Cast Stainless Steel Technology Developments

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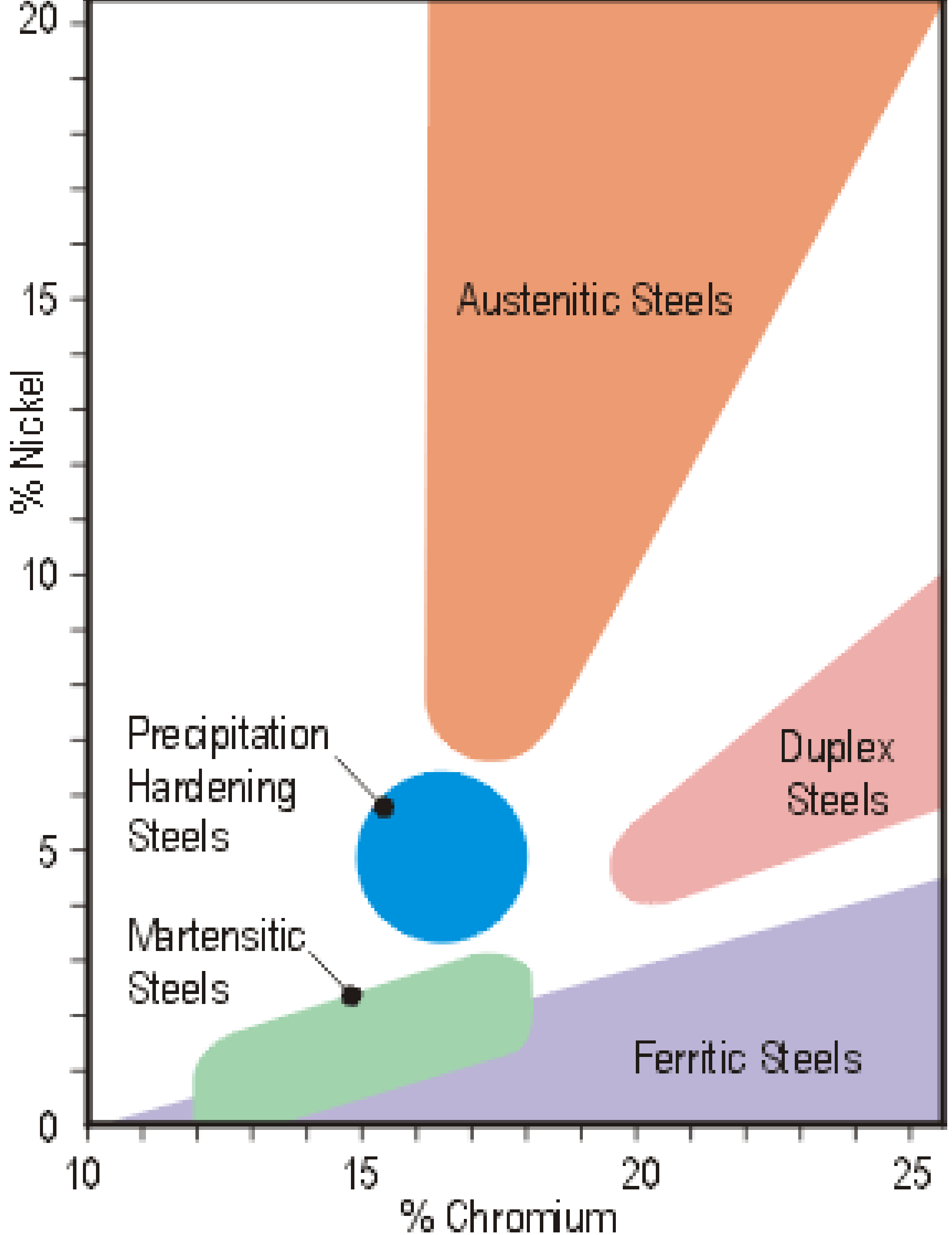

Austenitic Steels
Precipitation Hardening Steels
Duplex Steels
Martensitic Steels
Ferritic Steels
% Nickel
% Chromium
0
5
10
15
20
10
15
20
25

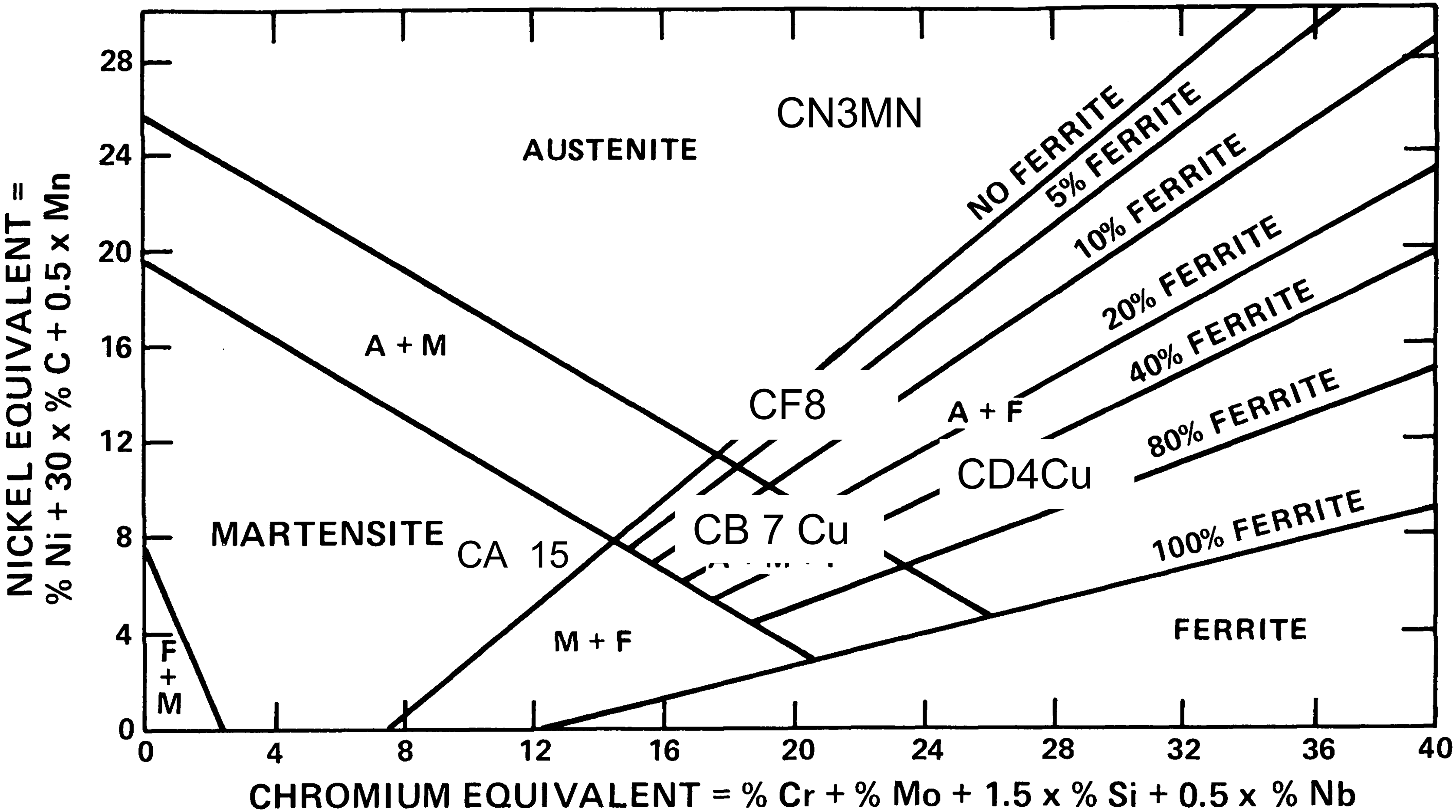
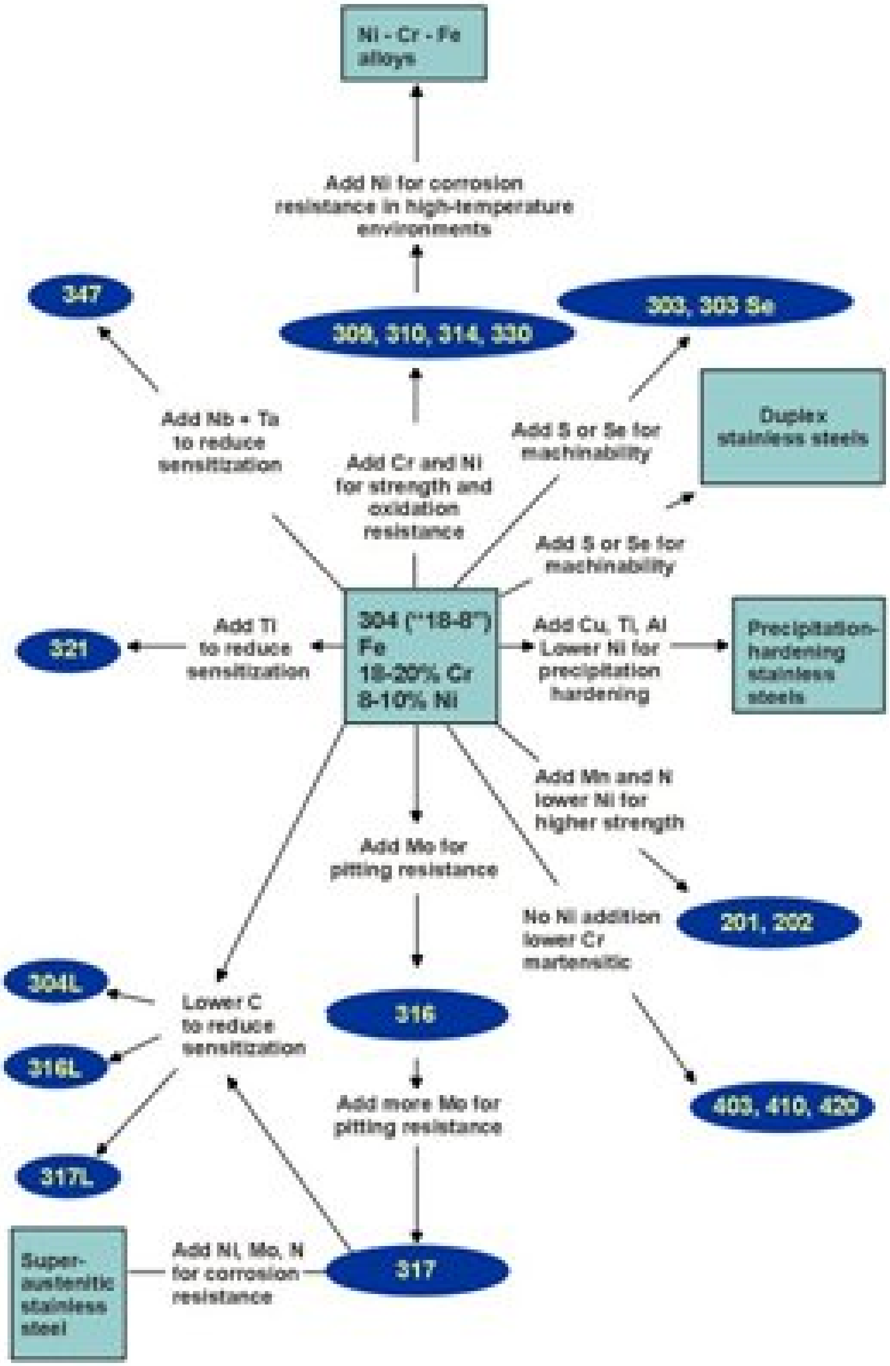


Figure 1.2 Schaeffler diagram showing the amount of ferrite and austenite present in weldments as a function of Cr and Ni eqivalents. (4)

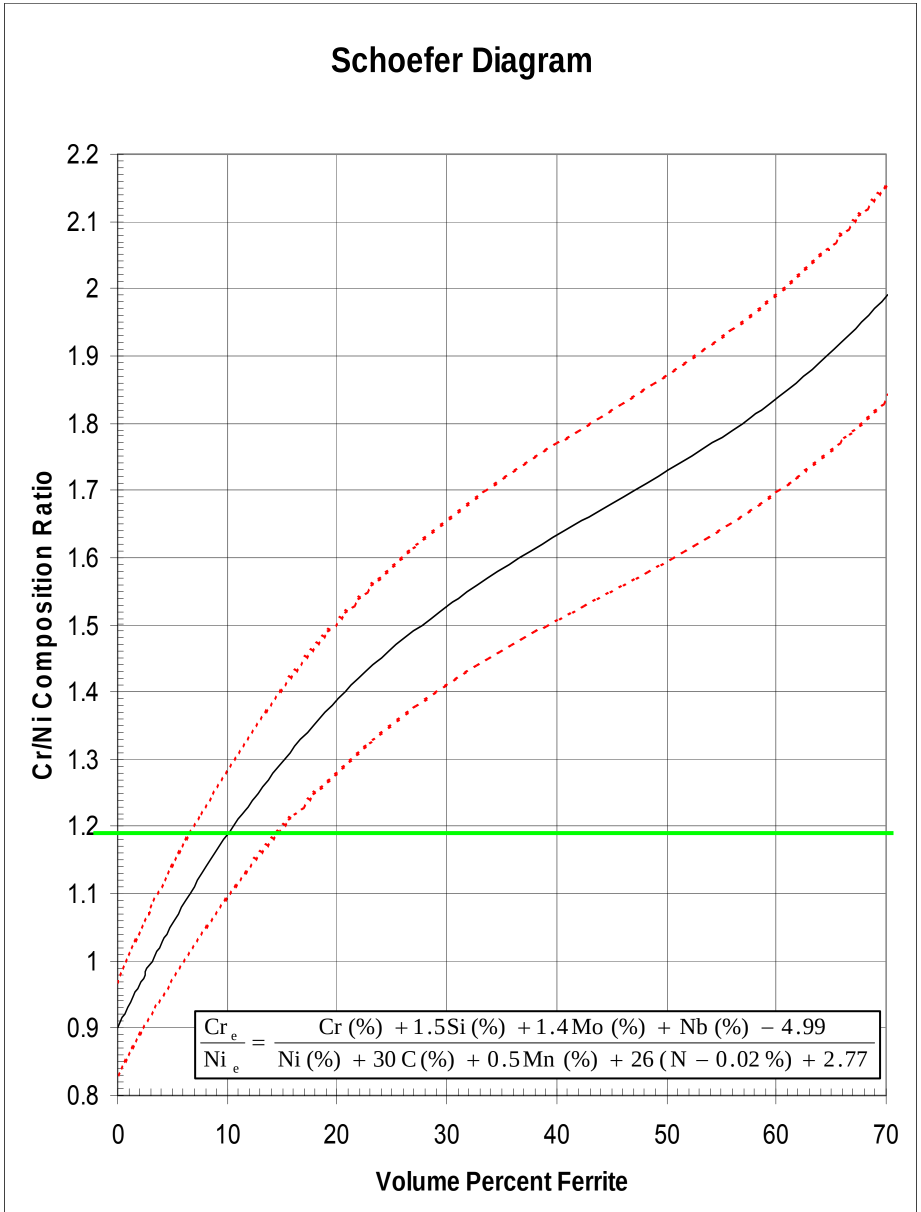

Ni - Cr - Fe alloys
Add Ni for corrosion resistance in high-temperature environments
347
309, 310, 314, 330
303, 303 Se
Add Nb + Ta to reduce sensitization
Add Cr and Ni for strength and oxidation resistance
Add S or Se for machinability
Duplex stainless steels
Add S or Se for machinability
321
Add Ti to reduce sensitization
304 ("18-8") Fe 18-20% Cr 8-10% Ni
Add Cu, Ti, Al Lower Ni for precipitation hardening
Precipitation-hardening stainless steels
Add Mn and N lower Ni for higher strength
Add Mo for pitting resistance
No Ni addition lower Cr martensitic
201, 202
304L
Lower C to reduce sensitization
316
316L
Add more Mo for pitting resistance
403, 410, 420
317L
Super-austenitic stainless steel
Add Ni, Mo, N for corrosion resistance
317

Calculation of Chromium Equivalent and Nickel Equivalent

$$Cr_E = \%Cr + 2 \times \%Si + 1.5 \times \%Mo + 5 \times \%V$$

$$Ni_E = \%Ni + 0.5 \times \%Mn + 30 \times \%C + 0.3 \times \%Cu$$

Ferrite from Chemistry



- Chemistry: C=0.07, Mn=0.56, Si=1.30, P=0.028, S=0.009, Cr=19.5, Ni=10.7, Mo=2.18 (Cb ~ 0.05 and N ~ 0.04)
- ASTM A800 predicts 10.5 volume percent ferrite with a range of 6.5 to 14.5 (chromium equivalent to nickel equivalent = 1.19)

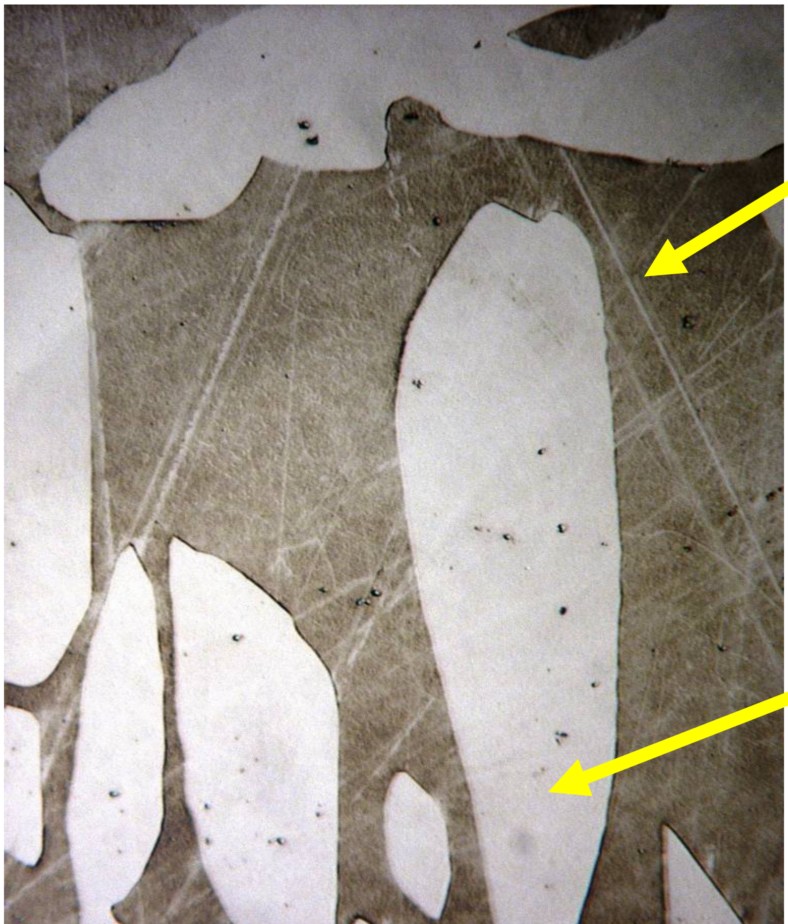
Means of Calculating Ferrite

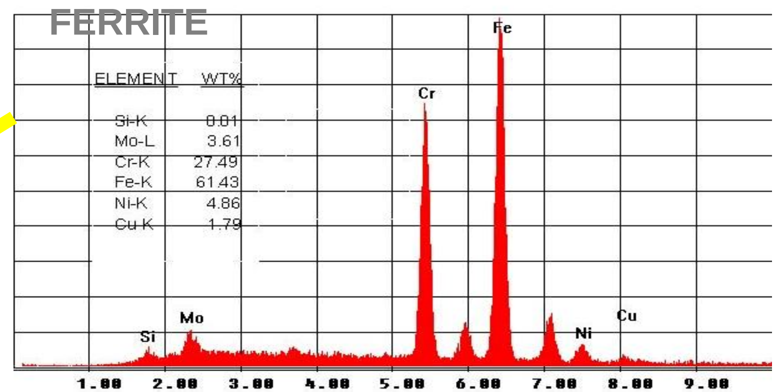
- Severn Gage: 11
- Feritscope: 7
- Magne-Gage: 2
- *Two different instruments*: 5
- Manual point count
- ASTM A800
- 1949 Schaeffler Diagram
- WRC Diagram

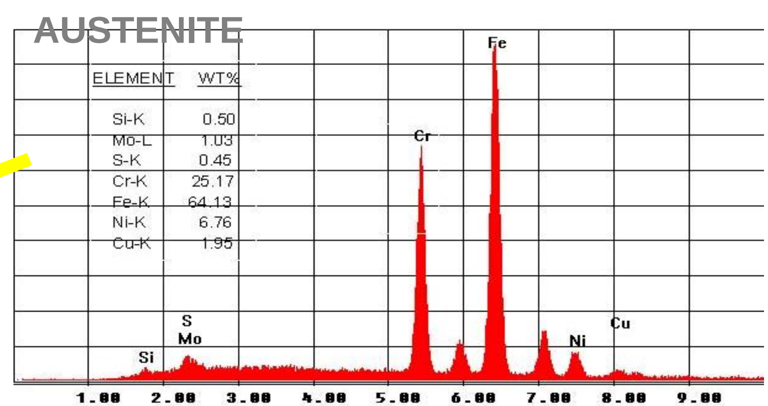
Unit of measure:

- FN: 8 (all 4 of the non-foundry)
- Volume percent: 7
- *Use both methods*: 2

Identification of Phases by Composition







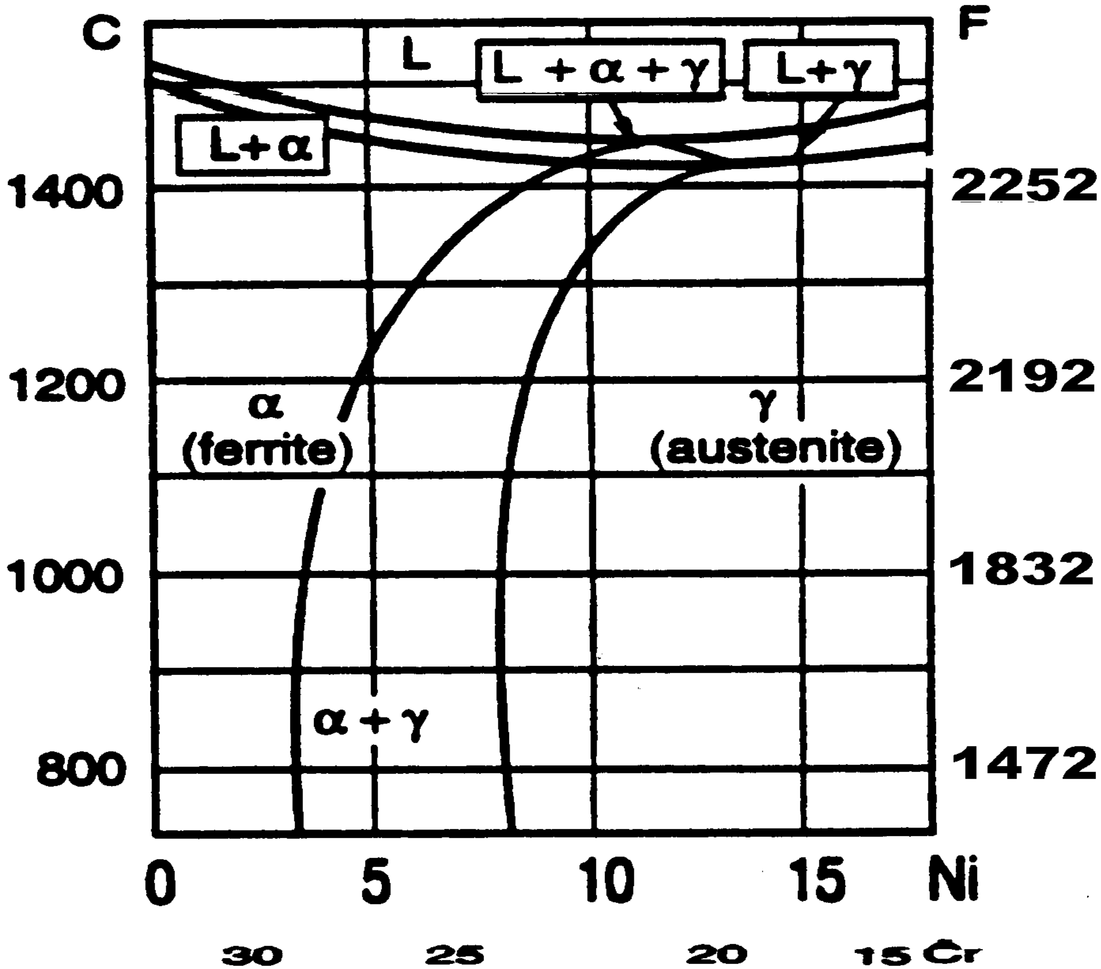
Stainless Steels - Strength

Grade	Yield (ksi)	UTS (ksi)
CF8	70	30
CF3MN	75	37
4A(2205)	90	60
6A(Zeron 100)	100	65

Stainless Steel - Corrosion

Grade	Critical pitting temperature ^{o}C
CF8	5 (calculated)
CF3MN	29 (calculated)
4A(2205)	35 - 40
6A(Zeron100)	45 – 55

Pseudo Phase Diagram for 68 % Fe – Cr Ni



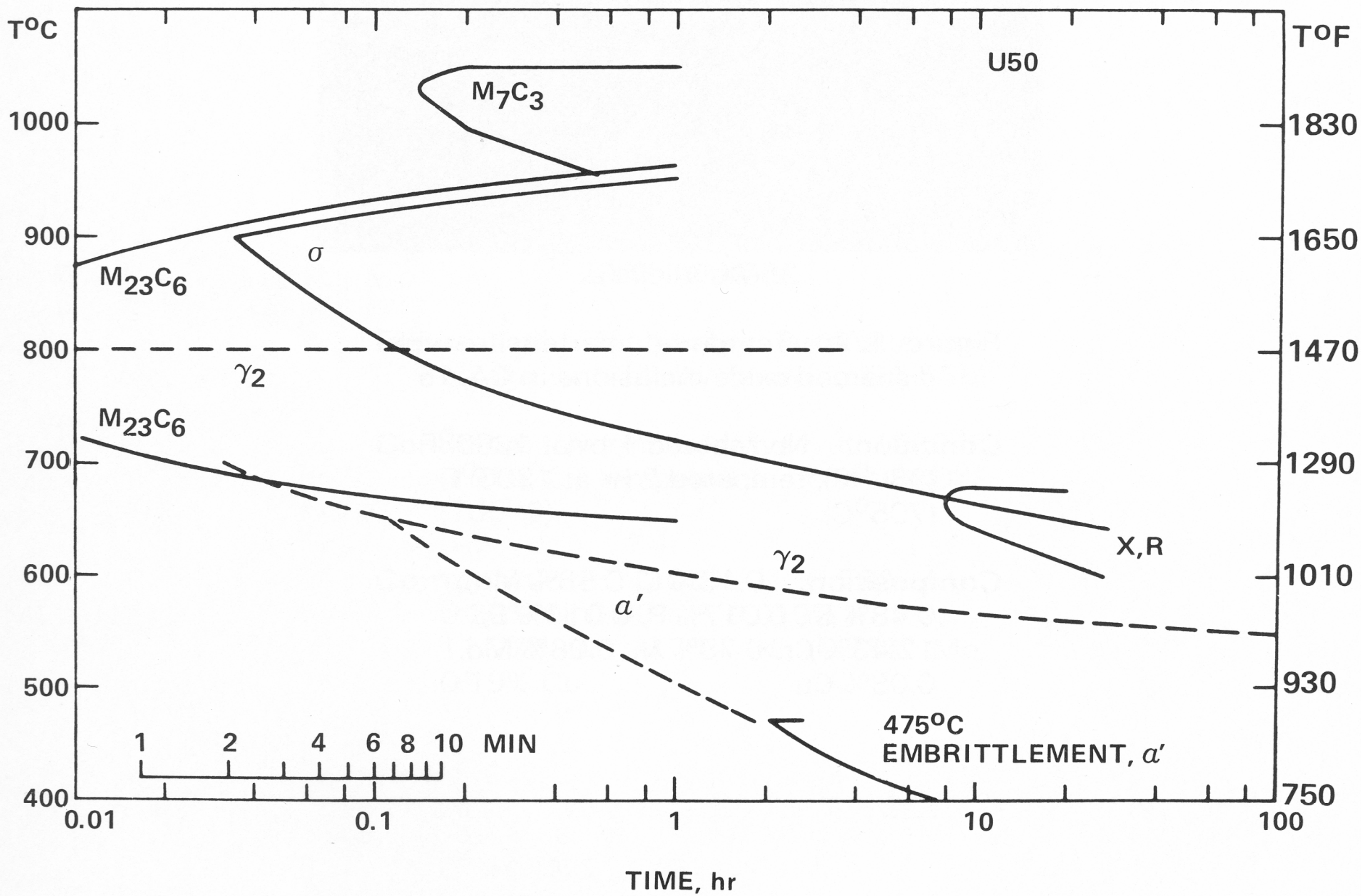
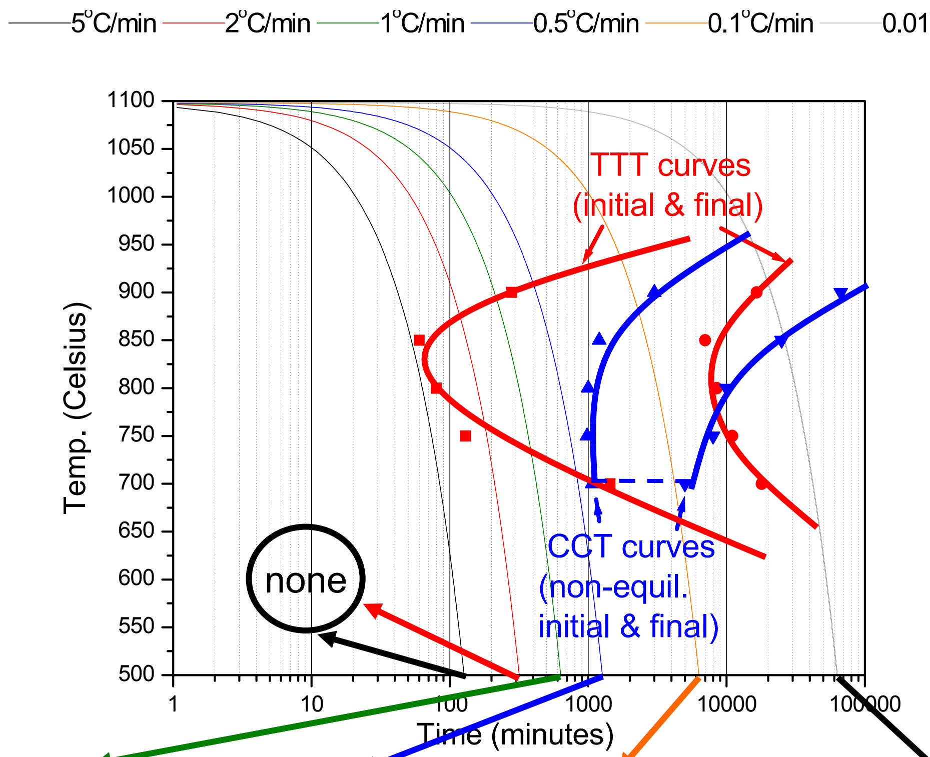
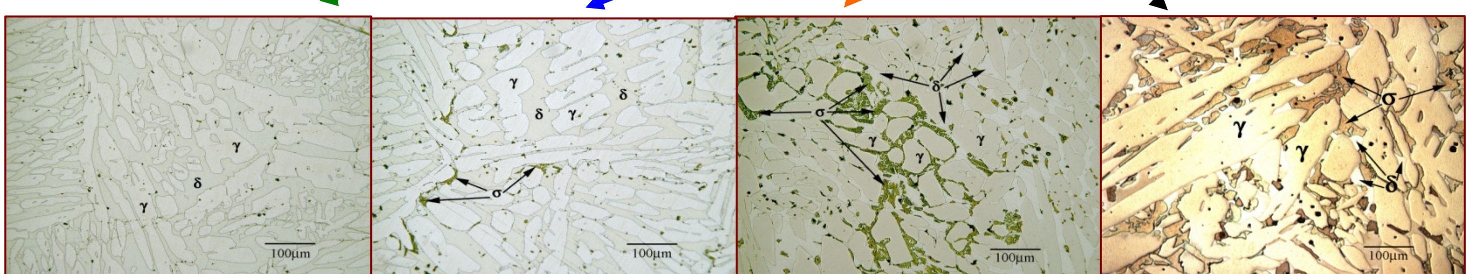


Figure 1.6 Temperature-time precipitation curves for various phases observed in alloy U50. (9)

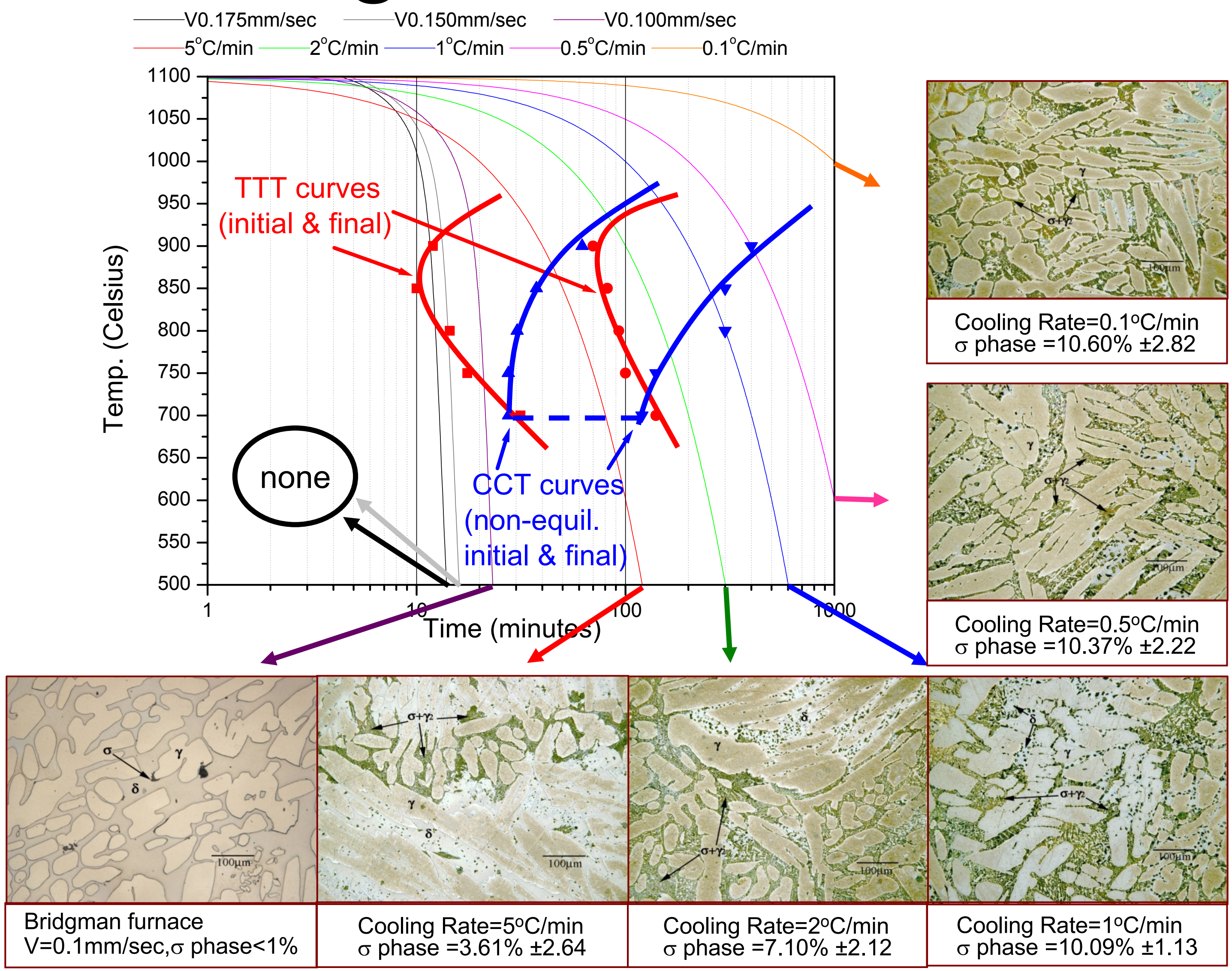
CCT Diagram - CD3MN





Cooling Rate=1°C/min, σ phase <<1%	Cooling Rate=0.5°C/min σ phase <1%	Cooling Rate=0.1°C/min σ phase =8.72% ±3.38	Cooling Rate=0.01°C/min σ phase =17.62% ±3.46

CCT Diagram - CD3MWCuN



Cooling Rate=0.1°C/min
σ phase =10.60% ±2.82

Cooling Rate=0.5°C/min
σ phase =10.37% ±2.22

Bridgman furnace
V=0.1mm/sec,σ phase<1%

Cooling Rate=5°C/min
σ phase =3.61% ±2.64

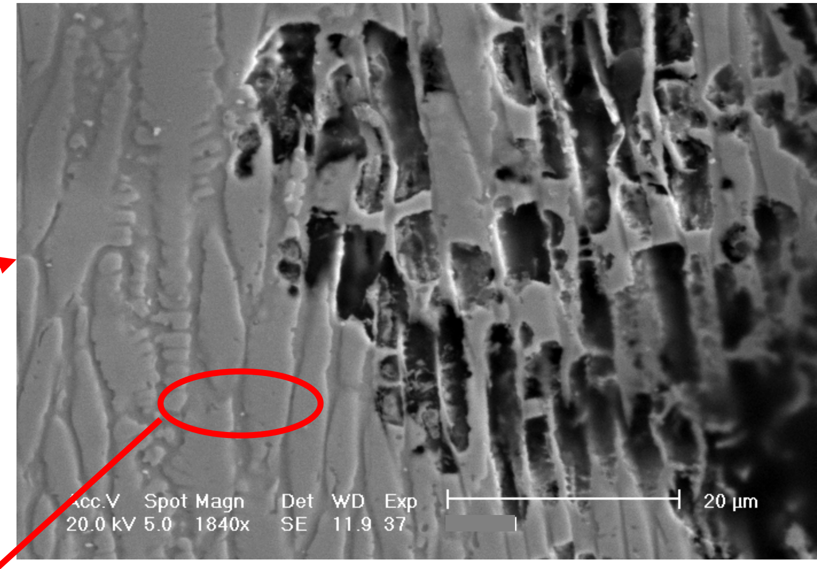
Cooling Rate=2°C/min
σ phase =7.10% ±2.12

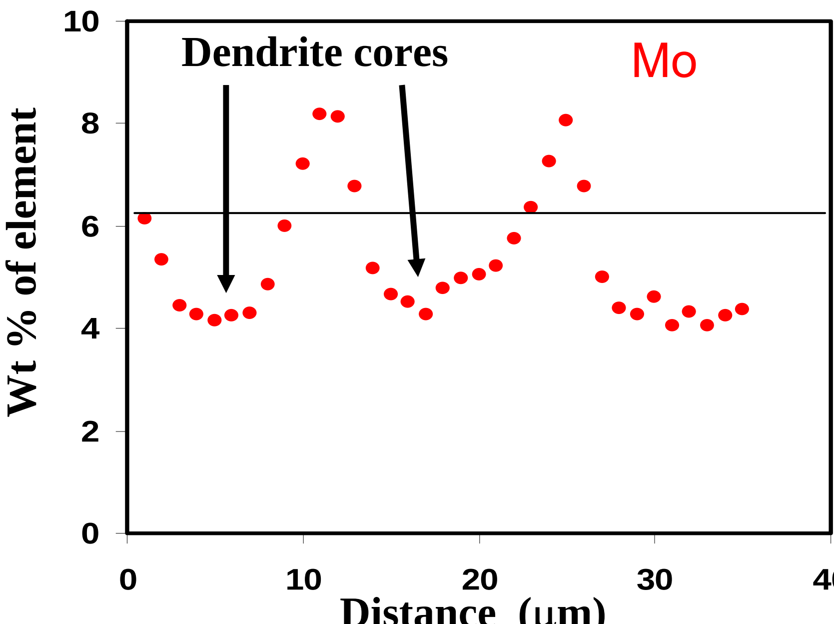
Cooling Rate=1°C/min
σ phase =10.09% ±1.13

PROBLEM - Corrosion of High Alloy (6 wt% Mo) Stainless Steel Castings

AL6XN

CN3MN
1150ºC/4 hrs





Current minimum required heat treatment

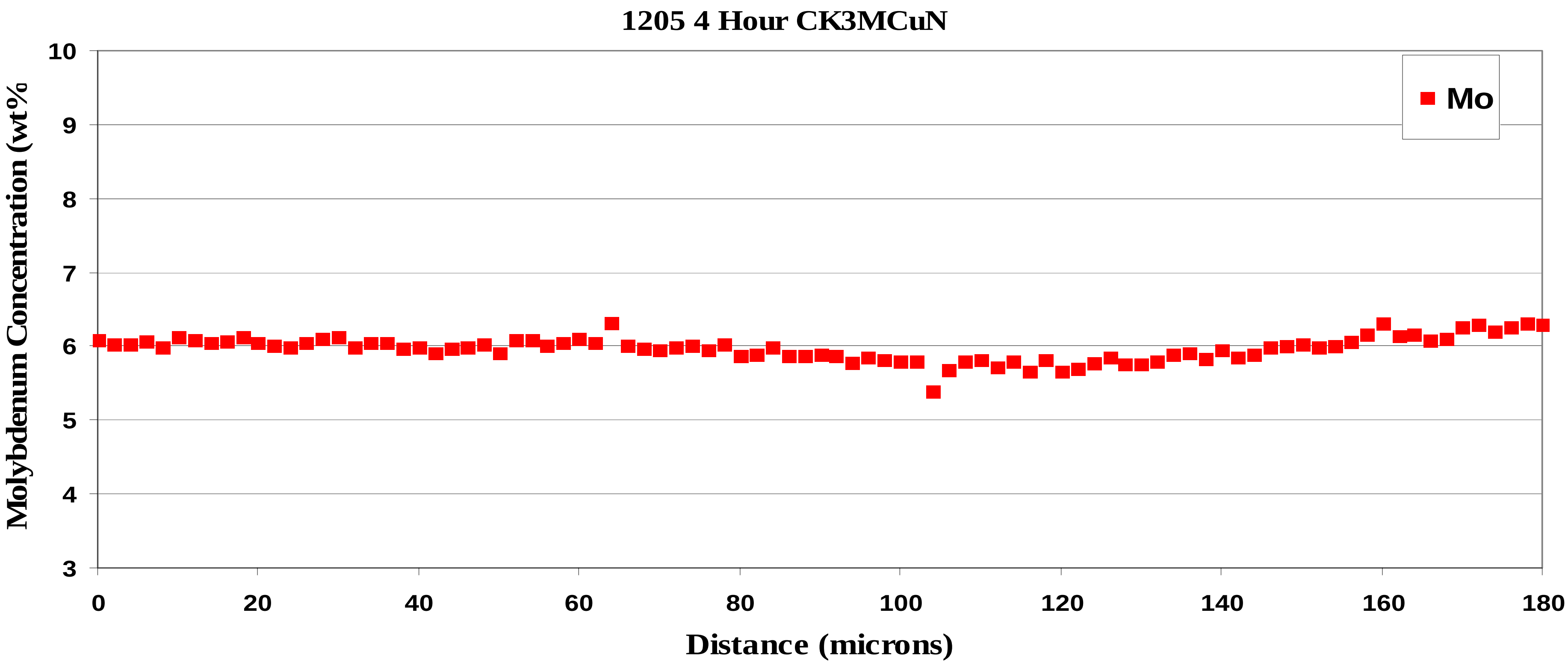
- 1150 °C/ 1hr (ASTM Standards A743 and A351)

Cast alloys and welds not as corrosion resistant due to:

- microsegregation
- presence of σ phase

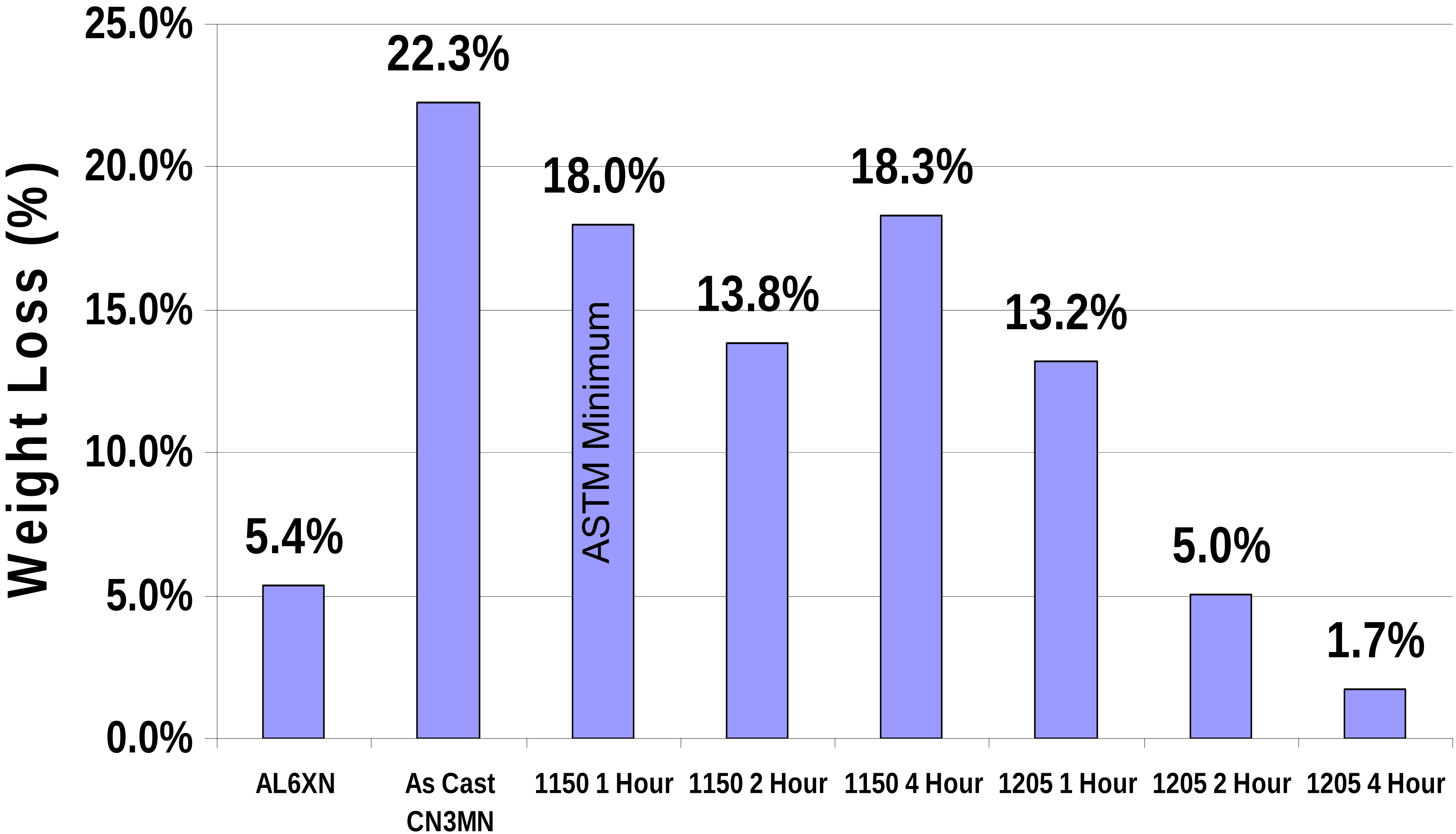
OBJECTIVE: Develop heat treating schedules and welding procedures that restore the corrosion resistance of castings and welds to a level comparable to that of wrought counterpart alloys

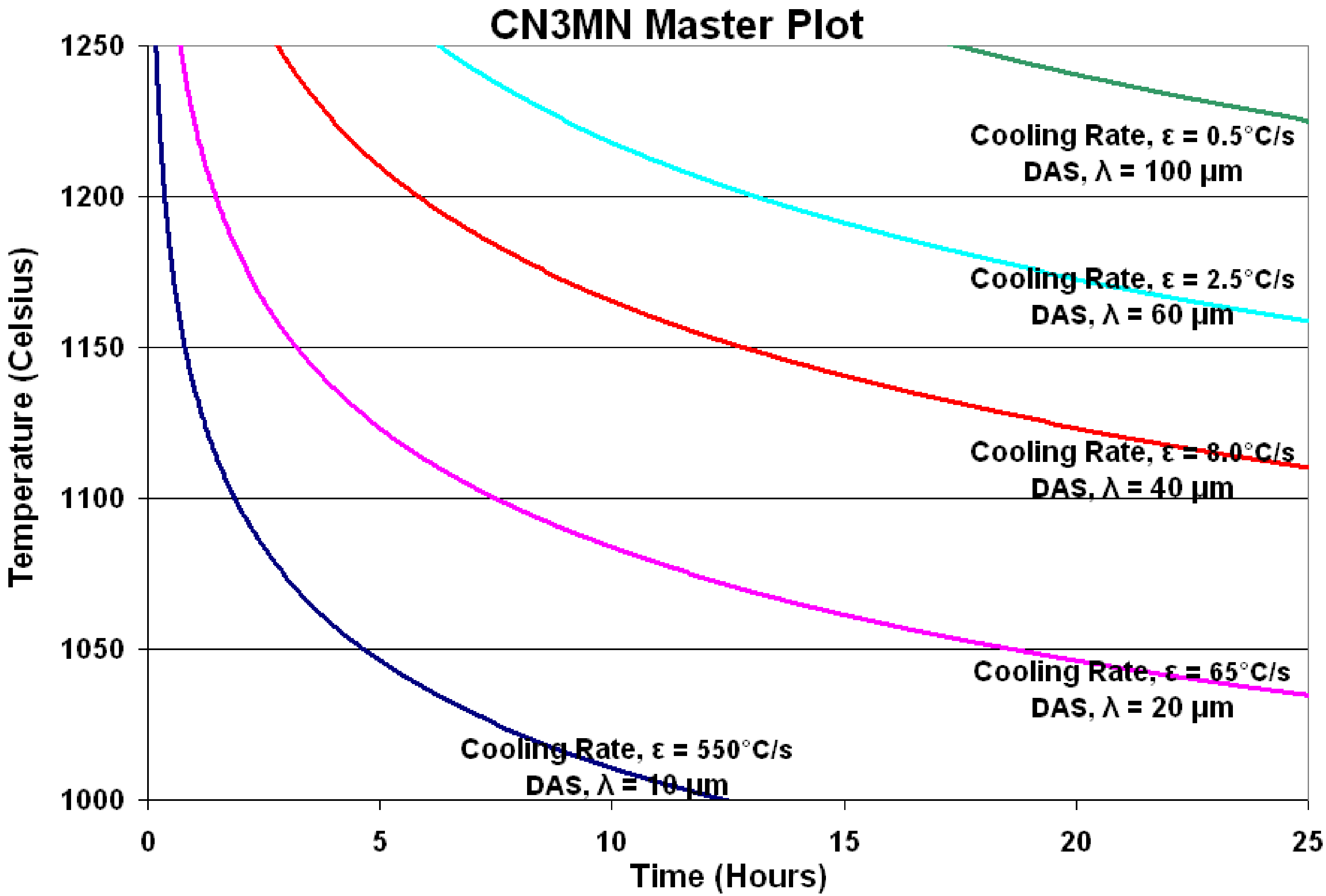
Typical Homogenization Results



- **1205 °C/4 hours needed for complete homogenization**

CN3MN Corrosion Results – ASTM G48A



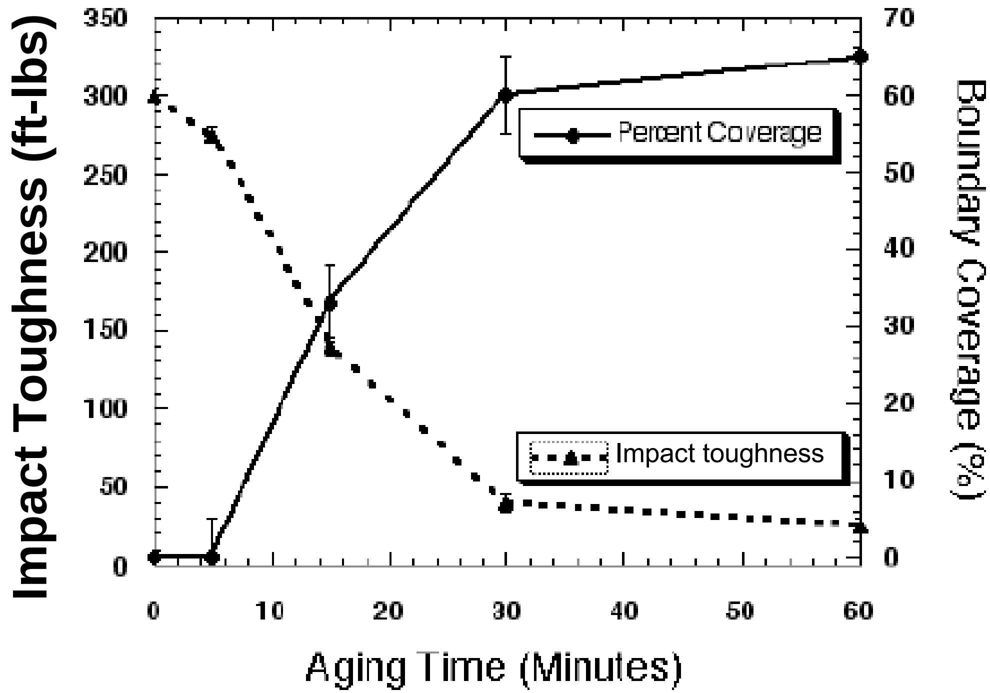


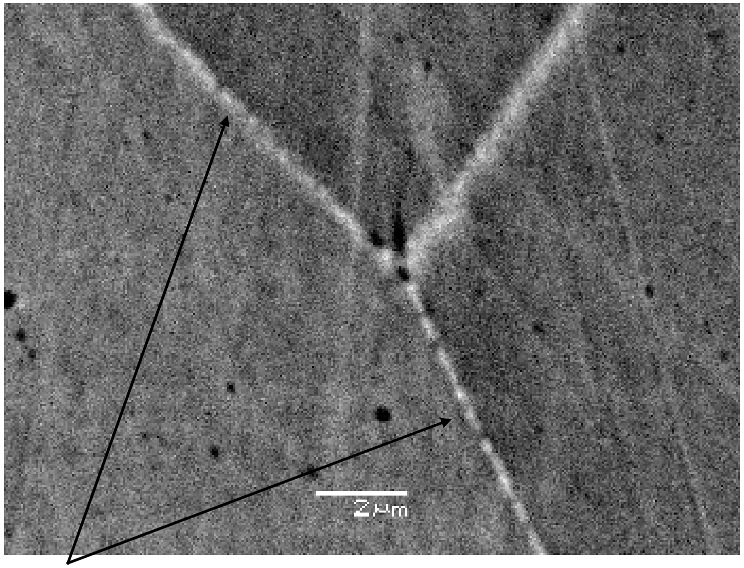
$$\lambda = 80\varepsilon^{-0.33}$$

Model can be used as a predictive tool to determine effective heat treatment times for CN3MN prepared with various cooling rates

Need to establish acceptable cooling rate from the heat treating temperature to avoid formation of brittle secondary phase
Collaboration with Scott Chumbley (Iowa State)

Results from C. Muller and Scott Chumbley, Iowa State University



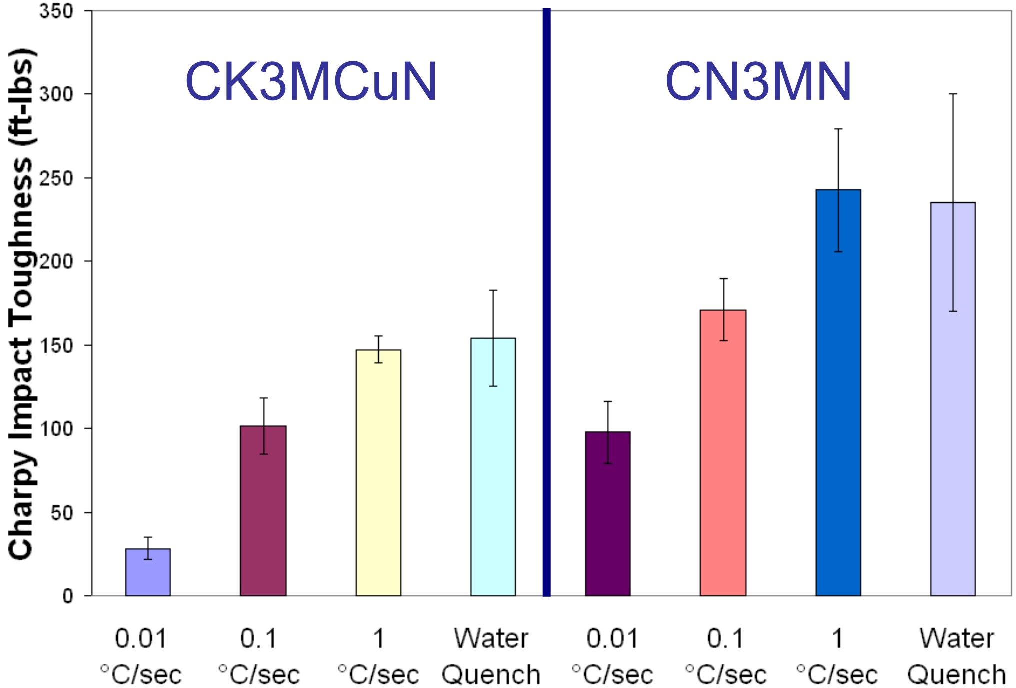


Grain boundary precipitates

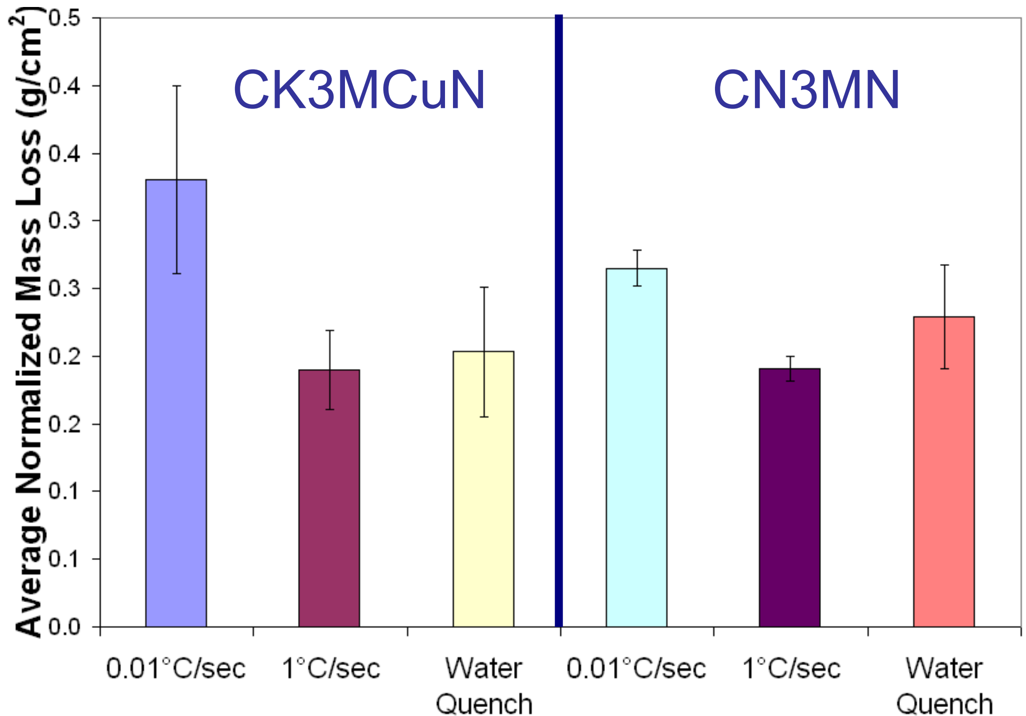
Impact toughness decreases significantly with time at 870 °C, which could occur for large castings cooled slowly from the heat treating temperature

Need to establish critical cooling rates in order to avoid embrittlement.

Toughness and Corrosion Performance



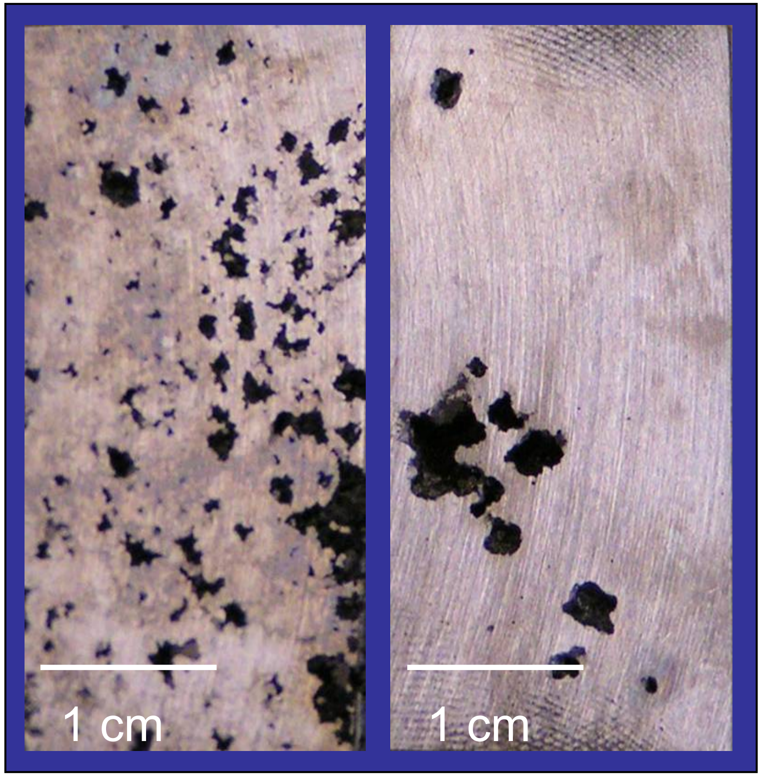
- Charpy Impact Toughness decreases significantly with an extremely slow cooling rate (0.01°C/sec)
- Charpy Impact Toughness is unaffected by cooling rate above 1°C/sec



- Corrosion Performance decreases at an extremely slow cooling rate (0.01°C/sec)
- Corrosion Performance is unaffected by cooling rate above 1°C/sec
- Slow cooling rate sample shows evidence of grain boundary attack

Corrosion of Welds in Super Austenitic Stainless Steel Castings

CN3MN As-Cast | **CN3MN 1205°C/4 hrs**

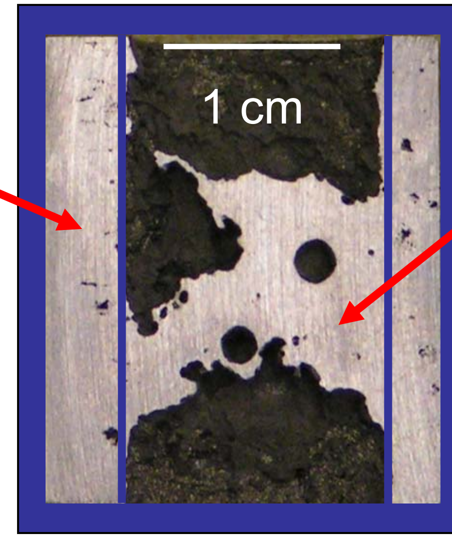


Percent Mass Loss

CN3MN As-Cast	CN3MN 1205°C/4hr
22%	2%

CN3MN 1205°C/4 hrs with Autogenous Weld

Base Metal



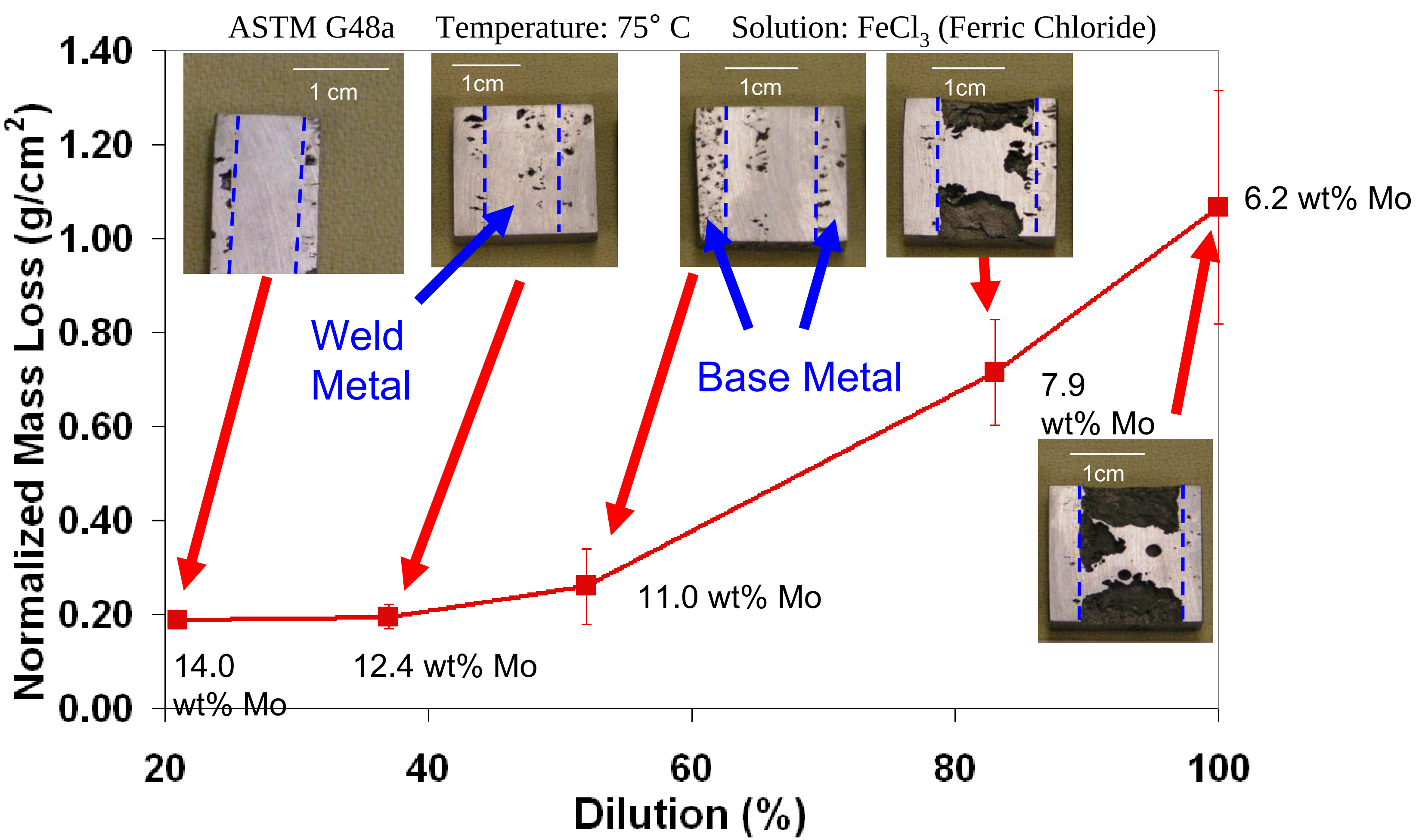
Weld

Welding reintroduces the microsegregation profile

Percent Mass Loss

CN3MN 1205°C/4hr with Autogenous Weld
14%

Corrosion Resistance as a Function of Dilution
(IN686 Filler Metal Welds on CN3MN)

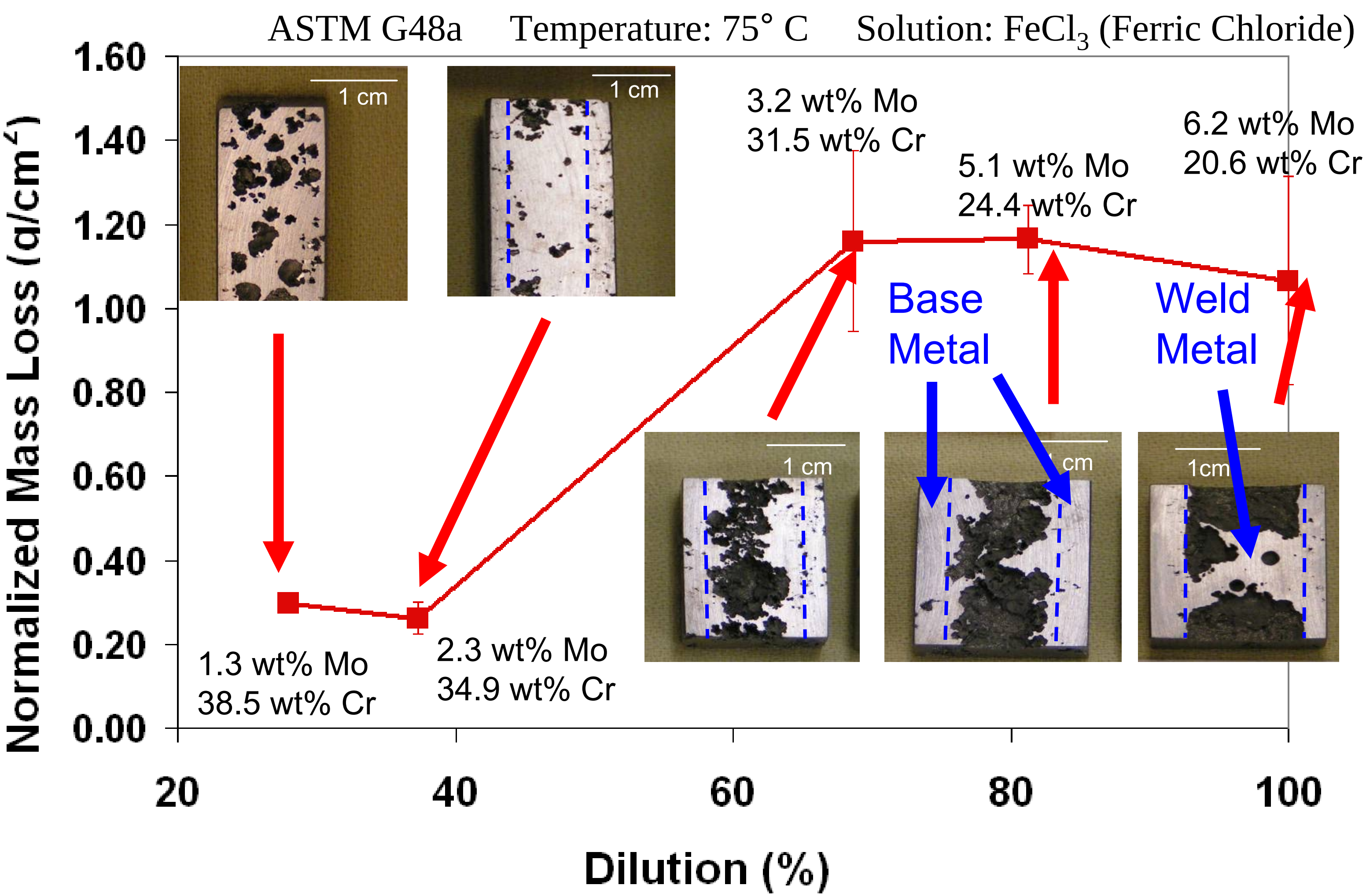


Corrosion performance increases with decreasing dilution level

Corrosion performance of weld can restored to level of cast material at dilution levels below ~ 50%

Corrosion Resistance as a Function of Dilution

(IN72 Filler Metal Welds on CN3MN)



Corrosion performance increases with decreasing dilution level
IN72 Filler metal unable to avoid localized corrosion in weld

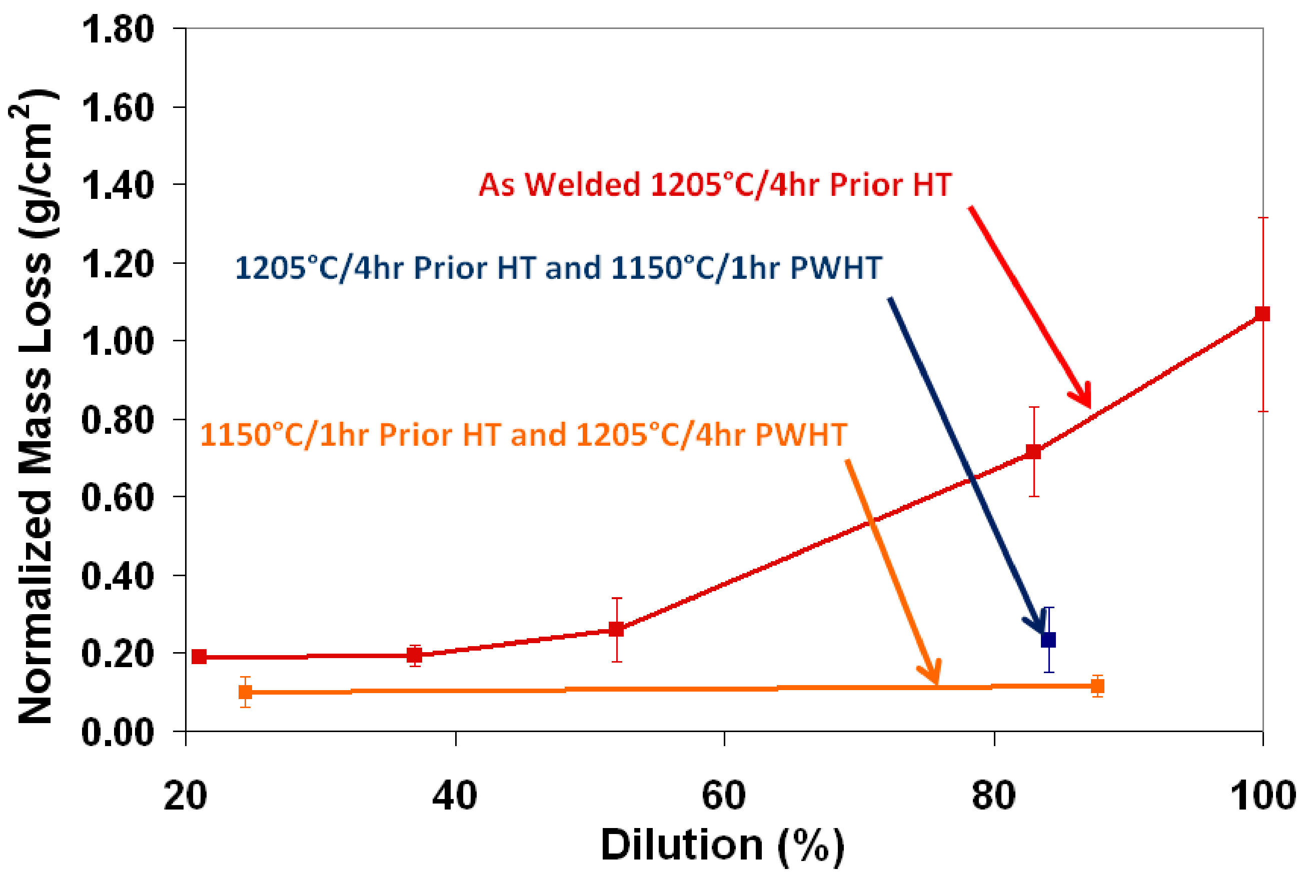
Corrosion Results: IN686 Filler Metal

Heat Treatments have a significant effect on corrosion performance

Post weld heat treatments (PWHT) will mitigate negative effects of dilution

Heat treatments should be done after welding, if possible (no need to control dilution)

Post Weld Heat Treatment at 1205°C/4hr produces the best corrosion resistance



Air-Set Pouring

Nondestructive Examination

- Surface
  - Visual
  - Magnetic particle examination (MT)
  - Liquid penetrant examination (PT)
- Volume
  - Radiographic examination (RT)
  - Ultrasonic examination (UT)

Examination

- Visual
  - ASTM A802
  - MSS SP55
- Magnetic Particle
  - ASTM E709
  - ASTM E125
  - MSS SP53
- Liquid Penetrant
  - ASTM E165 Method
  - ASTM E433 Acceptance
  - MSS SP93

Visual Examination

- Equipment required: surface comparator, pocket rule, straight edge, workmanship standards
- Enables detection of: surface flaws – cracks, porosity, slag inclusions, adhering sand, scale, etc.
- Advantages: low cost, can be applied while work is in process to permit correction of faults
- Limitations: applicable to surface defects only, provides no permanent record
- Remarks: should always be the primary method of inspection, no matter what other techniques are required

Inspection 1 | Inspection 2

Operator 1

Casting 3

Operator 2

Foundry 3

Inspection 1

Inspection 2

Operator 1

Operator 2

Liquid Penetrant Examination

- Equipment required: commercial kits containing fluorescent or dye penetrants and developers, application equipment for the developer, a source of ultraviolet light – if fluorescent method is used
- Enables detection of: surface discontinuities not readily visible to the unaided eye
- Advantages: applicable to magnetic and nonmagnetic materials, easy to use, low cost
- Limitations: only surface discontinuities are detectable

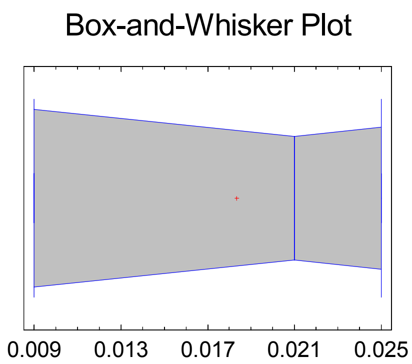
Methodology

- To determine the resolution of the process
  - Only data from a minimum of three inspections per casting for each inspector was used.
  - An indication must be detected at least 50% of the time or the data was not considered so results are a best case situation.
- The results were grouped by casting type, if multiple geometries were used, and also by inspector (to eliminate variation from inspector to inspector).
- Sample standard deviation was used as a measure of resolution.

Foundry 3

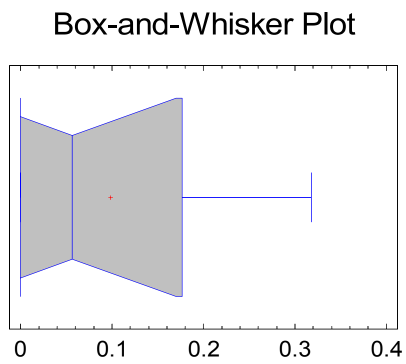
- High alloy steel, visible liquid penetrant.
- One casting shape, 10-15 lb cast weight.
- Three Inspectors.
- Twenty-four pieces per part type.
- Three runs per inspector
- Measured length and sketched location of indications on part drawing.
- A total of 216 inspections were made.

Casting Geometry 1



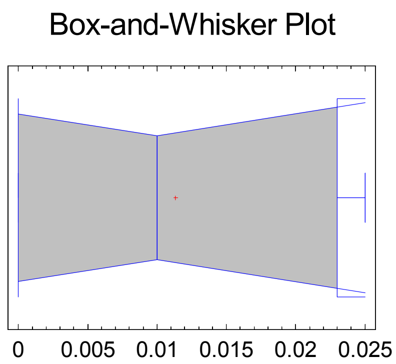
Standard Deviation

95% confidence interval for mean
0.0” to 0.04”



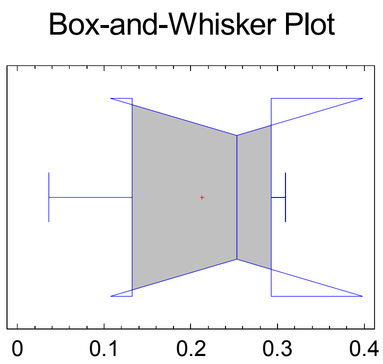
Standard Deviation

95% confidence interval for mean
0.0” to 0.2”



Standard Deviation

95% confidence interval for mean
0.0” to 0.02”



Standard Deviation

95% confidence interval for mean
0.01” to 0.5”

Punch Line – The resolution for all inspectors is about 0.4”.

Radiographic Examination

- Equipment required: commercial x-ray or gamma units made especially for inspecting welds, castings, and forgings with film and processing facilities
- Enables detection of: internal macroscopic flaws – cracks, porosity, blow holes, non-metallic inclusions, shrinkage, etc.
- Advantages: when the indications are recorded on film, gives a permanent record
- Limitations: cracks difficult to detect, requires safety precautions, requires skill in choosing angles of exposure, operating equipment, and interpreting indications
- Remarks: radiographic inspection is required by many codes and specifications, useful in qualification of processes, its use should be limited to those areas where other methods will not provide the assurance required because of cost

Results for Unanimous Agreement in X-Ray Ratings

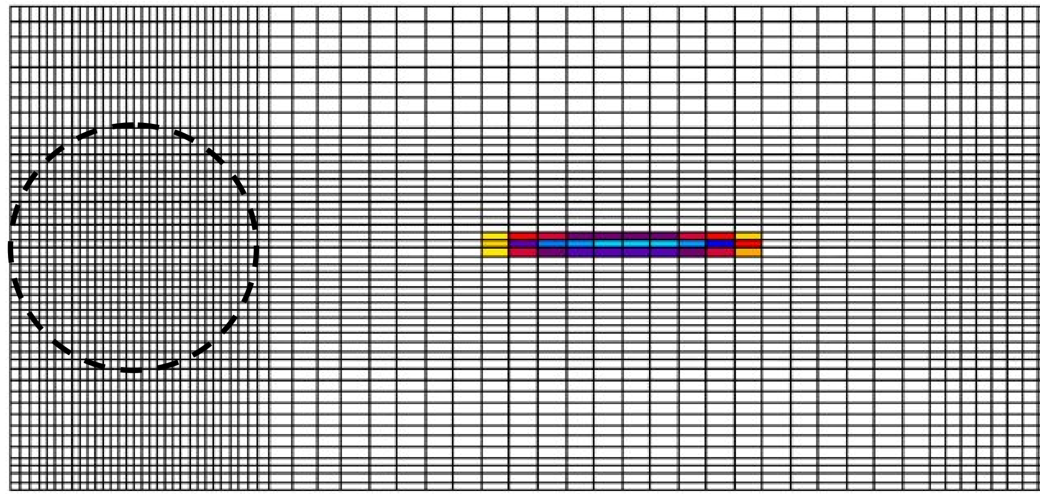
- **Unanimous agreement in shrinkage type: 37% (47/128)**
  - 14 Level 0 (no type)
  - 20 CB
  - 7 CA
  - 6 CC
- **Unanimous agreement in shrinkage level: 17% (22/128)**
  - 14 Level 0
  - 1 Level 1
  - 1 Level 2
  - 1 Level 3
  - 5 Level 5
- **Unanimous agreement in level and type: 12.5% (16/128**)
  - 14 Level 0
  - 2 CB5

Casting Simulation

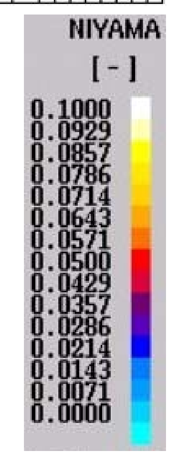
– Each trial plate was simulated with recorded casting conditions

– Niyama values (*Ny*) were measured

- minimum *Ny*
- area of *Ny* $< 0.1\ (\mathrm{K\text{-}s})^{1/2}\mathrm{mm}^{-1}$



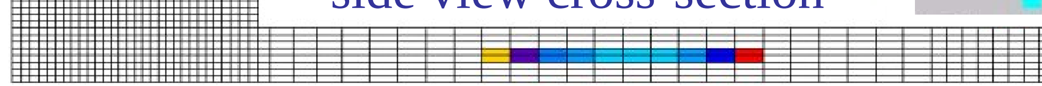
top view cross-section



$$Ny = \frac{G}{\sqrt{\dot{T}}}$$

G: temperature gradient (K/mm)

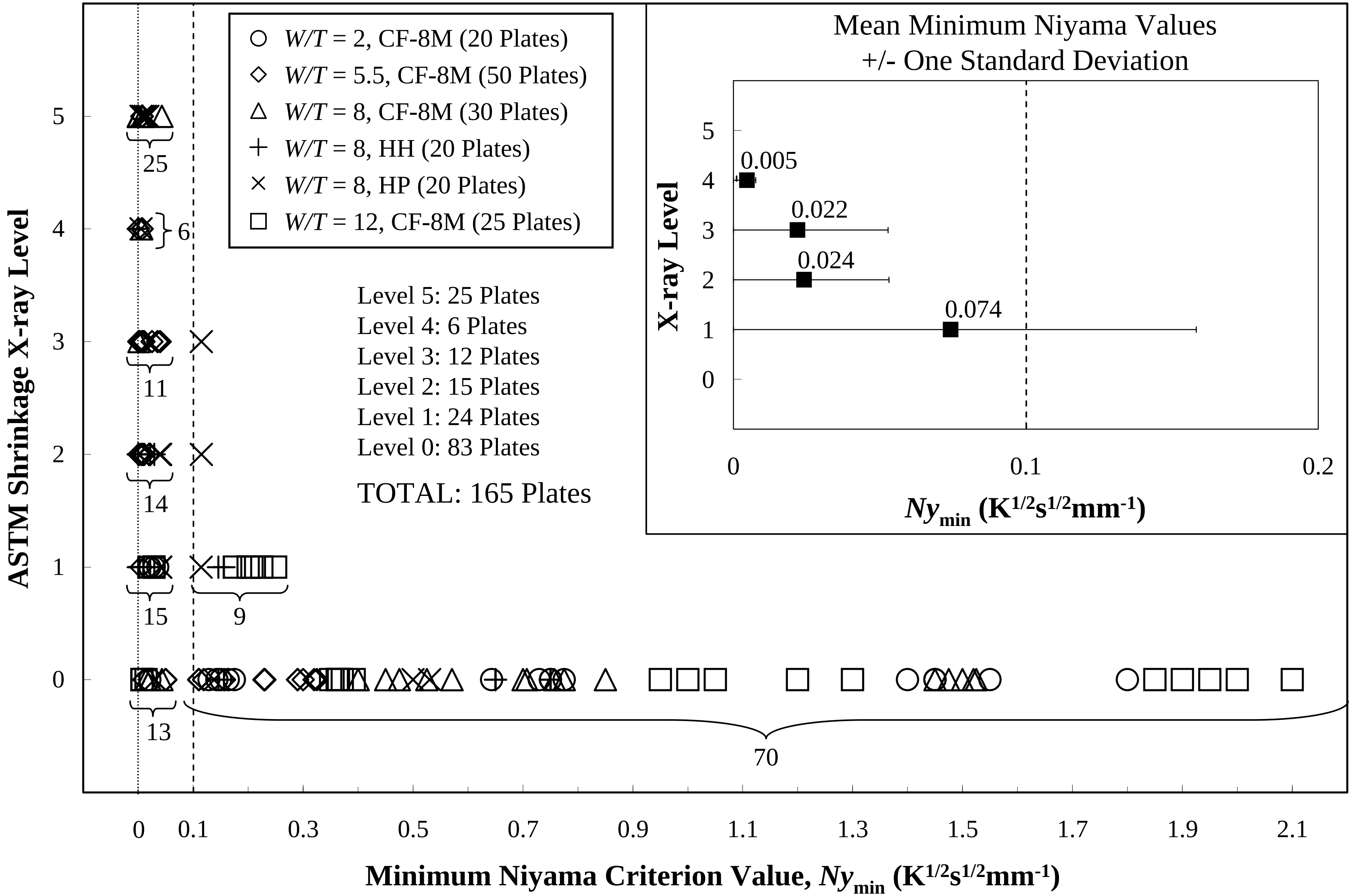
$\dot{T}$: cooling rate (K/s)



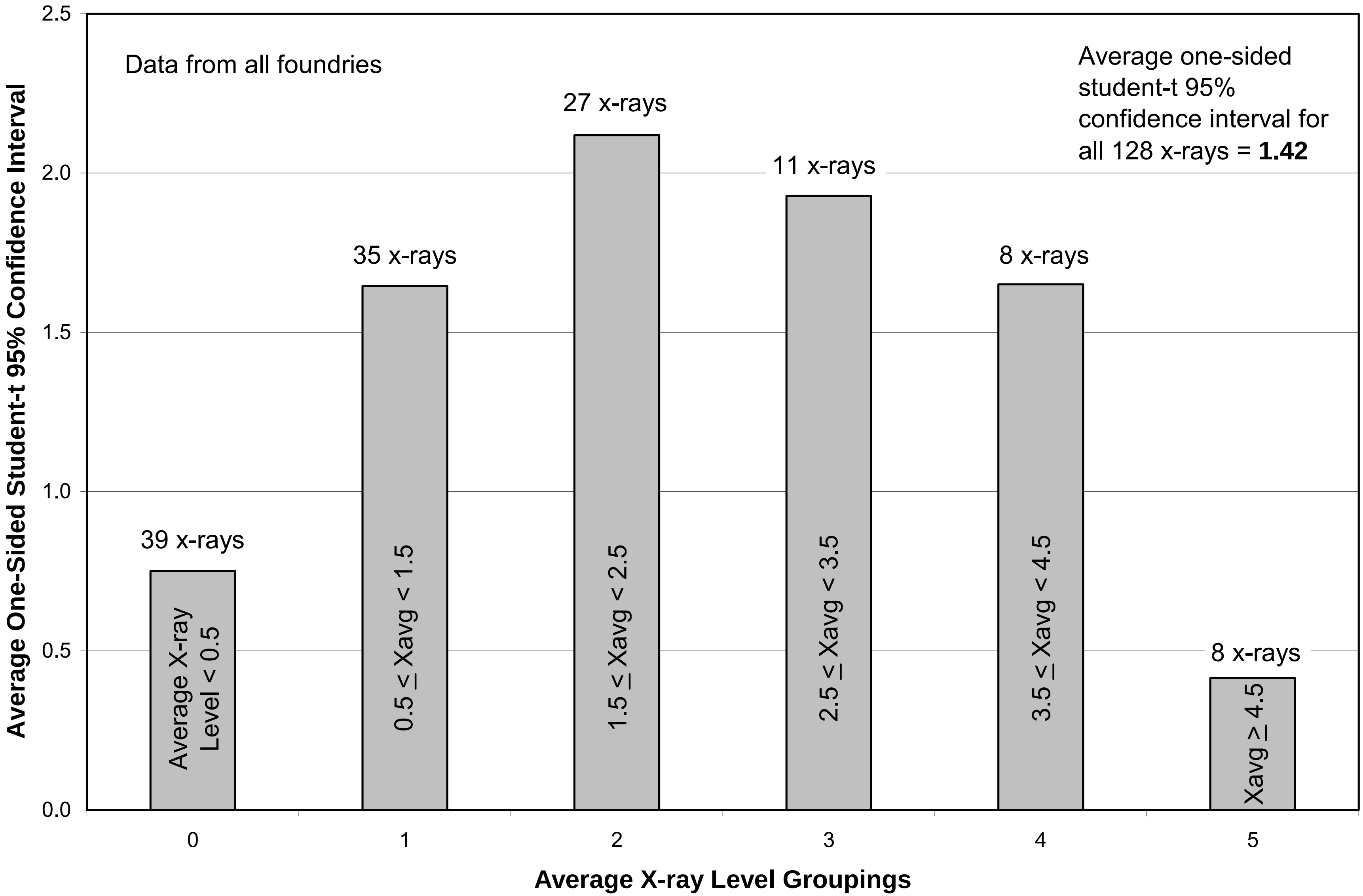
side view cross-section

Casting Simulation

– Combine trial and simulation results:

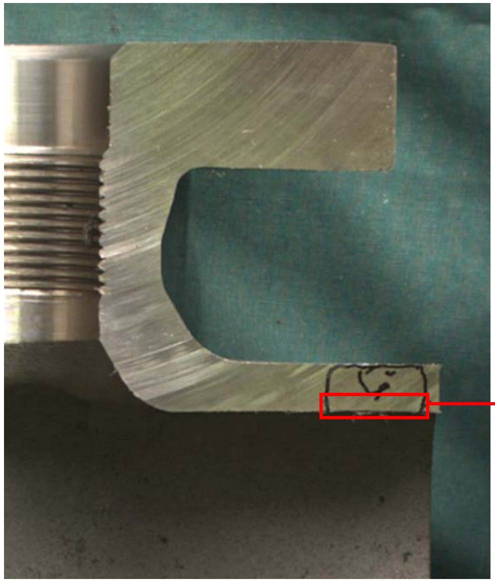


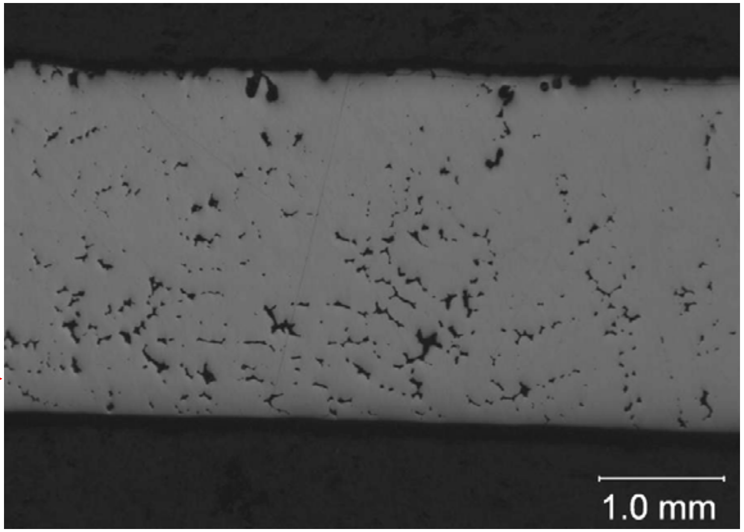
Variation in the Ratings:
Confidence intervals of x-ray level ratings grouped by average x-ray level



Background

- The root cause of leaks in fluid-containing castings can be shrinkage porosity that extends through a wall.
- Sometimes, porosity is so small that it cannot be detected using industrial radiography.
- No method available to assure quality.

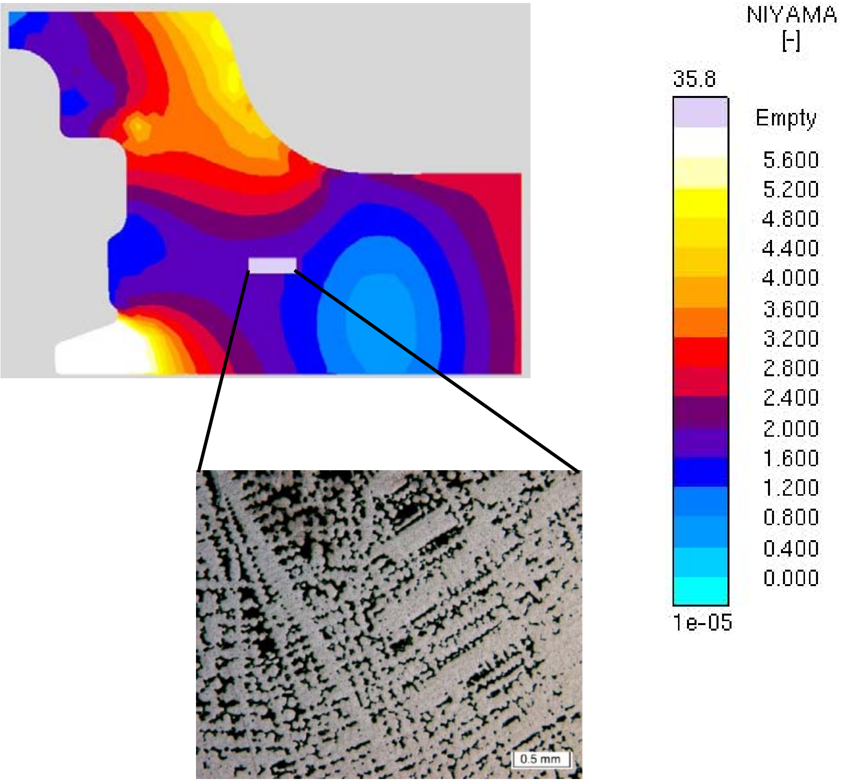




Background

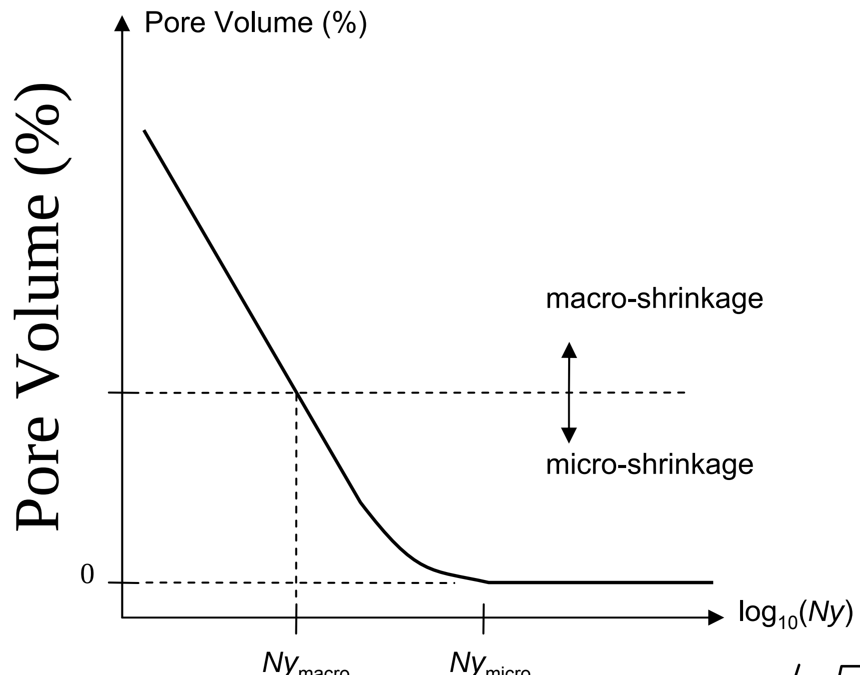
- The Niyama criterion, a common output from a casting computer simulation, can be used to predict shrinkage porosity.

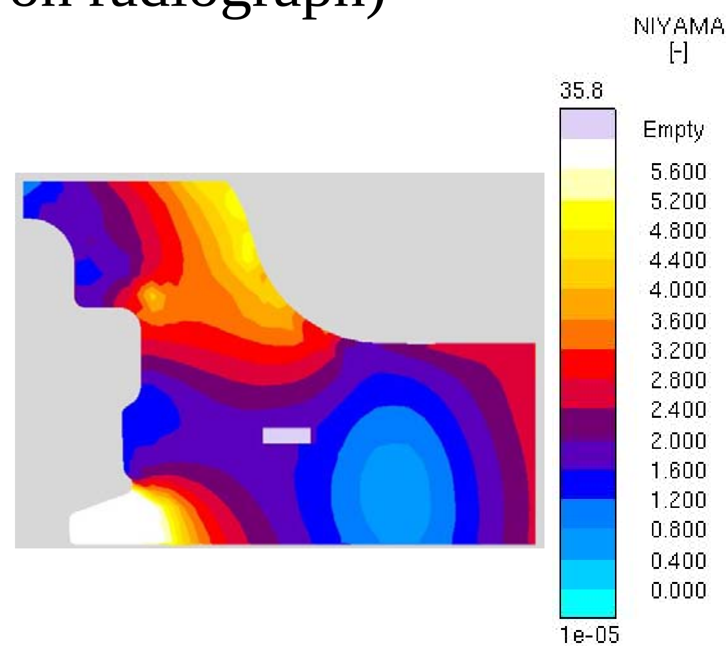
$$Ny = G \big/ \sqrt{\dot{T}}$$



Background

- What is the critical Niyama below which shrinkage porosity forms? (especially for high-Ni alloys)
  - o Micro-porosity, Ny_{micro} (not visible on radiograph)
  - o Macro-porosity, Ny_{macro} (visible on radiograph)

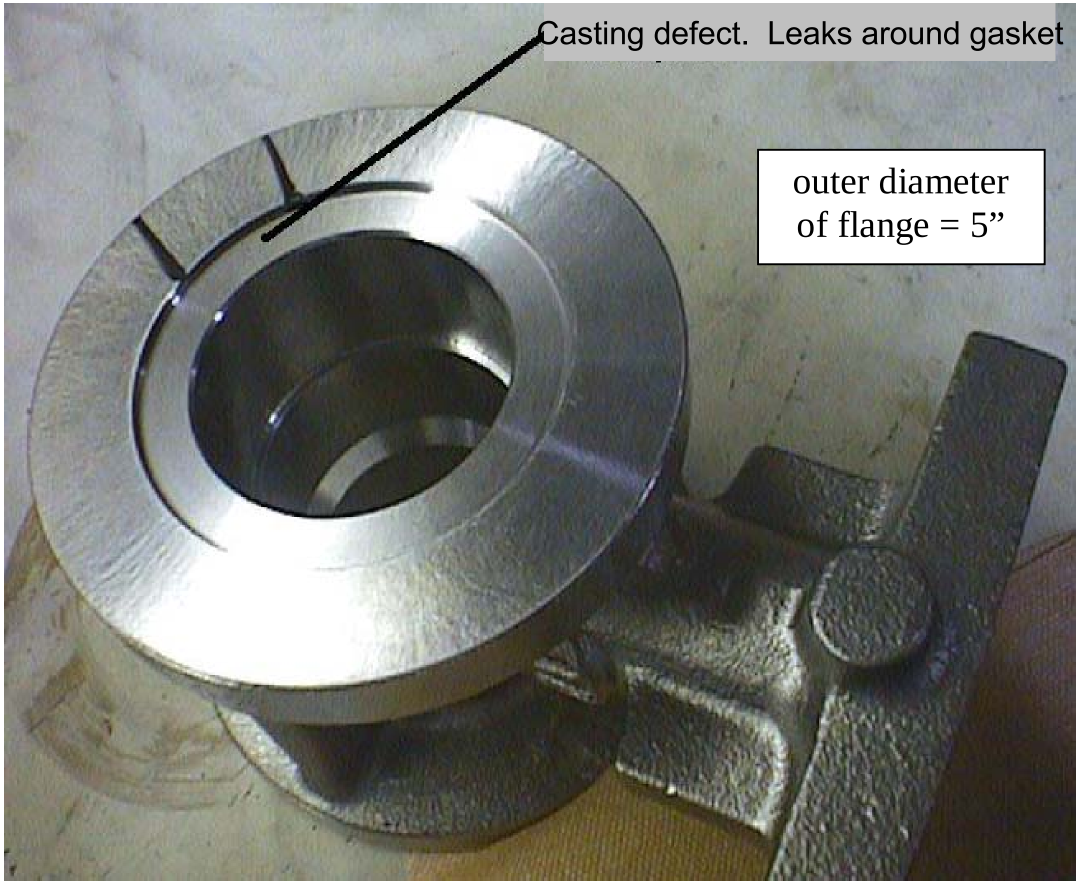




$$Ny = G\big/\sqrt{\dot{T}}$$

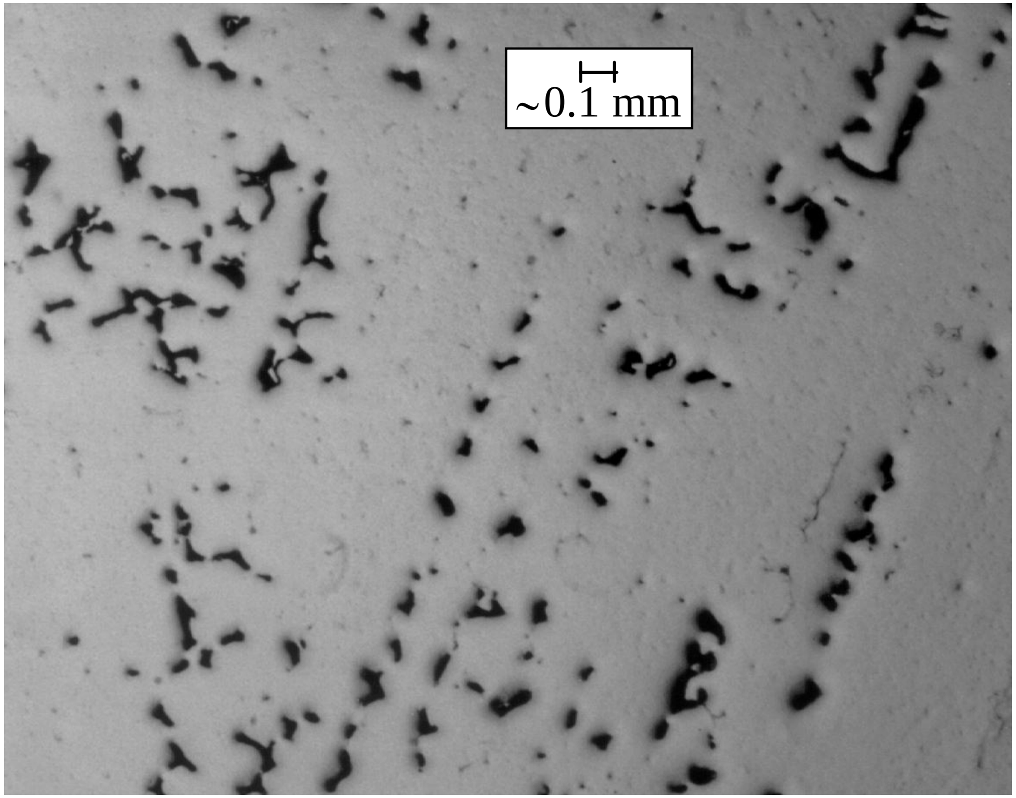
Case Study #3: Valve B

- CG8M steel valve cast in a silica sand shell mold
- After machining, 22% leaked around gasket on flange face during pressure testing
- No shrinkage visible on x-rays



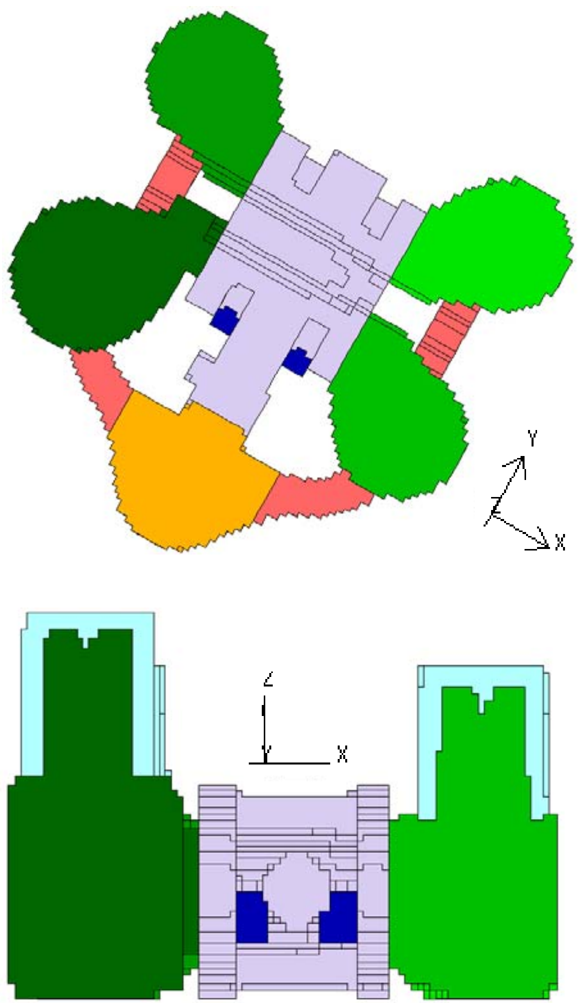
Case Study #3: Valve B

- leaking castings were sectioned, and photomicrographs were taken
- microporosity evident in leaking area

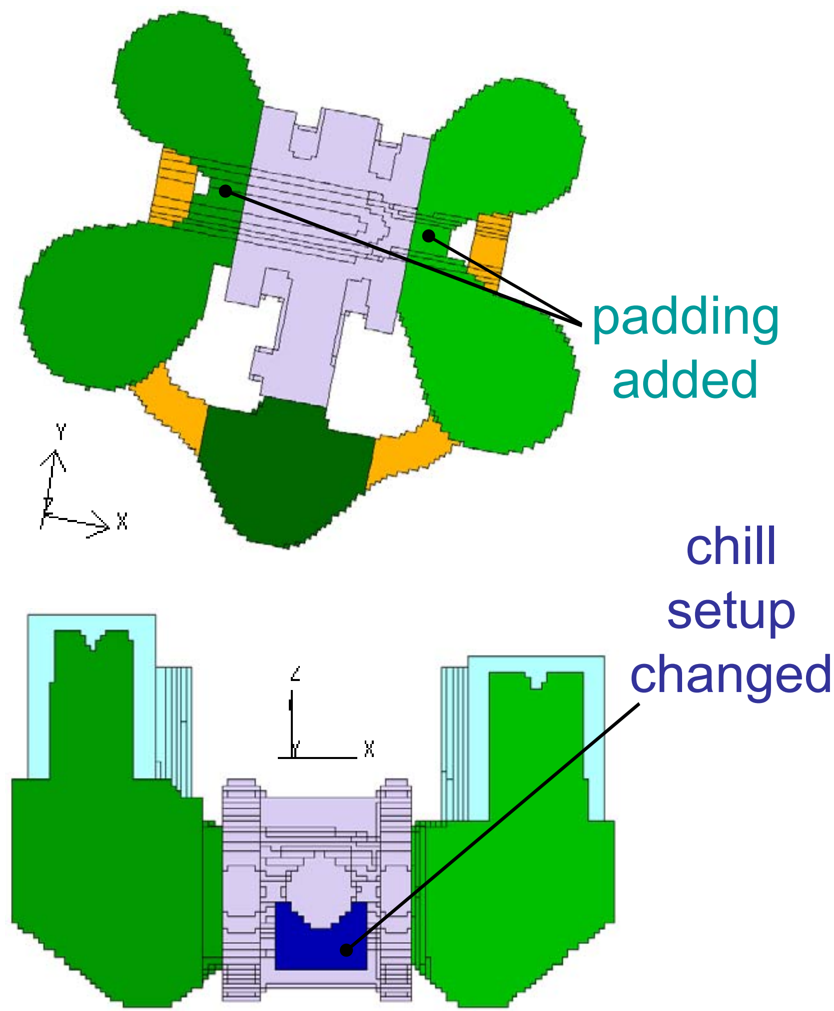


Case Study #3: Valve B

original rigging

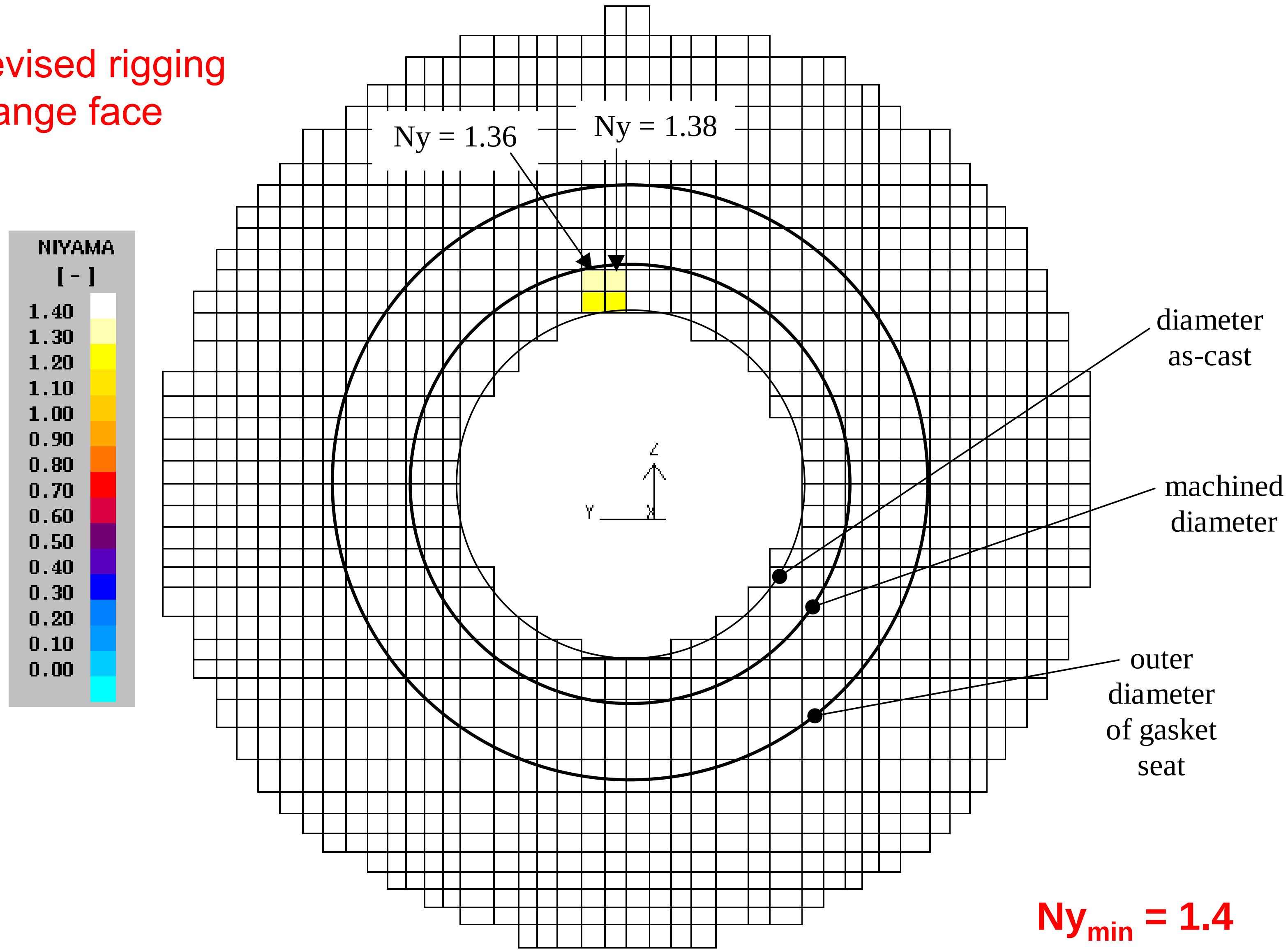


revised rigging



Case Study #3: Valve B

revised rigging
flange face



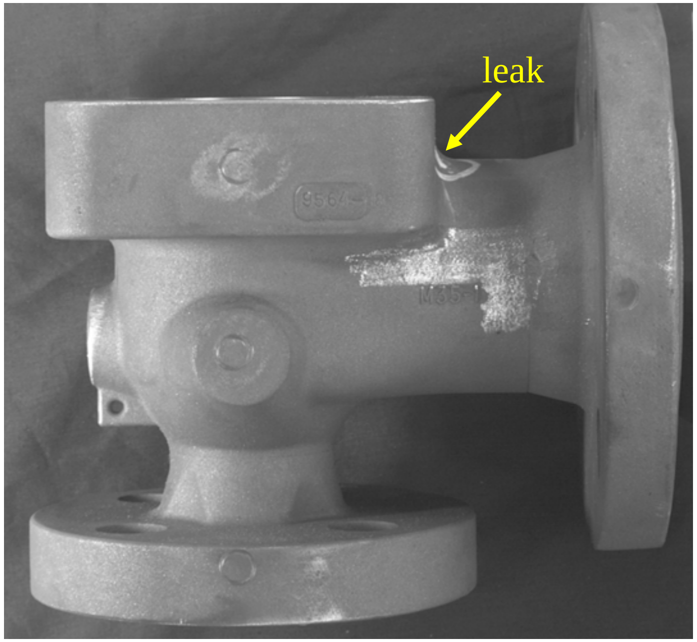
$Ny_{min} = 1.4$

Case Study #3: Valve B

- Microporosity caused leaks in original rigging with Ny_{min} = 0.5 - 0.7
- Ny_{min} = 1.4 for revised rigging
- Valves cast since rigging revised:
  - none have leaked
  - none have had any shrinkage indications on x-ray

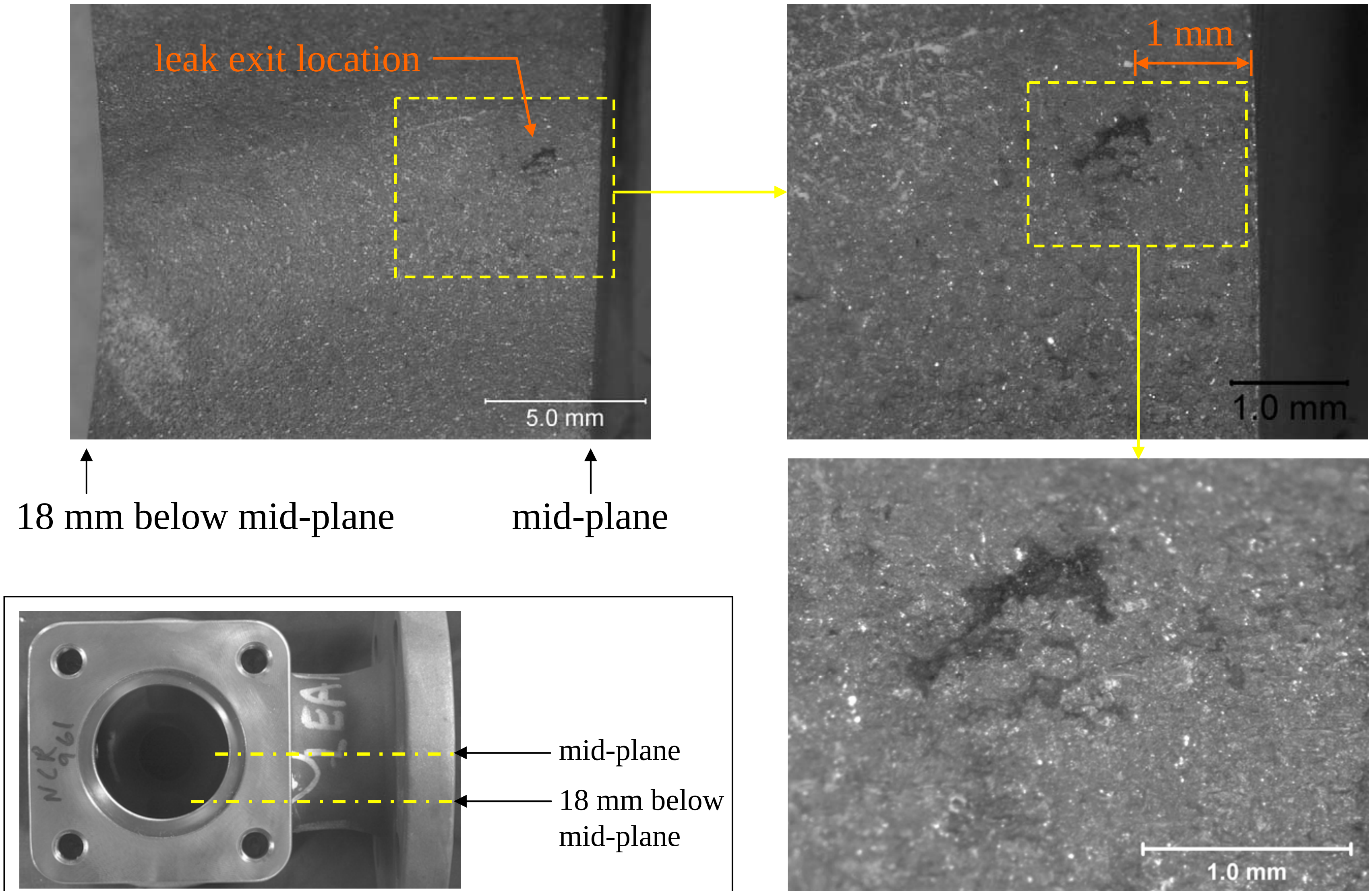
Leaker Case Study #1

- Leaker was a 20# investment cast M35-1 valve
- 8 valves were cast and shipped to the customer, and one leaked during the customer's pressure testing
- Leaker was returned to the foundry, with leak area circled
- Metallographic analysis (John Griffin, UAB)



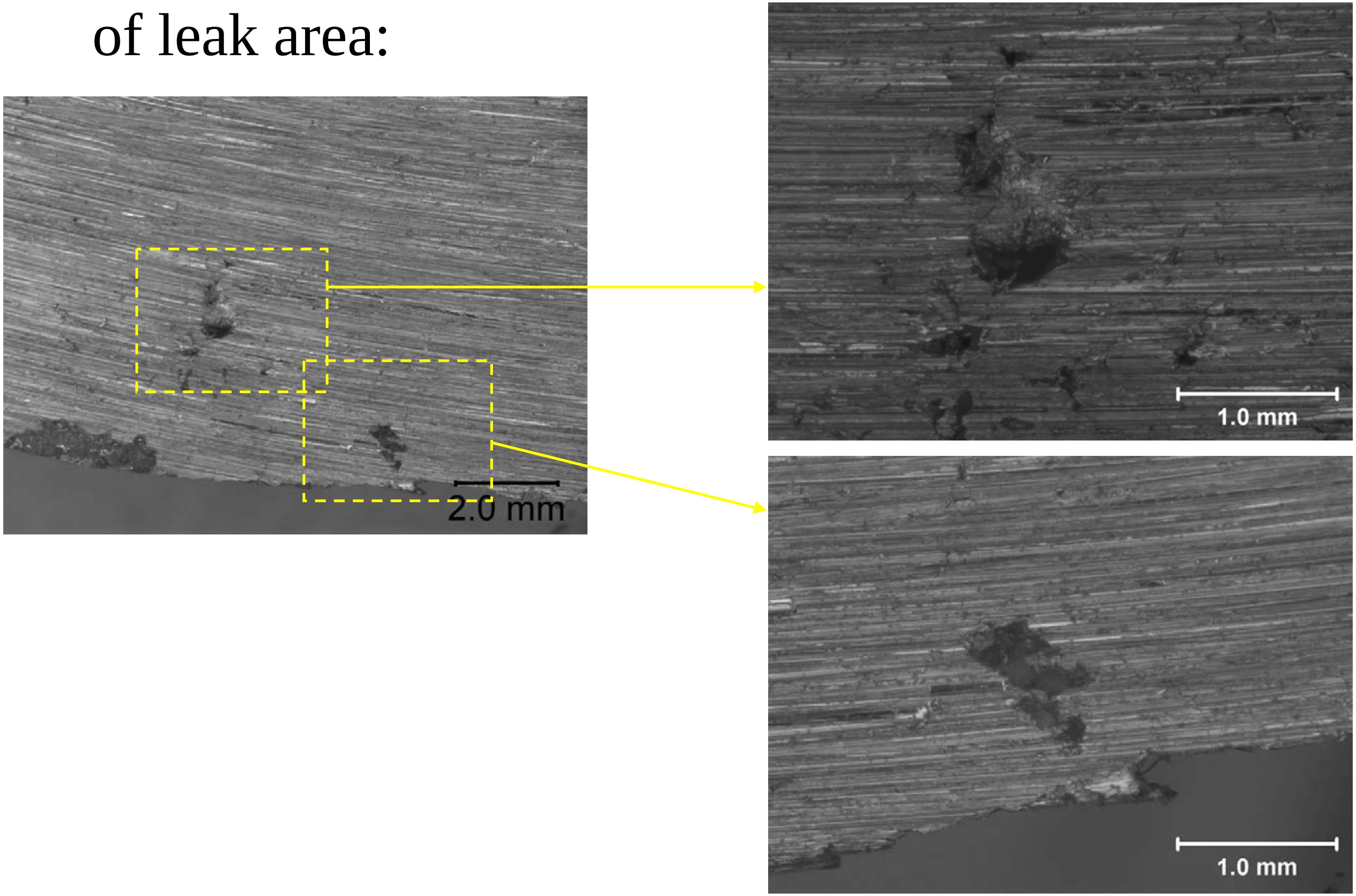
Photographs of Defects in Leak Area

- Outer diameter (OD) of leak area:



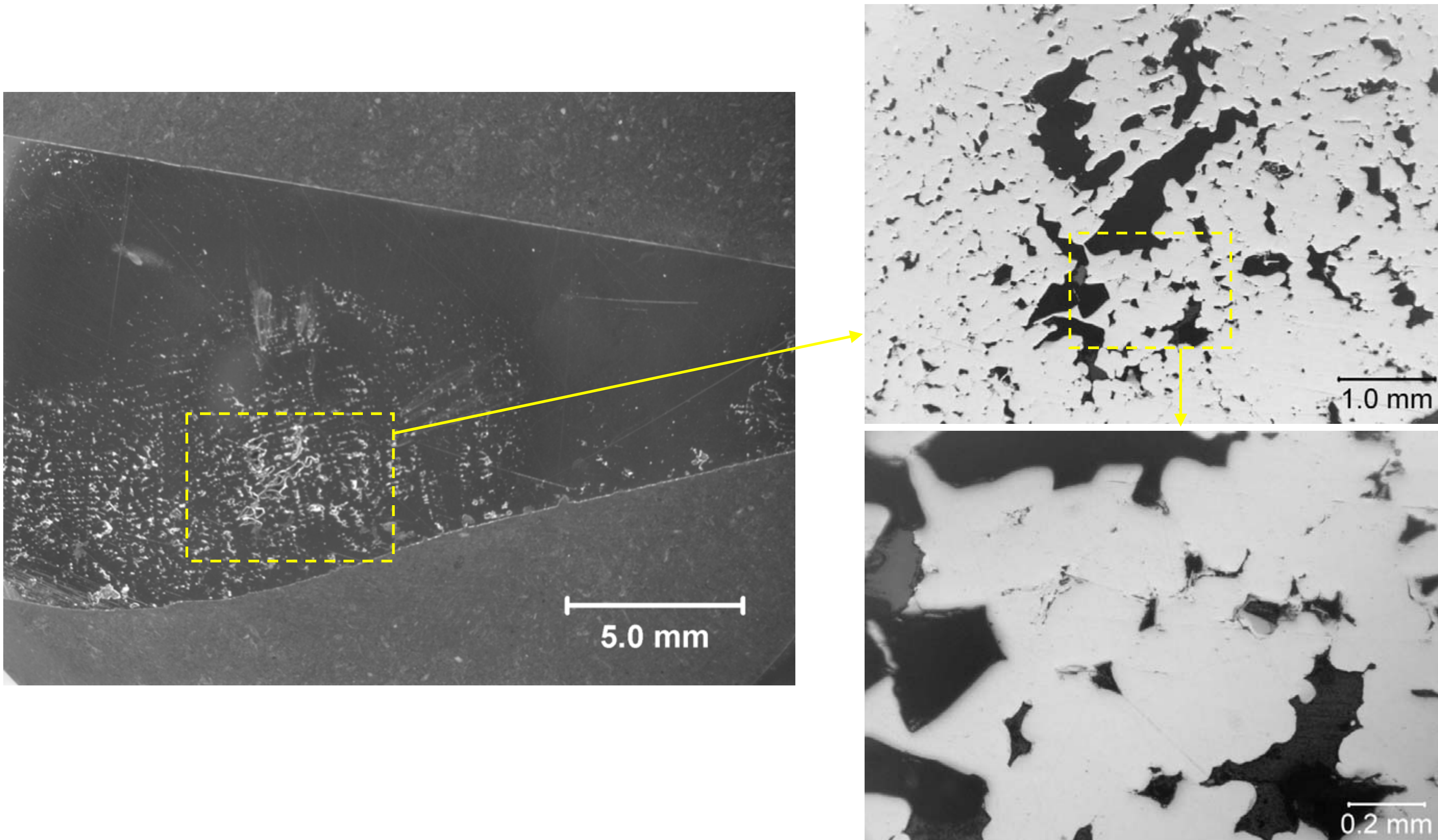
Photographs of Defects in Leak Area

- Casting through-thickness toward inner diameter (ID) of leak area:

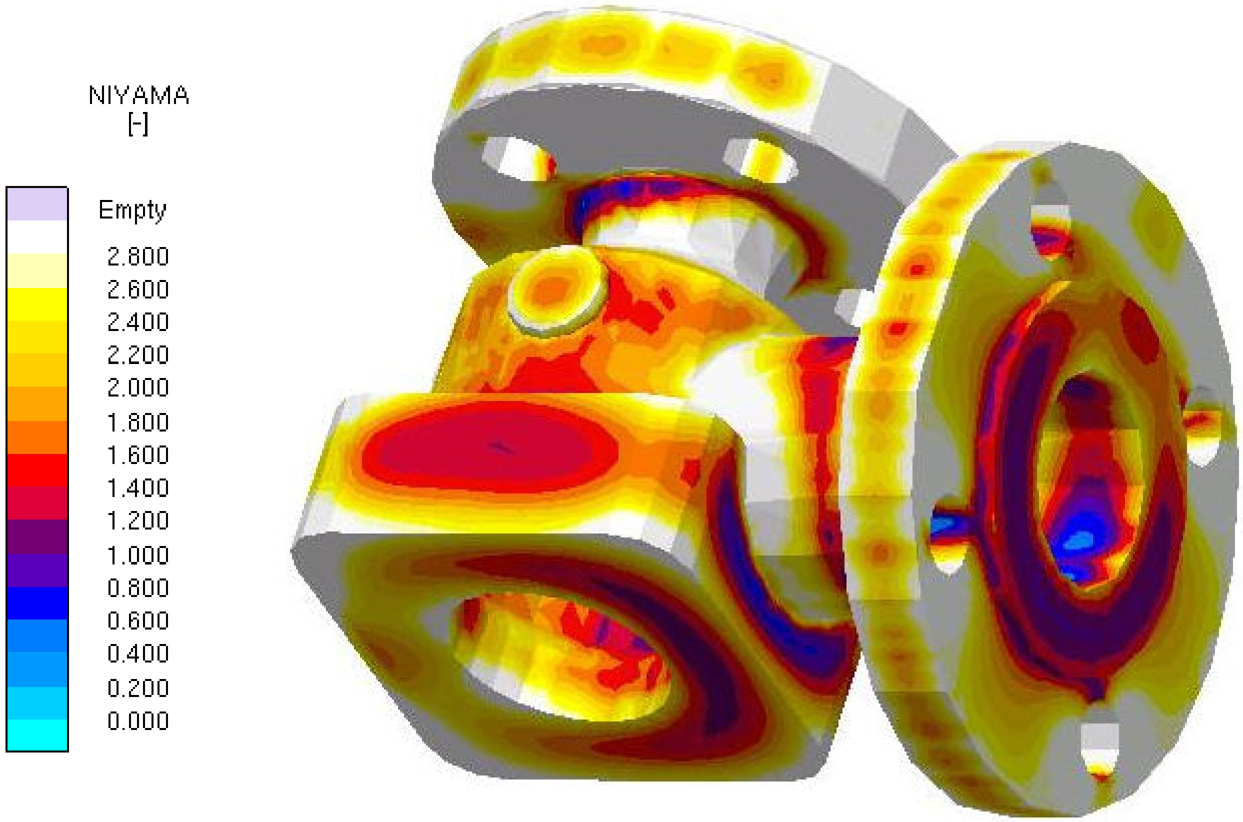


Photographs of Defects in Leak Area

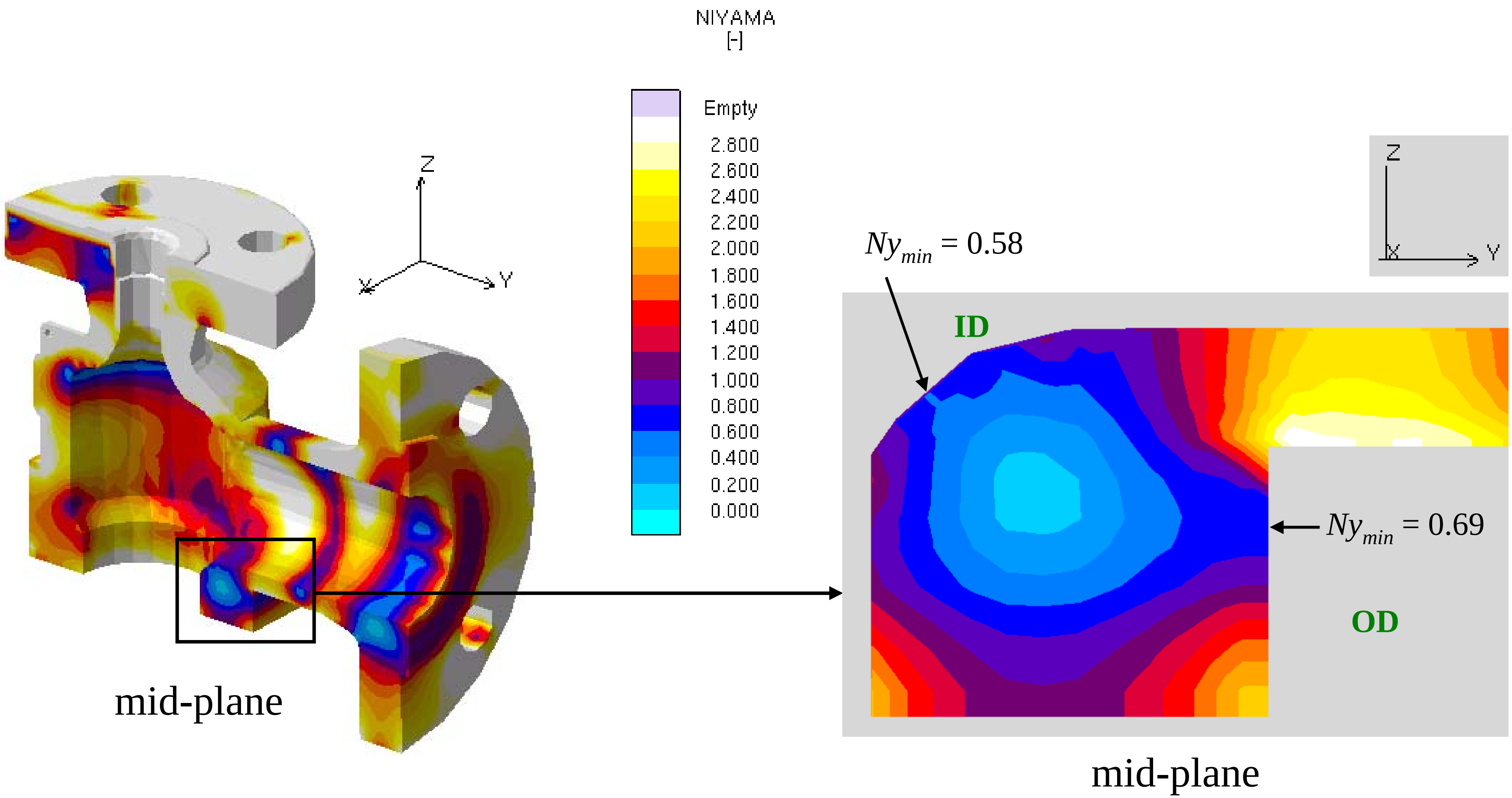
- Polished through-thickness specimen toward ID of leak area, showing shrinkage porosity:



Niyama Values in Entire Valve

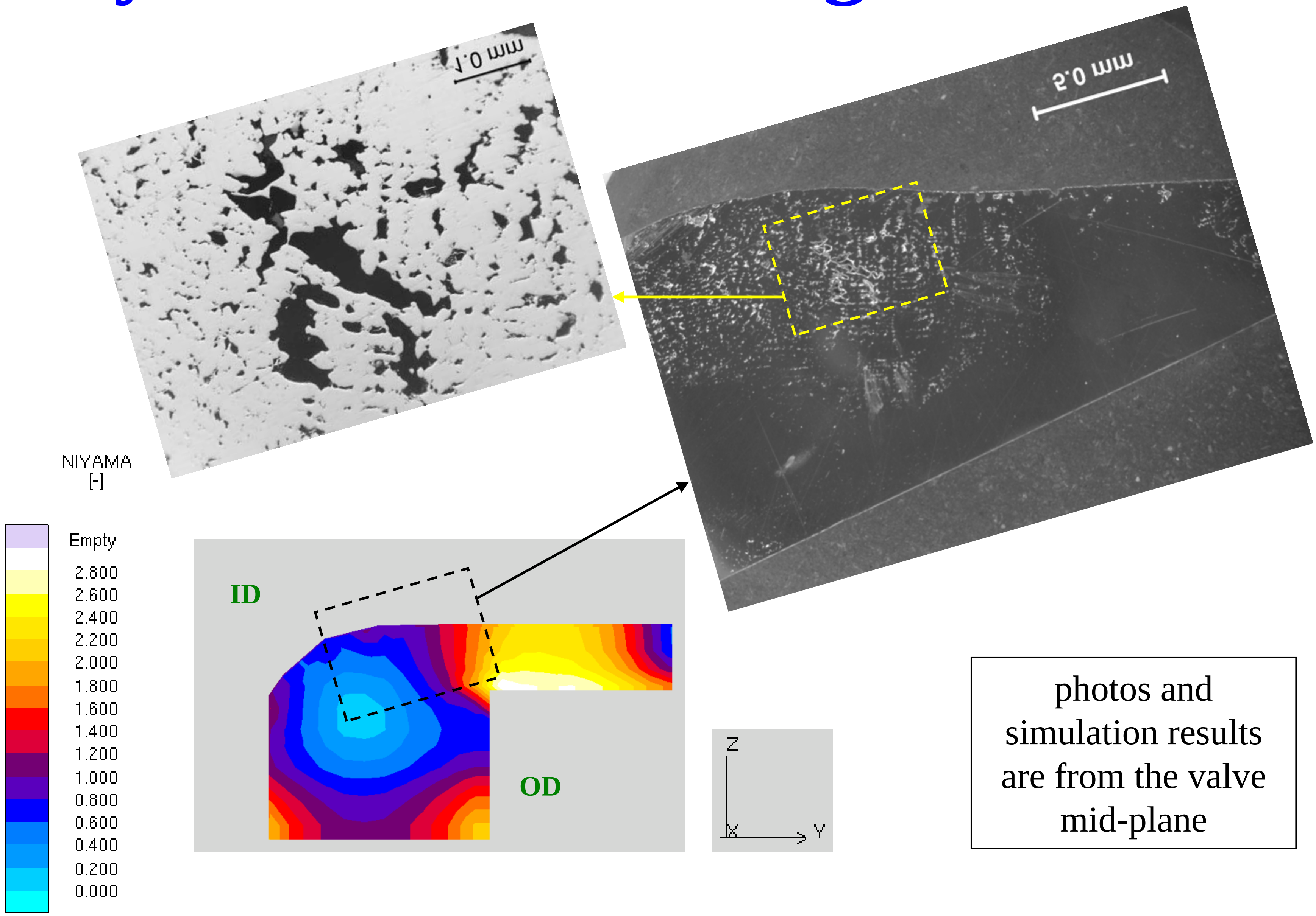


Niyama Values in Region of Leak



Niyama values are in units of (°C-s)$^{1/2}$/mm

Niyama Values in Region of Leak



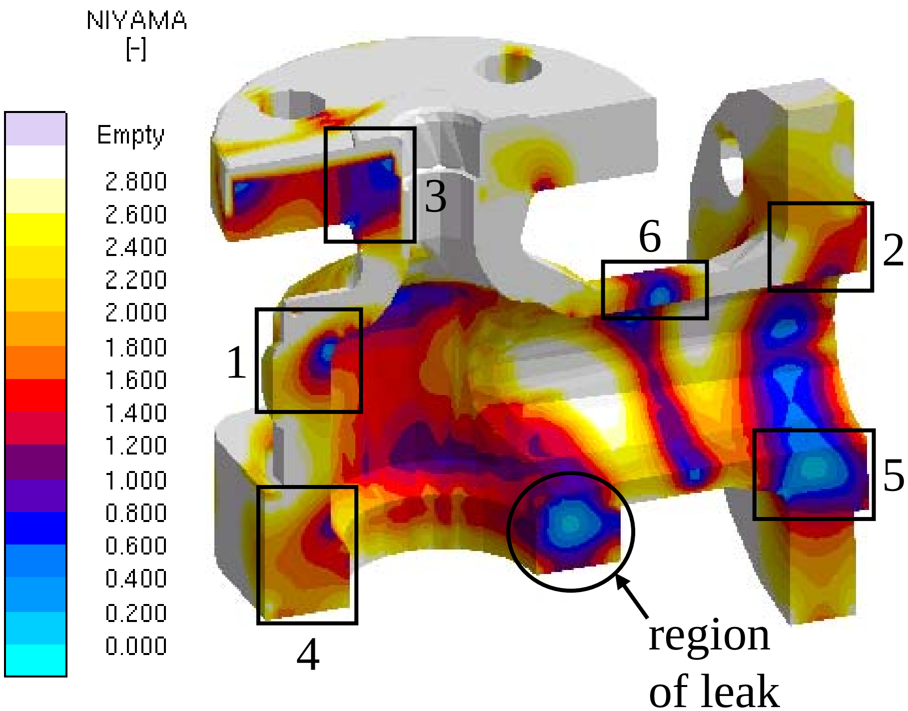
photos and simulation results are from the valve mid-plane

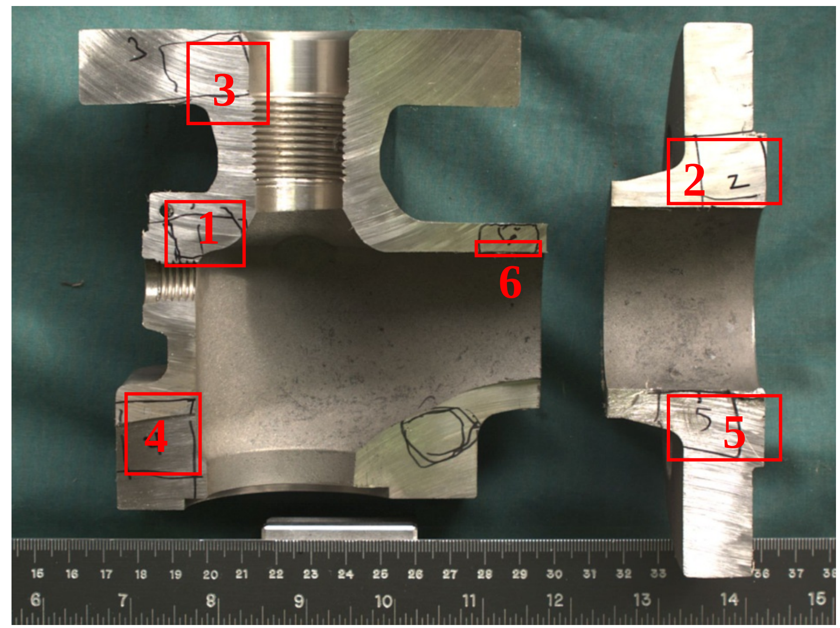
Case Study #1 Summary

- Simulation suggests potential for leak in valve
  - At valve mid-plane:
    Ny_{min} = 0.58 (°C-s)$^{1/2}$/mm at ID, Ny_{min} = 0.69 at OD
- These low Niyama values (Ny_{min} < 1) correspond well with shrinkage porosity observed in metallographic sections.

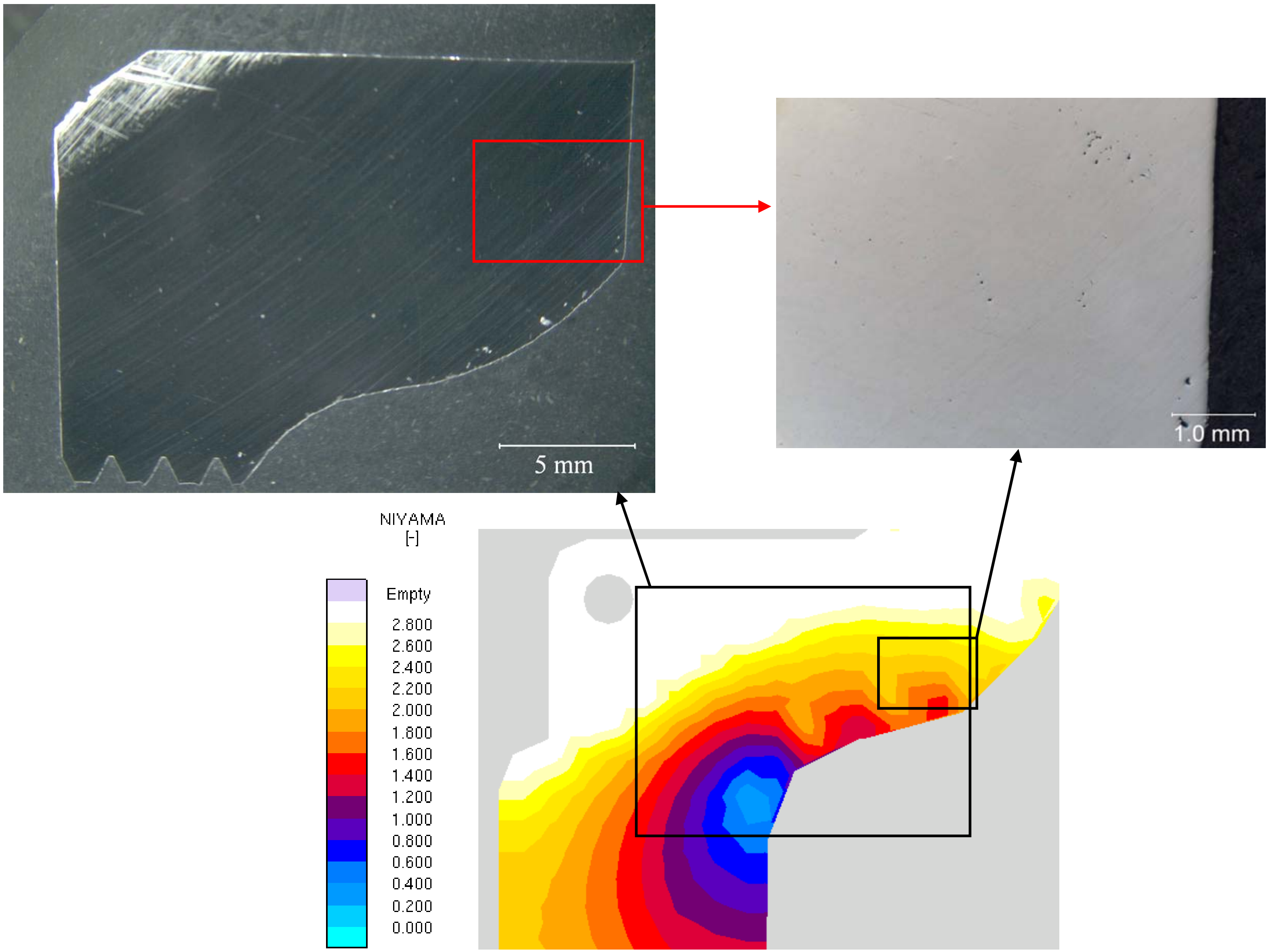
Additional Examination Areas

- After examining the leaking area, additional areas were selected for metallographic examination (all regions on valve mid-plane):

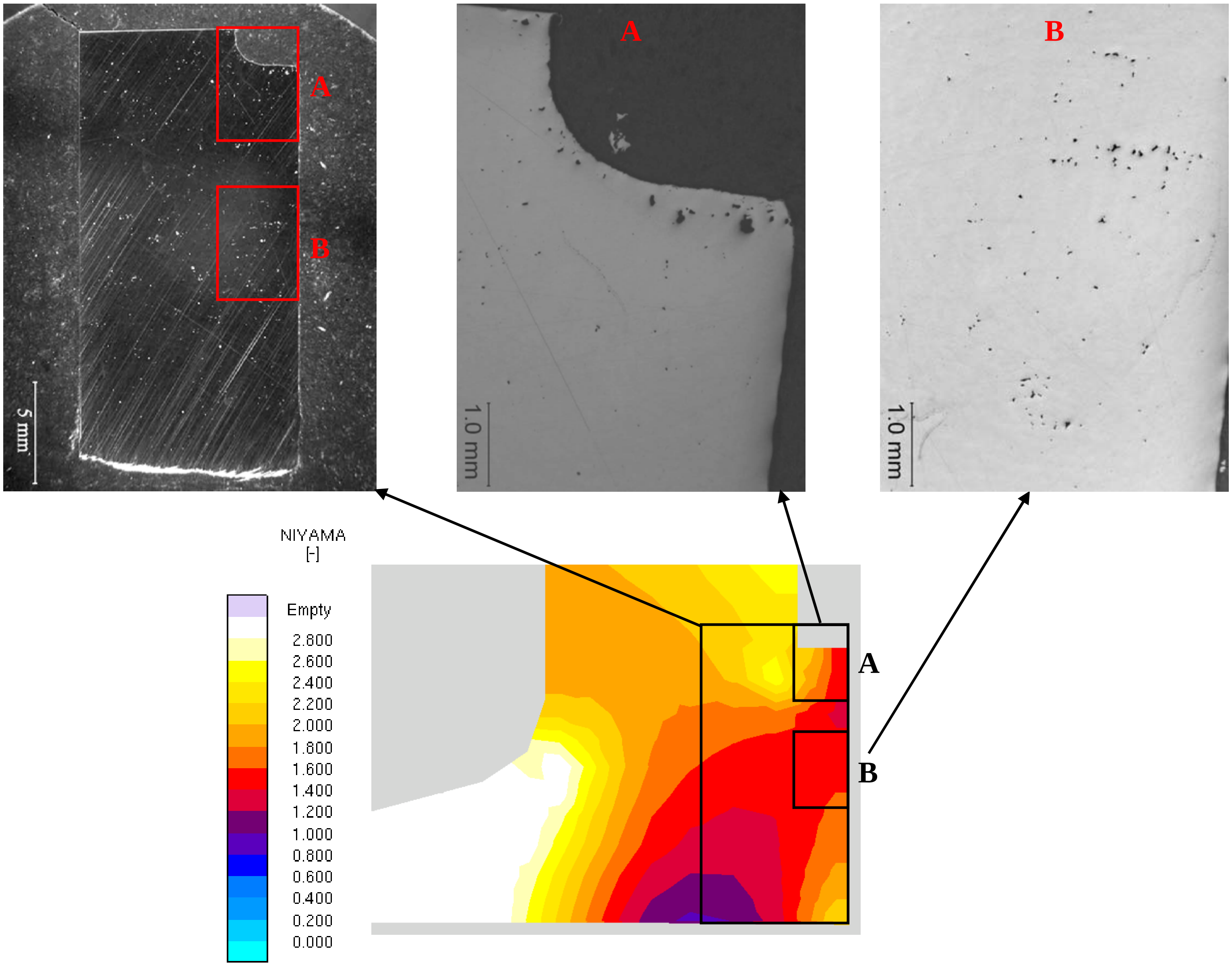




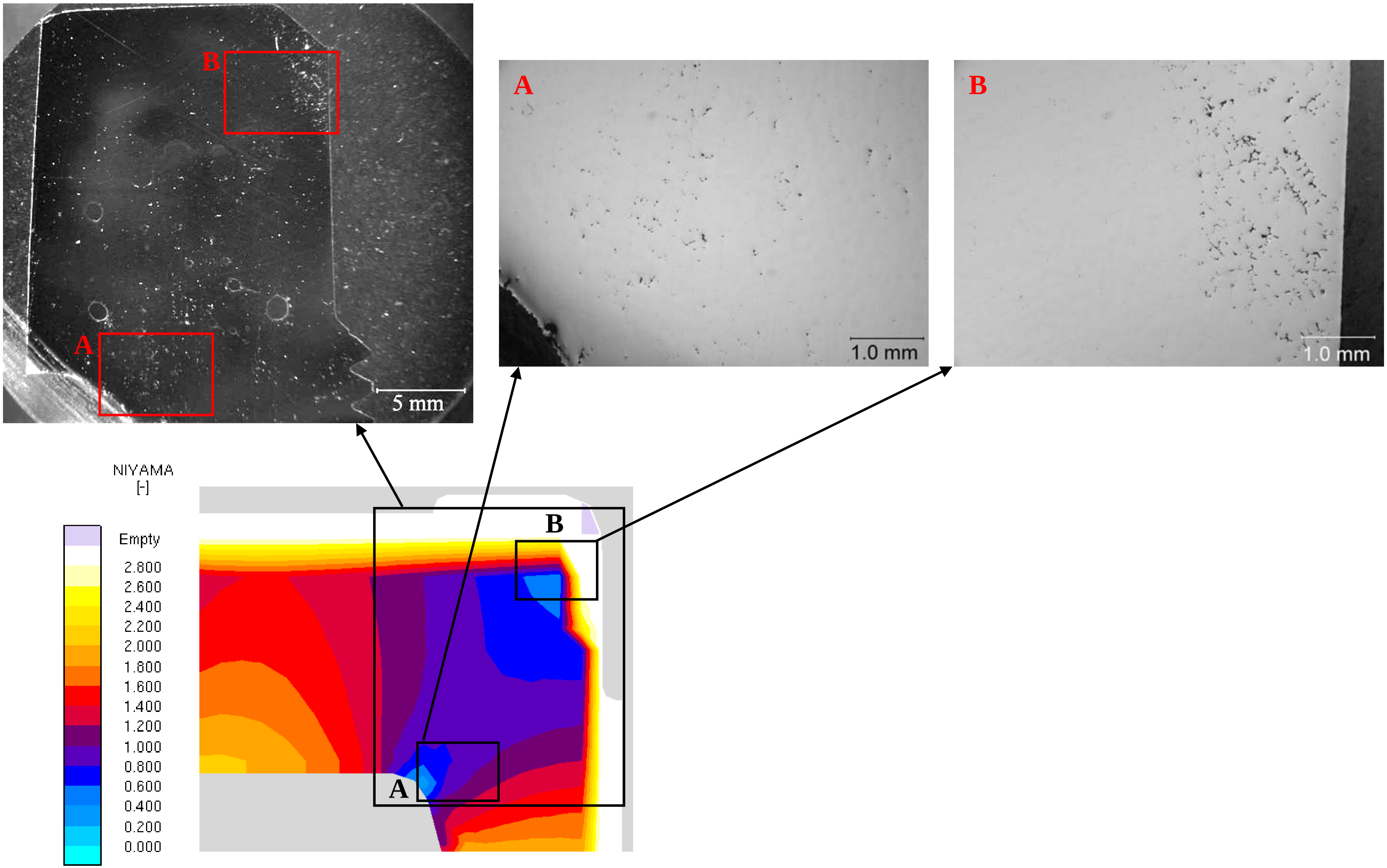
Comparison: Region #1



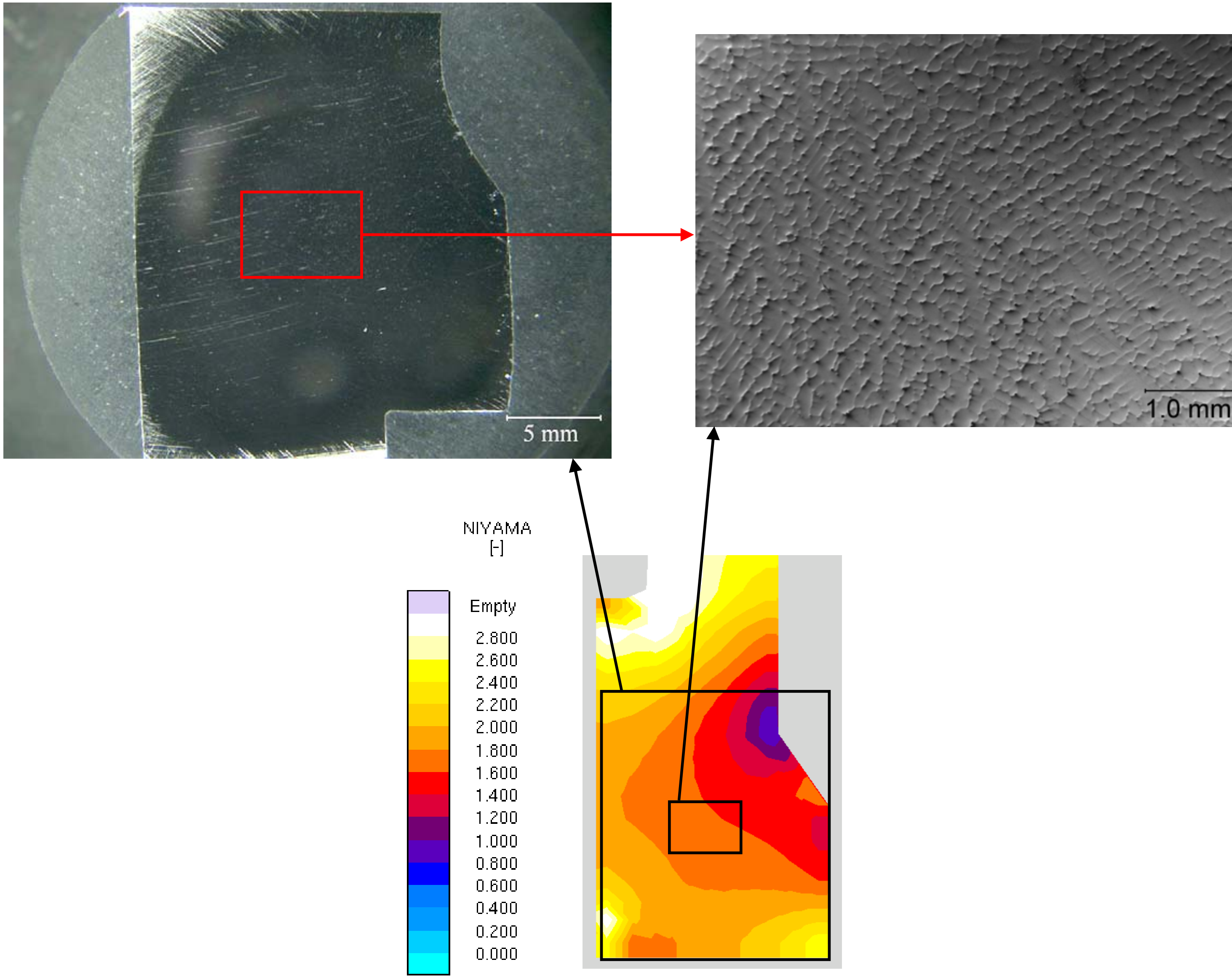
Comparison: Region #2



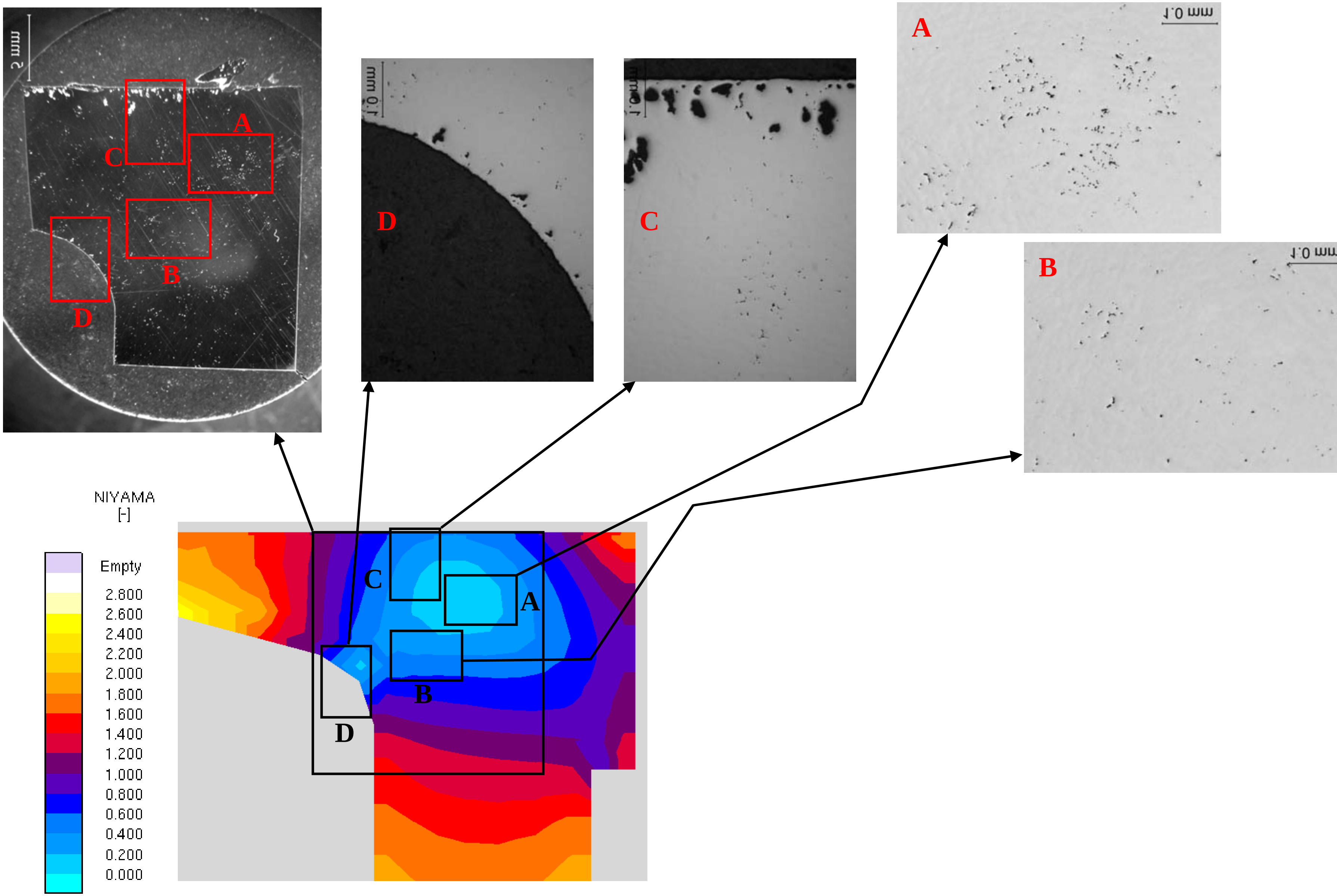
Comparison: Region #3



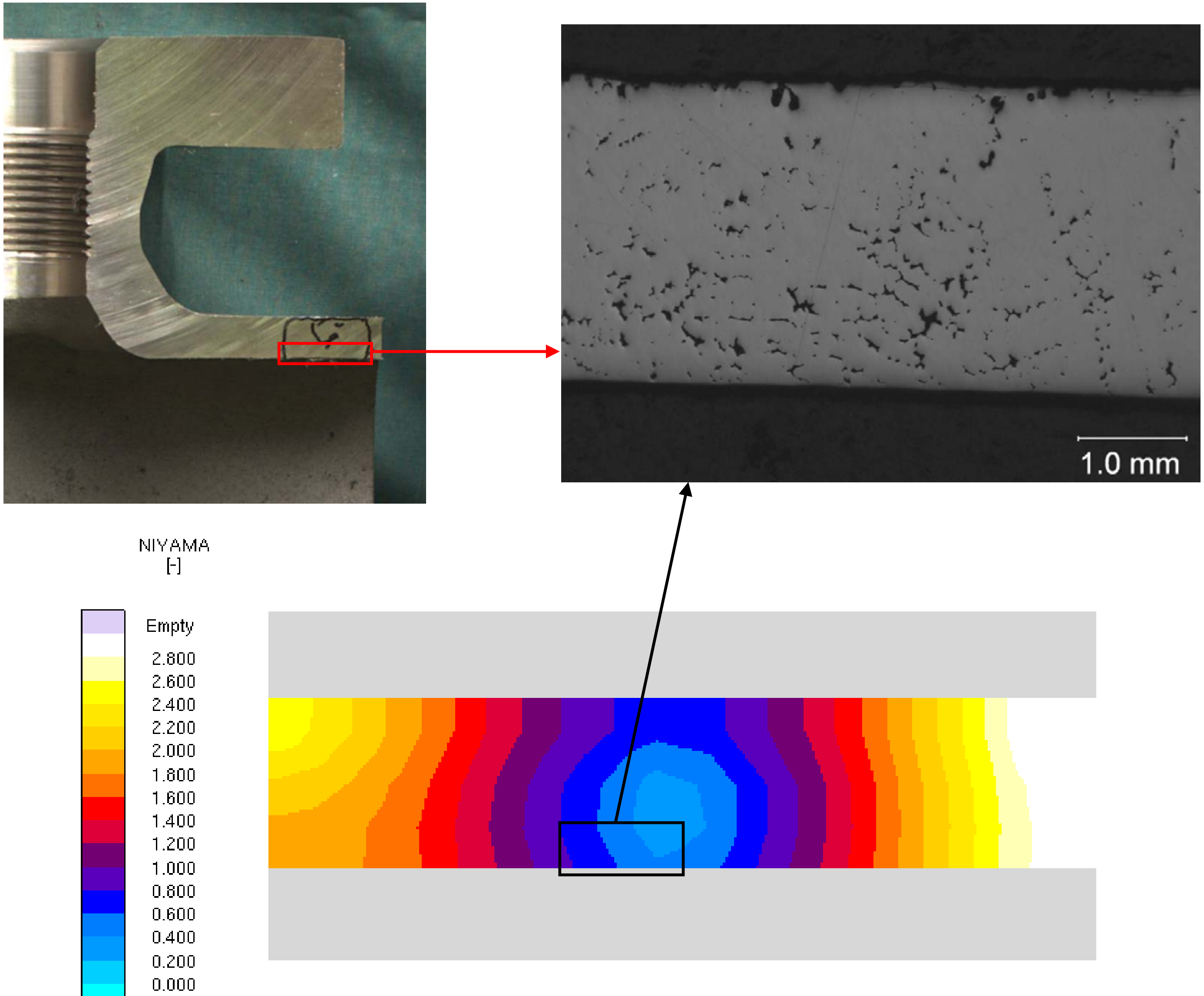
Comparison: Region #4



Comparison: Region #5



Comparison: Region #6

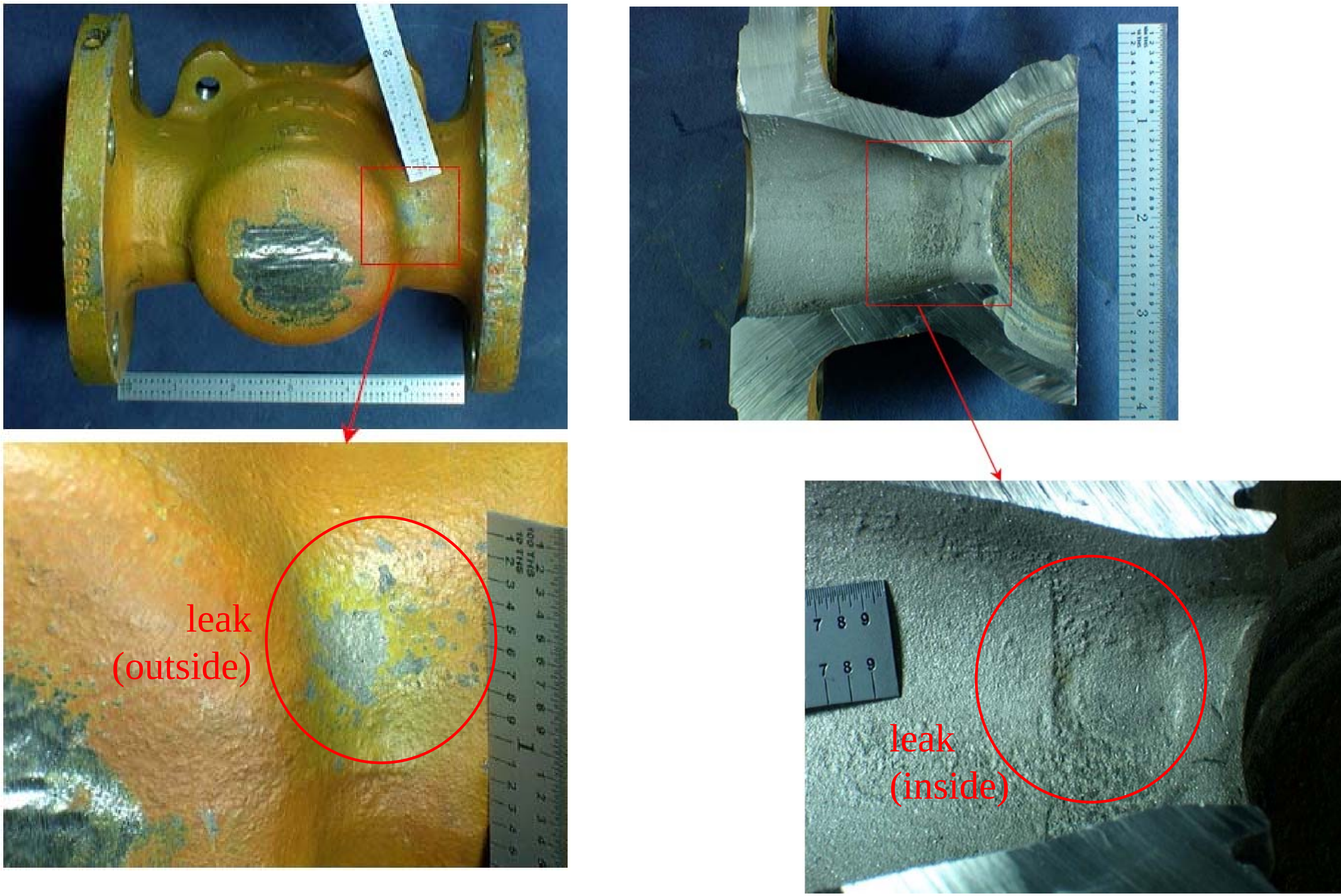


Additional Region Summary

- In general, areas with $Ny < 1$ show a significant amount of porosity (macroporosity)
- In general, areas with $1 < Ny < 2$ show a noticeable amount of microporosity
  - Region #4 was a slight exception, with no substantial microporosity in a region with $1.5 < Ny < 1.8$
- In general, areas with $Ny > 2$ were free from shrinkage porosity

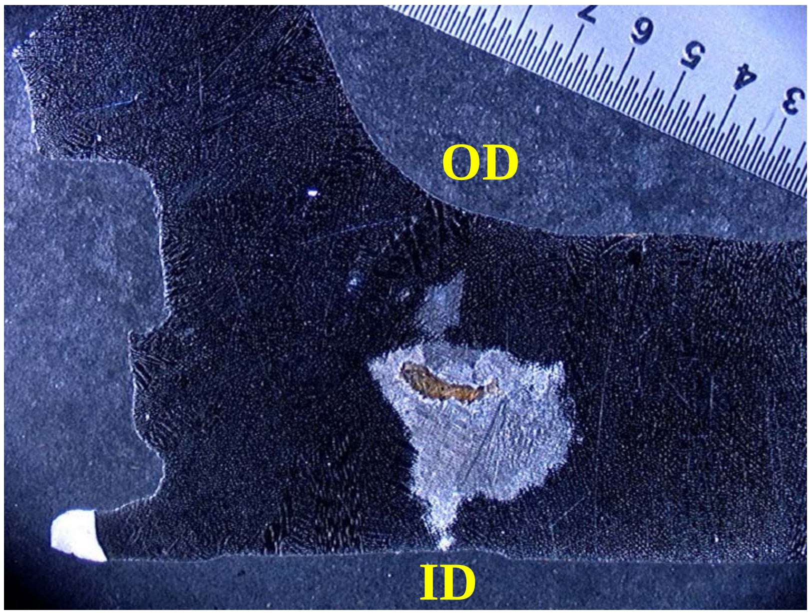
Leaker Case Study #2

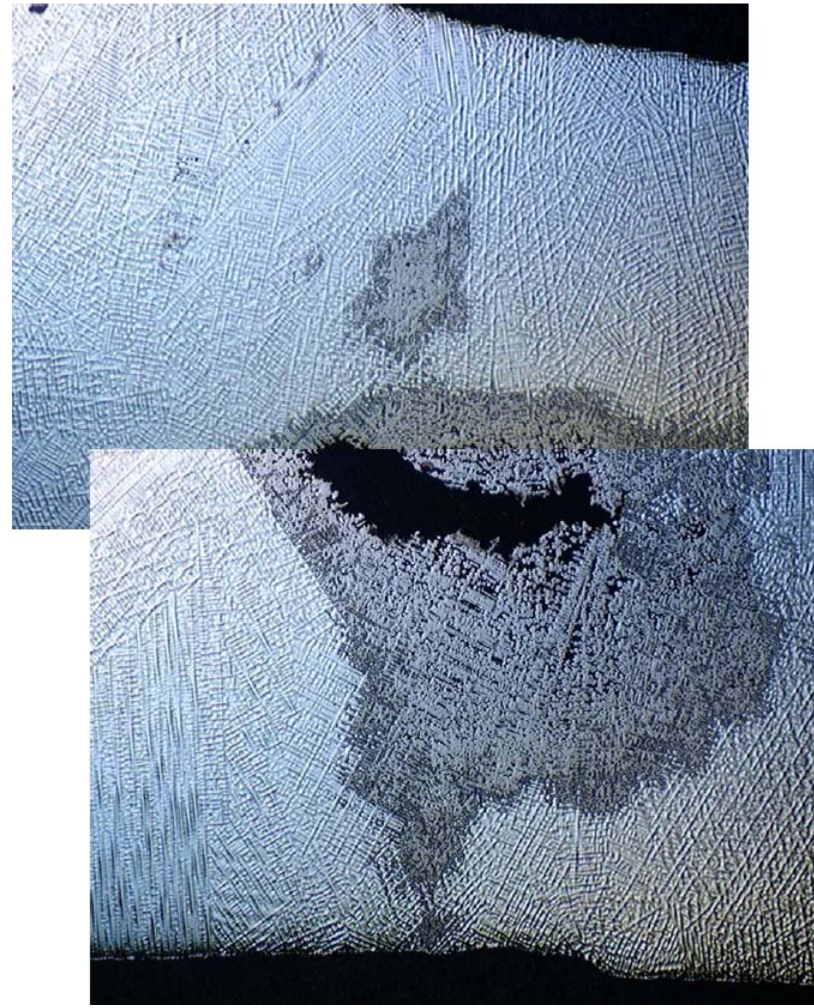
- 150# CN7M Valve Sand Casting:



Leaker Case Study #2

cross-section of leaking area

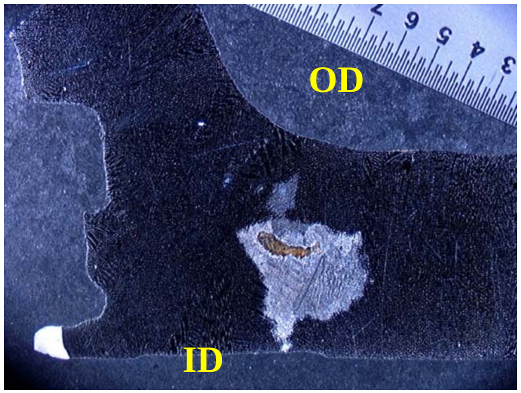


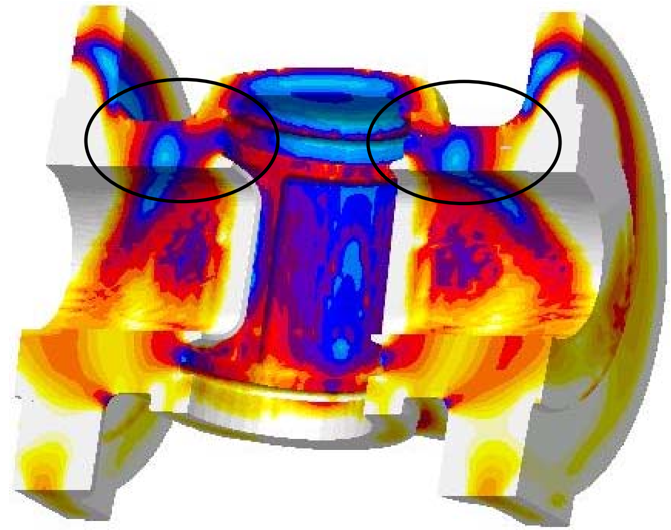


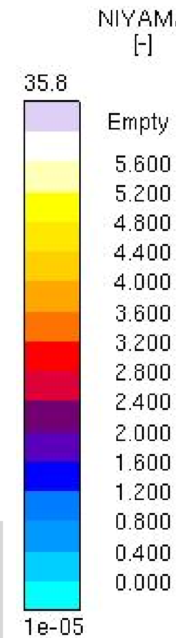
shrinkage, possibly segregation

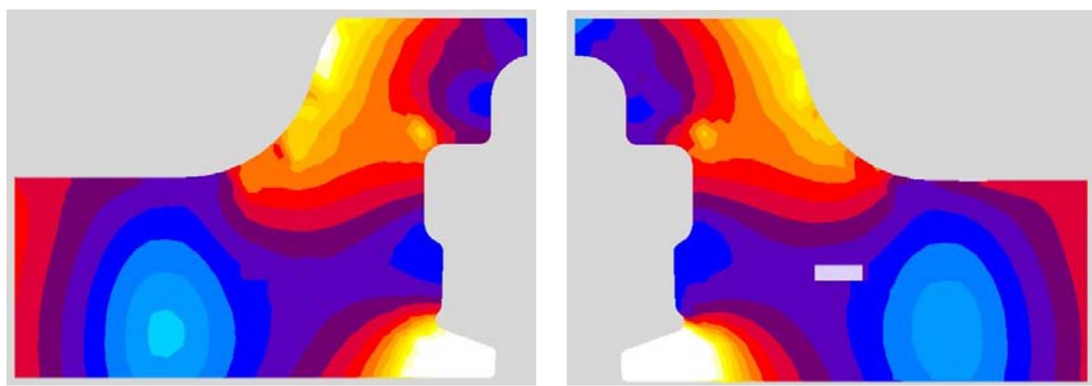
Case Study #2 Simulations

- Original rigging:









- Ny_{min} = 1.6 at OD, Ny_{min} = 0.5 at ID
- visible macro-porosity for $Ny_{min} < 1.0$

Conclusions

- In general, areas with Ny < 1 show a significant amount of porosity (macroporosity)
- In general, areas with 1 < Ny < 2 show a noticeable amount of microporosity
- In general, areas with Ny > 2 were free from shrinkage porosity
- It appears that the Niyama criterion can be used for quality assurance, especially if shrinkage porosity is so small that it cannot be detected by radiography.
- Note for MAGMAsoft users: the valves had only minimal feeding indications (porosity %); the shrink seen in the valves was only predicted using Niyama criterion.