Thomas, B.G., "Metals Processing", Chapter 14 in Structure, Processing, and Properties of Engineering Materials, J. Adams, editor, Addison Wesley, in press.

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Ch. 14

METALS PROCESSING

1. INTRODUCTION

Even if an engineer is not directly involved with materials processing, it is important to know something about how materials are made into parts. A material is not useful until it is processed into a desired shape. Furthermore, the final shape, structure and properties of a component are determined by its processing. Processing can be costly, so the possible shapes and properties of a low-priced part are limited. In addition, processing may be the source of defects in the final product.

One of the advantages of metals is the wide range of economical processes available to alter their shape and properties. The basic processes of extraction, casting, thermal treatment, and deformation are discussed in turn in this chapter in the context of metals. In addition to these processes, manufacturing also involves joining parts together by a variety of methods including welding, brazing, soldering, fasteners, and adhesives. Their shape and surface finish can be altered by mechanical and chemical treatments, such as machining and plating. These are important operations but are beyond the scope of this text.

Steel Production: a case study in metal processing

The manufacture of steel requires a long sequence of processing steps, shown in Figure 14.1. Steel production starts with making iron in a **blast furnace**. Iron ore (most commonly Fe_2O_3) is **charged** (added) with **coke** (carbon) and limestone (mainly $CaCO_3$) to the top of the tall, shaft-like, furnace. Air is blown through the furnace to burn the coke to provide heat as well as CO gas, which reacts with the oxygen in the iron ore to release the iron atoms as liquid metal. The limestone reacts with the waste rock in the ore to form a low-melting slag that floats on top of the iron. The **molten** (liquid) iron is **tapped** (removed) from the bottom of the furnace. This iron is saturated with carbon, (over 4% C) and also absorbs other impurities such as S, P, and Si from the ore, limestone, and coke. This impure product must be refined to make steel. To do this, the metal is usually poured into a large (250 ton) vessel called a Basic Oxygen Furnace, along with scrap iron and slag-forming materials. Bubbling oxygen through the iron bath for a short time (about 30 min.) takes away most of the unwanted carbon as CO bubbles, transforming the iron into steel (0 - 1%C). Other refining stages and alloy additions are made to remove the impurites and adjust the final composition. For example, Al or Si is added to combine with the unwanted excess oxygen. The finished steel is poured into a ladle and then cast. In the past, permanent molds were used to cast large, steel shapes called **ingots**. The more efficient process of continuous casting has recently transformed the steel industry. In this process, the steel moves through a holding vessel, called a **tundish**, and down through a **continuous casting machine**, where it solidifies into long rectangular **slabs**, or square **billets**. These **semi-finished** shapes are processed by sequences of thermal cycling (eg. annealing and cooling), chemical baths, and deformation processes (eg. hot and cold rolling) to produce finished shapes with a wide range of shapes, structures and properties. This procedure is used to produce 90% of the world's steel, efficiently enough for it to be sold for pennies per pound. Similar processes are used to make most other commercial metals. Further details on the many complex thermal processes, or **heat treatments**, possible in steel are described in the next chapter.

Key Concepts

- extraction - production of liquid metal
- casting - solidification of liquid metal into a solid shape
- thermal treatment - sequences of heating and cooling to alter structure and properties
- deformation processing - changing shape, structure, and properties via mechanical working

2. METAL EXTRACTION

The first step in producing metallic parts is to extract the metal from its ores, which usually creates liquid metal with the desired composition. This stage is important because, if not done carefully, the liquid metal can contain too many impurities, detrimental inclusion particles or dissolved gases, which can initiate defects later.

An **ore** is a mineral deposit from which metal can be economically extracted by chemical **reduction**. There are two fundamental approaches to the extraction of metals: 1) produce a relatively impure metal from the ore, which is then refined, or 2) produce a purified mineral from the ore, which is then reduced into a pure metal. Steelmaking is an example of the first approach, described in Figure 14.1.

The production of aluminum from its ore, bauxite, (mainly Al_2O_3) is an example of the second approach. By a series of solution and precipitation steps, a very pure aluminum oxide is produced, which is then melted and reduced to metallic aluminum by electrolysis. Enormous amounts of electricity are required for this process, which makes the recycling of aluminum environmentally as well as economically sound.

After the metal is produced, further processing steps are usually required before it is ready for manufacturing. These steps include **refining**, which removes impurities from the molten metal, and **alloying**, which adjusts its composition.

Example 14.1 - Refining

Gases dissolved during the extraction of molten metal can be removed by **vacuum degassing**, in order to avoid defects during later processing, such as **porosity**. (See Section 14.3C). How much dissolved hydrogen gas could be removed from molten aluminum at 700^{o}C by passing it through a 10^{-4} atm vacuum chamber? Assume the initial ambient environment contains 0.1 atm H_2 (due to high moisture content of the air).

Answer:

First, find the amount of gas that can be dissolved in the molten metal, which is given by Sieverts' law, which is plotted in Figure 14.2 for hydrogen in aluminum:

$$\text{dissolved gas} = K\sqrt{p_{gas}}$$

where p_{gas} is the partial pressure of the gas in the environment above the liquid (atmospheres) and

K is an empirical **equilibrium constant** (wt. ppm at 1 atm) that increases with temperature:

$$K(H\ \ in\ \ Al) = 505\exp\left(\frac{-6255}{T(^{\circ}K)}\right)$$

So, at T = 700^{o}C, $K = 505\ \exp\left(\frac{-6255}{700+273}\right) = 0.816$

and the initial equilibrium H content, $[H] = K\sqrt{p_{gas}} = 0.816\sqrt{0.1} = 0.26$ ppm H in Al.

Next, find the maximum H content in the refined Al produced by the partial vacuum:

$$[H] = 0.816\ \sqrt{0.0001} = 0.008 \text{ ppm}$$

H removed by this high vacuum = 0.26 - 0.008 = 0.25 ppm.

Thus, most of the original dissolved gas can be removed, if sufficient time is allowed to reach equilibrium. Care must be taken to avoid exposing the refined metal to air or moisture after the degassing treatment, or gas may redissolve. Porosity defects will form during solidification if aluminum contains more than 0.1 wt. ppm dissolved H (1 ml H_2 gas / kg).

3. CASTING

The next manufacturing step is to create the basic shape. For almost all metals, this is done by **casting**: liquid metal is poured into a mold cavity, where it transforms, or **solidifies** into a solid of the desired shape.

Sometimes casting produces the final part. Sand casting, for example, is one of the oldest manufacturing processes, dating back thousands of years, and is often still the most economical one. This process is the only way to make certain large complex metal shapes, such as 100 ton turbines for hydro-electric dams, or to manufacture parts from brittle materials, such as gray cast iron.

Usually, the initially-solidified metal shape is an intermediate product requiring further processing steps before becoming a finished part. These steps include remelting and recasting (to change its shape), thermal treatment (to change its properties) and / or deformation (to change both).

Because the manufacturing of metal parts almost always includes a casting process, it is important to understand the fundamentals of solidification and the inherent structure and defects that it can create.

3A. STEPS IN SOLIDIFICATION

Solidification occurs in several stages:

1) **nucleation** , or formation of tiny solid crystals,
2) growth of these crystals into larger crystals called **dendrites**, and
3) further growth into grains, which make up the final solidified structure.

Nucleation and Growth

The first step of metal solidification is the creation of tiny, stable, solid crystals, or **nuclei** in the liquid metal. Cooling the liquid below its equilibrium freezing temperature, or **undercooling**, provides the driving force for solidification. For the new solid to be stable, however, the energy released in forming the new solid volume must be larger than the energy needed to create the new solid / liquid interface. Larger clusters of solid atoms are more stable than small ones, since they have less surface area per unit volume. Once a cluster reaches a critical size, it becomes a stable nucleus and continues to grow. The mold walls and any solid particles present in the liquid make nucleation easier. They do this by providing solid surfaces for liquid atoms to solidify upon, which reduce the undercooling needed to less than 1°C.

Each nucleus eventually grows into a single grain, whose shape depends on how neighbouring grains impinge upon each other. Thus, greater numbers of nuclei produce a **finer** (smaller) grain size. A finer grain size is generally beneficial to strength and toughness in the final product. Nucleation is enhanced by adding alloying elements or other materials (called **grain refiners**) that form small solid particles in the liquid. The seeding of clouds to precipitate rain is a similar process.

Dendrites

A casting usually begins with rapid nucleation and growth against the cold mold walls. This produces a thin **chill zone** of tiny grains at the casting surface. This shell of solid metal grows into the remaining liquid as solidification continues.

Due to the combined effects of alloy segregation during freezing, slow diffusion and shallow temperature gradients in the liquid, the solid / liquid interface usually does not remain planar. Instead, tree-shaped spikes called **dendrites** shoot into the liquid in the direction of heat flow. The dendrites also grow short, perpendicular **secondary arms**, as seen in Figure 14.3. Dendrites create a **mushy** zone between the solid shell and the liquid, bounded roughly by the liquidus and solidus temperature contours.

Certain crystallographic directions in the solid metal tend to grow faster than others. Thus, some dendrites grow faster than others into the direction of heat flow. The result of this competition is an array of parallel aligned dendrites growing away from the randomly-oriented chill zone. The parallel dendrites eventually form a large region of grains with a similar orientation, perpendicular to the mold wall, called the internal **columnar zone**. These columnar grains are very long and thin, with long parallel grain boundaries that can be a source of weakness in the final casting.

Grain Structure

While columnar grains are growing inward from the mold walls, other nuclei are simultaneously growing in the central liquid pool. These central nuclei survive because the first solid to freeze in a typical commercial alloy has a lower alloy content, and hence a higher melting point, than the surrounding liquid. The central crystals then grow equally in all directions, forming roughly-round-shaped, **equiaxed** grains. Eventually, the growth of the columnar grains is stopped when they impinge on the equiaxed grains. The result is a **macrostructure** consisting of three zones, as shown in Figure 14.4.

The relative proportions of the chill, columnar, and equiaxed zones depends on the alloy and thermal conditions during solidification. Preheated molds decrease the depth of the chill zone. Conditions that produce large numbers of nuclei in the central zone tend to result in a large equiaxed zone with a smaller average grain size. A lower pouring temperature promotes a larger equiaxed zone, by making it easier for nuclei to survive in the center. Alloys with a wide **freezing range**, or large difference between the solidus and liquidus temperatures, similarly promote equiaxed grains. This is because dendrite arms may be broken off by stirring and transported to the center, where they are able to avoid remelting, due to their different composition, and act as nuclei. Castings that consist mainly of uniform equiaxed grains usually have the best mechanical properties.

Example 14.2 Solidification Structure

How does reducing the secondary dendrite arm spacing (SDAS) of an aluminum alloy from 0.1 mm to 0.05 mm affect the strength of the casting?

Answer:

The tensile strength, UTS, generally increases with decreasing SDAS. The specific relation for aluminum is:

UTS (MPa) = 48.5 - 90 SDAS (mm)

So, Strength of large SDAS = 48.5 - 90 (.1) = 40 MPa

Strength of small SDAS = 48.5 - 90 (.05) = 44 MPa

Thus, the strength increases from 40 to 44 MPa with this decrease in SDAS. Mechanical properties are improved by casting processes which refine the microstructure, by decreasing the SDAS and the grain size.

3B. CASTING PROCESSES

Continuous casting involves pouring liquid metal through a bottomless permanent metal mold. The thin shell that solidifies against the mold walls is pulled continuously out of the bottom and acts as a container for the remaining liquid. (See Figure 14.1) As the soft shell is withdrawn, it is spray cooled with water and may need to be supported between rollers. The shell continues to solidify and thicken until the cross section of the casting is fully solid. The final strand of metal leaving the machine is cut with a torch to the desired lengths.

This process is the most efficient way to solidify large volumes of metal into simple shapes for subsequent processing. It can be applied to most metals, including steel, with a variety of sizes and shapes. Cross-sections can be rectangular, square, circular, and even “dog-bone” shapes, for rolling into I-beams. Most of the 500 million tons of steel produced in the world each year is continuously cast.

Sand casting uses a two-piece mold formed by packing sand around a wood or metal **pattern** that is shaped like the intended part. (See Figure 14.5) The sand is held together by a **binder**, consisting of oil or clay. A **gating system** is designed to let liquid metal flow into the mold cavity as fast as possible with a minimum of turbulence. The pattern also includes features to minimize defects, such as risers and chills that control heat transfer (see Section 14.3C). A recent development is the molded styrofoam pattern, which does not have to be removed before casting.

Sand casting is the most common, versatile, and economical casting process for manufacturing parts, especially in small numbers. It is also one of the few processes that can mass produce large ferrous parts, such as automotive engine blocks. Since the sand mold must be remade for each casting, the process is labor intensive.

Permanent mold casting, also called gravity die casting, is similar to sand casting with the advantage of a reusable metal mold. Before continuous casting, permanent cast-iron molds were popular for making large semi-finished steel shapes, called ingots. Now, the process is used mainly for small, low melting point castings (eg. Al or Mg), when hundreds of identical castings are needed. Casting hotter metals such as steel into finished parts is usually not economical because the metal attacks the mold and shortens its life.

Die casting involves injecting liquid metal under pressure into a permanent metal mold. The two pieces making up the mold, called **dies**, are clamped together prior to metal injection and open quickly after solidification to achieve high production rates (100 parts per hour per cavity). The process is similar to injection molding used in ceramic and plastic processing, shown in Figures 16.11 and 17.8.

Die casting can rapidly produce shaped parts with high dimensional accuracy. The dies are very expensive, but are cost-effective for mass production, since they can be reused thousands of times. Like gravity die casting, this process is limited to relatively small shapes and to nonferrous alloys with low melting temperatures.

Investment casting, also called the **lost wax** method, starts with a wax pattern of the desired shape. The pattern is dipped repeatedly in a ceramic slurry to form a thin coating. After melting out the wax, the ceramic is usually **fired** (baked). The strong ceramic shell that remains is the mold for casting the liquid metal. Investment casting reproduces fine detail very well and achieves excellent surface finish and dimensional accuracy. Its high cost limits the process to small quantities of small castings such as jewelry, dental work, and gas turbine blades.

Directional solidification is a modification of the investment casting process, designed to control solidification to progress only in a single **casting direction**. One way to accomplish this is to slowly withdraw the mold, filled with molten metal, down through a hole in the floor of a two-zone vacuum furnace, shown in Figure 14.6. Solidification occurs only at the junction between the hot (upper) zone and the cold (lower) zone. This process aims to avoid the formation of grain boundaries, particularly those perpendicular to the casting direction. If solidification progresses from a single nucleus, then a single crystal casting is formed. This is often promoted by placing a **grain selector** at the bottom of the mold, which forces solidification through a spiral-shaped passageway. Only the grain with the most favorable orientation survives. The advantage of producing single crystal parts (with no grain boundaries) is improved creep strength at high temperature, as discussed in Chapter 10. This is important for parts such as rotating, high-temperature, jet-engine turbine blades, which are often cast as single crystals, despite their complex shape (See Figure 14.7). Other types of directional solidification processes are used to purify metals (**zone refining**) or to make pure, single-crystal bars such as silicon semiconductor material.

Other casting processes exist for making specialized parts. For example, hollow pipes can be made by **centrifugal casting**, where metal is poured into a rotating cylindrical mold. **Vacuum casting** processes, such as ESR (electro-slag remelting), are used to remelt and resolidify metal in order to remove inclusions and reduce segregation for parts with critical applications. Other parts can be made by squeezing them into shape from semi-solid metal. Metal droplets can be **spray cast** into powders and later sintered together into shaped parts in a similar manner to the way ceramics are produced. Thin metal sheets can be produced by casting onto a rotating wheel, between rotating wheels, or onto moving belts. The high cooling rates possible in some of these processes achieve highly non-equilibrium conditions, which increase the range of microstructures and properties possible. Development of new casting processes such as these is the subject of intense current research.

Example 14.3 Casting Processes

What casting process would you use to manufacture steel I-beams for building construction?

Answer:

Continuous casting of "beam blanks" is the most efficient way to produce long shapes, which have a uniform cross-section, shaped like a dog-bone in this case. These semi-finished shapes are later rolled to their exact shape and dimensions to produce I-beams.

Example 14.4 Casting Processes

What casting process would you use to mass produce steel camshafts for auto engines?

Answer:

Foundry (sand) casting is the most practical approach for steel parts. Die casting would be more efficient, but is not economical for steel, because the melting point is so high.

3C. CASTING DEFECTS

Casting may produce internal and surface defects. If strength and toughness are critical and cost is not of overriding importance, then castings are often subjected to further processing to improve their properties. Many of the problems that occur in finished products have their origin in the original casting. Internal defects created during casting can be very costly, since they are usually difficult to detect, and are often not found until later processing stages or even in service. Some defects are caused by simple mistakes, but these are specific to the individual casting process. The following generic problems are always a concern.

Inclusions

Nonmetallic particles, or **inclusions**, can be created by oxidation of the liquid metal, or particles entrained from slag, dirt, or refractories when the metal is fed into the mold. These particles, such as alumina (Al_2O_3), cannot deform as metal does, owing to their brittle ceramic structure. Large inclusions are serious defects. For example, the production of beverage cans is limited by the number of inclusions in the metal, since every particle bigger than about half the wall thickness will cause a failure. Large inclusions can also initiate cracks when a part is in service. (See Chapter 9). Inclusions can be minimized by preventing exposure of the liquid metal to air, passing the liquid through a holding vessel to allow time for the inclusions to float into the slag layer, filtering the flow, carefully positioning the feeding gates into the mold cavity to prevent erosion, and keeping the mold clean. Alternatively forming many very tiny inclusions is beneficial. Small (sub-micron sized) particles provide strengthening, as discussed in Chapter 7.

Shrinkage cavities

Voids, or **shrinkage cavities**, are created by volumetric shrinkage of the metal during solidification. This type of defect is especially dangerous when the cavities are hidden internally. They occur because most metals contract by 2 - 6 % by volume when the liquid transforms to a solid. (See Table 14.1) Exceptions include Ga, Ge, Bi, and some cast irons, where the density of the solid is less than the liquid, so expansion occurs and shrinkage cavities are unlikely.

Shrinkage cavities may take the form of either a few large voids, or many small holes distributed throughout the casting. Large voids form in relatively pure metals, with narrow freezing ranges, when a volume of liquid becomes surrounded by solid or isolated from its liquid metal source during casting. This liquid produces a cavity when it solidifies and shrinks. A high pouring temperature increases the extent of this defect, since liquid metal also contracts as it cools.

Alloys with wide freezing ranges produce tiny jagged shrinkage cavities dispersed throughout the casting, illustrated in Figure 14.8. This is because a large mushy zone of long dendrites forms during their solidification. It is difficult for liquid metal to feed through this network of dendrites, so **interdendritic** shrinkage results. This type of shrinkage defect is also called **shrinkage porosity**. It is very difficult to remove, but less detrimental than large cavities.

Large shrinkage cavities can be minimized by careful control of heat transfer during the solidification process. For example, attaching a liquid metal reservoir, or **riser**, to a sand casting encourages shrinkage to occur in the riser, which feeds metal into the casting, as shown in Figure 14.8. Later, the riser is cut off, leaving a sound casting. Adding metal **chills** or insulating materials to selected locations in the mold can further control the local heat transfer to help avoid shrinkage cavities. Heat transfer calculations using sophisticated computer models of solidification can be used to aid in this design.

The complexity of a casting is limited by the ability of the liquid metal to completely fill the mold cavity before it freezes. Processes with high conductivity molds, such as die casting, are more prone to incomplete filling. Alloys with a wide freezing range are also more prone to this problem, since it is more difficult for liquid metal to **feed** through the network of dendrites. For this reason, eutectic cast iron can be used for more intricate, thin-walled castings than steel. Feeding problems may be reduced by heating the molten metal sufficiently above its solidification point before it is poured. The temperature difference between the pouring and the liquidus temperatures is called the **superheat** temperature and is important to the formation of both defects and microstructure.

Example 14.5 - Casting Shrinkage

How large a shrinkage cavity could form in a bar-shaped sand casting of an aluminum alloy containing 4.5 % Cu? What would be the final size of the casting after cooling to ambient? Assume that feeding is prevented just after mold filling and that the mold cavity dimensions are 10 x 10 x 30 cm.

Answer:

From Table 14.1, solidification shrinkage of this alloy is 6.3 % by volume.

$$\text{Shrinkage cavity volume} = (10\text{cm})(10\text{cm})(30\text{cm})\ (0.063) = 190\ \text{cm}^3$$

If it were spherical, the largest shrinkage cavity could be a void with a diameter of:

$$D = \sqrt[3]{\frac{6V}{\pi}} = \sqrt[3]{\frac{6\ (190)}{\pi}} = 7.1\ \text{cm}$$

The final dimensions are controlled by thermal contraction in the solid state during cooling from the solidus temperature to ambient (25 ^{o}C). From Table 14.1, this cooling contraction should be 5.3%. Linear contraction is one third of the volumetric contraction. (When expressed per degree temperature change, this is the thermal expansion coefficient). Thus, the length of a side becomes:

$$\text{casting length} = \left(1 - \frac{5.3\ \%}{3}\right)(\text{mold length})$$

final length of 10 cm side = 10 (1-0.053/3) = 9.82 cm

The other side is 3 times longer, so that the final casting dimensions are: 9.8 x 9.8 x 27.5 cm.

Conditions after mold filling, including solidification shrinkage, do not greatly affect the final dimensions. This is because the first liquid to solidify will always conform to the shape of the mold surface.

Porosity

Porosity is the name given to small voids in a casting. This problem can arise due to solidification shrinkage, as discussed in the previous section. Alternatively, **gas porosity** is caused when gas bubbles are evolved during solidification and become trapped to form small, smooth, round voids or **pinholes** inside the casting. Gases such as hydrogen and nitrogen can dissolve easily in liquid metals. Bubbles form because the solubility of gases in the solid metal is much less than that in the liquid phase. Bubbles can also form by chemical reaction, such as dissolved oxygen in steel combining with carbon to create carbon monoxide bubbles. Dissolved gases can be harmful even when they do not form bubbles, since they can react to form inclusions, in the case of oxygen and nitrogen, or cause embrittlement of some alloys, in the case of hydrogen.

Dissolved gases can be prevented by protecting the metal from contact with air or moisture (which creates hydrogen). Gases can be removed by lowering the liquid temperature or by **vacuum degassing** the liquid metal. This involves holding the ladle of molten metal under a vacuum and / or injecting an inert gas such as Argon to rapidly stir the liquid and promote removal of unwanted Hydrogen, Nitrogen, and Sulfur from the top surface.

When the bubbles cannot escape, pinhole porosity is produced, particularly in cast iron, aluminum, and copper. To encourage the escape of trapped air and gas, **vents** (vertical holes) are sometimes added to sand castings. Gas bubbles can also be prevented by alloy additions that form solid precipitates instead. For example, Al or Si is added to steel to combine with the excess oxygen and prevent the formation of CO gas bubbles. Unfortunately, the precipitate particles (SiO_2 or Al_2O_3 in this example) sometimes act as detrimental inclusions, unless they can float out into the slag.

During subsequent deformation processes, defects such as internal porosity and internal cracks often can be squeezed together and completely healed. If these defects reach the metal surface and are exposed to the environment, however, they will oxidize and become permanent.

Segregation

The solidification process often produces differences in composition in different parts of the casting. When composition differences exist over small distances (microns), this is called **microsegregation**. Composition differences over large distances (centimeters or more) is **macrosegregation**. Macrosegregation is a persistent problem that cannot be removed, even if the metal part is subjected to severe deformation or long annealing times (see Figure 14.9).

The driving force for segregation is the difference in composition between the first and last metal to freeze in an alloy, specified in the equilibrium phase diagram. Segregation occurs because diffusion in the solid phase is too slow to achieve the uniform equilibrium structure found in the phase diagram, as introduced in Chapter 13. It is worse when there is a wide composition range across the solidus and liquidus temperatures, which corresponds to a large solidification range.

Consider, for example, the solidification of Al - 1% Si alloy, shown in Figure 14.10. The first metal to solidify will form the "trunk" of a dendrite at 650^{o}C with a composition of only 0.2% Si. It will consist entirely of α phase aluminum. Further cooling to 640 ^{o}C will solidify more α Al around the existing dendrite trunk. The new solid will contain more Si (0.4%), however. Equilibrium favors uniform composition, but the diffusion of metal atoms through the solid phase is very slow, so it rarely affects the composition of the purer dendrite trunk. Thus, the average composition of the solid dendrite, ranging from 0.2% - 0.4%, is less than the equilibrium value of 0.4%. As solidification continues, the solid dendrite crystal will become "cored": an increase in alloy content exists when traversing from the center to edge layers. Final solidification will be delayed below the equilibrium solidus temperature of 612 ^{o}C.

As the solid rejects Si and other impurities, the liquid steadily increases in alloy content. The final liquid to freeze will contain at least 2.6% Si, according to the phase diagram. If the composition of the final liquid to freeze increases to 12.6% Si, then the phase diagram indicates that some eutectic will form. Thus, it is possible for some eutectic to be present in a cast Al - 1% Si alloy, which is contrary to the equilibrium phase diagram prediction for this composition. This phenomenon often occurs between the dendrites or at the grain boundaries of metal alloy castings. This gives rise to alternating composition differences over small distances in the solid with a period equal to the dendrite spacing or the grain size, as shown at the bottom of Figure 14.10 and in Figure 13.17. In the present example, the maximum range would be from 0.2% to 12.6%.

Microsegregation, as described above, usually arises between dendrite arms. It is important because the concentration of impurities and possible presence of a second phase can reduce the strength at the boundaries. In a columnar structure, where all the dendrites are aligned, this produces **anisotropic** properties, where the strength and ductility are lower in the direction transverse to the long axis of the dendrites.

Macrosegregation has the same fundamental basis as microsegregation. When there is also bulk motion in the fluid during solidification, then mixing induces the segregation to occur on the scale of the casting. The first liquid to freeze (at the casting surface) then has a different composition than the last liquid to freeze (usually near the center). Thus, composition varies from the surface to the center of the casting. This concentration of impurities at the center can create weakness, non-uniform properties, and other problems.

The fluid motion, necessary for macrosegregation, can be caused by density differences between the alloy phases, natural thermal convection, the stirring action of gas bubbles, or it can even be caused intentionally by stirring the liquid. Sometimes macrosegregation is beneficial, such as the smooth **rim** of pure iron that forms at the surface of some steel ingots, due to the effervescent mixing action of CO bubbles produced during solidification. Segregated regions in castings may appear as lines or planes in the product if it has later been rolled or otherwise mechanically deformed.

Microsegregation can be reduced by holding a casting for a long time at high temperature, (just below the solidus temperature). This process is called **homogenizing**, and allows atomic diffusion to even out concentration differences over short distances (a few microns per hour). It is easier for interstitial alloy atoms, which diffuse faster than larger substitutional atoms. Homogenizing is also easier for fine-grained microstructures, where the spacing between the dendrite arms is smaller, so the diffusion distance is smaller than in course grains. Macrosegregation is impossible to correct, however, since millions of years of diffusion time would be required.

Residual stress and cracks

Stresses are generated in a casting mainly by the few percent of thermal contraction, or strain, that accompanies cooling of metal in the solid state. The thermal expansion data in Table 14.1 shows that solid steel shrinks about 6% in cooling from 1500 ^{o}C to ambient temperature. To allow for this shrinkage, the mold must be a little larger than the intended part. If the shrinkage is restrained by the mold, such as when sand casting a large hollow pipe around a large internal core, then large stresses can be induced. These stresses can start cracks when the metal is hot and brittle.

Metals at elevated temperature are generally very ductile. However, at very high temperatures, near the melting point, metals can be pulled apart at the grain boundaries at very low strains. Because of microsegregation, the grain boundaries usually have high impurity concentrations that lower their melting point significantly relative to the average composition of the alloy. For example, sulfur in steel segregates to the grain boundaries and, in the most extreme case, could lower the melting point locally to the Fe / FeS eutectic temperature of 988^{o}C. In practice, manganese is added to steel to form MnS inclusions that raises this critical temperature to about 50 ^{o}C below the equilibrium solidus temperature. An even better solution is to remove embrittling elements such as sulfur and phosphorus during the steelmaking process.

While its temperature is between the equilibrium and non-equilibrium solidus, a liquid film coats the grain boundaries, and solid metal has almost zero ductility. Tensile stress across the grain boundaries at this time and location will produce cracks called **hot tears** or **hot shortness** with a strain to failure of less than 1%. (For example, see Figures 14.11 and 14.12) Thus, simultaneous embrittlement and tensile stress must be avoided. In particular, mechanical interaction between the casting and mold must be minimized. Control of mold and part geometries, cooling conditions, and alloy composition are all important to preventing hot tearing.

If hot tears can be avoided, the thermal strains generated during cooling after solidification can usually be accommodated easily by plastic creep. However, after some regions of the casting have cooled sufficiently, and no longer creep, they restrain those regions that cool later. The result is a system of balanced residual stresses in the completely-cooled casting. Generally, compression develops in the first regions to cool and tension in the later ones. Residual stresses can distort the shape of the casting, and in extreme cases, cause sudden catastrophic failures. They are worse for high cooling rates. Thus, residual stresses are an even greater potential problem during thermal processes such as quenching, discussed next. Other thermal processes, such as annealing, are used to reduce these stresses.

3D. CASTING PROCESS ANALYSIS

Complex manufacturing processes, such as modern casting processes, are developed and improved by combining laboratory, pilot plant and industrial-scale experimentation, evaluation of previous work in the literature, and process modeling. Process modeling is done both with physical models, such as using water to simulate molten metal, and with mathematical models, which range from simple analytical equations to sophisticated computer calculations of flow, heat transfer, microstructure, and stress. The basic equations are based on Chvorinov's rule that relates the solidified shell thickness, s, with the time elapsed since filling the mold, t.

$$s = K\sqrt{t} \qquad [14.1]$$

The total solidification time of a casting can be calculated by rearranging this equation to get $t=(s/K)^2$. For complex-shaped castings, the final s can be approximated by the ratio of volume to surface area. Chvorinov's constant, K depends on the material properties and casting conditions.

Example 14.6 - Shell Thickness in Continuous Casting

How thick is the steel shell at exit from the bottom of the mold of a continuous casting machine, if the mold is 0.7m long and the shell is withdrawn at a casting speed of 1 m/min?

Answer:

Experimental studies of continuous cast steel have determined that K is about 1 inch-min$^{-0.5}$. The time needed to travel from the top-surface meniscus (where the shell starts to solidify) to mold exit is:

t = distance / velocity = 0.7/1 = 0.7 min.

Thus, $s = K\sqrt{t} = 1\sqrt{0.7} = 0.84\ inch$

This calculation is important, because this thin shell must be strong enough to act as a container to support the remaining liquid below the mold in this process.

Example 14.7 - Solidification Time in Sand Casting

About how long would a 1 m^3 cube-shaped aluminum casting take to solidify in a sand mold?

Answer:

For sand castings, where conduction through the mold controls the heat transfer, K can be approximated from the metal and sand properties (conductivity, density, specific heat, latent heat, fusion temperature, etc.) by:

$$K = \frac{2}{\sqrt{\pi}}\left(\frac{T_f - T_{ambient}}{\rho_{metal}\Delta H_f}\right)\sqrt{k_{sand}\rho_{sand}C_{psand}}$$

Assuming	For Al:	k = 0.53 cal/cm-s-˚K	For sand:	k = 0.00145 cal/cm-s-˚K
		ρ = 2.7 g/cm^3		ρ = 1.5 g/cm^3
		ΔH_f = 95 cal/g		C_p = 0.27 cal/g-˚C

T_f = 660 ˚C $T_{ambient}$ = 25˚C

Chvorinov's constant, K, is then:

$$K = \frac{2}{\sqrt{\pi}}\left(\frac{660-25}{2.7*95}\right)\sqrt{.00145*1.5*0.27} = .0677 cm/\sqrt{s}$$

Assuming the casting is completely surrounded by sand,

$$s = \frac{volume}{surface\ \ area} = \frac{1m^3}{6m^2} = .167\text{m} = 16.7\text{cm}$$

This shows that heat lost through the sides and ends reduces the equivalent thickness of this casting significantly from that of a 1-m thick slab, where s=50cm. The final solidification time can now be found:

$$t = \left(\frac{s}{K}\right)^2 = \left(\frac{16.7}{.0677}\right)^2 = 60{,}600 \text{ s} = 1000 \text{ min} = 17 \text{ hours}$$

This calculation shows when the casting can safely be shaken out of its sand mold.

3E. SUMMARY OF CASTING

Casting is the first step in manufacturing parts from liquid metal. Many different casting processes are available to make both semi-finished and final products. These include continuous casting, sand casting, die casting, investment casting, directional solidification, and other specialized processes. The solidified structure of a casting is determined by nucleation and growth phenomena and has several zones, ranging from large, long, parallel columnar grains to small, uniform equiaxed grains. Many inherent defects can arise during casting, including inclusions, porosity, shrinkage cavities, segregation, residual stress and cracks. Some of these, particularly inclusions and macrosegregation, are impossible to correct during subsequent processing and can adversely affect the final properties. Casting is usually not the final manufacturing process. The next sections describe the thermal and deformation processes that often follow casting.

4. THERMAL PROCESSING

It is possible to greatly alter the structure and properties of metals simply by heating and cooling them through controlled sequences of time and temperature. This **thermal processing** produces a wide range of complex effects, which generally exploit two different phenomena. The first is to increase the diffusion rate to enable faster atomic movement. Diffusion rates increase exponentially with increasing temperature. This is the basis for processes such as annealing, homogenizing and spheroidizing. The second effect is to cause phase transformations, especially the formation of a non-equilibrium structure by cooling rapidly through a boundary on the phase diagram. This is the basis behind martensitic hardening and age hardening.

Thermal treatments consist primarily of hardening processes and softening processes. The basic softening process, annealing, applies to all cold-worked metals. It consists of three stages: recovery, recrystallization, and grain growth (see Chapter 7). The extent of these softening phenomena depends on diffusion, so it increases exponentially with temperature. Mild softening, based on recovery, is called **stress relief**. It occurs at relatively low temperatures and is used to increase toughness and remove residual stress. Full annealing is used to completely remove the effects of any prior heat treatments, resulting in greatly improved ductility.

Because steels behave so differently from other materials, metal alloys are classified as **ferrous** and **nonferrous** according to their iron content. The thermal treatment of steel, which is so important to its behavior, is relatively complex and is treated separately (see Chapter 15)

Thermal processes to achieve hardening usually involve quenching (fast cooling) and tempering (subsequent reheating to relieve the stresses and reverse the quenching effects partially in a controlled manner) The most important hardening process for nonferrous metals is **precipitation hardening**.

4A. PRECIPITATION HARDENING

Strengthening at room temperature is achieved by making dislocation motion more difficult. One way to do this is to form a second phase, dispersed in the metal matrix. Hardening is more effective when the second phase is finely distributed. The heat treatment process of **precipitation hardening** uses non-equilibrium cooling to achieve this strengthening in many metals, including aluminum, copper, stainless steel, nickel and cobalt-based superalloys for high temperature application. Its stages are shown in Figure 14.13.

Precipitation hardening begins with a **solution heat treatment**, whereby the alloy is heated into a single-phase region of the phase diagram. Increasing temperature as much as possible allows diffusion to distribute the **solute** uniformly throughout the matrix in a minimal time. Care must be taken, however, not to heat too near to the solidus temperature. If melting does occur, the alloy has been **burned**. During burning, the expansion upon melting causes local swelling, and after cooling leaves voids or cracks and terrible mechanical properties. Segregation makes burning most likely at grain boundaries, where melting occurs at lower temperatures and cracks can form. Thus, solution treatment must be done below the non-equilibrium solidus temperature.

After heating, the alloy is quickly cooled to ambient, to avoid precipitation. The alloy atoms are trapped in a super-saturated solid solution. The slow kinetics of diffusion in the solid phase prevents the formation of the equilibrium second phase, if cooling is sufficiently rapid. Sometimes, refrigeration is needed to prevent precipitation when solution treated parts, such as rivets, are stored for a long time before use. When precipitation eventually occurs, the second phase is finely distributed and produces significant strengthening. The strengthening increases over time, as the precipitates form, so the phenomenon is also called **age hardening**.

If this process occurs at ambient temperature, it is called **natural aging**. Usually, the alloy is reheated to an intermediate temperature to speed up the precipitation hardening process. This **artificial aging** must be done below the **solvus** temperature, to prevent redisolving the second phase. Care must also be taken not to heat for too long or at too high a temperature, or **overaging** may occur. During overaging, the many small second-phase particles grow into fewer larger ones, which reduces the strengthening effect. Figure 14.14 shows the effects of artificial aging temperature and time on the strength of a typical Al alloy, precipitation hardened with Si, Mn, Mg, Cu, and Cr.

The precipitation hardening phenomenon is more complex than the simple dispersion effect just described. Optimal strengthening occurs when the solute atoms cluster together in a series of pre-precipitation configurations whose crystal structures are continuous (or **coherent**) with the matrix, but cause significant lattice distortion. (See Figure 14.13b). Lattice distortion increases in proportion to the mismatch between the structure of the small clusters and the metallic matrix, so atoms with dissimilar sizes generally make the best alloying elements for precipitation hardening.

The composition of an age hardening alloy is chosen to maximize the volume of the matrix phase that is affected by the precipitate. Any alloy with a solid solubility of a second phase that decreases with temperature is a potential candidate for precipitation hardening. Hardening is more effective when the second phase is hard, (common for intermetallics), and has a dissimilar lattice structure that remains coherent. Eutectic alloys do not respond to a precipitation hardening treatment because the relative coarseness of the eutectic plates is not affected by the solution and aging treatments. Larger parts can be precipitation hardened only when the matrix metal has a high thermal conductivity for easy quenching.

Precipitation hardened parts are limited in their maximum service temperature. Exposure to high temperatures lowers their strength due to overaging. Temperatures above the solvus redissolve the precipitates, producing a completely softened metal.

4B. WELDING

The process of joining two metal parts together by heating their surfaces until they melt is called **welding**. Joining processes that melt only the filler metal (and not the parent metal parts) include brazing and soldering. Welding processes are classified according to heating method, and include arc welding, gas welding, resistance welding, and laser welding. Welding is a combination of casting and thermal treatment. After heating, the liquid region solidifies like a casting, forming a fusion zone (Figure 14.15). The region adjacent to the weld undergoes tremendous local changes in structure and properties due to this heating and cooling sequence, which is not intended, but unavoidable. The result is a **heat affected zone**, (HAZ), near the weld interface where problems often arise. Welding very hardenable steels can produce martensite due to the rapid cooling of this zone, which can lead to catastrophic failure. Similarly, the heat affected zones of non-ferrous metals are weakened due to negation of previous thermal strengthening treatments such as cold work or age hardening.

Example 14.8 - Welding Steel

Several steel plates (alloy designations 1020 and 4340) are fully annealed by furnace cooling at 0.1 ^oC per s. They are then welded together by an arc welding process. Figure 14.16 shows the temperature histories recorded by thermocouples on the plate surface at three different distances from the weld centerline, shown as points A, B, and C in Figure 14.15. In separate experiments, (called Jominy tests), the hardness produced in these steel alloys was measured as a function of cooling rate at 700 ^oC, and plotted in Figure 14.17. Predict the hardness in the welded plates at positions A, B, and C for each steel. Which location is most likely to crack?

Answer:

At each position in the heat affected zone, first calculate the cooling rate, by finding the slope at 700 ^oC of the cooling curve on Figure 14.16. For example, at location A,

$$\text{slope at } 700\ ^{o}\text{C} = \frac{400 - 1300}{30} = -30\ ^{o}\text{C/s}$$

The negative sign simply indicates cooling rather than heating.

Next, look up the hardness in Figure 14.17. For 4340 steel, the hardness is 58 HRC, while for 1020 steel, it is 23.5 HRC. Similarly, at location B, the slope is -8 ^{o}C/s, giving hardnesses of 56 and 20 HRC for 4340 and 1020 steel respectively.

At location C, however, the steel never heats above 700 ^{o}C. Thus, this location is relatively less affected base metal. The appropriate cooling rate is the original -0.1 ^{o}C/s from the previous annealing heat treatment. Extrapolating Figure 14.17 indicates that this cooling rate should have produced less than 32 and 2 HRC in 4340 and 1020 steel respectively, throughout the base metal, including location C.

Predicting crack susceptibility is extremely difficult, because there are many different potential causes of cracks, including temper embrittlement, thermal shock, and martensite formation. Assuming the latter cause is most important, location A in the 4340 steel is the most likely to crack. This location has the highest hardness, which likely corresponds to the lowest ductility, and indicates the most brittle martensite. Further explanation about the effect of heat treatment on steel is given in Chapter 15.

4C. SUMMARY OF THERMAL PROCESSING

Thermal treatment is used to produce significant changes in the structure and properties of metals. Strengthening is usually accompanied by a corresponding drop in ductility. Heat treatment is not always an intended manufacturing process. An engineer needs to beware of these “side effects” of manufacturing steps such as welding and grinding that involve a significant temperature change. Unintended heat treatment can also arise in service, due to changes in the operating environment or problems such as friction heating. Care must also be taken to consider potential side effects of intended heat treatments. For example, residual stress is generated by most heat treatments, which can result in distortion and fracture, especially when there is a phase transformation, such as in steel between 700 and 900 ^{o}C.

5. MECHANICAL PROCESSING

Under a favorable state of stress, most metals can undergo large amounts of plastic deformation without fracture, owing to the mobility of their dislocations. This allows a wide range of processes to economically form materials into complex shapes, often accompanied by great changes in microstructure and properties.

5A. COLD WORKING

Deformation at low temperatures is called **cold working**. and it simultaneously deforms the microstructure and the overall shape. As seen in Figure 14.18, cold working elongates the grains of the metal part in the working direction. This greatly increases the strength and toughness, particularly in the direction of elongation, due to strain hardening (See Chapter 7). Cold working processes include cold rolling, deep drawing, pressing, and sheet forming.

Since cold deformation processes simultaneously change both the shape and properties of the metal, the dimensions of the initial shape to be formed, called the **blank**, must be chosen carefully. The forces from the rolls, dies, and presses must be sufficient to deform the metal to the desired shape at a controlled low temperature, while achieving the desired degree of strengthening. The important plastic strain induced by cold working is defined by the change in cross-sectional area of the part:

$$\%\ \text{cold work} = \frac{A_{\text{initial}} - A_{\text{final}}}{A_{\text{initial}}} \qquad [14.2]$$

Since deformation, and the resulting strain hardening, is not equal in every direction, the product should be designed to take advantage of this anisotropy by orienting the most highly-deformed (and therefore toughest) metal with the direction in the part that will experience the highest stress.

5B. HOT WORKING

If the deformation is done at a high enough temperature, then recrystallization occurs continuously during the process. This is called hot working. The original equiaxed grain structure of the metal is recreated, as seen in Figure 14.19. This makes the part softer and easier to deform. Thus, hot working is used primarily to achieve the desired shape with minimum effort. The amount of hot work is calculated in the same manner as cold work. The temperature for hot working, $T_{\text{hot work}}$ can be approximated by:

$$T_{\text{hot work}} \sim 0.7\ T_{\text{melting temperature}} \qquad [14.3]$$

where both temperatures are absolute, (measured in K). It should be safely above the recrystallization temperature, which varies from 0.3 to 0.5 of the melting temperature.

Care must be taken not to heat the metal too much, or embrittlement due to melting or drastic weakening of the grain boundaries may occur, as discussed in Section 14.3C. **Hot shortness** is the name given to this cause of fracture of metal parts during hot working. Hot working also produces surface oxidation, so the surface finish is not as smooth and clean as that from cold working. Processes used for hot working include hot rolling, forging, drawing, and extrusion.

5C. MECHANICAL DEFORMATION PROCESSES

Many different processes have been developed to change the shape of metals. Some of these also apply to ceramics at high temperatures and to polymers. Table 14.2 classifies some common deformation processes according to the major mechanical stress state employed, with an example product using each. Processes that use compression will reduce one dimension of the part, causing the other dimensions to increase to maintain a constant volume. Other deformation processes use tension to stretch shapes such as bars, tubes, and sheets while simultaneously making them thinner. Bending processes, often applied to sheet products, create complex shapes such as fenders, while maintaining a relatively constant thickness. Finally, shearing forces are used in mechanical processes to cut parts, stamp out shapes from sheet (blanking), machine and grind.

Rolling is used for both hot and cold working. Hot rolling compresses a heated metal slab in many successive **passes** between rolls. Recrystallization usually occurs just after each hot rolling pass, softening the metal before the next pass. This is often used simply to elongate a thick slab into plate or sheet of a desired thickness, that can be more than 100 times thinner than the original slab. If the product temperature after the last hot rolling pass is low, then grain growth can be lessened and the extra benefit of refined grain size can be gained. This benefit is enhanced by small alloy additions, which form fine dispersions of particles that delay recrystallization and grain growth. One example of this is controlled rolling of HSLA (high-strength-low-alloy) steels.

Cold rolling can be used as the final stage of metal processing to increase the strength, reduce the thickness and improve the surface finish. To ensure uniform product thickness, outer **back-up rolls** support the inner **work rolls** to prevent them from warping under the high forces needed for cold rolling. In addition, the work rolls are cambered to be thicker in the center, so they will be squeezed flat during rolling. The thickness reduction possible in a given pass is limited by the friction available to start gripping the sheet between the rolls.

By contouring the rolls, long products of varied shapes, including channels, bars, and rails, can be made (Figure 14.20). Seamless tubing is produced by off-center rolls that force the center of a round bar to open up. Continued rolling forces the metal to flow around a mandrel, which is a blunt, funnel-shaped rod placed inside the tube being formed.

Example 14.9 Hot and Cold Rolling

How can a plate of brass (70 % Cu and % 30 Zn) with a thickness of 20 mm be rolled into 2.0 mm sheet with a tensile strength of at least 500 MPa and a ductility of at least 5 %R.A.?.

Answer

Several different processing methods could achieve the simultaneous goals of matching both the mechanical properties and the desired dimensions. One common way is to hot roll the plate to reduce its thickness and then cold roll the last few passes to increase its strength. The second step (cold work) is calculated first:

According to Figure 14.21, cold work must exceed 36% to achieve enough strengthening for this alloy. To meet the ductility requirement, cold work must be less than 43%. Thus, 40% cold work can achieve both properties. The width stays roughly constant during rolling, so Eq. 14.2 becomes:

$$\%\text{ cold work} = \frac{A_{initial} - A_{final}}{A_{initial}} = \frac{t_o - t_f}{t_o} = 40\%$$

Knowing the final thickness, t_f=1.0 mm, the thickness prior to cold rolling, t_o is solved to be 3.3 mm.

Thus, the hot rolling passes should reduce the plate from 20 to 3.3 mm. This step must be done above the recrystallization temperature, to prevent cracking and to ensure a fully-recrystallized sheet prior to cold working. Based on the higher melting temperature component in the brass (copper), Eq. 14.3 indicates that hot working should be performed at a temperature near:

$$T_{hot\ work} = 0.7\ (1083 + 273) - 273 = 670\ ^{o}C.$$

An alternative approach could replace the hot rolling step with a series of cold rolling passes, with annealing in a furnace at about 670°C after each few passes. The final cold rolling step from 3.3 to 2.0 mm would be the same. Many passes are needed to enable the sheet to enter the smaller roll gap without slipping. The annealing is required to soften the metal and restore ductility. Without annealing, the effects of cold work accumulate and could cause cracking. This method is more costly, but might produce a better surface finish.

Forging is an economical process to form metal parts into arbitrary, complex shapes using compression. In its oldest form, used by the village blacksmith, hot metal is pounded with a hammer against an anvil. In one popular modern-day forging method, upset forging, an upper die is pounded repeatedly into stationary lower die, which holds the initial blank of metal. With careful die design, and control of temperatures and forces, complex shapes can be consistently reproduced to close tolerances with this process. In hot forging, shown in Figure 14.22, many stages are required to allow time for recrystallization to soften the metal between each of the rapid straining steps. Forging helps to seal internal crack defects and produces a strong, tough elongated grain structure in the final product. Thus, forging is often used as an alternative to casting, when the loading conditions on the part in service are demanding.

Extrusion involves squeezing metal through a die to make long shapes of constant cross section, including tubing. (Figure 14.23) It is most popular for soft metals, such as aluminum and copper, which can be further softened by heating to reduce the applied forces and thereby prolong the life of the die. Adequate lubrication and die angle are critical to produce defect-free parts with minimum die wear.

Drawing pulls (rather than pushes) the metal through the die. It is used to make products such as wire (Figure 14.24). Wire drawing must be performed at low temperature, to increase the strength of the product, so that it can withstand the high tension of this process.

Sheet forming processes are used to bend, punch, and press thin metal sheets into a wide variety of thin-walled products. For example, continuous roll forming uses a series of contoured rolls to form metal sheet into shaped products. (Figure 14.25) These processes are distinguished by relatively little change in thickness of the part, although its shape changes greatly. Deep drawing is a sheet forming process used to make products such as bathtubs and pots, which involve a lot of bending. It should not be confused with the unrelated process of wire drawing.

Ironing simultaneously stretches and thins down a metal section, a two-dimensional analog of wire drawing. Complex forming operations, such as the manufacture of beverage cans, usually combine sheet forming (deep drawing) with ironing, as shown in Figure 14.26. This process controls thickness better than free drawing by forcing the metal to conform to the gap between the die and the ram, punch or mandrel. To achieve a lot of deformation without failure, "drawing and ironing" may require several stages.

Machining carves a part from a metal blank by cutting metal from its surface using a sharp, hard **tool**. Although expensive, this process is readily automated. Both cutting and shearing deformation are used to remove unwanted metal in the form of chips (preferably) or coils. Machining takes less energy and produces a better surface finish when chips form easily. This is encouraged by alloy additions which embrittle the metal, such as increasing the sulfur content of steel. This shows that the best properties for manufacturing unfortunately are sometimes opposite to those desired in finished parts.

5D. MECHANICAL PROCESS DESIGN

In designing a deformation process, care must be taken not to stretch or compress the metal so much at any location that fracture occurs. The true stress - true strain behavior must be considered, because there is so much plastic strain involved. This behavior is complicated by the multiaxial nature of the strains, which is not taken into account in a simple uniaxial tensile test. Engineers often employ the material property of **formability**, which is a measure of the change in a metal's ductility when it is stretched **biaxially** (in two directions at once).

Another concern is the degree of anisotropy that occurs during forming. Anisotropy is quantified in sheet products by ΔR values, defined by the difference between width strain to thickness strain ratios (R values) measured on tensile test samples, cut from the sheet with different orientations. The deformation induced during the process can be inferred experimentally from the movement of grid lines, drawn uniformly on the part surface before deformation begins (See Figures 14.22-24).

Finally, it is important to account for elastic **springback**, after deformation. The process must be designed to slightly overdeform the part, so that the final shape has the desired dimensions after springback. The design considerations involved in complex forming processes, such as the manufacture of a beverage can, almost rival those required to launch a vehicle into outer space.

5E. SUMMARY OF MECHANICAL PROCESSING

Many deformation processes exist to shape metals into parts with the desired microstructure and properties, including rolling, forging, extrusion, sheet forming, deep drawing. Hot working processes change the shape, with relatively little change in properties. When the temperature is below the recrystallization temperature, cold working processes change shape while simultaneously adding strength and other microstructure and property changes. Mechanical processes are popular in part because they help to overcome some of the defects created during casting. Undesirable internal microstructures can be broken down and internal cracks can be welded together by the deformation. Exposed cracks still pose problems, because the accompanying oxide leads to surface problems such as delamination, and inclusion particles which act as sites of internal weakness. Deformation processing is an important processing step, often employed after casting to manufacture high quality parts of many shapes.

6. SUMMARY

Casting is the first and sometimes the final processing step in manufacturing metal parts. Many different casting processes have been developed, each with advantages and limitations. The microstructure of a casting ranges from columnar to equiaxed, and it greatly affects properties. Castings are subject to many defects, including inclusions, porosity, shrinkage cavities, segregation, residual stress, and cracks. Subsequent processing includes thermal and mechanical processing steps. Heat treatment can be used to remove internal stresses, increase or decrease strength, or make other changes in the material properties. These changes are usually accomplished by corresponding changes in material microstructure. A variety of mechanical deformation processes exist to produce parts of various shapes. In addition, microstructure and properties are changed when the process involves cold working.

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Table 14.1 Solidification and cooling shrinkage of various metals

Metal alloy	Solidification Shrinkage (Volume %)	Cooling shrinkage (Volume %)	Solidus Temperature (˚C)
Al	7.1	5.1	660
Al - 4.5 Cu	6.3	5.3	570
Al - 12 Si	3.8	4.8	580
Au	5.1	5.2	1063
Bi	-3.3 (expansion)	1.0	271
Cu	5.1	6.4	1083
Fe (pure)	3.5	6.0 to 7.5	1535
Steel	2.5 to 3.0	4.2 to 6.0	1500
ductile cast iron	-4.5 to +2.7	3.0	1148
gray cast iron (2% C)	4.0	3.0	1155
gray cast iron (5% C)	-2.5	3.0	1148
white cast iron (5%C)	5.0	3.0	1148
Ga	-3.2	0.0	30
Ge	-5.1	1.6	937
Mg	4.2	5.4	649
Ni	5.1	7.0	1453
Pb	2.7	2.8	327
Sn	2.3	1.5	232
Sb	0.6	2.0	631
Zn	4.7	4.0	420

Table 14.2 Classification of Deformation Processes

Dominant Stress State	Example Process	Example Product
Compression		
	Hammering	Horseshoe
	Forging	Crankshaft
	Rolling	Sheet and plate
	Extrusion	Channel
Tension		
	Wire Drawing	Wire
	Ironing	Beverage can
Bending		
	Bending	Bracket
	Deep drawing	Beverage can
	Press forming	Fender
	Roll forming	Trim
Shear		
	Shearing	Strip
	Blanking	Washer
	Machining	Gear
	Grinding	Roller bearing

FIGURE CAPTIONS

Figure 14.1	Steps in steel processing
Figure 14.2	Hydrogen gas solubility in aluminum at equilibrium (See Example 14.1) (Based on data from Smithels p. 12-2) The discontinuity at 660 °C is due to freezing.
Figure 14.3	Dendritic structure of solidifying metal showing growing crystals that will eventually form columnar grains (left) and equiaxed grains (right)
Figure 14.4	Typical grain structure in a cross section through a continuously cast billet, showing the chill, columnar, and equiaxed zones
Figure 14.5	Steps in Sand casting: A **pattern**, shaped like the intended part, is used to create the two halves of a mold cavity. Hollow parts can be made by inserting sand **cores** into the mold cavity before putting the two mold halves together. Liquid metal is then poured into a pouring basin, down a sprue, and through a system of runners and ingates to fill the mold cavity.
Figure 14.6	Directional Solidification Process: Temperature gradients are maintained during solidification to produce only columnar grains. Single crystal parts can be produced by forcing the metal to solidify initially through a **grain selector**, usually a spiral path where only one grain survives.
Figure 14.7	Nickel-base alloy turbine blades for an aircraft engine etched to show different grain structures possible from different processing methods: Conventional fine equiaxed-grain structure from investment casting (left); Long columnar grains (center), and Single crystal blade (right), produced via directional solidification .
Figure 14.8	Shrinkage cavity defects in a sand casting: Alloys with a wide freezing range (top) exhibit dispersed shrinkage that is hard to remove. Pure metal with a narrow freezing range develops a single shrinkage void (middle).

	The latter defect may be avoided by including **riser(s)**, which are designed to freeze last and feed liquid metal into the casting.
Figure 14.9	Effect of deformation on a casting with macrosegregation. Composition differences between center and surface persist even after forming the billet into an L-shaped bar.
Figure 14.10	Microsegregation: Portion of Si-Al phase diagram showing cooling of Al - 1% Si alloy (top) which produces composition differences across the dendrite arms (bottom) called microegregation or “coring”.
Figure 14.11.	**Hot tear** crack in a large steel casting showing fracture along liquid film between columnar dendrites.
Figure 14.12.	Effect of temperature on ductility of steel: Hot tearing just after solidification is responsible for most of the cracks that form during casting, as ductility is about zero. Another, less severe drop in ductility occurs at intermediate temperatures (700 - 1000 ^{o}C).
Figure 14.13.	Schematic depiction of the stages of precipitation hardening: a) supersaturated solid solution b) coherent precipitate particle that produces maximum strengthening c) equilibrium precipitate particle that produces less strengthening d) overaged structure
Figure 14.14.	Precipitation heat treatment: effect of artificial aging temperature and time on strength of aluminum alloy 6061 (97%Al, 1% Mg, 0.7%Fe, 0.6% Si, 0.3%Cu, 0.2%Cr, 0.2%Mn). Higher aging temperatures decrease the time needed to attain maximum strength, but also decrease the time to overaging.
Figure 14.15	Schematic of weld macrostructure near the joint where two plates were arc-welded together, after heat source has passed.

Figure 14.16	Typical temperature histories at 3 different locations from the centerline of a steel weld, identified in Figure 14.15.
Figure 14.17	Effect of cooling rate (at 700 ºC) on hardness of steel (found from Jominy test explained in next chapter)
Figure 14.18.	Microstructure of metal slab undergoing cold rolling showing deformed grains
Figure 14.19.	Microstructure of metal slab undergoing hot rolling showing recrystallization of deformed grains into new soft, equiaxed grains.
Figure 14.20.	Schematic of contoured rolling process for manufacturing long shapes, such as angle iron channels. (Usually, more than the two steps pictured are needed)
Figure 14.21.	Effect of cold work on mechanical properties of 70% Cu - 30% Zn brass
Figure 14.22.	Forging operation showing elongation of grains in the direction of highest deformation.
Figure 14.23.	Extrusion: soft metal is pushed through a die
Figure 14.24.	Wire drawing: metal rod is pulled through a die
Figure 14.25.	Continuous roll forming: a series of contoured rolls shape metal sheet
Figure 14.26.	Deep drawing compared with drawing and ironing process.
Figure 14.27	Beryllium - copper phase diagram (for Problem 14.4.1)
Figure 14.28	Wire drawing process (for Problem 14.5.10)

FIGURES

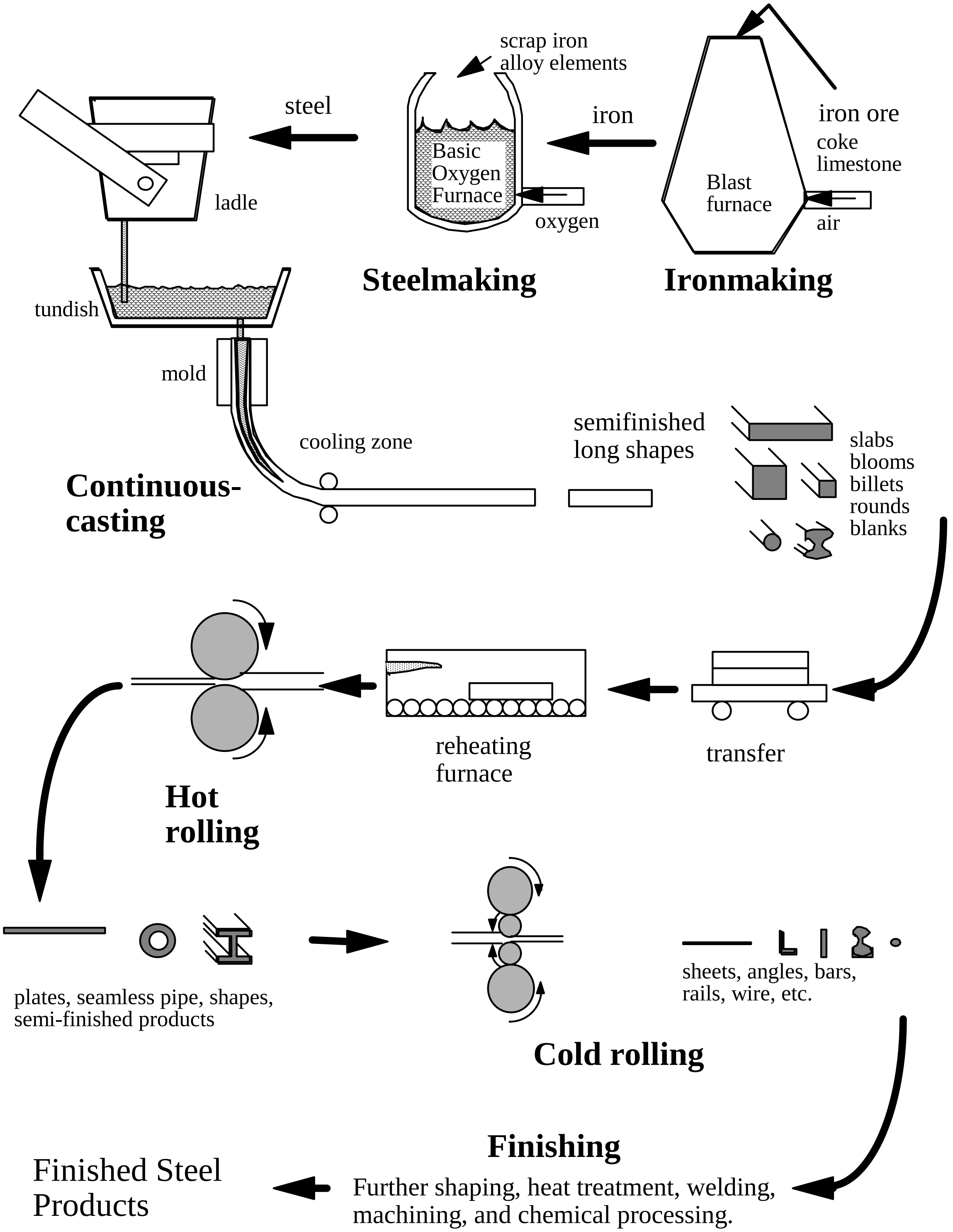


Figure 14.1

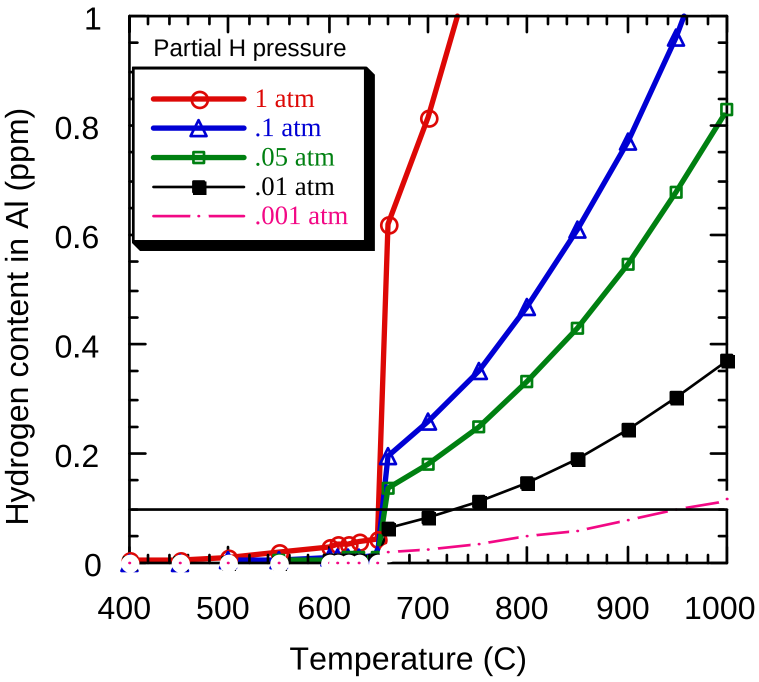


Figure 14.2

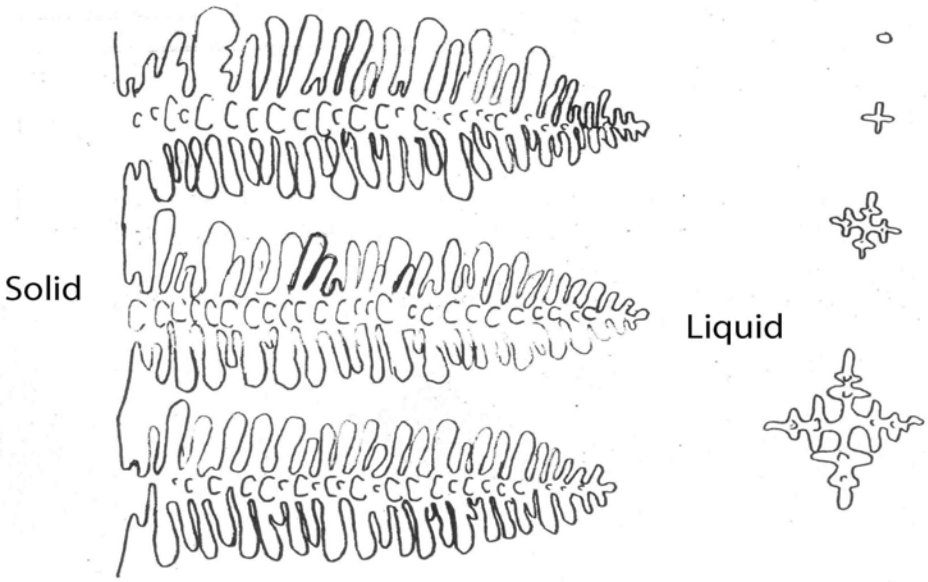


Fig. 14.3

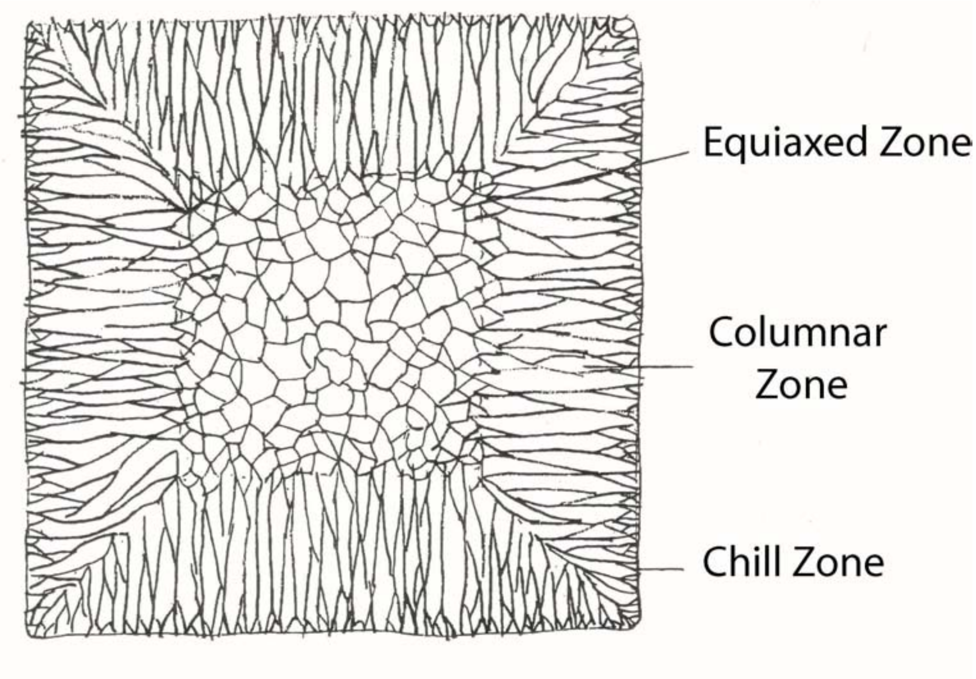


Figure 14.4

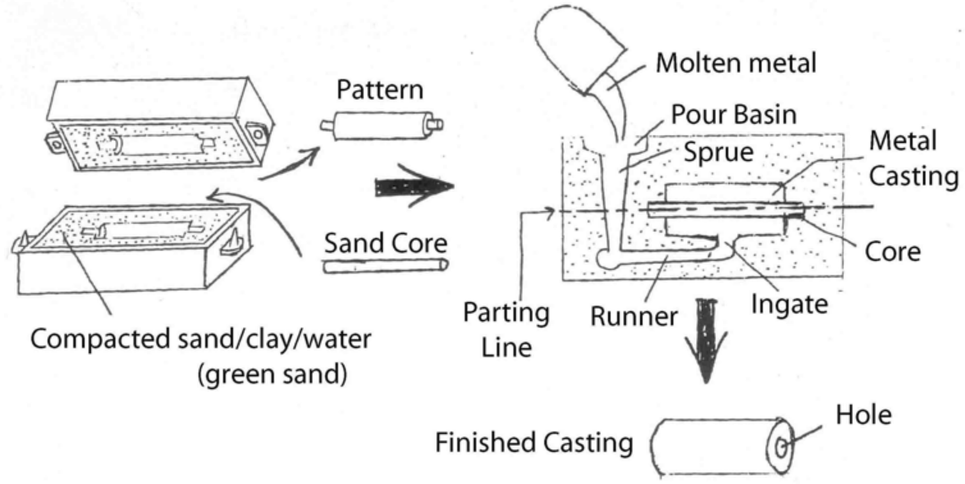


Figure 14.5

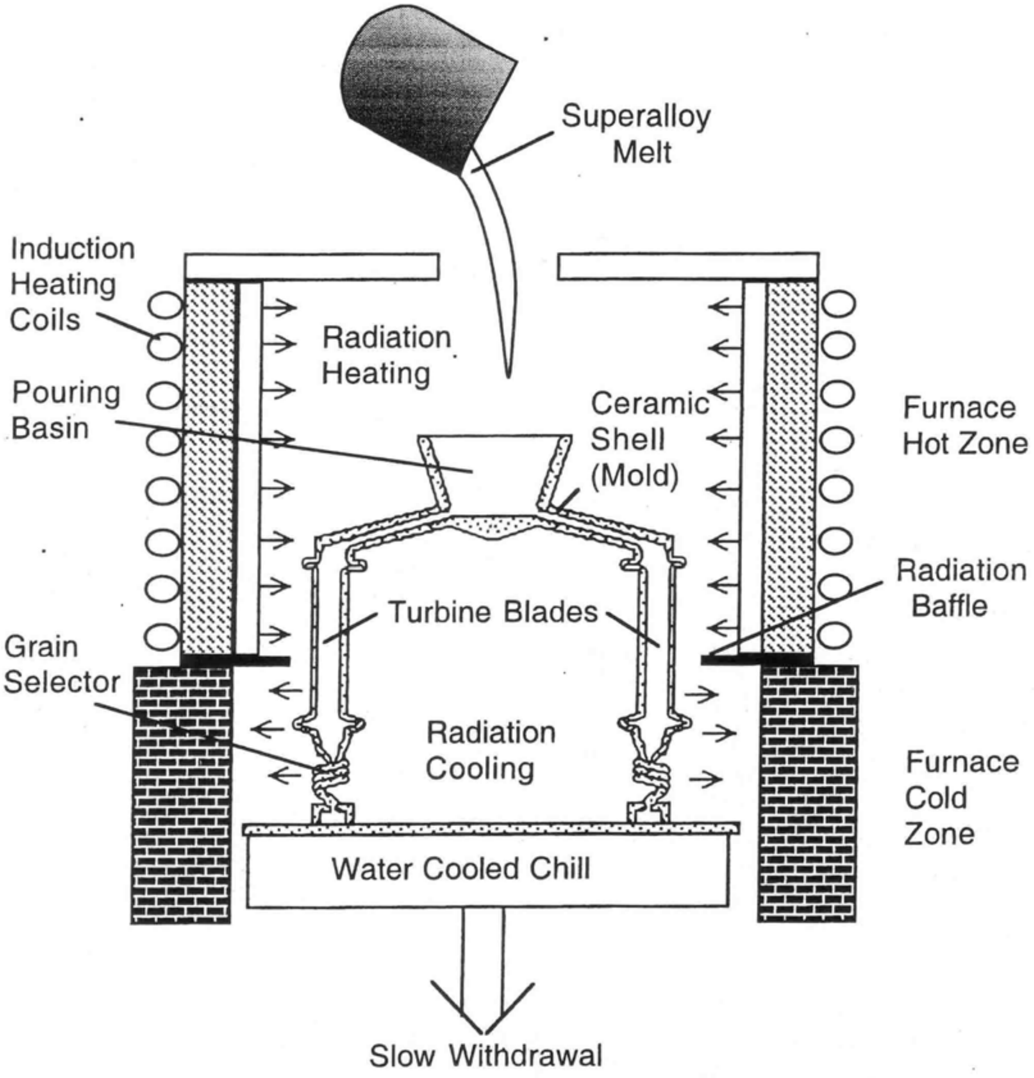

Superalloy
Melt
Induction
Heating
Coils
Radiation
Heating
Pouring
Basin
Ceramic
Shell
(Mold)
Furnace
Hot Zone
Radiation
Baffle
Turbine Blades
Grain
Selector
Radiation
Cooling
Furnace
Cold
Zone
Water Cooled Chill
Slow Withdrawal

Figure 14.6

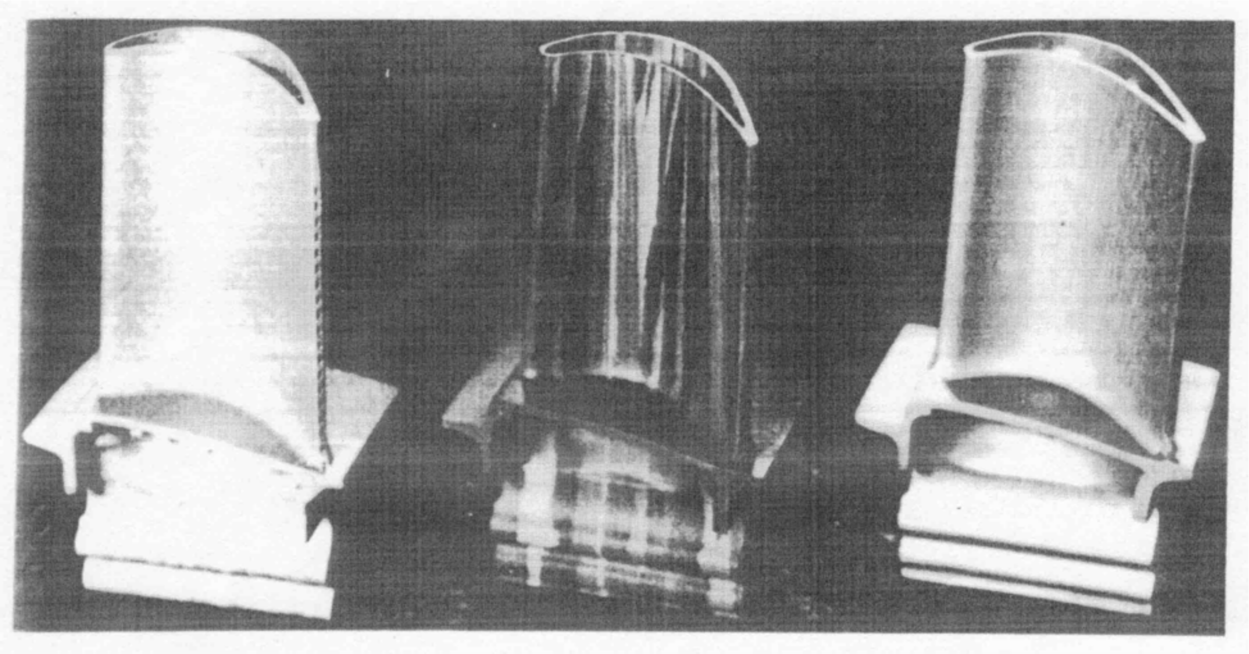


Figure 14.7

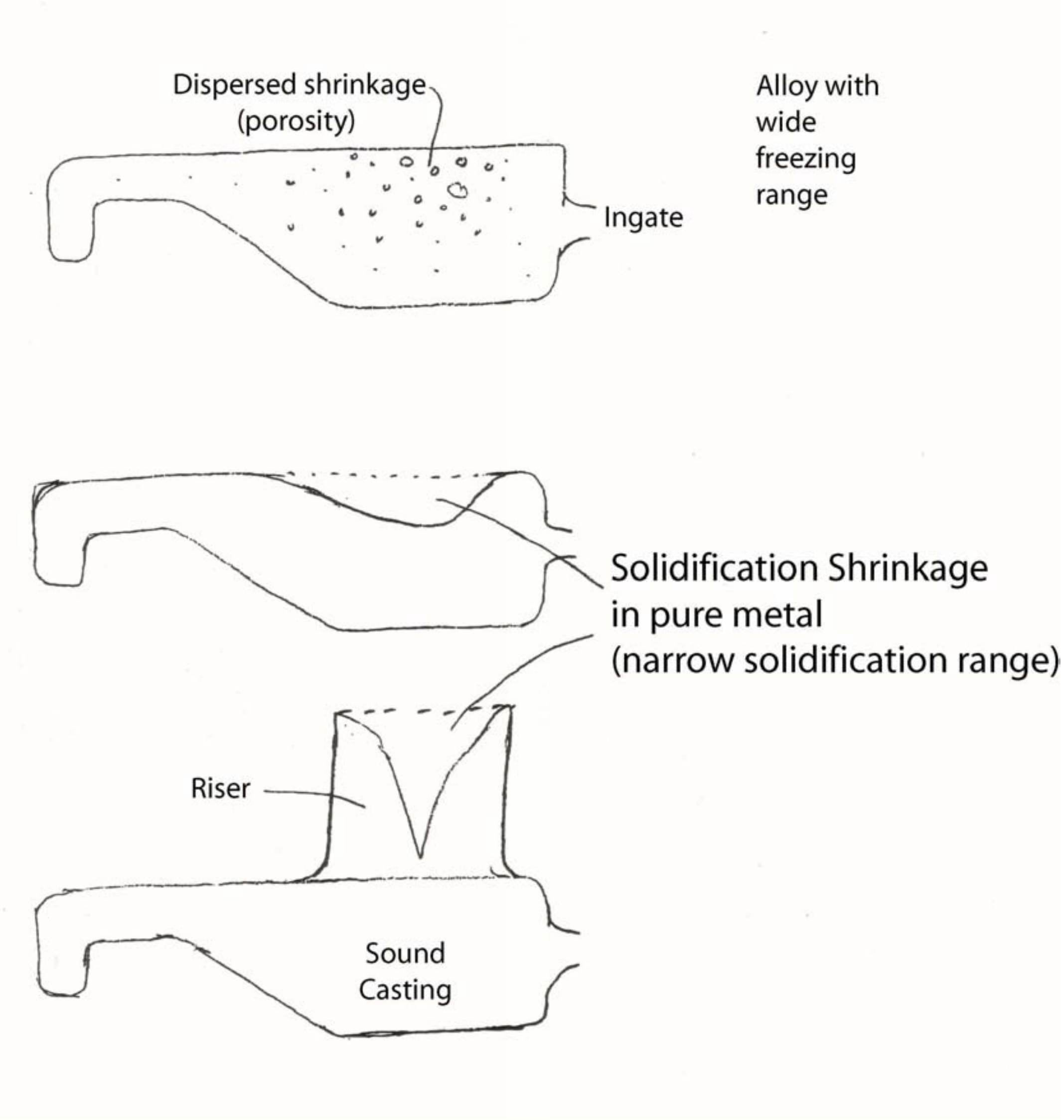


Figure 14.8

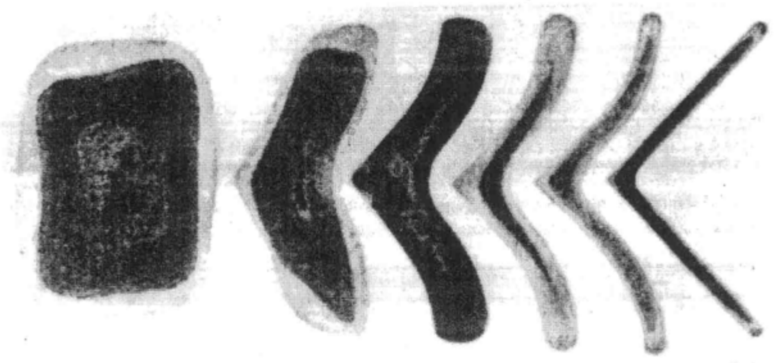


Figure 14.9

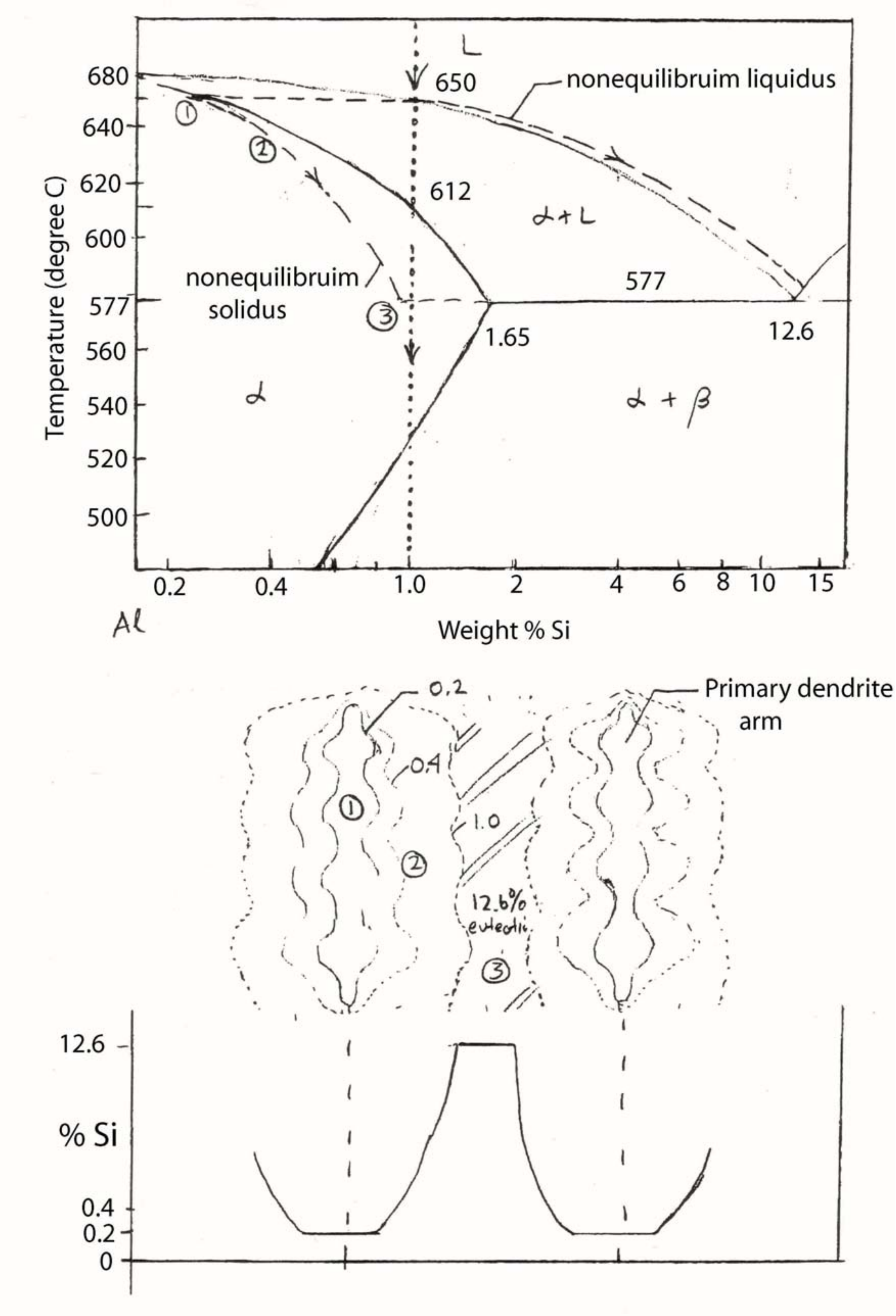

L
680
640
620
600
577
560
540
520
500
Temperature (degree C)
650
nonequilibruim liquidus
①
②
612
α+L
nonequilibruim solidus
577
③
1.65
12.6
α
α + β
0.2
0.4
1.0
2
4
6
8
10
15
Al
Weight % Si
0.2
Primary dendrite arm
0.4
①
1.0
②
12.6% eutectic
③
12.6
% Si
0.4
0.2
0

Figure 14.10

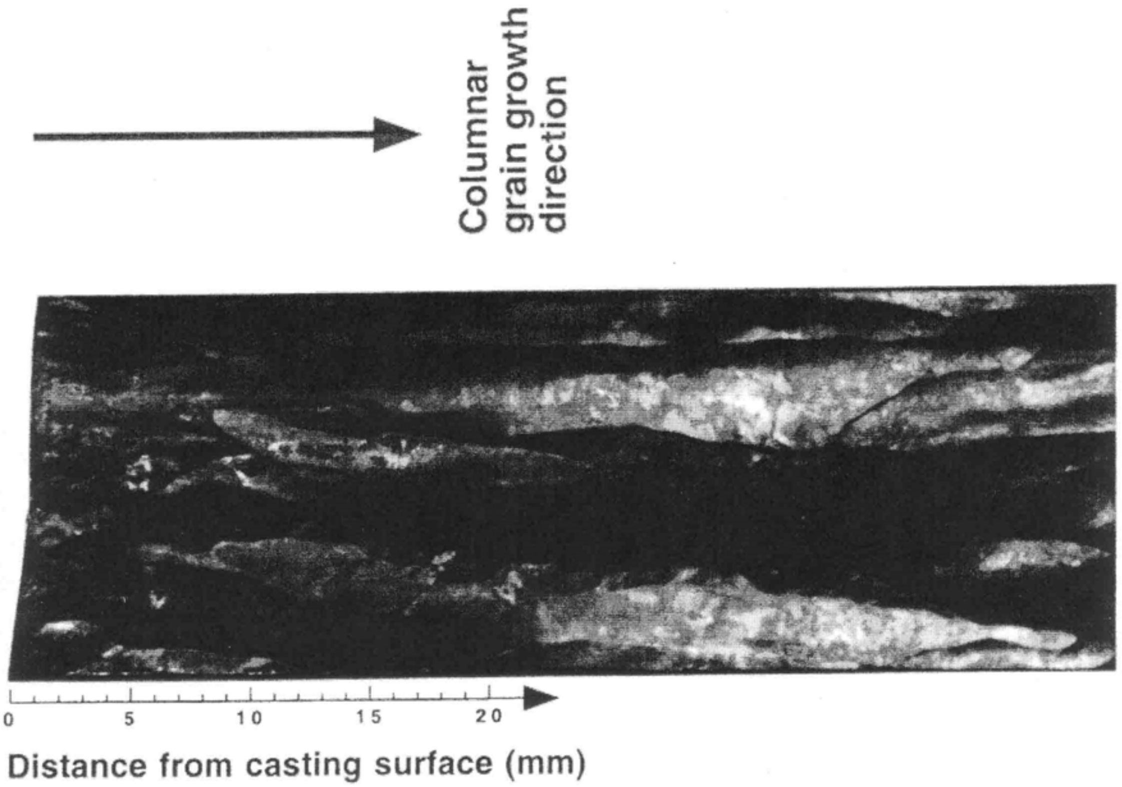

Columnar grain growth direction
0
5
10
15
20
Distance from casting surface (mm)

Figure 14.11

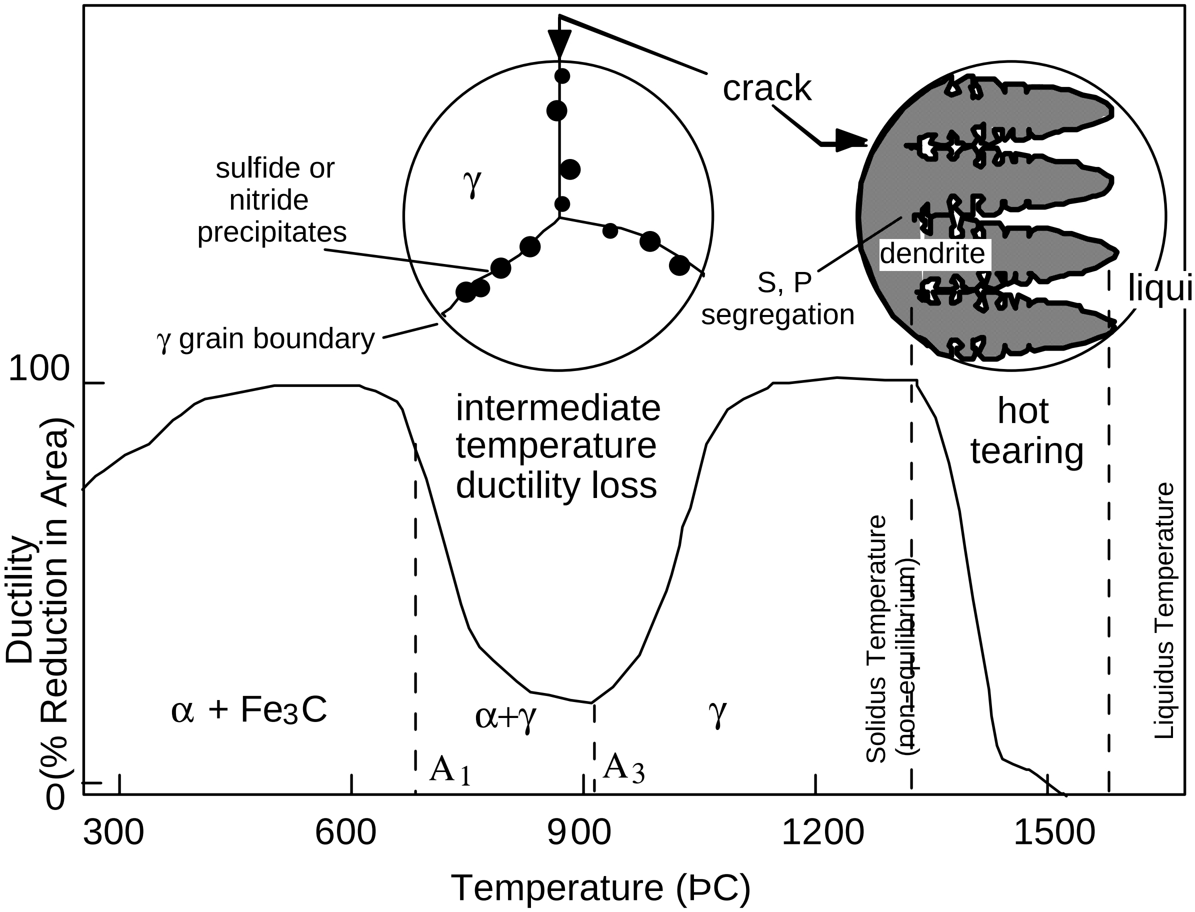

crack
sulfide or nitride precipitates
γ
γ grain boundary
dendrite
S, P segregation
liquid
100
0
Ductility (% Reduction in Area)
intermediate temperature ductility loss
hot tearing
Solidus Temperature (non-equilibrium)
Liquidus Temperature
α + Fe3C
α+γ
γ
A1
A3
300
600
900
1200
1500
Temperature (ÞC)

Figure 14.12

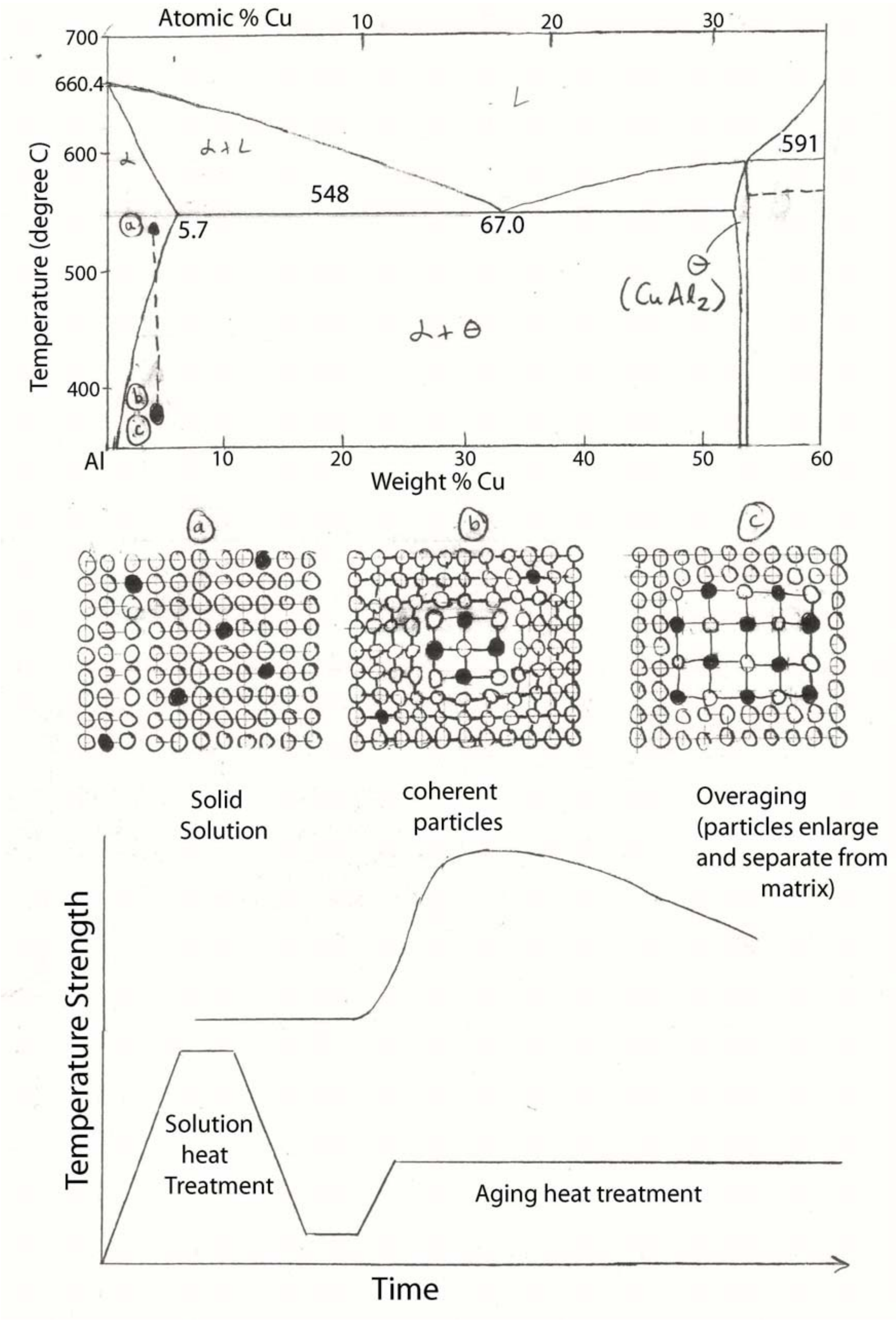

Atomic % Cu
10
20
30
700
660.4
600
500
400
Temperature (degree C)
L
α+L
α
548
591
5.7
67.0
θ
(CuAl₂)
α+θ
a
b
c
Al
10
20
30
40
50
60
Weight % Cu
a
b
c
Solid Solution
coherent particles
Overaging (particles enlarge and separate from matrix)
Temperature Strength
Solution heat Treatment
Aging heat treatment
Time

Figure 14.13

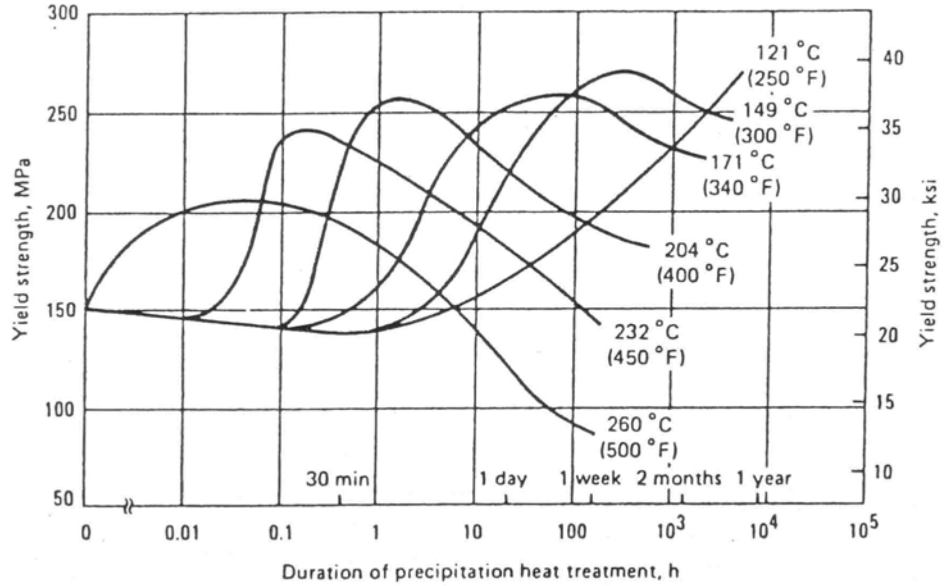


Figure 14.14

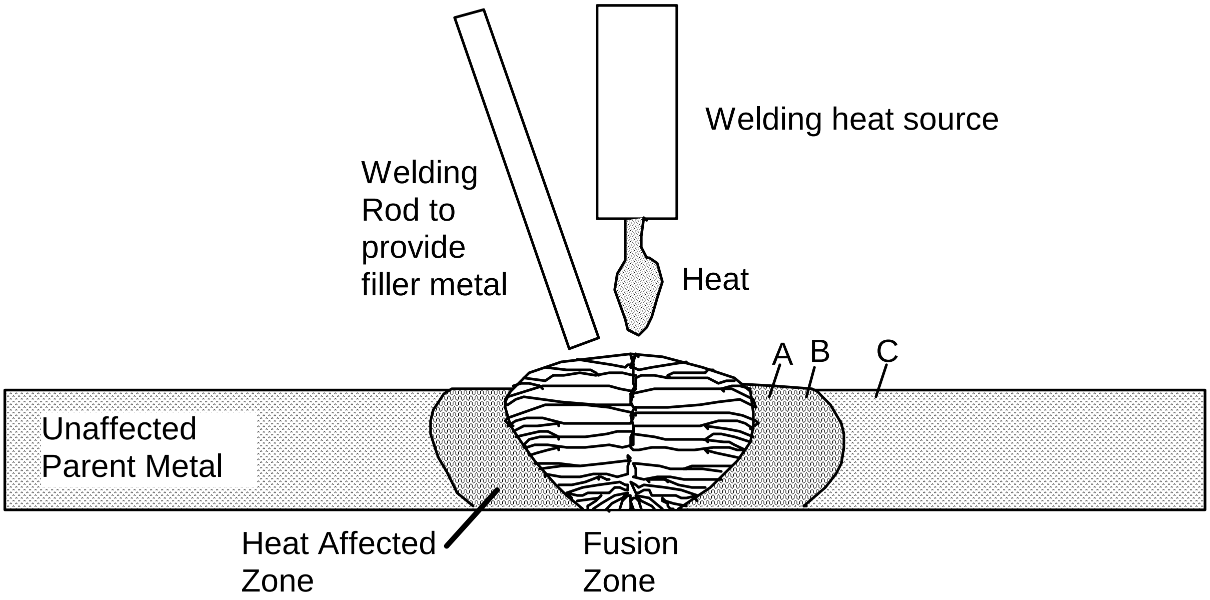


Figure 14.15

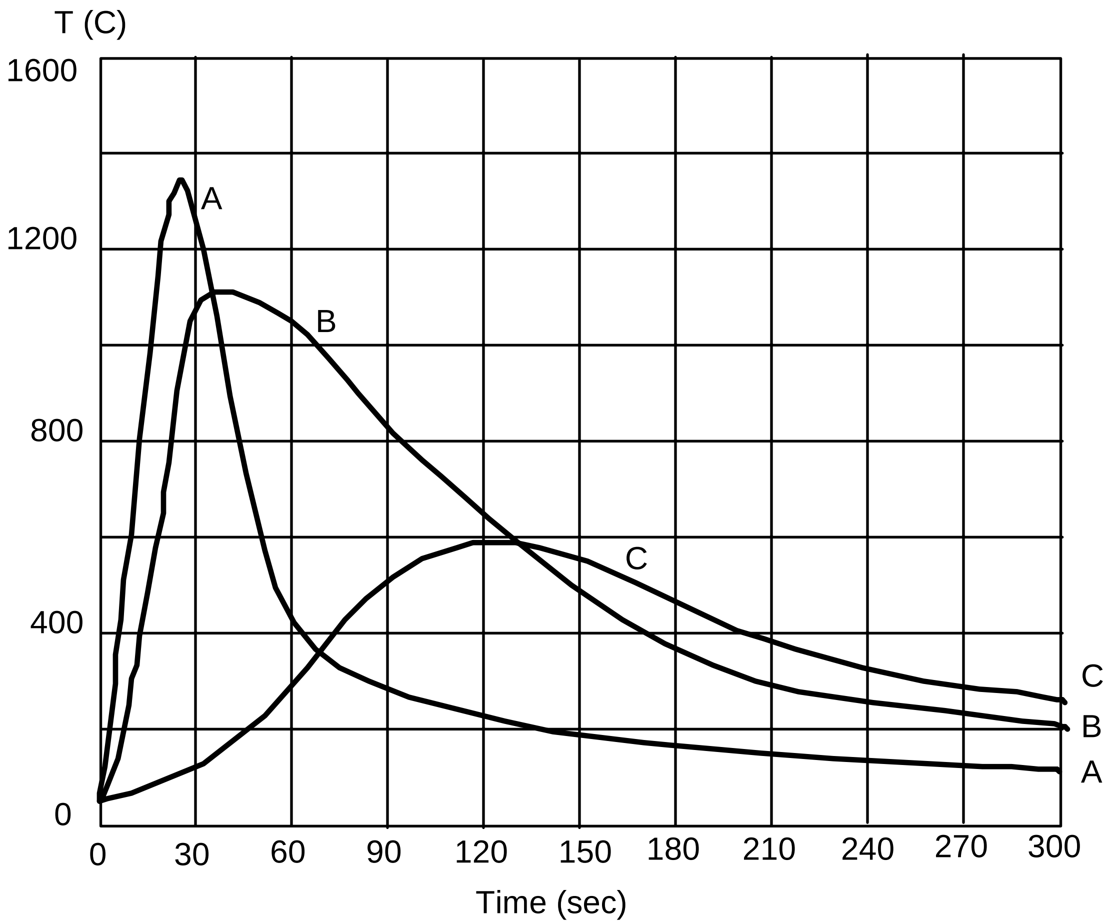

T (C)
1600
1200
800
400
0
A
B
C
C
B
A
0
30
60
90
120
150
180
210
240
270
300
Time (sec)

Figure 14.16

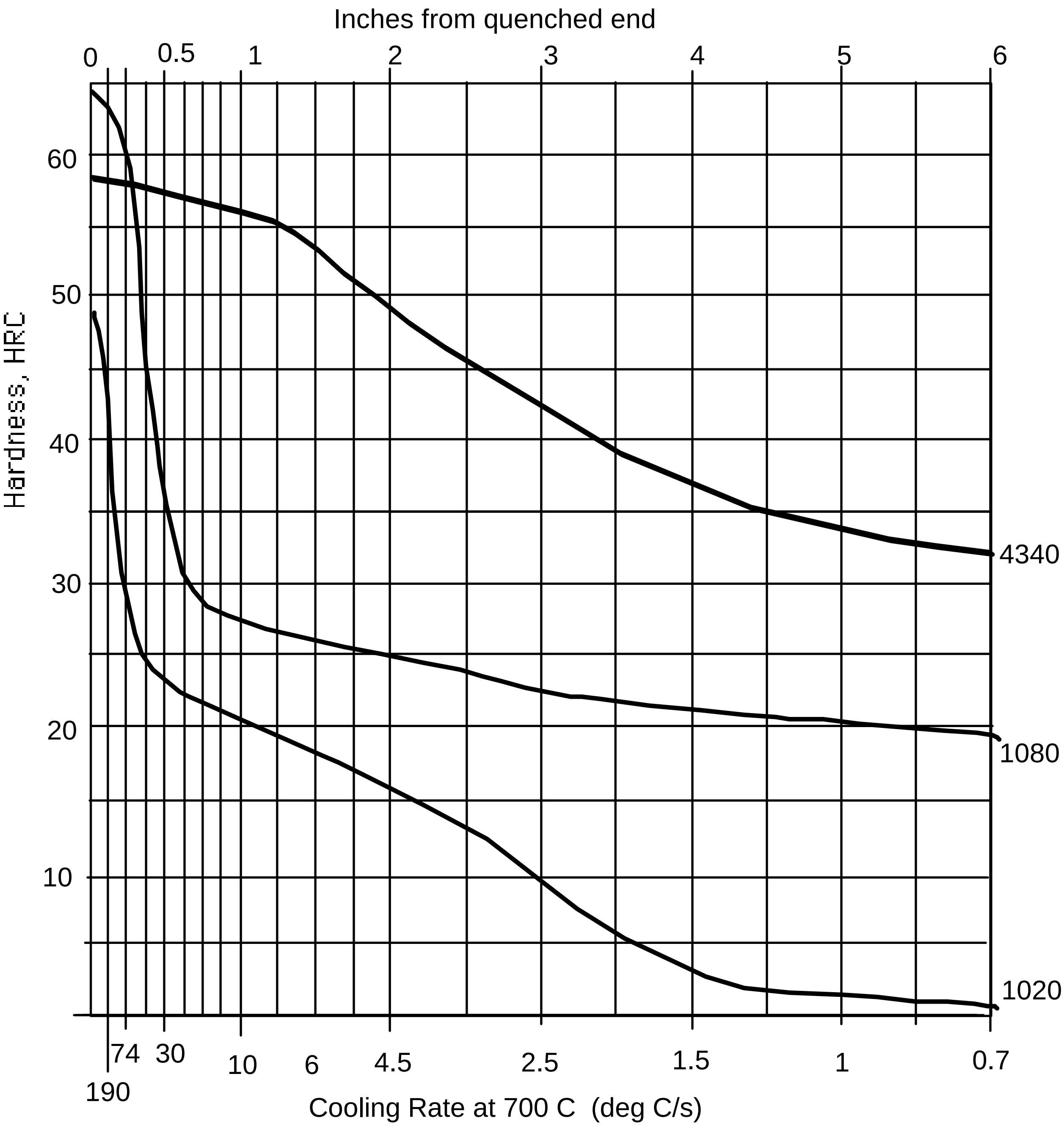

Inches from quenched end
0
0.5
1
2
3
4
5
6
Hardness, HRC
60
50
40
30
20
10
4340
1080
1020
74
30
10
6
4.5
2.5
1.5
1
0.7
190
Cooling Rate at 700 C (deg C/s)

Figure 14.17

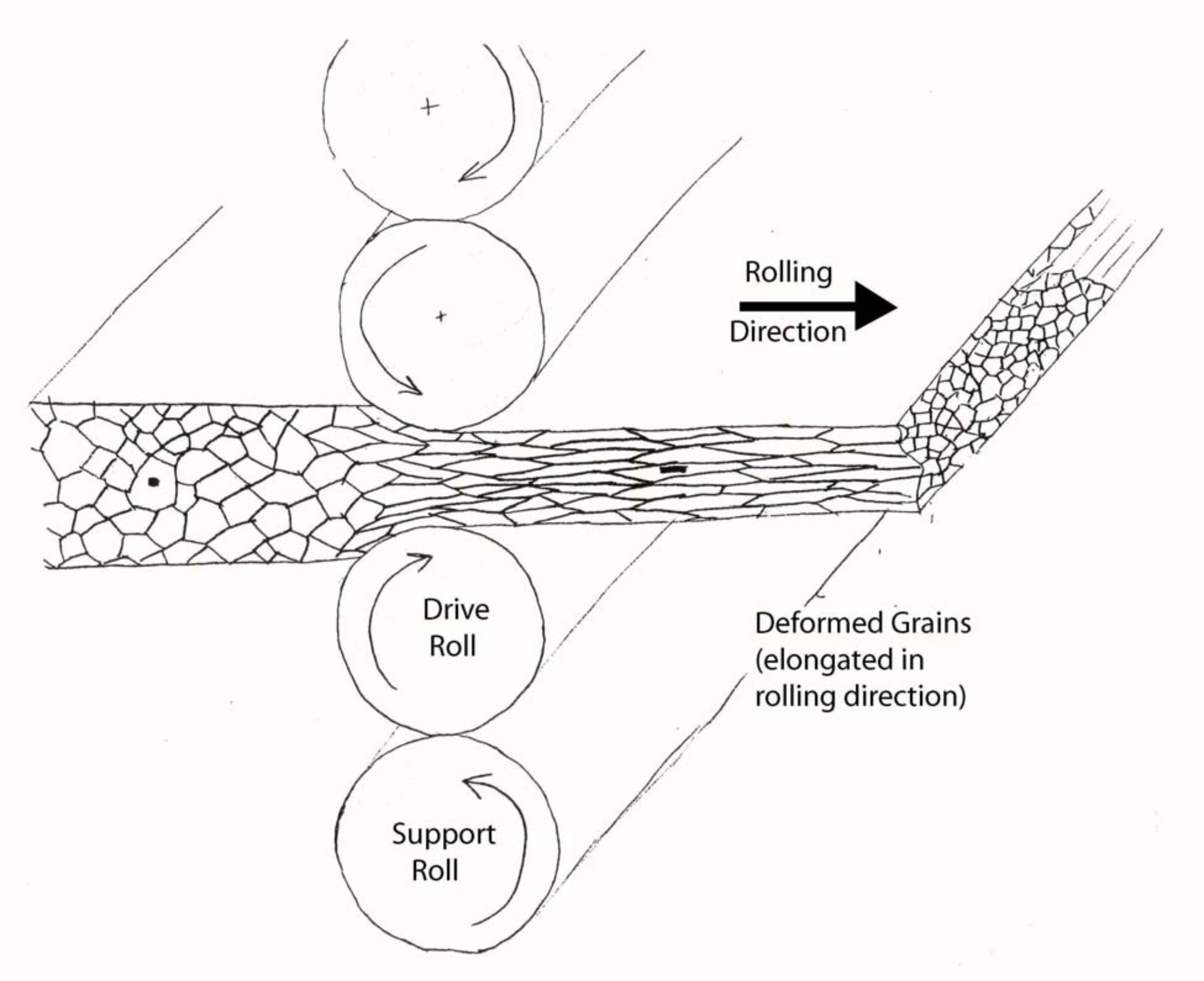

Rolling
Direction
Drive
Roll
Deformed Grains
(elongated in
rolling direction)
Support
Roll

Figure 14.18

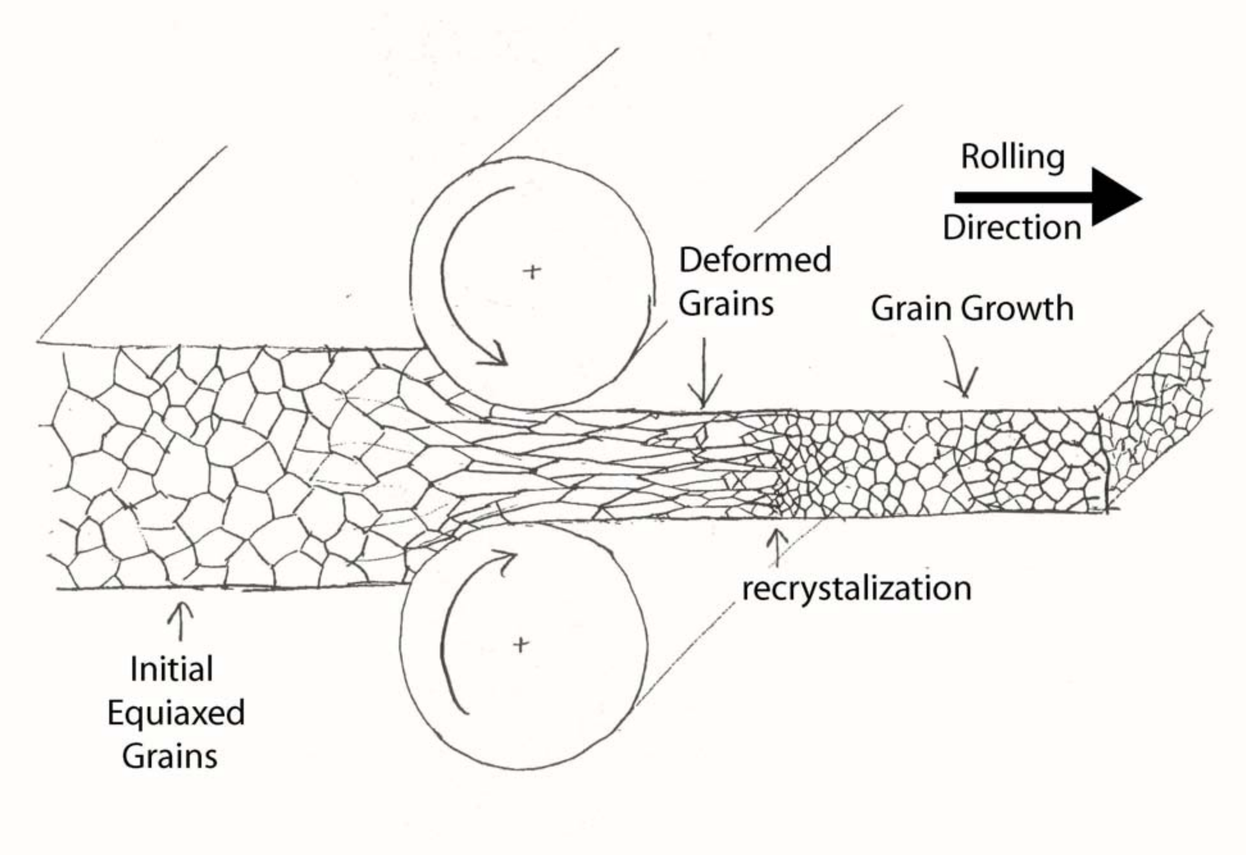


Figure 14.19

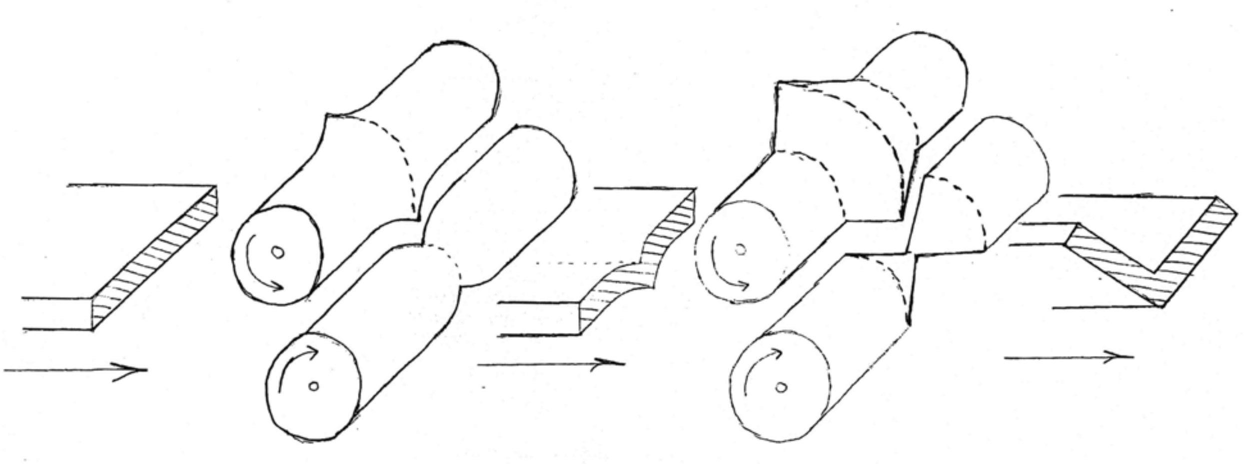


Figure 14.20

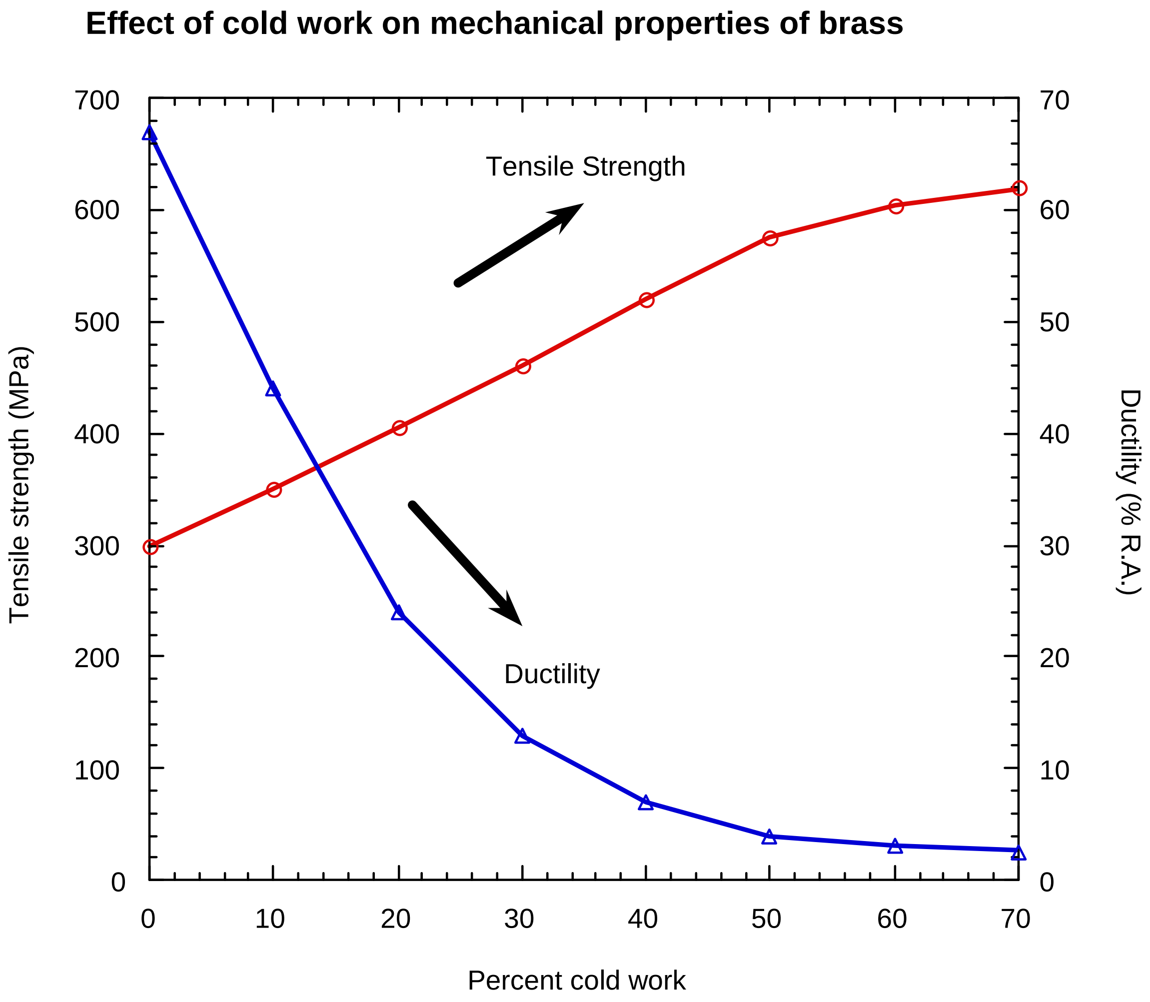

Effect of cold work on mechanical properties of brass
Tensile Strength
Ductility
Tensile strength (MPa)
Ductility (% R.A.)
Percent cold work
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60
70
0
10
20
30
40
50
60
70

Figure 14.21

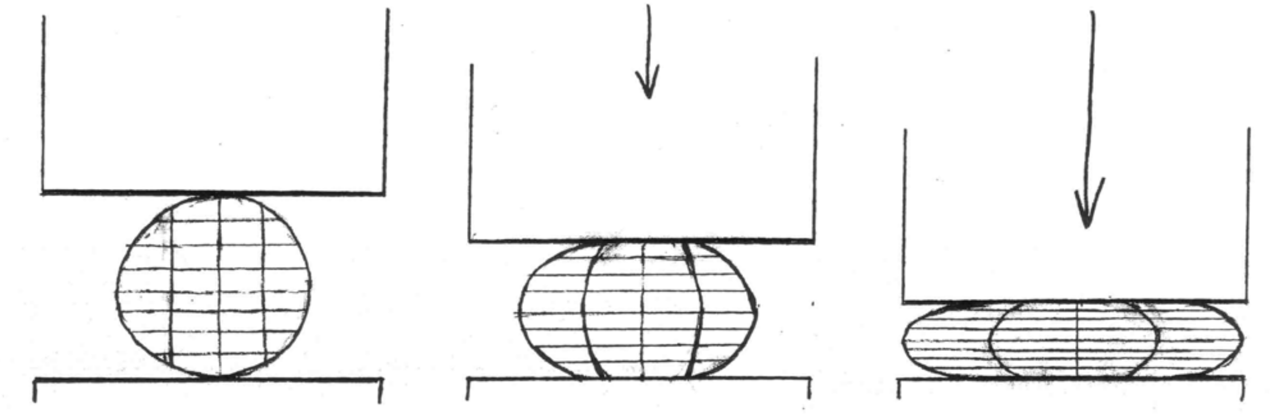


Figure 14.22

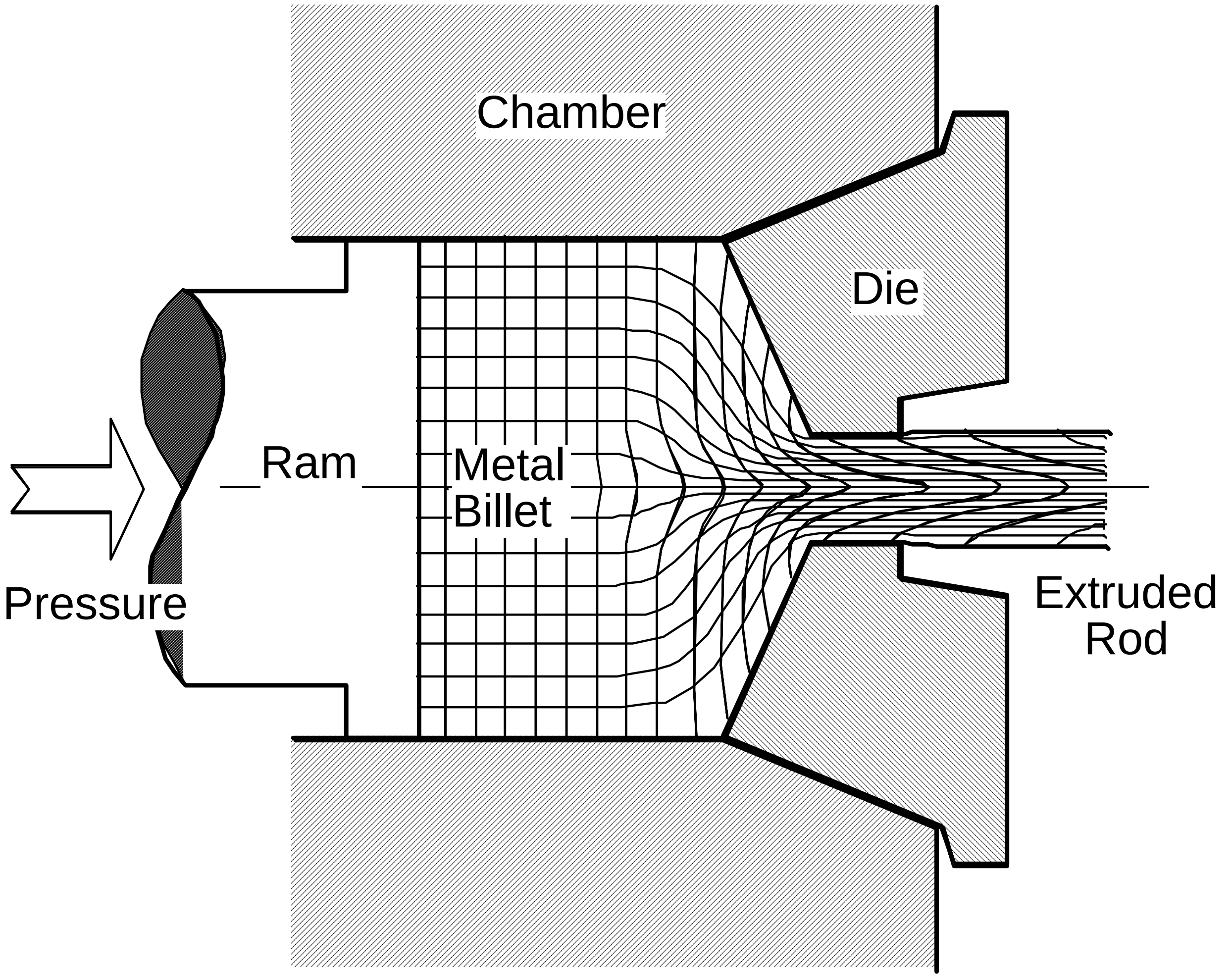


Fig. 14.23

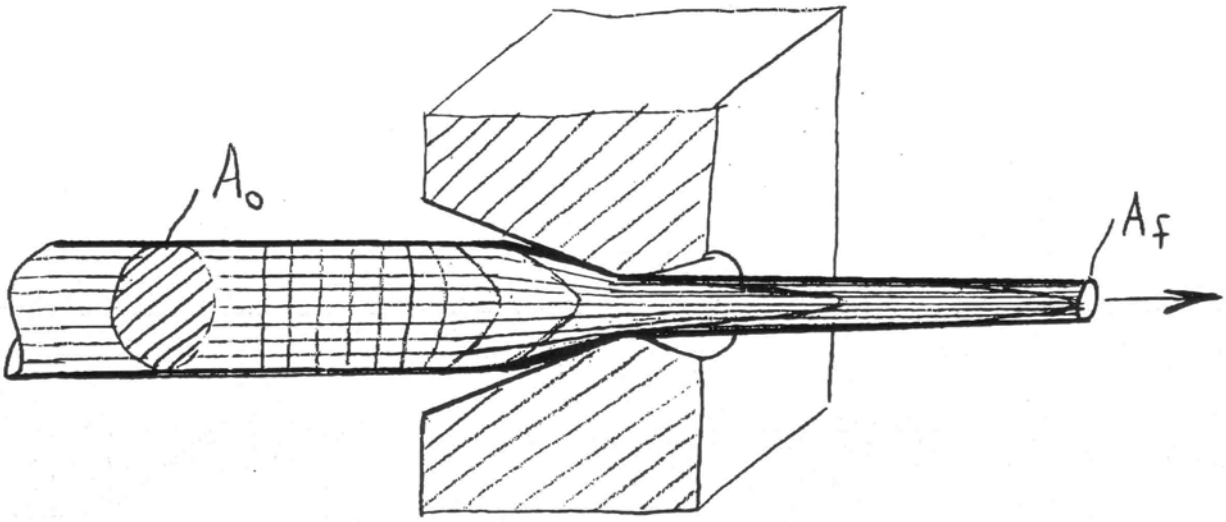


Figure 14.24

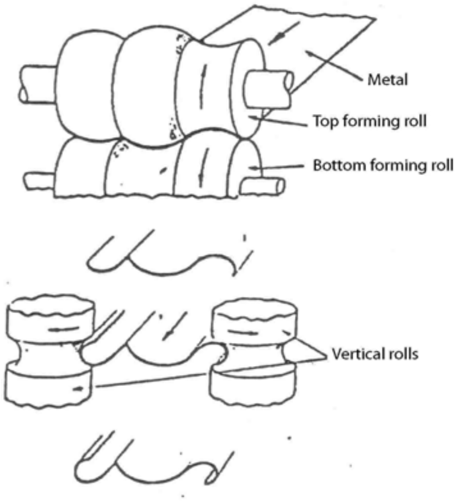
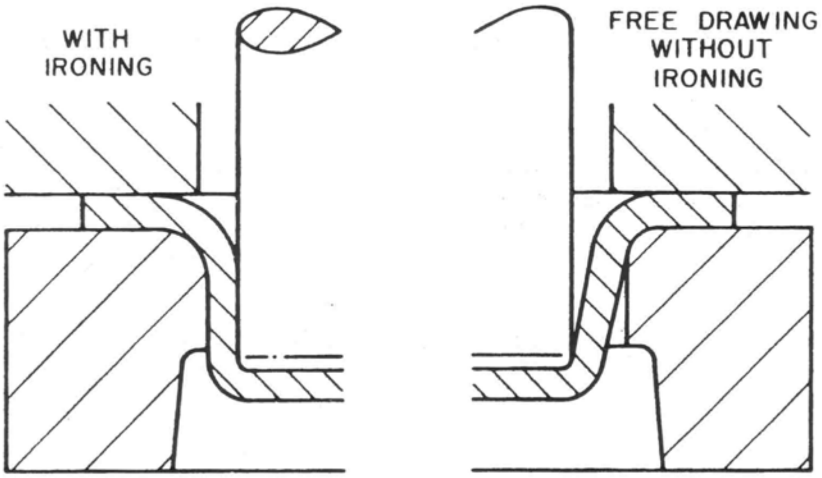
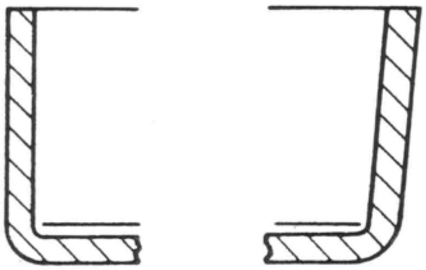


Figure 14.25



IN OPERATION



COMPLETED CUP

Figure 14.26

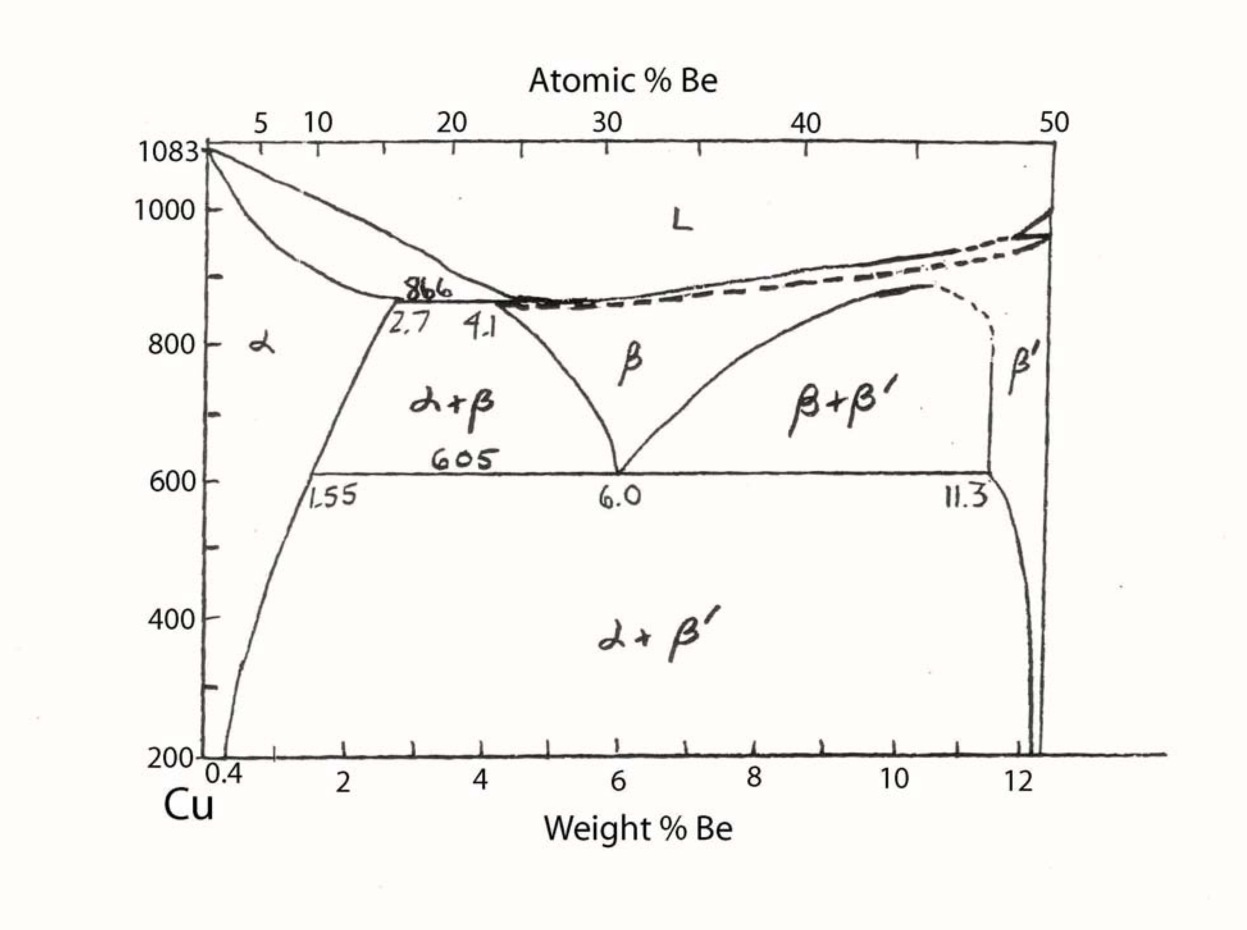


Figure 14.27

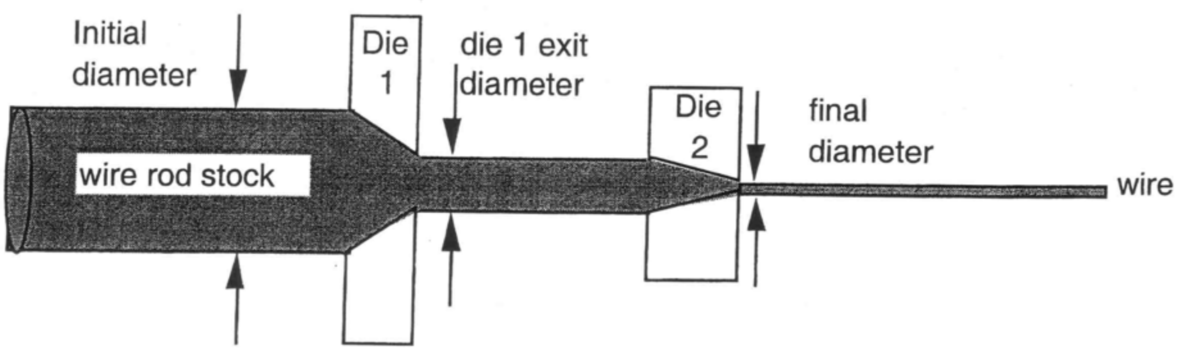


Figure 14.28

GLOSSARY

age hardening	precipitation hardening
alloying	process of combining metals together to control the composition
anisotropic	differences with direction
artificial aging	precipitation hardening via heating after supersaturation
back-up rolls	rolls which support the work roll to prevent distortion
billet	semi-finished metal shape, with small (.1m) square cross-section
binder	oil or clay used to hold foundry sand together
blank	rough piece of metal to be shaped into a part by deformation
blast furnace	tall, shaft-like furnace used to extract molten metal from its ore using air
burned	defect formed during furnace heat treatment of a metal part
casting	manufacturing process involving solidification
casting direction	direction of movement of solidification interface
centrifugal casting	casting process performed by spinning the mold
charge	add (to a furnace)
chill	metal device to increase heat transfer during casting
chill zone	thin zone of small grains at surface of a casting.
coherent	continuous crystal structure
coke	carbon, (purified from charcoal)
cold work	deformation below the recrystallization temperature
columnar zone	region of long, parallel grains in a casting
continuous casting	process to solidify metal continuously through a bottomless mold
dendrites	tree-shaped spikes forming solid / liquid interface in crystal solidification
dies	pieces of a permanent mold or extrusion cavity used to rapidly shape metal which flows through it
drawing	pulling material through a die
equiaxed zone	region of roughly-round-shaped grains in a casting
equilibrium constant	empirical ratio of equilibrium concentrations for a chemical reaction
extrusion	squeezing material through a small opening to produce a desired shape of cross section
feeding	uninterrupted flow of metal through a casting mold
ferrous	pertaining to iron
finer	smaller
formability	measure of ductility during stretching in two directions at once

freezing range	difference between the solidus and liquidus temperature
gas porosity	casting defect consisting of void caused by gas bubbles
gating system	passageways through sand from ambient to the casting cavity in a sand mold
grain selector	spiral-shaped mold passageway which favors emergence of a single grain during directional solidification
grain refiner	alloy that encourages nucleation and formation of small grain size
heat affected zone	region of a weld where structure and property changes occur
homogenizing	thermal process to diffuse away segregation by holding in a furnace
hot shortness	hot tear-like fracture formed during hot working
hot tears	cracks in a casting formed during solidification due to strain on liquid films
hot work	deformation above the recrystallization temperature
inclusions	Nonmetallic impurity particles in metal
ingot	large, simple-shaped casting
interdendritic	between dendrites
lost wax	investment casting process
macrosegregation	nonuniform composition distribution on a scale relative to the entire part
macrostructure	grain structure on the size of a casting
microsegregation	nonuniform composition distribution on a scale relative to the grain size
molten	liquid
mush	semi - solid / liquid state between solidus and liquidus temperatures
natural aging	precipitation hardening at ambient temperature after supersaturation
nucleation	creation of new tiny, stable, solid crystals in an existing medium
ore	mineral deposit containing metal for extraction
overaging	loss of strength of a precipitation hardened alloy due to coursening of the precipitates
passes	trips between the rolls during hot or cold rolling
pattern	model of intended cast part used to imprint the sand mold
pinholes	casting defect consisting of small voids
porosity	casting defect caused by gas bubbles or voids.
precipitation hardening	strengthening by forming second phase after supersaturation
recrystallization temperature	temperature range where old deformed grains spontaneously transform into new equiaxed grains
reduction	chemical transformation of a metal oxide to form metal
refining	remove impurities

riser	liquid metal resevoir to slow down heat transfer in sand casting
rolling	deformation process involving squeezing material between rotating rolls
SDAS	secondary dendrite arm spacing
secondary arms	branches on dendrites
semi-finished	intermediate product designed for further processing
shrinkage cavities	voids in a casting
shrinkage porosity	castng defect consisting of void caused by shrinkage
slab	semi-finished metal shape, with large rectangular cross-section
solidification	phase transformation from liquid to solid
solute	alloy dissolved in another material as a single phase.
solution heat treat	heat an alloy above the solvus temperature to dissolve all precipitates and form a single phase
solvus	temperature above which second phase particles dissolve into a single phase
spray cast	casting process which directs molten metal droplets
springback	elastic expansion of a part after a load is released
stress relief	remove stress
superheat	heat contained in liquid above the liquidus temperature
tap	remove liquid from a furnace
thermal processing	subject to a particular sequence of temperature changes
tool	sharp, hard device, such as a blade, used to cut and shape metal parts
tundish	holding vessel for molten metal prior to casting
undercooling	temperature of a liquid below its eqilibrium solidification temperature
Vacuum casting	casting process performed in a vacuum
vacuum degassing	process to remove dissolved gas by exposing molten metal to a vacuum
vents	vertical holes in casting mold to allow trapped air and gas to escape
welding	joining metal parts together by heating their surfaces until they melt
work rolls	rolls which shape the material or part
zone refining	casting method to purify metal via solidification

PROBLEMS

14.2.1. What are two basic strategies to produce pure metal from its ore.

14.2.2. List two reasons why it is important to recycle aluminum.

14.2.3. How does decreasing temperature affect the amount of gas dissolved in a liquid metal?

14.2.4. Why should the temperature of liquid metal be kept as low as possible if it must be exposed to the atmosphere after refining?

14.2.5. Why is it important to protect molten metal from contact with humid air or wet refractory bricks before it is cast?

14.2.6. What fraction of the H dissolved in molten aluminum at 900 ^oC can be removed simply by dropping the temperature to 700 ^oC ? (assuming the ambient H partial pressure remains constant)

14.2.7. Can the H content of molten aluminum exposed to 0.05 atm H environment be lowered to a safe level (less than 0.1 ppm) simply by lowering the temperature? (Hint: aluminum solidifies at 660^oC)

14.2.8. What is the equilibrium H content dissolved in molten aluminum at 750 ^oC at 0.05 atm partial pressure H?

14.2.9. Is a $1x10^{-2}$ atm vacuum degassing treatment sufficient to lower the H content of aluminum at 800 ^oC to a safe level? (less than 0.1ppm)

14.2.10. What is the highest partial pressure of H (atm) that can tolerated during the vacuum degassing of aluminum at 750 ^oC to less than 0.003 ppm H?

14.2.11. Nitrogen can be removed by degassing molten steel. The equilibrium constant in Sievert's law, K for N in Fe at 1600 ^oC is 44 ppm at 1 atm.

a) What is the equilibrium nitrogen content of steel at 1600 ^oC exposed to air (79% N)?

b) To what level can the nitrogen content of steel be lowered by vacuum degassing at 10^{-3} atm at 1600 ^{o}C?

c) How much nitrogen can be removed from steel by vacuum degassing at 10^{-4} atm at 1600 ^{o}C.

14.3.1. Describe the three macrostructural regions in a typical casting.

14.3.2. List two ways to change the microstructure of a casting to increase its tensile strength.

14.3.3. What casting process would you use to manufacture 5 large aluminum ashtrays? 500,000 aluminum ashtrays?

14.3.4. What process would you use to cast a custom-designed platinum wedding ring? 500,000 silver wedding rings to be gold plated for costume jewelry?

14.3.5. What casting process would you use to make intricate turbine blades (airfoils) for jet engines? How would you modify the process to make single crystal airfoils, with a higher creep resistance?

14.3.6. What casting process would you use to make five cast iron engine blocks for tractors? 500,000 cast-iron engine blocks?

14.3.7. What casting process would you use to mass-produce:

a) long steel bars for rolling into steel rails for the railroad industry?

b) stainless steel sheets for stamping and forming into car mufflers?

14.3.8. What casting process would you use to make a gold tooth filling?

14.3.9. List 5 different defects that could occur in a sand casting and describe briefly what steps you might take to prevent each one.

14.3.10. What is microsegregation? How can it be removed from a casting?

14.3.11. Why is liquid metal usually covered with slag or other means to prevent contact with air?

14.3.12. What is superheat? What problems could occur if the superheat is too high? Too low?

14.3.13. A casting is found to contain many round smooth holes. What steps would you take to prevent this casting defect?

14.3.14. A casting is found to contain a single, large, hole in its center, with solid dendrites visible around its edges. What steps would you take to prevent this casting defect?

14.3.15. Why are critical cast parts often subjected to a series of expensive melting and remelting processing stages?

14.3.16. Suggest two casting defects that can be improved by avoiding contact between molten metal and air during processing?

14.3.17. Which casting defect is most difficult to remove by subsequent processing (rolling and / or heat treatment)?

14.3.18. Why do some steel alloys have an upper limit on sulfur and some have a lower limit?

14.3.19. "Sliver" defects on the surface of cast product that has been rolled consist of long bands of oxide particles. Suggest what causes these defects and how to prevent them.

14.3.20. Casting is easier (ie. thin wall sections will feed with less chance of porosity or shrinkage cavities) when the liquidus-to-solidus temperature range is narrow (smaller mushy zone) and the solidus temperature is low (slowing down heat transfer). What composition of Ag - Cu is easiest to cast? (Hint: Examine the phase diagram in Figure 13.7 and consider the freezing range of the alloy)

14.3.21. What composition of iron and carbon has the best castability and why?

14.3.22. Which of these copper / zinc alloys has better castability?
80%Cu, 20%Zn; 70%Cu, 30%Zn, or 60%Cu, 40%Zn

14.3.23. Why is the shrinkage cavity in pure aluminum larger than that in an alloy of 88% Al - 12% Si?

14.3.24. Calculate the largest final dimensions of a steel slab cast in a 5 x 5 x 25 cm sand mold.

14.3.25. Why are shrinkage cavities rare in high-carbon (5%C) gray cast iron?

14.3.26. How long should a 2-cm thick plate of aluminum take to solidify in a sand mold? (See example 14.7 for property data)

14.3.27. Calculate approximately how long it would take to solidify a long round steel bar casting with 20 cm diameter in a sand mold. (See example 14.7 and assume that for iron, $\rho = 8$ g/cm^3, $\Delta H_f = 65$ cal/g, and $T_f = 1500$ ˚C)

14.3.28. Consider a continuous caster that produces 8 inch thick slabs of steel at a casting speed of 1.5 m/min. Inspection of the solid slabs revealed a band of cracks 3.2 inches beneath the surface. They most likely formed when tensile stress from a misaligned roll caused hot tearing at the solidification front. How far from the point of initial solidification is the misaligned roll that caused the cracks? Assume K=1.05 inch-min$^{-0.5}$.

14.4.1. a) Can a 1% Be - 99% Cu alloy be precipitation hardened? If so, explain how you would do it using information from the phase diagram in Figure 14.27.

b) What is the maximum amount of precipitate possible at 200 ^{o}C?

c) What is the composition of the precipitate and what is its chemical formula? (Hint: examine the atomic % Be axis of Figure 14.27)

14.4.2. Two different aluminum samples were each heated to 220 ^{o}C, held for one hour, and cooled. The strength of one sample was observed to increase while that of the other decreased. Explain how this could be. (Describe the most likely original state of each sample and describe the phenomena that must have occurred in each sample during the heat treatment).

14.4.3. Name and describe the features of the three zones of a weld.

14.4.4. Why is it dangerous to weld a precipitation hardened alloy without later heat treating? Which zone of the weld might fail?

14.4.5. How long can a 6061 aluminum part be used in service at 150 °C before it begins to overage? Estimate how long it can be used at this temperature before its strength drops below 35 ksi.

14.4.6. Design a heat treatment process to produce 6061 aluminimum parts, if 20 minutes is available to spend in the aging furnace. Be sure to specifiy the best operating temperature to produce maximum strength parts. (See Figure 14.14)

The following problems are based on Example 14.8 and would be easier after reading Chapter 15 to understand hardenability.

14.4.7. a) What cooling rate is achieved at 700 °C in a 2-mm diameter drill rod of 1080 steel that is subjected to a heat treatment that produces a hardness of 35 HRC? (See Figure 14.17).

b) What hardness would result in a 1020 steel drill rod given the same heat treatment?

c) What hardness would result in a 4340 steel drill rod given the same heat treatment?

d) What cooling rate at 700 °C would be needed to raise the hardness in the 1080 steel drill rod to 60 HRC?

14.4.8. A high quality axle should have a hard surface for good wear resistance, combined with a soft, tough center for long fatigue life. For a specific application, suppose that the requirements for a steel axle are a *minimum* surface hardness of 55 HRC and a *maximum* center hardness of 35 HRC. A test axle made from 1080 steel is heated to 800 °C and then quenched in a cool polymer bath. This heat treatment produces 25 HRC at its surface and 20 HRC at its center.

a) Would 1020 steel be an acceptable material for the axle, given the same heat treatment? Explain why or why not.

b) Repeat a) for 4340 steel.

c) Design a possible steel hardenability curve that would satisfy the requirements.

d) Suppose the heat treatment was changed, so that the test axle now produces 50 HRC at the surface and 20 HRC at the center. Re-evaluate the potential of 4340 and 1020 steels for axles produced with this new heat treatment.

14.4.9. A 2400 cal/s power source is used to weld a thick plate of SAE 4340 steel. The centerline hardness on the top surface should be less than 50 HRC. What is the maximum welding speed which will satisfy this requirement? Use hardenability data in Figure 14.17 and assume that the Rosenthal model for thick plate welding can be applied, wherein the cooling rate along the top surface centerline is expressed by:

$$\frac{\partial T}{\partial t} = 2 \pi k \frac{v}{Q} (T - T_o)^2$$

where k = metal thermal conductivity (W/mK)
v = weld velocity (m/s)
Q = power input (W)
T = temperature = f(t)
T_o = initial temperature (^oC)

Assume that all steels have about the same thermal conductivity of 40 W/mK at 700 ^oC.

14.4.10. Two thick plates of 1080 steel are welded together with a 3500 cal/s power source moving at 50 mm/min. Predict the centerline hardness using Rosenthal's model (See Problem T9). In real applications, thick plates are often welded using many separate passes, in order to minimize the size of the heat affected zone.

14.5.1. What is the difference between hot and cold work?

14.5.2. A 20 mm thick plate of steel is cold rolled to 12 mm thick. It is then rolled to 8 mm thick.

a) What is the percent cold work after the first rolling stage?
b) What is the percent cold work after the second stage?
c) What is the total cold work?
d) Based on your answer to c), is cold work simply additive?

14.5.3. A Nickel rod of 15 mm diameter is drawn to 10 mm diameter. What is the percent cold work?

14.5.4. A 15 mm plate of tin (Sn) is extruded at room temperature (25 ^oC). Is this hot or cold working? Explain. (Hint: calculate the recrystallization temperature)

14.5.5. A 10 mm thick plate of cast copper is rolled at 500 °C to 4 mm thick. It is then rolled at 100 °C to 3 mm thick.

- a) What is the percent cold work?
- b) What is the percent hot work?

14.5.6. Why would dies designed for drawing annealed aluminum wire not produce the same diameter wire when drawing annealed copper?

14.5.7. What deformation process would you choose to produce:

- a) copper wire
- b) aluminum beverage cans
- c) fenders for car bodies
- d) plate for a pressure vessel
- e) hard steel rails
- f) long aluminum I-beams
- g) seemless steel pipe for oil wells
- h) mild steel bathtubs

14.5.8. What is the difference between deep drawing and wire drawing?

14.5.9. Suggest a good hot rolling temperature for steel.

14.5.10. Brass wire (85 Cu- 15 Zn) with an initial diameter of 2.0 mm is being drawn through a series of dies (Figure 14.28) to reduce its diameter and increase its strength via cold work.

- a) To achieve a sufficiently high strength, (350 MPa yield) the wire should be cold worked at least 23%. However, to achieve sufficient ductility, (10% elongation) the wire should be cold worked at most 25%. Design a processing sequence that will produce 0.2 mm diameter wire that meets these requirements. Indicate the temperatures and exit diameters for the dies and explain all reasoning, assumptions, and calculations that you make.

b) Qualitatively, describe how you could achieve the same wire properties using a completely different processing sequence, assuming the dies could not withstand the elevated temperatures indicated in the first step of the previous question.

14.5.11. Repeat problem 14.5.10 for brass with 70% Cu - 30% Zn, where the strength must exceed 400 MPa and the ductility must exceed 20 % R.A. Initial and final wire dimensions are the same.