resistance to cracking under a sudden impact
2. Based on the diagram, how and why does the malleability of the alloy differ from that of pure metal A?
    A. Malleability is higher because atoms of B occult a larger volume.
    B. Malleability is lower because the atomic arrangement is less uniform.
    C. Malleability is lower because dissimilar atoms interact more strongly.
    D. Malleability is higher because atoms of B interact with a larger number of neighboring atoms.
    E. Malleability is lower because it is more difficult for layers to move over each other.

Answer

Part 1

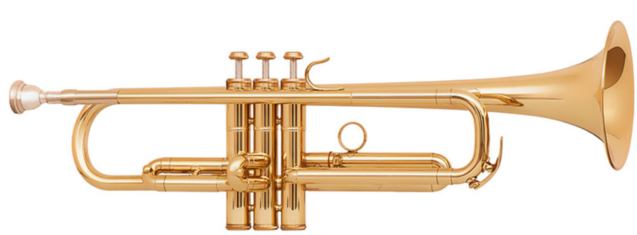
Malleable materials are ones that can be hammered or pressed into different shapes and thin sheets without breaking or cracking. This definition is very similar to answer A; therefore, we can conclude that the first part of this question should be answered with A.

Part 2

It is easier for one layer of metal particles to slide over another layer of metal atoms if all the metal atoms have a similar size and are arranged in a simple three-dimensional lattice. Pure metal elements are usually more malleable than alloys because pure metal elements are made up of what are essentially identical atoms. This description is very similar to answer E, so we can determine that E is the correct answer for the second part of this question.

Brass is thought to have first been manufactured sometime around the year 500 BC, although there are a few examples of archaeologists discovering calamine brass artifacts that are thousands of years older. Brass has a characteristic yellow color that is somewhat similar to the color of pure gold, but brass metal is usually much less lustrous and much less valuable. Brass is usually made by combining pure copper metal with zinc in an approximate 2 : 1 weight ratio.

Brass is significantly more malleable than bronze, and it is regularly beaten into long and complex shapes to make lustrous instruments that have exceptional acoustic properties. The alloy is also more malleable than pure copper or zinc metal. Brass has also been used a lot during the last two and a half thousand years to make decorative ornaments because it is much cheaper than pure gold and also quite easy to sculpt and reshape. Brass is still used even today to make gears and hinges because it has very low friction parameters and can also be designed to be highly resistant to most forms of corrosion.



Definition: Lustrous Materials

Lustrous materials are ones that can reflect light evenly and efficiently without glitter or sparkle.

Brass has a relatively low electrical conductivity value. It has a much lower electrical conductivity value than pure copper, and it tends to be unsuitable for making electrical wires. Pure copper metal has an electrical conductivity of 6.0×10^7 S/m, and brass alloys have electrical conductivity values that tend to be no lower than 1.0×10^7 S/m and no higher than 2.2×10^7 S/m. Copper metal has become very valuable during the last few decades because it has such a high electrical conductivity value. Pure copper usually ends up being much more expensive than brass and other types of copper-based alloys.

Example 4: Identifying the Alloying Metal in Brass

Fill in the blank: Brass is an alloy of copper and ______.

A. nickel
B. tin
C. iron
D. lead
E. zinc

Answer

Brass is a yellow alloy that is usually made by combining pure copper with zinc in an approximate 2 : 1 weight ratio. The list shows five different types of elements, and only one of these is zinc. Zinc is listed as answer E. We can use these statements to determine that E is the correct answer for this question.

Bronze and brass are just two types of alloys that can be made by mixing copper with another pure metal element. Copper can similarly be combined with nickel to make a copper–nickel metal alloy that is colloquially known as cupronickel. Cupronickel is quite an interesting copper metal alloy because it has a melting point of 1 171°C. Bronze and brass have a melting point of 900–950°C, and copper has a melting point of 1 085°C. Cupronickel has a higher melting point than copper, whereas bronze and brass have a lower melting point.

Cupronickel has a rather uninteresting silver color, and it is almost never used to make decorative items. But it does have at least a few interesting applications. It is highly resistant to salt water, and it is regularly used to make piping and heat exchangers for seawater systems. Cupronickel can even be used to make the propellers and hulls of expensive boats and the supporting structural components of desalination plants and offshore oil platforms. Some countries have also used the highly corrosion-resistant cupronickel alloy to make coin currencies like the Swiss franc and the South Korean 500- and 100-won coins.

Gold is a highly precious metal that has been revered and highly desired by almost all cultures for thousands of years. It is a highly lustrous metal that has a pleasing aesthetic appearance, and many societies have used it as a form of currency or as a means to regulate the value of bank notes. Pure gold is generally not suitable for making most small trinkets and small pieces of jewelry because it is too malleable and not hard enough on its own. Gold is usually combined with a small amount of pure metal elements like copper or nickel to make it harder and more corrosion resistant. The content of the alloying metal is usually kept low because gold alloys look less and less like gold as the content of the other alloying metal is increased. Pure gold (24-carat gold) has an attractive and highly desirable golden hue, but gold alloys have a much less desirable color that is some combination of yellow and either brown or silver.

Example 5: Use of Gold Alloys in Jewelry

Jewelry is often produced from alloys of gold with copper and nickel. Which of the following properties is **not** improved by alloying gold with these metals for jewelry making?

A. Color

B. Cost

C. Corrosion resistance

D. Hardness

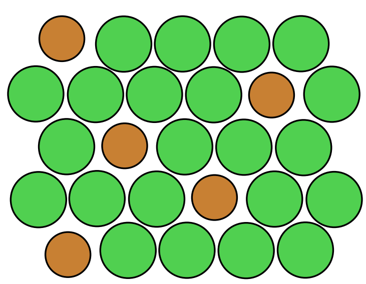
E. Strength

Answer

Gold can be combined with other metals like copper to make an alloy that is mechanically robust and highly resistant to most forms of corrosion. The price of gold alloys is relatively low because they contain relatively inexpensive metals. There are clearly good reasons to combine gold with other metals, but it is important to realize that the quantity of the alloying metal is usually kept quite low. Gold loses its aesthetically pleasing golden color if it is mixed with too much of another alloying element such as copper. We can use this information to determine that A must be the correct answer for this question.

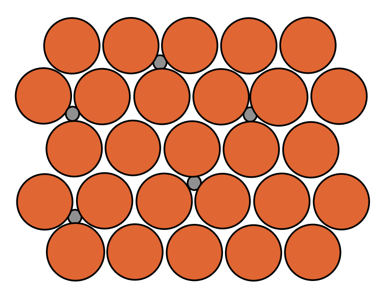
Alloys like brass and bronze are called substitutional alloys because they contain two different types of atoms that have similar bonding characteristics and not altogether different diameters. The atoms of one substitutional alloying metal can effectively take the place of the other metal element atoms, and this exchange of lattice positions can make a new composite lattice that has an irregular three-dimensional shape and structure.

Interstitial alloys have an altogether different shape and structure because they generally contain atoms that have very different bonding characteristics and different diameters. The two different element atoms cannot freely exchange lattice positions, and one of the atom types ends up occupying cavity positions in between the neatly aligned lattice of the other element. Steel is one example of an interstitial alloy that is made from a relatively high percentage of iron atoms and a relatively low percentage of carbon atoms. The carbon atoms cannot occupy the lattice positions of the iron atoms, and they must instead occupy positions in between the metallically bonded iron atoms.



Substitutional solid soln
(e.g., Cu in Ni)

Or



Interstitial solid soln
(e.g., C in Fe)

Steel has been used for more than one hundred years to make transport vehicles and large buildings because it is much stronger than pure iron and neither expensive nor challenging to make in large steelmaking plants. Iron can also be combined with a small amount of carbon and other metals like chromium to make stainless steel. Stainless steel is very stiff and strong, but it is also highly resistant to most forms of corrosion. Scientists have shown that a steel alloy can be harder and stronger if it has a higher carbon content. Soft steel alloys, like mild steel, are approximately 0.05%–0.30% carbon, and harder stainless steel alloys have a carbon content closer to 1%. The higher carbon content makes steel stronger but also makes it more brittle because it makes it less malleable. Stainless steel is used to make advanced medical and aeronautical equipment that needs to be both hard and corrosion resistant.

Example 6: Determining How to Classify Steel

Fill in the blank: Steel, a solid solution consisting of carbon atoms seated in the holes of an iron atom structure, is an example of ______.

A. an alkali metal

B. a pure metal

C. a substitutional alloy

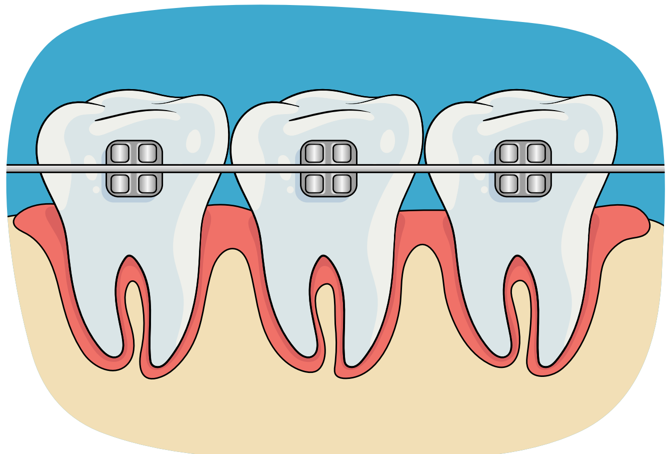
D. an interstitial alloy

Answer

Steel is an interstitial alloy that is made of carbon and iron. Iron is a metal element, and carbon is a nonmetal element. Carbon atoms cannot occupy the same lattice positions as iron atoms in a metallic-bonded iron lattice. The carbon atoms tend to occupy positions in between the metallically bonded iron atoms. We can use this information to determine that D must be the correct answer for this question.

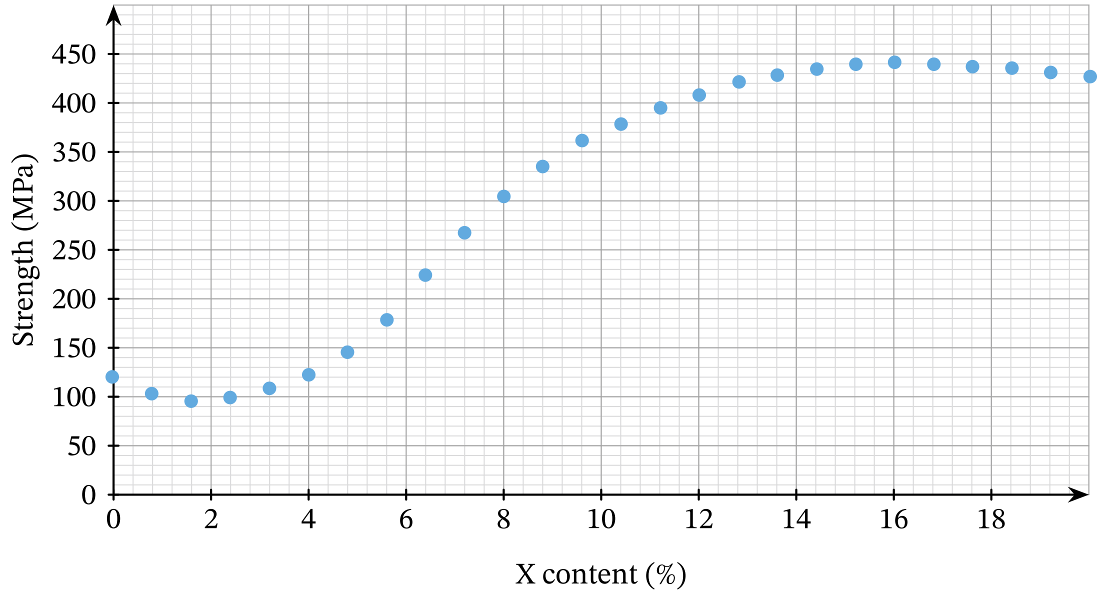
The first duralumin alloys were discovered just over one hundred years ago. Duralumin alloys are substances that ordinarily contain a large amount of aluminum metal and a relatively small amount of copper. They can also contain a small percentage of other pure metal elements such as 0.3%–0.9% manganese or 1.2%–1.8% magnesium metals. Duralumin alloys tend to be light because they contain so much aluminum metal. They also tend to be hard because they contain alloying metals like copper. Manufacturers regularly vary the abundance of aluminum and copper in duralumin alloys to change the density and strength of these alloys. The strength of duralumin alloys can be increased through age-hardening processes or particle-hardening processes. Heat treatment processes can be used to make duralumin alloys just as strong as soft steel. Duralumin alloys have been used to make planes and aircraft components because they are light and have high strength-per-unit-weight values. Duralumin metals are strong, and they rarely end up being cracked or fractured if they are affected by medium-to-high strength forces.

Scientists have progressively realized how the properties of two elements can be combined in different ways to make new composite materials that have desirable physical properties. Scientists are now producing so-called smart alloys that have interesting properties like superelasticity. Nitinol is a titanium–nickel metal alloy that was first discovered just a few decades ago, and it is now being used to make dental braces and stents for blood vessels. Nitinol is often described as having shape memory properties because it has a high recoverable strain modulus and returns to one shape if it is deformed. Nitinol is ideally suited for making dental braces because it can continuously apply a weak force to misaligned teeth. It can slowly force teeth to become straight and neatly aligned.



Nitinol alloys are highly resistant to most forms of corrosion, and they will not deteriorate if they are put into different parts of the human body. The alloy has many desirable physical properties, but it is also quite expensive to make and this can limit its application in hospital and orthodontic settings. It also tends to be highly susceptible to metal fatigue. The alloy can become weak and accumulate lots of cracks over time because it contains highly flexible structures that can undergo large structural changes during deformation processes.

Scientists can use graphs to determine how the physical properties of any one alloy type depends on its composition. They can then use this understanding to make new alloy substances that have a set of highly desirable physical properties. The following figure shows how the strength of one alloy type depends on the abundance of an unspecified metal element (X). The alloy type has a relatively low strength value when it contains a small amount of X, and it has a much higher strength value when it contains a relatively large amount of X. The graph can be used to make alloy substances that have strength values between 100 MPa–400 MPa. Comparable graphs can be produced for almost any type of physical property. Graphs can be used to determine the relationship between alloy composition and physical properties like electrical conductivity, malleability, and corrosion resistance.



Let us recap what we have learned in this explainer.

Key Points

- Alloys are metallic solid solutions that contain at least two different types of chemical elements.
- Brass is an ancient alloy that contains copper and tin.
- Bronze is an ancient alloy that contains copper and zinc.
- Alloys have a unique set of physical properties that distinguish them from pure metal elements.
- Cupronickel is a decorative alloy that contains copper and nickel.
- Gold can be combined with a small amount of copper or nickel to make it harder and more corrosion resistant.
- Alloys can usually be described as substitutional or interstitial metallic solid solutions.
- Steel is a very hard interstitial alloy that is made from iron and carbon atoms.
- Duralumin is a strong and lightweight alloy that contains aluminum and copper.
- Nitinol is a titanium–nickel alloy that has a high recoverable strain modulus.