Residual stress caused by heat treatments of Steel and Aluminum alloy castings

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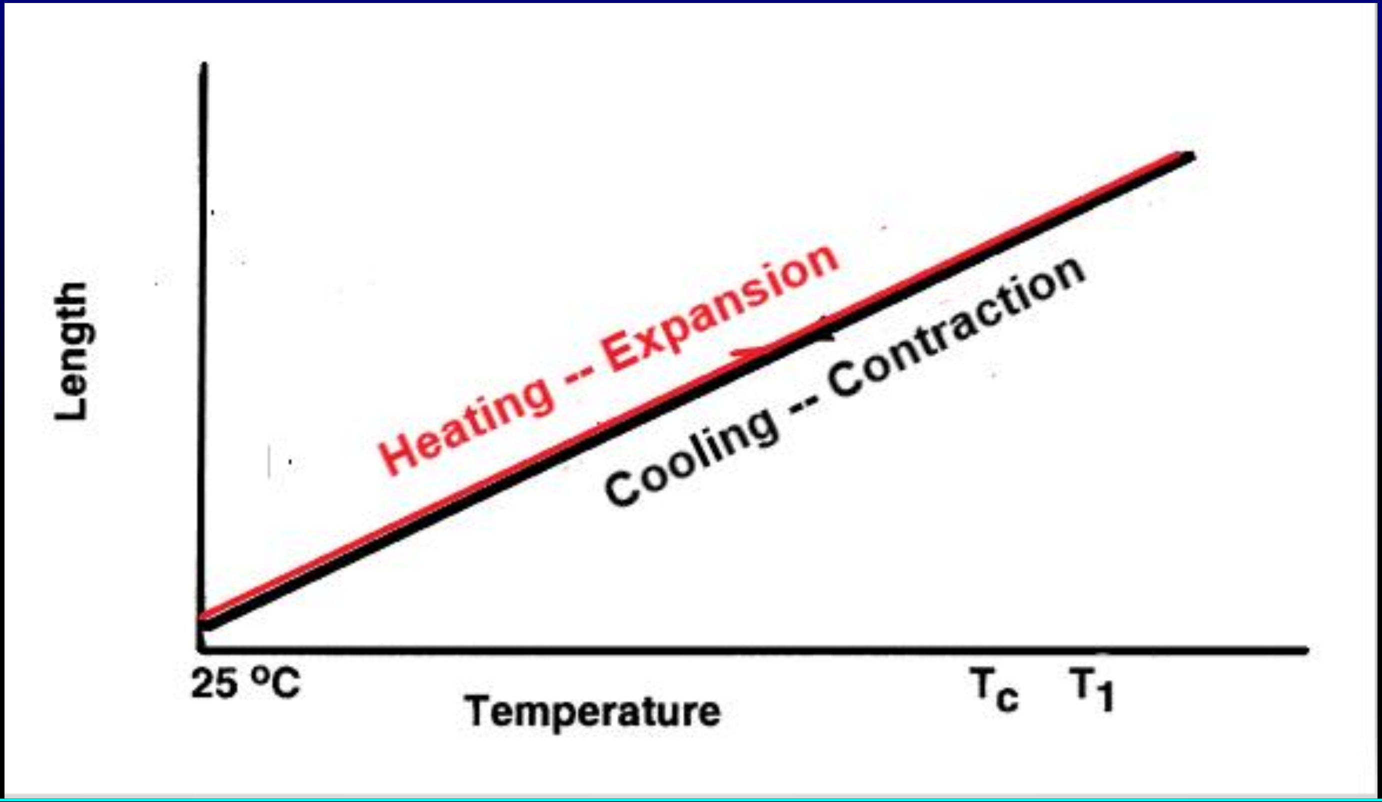
Outline

- 1. Introduction to residual stress
  - Effect of thermal gradient
  - Effect of phase transformation
  - Effect of casting geometry
- 2. Objective
- 3. Consequences of the residual stress
- 4. Case histories:
  - #1 – Distortion during solidification (steel casting)
  - #2 – Fracture during field working (steel casting)
  - #3 – Fracture during heat treatment (steel casting)
  - #4 – Distortion during heat treatment (aluminum casting)

Introduction to residual stress

Introduction to residual stress

- Metallic parts present thermal expansion during heating operations and thermal contraction during cooling operations;



Introduction to residual stress

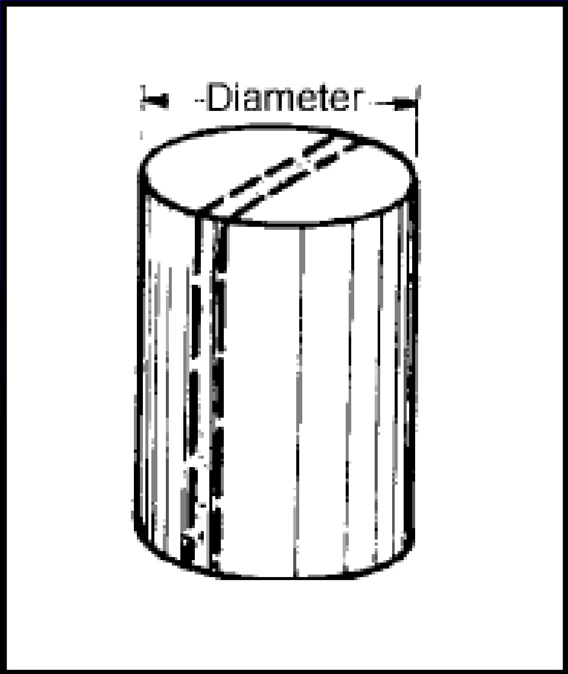
- **Thermal Gradients promotes residual stress**

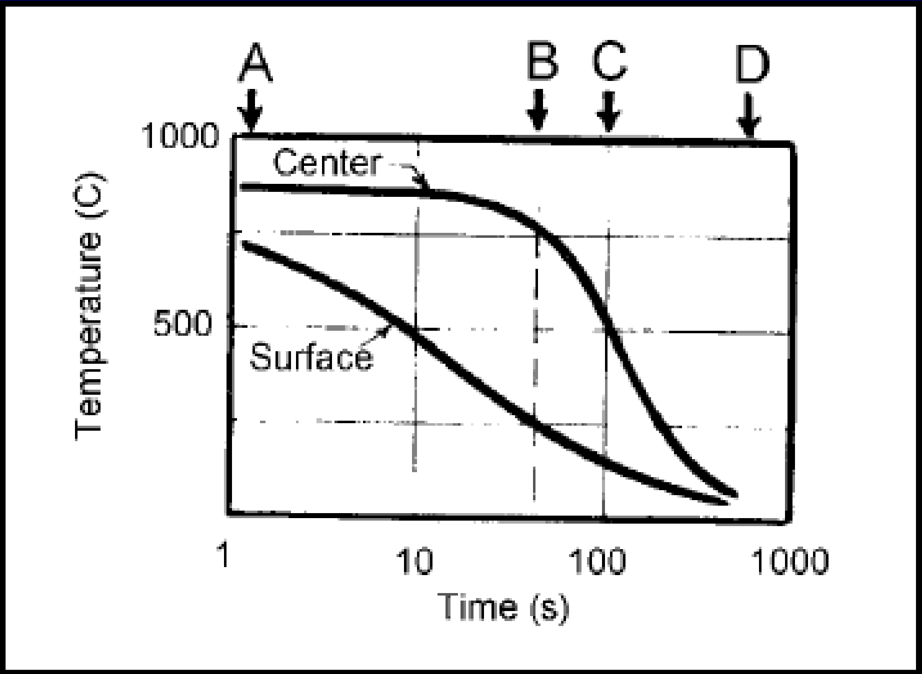
- **At high temperature residual stress are relived**

- **Most of residual stresses are generated during cooling operations;**

Introduction to residual stress

Cooling operation

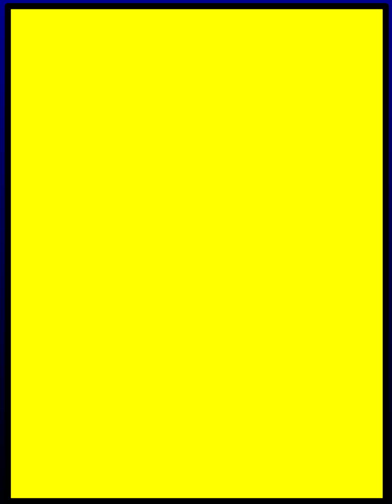




Simulation of Heat Treatment Distortion - R.A. Hardin1and C. Beckermann – Proceedings of the 59th SFSA Technical and Operational Conference – Paper #33, 2005.

Introduction to residual stress

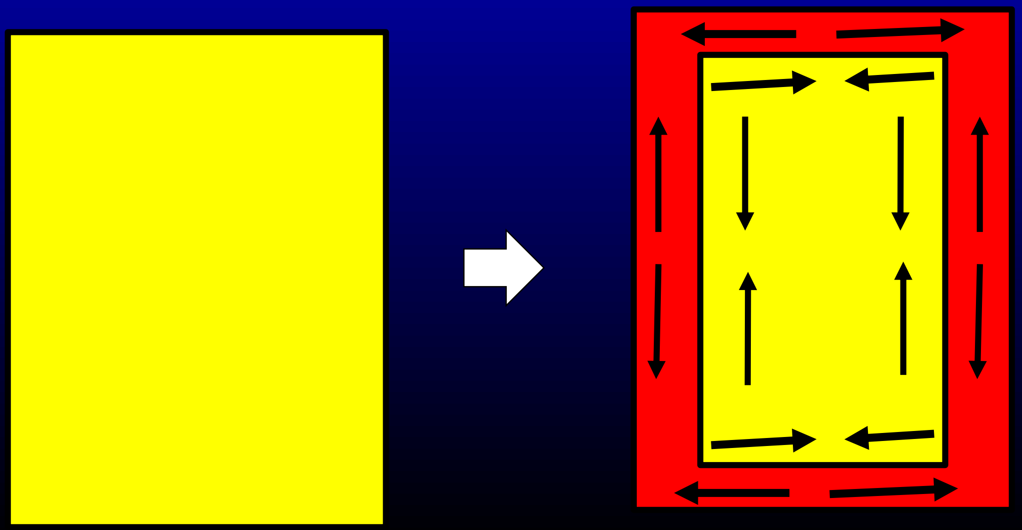
Cooling operation



Part at homogeneous temperature

Introduction to residual stress

Cooling operation

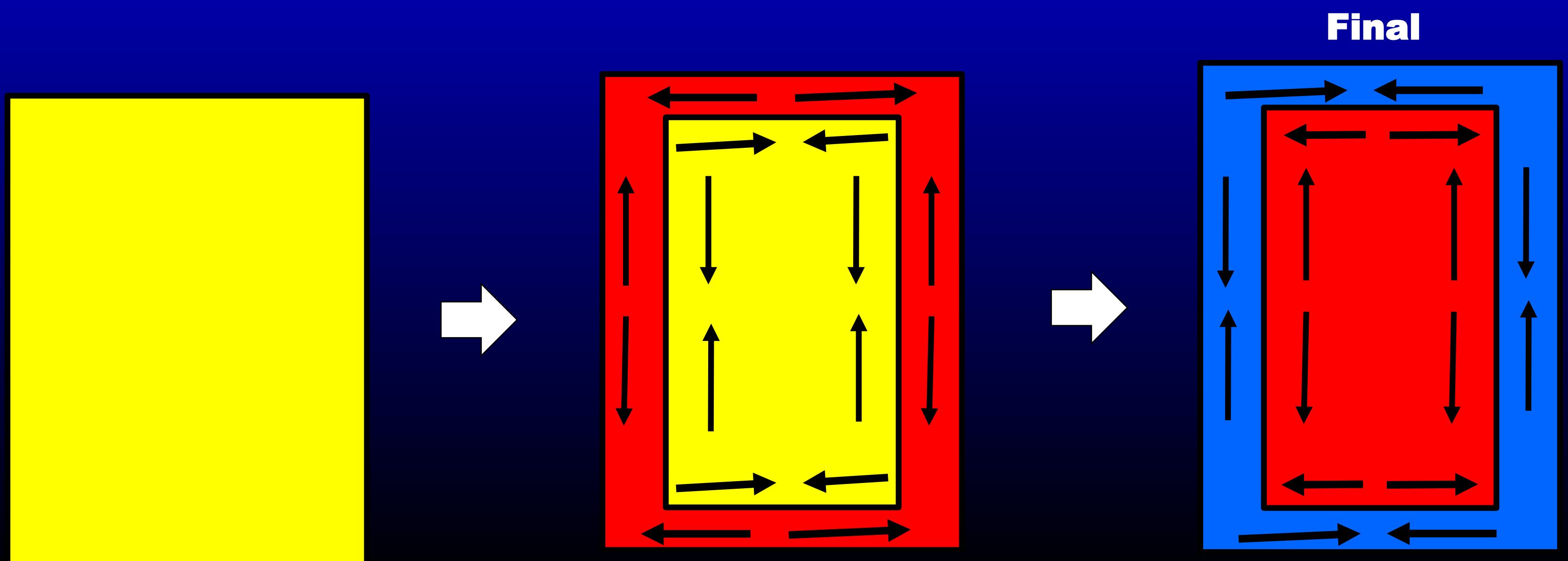


Part at homogeneous temperature

Surface contraction restricted by the core (surface with tensile residual stress)

Introduction to residual stress

Cooling operation



Part at homogeneous temperature

Surface contraction restricted by the core

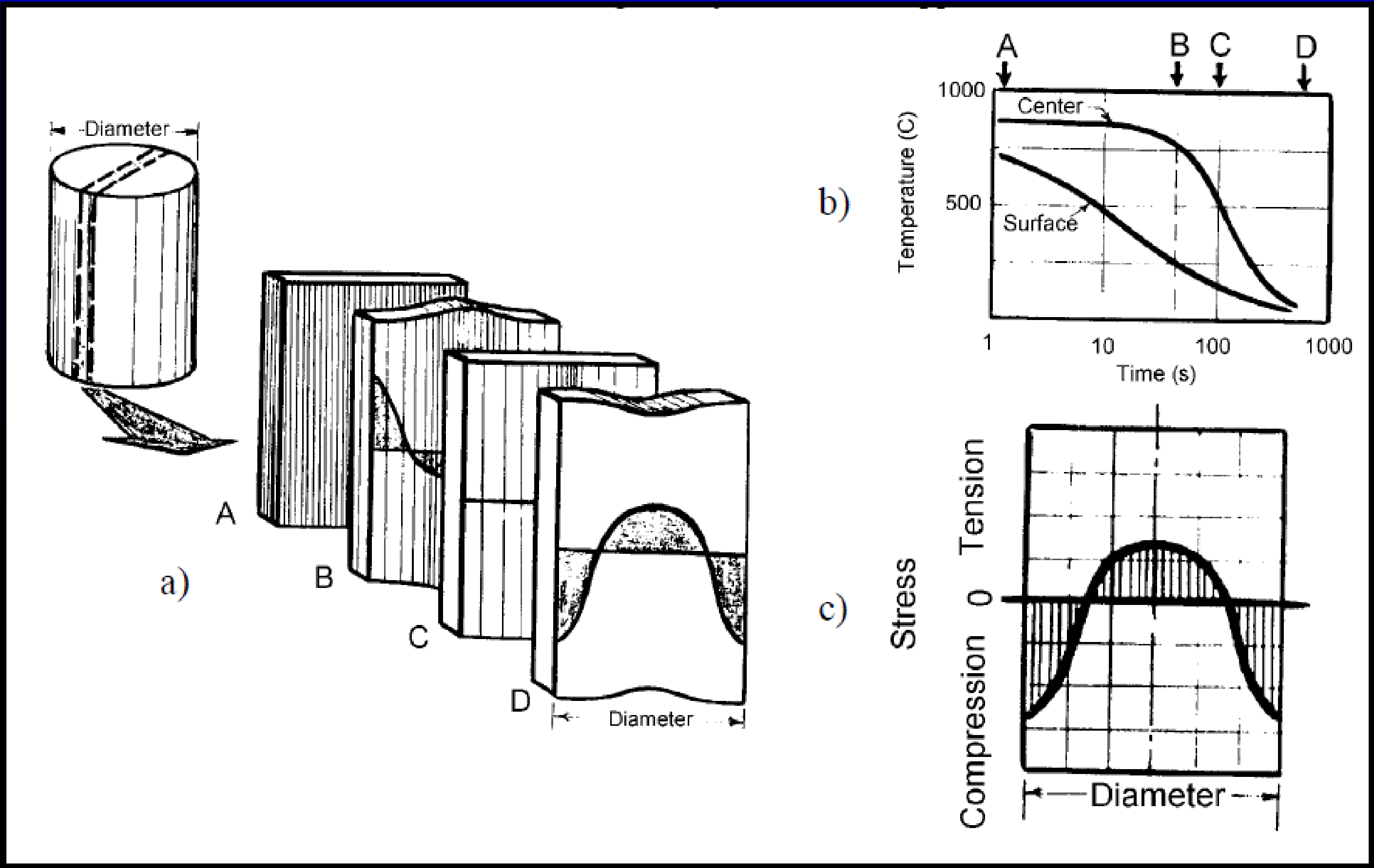
Surface with tensile residual stress

Core contraction restricted by the surface

Surface with compressive residual stress

Introduction to residual stress

Cooling operation



Simulation of Heat Treatment Distortion - R.A. Hardin1and C. Beckermann – Proceedings of the 59th SFSA Technical and Operational Conference – Paper #33, 2005.

Introduction to residual stress

- **Compressive stresses** in the surface of the casting are considered positive, since these stresses can minimize the possibility of crack formation;

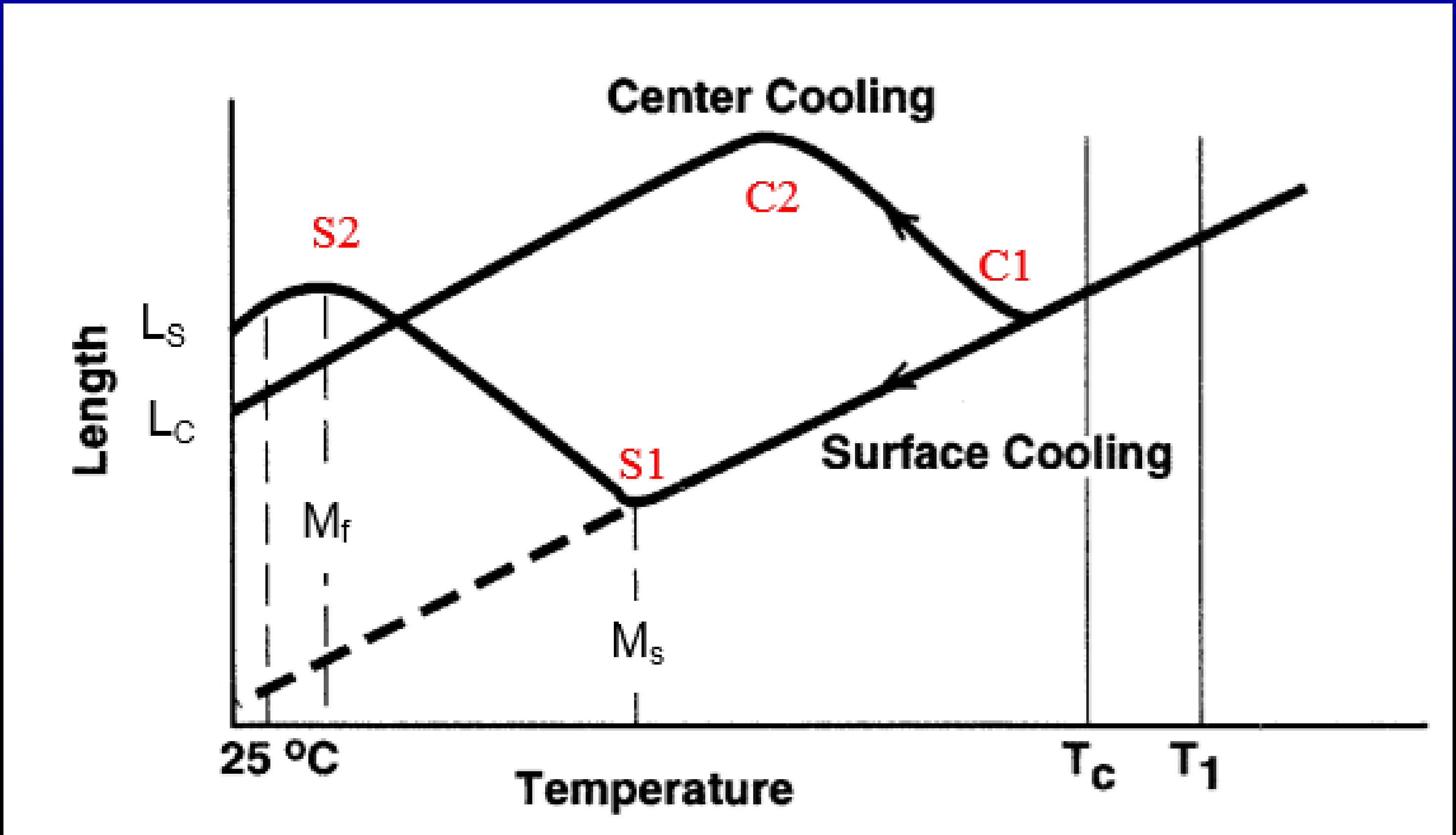
- On the other hand, **tensile stresses** in the surface of a casting can promote distortion or can contribute to crack initiation;

Introduction to residual stress

Effect of thermal gradient

Introduction to residual stress

Effect of thermal gradient



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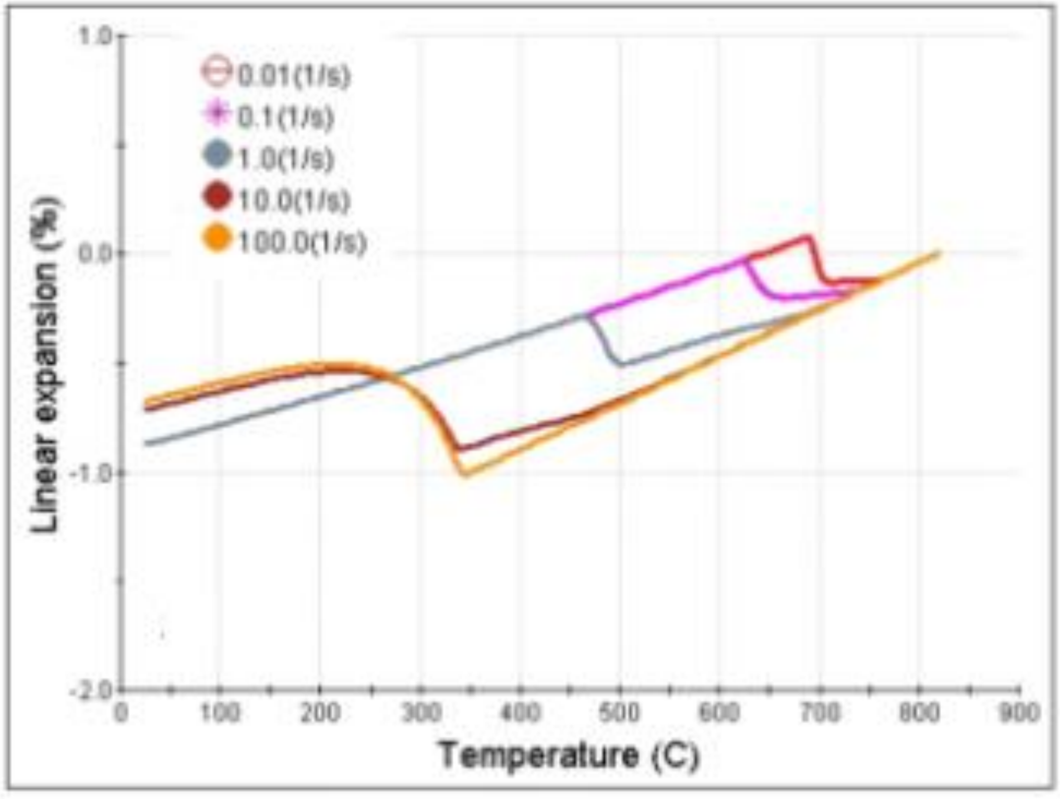
Introduction to residual stress

Effect of phase transformation

Introduction to residual stress

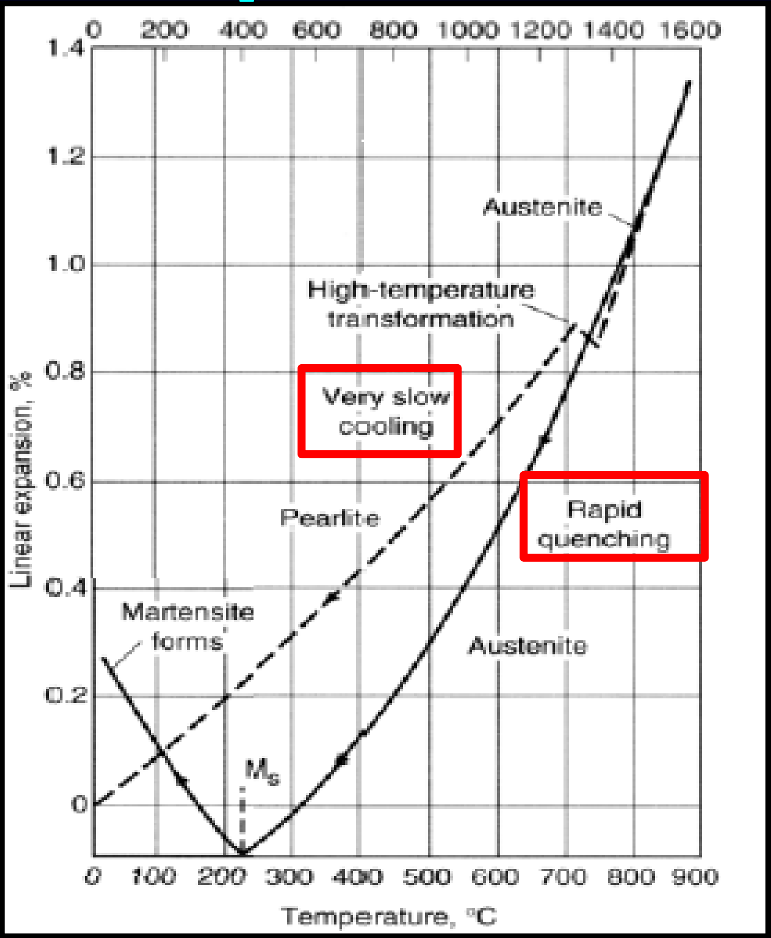
Effect of phase transformation



Linear expansion for 4140 steel at cooling rates of 0.01 to 100°C/s (Guo et al, 2009)

Introduction to residual stress

Effect of phase transformation

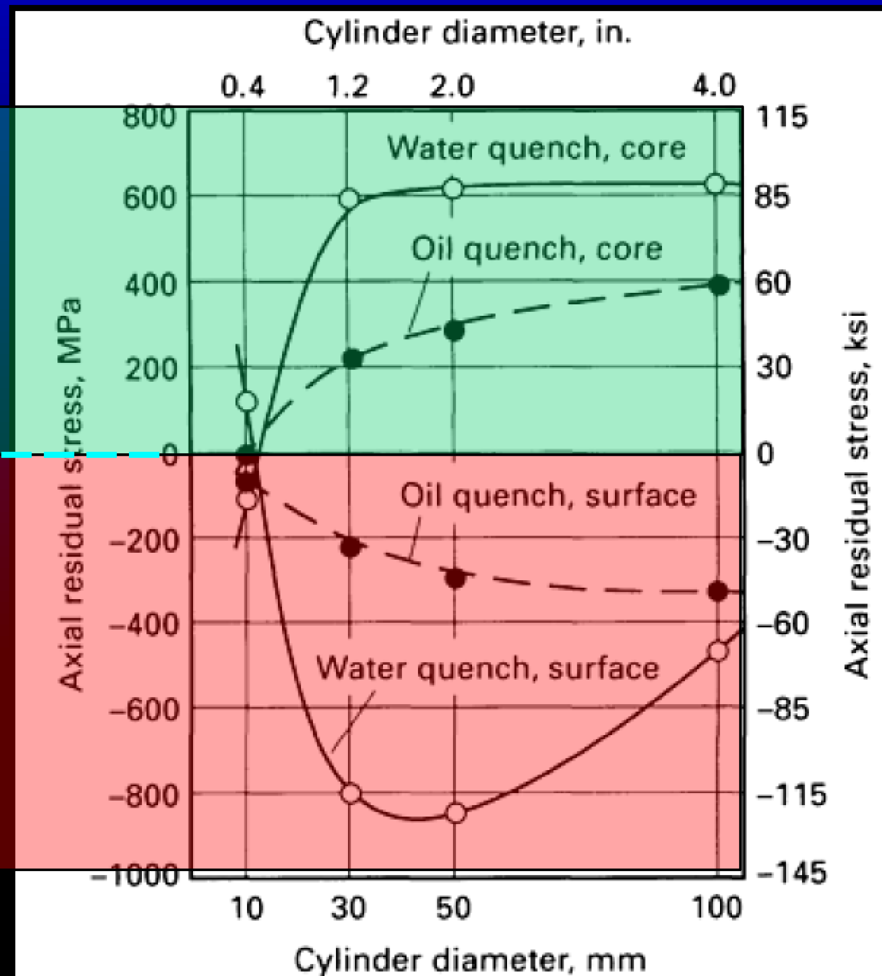


Failures Related to Heat Treating Operations - G.E. Totten, G.E. Totten & Associates, Inc. M. Narazaki, Utsunomia University (Japan) R.R. Blackwood, Tenaxol Inc.

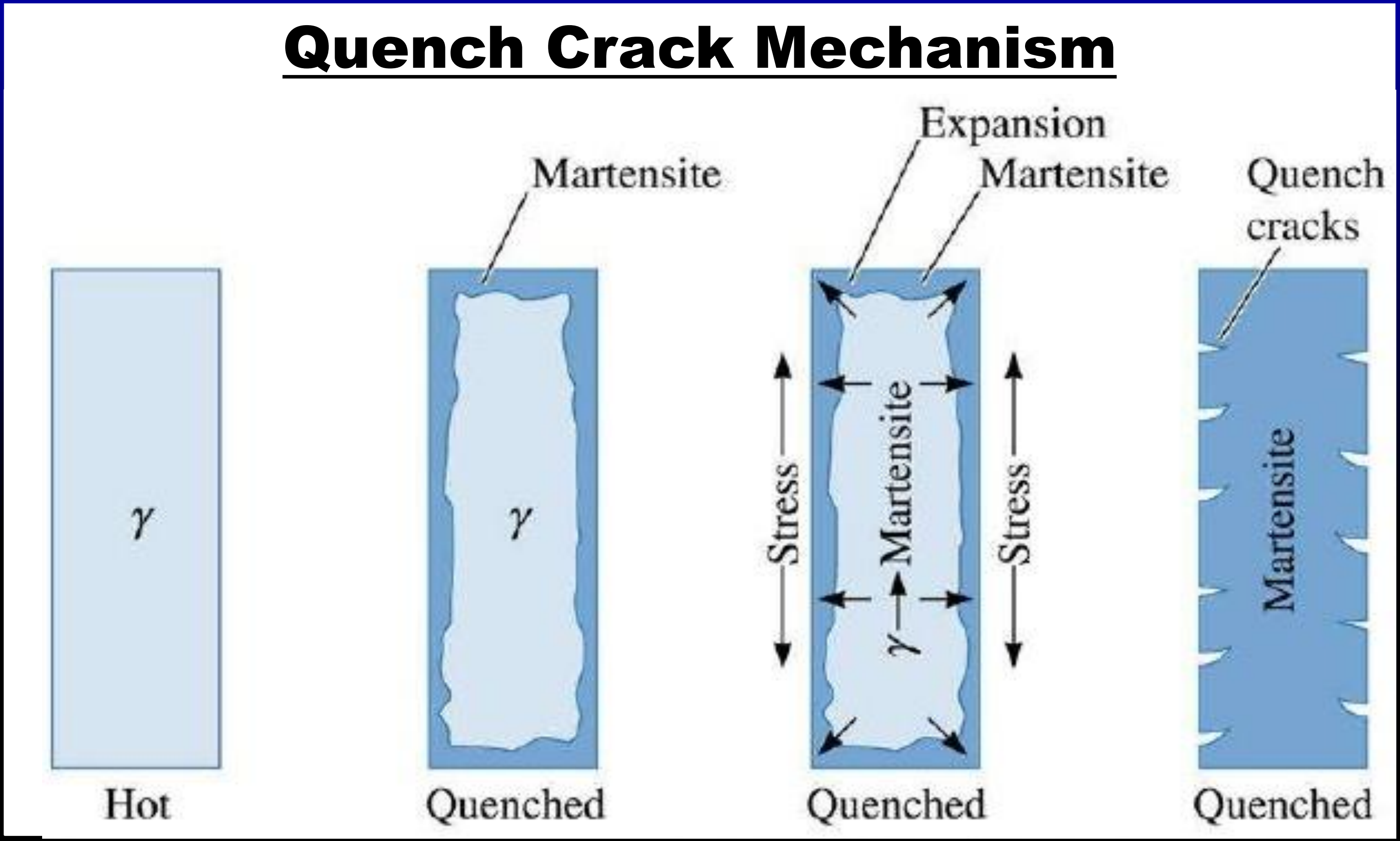
Introduction to residual stress
Effect of phase transformation

Core: Compressive stress

Surface: Tensile stress



Introduction to residual stress
Effect of phase transformation

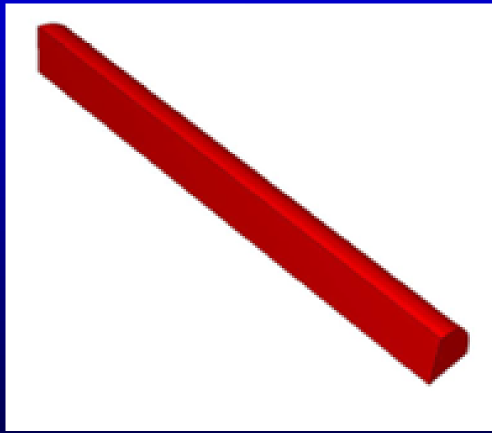


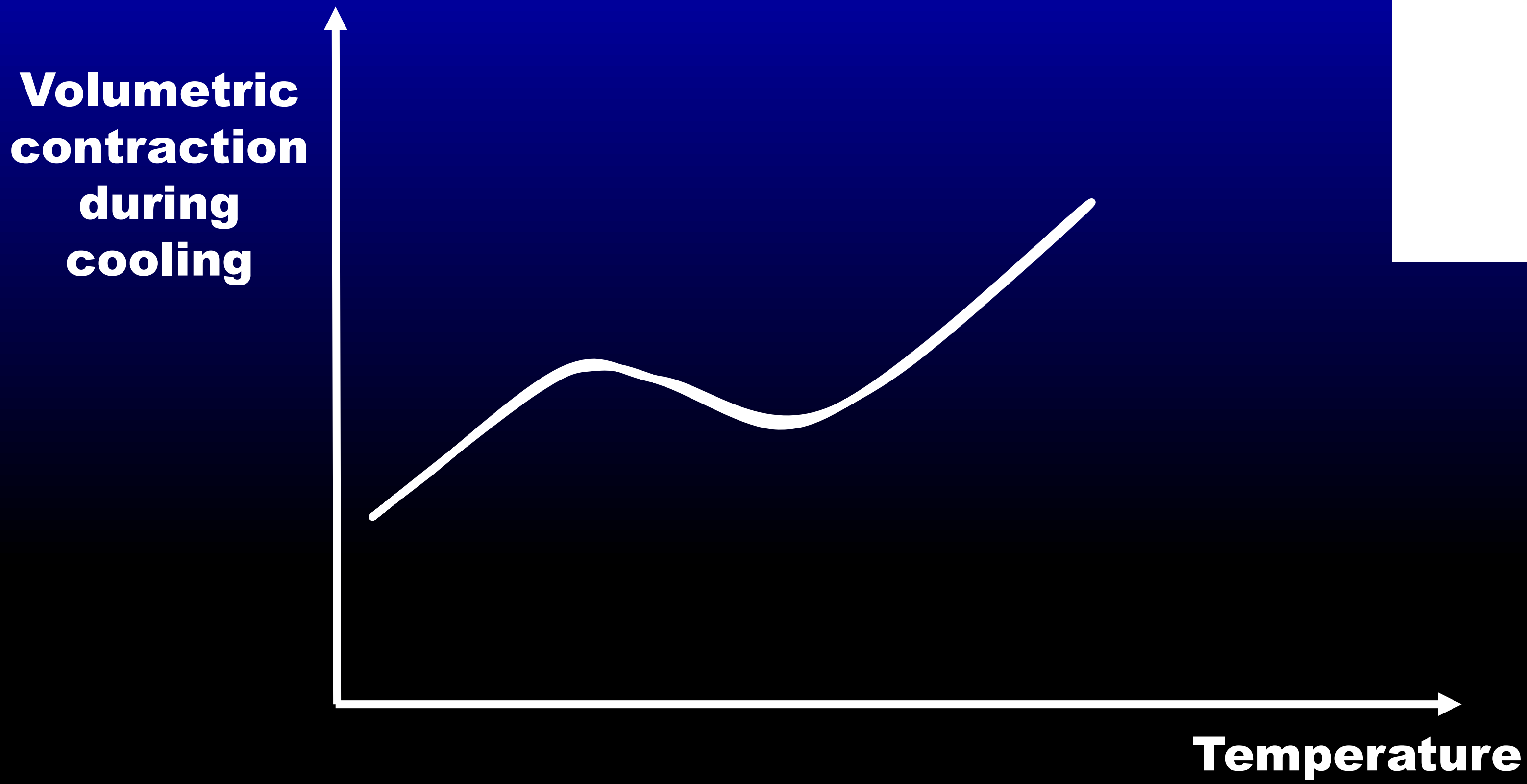
Introduction to residual stress

Effect of casting geometry

Introduction to residual stress

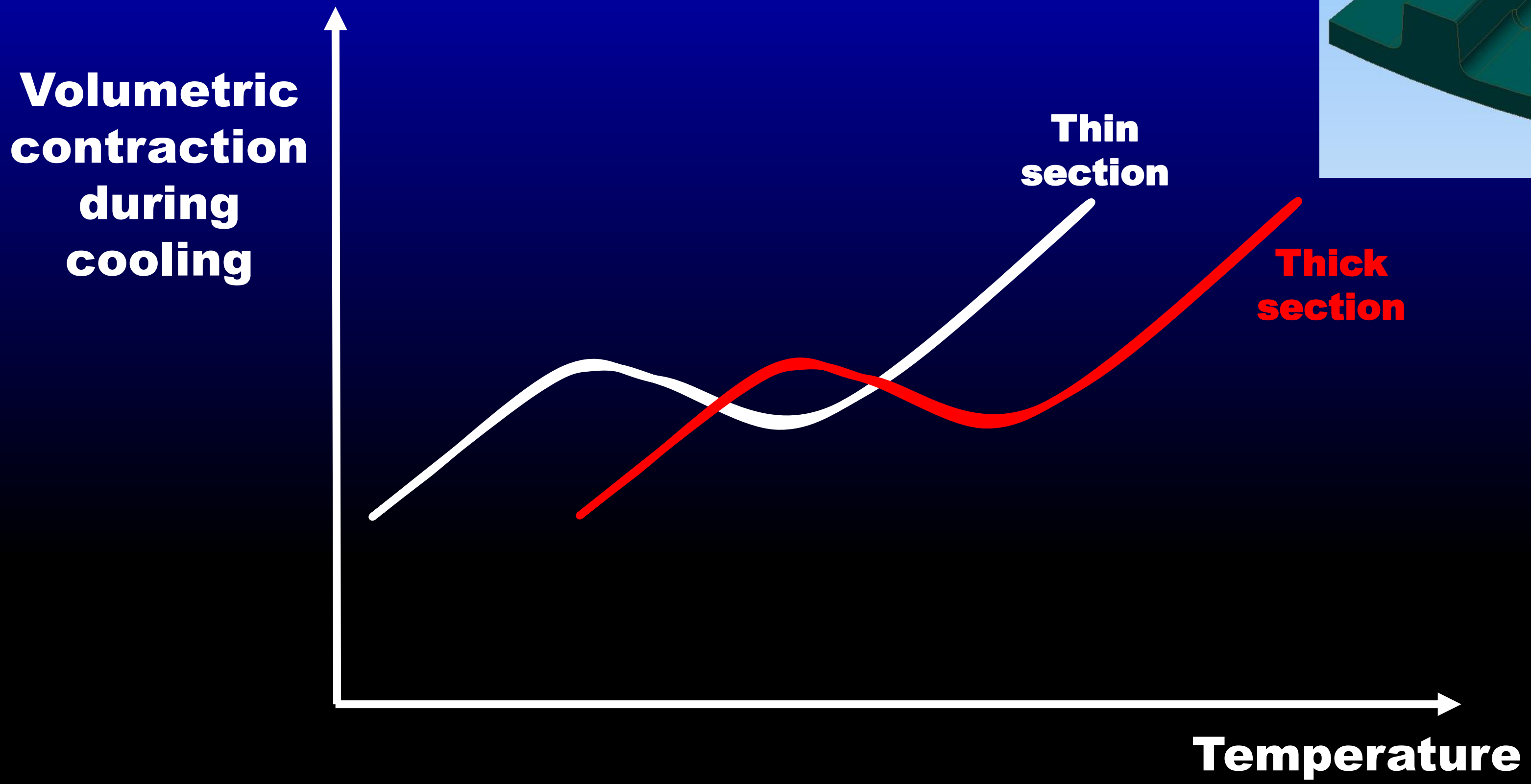
Effect of casting geometry

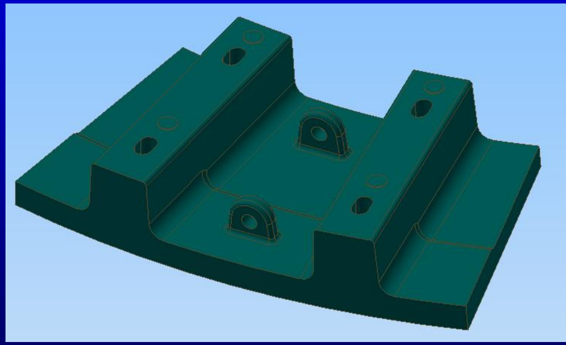




Introduction to residual stress

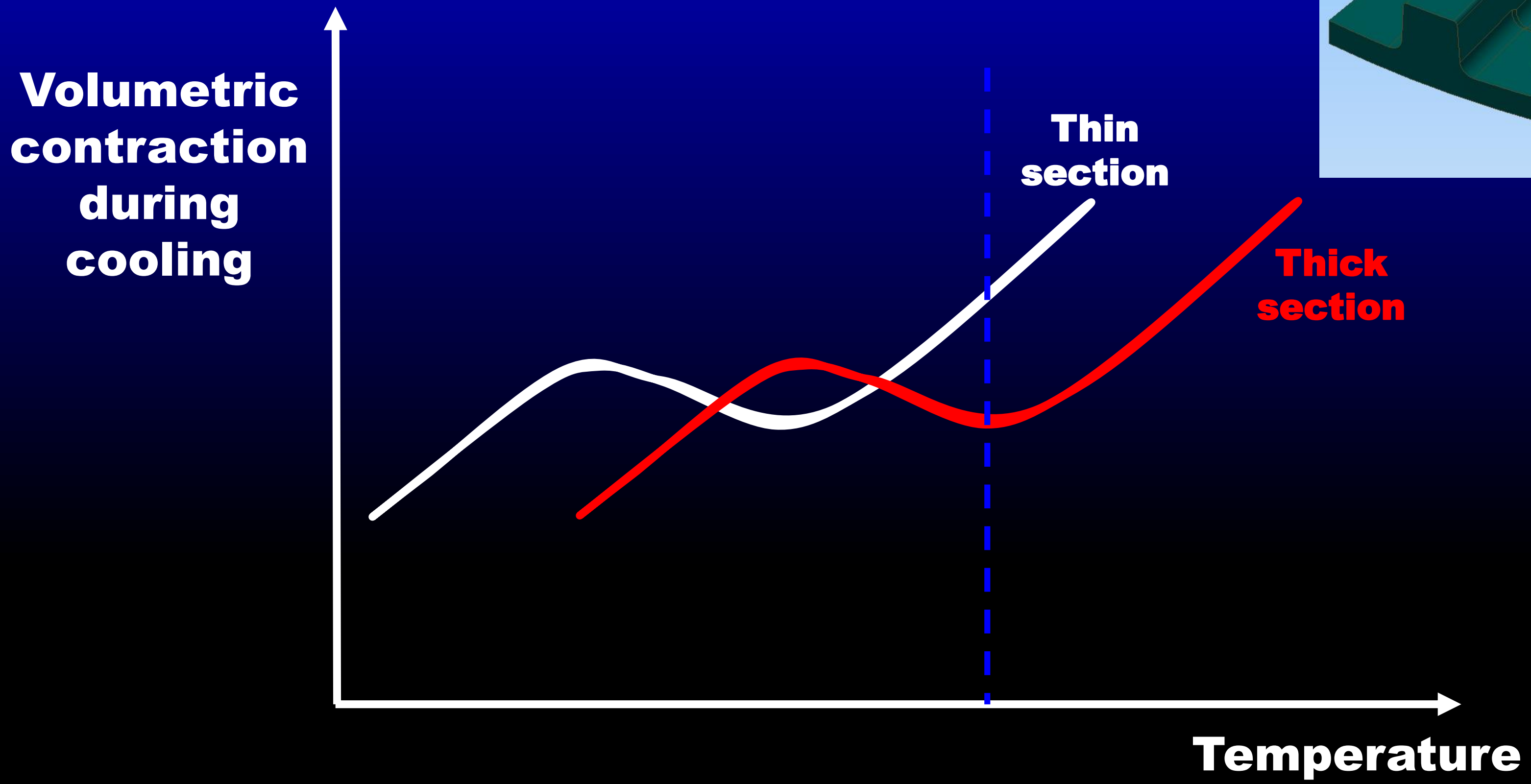
Effect of casting geometry

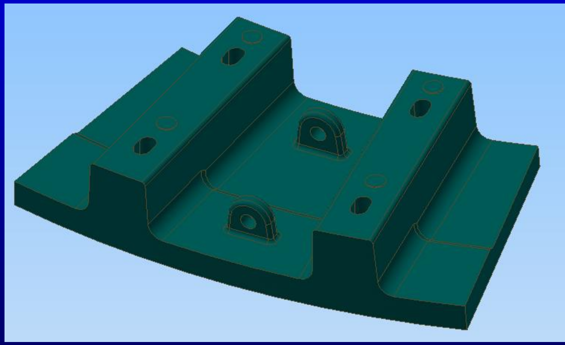




Introduction to residual stress

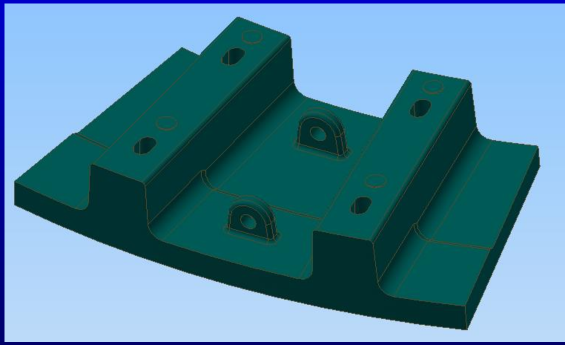
Effect of casting geometry

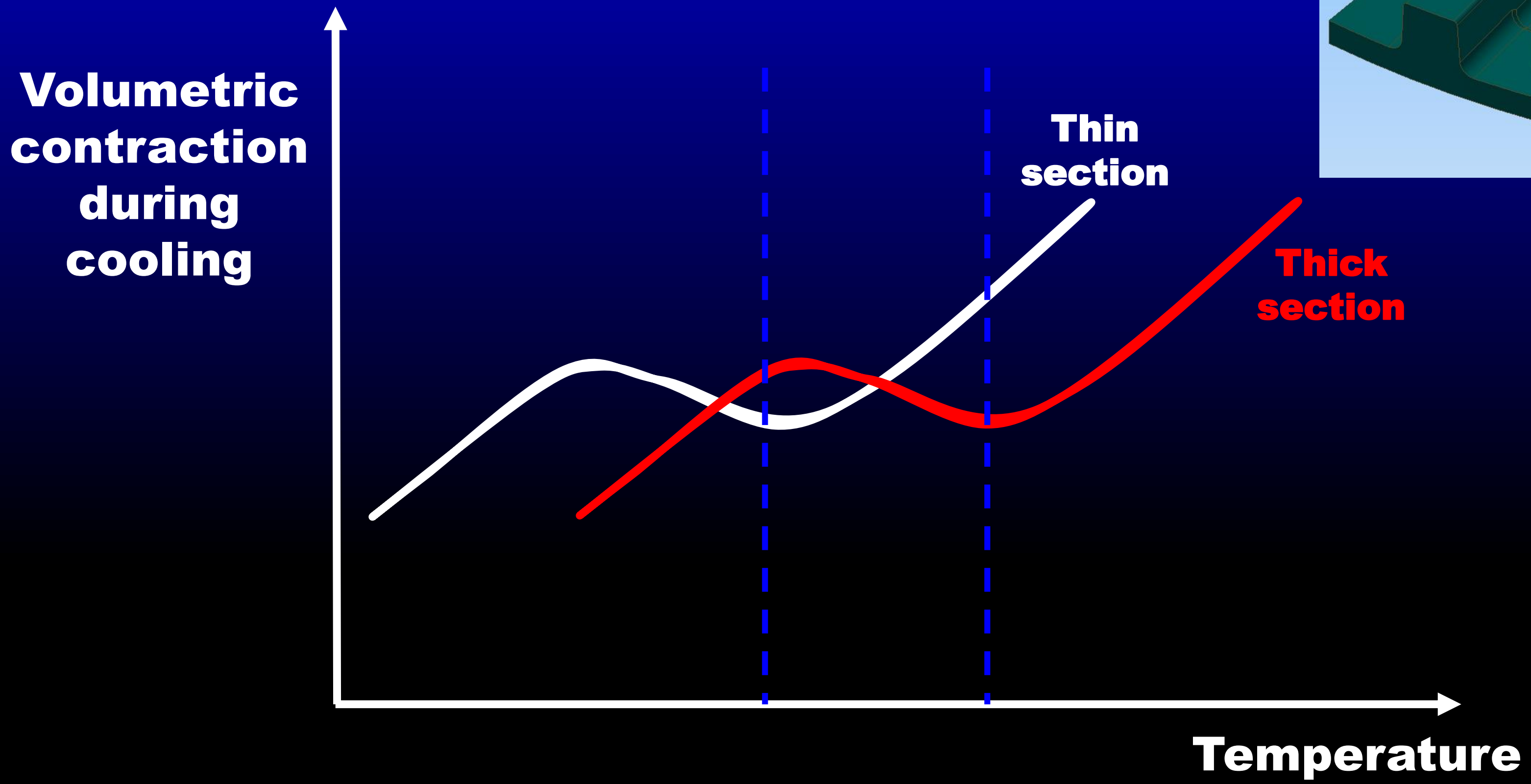




Introduction to residual stress

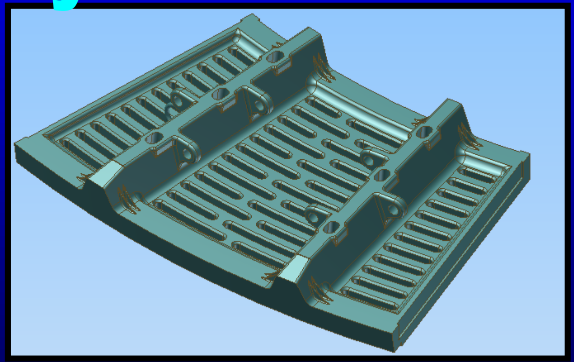
Effect of casting geometry

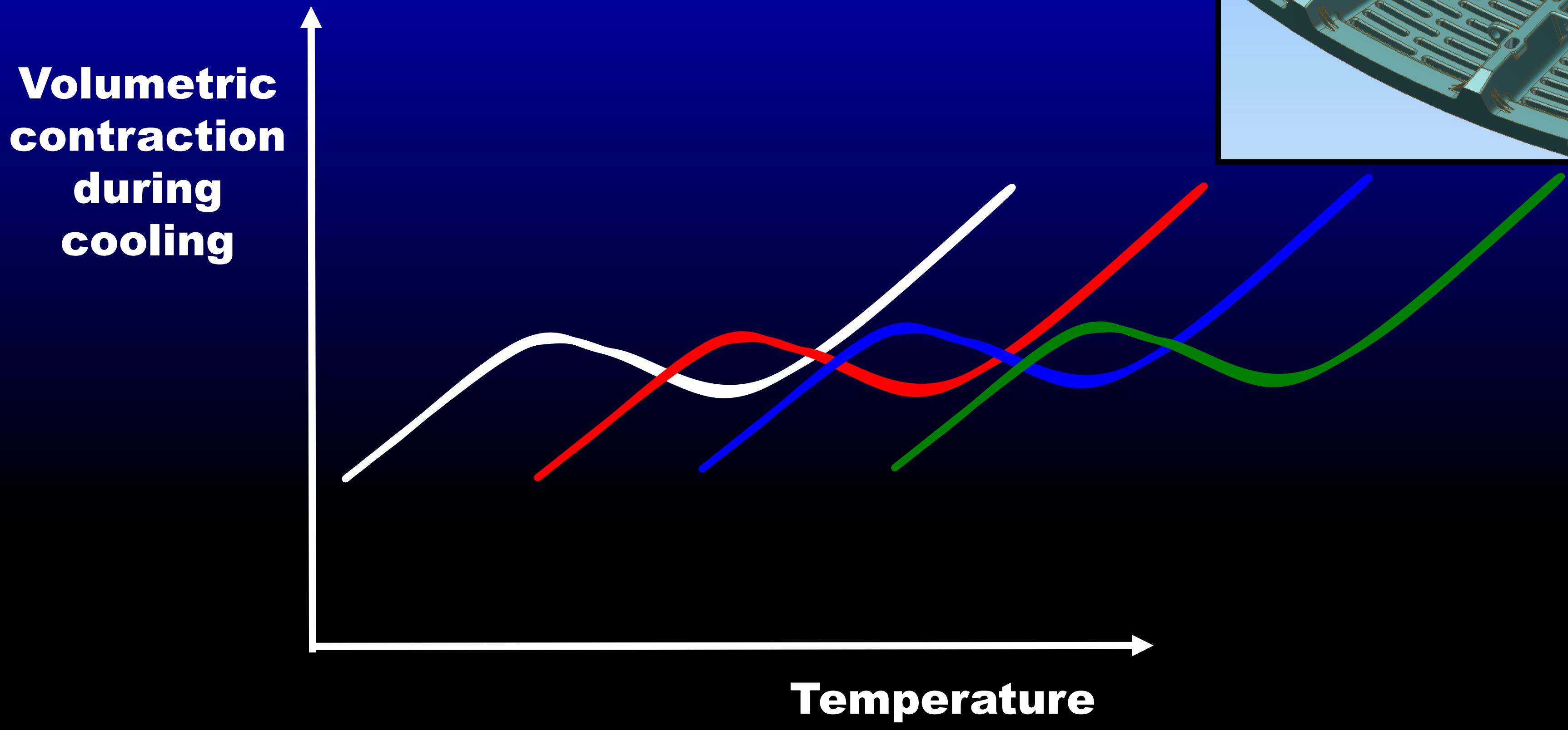




Introduction to residual stress

Effect of casting geometry





Objective

Objective

- The main objective of the article is to evaluate the reliability of the MAGMASOFT Stress Simulation to explain some distortion and breakage problems of Steel and Aluminum alloy castings;

- A second objective is to use the simulation tool to adjust the production process in order to minimize these problems;

Consequences of the residual stress

Consequences of the residual stress

- The main consequences of the tensile residual stresses are casting distortion and casting breakage;

Consequences of the residual stress

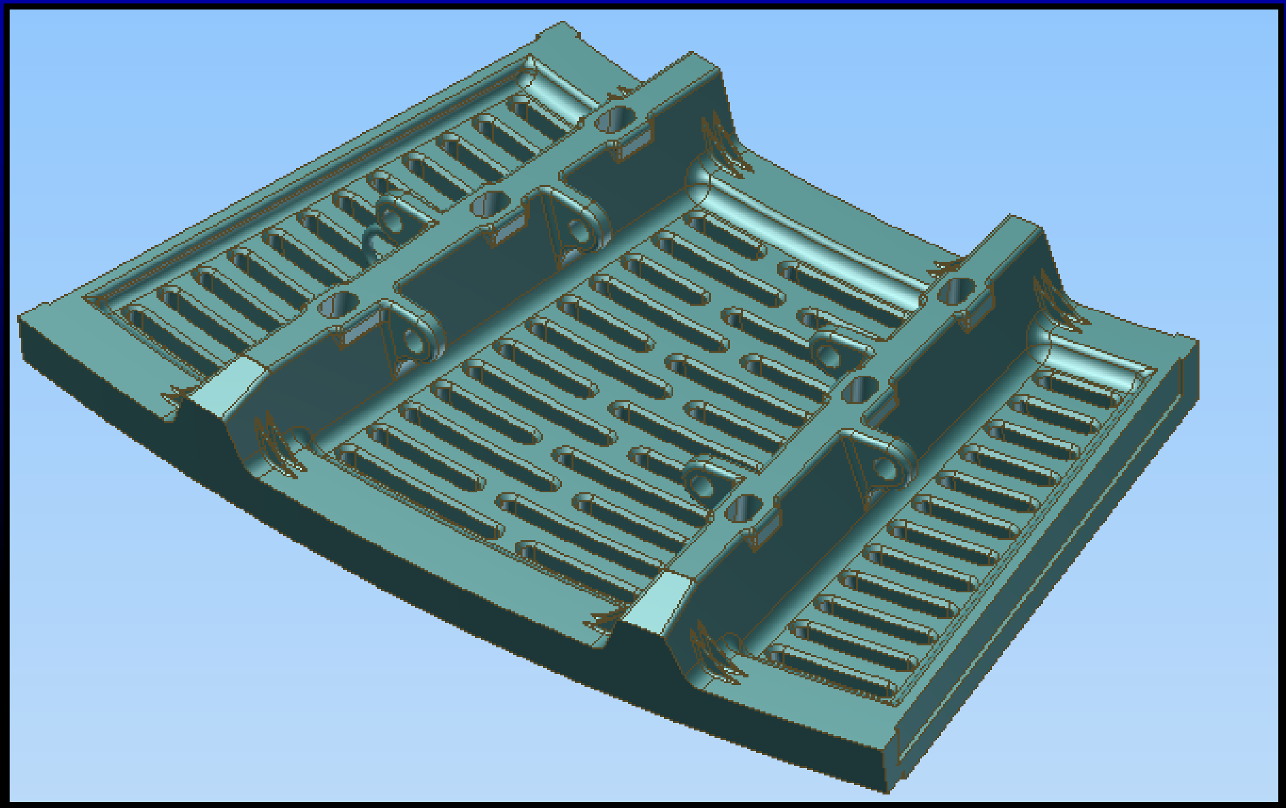
- Value of the tensile residual stresses:
  - **Stresses < YS** – Contribution to distortion or breakage in field application;
  - **Stresses > YS** - Distortion during manufacture and can break in the field;
  - **Stresses > UTS** - Fracture during the manufacture;

Case history #3

Fracture during heat treatment (steel casting)

Case history #3

Fracture during heat treatment (steel casting)



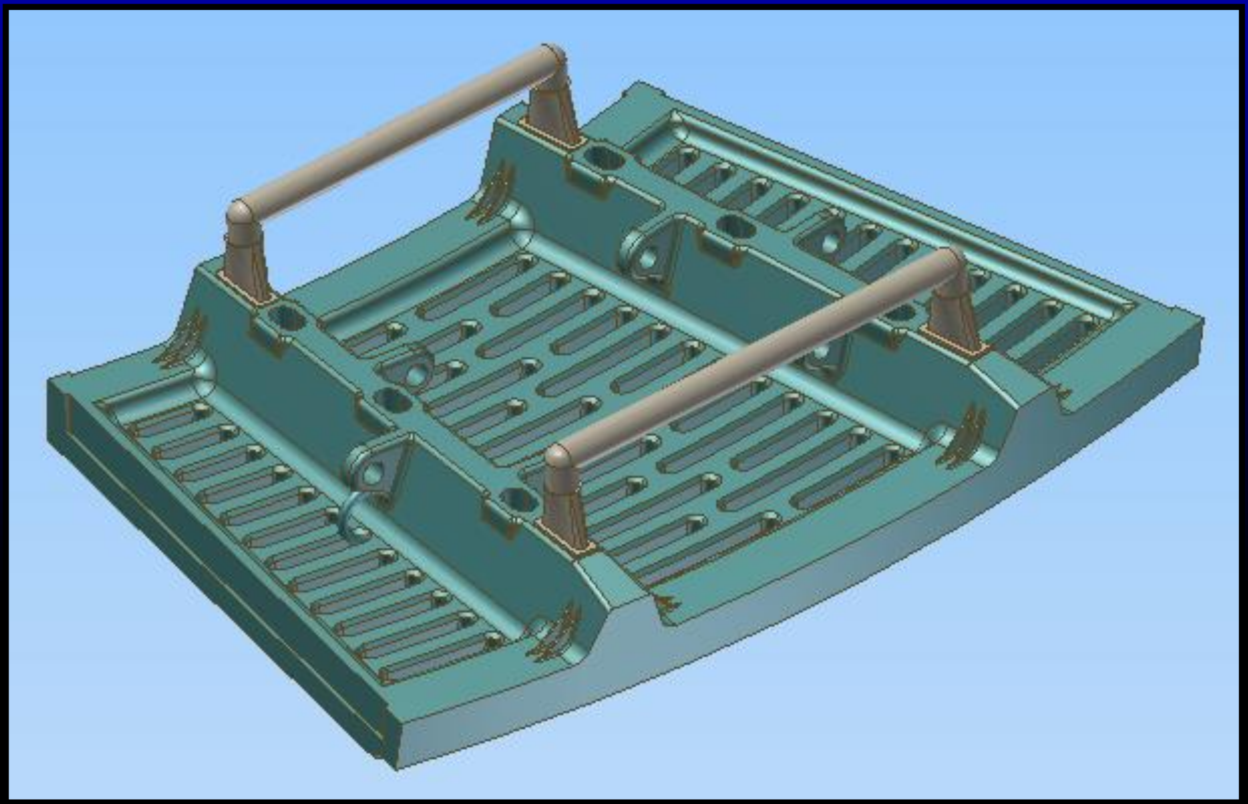
Grate Liner for SAG Mill

Part weight: 2670 kg

Alloy: Cr-Mo Pearlitic low alloy steel

Case history #3

Fracture during heat treatment (steel casting)

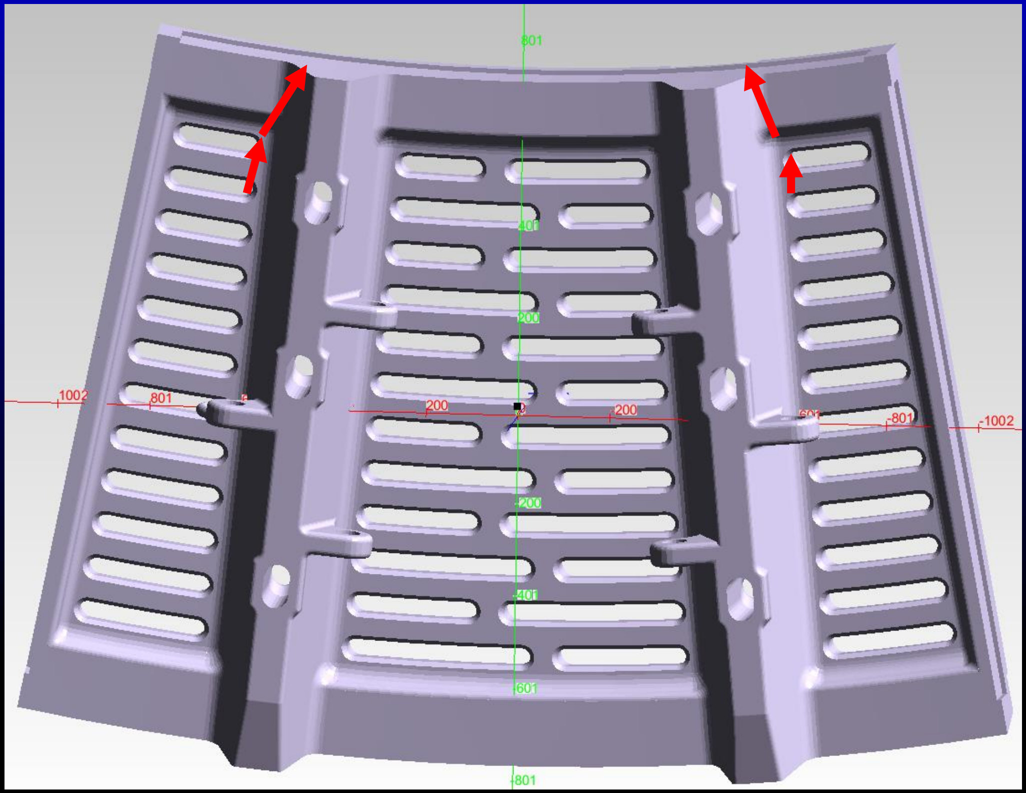


Grate Liner for SAG Mill

Peso: 942 kg

Case history #3

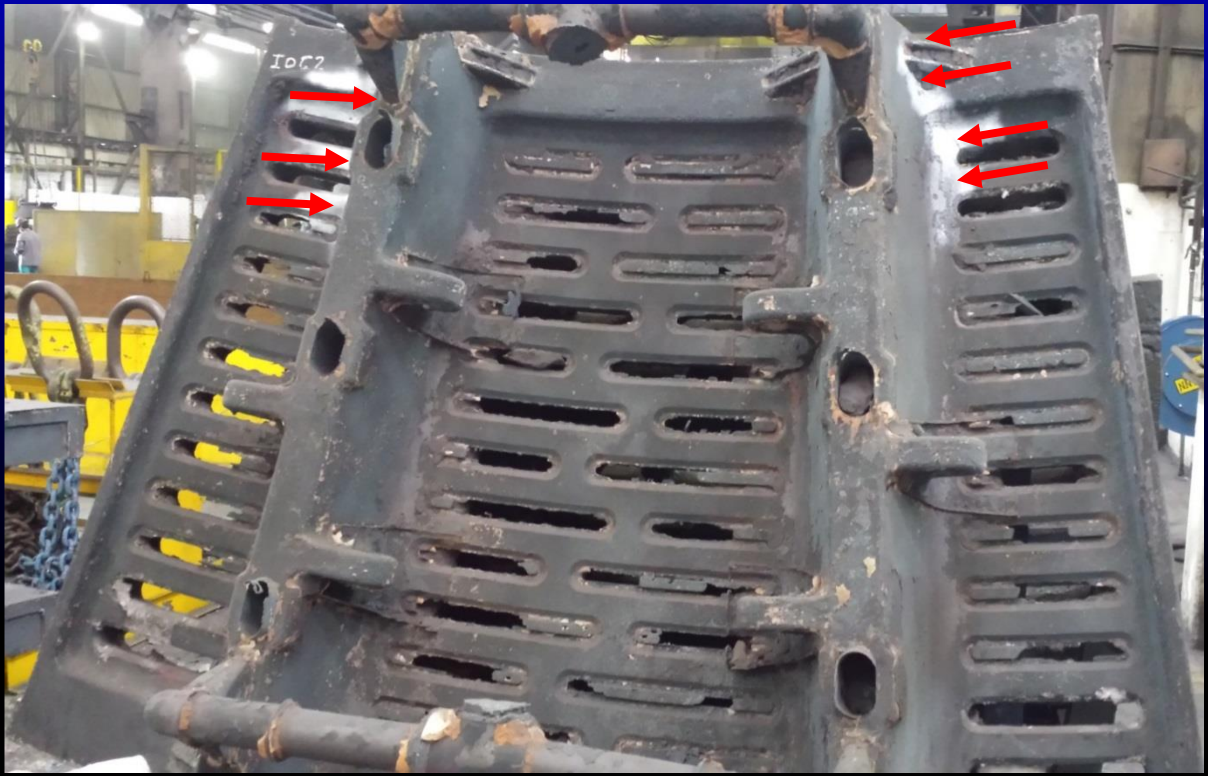
Fracture during heat treatment (steel casting)



Crack position at the end of Normalizing heat treatment (still air cooling)

Case history #3

Fracture during heat treatment (steel casting)



Crack position at the end of Normalizing heat treatment (still air cooling)

Case history #3

Fracture during heat treatment (steel casting)

Crack position at the end of Normalizing heat treatment (still air cooling)

Case history #3

Fracture during heat treatment (steel casting)

Failure analysis - Crack position with lateral displacement of the material

Case history #3

Fracture during heat treatment (steel casting)

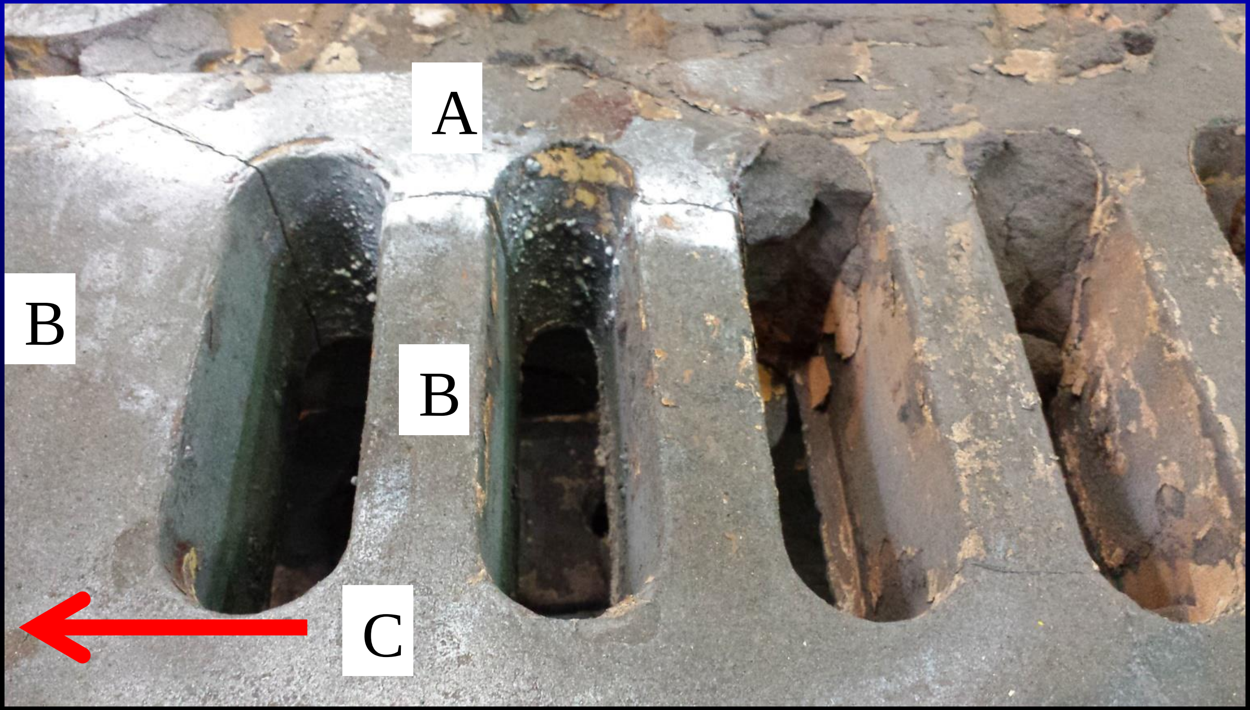
Failure analysis – Fracture surface without oxidation (low temperature) and evident Chevron marks.

Case history #3

Fracture during heat treatment (steel casting)

Failure analysis – Fracture surface without oxidation (low temperature) and evident Chevron marks showing the fracture propagation direction.

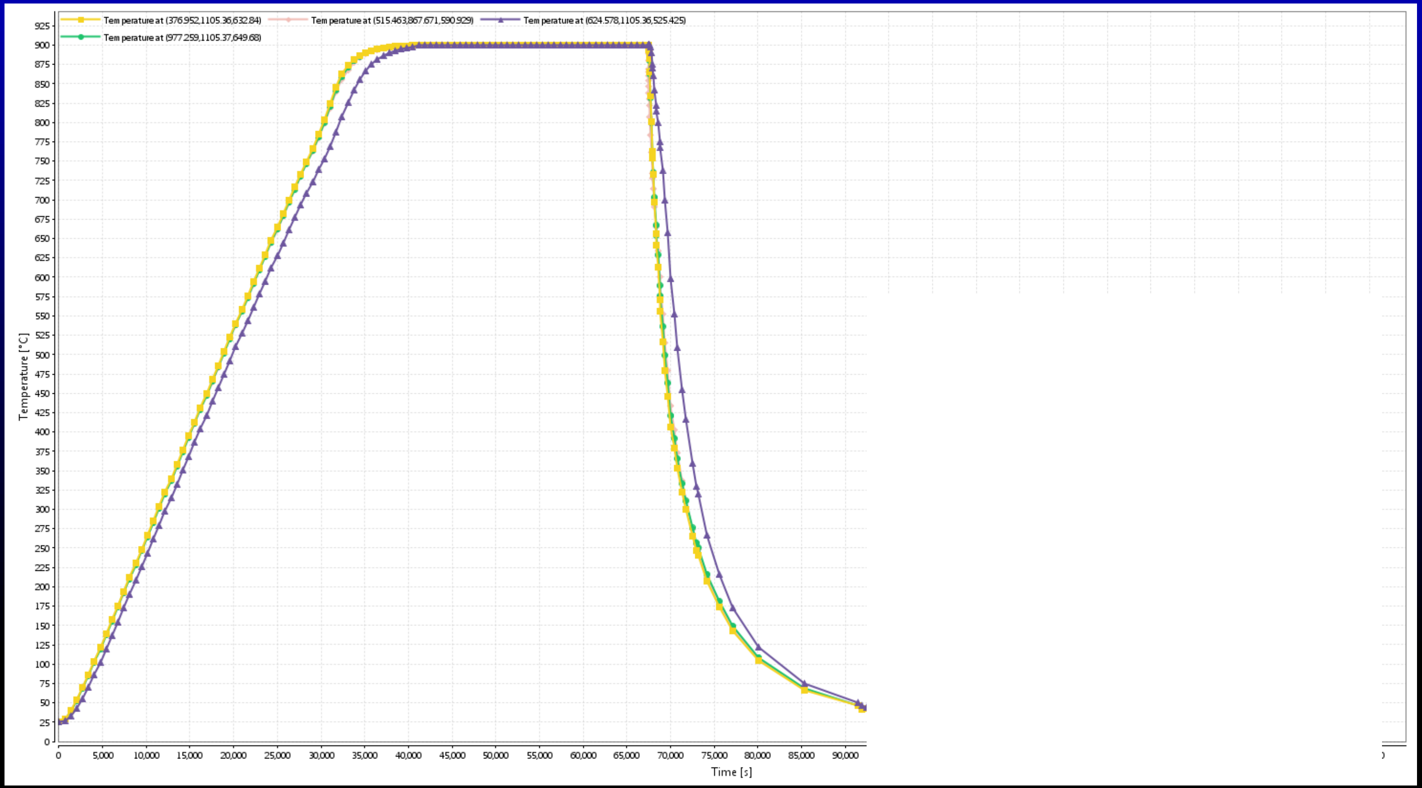
Case history #3
Fracture during heat treatment (steel casting)



Fracture mechanism – The thin sections B are the first to transform in Pearlite with free expansion. When section C transform in Pearlite, the correspondent expansion displace the lateral bar left and imposes tensile stress in the B section which is restricted by the thick A section, promoting the crack.

Case history #3

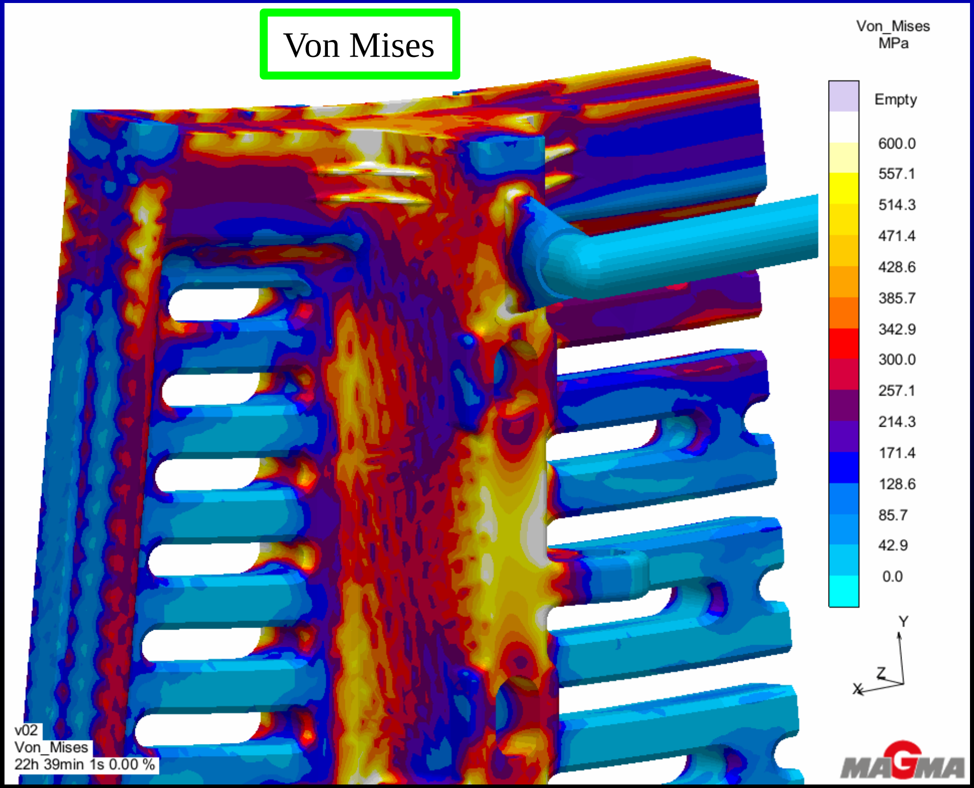
Fracture during heat treatment (steel casting)



Typical temperature curves variation from thin and thick regions of the casting during the normalizing heat treatment.

Case history #3

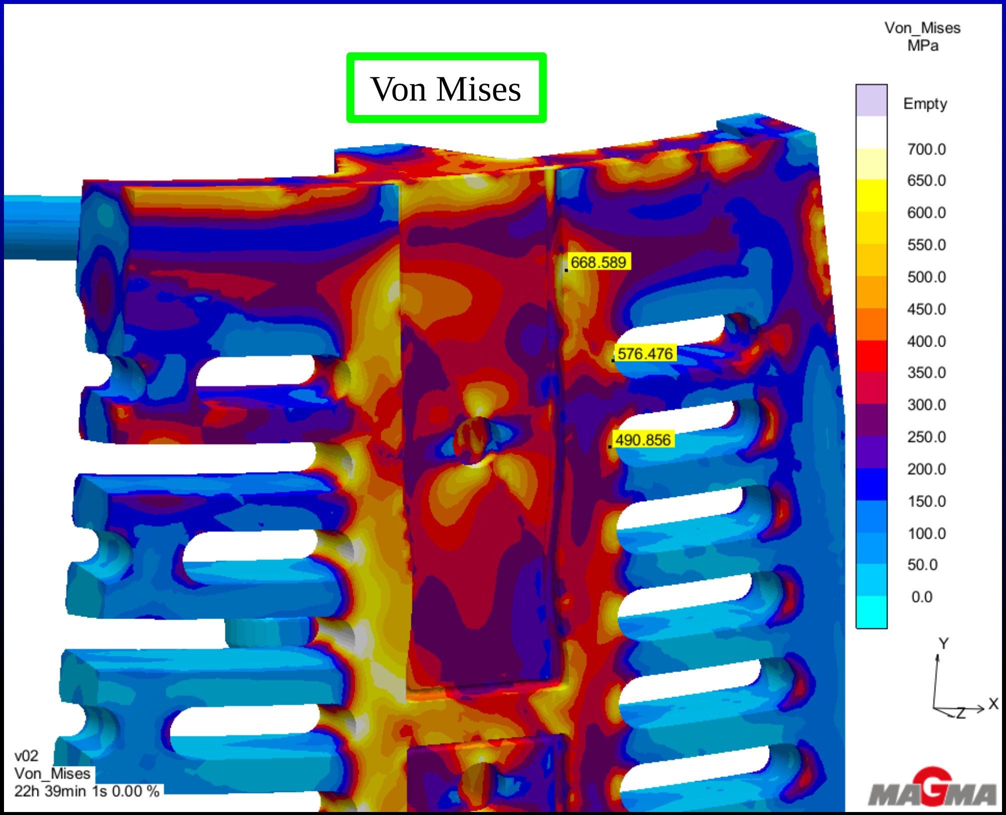
Fracture during heat treatment (steel casting)



Result of the stress simulation after the normalizing heat treatment: the maximum stress level is around 700 MPa and the UTS is around 700 MPa.

Case history #3

Fracture during heat treatment (steel casting)



Result of the stress simulation after the normalizing heat treatment: the maximum stress level is around 700 MPa and the UTS is around 700 MPa.

Case history #3

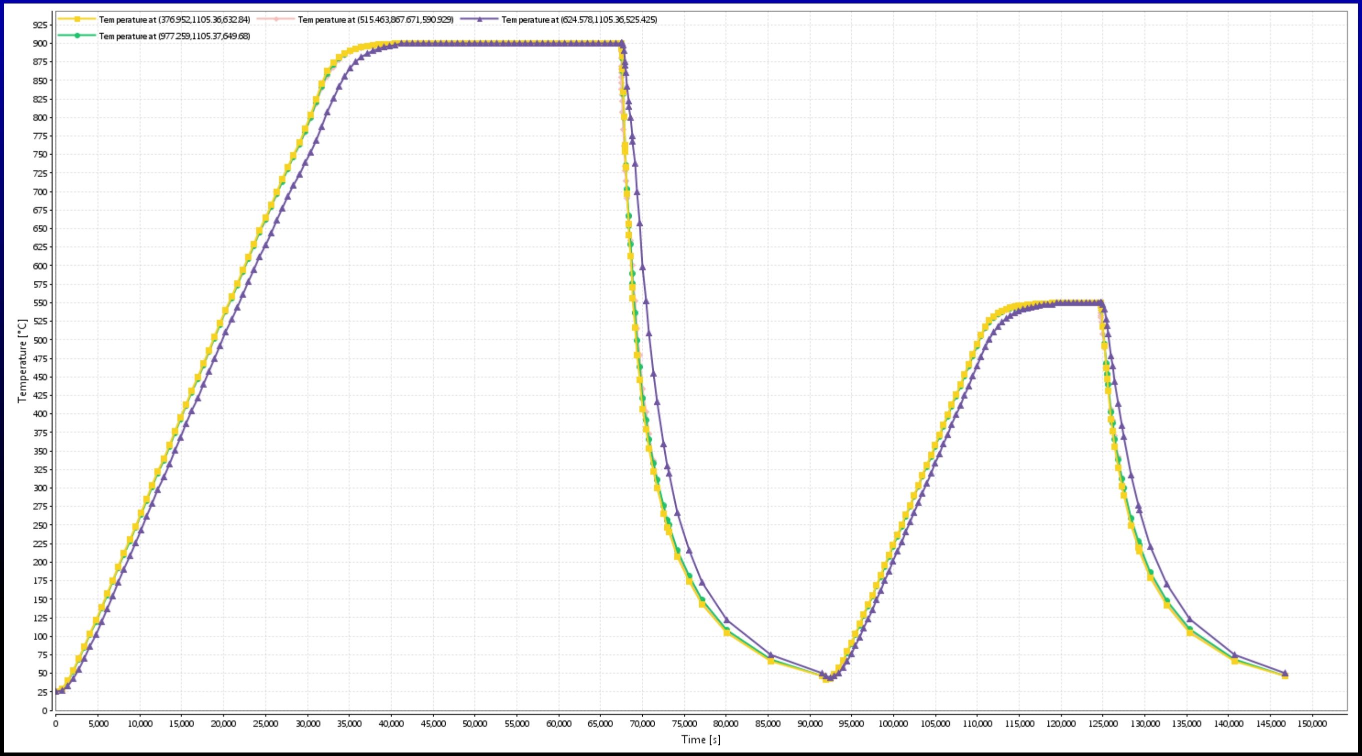
Fracture during heat treatment (steel casting)

- The maximum level of residual stress formed due to the normalizing heat treatment are around 700 MPa and the ultimate tensile strength of the low alloy steel is also around 700 MPa, so the residual stress should explain the fractures after normalizing heat treatment;

- Aiming to reduce the crack formation, the heat treatment was adjusted using the stress relieved immediately after normalizing heat treatment.

Case history #3

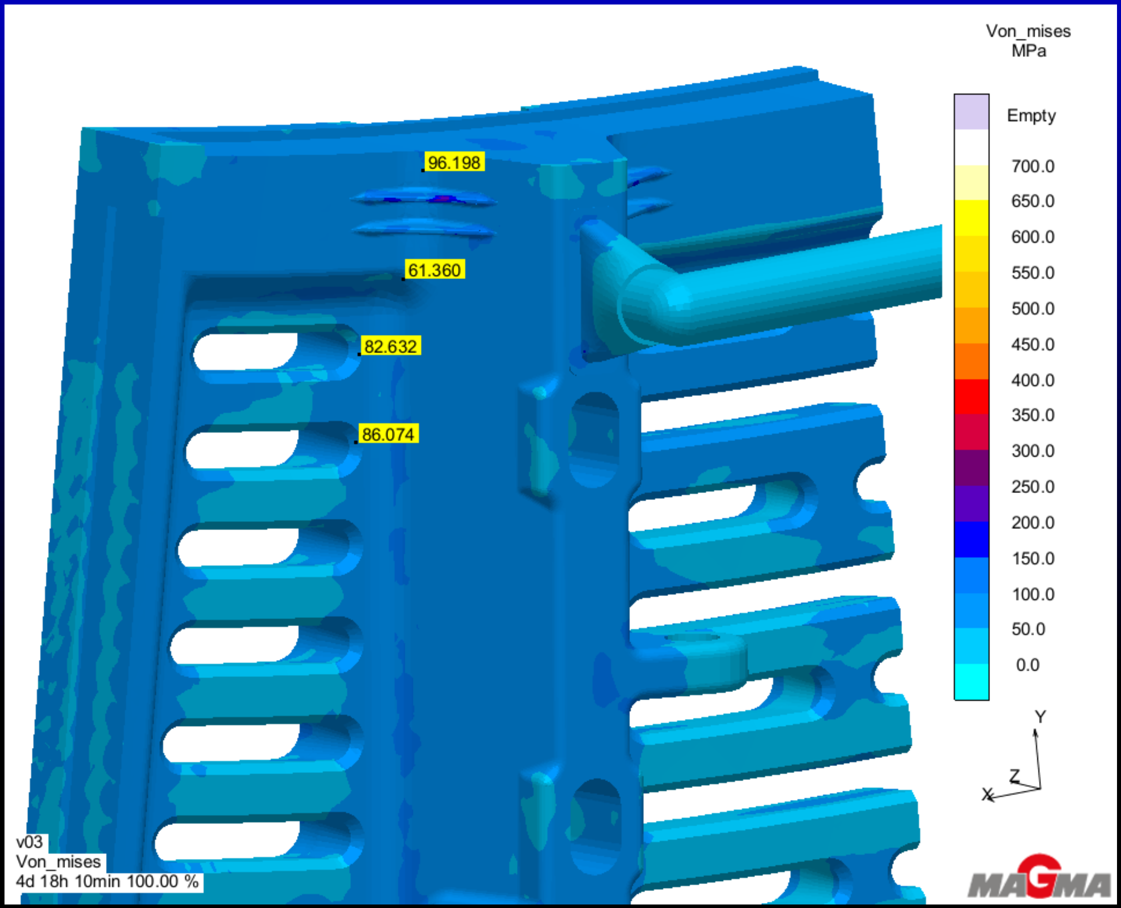
Fracture during heat treatment (steel casting)



Typical temperature curves variation from thin and thick regions of the casting during the normalizing and stress relieve heat treatment.

Case history #3

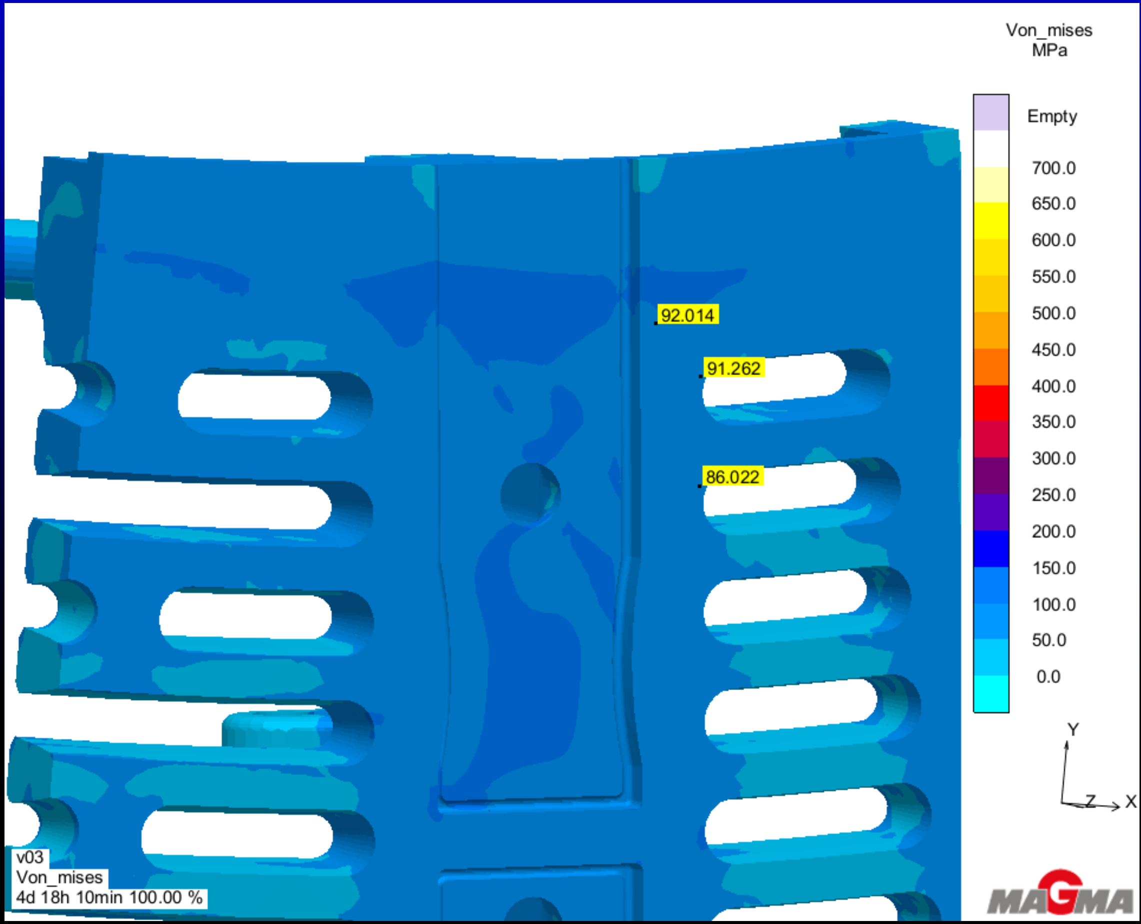
Fracture during heat treatment (steel casting)



Result of the stress simulation after the normalizing and stress relieve heat treatment: the maximum stress level was reduced to around 100 MPa.

Case history #3

Fracture during heat treatment (steel casting)



Result of the stress simulation after the normalizing and stress relieve heat treatment: the maximum stress level was reduced to around 100 MPa.

Case history #3

Fracture during heat treatment (steel casting)

- The maximum level of residual stress formed due to the normalizing heat treatment are around 700 MPa and the ultimate tensile strength of the low alloy steel is also around 700 MPa, so the residual stress should explain the fractures after normalizing heat treatment;

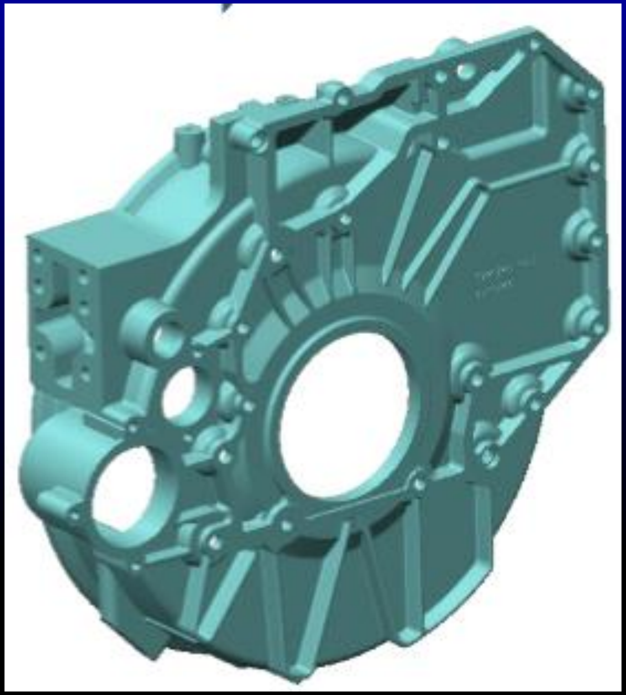
- Using the stress relieve heat treatment immediately after normalizing the residual stress level was reduced to around 100 MPa.

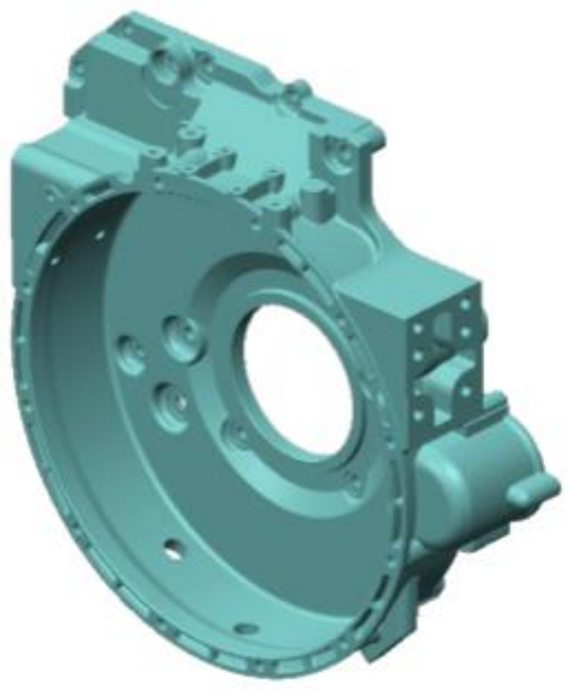
Case history #4

Distortion during heat treatment (Al casting)

Case history #4

Distortion during heat treatment (Al casting)

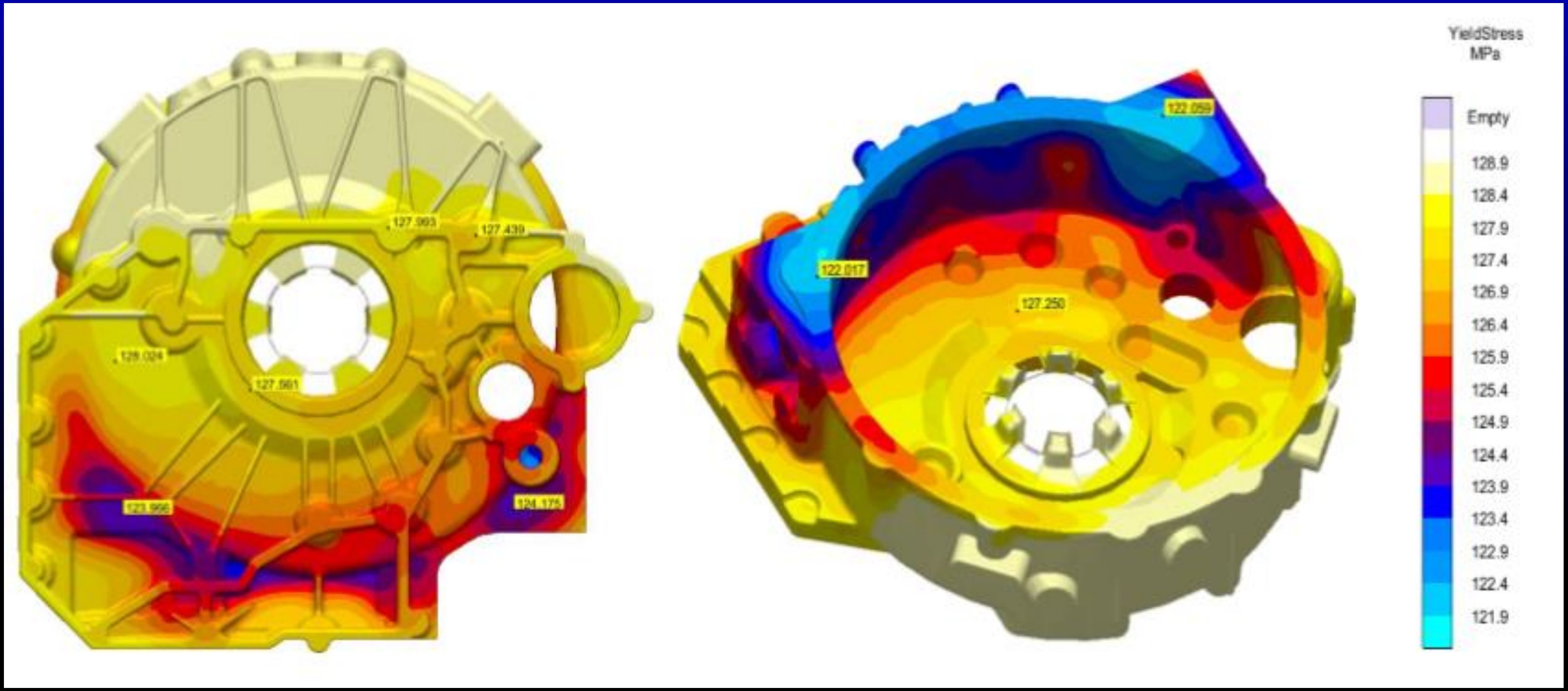




Flywheel housing for diesel engine

Alloy: A356 T6 aluminum alloy

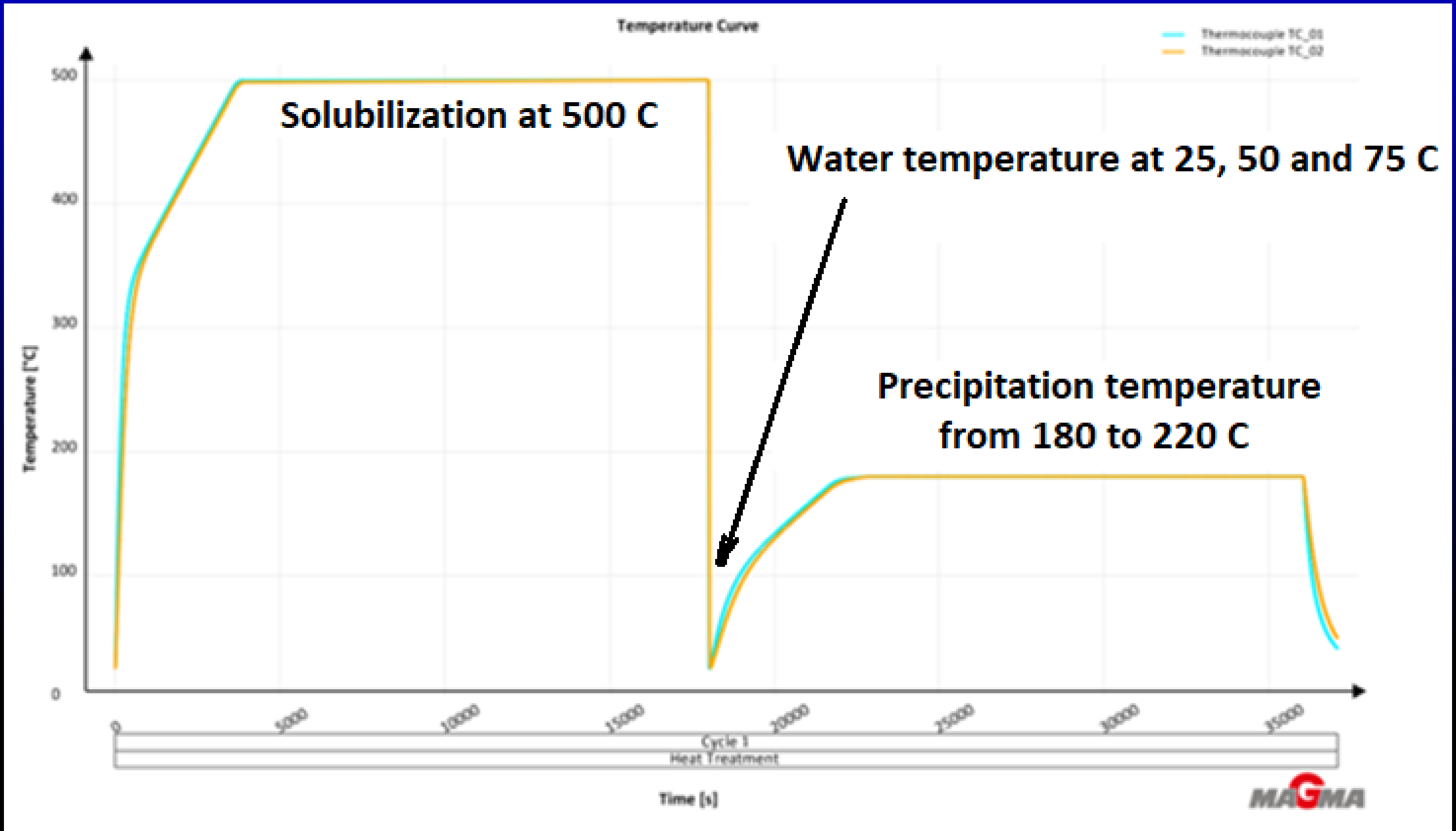
Case history #4
Distortion during heat treatment (Al casting)



Yield strength values in the as cast condition estimated by simulation (minimum value around 120 MPa)

Case history #4

Distortion during heat treatment (Al casting)



Description of the T6 heat treatment using a quench in water after the solution cycle which imposes residual stress.

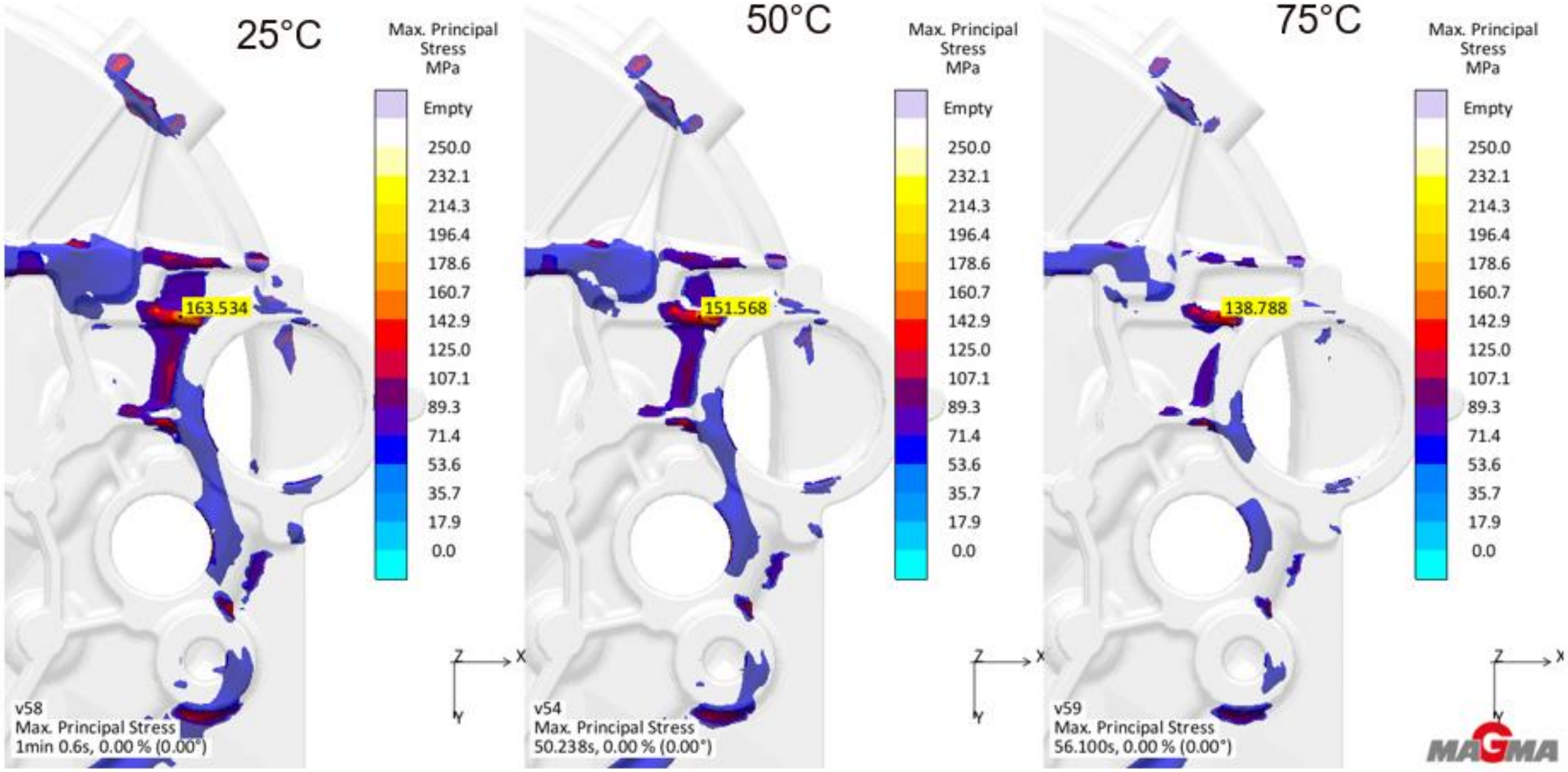
Case history #4

Distortion during heat treatment (Al casting)

- **Critical step to residual stress is water quench**
- **Typical YS during quenching = 120 MPa**

Case history #4

Distortion during heat treatment (Al casting)

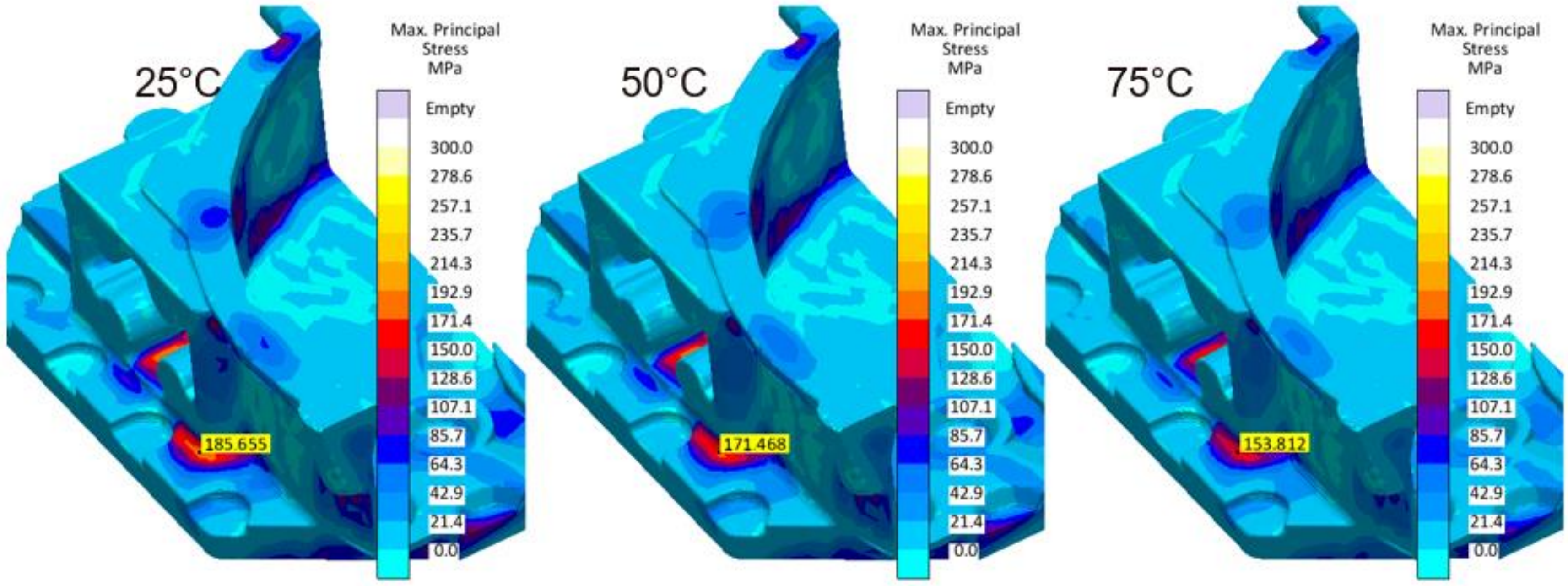


Maximum residual stress level is over YS and near the UTS value

HIGH PROBABILITY OF DISTORTION

Case history #4

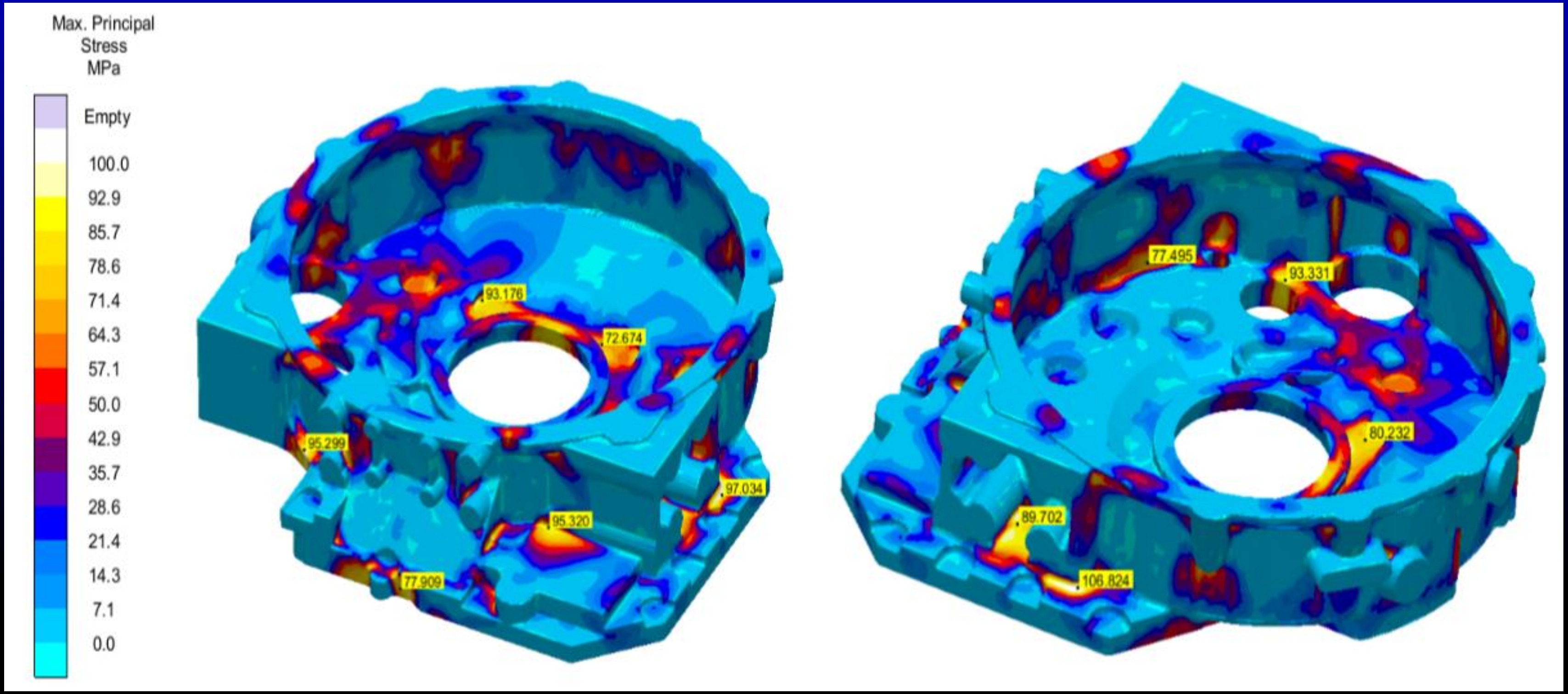
Distortion during heat treatment (Al casting)



Reduction of around 20% of the residual stresses level with increasing the water temperature from 25 to 75 C.

Case history #4

Distortion during heat treatment (Al casting)



Final stress level after complete heat treatment estimated by stress simulation (residual stress level of 105 MPa compromises almost 50% of the YS)

Case history #4

Distortion during heat treatment (Al casting)

- **Water temperature has a little effect on residual stress**
- **in order to reduce distortion = casting design adjustment**

Thank you