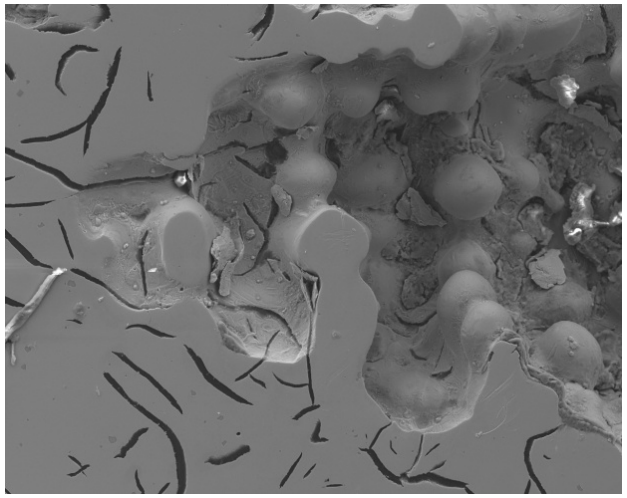
SCHOOL OF ENGINEERING
JÖNKÖPING UNIVERSITY

Defect formation in cast iron



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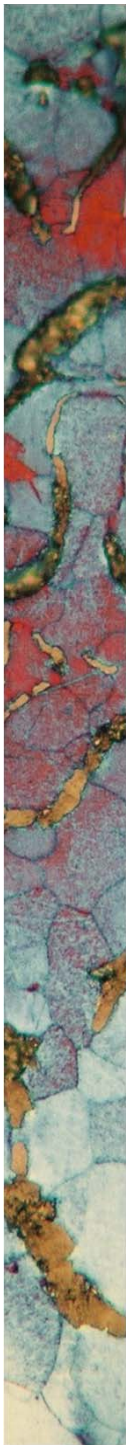
Jönköping University

Sweden

Tammerfors, Finland, November 8, 2012



Introduction

Casting

- Mould cavity
- Melting process
- Pouring
- Solidification
- Mould removal
- Cleaning and finishing

Advantages

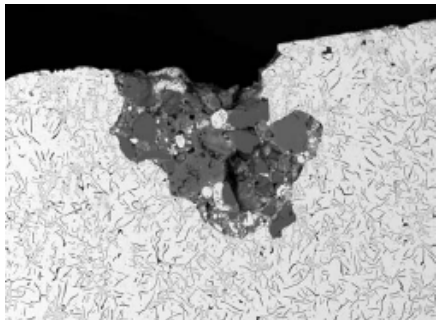
- Complex shapes
- Holes and inner cavities
- Wide range of alloys
- Melt treatment
- Economical

Introduction

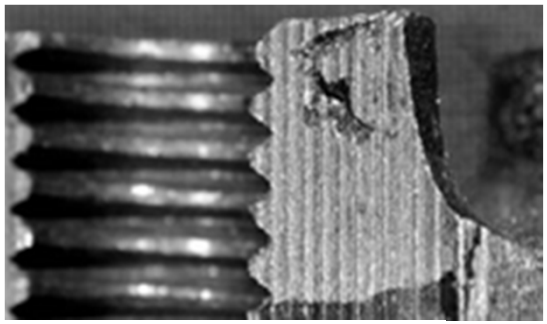
DEFECTS!

Common defects:

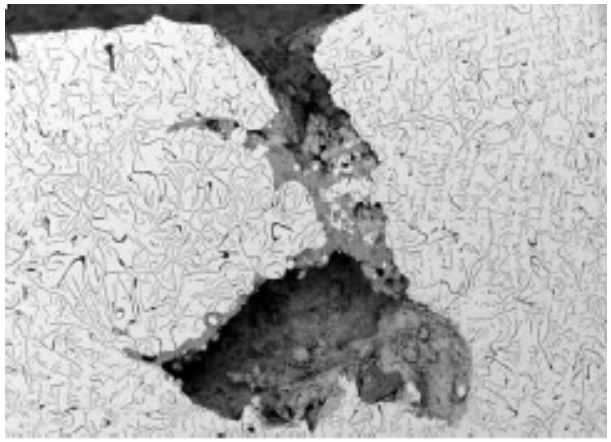
- Blowholes
- Pinholes
- Shrinkage
- Penetration
- Inclusions
- etc…



Slag inclusion defect

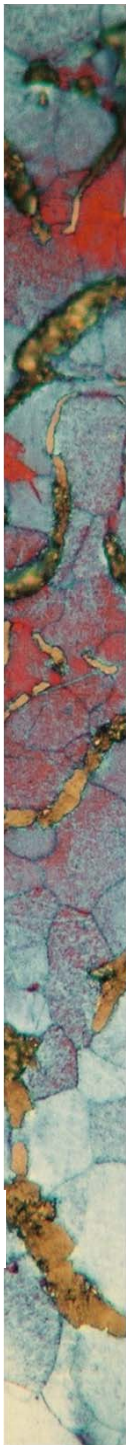


Shrinkage porosity



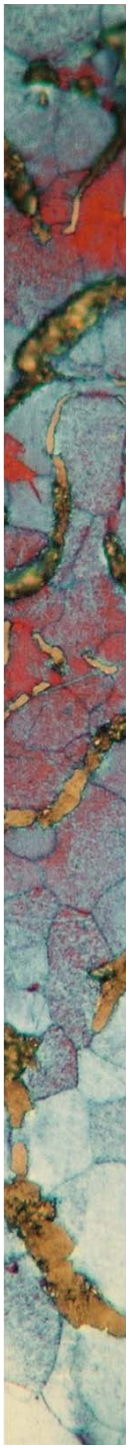
Carbon monoxide blowhole

Metal expansion penetration



Outline

- Gas defects
  - Gas absorption
  - Gas evolution
- Inclusions
- Shrinkage porosity
  - Defect characterization
  - Migrating hot spot
  - Primary austenite
- Metal expansion penetration
  - Primary austenite
- Other quality problems
- What about the future?
- Summary



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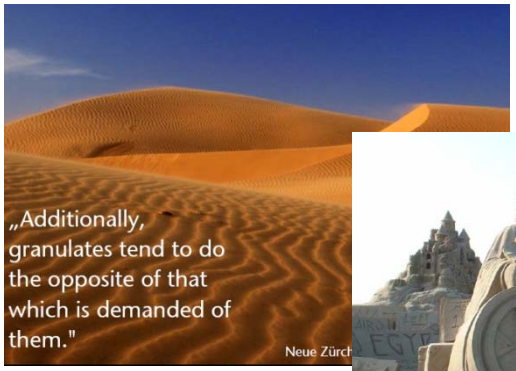

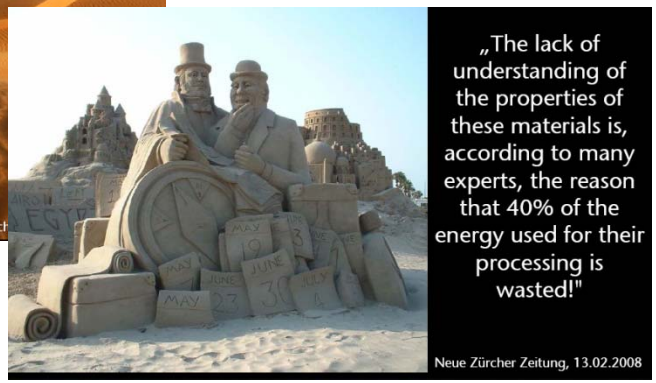

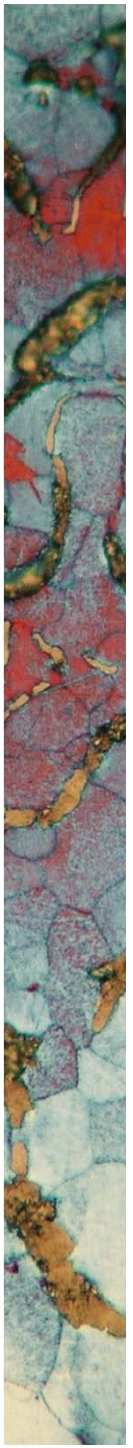

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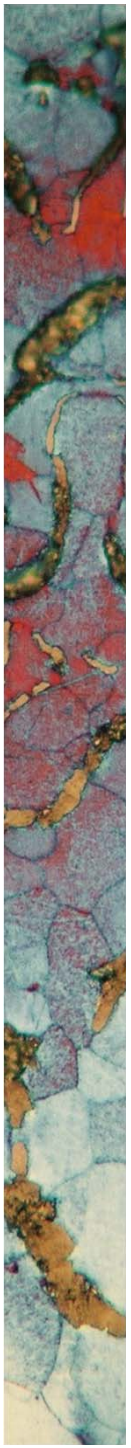
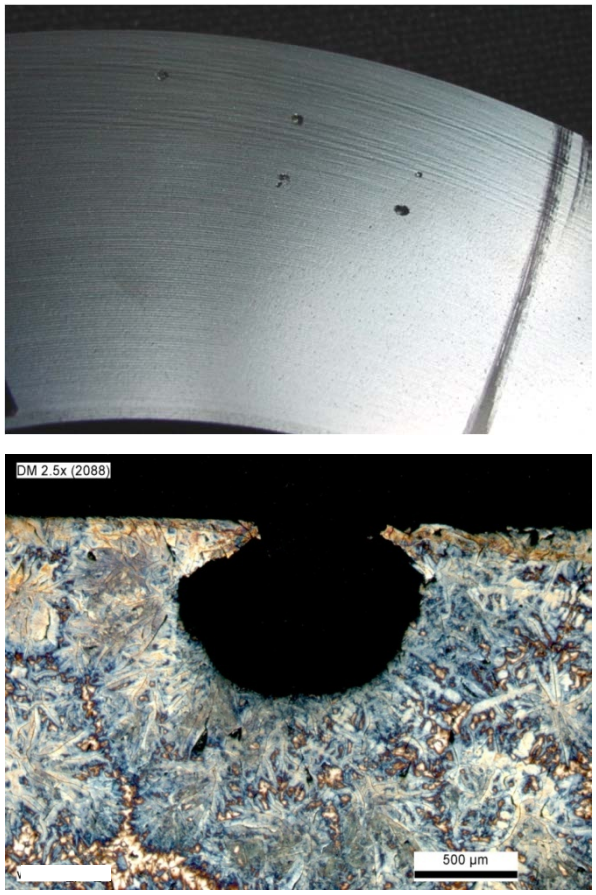
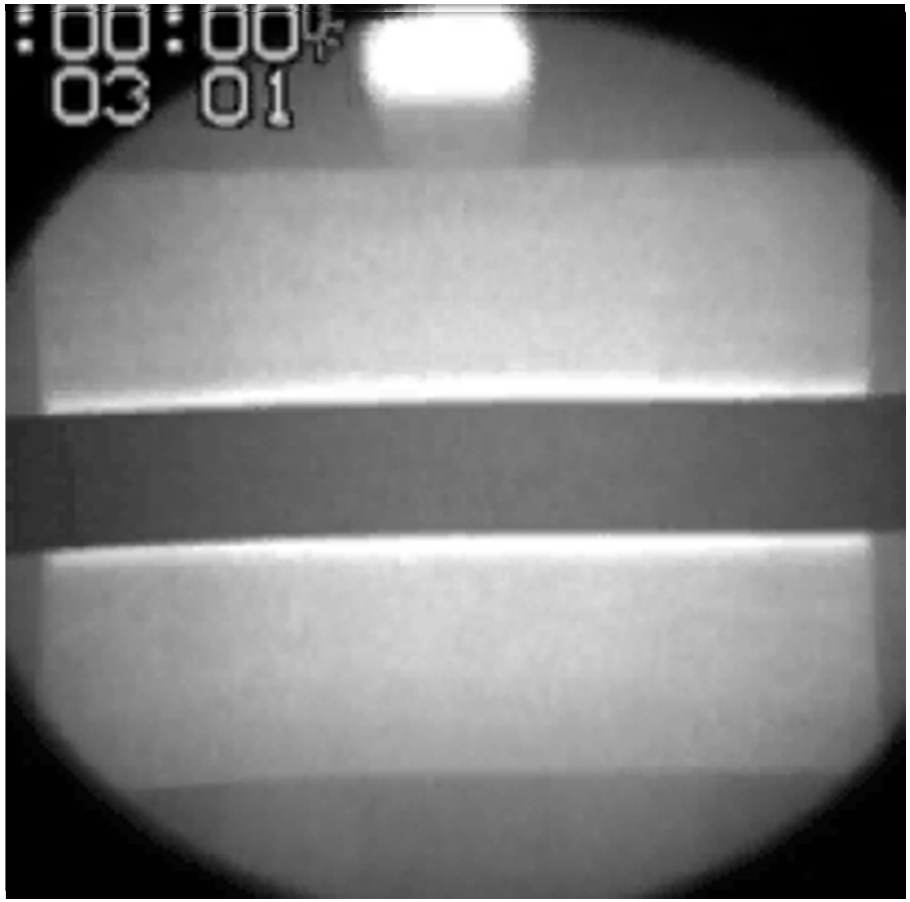


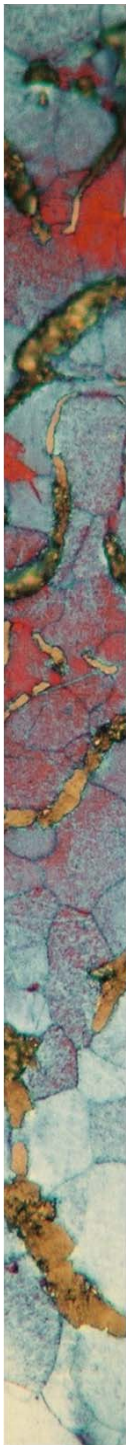
Gas defects – Introduction



Source: Diószegi, 2005

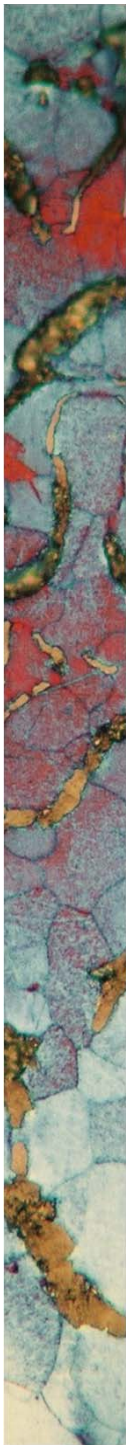


Source: UAB Casting Engineering Laboratory (CEL), 2005



Gas defects – Introduction

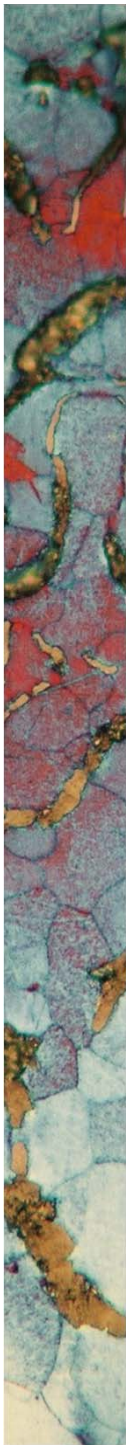
- Degradation of binder material
- Gas precipitate during solidification due to decreased solubility
- Gas may be picked up by the melt during mould filling
- Slag constituents can react with alloying additions in the metal and form gaseous reaction products



Gas defects – Introduction

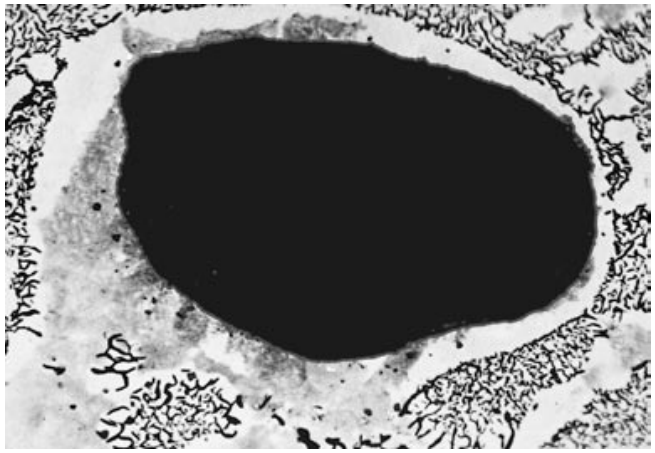
- Hydrogen pinholes
- Nitrogen pinholes
- Blowholes
- Fissures
- Carbon monoxide
- Slag blows

Source: www.ikominerals.de



Pinholes

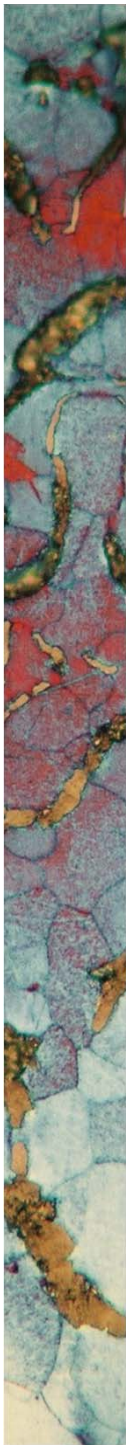
- Hydrogen, nitrogen, CO
- Revealed after machining
- Usually small
- Round shape
- Graphite lining



Source: www.ikominerals.de

Remedies

- Low levels of Al and Ti
- Control of steel scrap
- Cores and water-based coatings fully cured and dried



Pinholes

Hydrogen pinholes

- Water and organic materials
- Air humidity
- Rusty charge material
- Damp refractory material
- Moisture in mold and core
- Core binder

Nitrogen pinholes

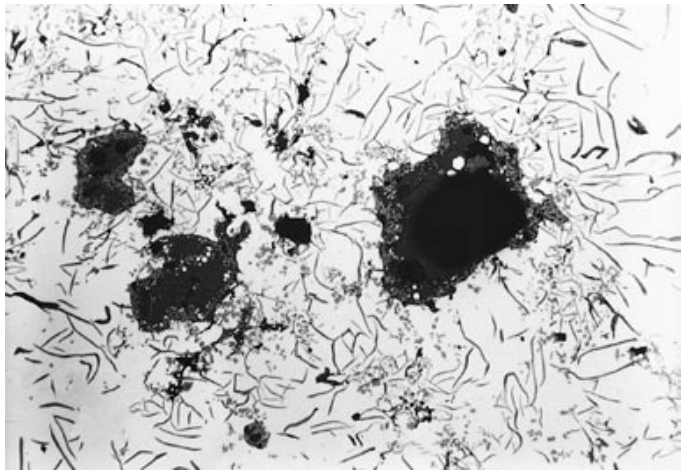
- Resin-bonded cores and molds
- Sand additives
- Coatings and glues
- Charge materials

Source: http://www.objet.sk/content/products/sand_casting_a4.pdf

Pinholes

Carbon monoxide pinholes

- Reaction of carbon and oxygen
  - Liquid slag rich in iron oxide
  - CO_2 react with iron
  - Carbon react with water
- No graphite lining
- MnS and slag inclusions



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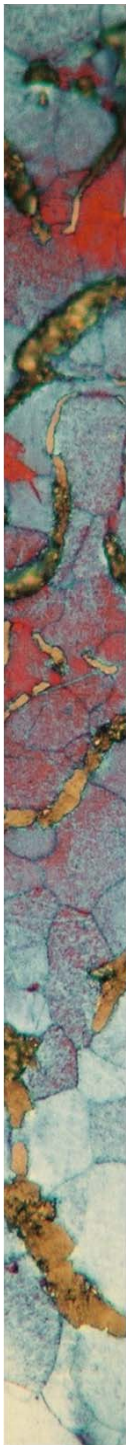
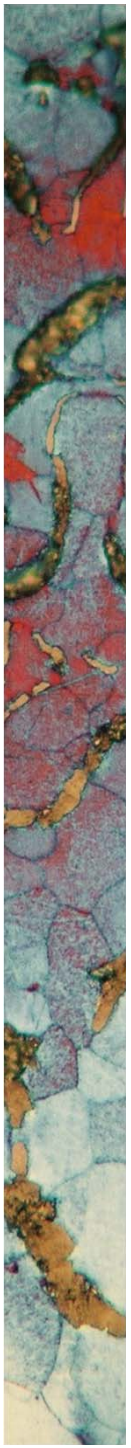


Blowholes

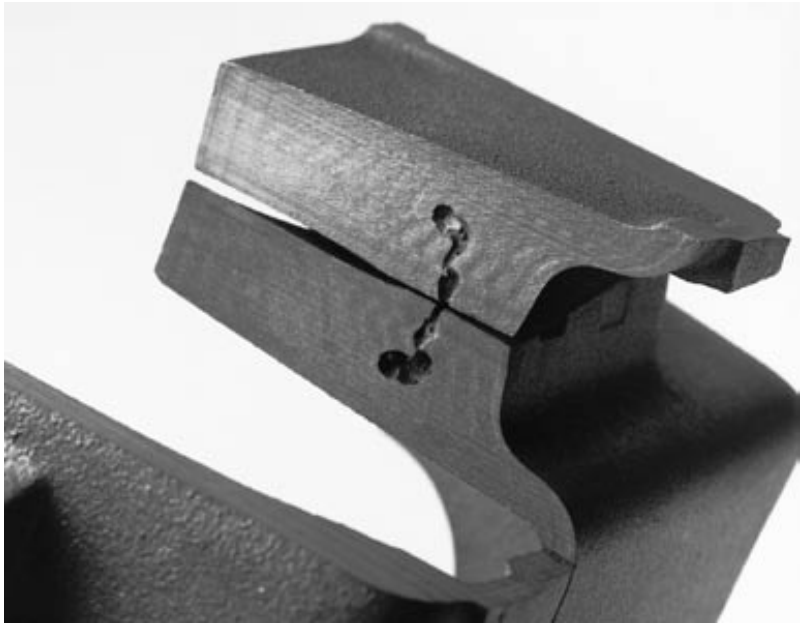
- Large cavities
- Normally irregular in shape
- Smooth walls
- Graphite lining
- High turbulence during mold filling
- High gas pressure in the mold

Source: www.ikominerals.de



Blowholes

- Casting design
- Gating
- Sand permeability
- Core print area
- Type of resin system
- Extent of cure and drying
- Pouring temperature
- Rusty chaplets
- Clogged vents
- ……etc



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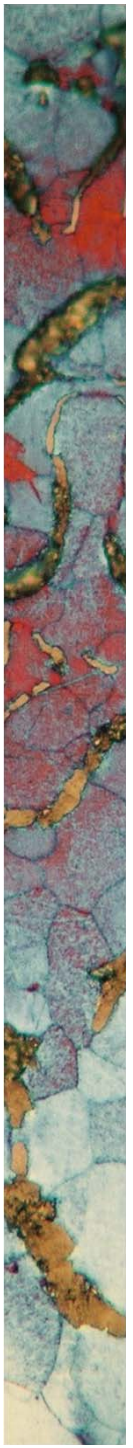


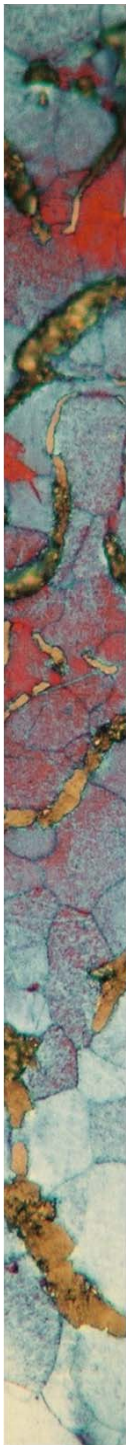
Fissures

- Narrow crack-like cavities
- Frequently have dendritic structures
- Excessive nitrogen main cause
- Hydrogen may intensify the defect

Source: www.ikominerals.de

Sources

- Nitrogen content high
- High nitrogen content in core binder
- Poor core venting

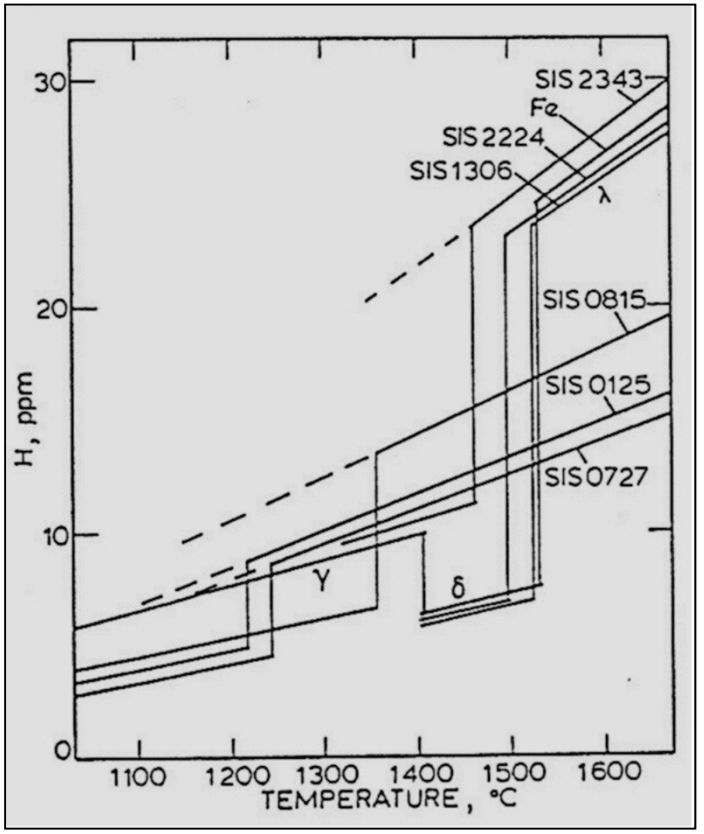


Solubility of gases

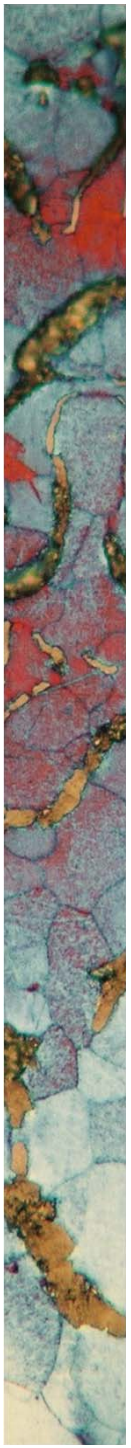
1. Diffusion of gas to the surface
2. Chemical reaction on the surface
3. Diffusion of one or more reaction products away from the surface

$$H_2(g) \leftrightarrow 2\underline{H}$$

$$[\underline{H}] = K_H \sqrt{P(H_2)}$$



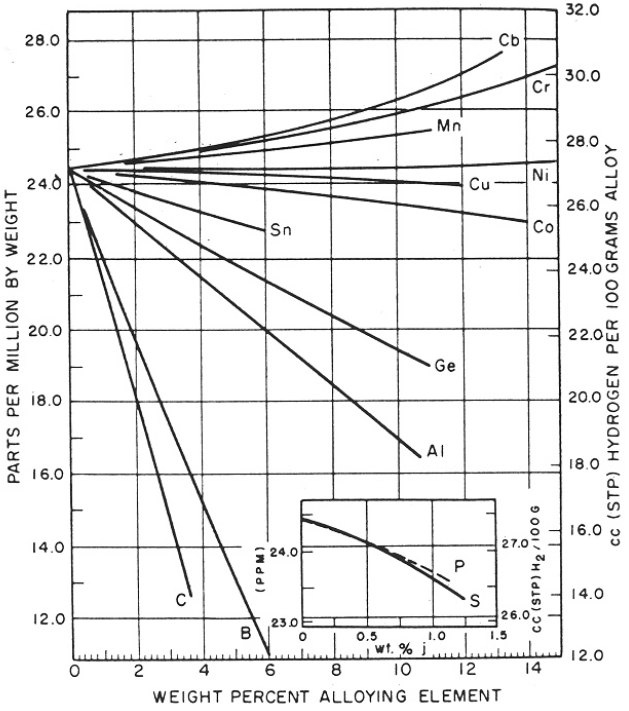
Source: Svensson et al, 1980



Solubility of gases

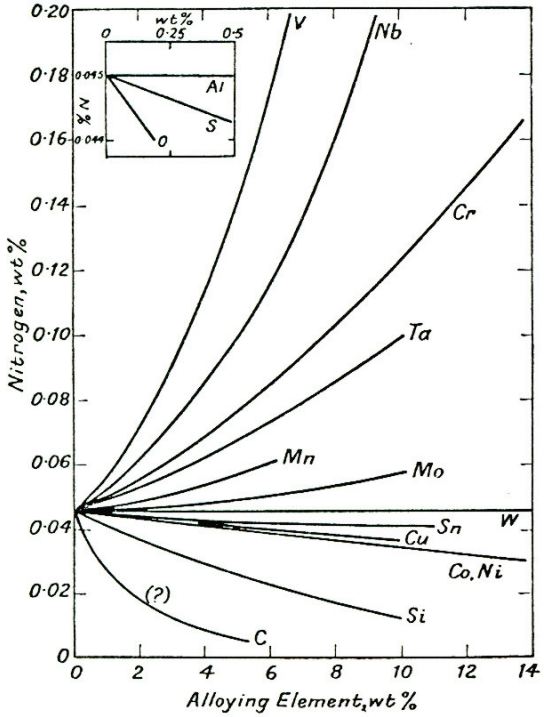
Influence of alloying elements on solubility

Hydrogen



Source: Weinstein et al, 1963

Nitrogen



Source: Dawson et al, 1965

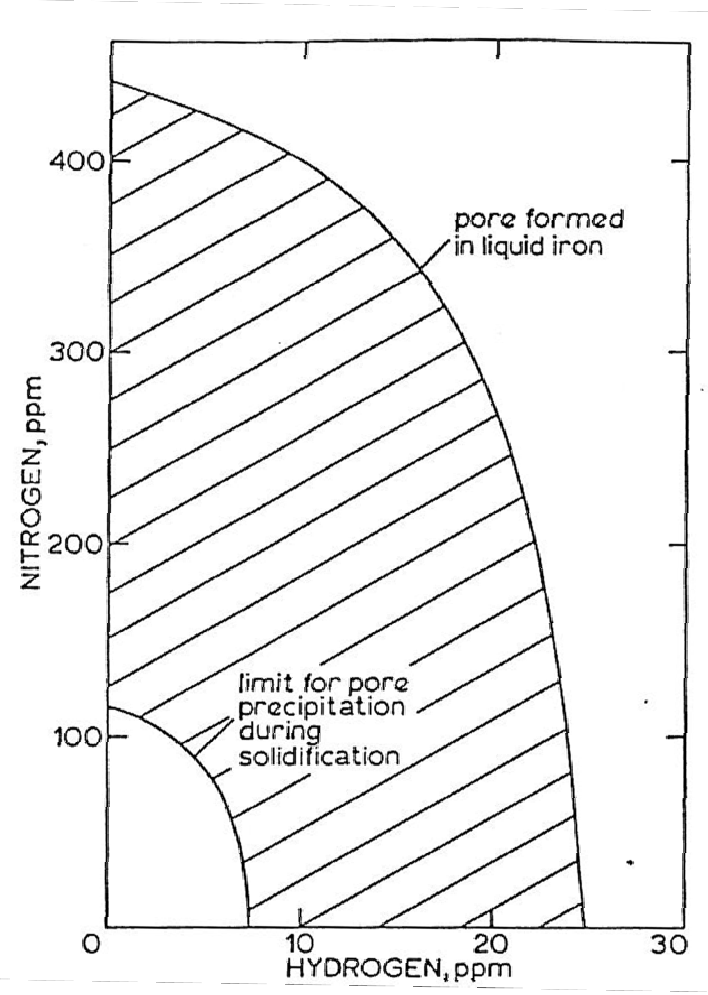
Solubility of gases

$$[\underline{N}] = K_N \sqrt{P(N_2)}$$

- The solubility of hydrogen and nitrogen affect each other

$$P_{TOT} = P_{H_2} + P_{N2}$$

- Cumulative effect that increase the risk for porosity



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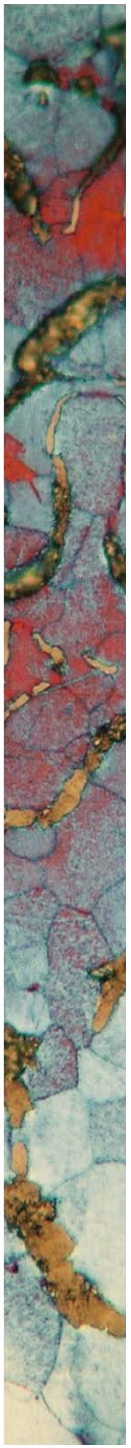
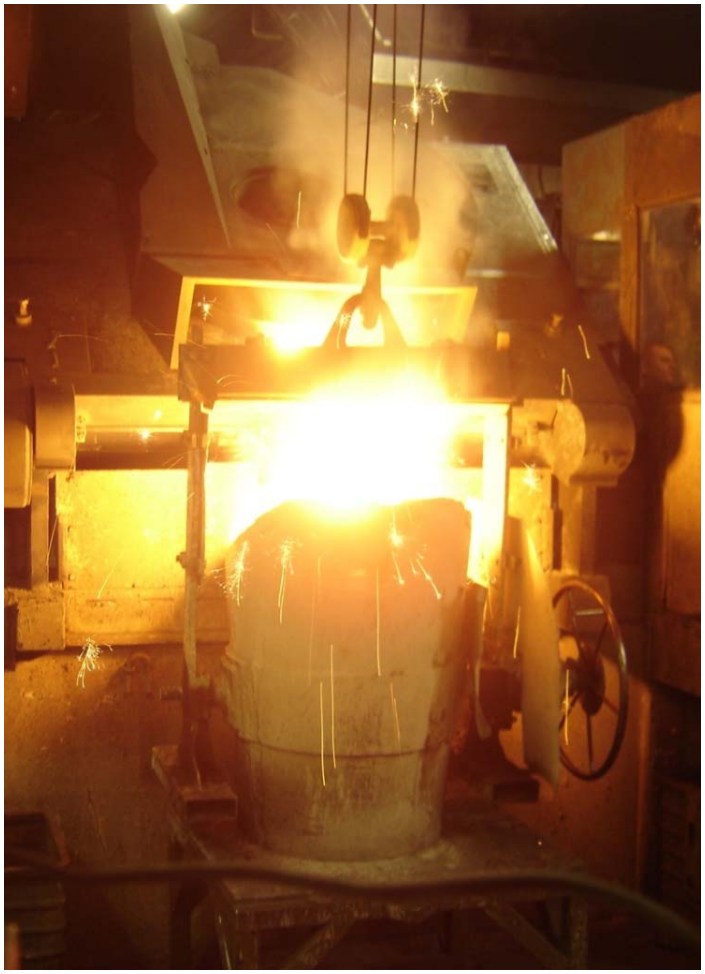


Gas levels in production

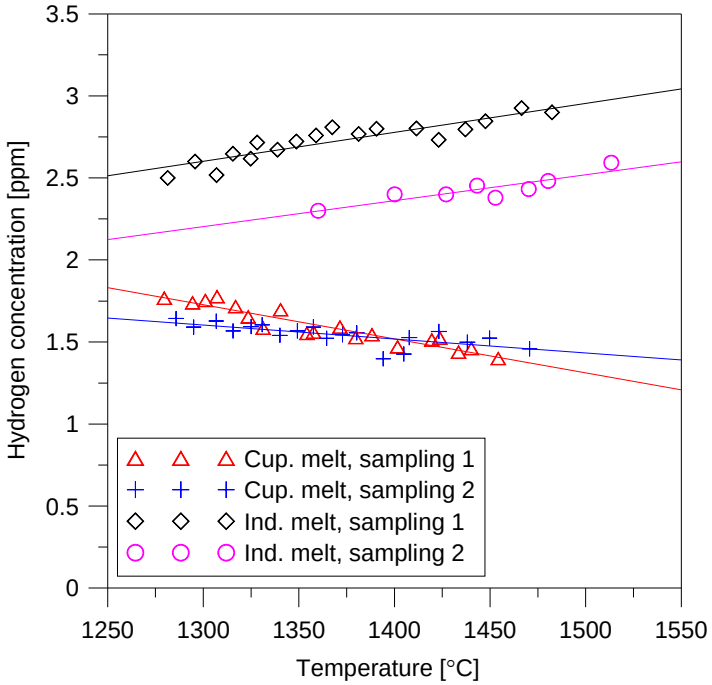
- Melting methods
- Different foundries
- Different furnaces
- Long period of time



Gas levels in production

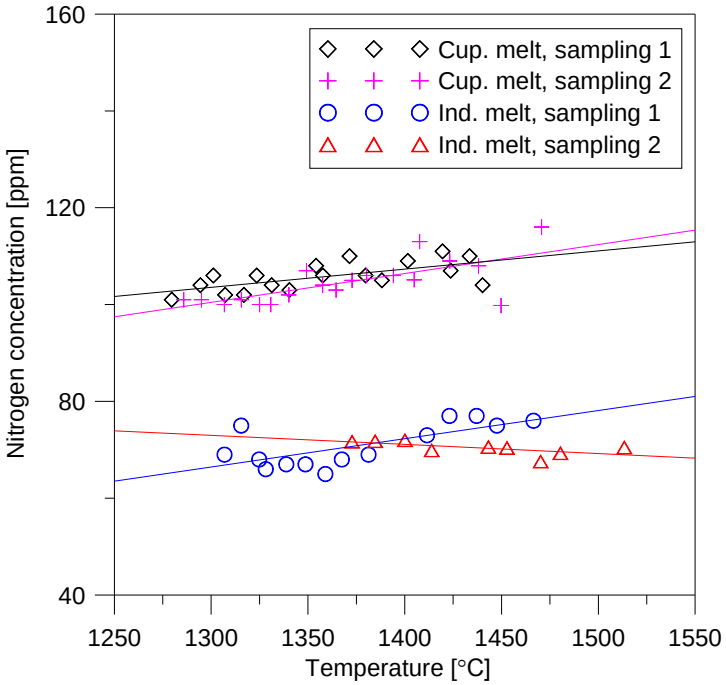
Hydrogen

- Preheating
- Holding-time

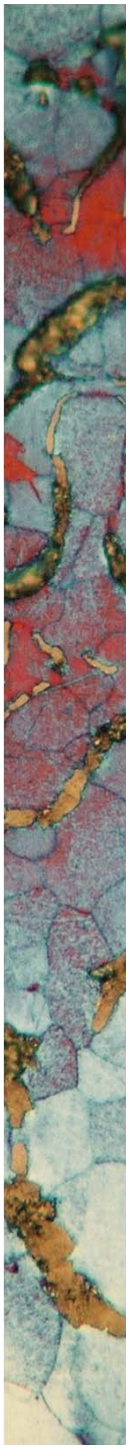


Nitrogen

- Melting method
- Charge material



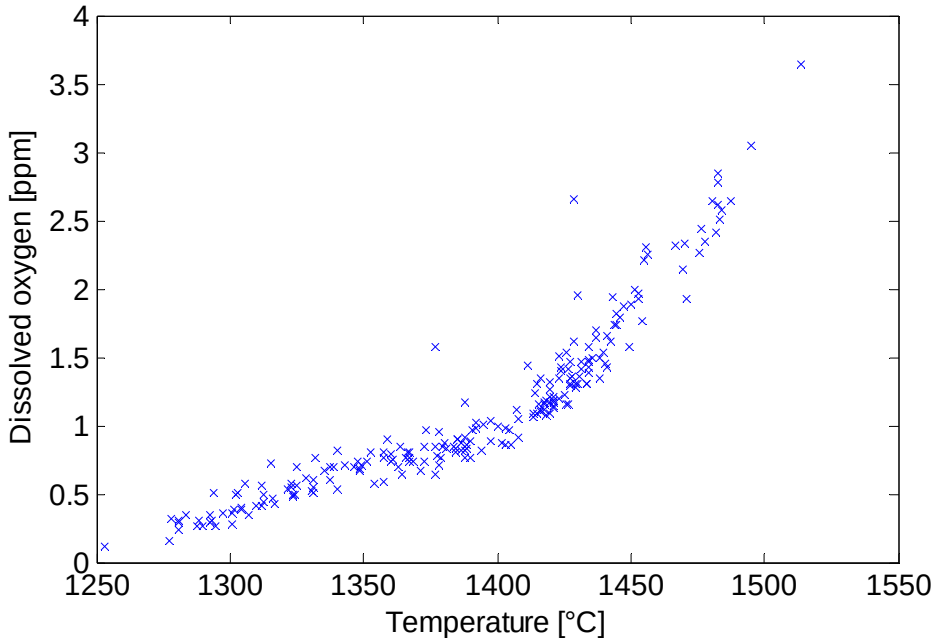
Source: Orlenius, Elmquist, Diószegi, 2007



Gas levels in production

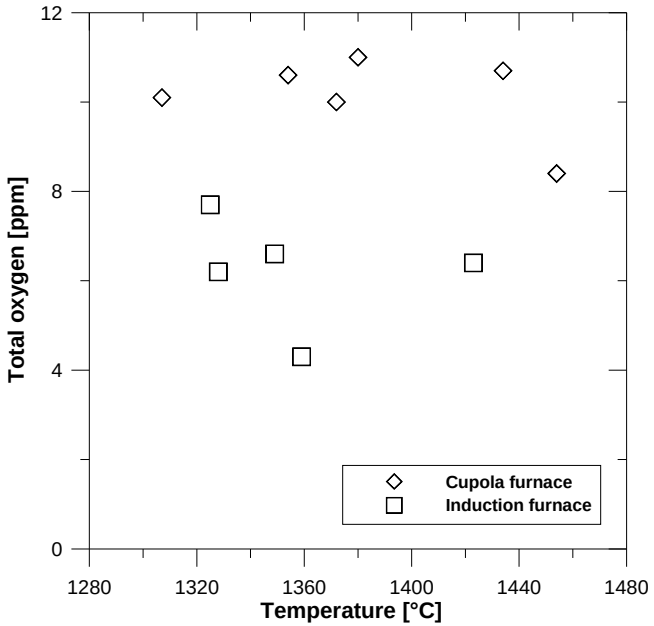
Oxygen

- Dissolved oxygen
- Oxygen found in oxides

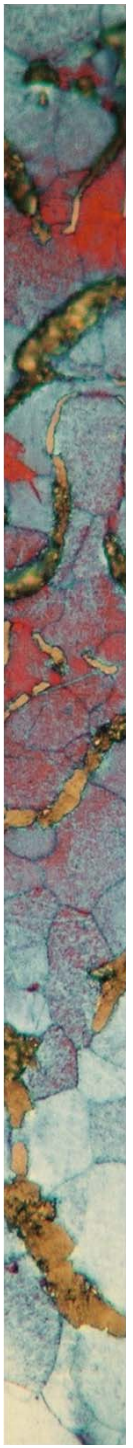


Total amount of oxygen

- Difference between processes

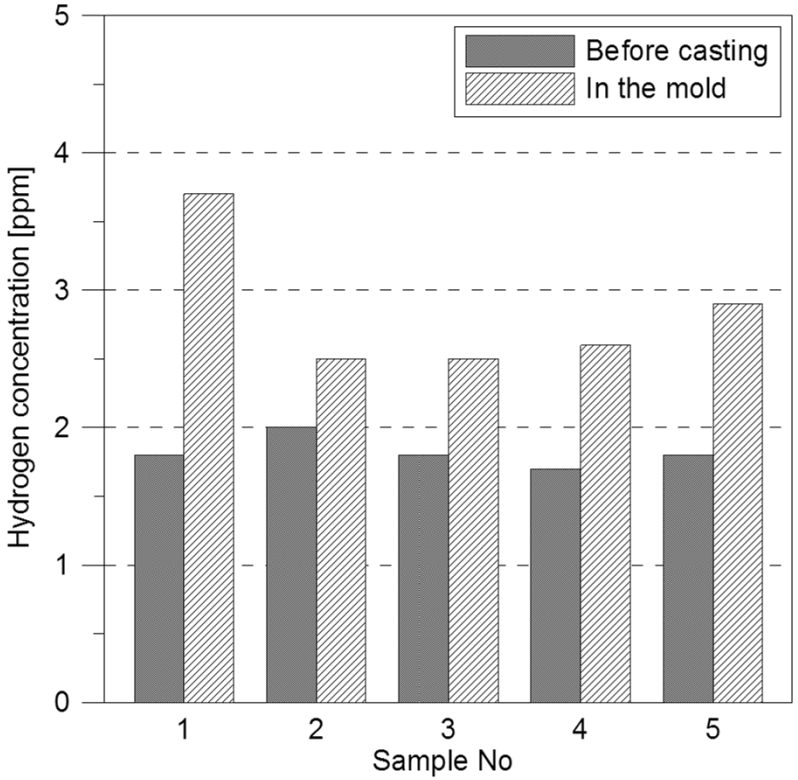


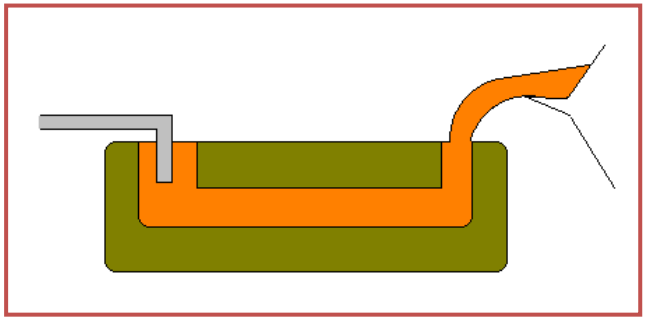
Source: Elmquist, Orlenius, Diószegi, 2007

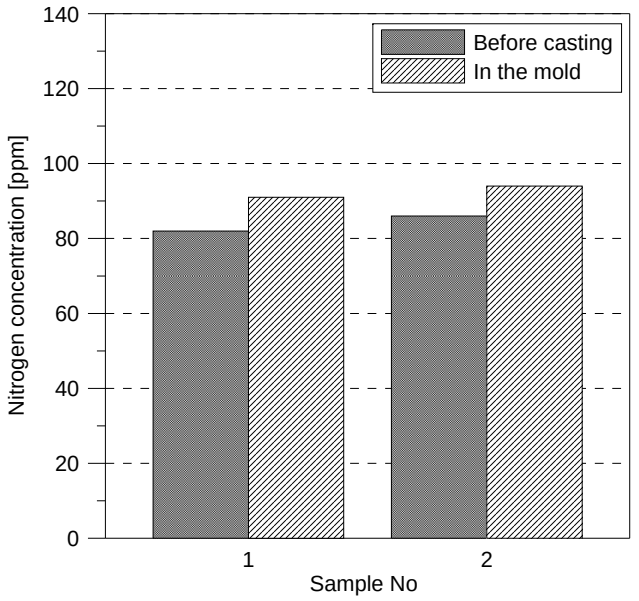


Gas levels in production

After mold filling







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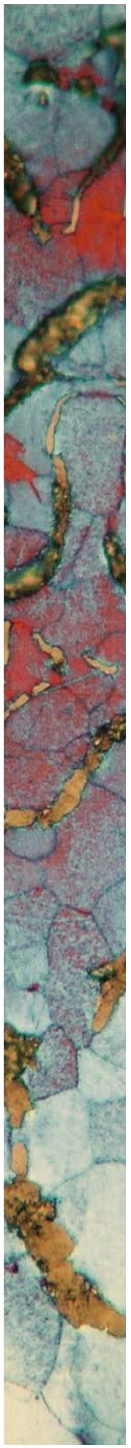

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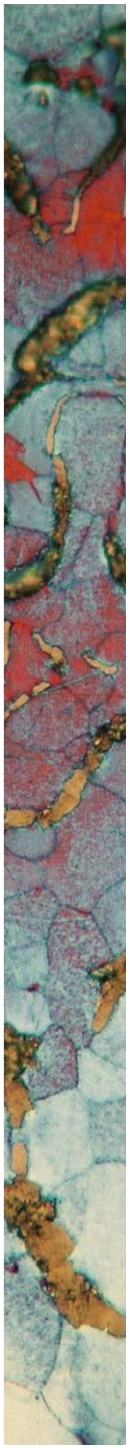
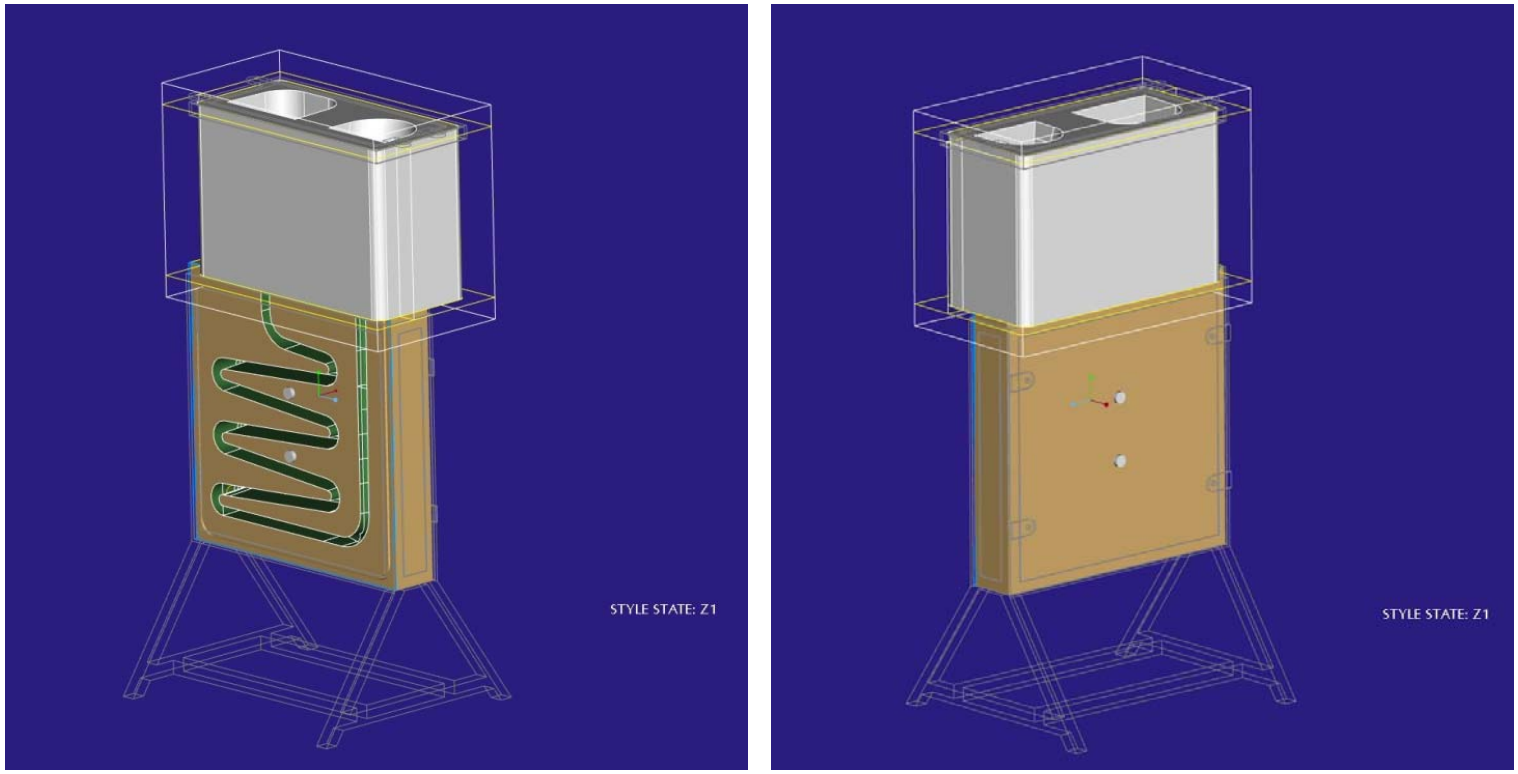


Gas absorption



Source: Orlenius et al, 2008

Gas absorption

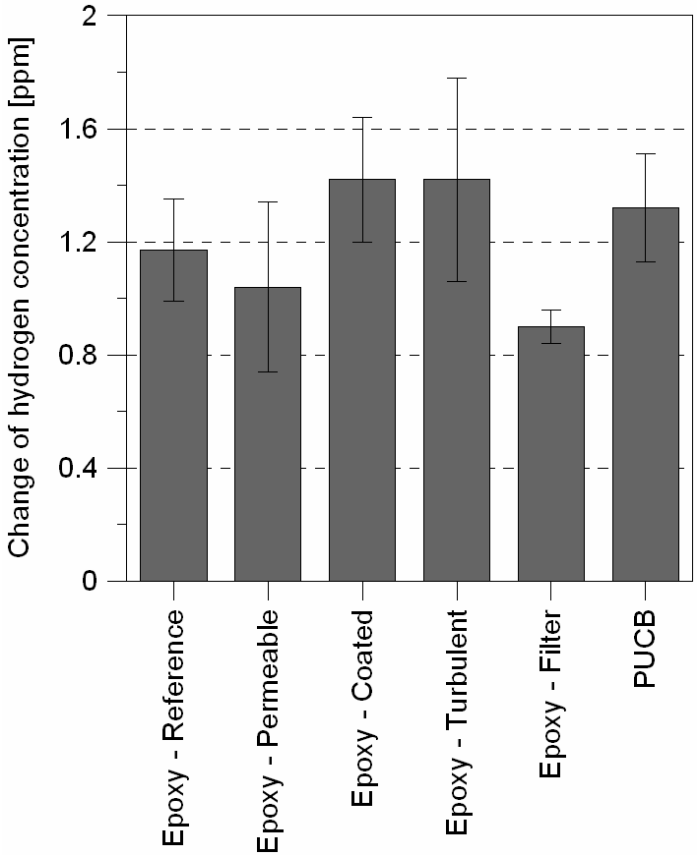
- Investigate relationship gas absorption – mold filling
- Compare simulation – reality
  - Turbulence during filling
  - Permeability
  - Binders

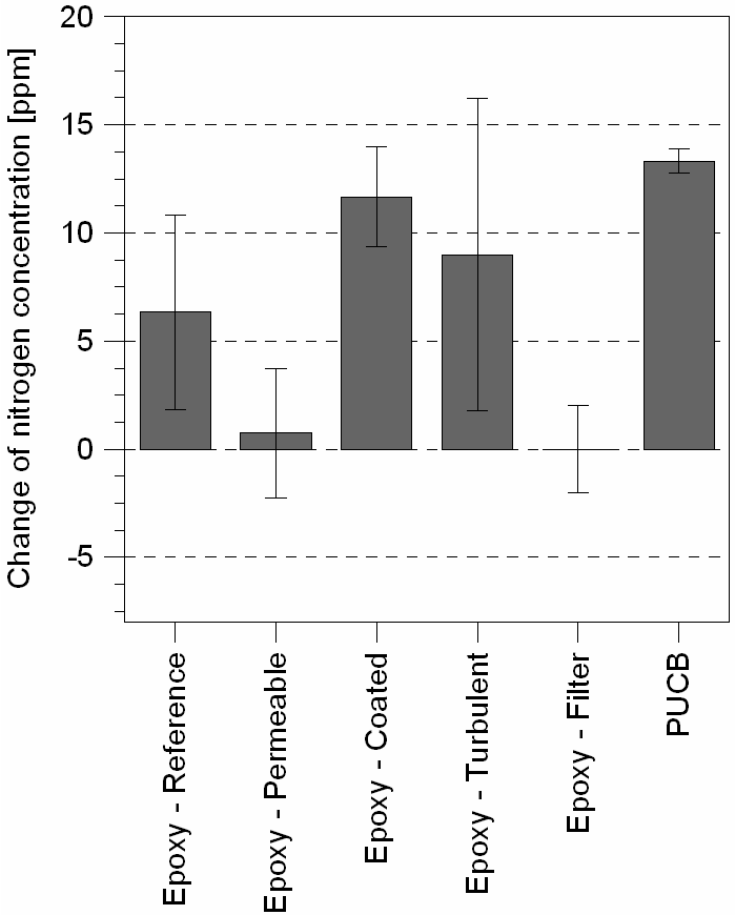
Sample	Binder		Coating	Steel plate	Gating system
Name	*Type*	*Content [%]*	*Type*		
Epoxy – Reference	Epoxy-SO_2	1.2		Closed	
Epoxy – Permeable	Epoxy-SO_2	1.2		Perforated	
Epoxy – Coated	Epoxy-SO_2	1.2	Aluminium silicate	Closed	
Epoxy – Turbulent	Epoxy-SO_2	1.2		Closed	High turbulence
Epoxy – Filter	Epoxy-SO_2	1.2		Closed	Low turbulence
PUCB	PUCB	1.6		Closed	
Green sand	Green sand			Perforated	

* This mould is used as a reference mould.

Source: Orlenius et al, 2008

Gas absorption





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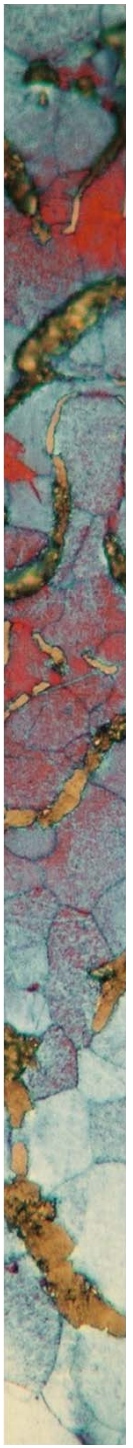
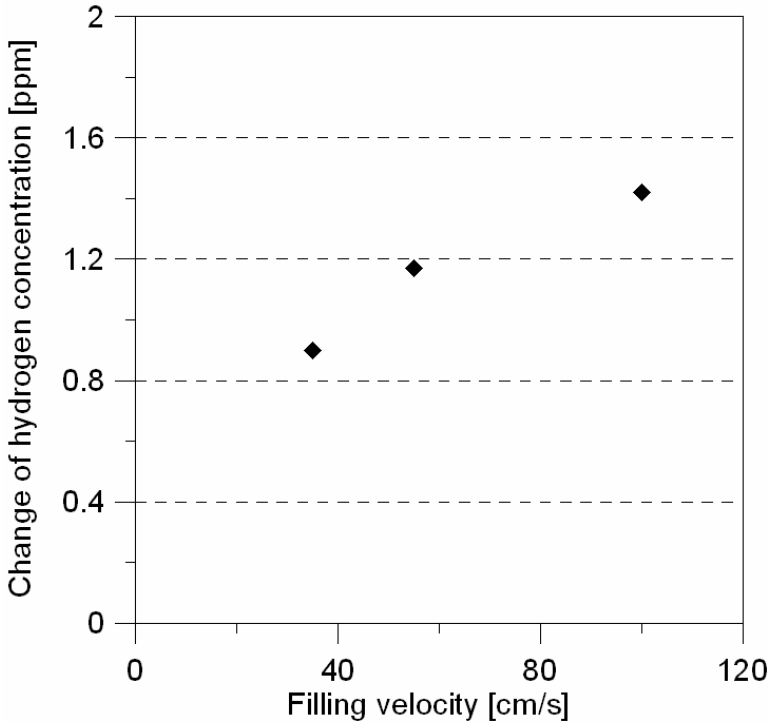


Gas absorption

Filling velocity



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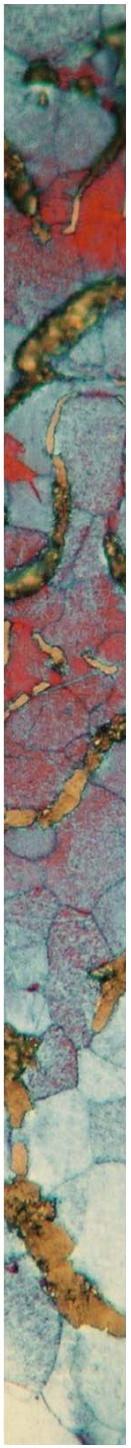

Gas absorption

- Turbulent mould filling

Source: UAB Casting Engineering Laboratory (CEL), 2005

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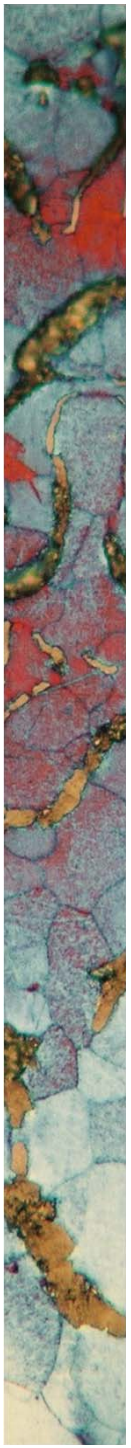
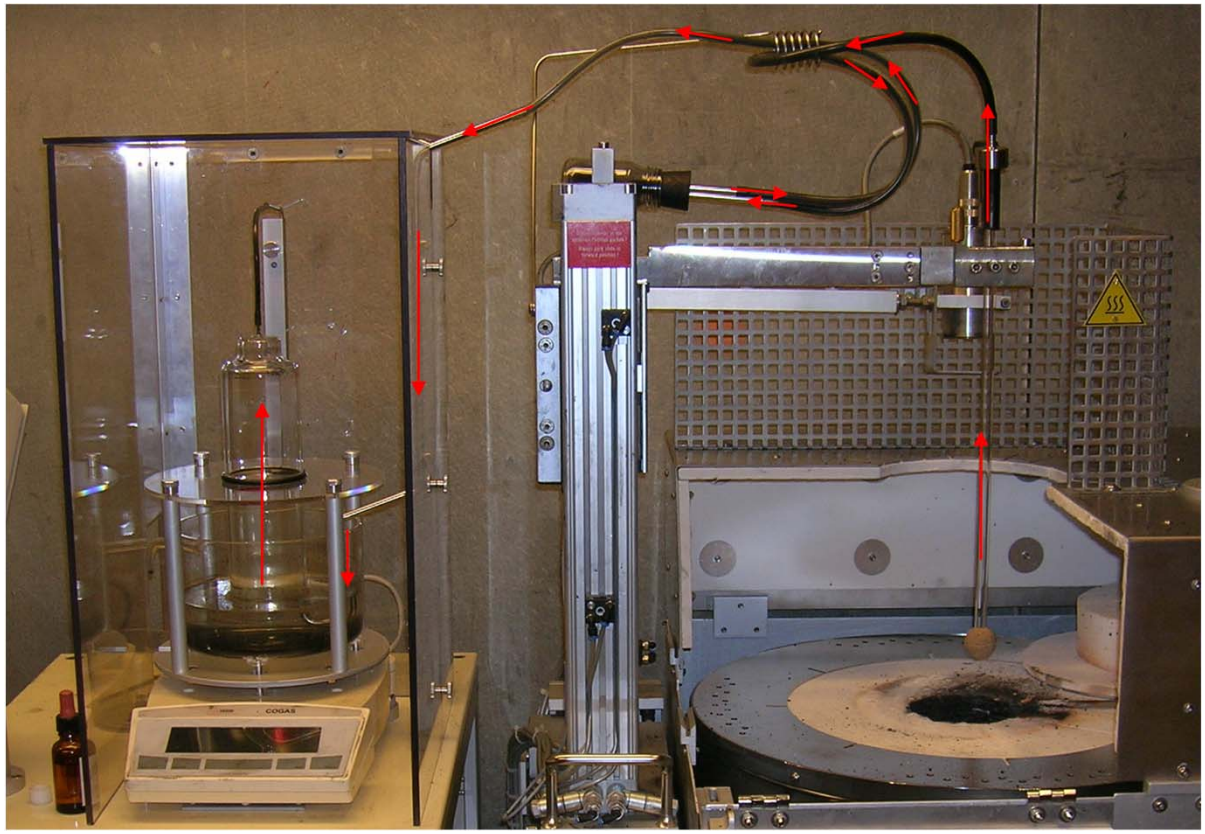


Mould and core gas evolution

Volume and rate of gas evolution

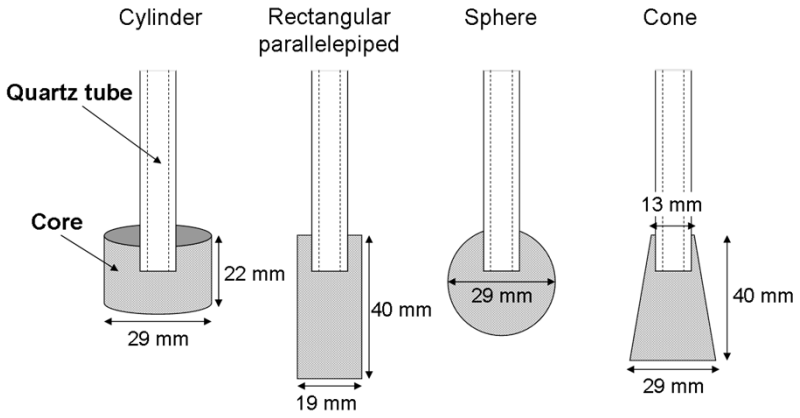


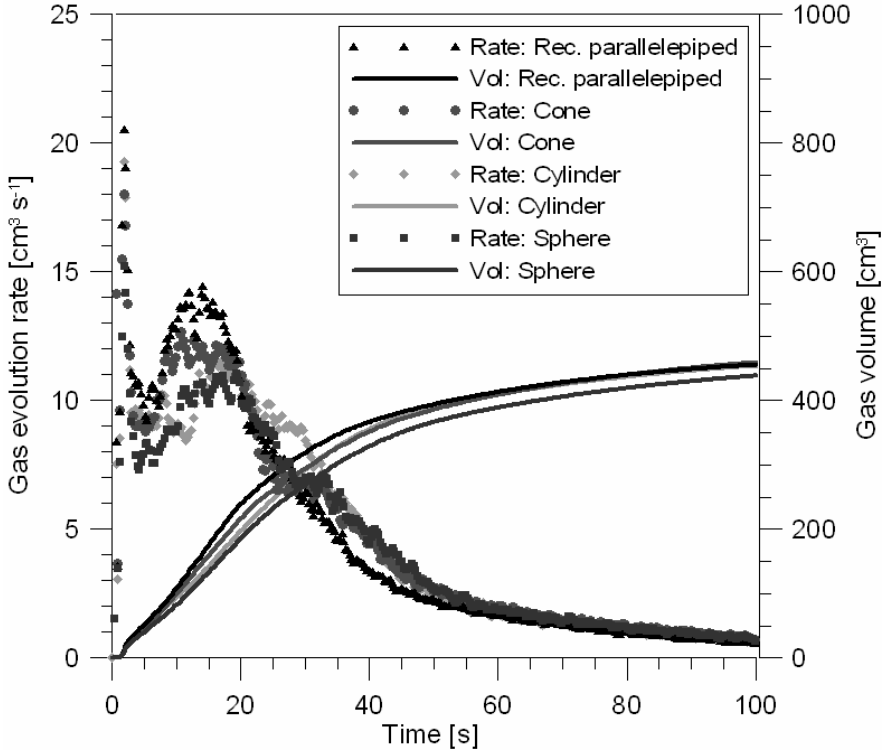
Source: Orlenius et al, 2008

Gas evolution

Core geometry

- Volume equal
- Amount of binder equal





- Highest rate for parallelepiped

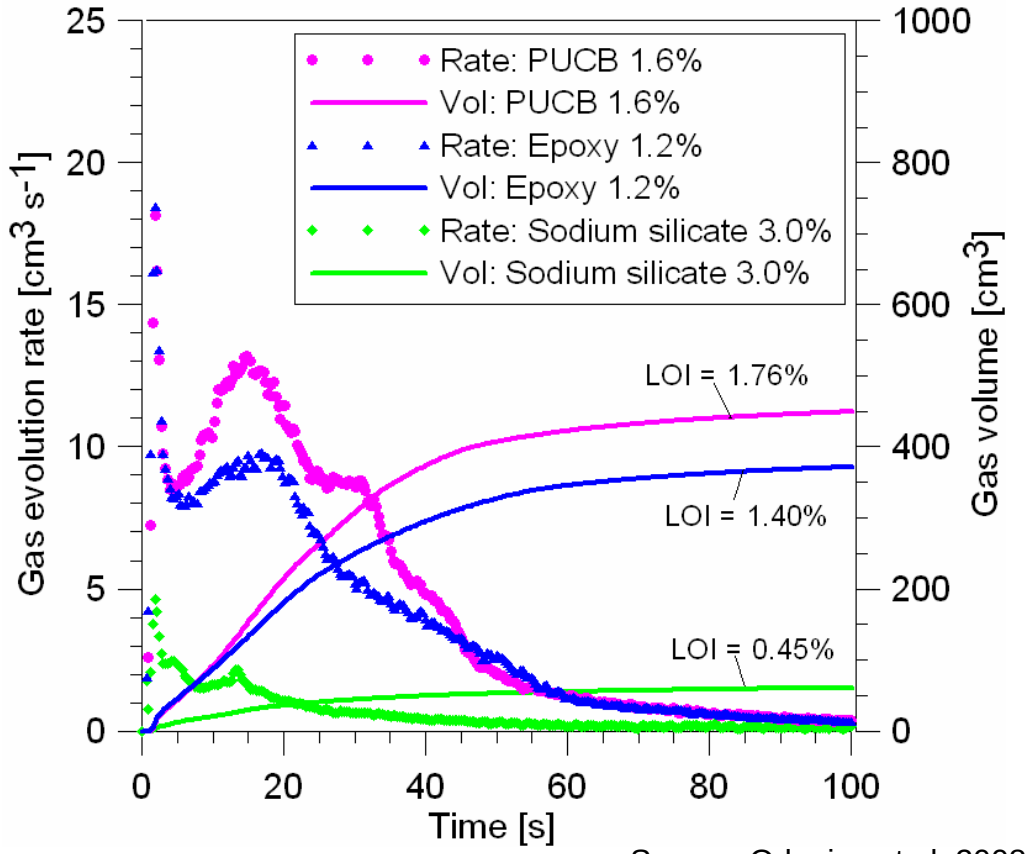
Source: Orlenius et al, 2008

Gas evolution

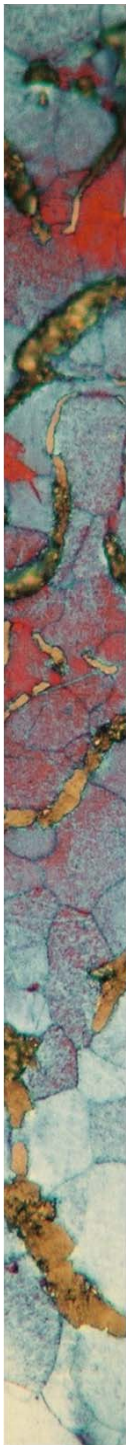
Binder type

- Inorganic binder
- Organic binder
- Amount of binder

- Storage time
- Temperature



Source: Orlenius et al, 2008

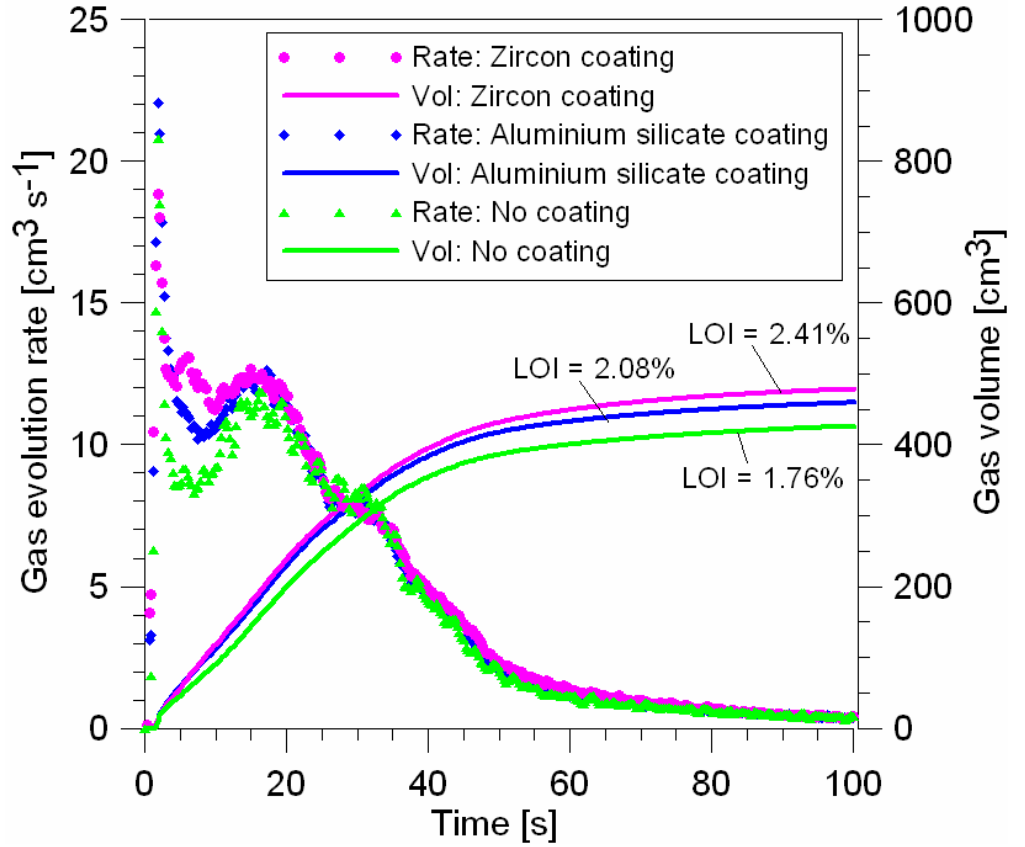


Gas evolution

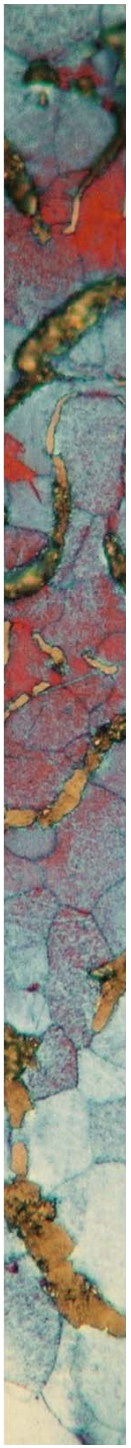
Coatings

- Improve surface
- Aluminium silicate
- Zircon

- Drying process



Source: Orlenius et al, 2008



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- Shrinkage porosity
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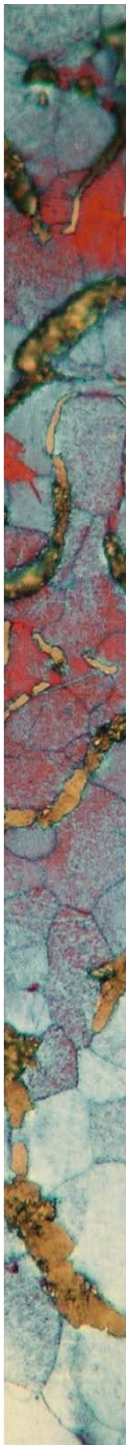
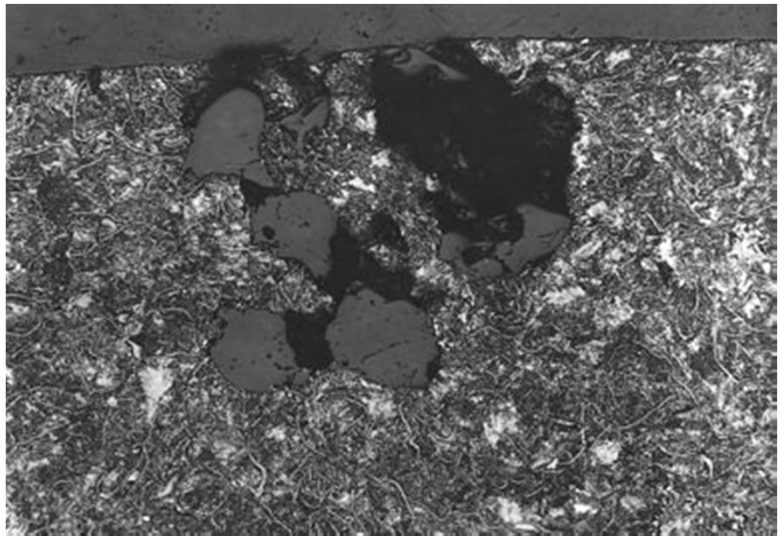


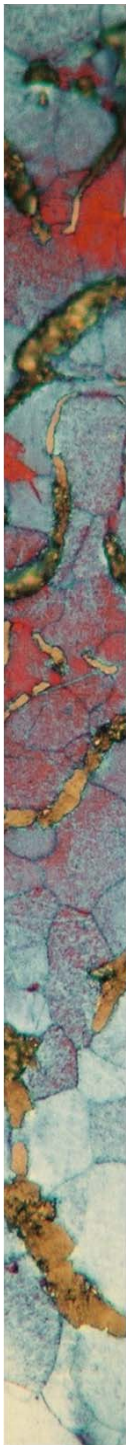
Inclusions – sand

- Occur at widely varying positions
- Sand torn away by metal stream
- In association with CO blowholes and slag
- Carefully blow out mold cavities
- Avoid high pouring rates
- Ensure uniform mold compaction

- Edge disintegration
- Sand crust formation
- Erosion

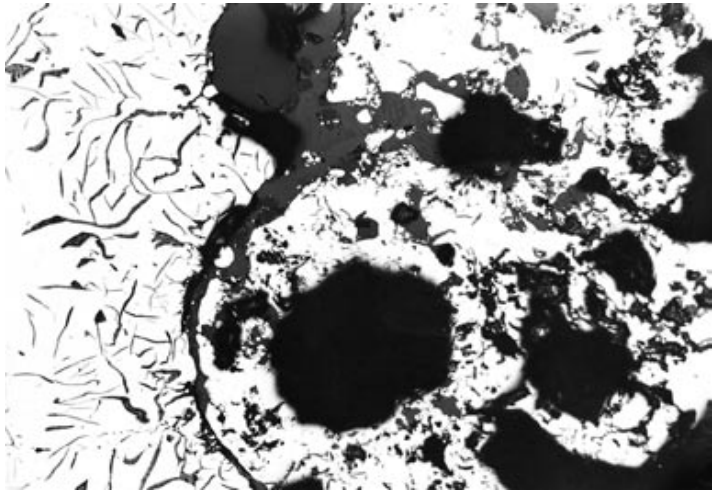


Source: www.ikominerals.de



Inclusions – slag

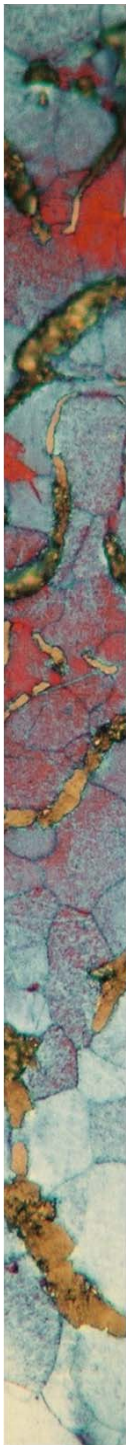
- Irregular-shape
- Non-metallic inclusions
- Upper casting surfaces
- Formation of CO



Source: www.ikominerals.de

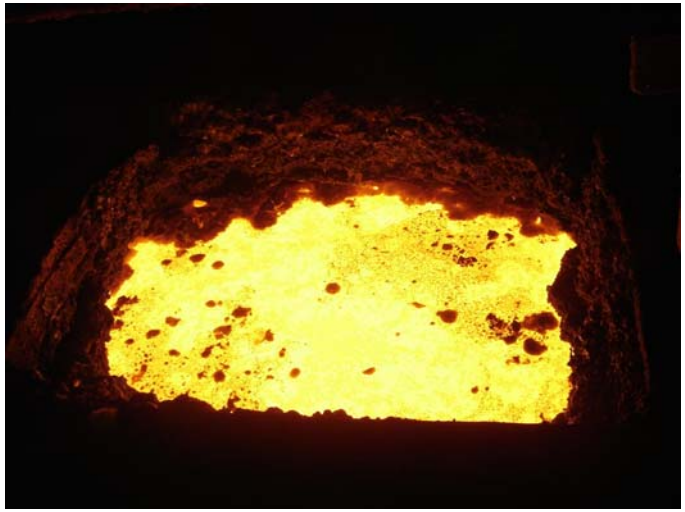
Possible causes

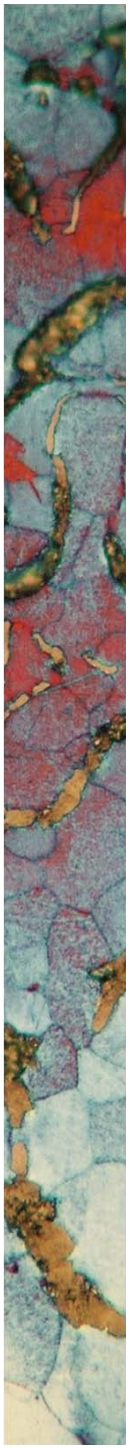
- Oxide content of the charge too high
- Poor dissolution of inoculants
- Poor slag practice



Inclusions – slag

- Filter
- Design of the gating system – slag traps





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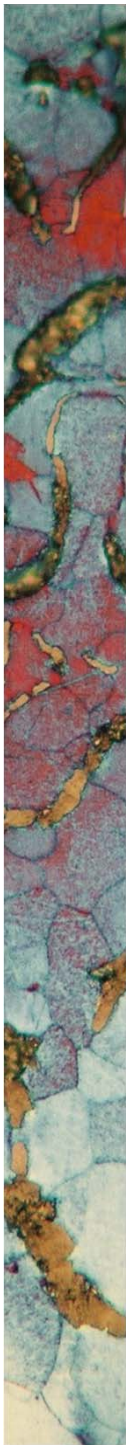
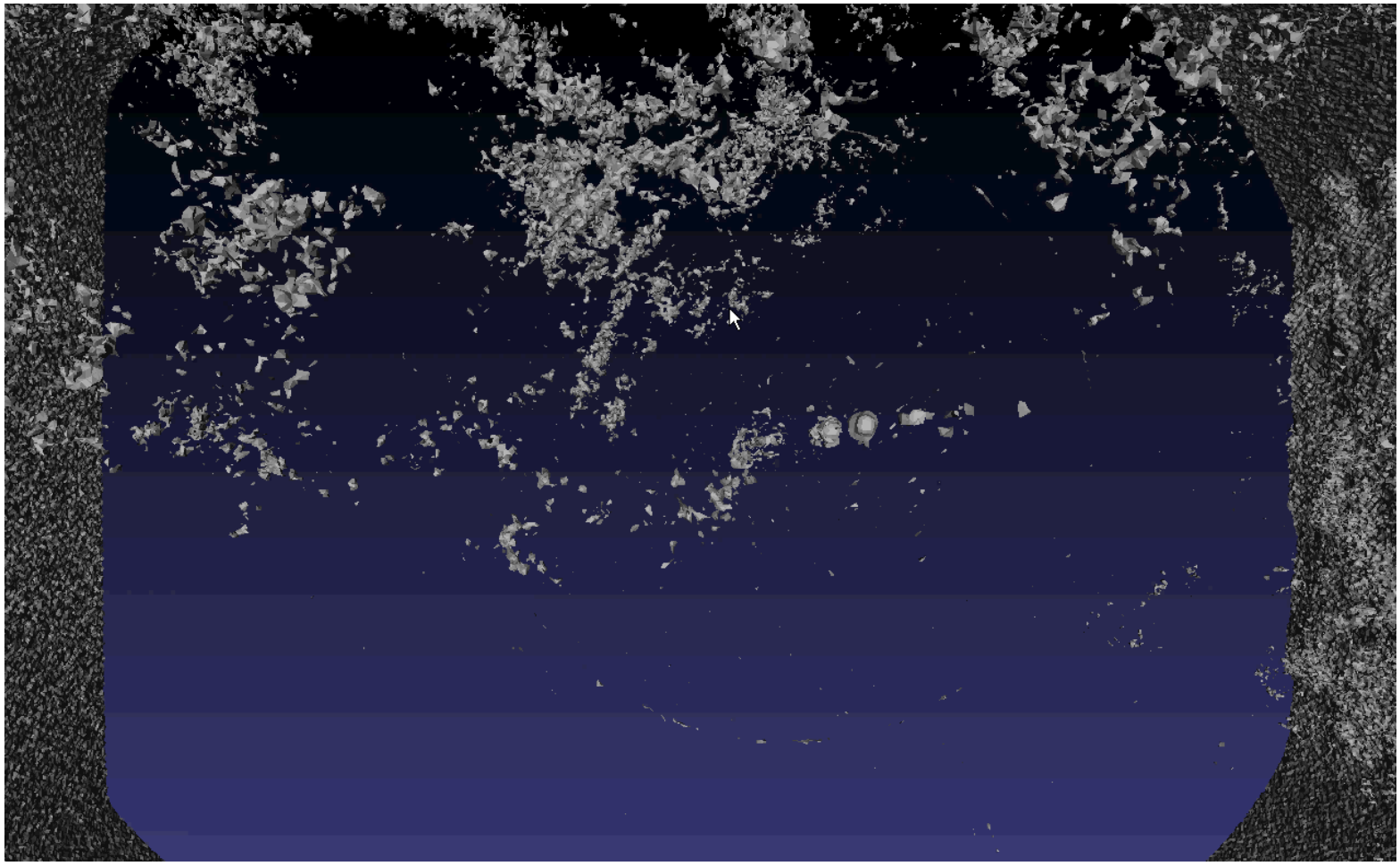
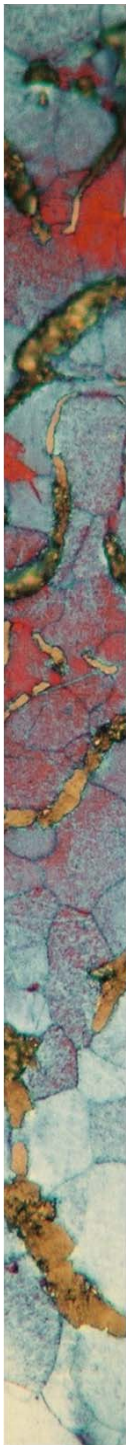


Introduction



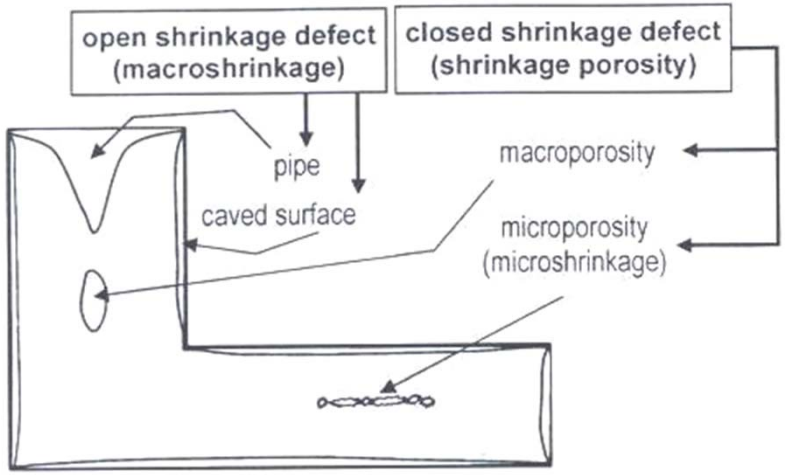
Source: Elmquist et al, 2008



Shrinkage – Introduction

Shrinkage defects

- Open shrinkage defects (macroshrinkage)
- Closed shrinkage defects (shrinkage porosity)

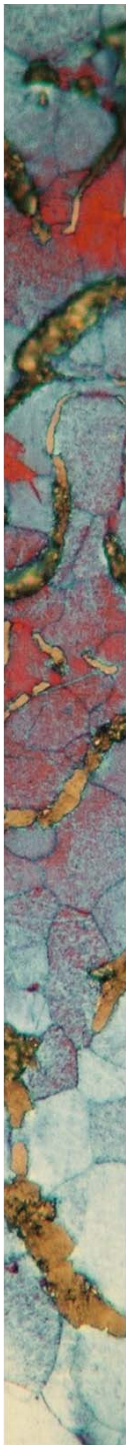


Source: Stefanescu, 2005

Generally

- Liquid contraction
- Liquid-to-solid contraction
- Solid contraction

Cast iron – graphite expansion



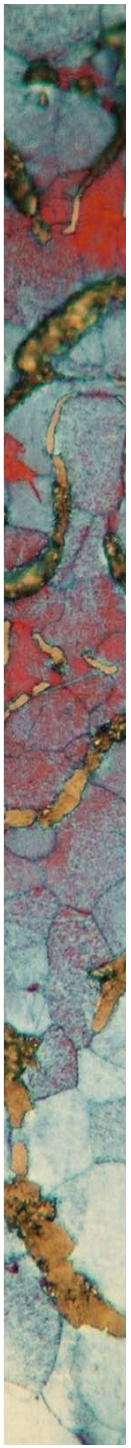
Shrinkage – Introduction

Factors promoting shrinkage porosity

- Nature and properties of the sand mould
- Metal composition
- Pouring temperature
- Degree of eutectic nucleation of the metal
- Solidification mode

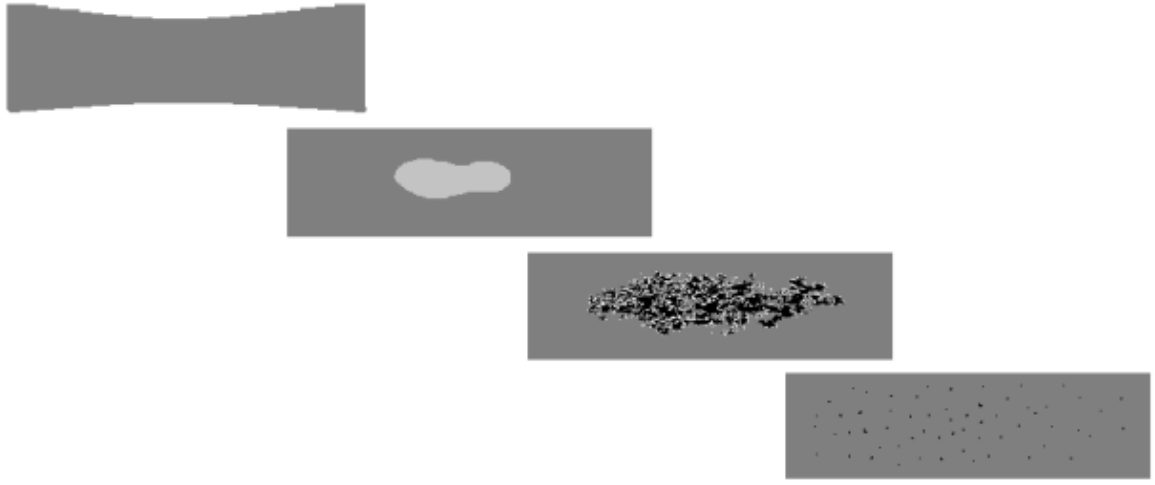
Compensates for the shrinkage

- Feeding of metal
- Graphite expansion
- **Atmospheric gas**
- **Dissolved gas (hydrogen, nitrogen)**

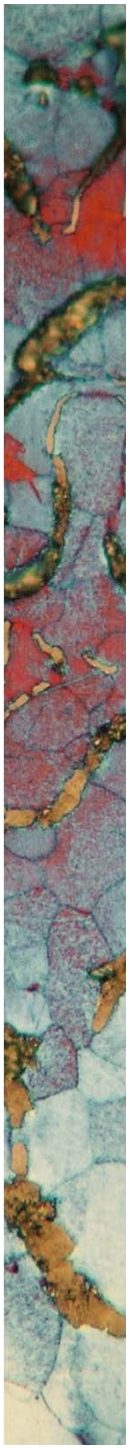


Shrinkage – Introduction

- Different types of shrinkage
- Related to cooling curve



Source: Soivio, Elmquist, 2012



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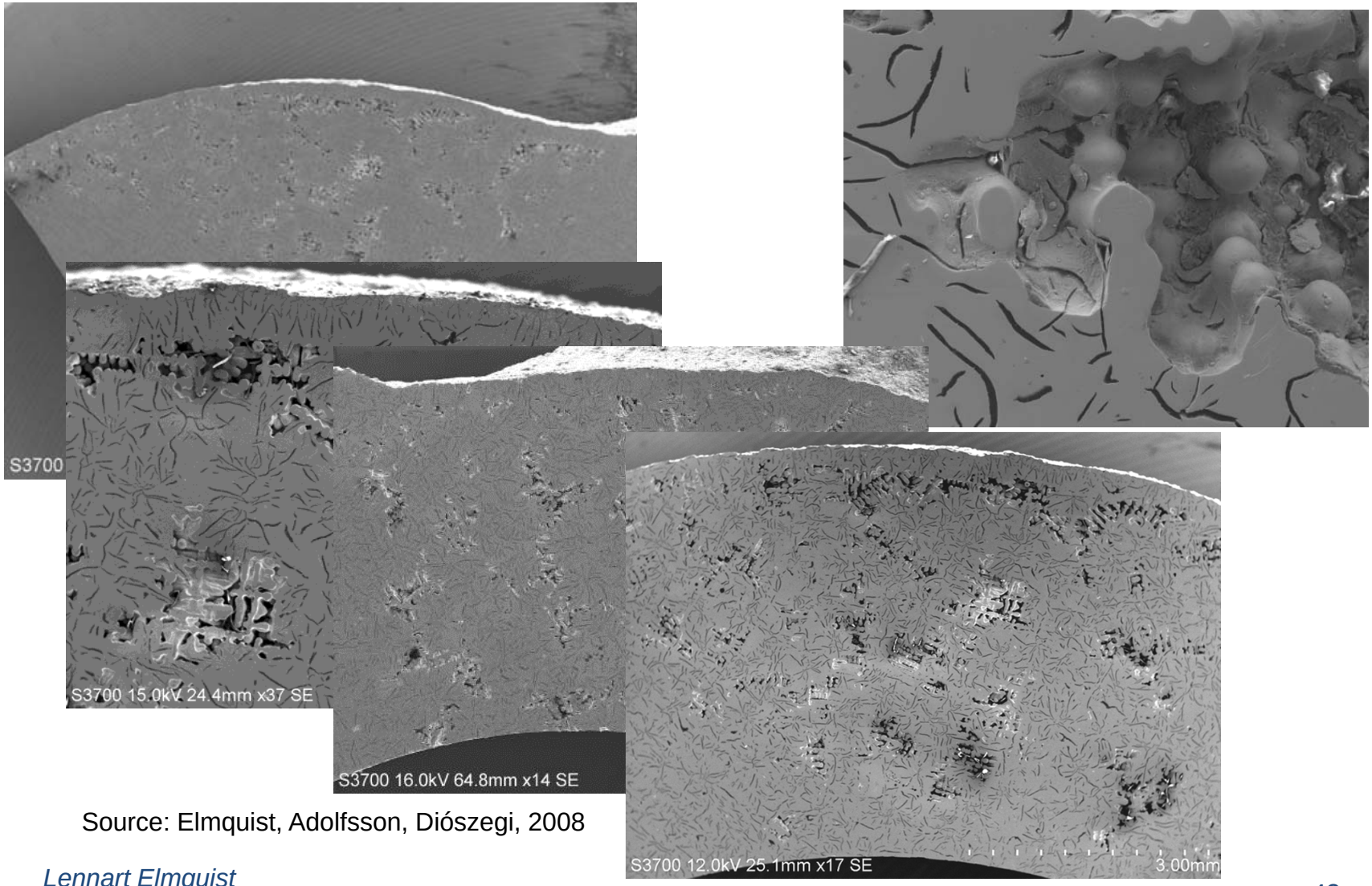

Source: Elmquist, Adolfsson, Diószegi, 2008

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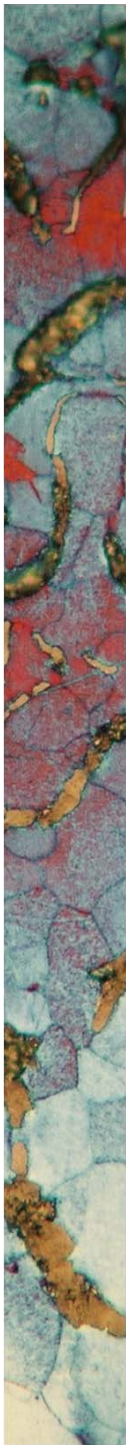


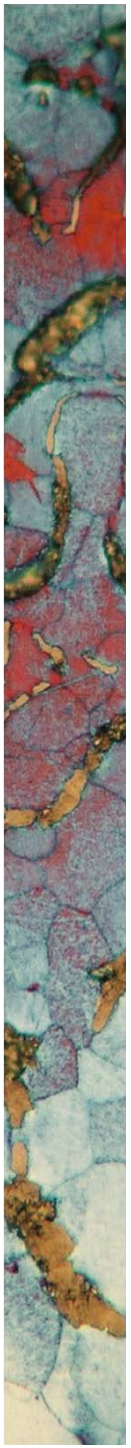
Defect characterization

Case: Cylinder Heads

- Economy
- Environment

- Two foundries
- Two designs
- Production line
- With and without porosity

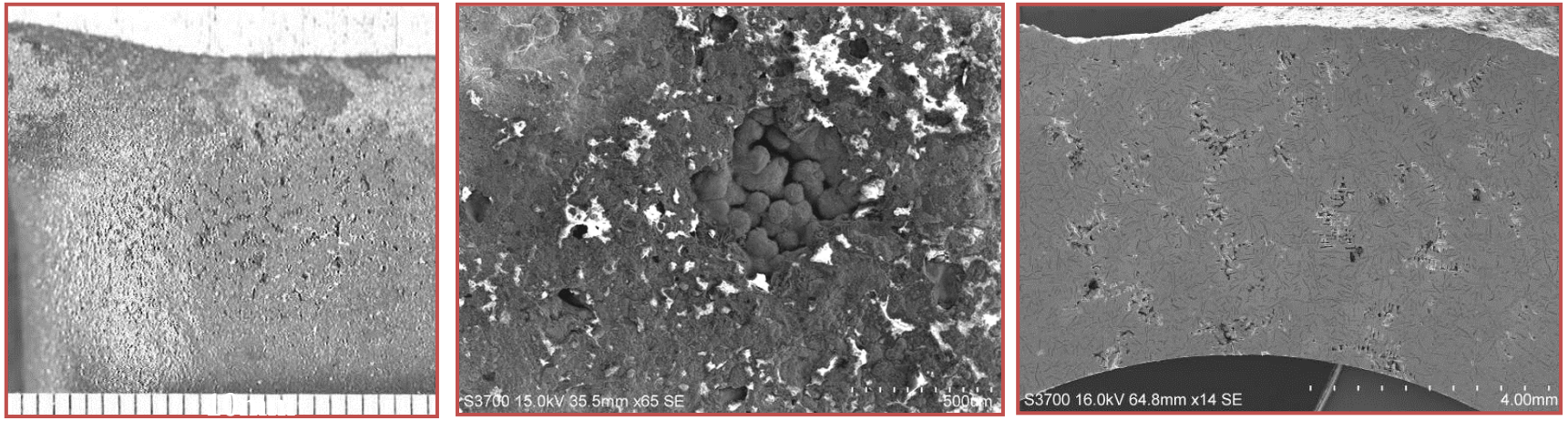
- **Shrinkage porosity**
- **Characteristic features**
- **Knowledge about mechanisms**



Defect characterization

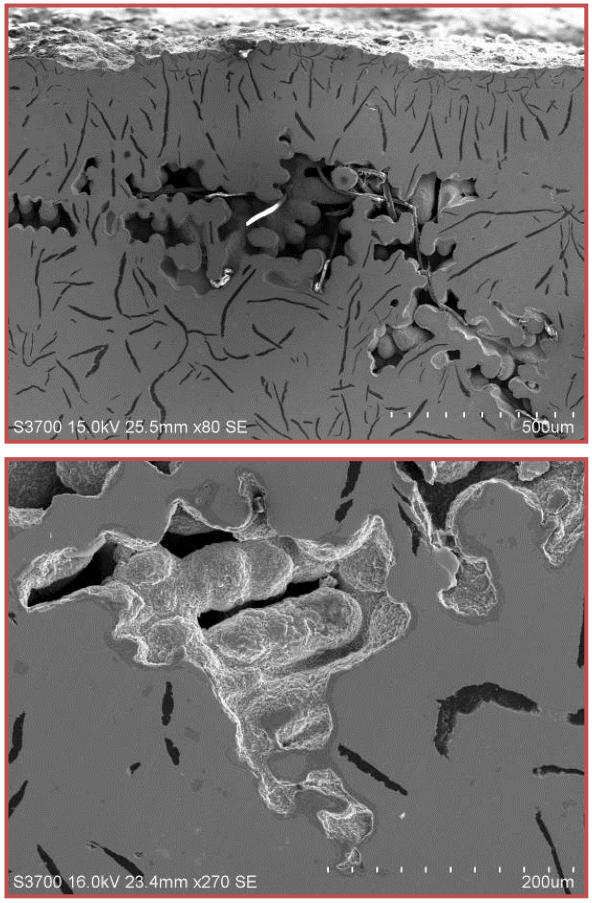
Similarities

- Position on casting
- Surface defect
- Connection surface – porosity
- Penetrating through the casting
- Enclosing certain units
- Primary crystals?



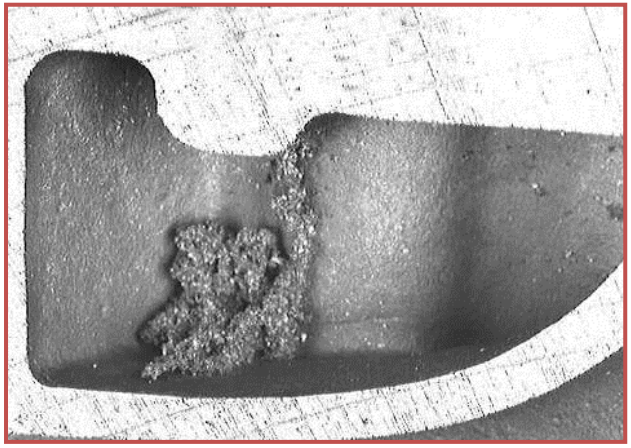
Source: Elmquist, Adolfsson, Diószegi, 2008

Defect characterization

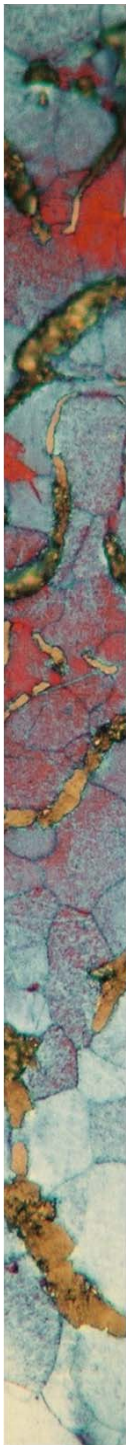


Source: Elmquist, Adolfsson, Diószegi, 2008

- Border between surface and porosity
- Oxide layer – connection to atmosphere
- No graphite layer



Shrinkage Porosity vs. Penetration



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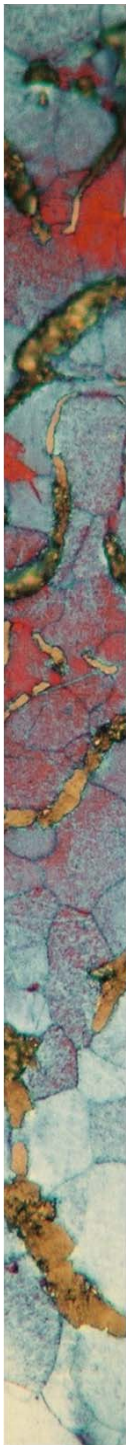
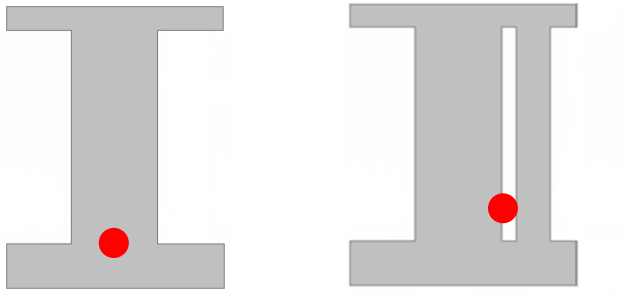


Migrating hot spot

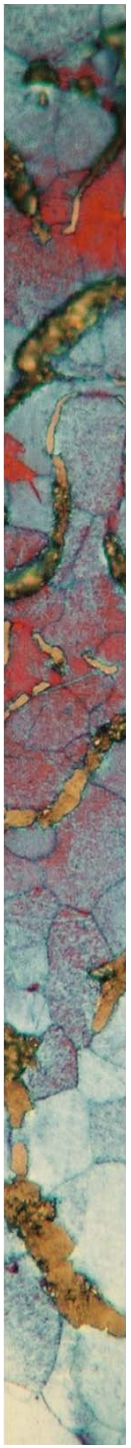
- Heat is removed during solidification
- Different cooling conditions in different parts
- Initial temperatures in casting/mold
- Part of the casting that solidifies last

LTY

- Migrates during solidification
- Depends on geometry
- Heat removal

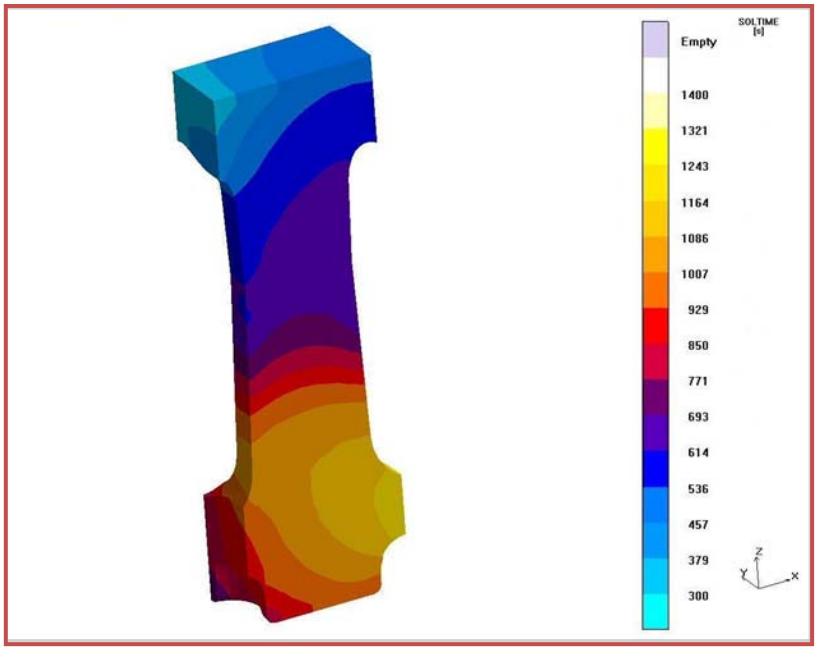


- Global/Local hot spots

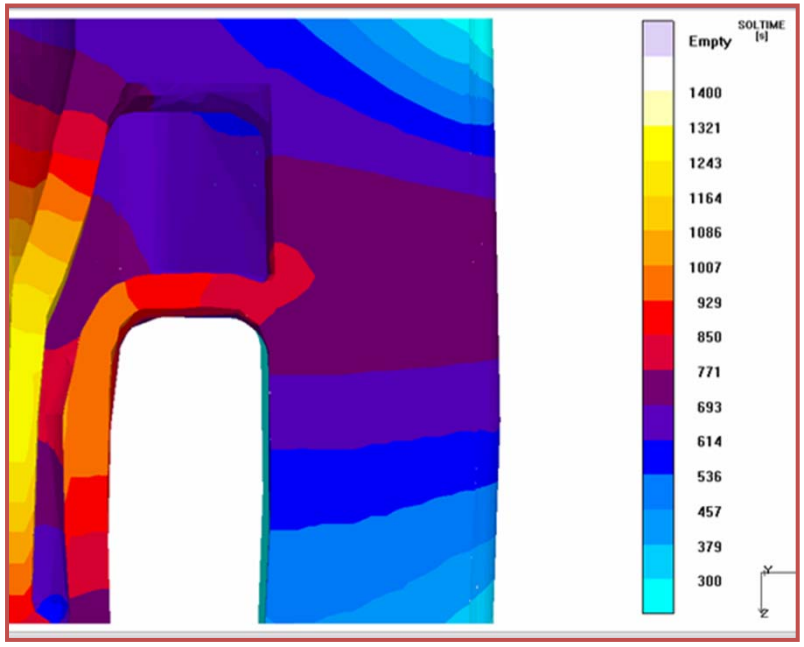


Migrating hot spot

CH1

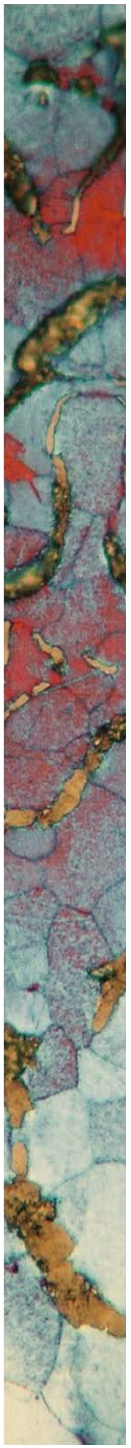


CH2

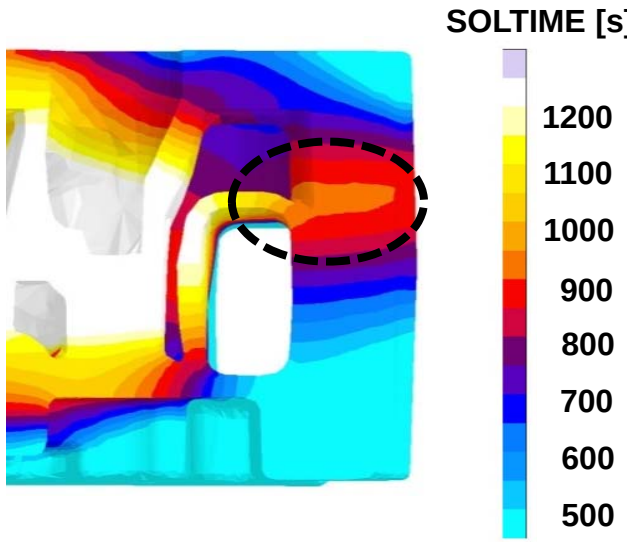


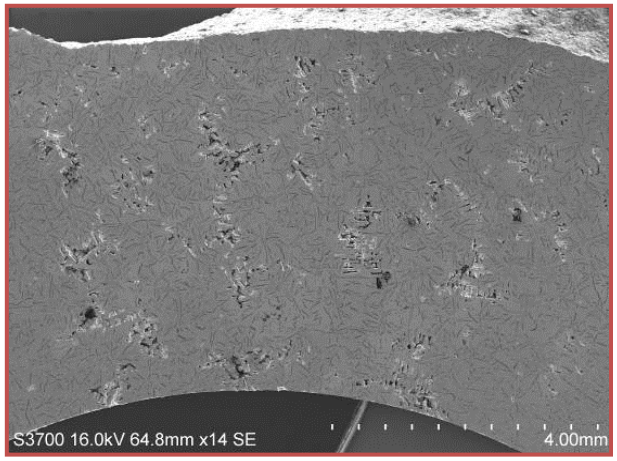
Source: Elmquist, Adolfsson, Diószegi, 2008

- Thermal centre at mold/metal interface
- Migrating hot spot



Migrating hot spot



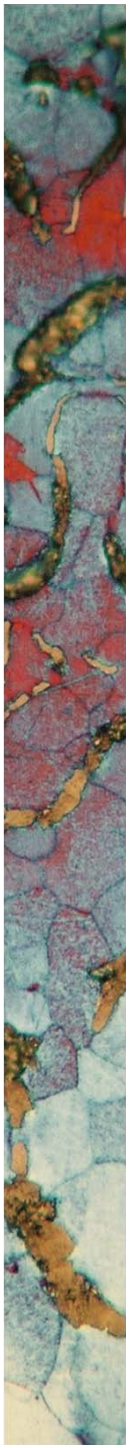


Hot spot migrates

- Casting/mold interface
- Shrinkage porosity
- Metal expansion penetration

- Geometry developed by simulations
- Final position of hot spot

Source: Elmquist, Adolfsson, Diószegi, 2008



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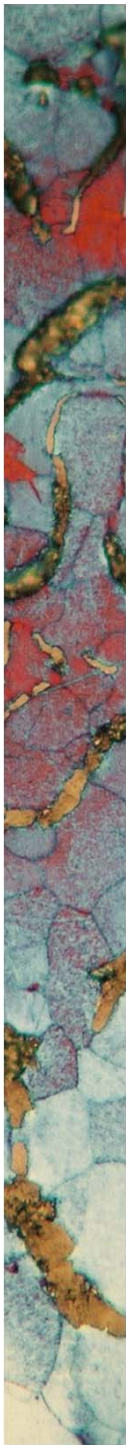
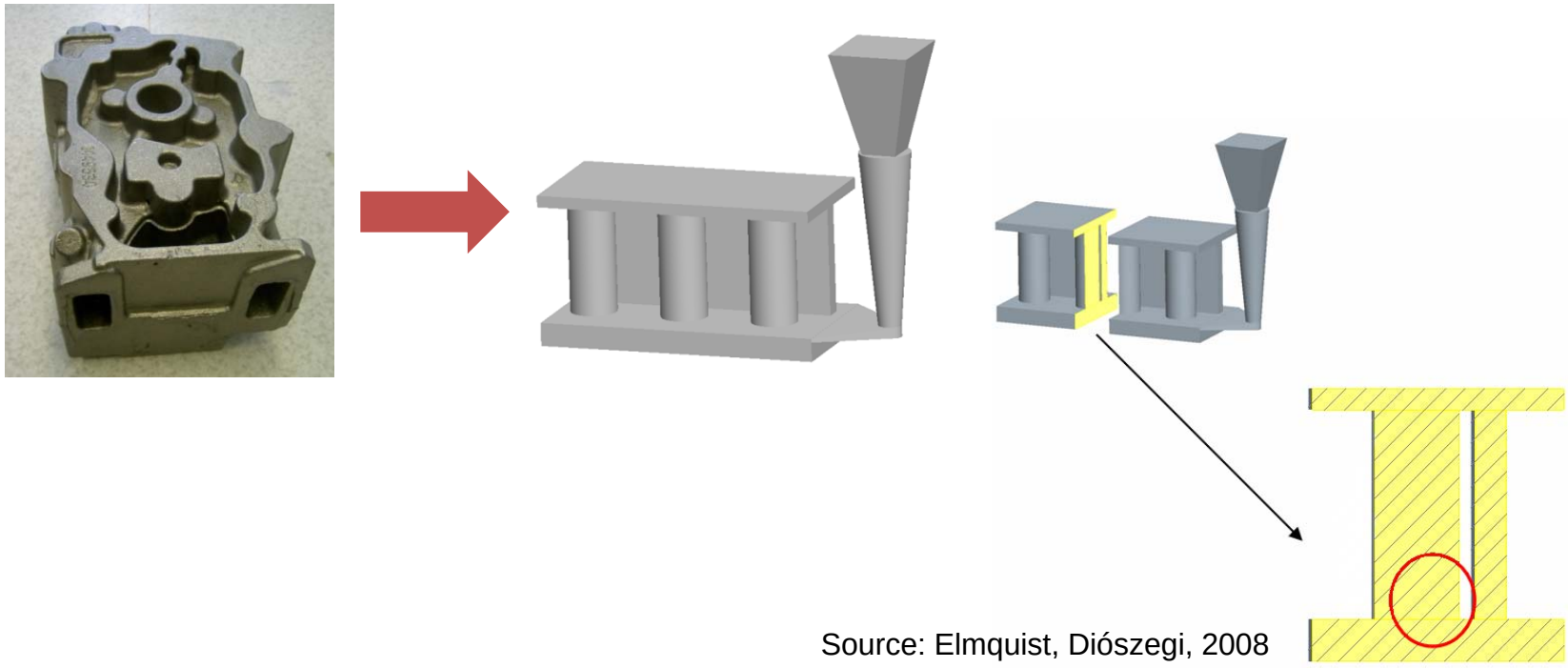


Shrinkage Porosity

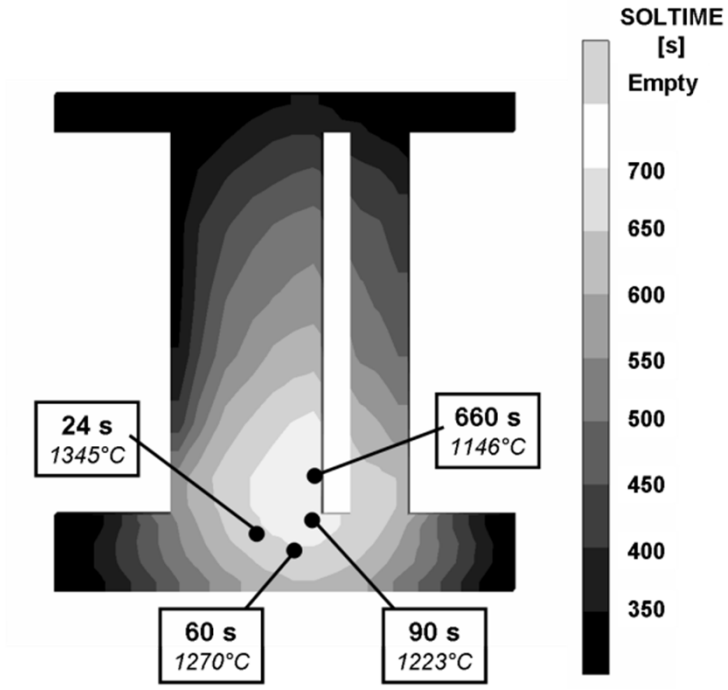
Develop a casting that generates shrinkage porosity



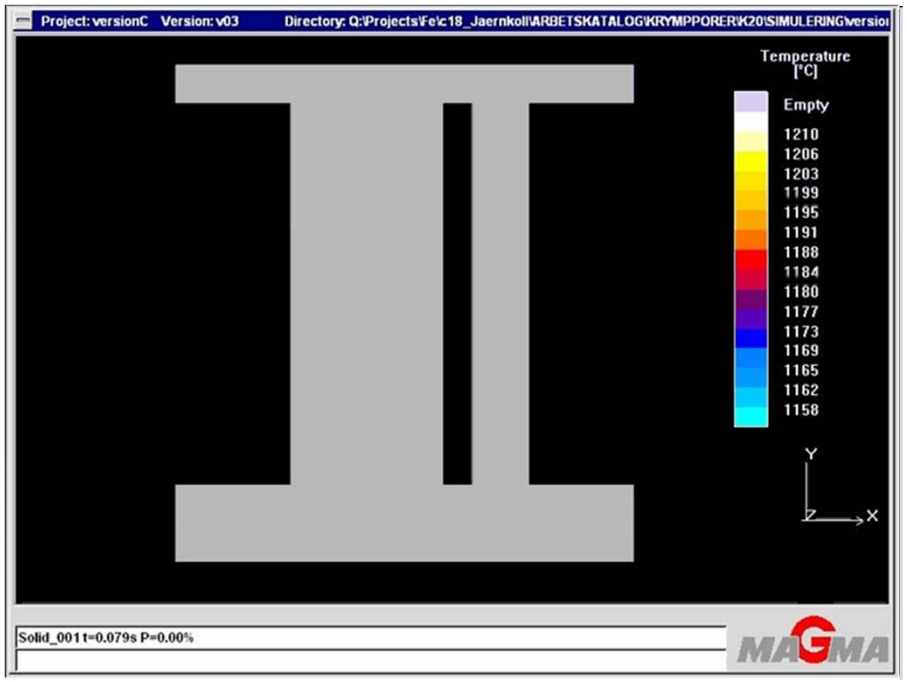
Source: Elmquist, Diószegi, 2008

Shrinkage Porosity

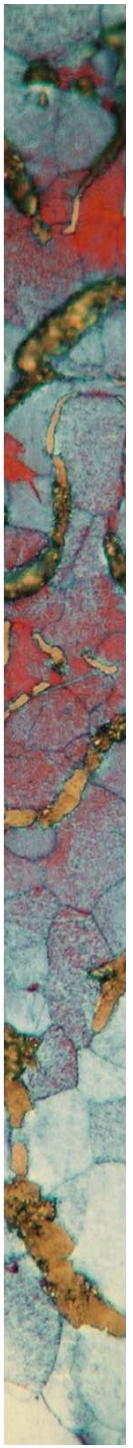
Geometry generating porosity



Migrating hot spot



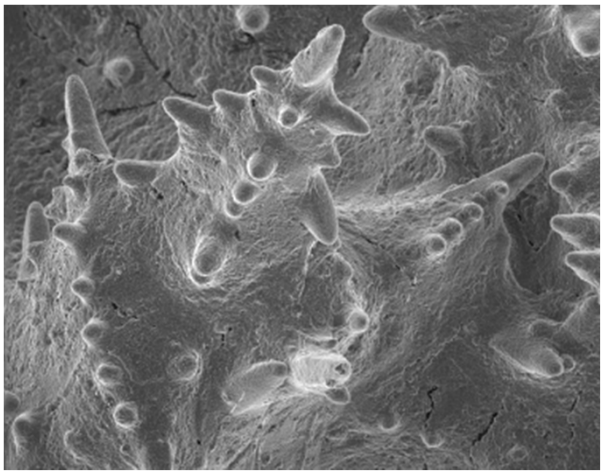
Source: Elmquist, Diószegi, 2008

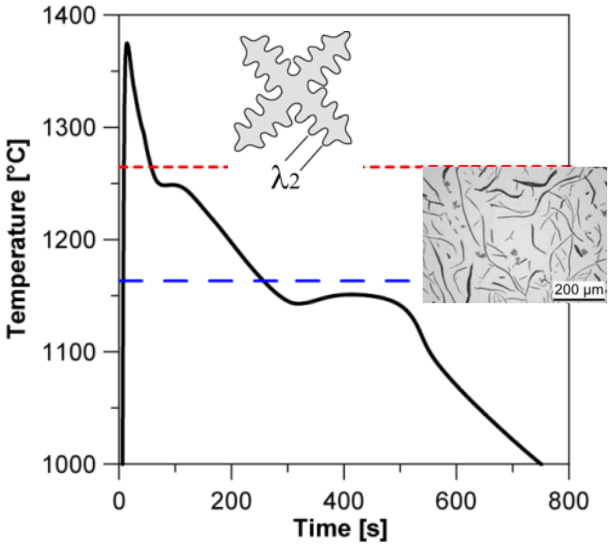


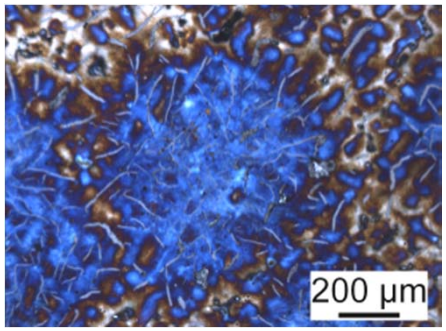
Solidification

Solidification of grey cast iron

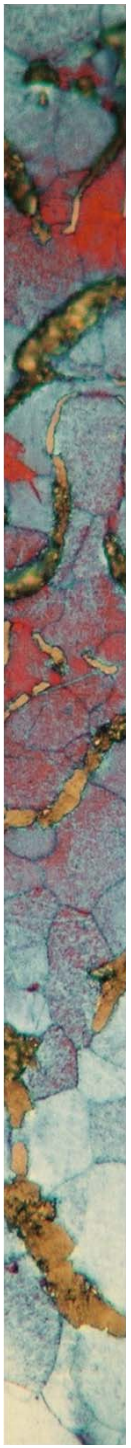
- Nucleation
- Growth
- Primary austenite
- Eutectic cells







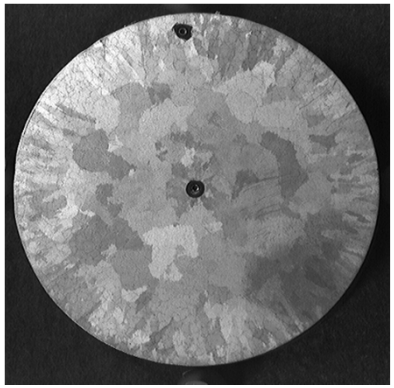
Source: Elmquist et al, 2008

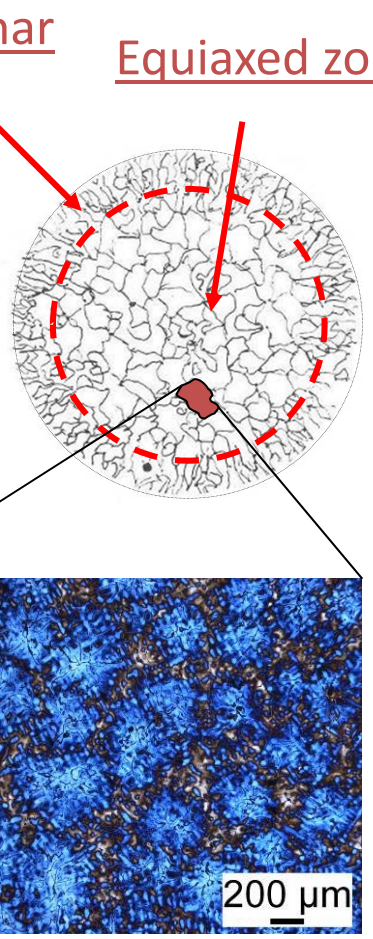


Solidification

Macrostructure

- Columnar dendrites
- Equiaxed dendrites
- CET

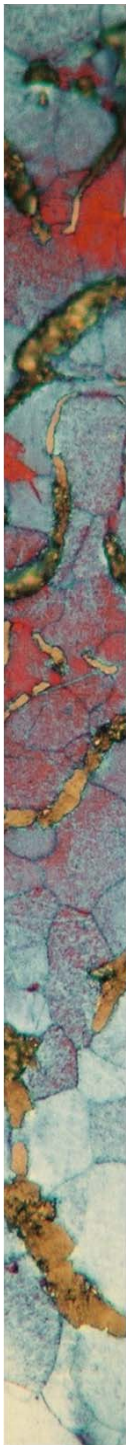




Microstructure

- Dendrite Arm Spacing (SDAS)
- Fraction Austenite
- Eutectic cell size

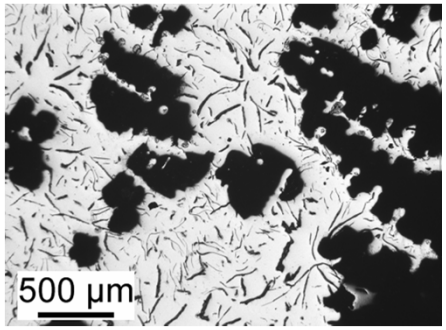
Source: Elmquist et al, 2008

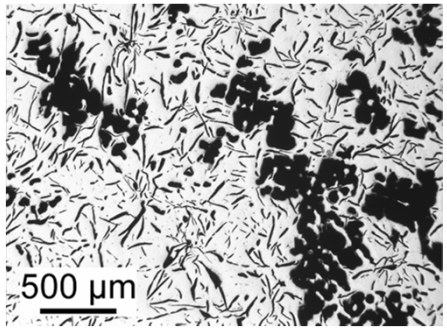


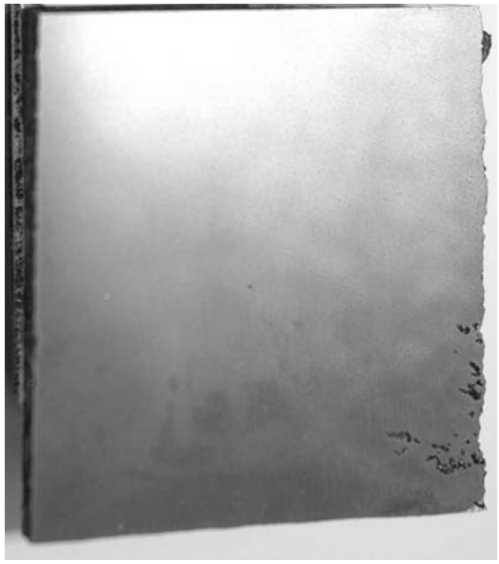
Shrinkage and the macrostructure

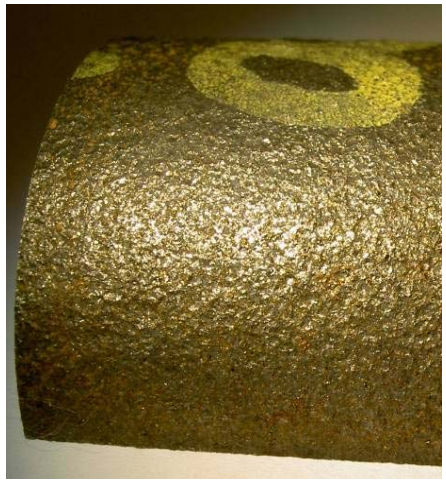
Similarities

- Shrinkage porosity
- Surface defects
- Penetrating network
- Contact with atmosphere

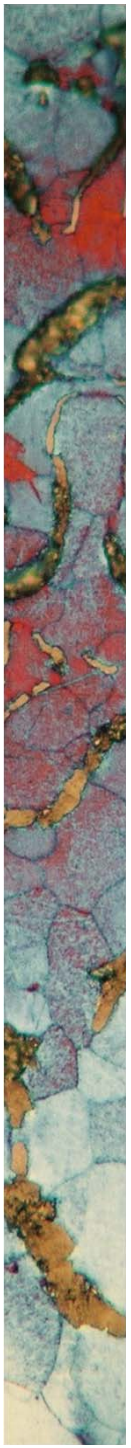




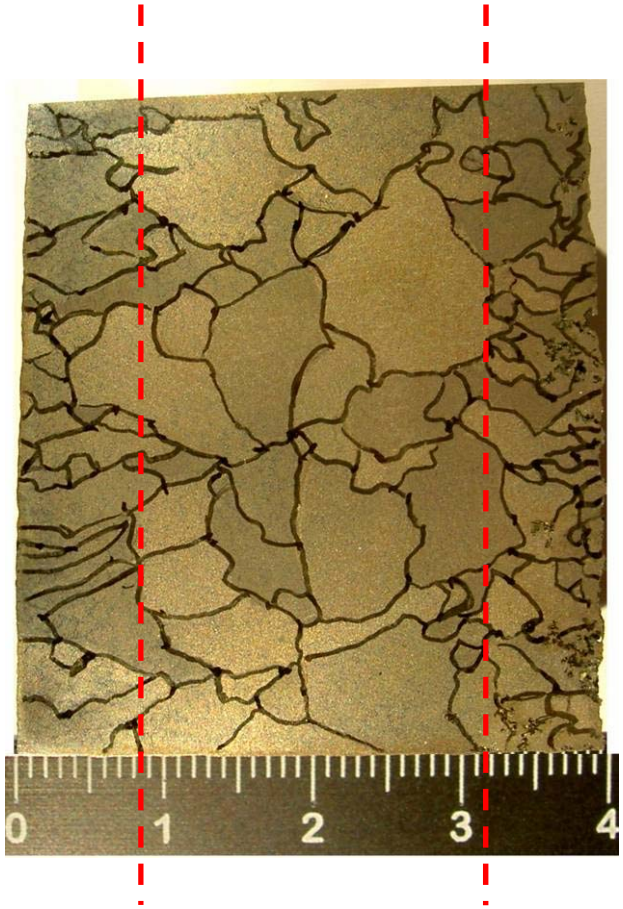




Source: Elmquist, Diószegi, 2008



Shrinkage and the macrostructure



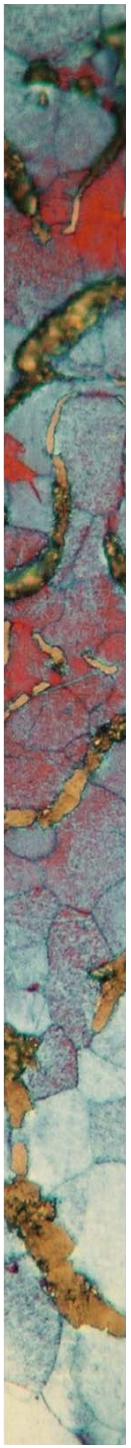
Source: Elmquist, Diószegi, 2008

DAAS (Direct Austempering After Solidification

Macrostructure

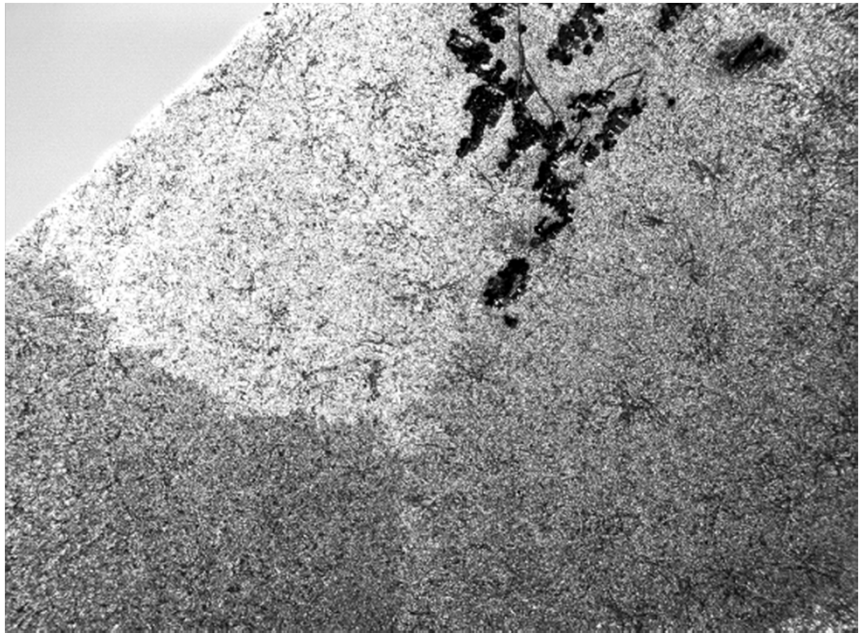
- Equiaxed dendrites
- Columnar dendrites
- CET

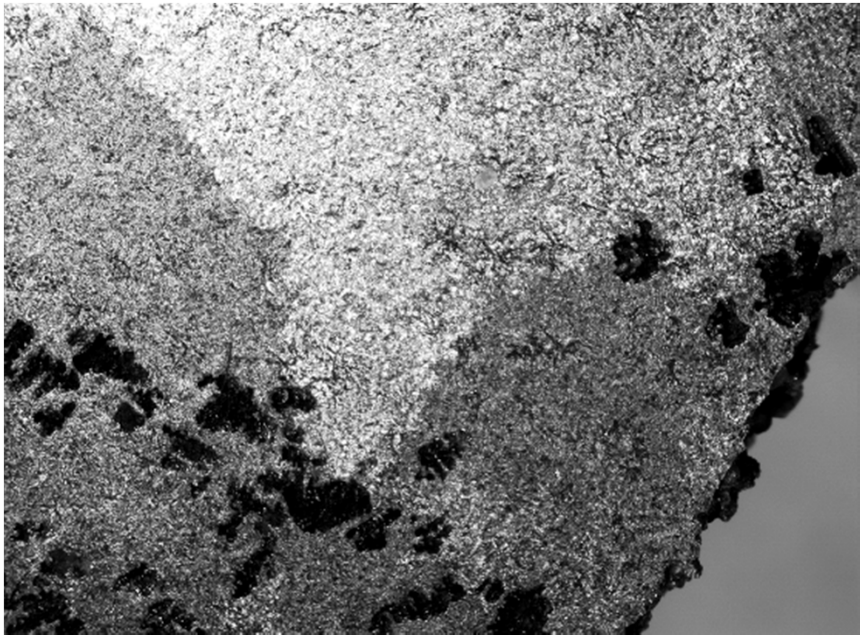
- ➢ Columnar zone
- ➢ Abnormal columnar zone
- ➢ Similar CET



Shrinkage and the macrostructure

Porosity between primary crystals





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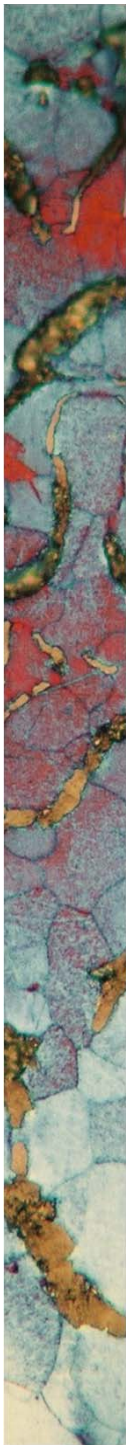
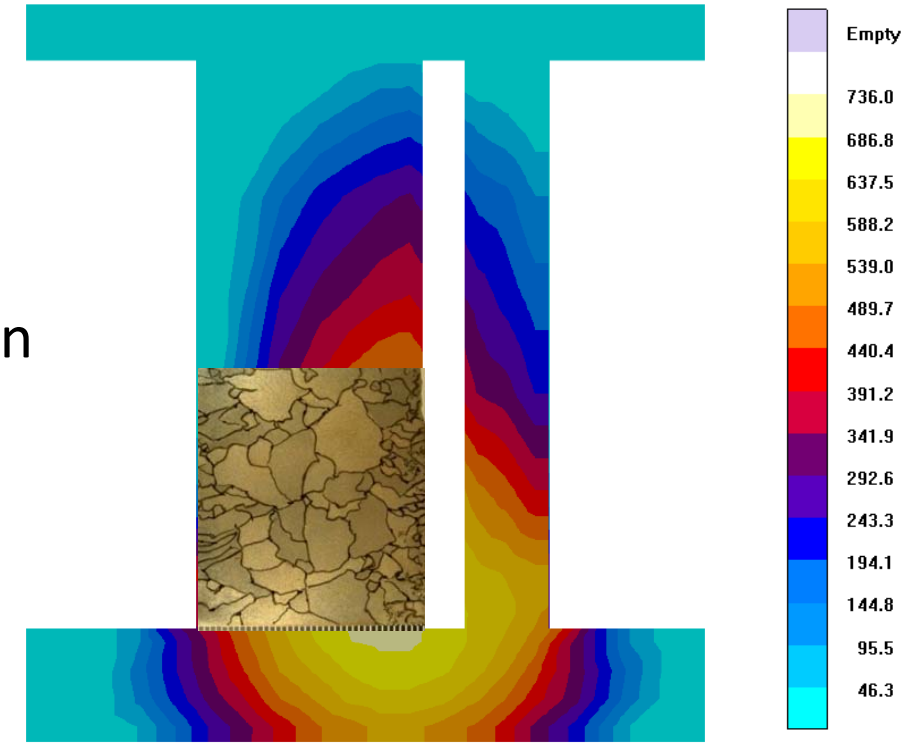


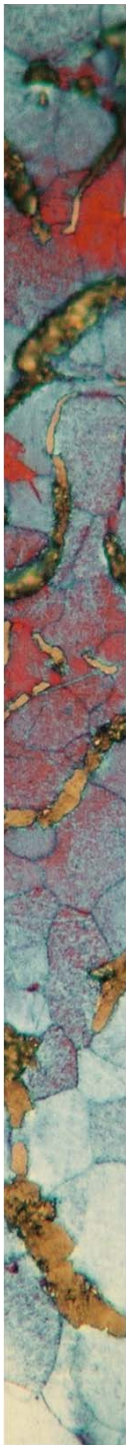
Shrinkage and the macrostructure

Formation of shrinkage porosity

- Hot spot
- Migration
- Last area of solidification
- Weak columnar zone
- Atmospheric gas
- Shrinkage porosity
- Surface defect



Source: Elmquist, Diószegi, 2008



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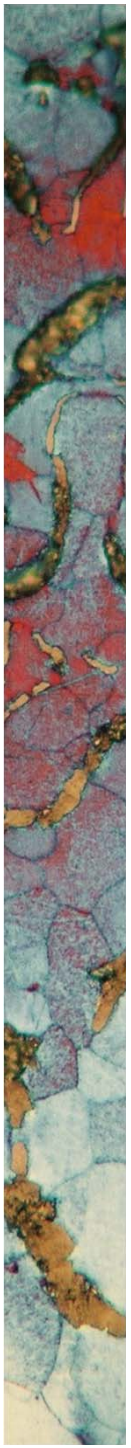
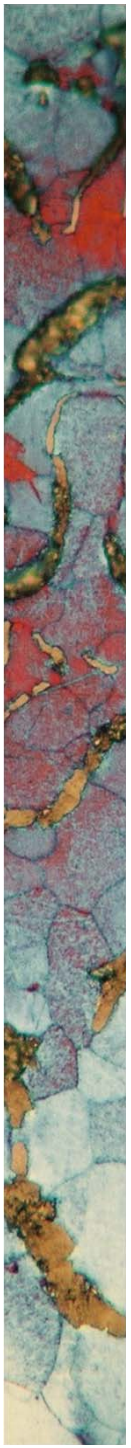
  - Primary austenite
- Metal expansion penetration
  - Primary austenite
- Other quality problems
- What about the future?
- Summary



Penetration – Introduction

- Metal penetration is a casting condition resulting from reactions at the mould-metal interface
  - Physical
  - Mechanical
  - Thermo-chemical

"Metal penetration is defined as the condition in which cast metal has entered into the pore spaces of the mold and core beyond the mid-point of the surface layer of sand grains."
(Draper and Gaindhar, 1977)



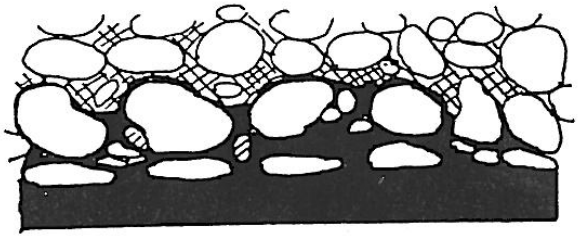
Penetration – Introduction

Four basic mechanisms:

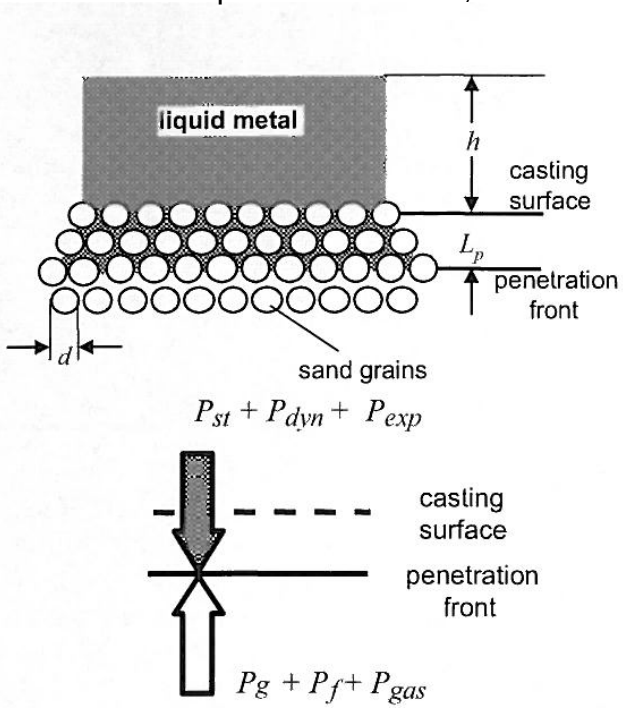
- Mechanical (liquid-state)
- Chemical
- Vapor-state
- Explosion penetration

The liquid metal exerts:

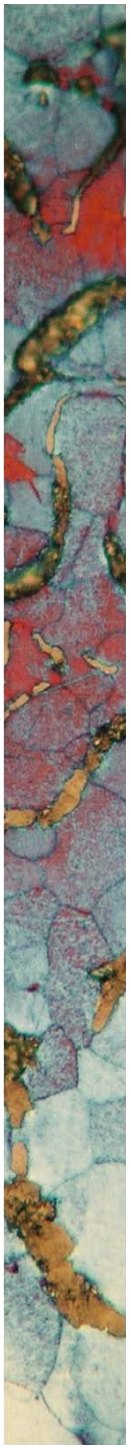
- Static pressure
- Dynamic pressure
- Pressure because of expansion



Source: Draper and Gaindhar, 1977



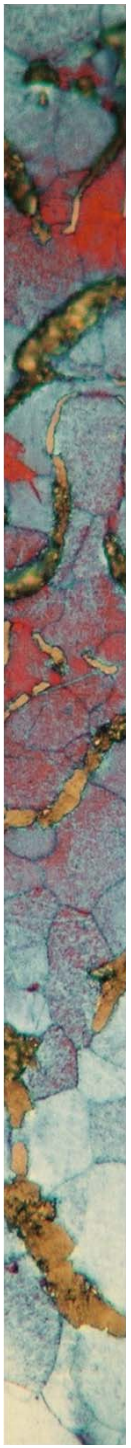
Source: Stefanescu, 2008



Penetration – Introduction

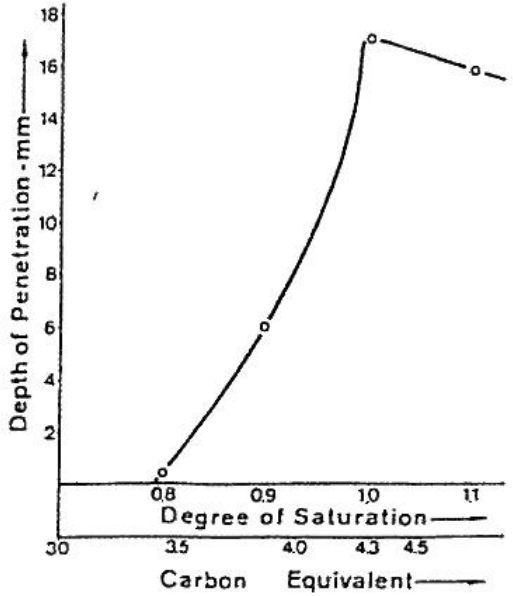
- Generally occurs at locations where the sand is the hottest (cores, concave sections) and is of lowest density
- Low surface tension
- High P, Si, or Mn content
- Elevated static or dynamic metal pressure
- High metal and sand temperature
- Sand too coarse, or insufficiently rammed
- Thermal conductivity of sand too low
- Poor quality mold wash or blacking

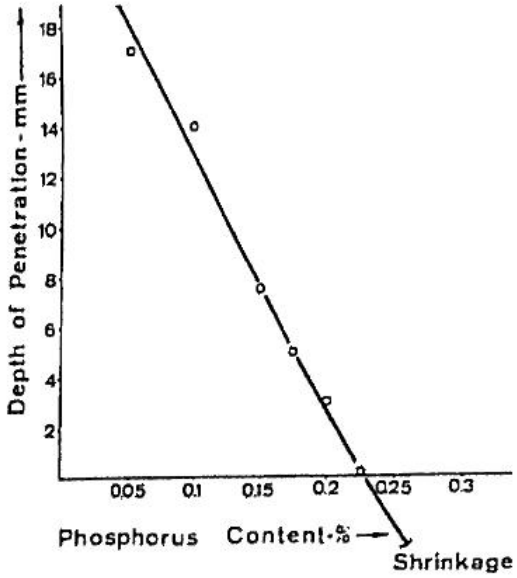
(AFS International atlas of casting defects)



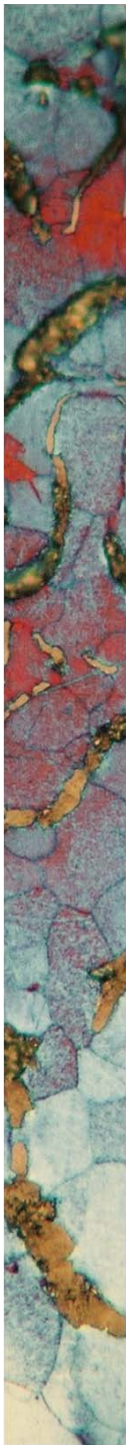
Penetration – Introduction

- Only removed by extensive chipping and grinding
- Often so severe that castings are beyond the point of economical rework and must be scrapped
- Tool wear





(Source: Levelink and Julien, 1973)



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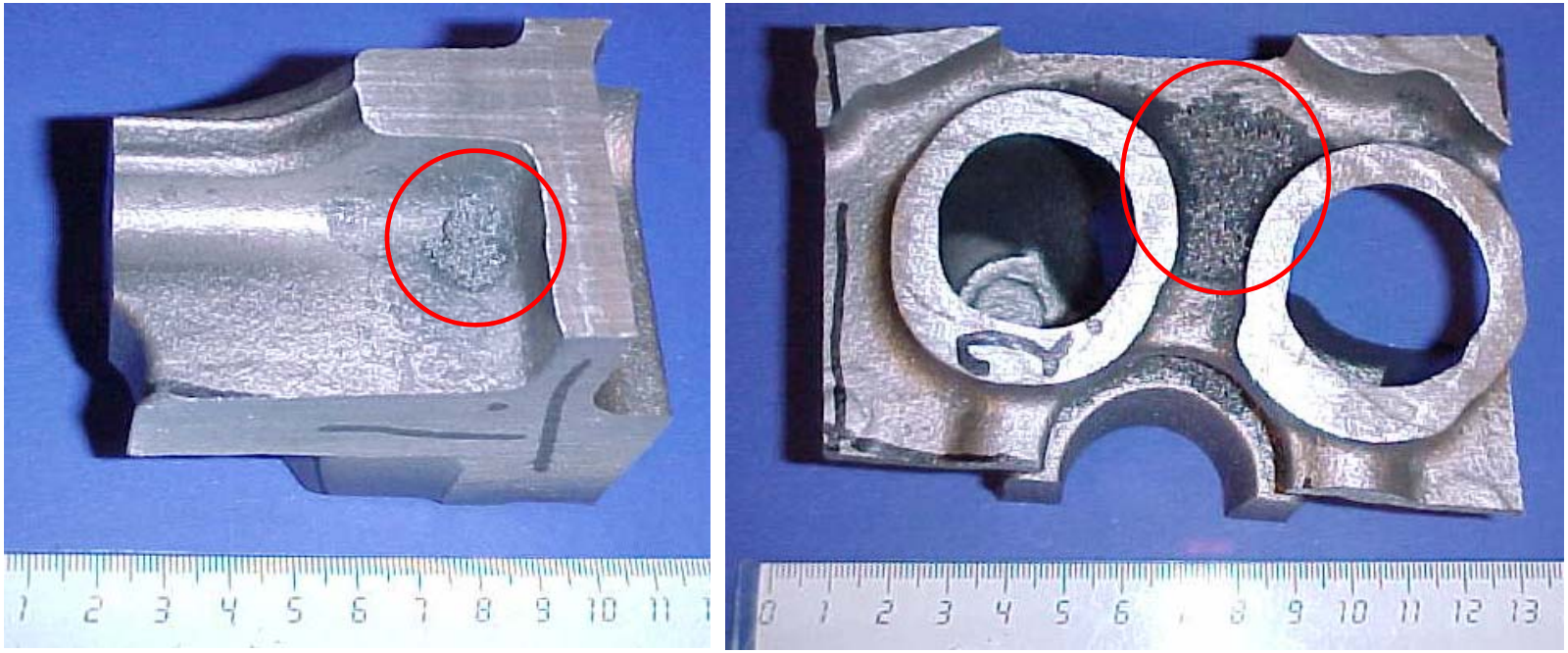
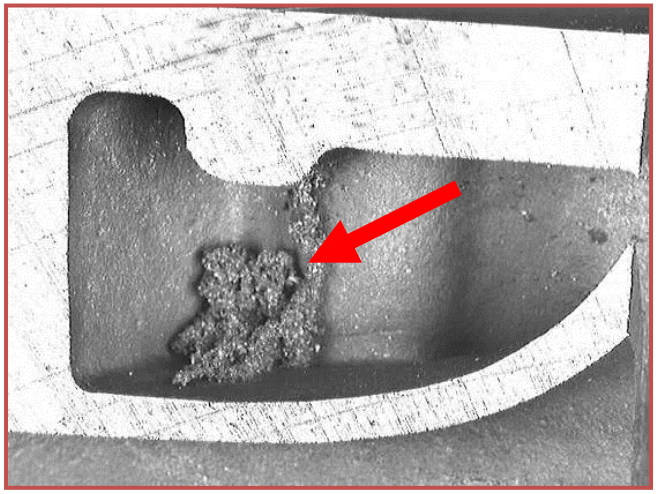


Source: Diószegi and Dugic, 2007

Metal Expansion Penetration

CASE Study – Cylinder heads

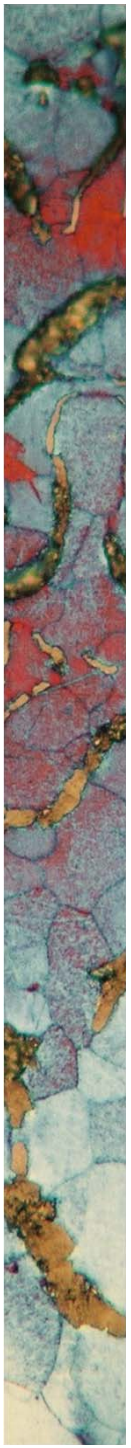
- Shrinkage – no Penetration
- No shrinkage – Penetration



Source: Elmquist et al, 2008

⇒ Shrinkage Porosity vs. Penetration

Migrating hot spot is related also to penetration problems



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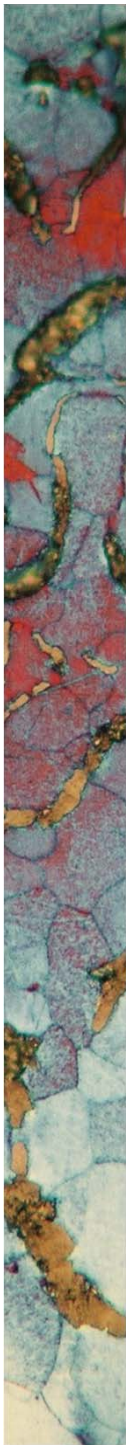
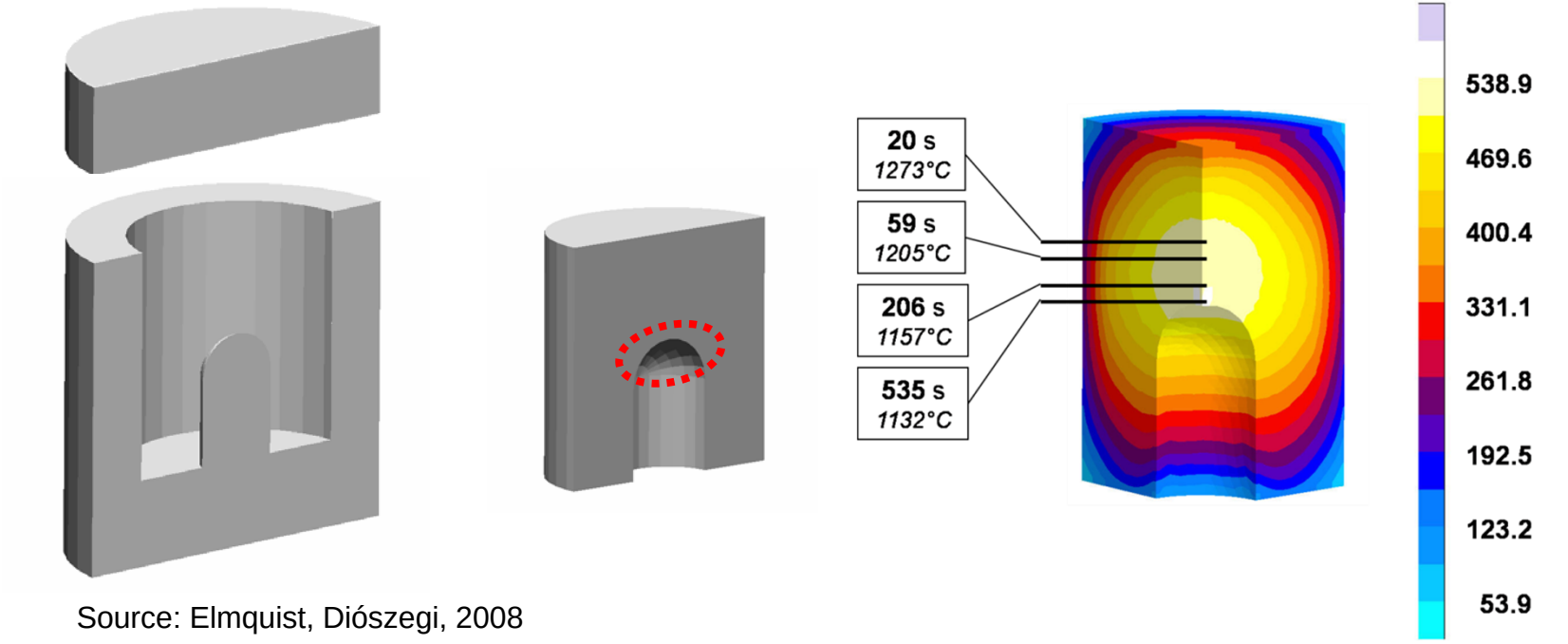
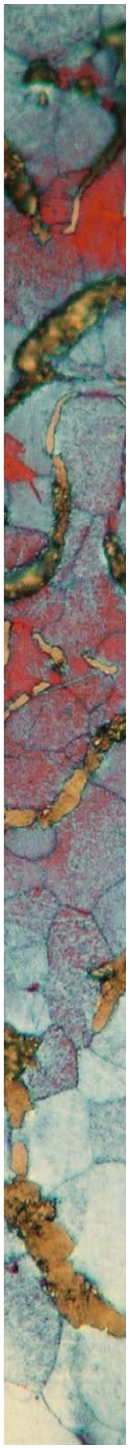


Metal Expansion Penetration

Geometry generating metal penetration

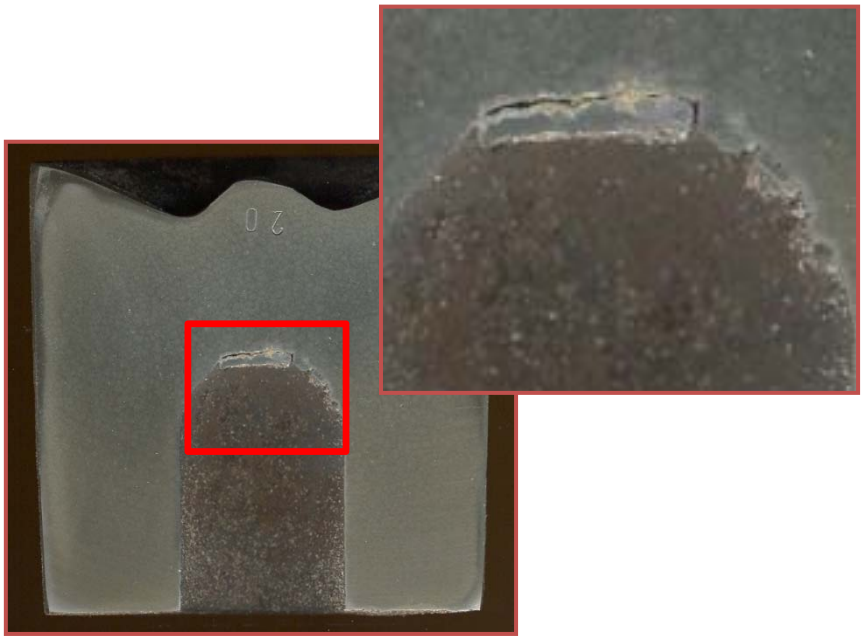


Source: Elmquist, Diószegi, 2008

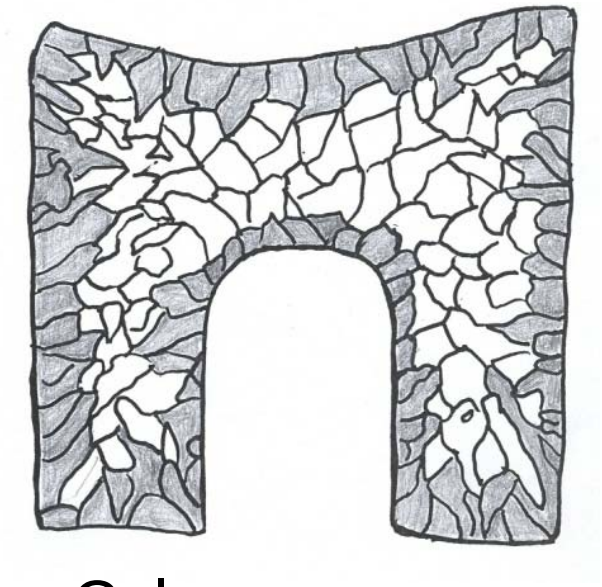


Metal Expansion Penetration

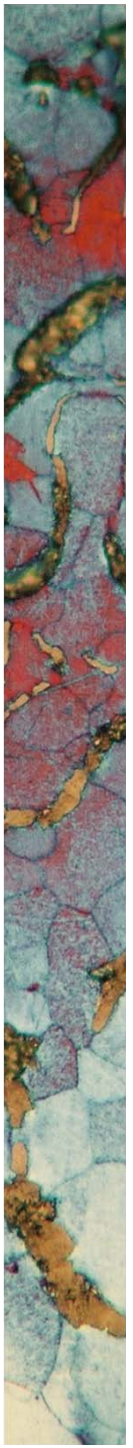
Test Casting



Source: Diószegi and Dugic, 2007



Columnar zone
Equiaxed zone



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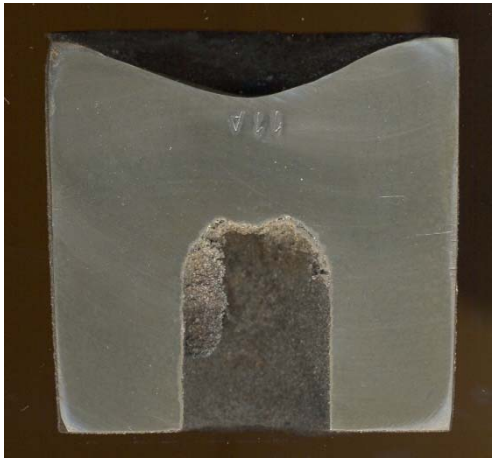
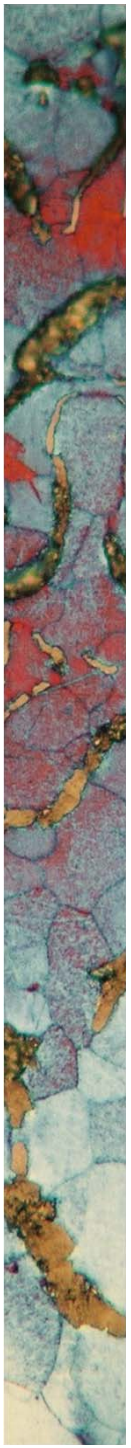


Source: Diószegi and Dugic, 2007

The volumetric changes cause either a surplus or a deficit of melt

Hot spot at casting/mold interface – the weakest part



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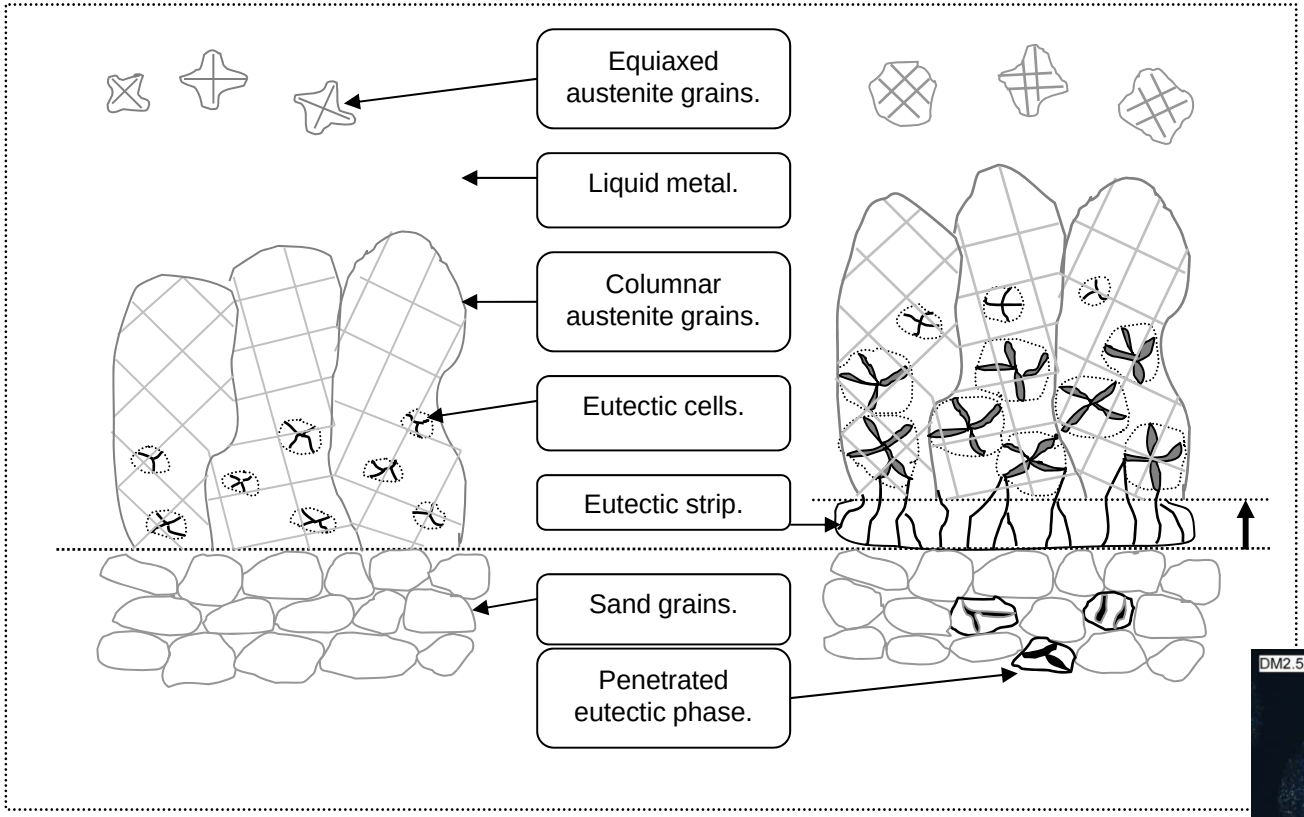

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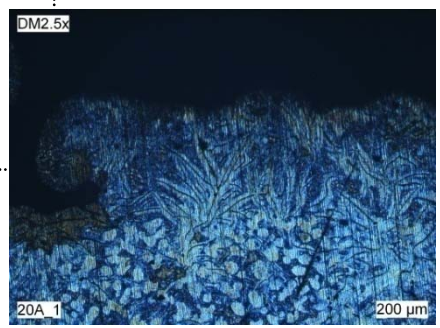

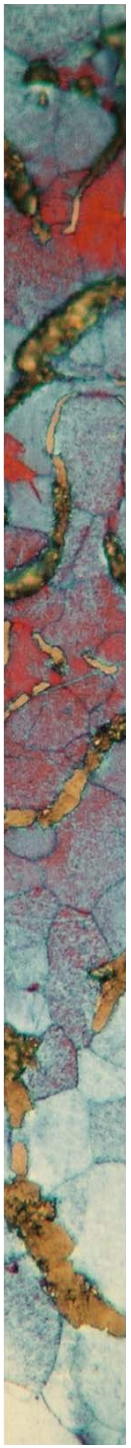

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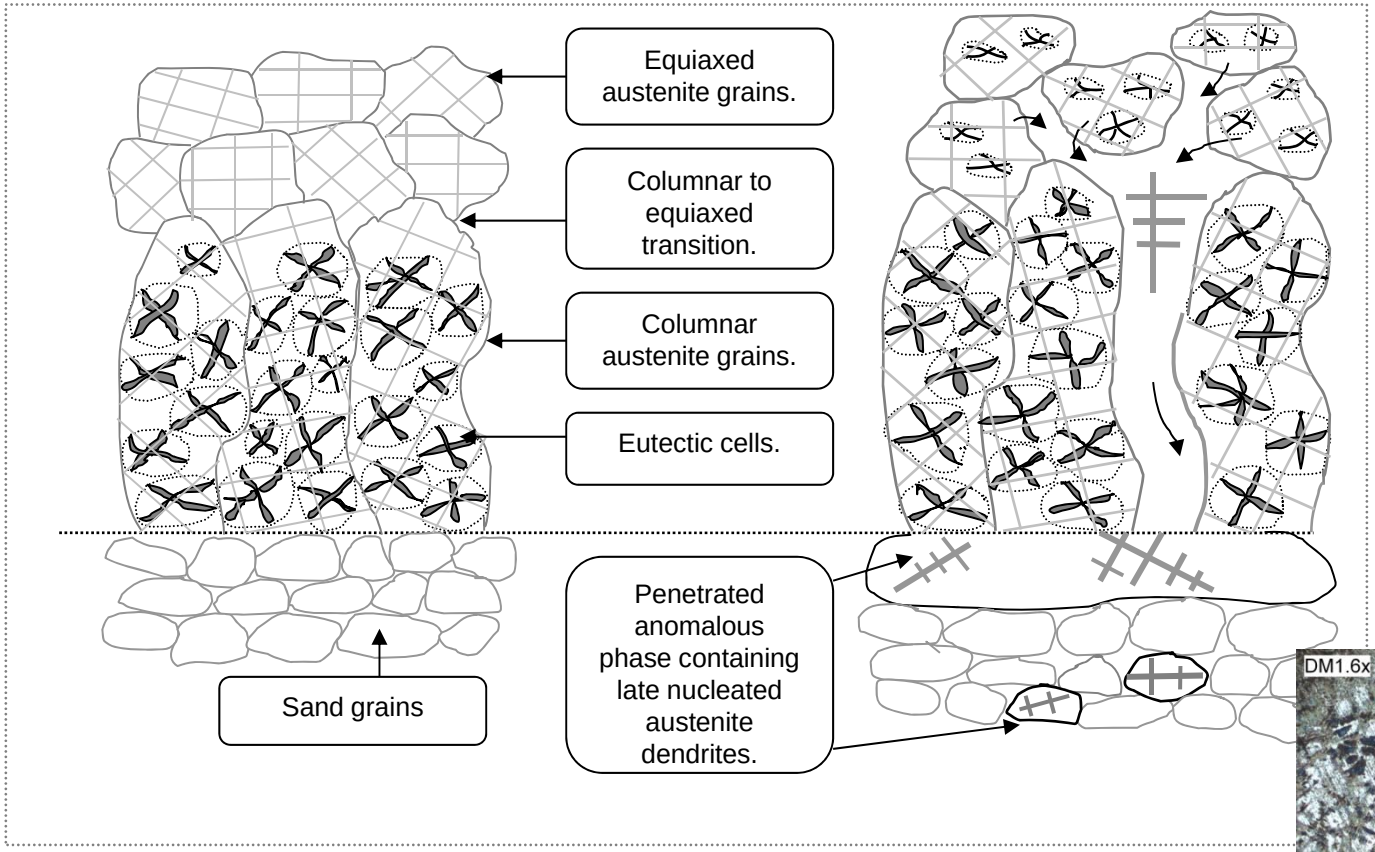

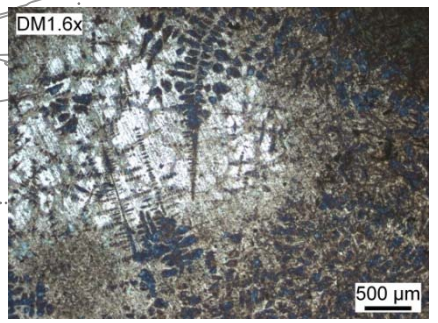

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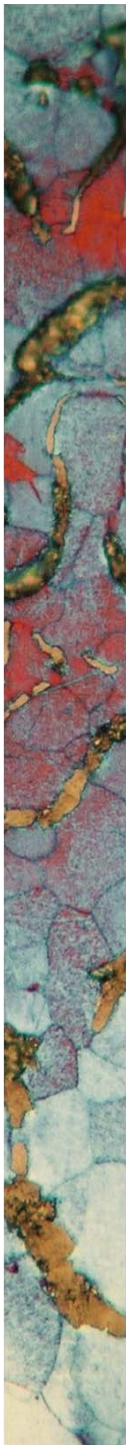

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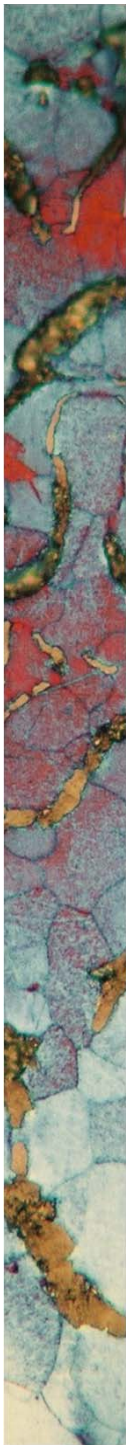
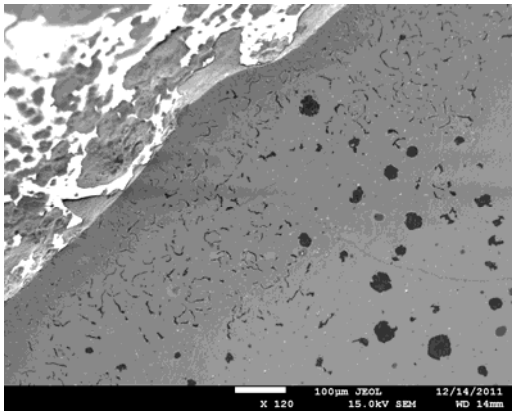
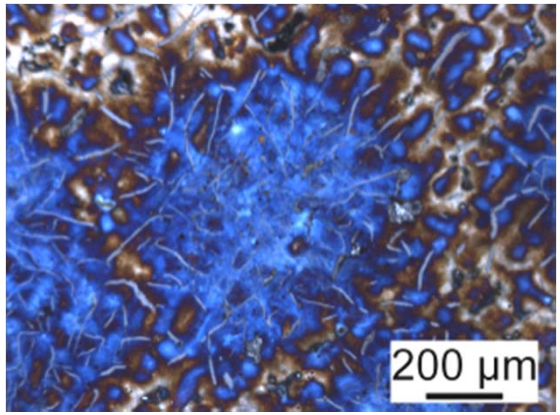


Other Problems

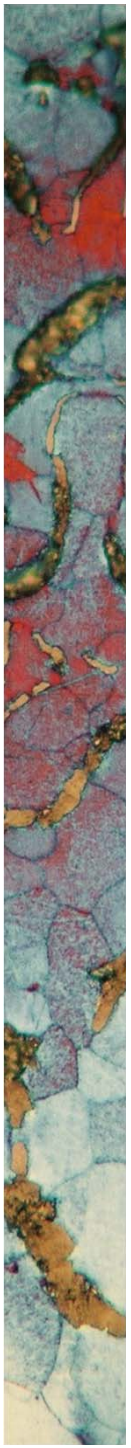
- Residual stresses
- Prior history of the material
- Segregation
- Degenerated graphite



Source: Soivio, Elmquist, 2011

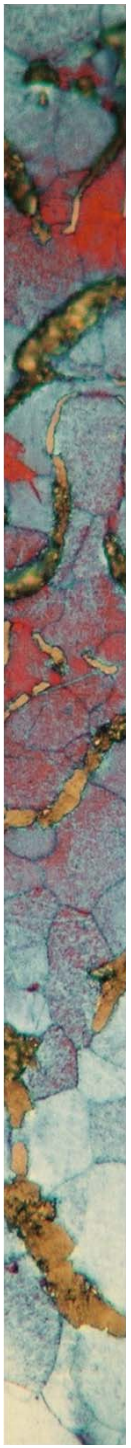


Source: Elmquist



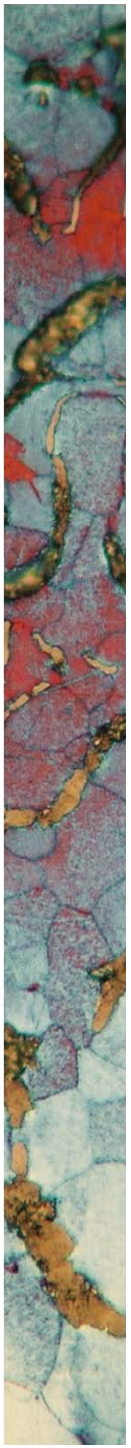
What About Future?

- Inspection/detection
  - Most of the problems never reach the customer
- Research
- Process control/thermal analysis
- Casting simulation
- Optimization
  - Many of the problems can be solved or minimized with a combination of process control and optimal design of component as well as gating system



Future

- Sustainability
  - Life cycle analysis
  - The influence of defects
- Near-net shape
  - Minimize the need for machining
- High-performing cast iron materials
  - Increased strength
  - Less variations in properties



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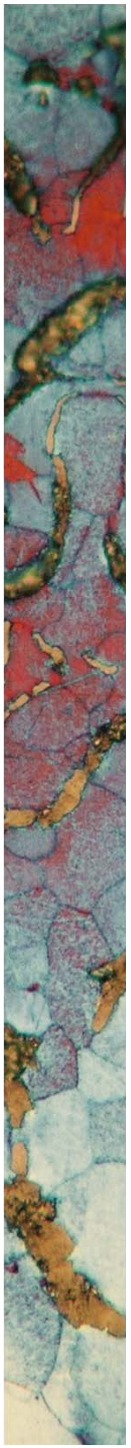


Summary

Casting

- Mould cavity
- Melting process
- Pouring
- Solidification
- Mould removal
- Cleaning and finishing

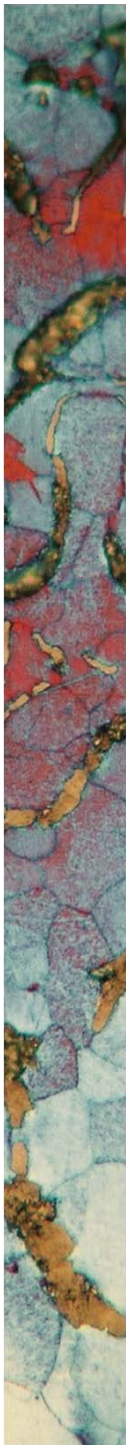
Advantages

- Complex shapes
- Holes and inner cavities
- Wide range of alloys
- Melt treatment
- Economical

Summary

Why?

Who cares?



Thank you for your attention!