Materials & Manufacturing Summer Institute
Southern Connecticut State University
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Science Fundamentals in Manufacturing

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I Introduction

Turning raw materials into products requires a combination of Science, Engineering, and imagination (and money). It is often possible to make the same product using different manufacturing technologies. For example, it is possible to make a length of pipe by

Extruding

Drawing

Casting

Welding

Or combinations of the above

I Introduction

In selecting among different manufacturing technologies, there are often no right and wrong solutions. There are only different advantages and disadvantages.

Manufacturing materials include Metals, Ceramics, and Polymers both singly and as composites. This brief introduction to manufacturing will concentrate on the fundamentals of metallurgy as applied to manufacturing.

This presentation will discuss some ways to make things, and some of the science concepts underneath the manufacturing processes.

II Fundamentals of Materials Processing - Metallurgy

To manufacture a product from a precursor, we usually change its shape and/or change its form.

In the metals industry, there are 2 basic processes to accomplish these changes:

1 Heat it

2 Beat it

3 Both

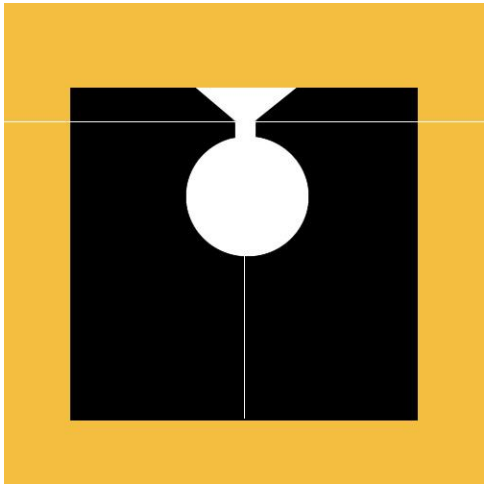
III Introduction to Casting

Casting is a versatile process which can be done using Metals, Plastics, and Ceramics. The basic process for casting a material is:

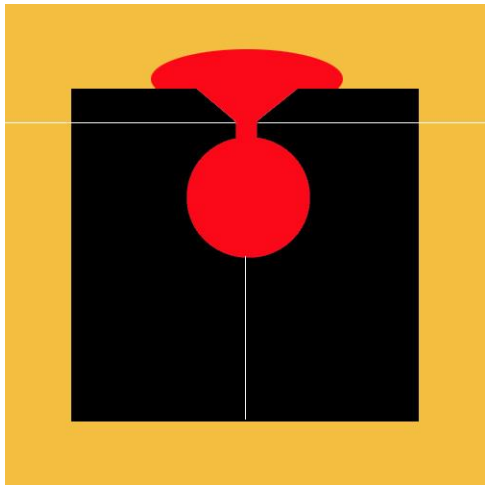
1. Melt or otherwise get the material into a liquid
2. Pour, force, or otherwise get the material into a mold of the required shape
3. Solidify (Freeze) the stuff
4. Remove the product from the mold
5. Sell the product for more than the cost of the materials and the processing

Simplified Casting of a Metal Clamshell Mold

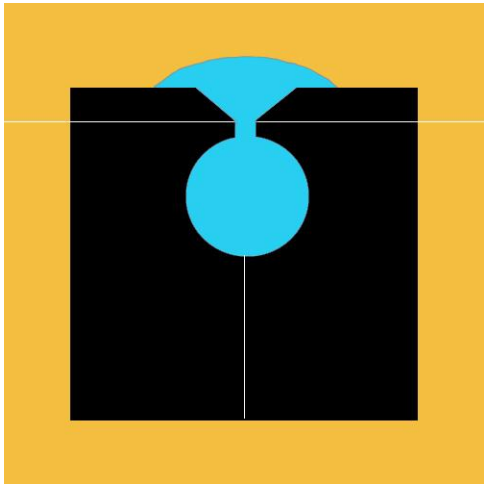
Empty Mold



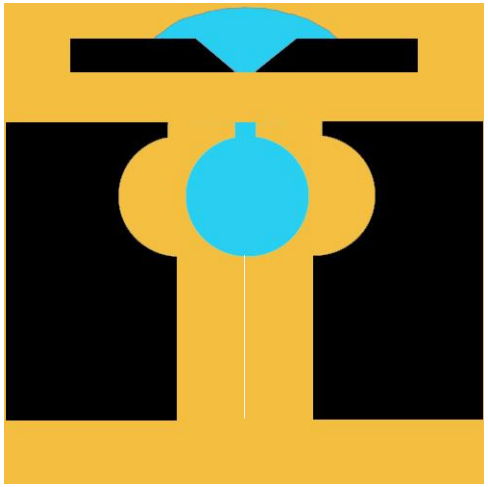
Fill Mold with Molten Metal



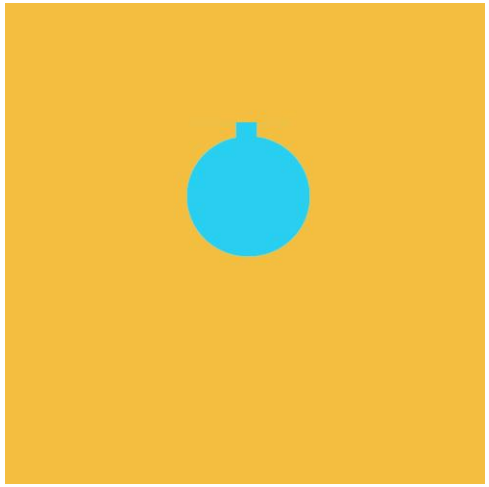
Solidify Molten Metal



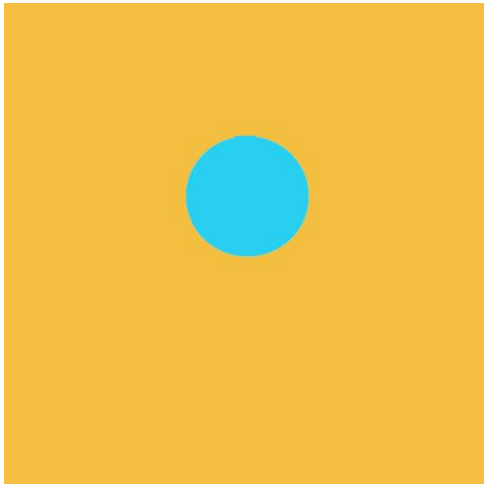
Open Mold



Remove Casting



Finish Surface if Required



Science Issues for Casting Metals

Process: Melt or otherwise get the material into a liquid

Science Concept 1: There are 3 Phases of Matter

Solids The solid phase maintains a fixed volume and resists deformation by an applied force

Liquids The Liquid phase maintains a fixed volume and flows under a constant applied force

Gasses The Gas phase has no fixed volume and obeys the Ideal Gas Law ($p V = n RT$)

Science Issues for Casting Metals

Process: Melt or otherwise get the material into a liquid

Science Concept 2: Transformation Temperatures

The Solid phase transforms to the liquid phase at the Melting Temperature

The Liquid phase transforms to the Gas phase at the Boiling Temperature

Bonus Questions: Do we need to be above the Boiling Point to have a Gas?

Do we care?

Science Issues for Casting Metals

Process: Melt or otherwise get the material into a liquid

Science Concept 3: Heat and Temperature

We need to add energy (heat) to a material to increase itstemperature. This is given by

$$\Delta Q = m C \Delta T$$

Where	Q	Heat added or removed
	m	Mass of material being affected
	C	Heat capacity of the material
	T	Temperature

Science Issues for Casting Metals

Process: Melt or otherwise get the material into a liquid

Science Concept 4: Heat and Phase

We need to add energy (heat) to a material to change its phase. This is given by

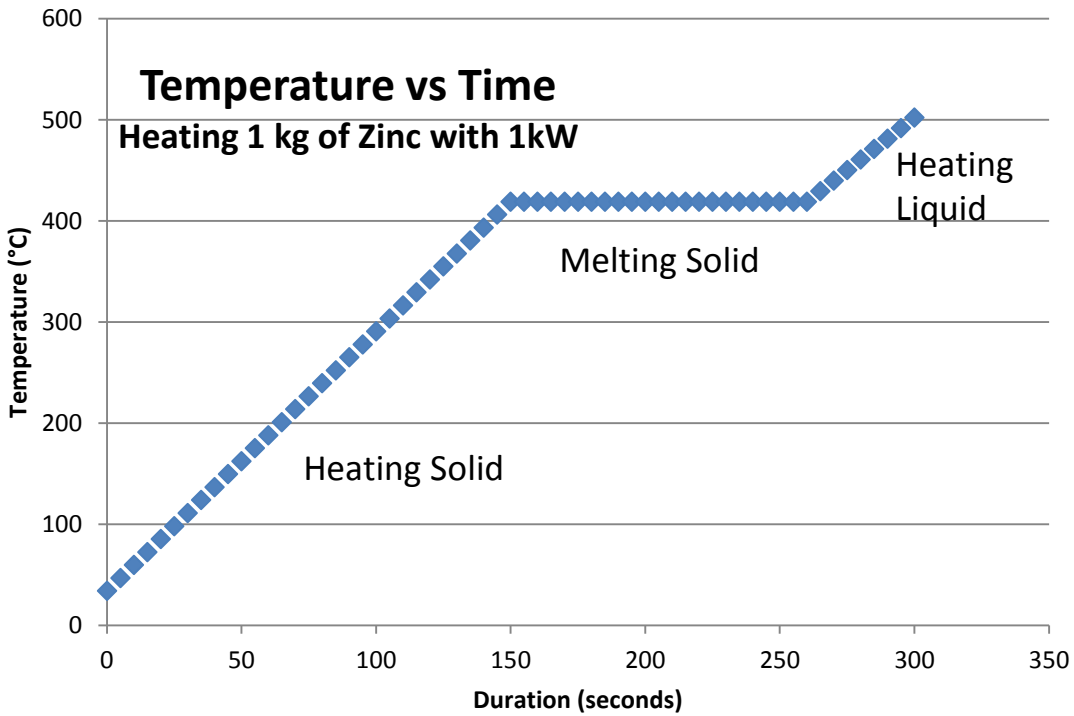
$$\Delta Q = m L$$

Where Q Heat added or removed
m Mass of material being affected
L Latent heat of phase change

Science Issues for Casting Metals

Process: Melt or otherwise get the material into a liquid

Science Concept: Summary of Transformation and Temperature



Science Issues for Casting Metals

Process: Pour, force, or otherwise get the material into a mold of the required shape

Science Concept: The Liquid phase maintains a fixed volume and flows under a constant applied force

We can use any convenient force to get a liquid into a mold. These include:

Gravity	$F = m\,g$
Pressure	$P = F / A$
Centrifugal forces	$F = m\,\omega^2\,r$

Bonus Question: How do we get air (bubbles) out of the mold?

Science Issues for Casting Metals

Process: Solidify (Freeze) the stuff

To solidify (freeze) the metal, we do the previous steps in reverse.

These are: We transform from a Liquid phase to a Solid Phase

By removing Heat

We cool the hot solid phase to ambient temperature

By removing Heat

Now how do we move Heat around?

Science Issues for Casting Metals

Process: Solidify (Freeze) the stuff

Science Concept: Heat Transfer

There are 3 mechanisms of Heat Transfer

All move heat from a Hot location to a Cold location

Conduction - Transfer of Heat through a solid material
Conduction - Transfer of Heat by the motion of a fluid

$$Q = \{\text{Geometry Constant}\} * \{\text{Material Constant}\} * \Delta T$$

Radiation - Transfer of Heat via Electromagnetic Radiation

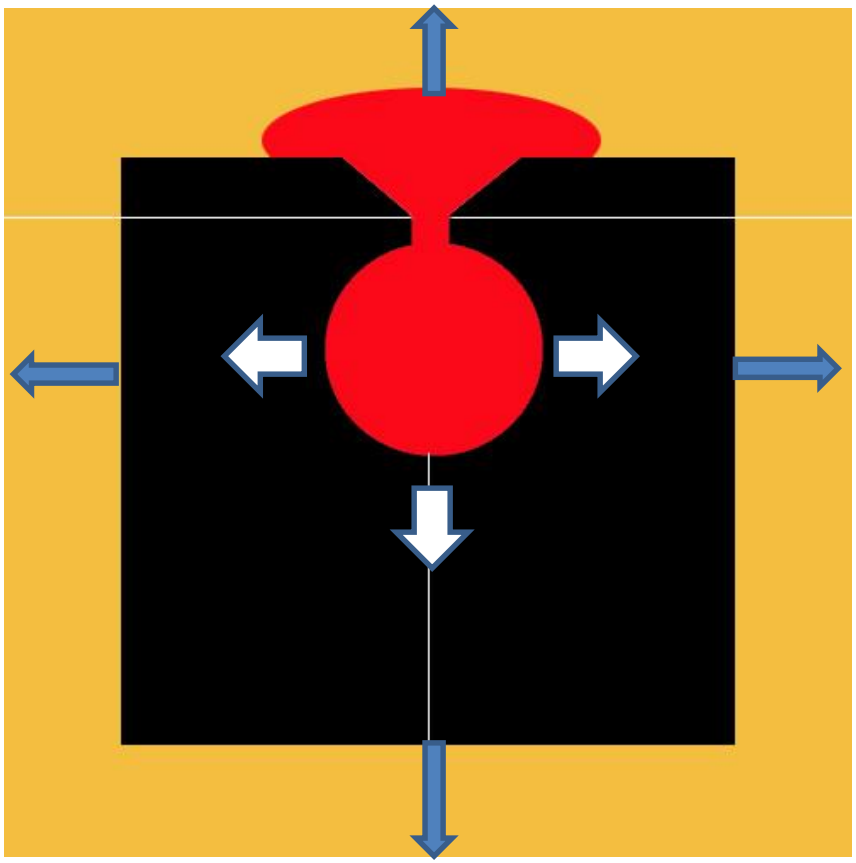
$$Q = \{\text{Material Constant}\} * \{\text{Constant of Nature}\} * (\Delta T)^4$$

Science Issues for Casting Metals

Process: Solidify (Freeze) the stuff

Science Concept: Heat Transfer

Convection



Conduction

Science Issues for Casting Metals

Process: Remove the Casting

Science Concept: Thermal Expansion

When materials change phase they (usually) expand or contract

When materials change temperature they (usually) expand or contract

$$\Delta l = lo\ \alpha\ L\ \Delta T$$

Where	Δl	Length Change
	lo	Original
	α	Material Constant
	ΔT	Temperature Change

Bonus Question: Do we care?

Engineering Issues for Casting Metals

Process: Making Heat

There are two common energy sources which are used for heating

Electrical Energy Electrical power = Current^2 * Resistance

Chemical Energy Combustion: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + Heat

Heat costs money

Electricity (CT)	\$0.13 / kWh	=	3.6×10^{-8} \$ / Joule
Natural Gas	\$2.90 / million BTU	=	2.7×10^{-9} \$ / Joule

Engineering Issues for Casting Metals

Process: Making Heat

Based on our understanding of Science and Technology

What are advantages of Electricity versus Natural Gas to provide heat?

Efficiency

Safety

Health

Effect on Product

Etc.

Engineering Issues for Casting Metals

Melt Temperature → Heat Added ($)

Mold Temperature → Heat Removed
Heat Management

Sprue Removal → Material Losses ($)

Scrap

Other Casting Concepts

The excitement is in the Mold

Single use Molds	Sand Casting Lost Wax Process
Injection Molding	Force the material into the mold under pressure
Mouldless Casting	Shot towers

Casting of Ceramics

Can we Cast a Ceramic? Yes

But: Can we **<u>Melt</u>** a Ceramic?

Usually Not

Solution: Mix particles of ceramic and Water to form a Slurry

Cast The Slurry into a mold

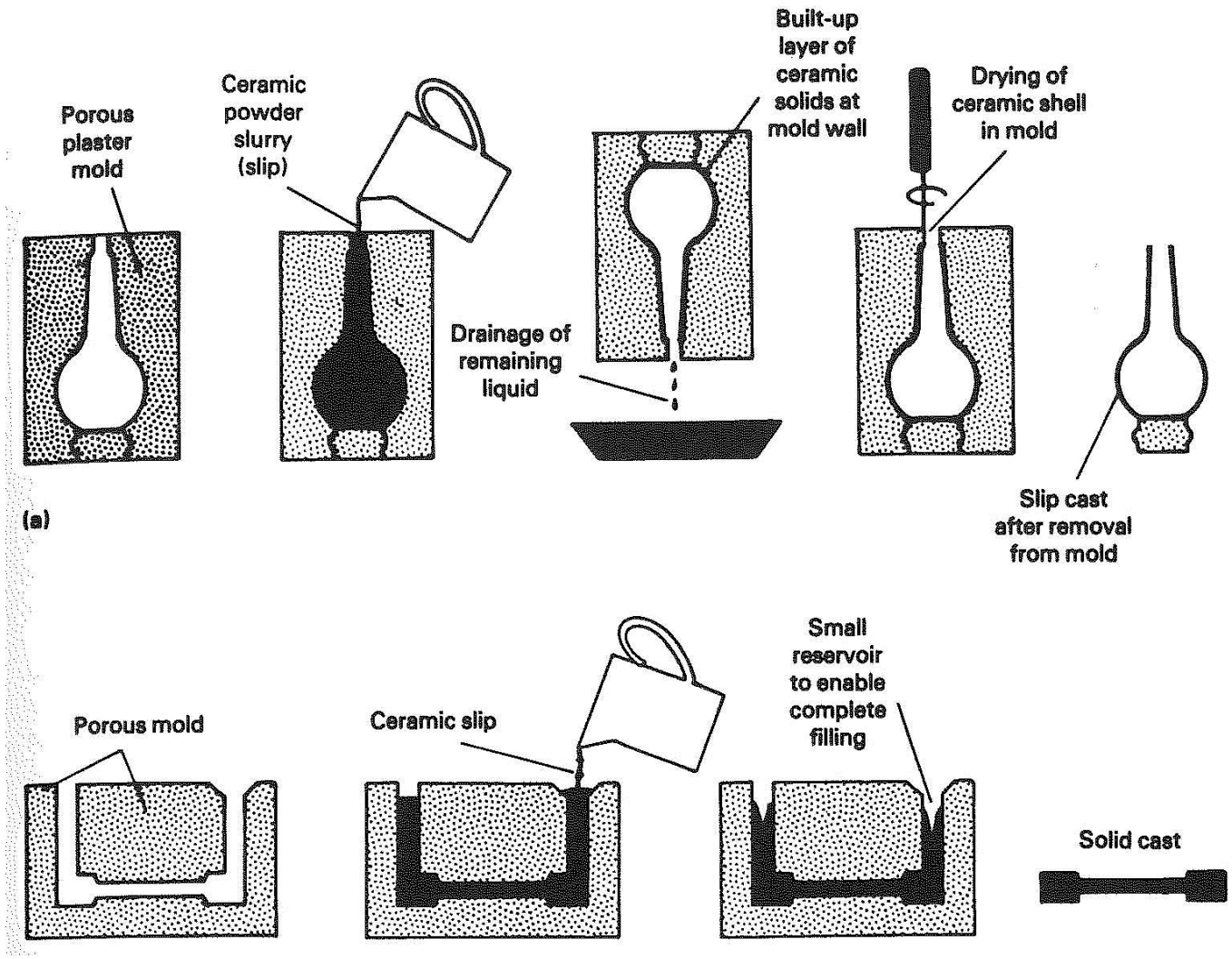
Remove the Water

Leave the Ceramic particles behind

Casting metals versus slip casting of ceramics

Process	Casting Metals	Slip Casting of Ceramics
Get the material into a liquid	Melt the metal	Mix particles of ceramic and Water to form a Slurry
Pour the material into a mold	Pour the material into a mold	Pour the Slurry into a mold
Solidify the stuff	Freeze the metal by removing heat	Solidify the ceramic by removing Water
Remove the product from the mold	Remove the product from the mold	Remove the product from the mold (Carefully)

Slip Casting of Ceramics



Taken from ASM Engineered Materials Handbook

But How Strong is it?

Sintering of Ceramics

For a Slurry Cast ceramic to be strong, we must form a strong attachment between the individual ceramic particles. This is called Sintering.

To sinter a ceramic, we heat it (sometimes under pressure). This joins the ceramic particles via atomic diffusion.

Sintering of Ceramics

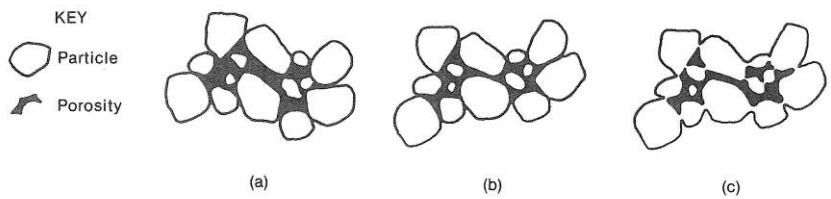


Figure 1. Changes which occur during the initial stage of sintering. (a) Starting particles, (b) rearrangement, and (c) neck formation.

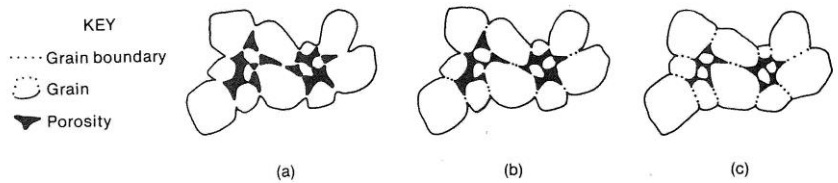


Figure 2. Changes which occur during the second stage of sintering. (a) Neck growth and volume shrinkage, (b) lengthening of grain boundaries, and (c) continued neck growth and grain boundary lengthening, volume shrinkage and grain growth.

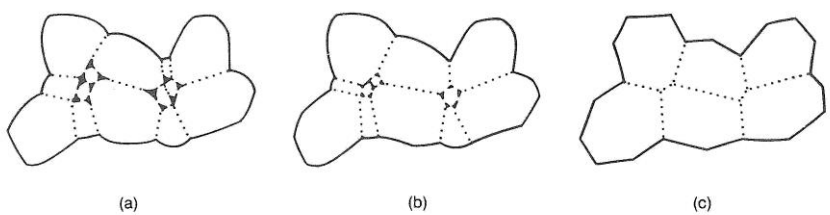


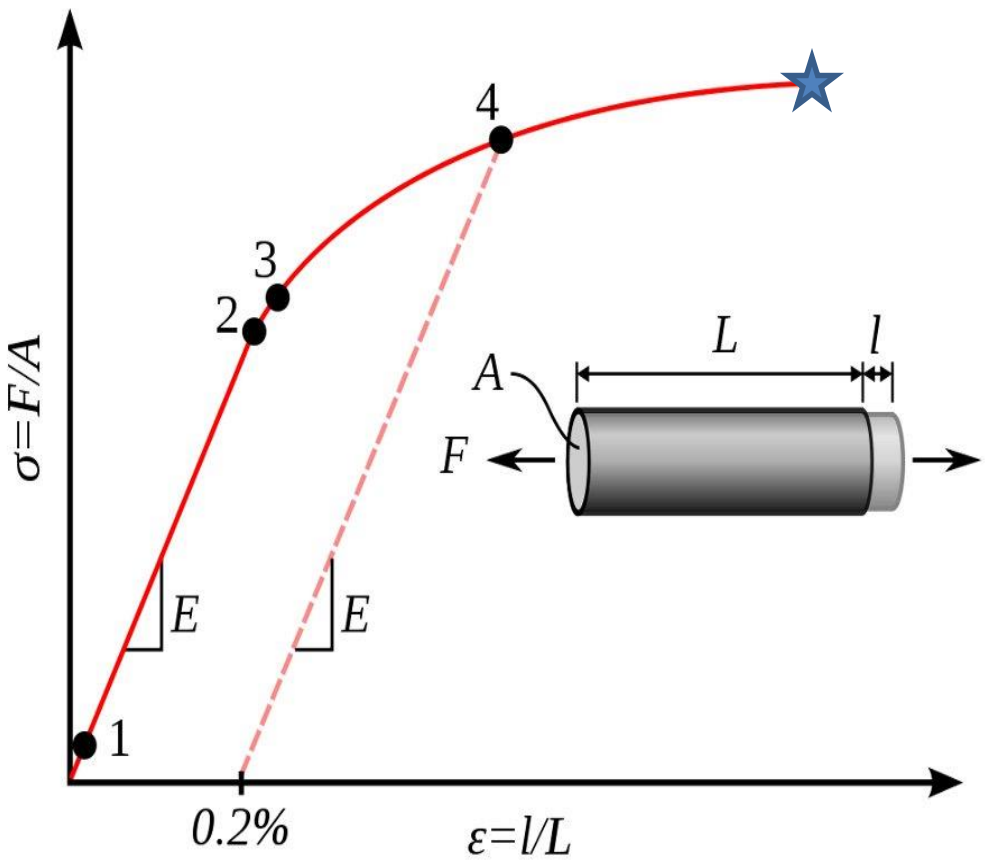
Figure 3. Changes which occur during the final stage of sintering. (a) Grain growth with discontinuous pore phase, (b) grain growth with porosity reduction, and (c) grain growth with porosity elimination.

Taken from ASM MEI Ceramics

IV

Introduction to Metal Deformation

We characterize the deformation of a material by plotting the Stress on the material versus the Strain by the material as below



0 – 2 Elastic Region
The material returns to its original length when the stress is removed

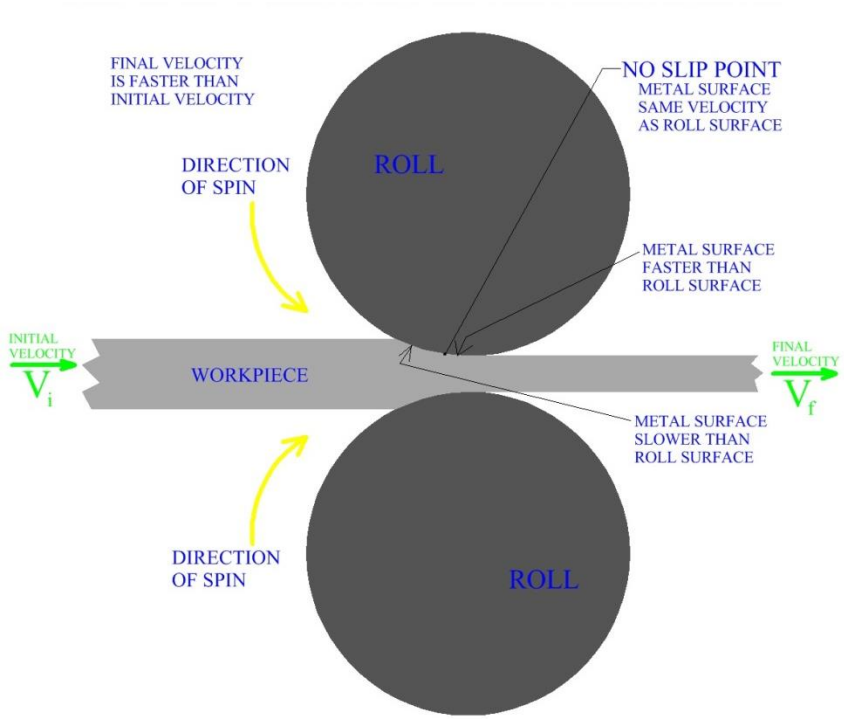
> 2 Plastic Region
The material is permanently deformed due to the stress

4 0.2% Yield Point
The Stress at which the permanent deformation is 0.2%

Fracture

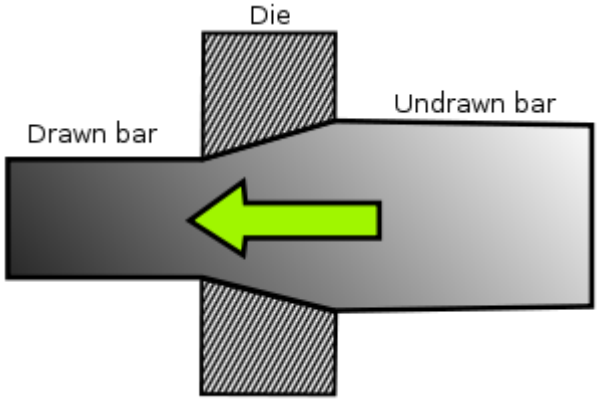
Metal Deformation

Rolling



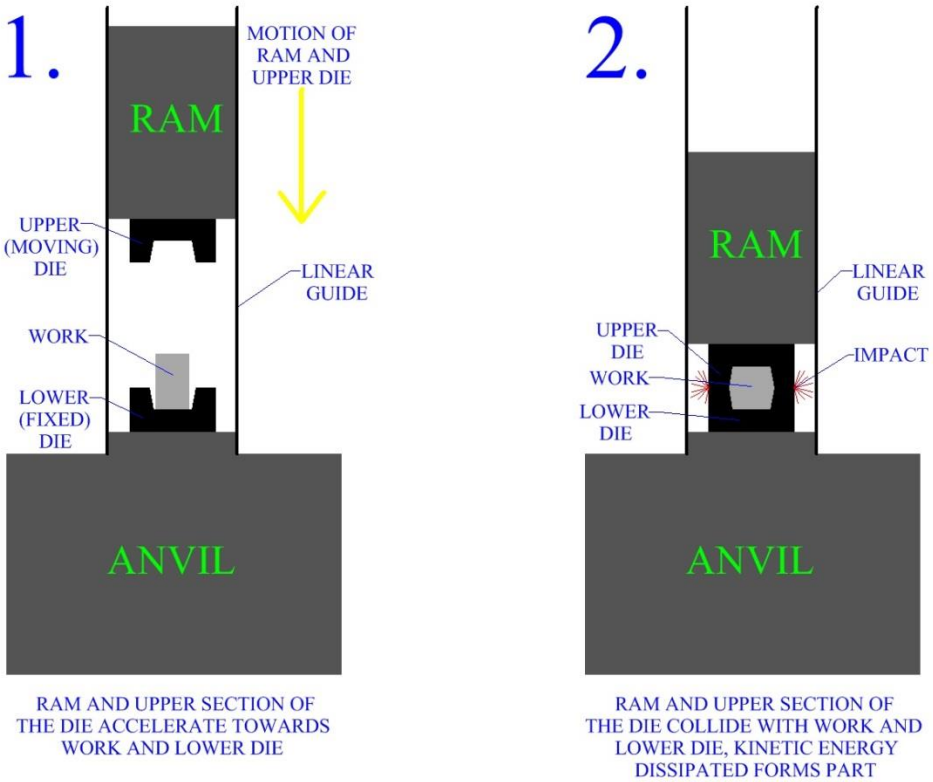
http://thelibraryofmanufacturing.com/metal_rolling.html

Drawing / Extruding



http://en.wikipedia.org/wiki/Drawing_(manufacturing)

FORGING HAMMER



RAM AND UPPER SECTION OF THE DIE ACCELERATE TOWARDS WORK AND LOWER DIE

RAM AND UPPER SECTION OF THE DIE COLLIDE WITH WORK AND LOWER DIE, KINETIC ENERGY DISSIPATED FORMS PART

http://thelibraryofmanufacturing.com/forging_hammers.html

Science Issues for Deforming Metals

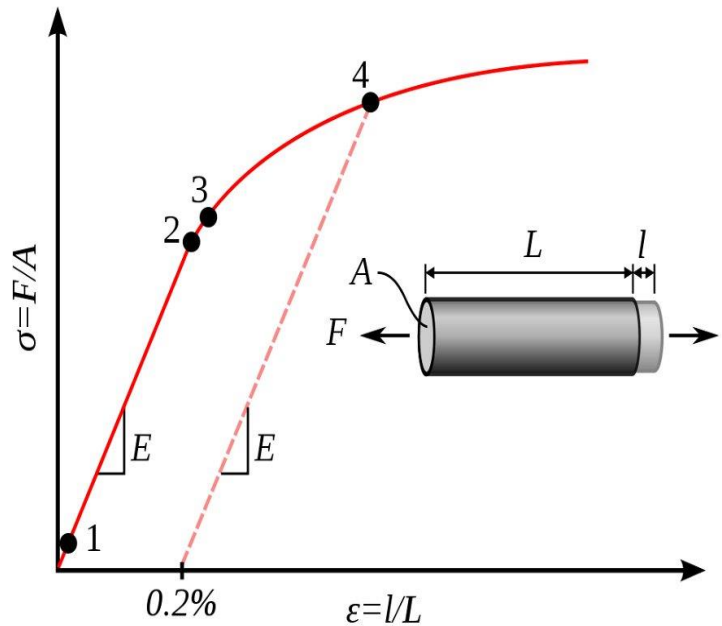
Science Concept: Work and Energy

The area under the Force Distance (Stress Strain) curve is Energy

Energy is Conserved

The forms of energy include:

Heat
Potential Energy
Internal Energy



Science Issues for Deforming Metals

Science Concept: Work Hardening

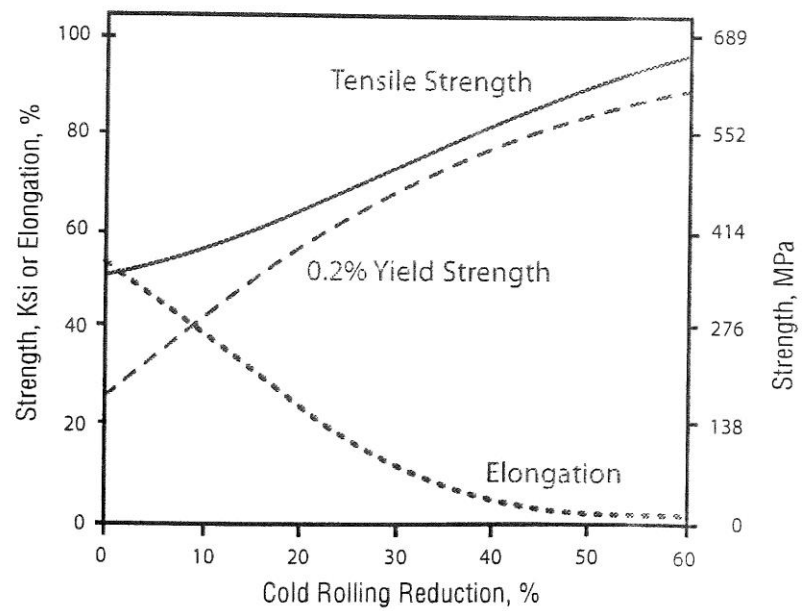
Work Hardening: What doesn't kill you makes you stronger

You put energy into a material when you "work" it.

This energy may increase the internal energy of the metal

Internal energy affects the properties of the Metal

FIGURE 4: Effect of Work Hardening on Tensile Strength, Yield Strength & Elongation (Ductility) of Annealed (Soft) Brass Alloy C26000

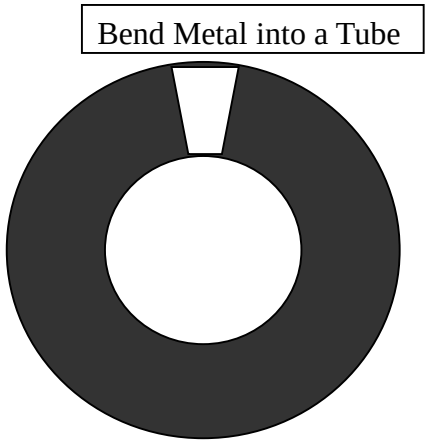


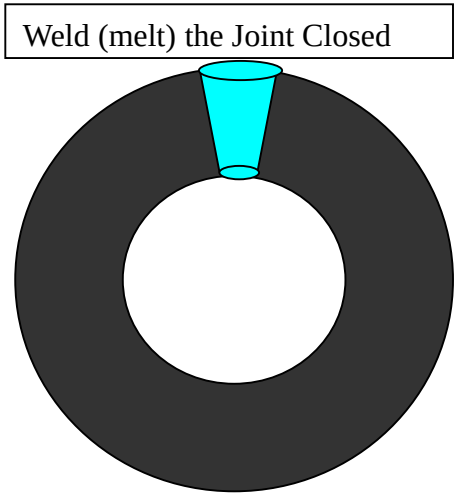
Taken from the Copper Development Association

V Properties versus processing – Welded Pipe

One common way to make pipe is to:

Cast a bar
Roll it flat to the desired wall thickness of a tube
Bend it into a tube
Weld the ends together





Microstructure of Weld Joint in Tube

http://www.met-tech.com/metallography.html

Platitude: Your manufacturing process may affect the properties of your materials

VI Other manufacturing processes which we don't have time to discuss:

Cleaning

Machining
Cutting, shearing, slitting

Drawing
Stamping
Extrusion

Joining

Electroforming, plating
Spraying
Vapor deposition
Dipping

Heat treating / cryogenic treating

Etc

VII Conclusions

Your manufacturing process will depend on:

The desired properties of your product
The properties of your feedstock
Science and Engineering
Money
Your imagination

There is a lot of interesting science underneath manufacturing processes