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Prediction of hot tearing of aluminium alloys

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Acknowledgement of **Country**

The University of Queensland (UQ) acknowledges the Traditional Owners and their custodianship of the lands on which we meet.

We pay our respects to their Ancestors and their descendants, who continue cultural and spiritual connections to Country.

We recognise their valuable contributions to Australian and global society.

Outlines

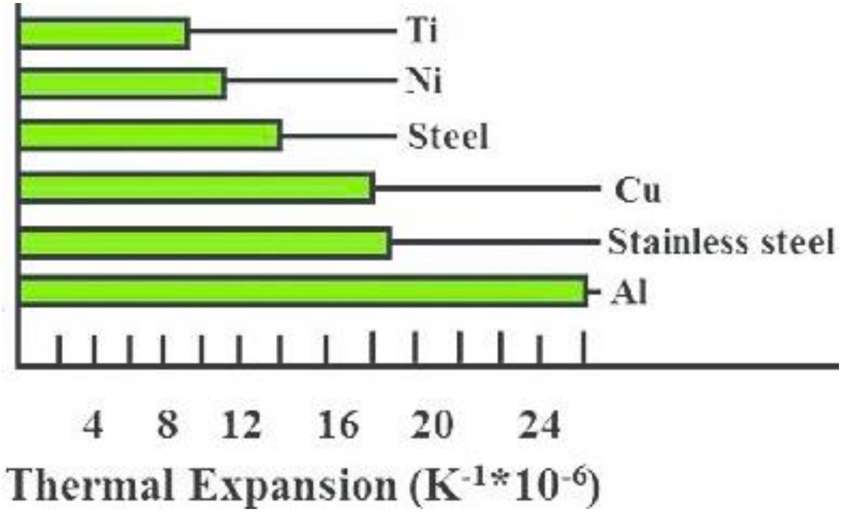
- Background
- Experiments, results, and validation using the ProCAST Virtual Casting Tool
- Conclusions

Hot tearing

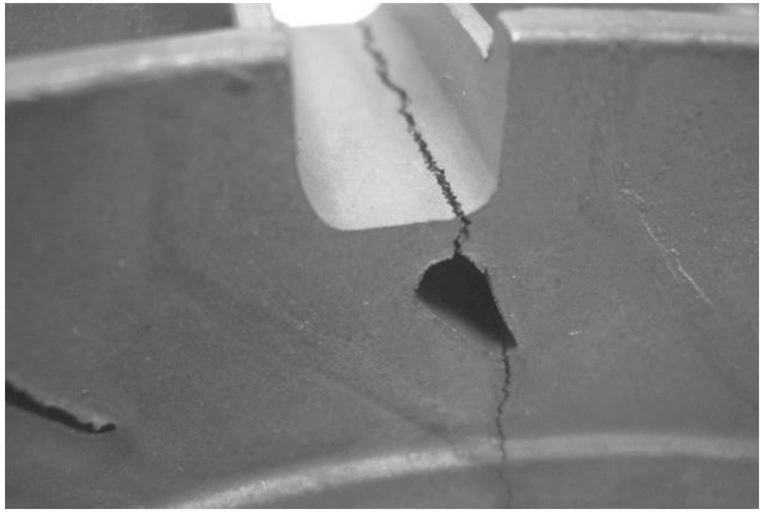
- Hot tearing is a common casting defect and is one of the key issues defining an alloy's castability
- The subject has been extensively studied through various perspectives
- Work continues on developing our understanding of the physics at play while the underlying cause of hot tearing is understood
- Numerous hot tear experiments have been developed using different configurations and various levels of complexity
- Many models have also been developed to predict hot tearing using computational models and simulation with those models
- The objective of this study is to access the capability and reliability of the virtual casting software tool ProCAST from ESI Group to predict the hot tearing of aluminium alloys

Hot tearing

- Aluminium casting will develop a high level of stress due to their high thermal contraction during solidification and cooling.
- This stress causes distortion, e.g. due to shrinkage constraints in the mould or cracks.



Extreme distortion caused by residual stresses



Tearing/Cracking caused by stress

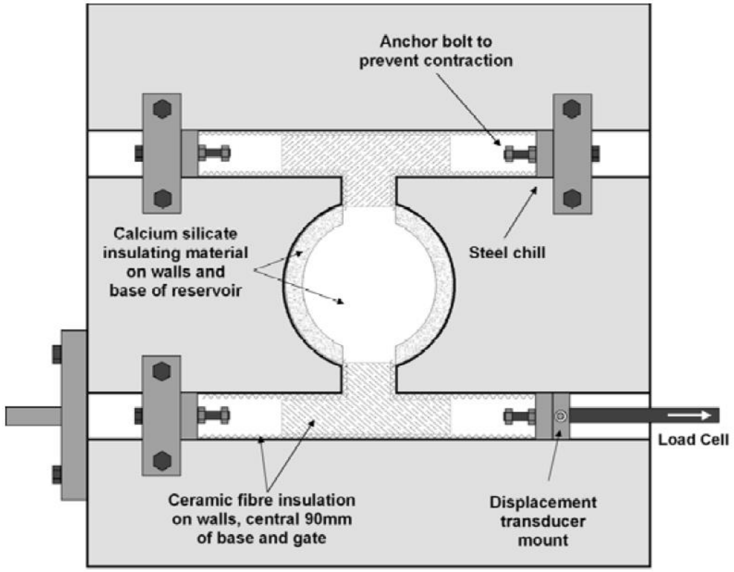
Hot tearing

Numerous theories and models have been proposed to predict hot tearing since the 1950s:

- Early theories considered issues such as strain accommodation during solidification, liquid feeding to compensate for solidification shrinkage, or the proportion of time during solidification that an alloy is prone to tearing.
- These early theories were able to qualitatively predict hot tearing susceptibility as a function of alloy composition but were quite difficult to apply.
- More recently, sophisticated models have been developed which take into account both the fluid flow and the deformation of the solid network. Further developments have incorporated capillary effects and equiaxed grain structures.
- These models are able to predict variations in hot tearing susceptibility as a function of casting parameters; some having been directly tested against actual casting trials.

Hot tearing research at UQ

- Solidification study since 1960s
- The CAST hot tear rig developed by the 1990s PhD Stephen Instone
- This has seen further work by the 2011 PhD David Viano
  - A range of Al-Cu and Al-Zn alloys
  - Hot tear severity was quantified
  - Data from the experiments was used to validate some established models.
- Current hot tearing study
  - Industrially focused
  - The simulation tool ProCAST is used to predict the hot tearing



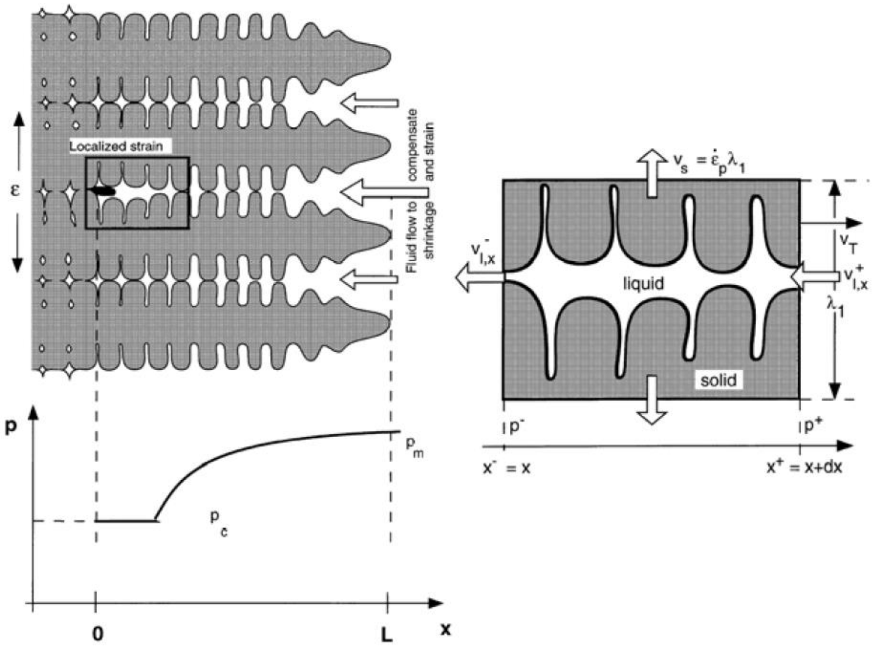
C

Hot tearing criterion in ProCAST

Rappaz-Drezet-Gremaud (RDG) hot tearing criterion is available within the software

The RDG criterion is based on the two pressure drop contributions associated with deformation (*ΔP*$_\varepsilon$) and shrinkage (*ΔPsh*).

- The interdendritic fluid flow using Darcy's law and treats the mush as a porous medium in which the permeability decreases as the solid fraction increases.
- The tensile deformation of the solid skeleton perpendicular to the growing dendrites.

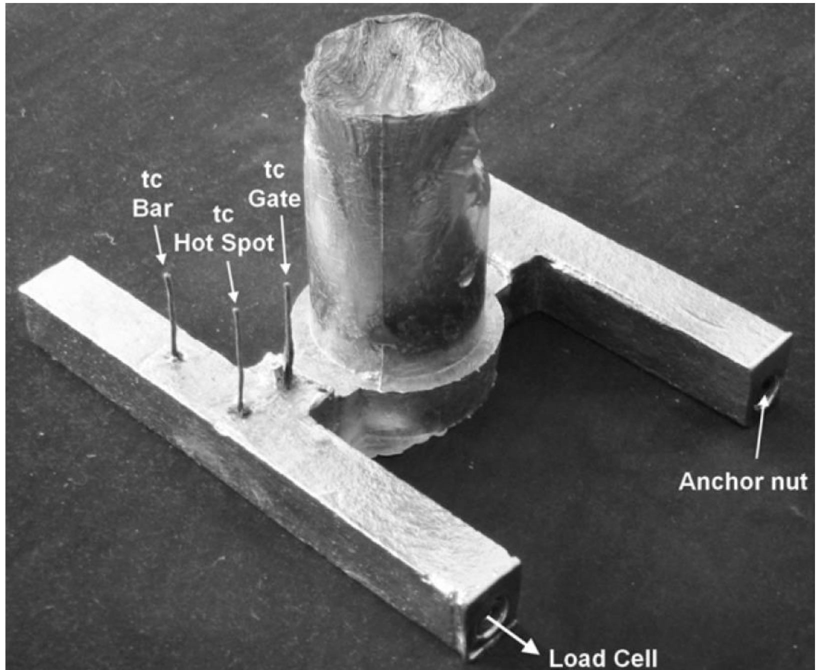


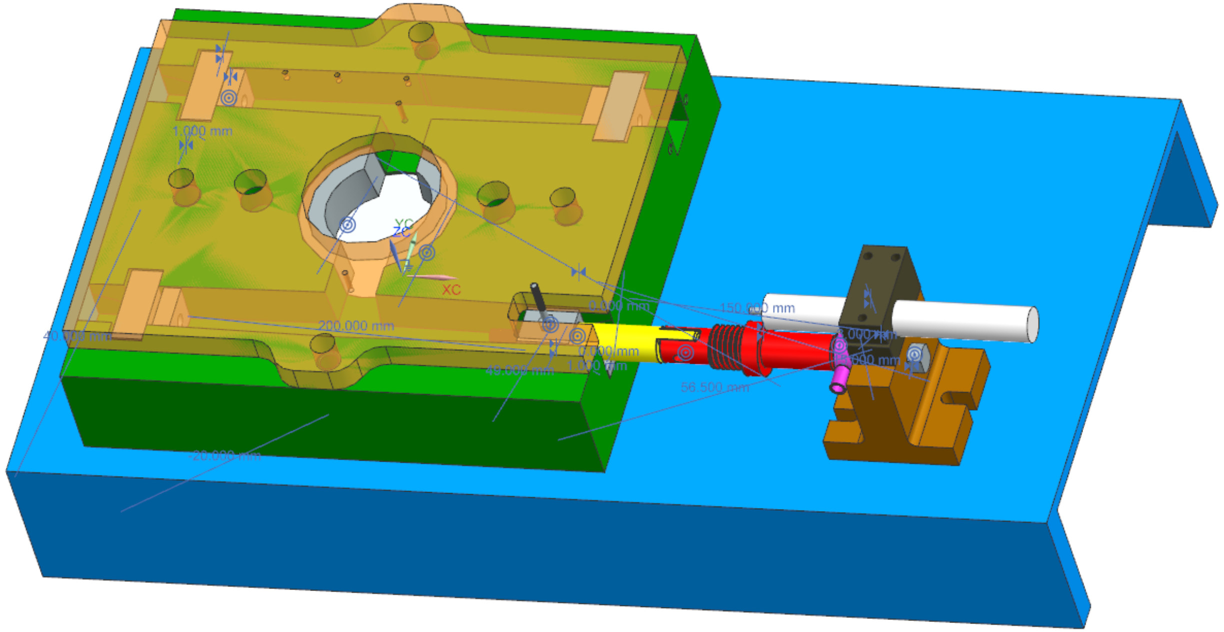
$$\mathrm{HTI} = 1/\left(\frac{G^2 \lambda_2^2}{180(1+\beta)B\mu\Delta T_0^2}\Delta P_{max} - \frac{v_t G \beta A}{(1+\beta)B\Delta T_0} \right)$$

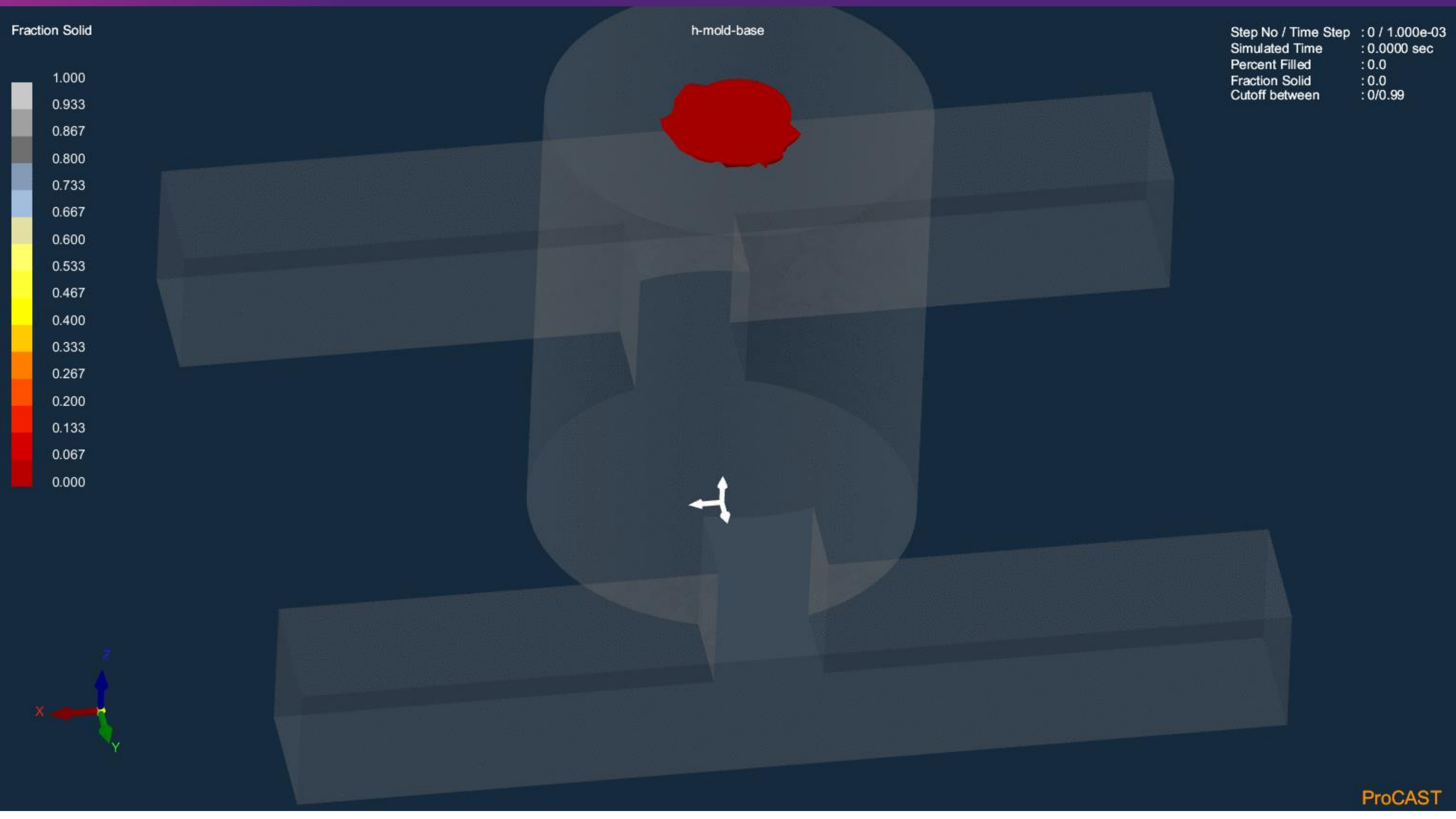
The columnar growth description used in the RDG model. From Rappaz *et al*.

Experiment and results

- Experimental casting, mould, and testing rig
- Alloys:
  - 7075 alloys: 5.6–6.1% Zn, 2.1–2.5% Mg, 1.2–1.6% Cu, an aerospace wrought alloy
  - Al-Zn alloys



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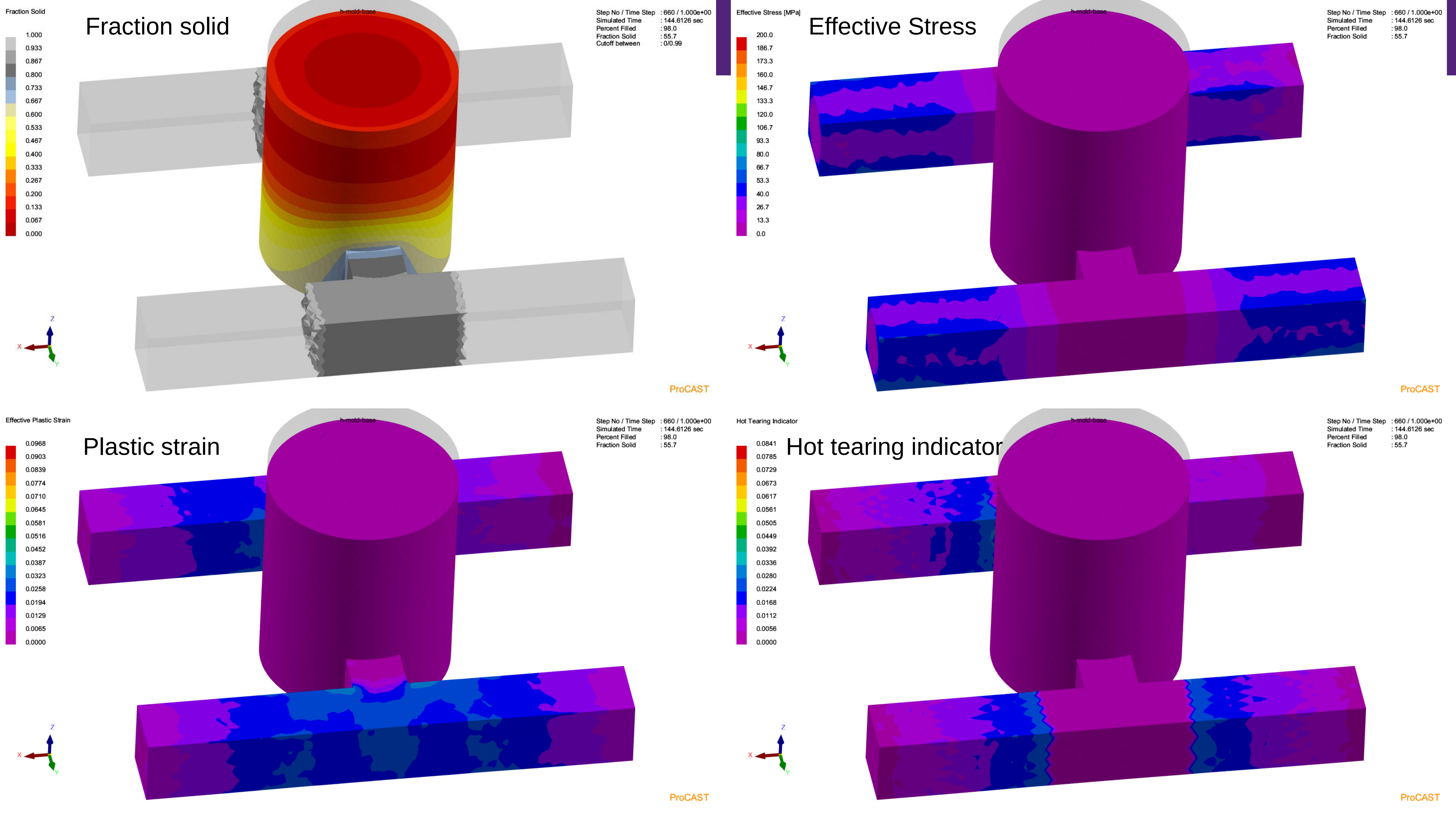
0.200
0.133
0.067
0.000
h-mold-base
Step No / Time Step : 0 / 1.000e-03
Simulated Time : 0.0000 sec
Percent Filled : 0.0
Fraction Solid : 0.0
Cutoff between : 0/0.99
Z
X
Y
ProCAST


Fraction Solid
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h-mold-base
Step No / Time Step : 660 / 1.000e+00
Simulated Time : 144.6126 sec
Percent Filled : 98.0
Fraction Solid : 55.7
Cutoff between : 0/0.99
ProCAST
Effective Stress [MPa]
Effective Stress
200.0
186.7
173.3
160.0
146.7
133.3
120.0
106.7
93.3
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40.0
26.7
13.3
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h-mold-base
Step No / Time Step : 660 / 1.000e+00
Simulated Time : 144.6126 sec
Percent Filled : 98.0
Fraction Solid : 55.7
ProCAST
Effective Plastic Strain
Plastic strain
0.0968
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0.0452
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h-mold-base
Step No / Time Step : 660 / 1.000e+00
Simulated Time : 144.6126 sec
Percent Filled : 98.0
Fraction Solid : 55.7
ProCAST
Hot Tearing Indicator
Hot tearing indicator
0.0841
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Step No / Time Step : 660 / 1.000e+00
Simulated Time : 144.6126 sec
Percent Filled : 98.0
Fraction Solid : 55.7
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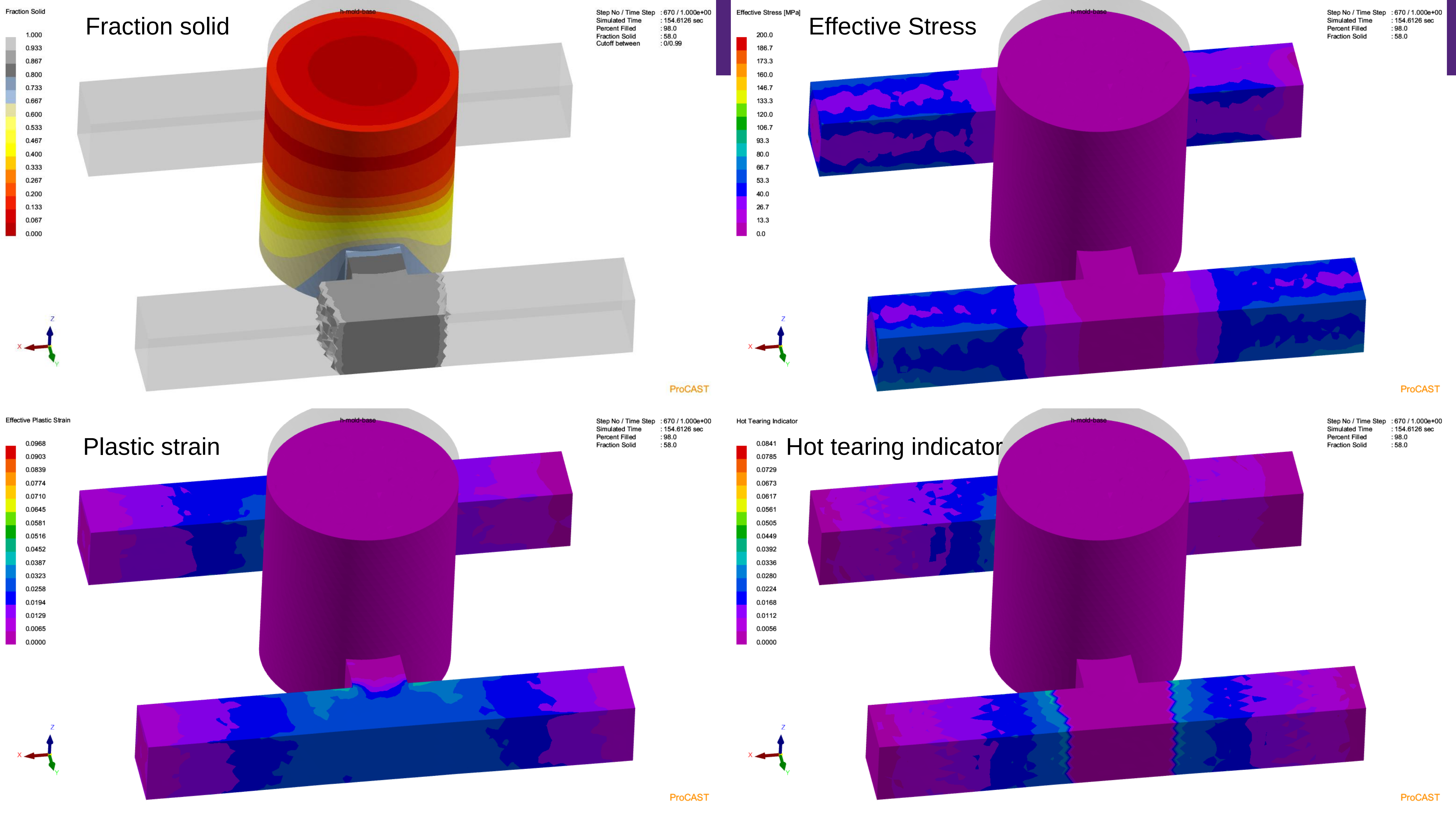

Fraction solid
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h-mold-base
Step No / Time Step : 670 / 1.000e+00
Simulated Time : 154.6126 sec
Percent Filled : 98.0
Fraction Solid : 58.0
Cutoff between : 0/0.99
ProCAST
Effective Stress
Effective Stress [MPa]
200.0
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173.3
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h-mold-base
Step No / Time Step : 670 / 1.000e+00
Simulated Time : 154.6126 sec
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Plastic strain
Effective Plastic Strain
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Fraction Solid : 58.0
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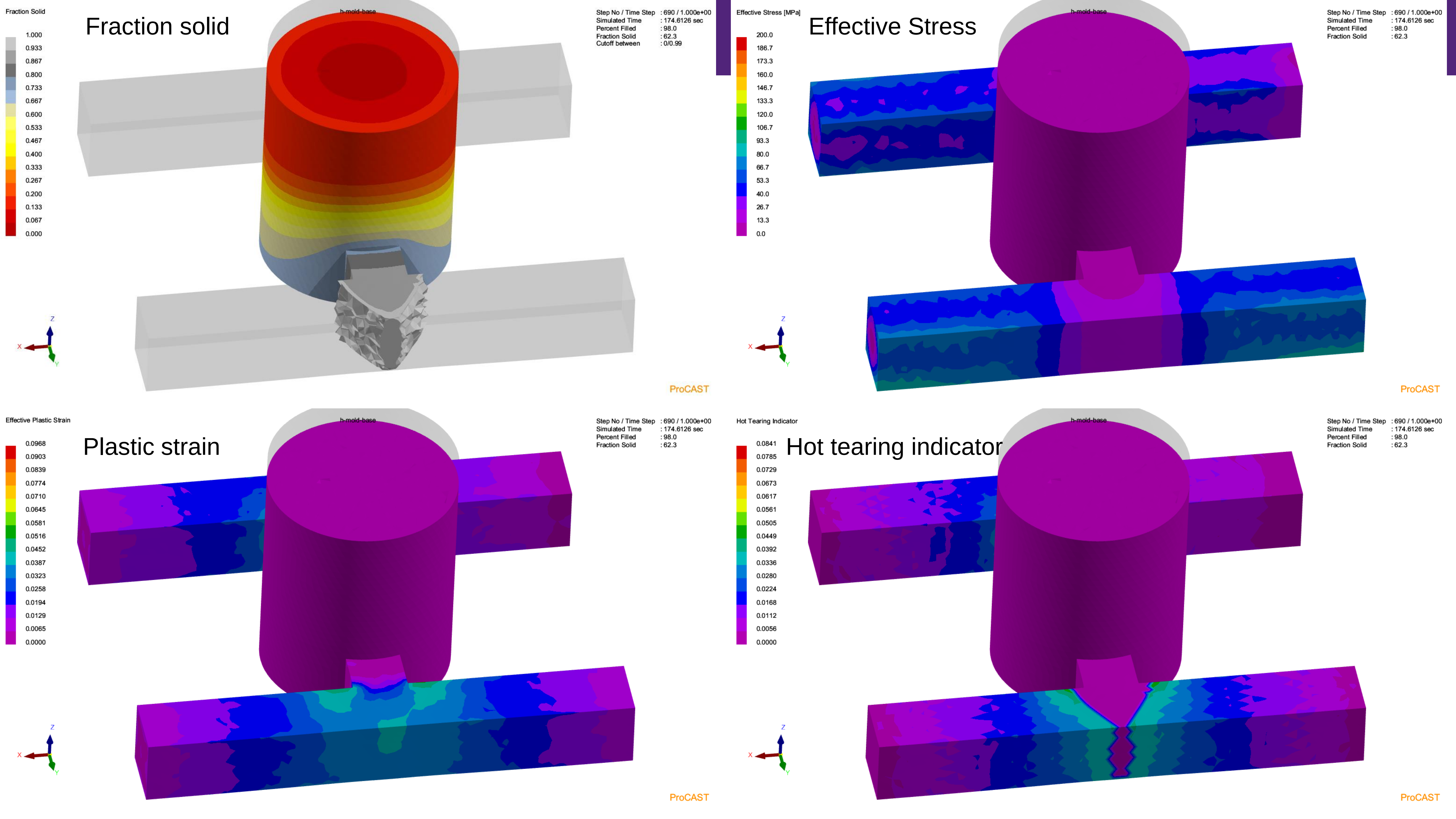
h-mold-base
Step No / Time Step : 670 / 1.000e+00
Simulated Time : 154.6126 sec
Percent Filled : 98.0
Fraction Solid : 58.0
ProCAST


Fraction Solid
Fraction solid
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h-mold-base
Step No / Time Step : 690 / 1.000e+00
Simulated Time : 174.6126 sec
Percent Filled : 98.0
Fraction Solid : 62.3
Cutoff between : 0/0.99
ProCAST
Effective Stress [MPa]
Effective Stress
200.0
186.7
173.3
160.0
146.7
133.3
120.0
106.7
93.3
80.0
66.7
53.3
40.0
26.7
13.3
0.0
h-mold-base
Step No / Time Step : 690 / 1.000e+00
Simulated Time : 174.6126 sec
Percent Filled : 98.0
Fraction Solid : 62.3
ProCAST
Effective Plastic Strain
Plastic strain
0.0968
0.0903
0.0839
0.0774
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0.0581
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0.0452
0.0387
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0.0258
0.0194
0.0129
0.0065
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h-mold-base
Step No / Time Step : 690 / 1.000e+00
Simulated Time : 174.6126 sec
Percent Filled : 98.0
Fraction Solid : 62.3
ProCAST
Hot Tearing Indicator
Hot tearing indicator
0.0841
0.0785
0.0729
0.0673
0.0617
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0.0168
0.0112
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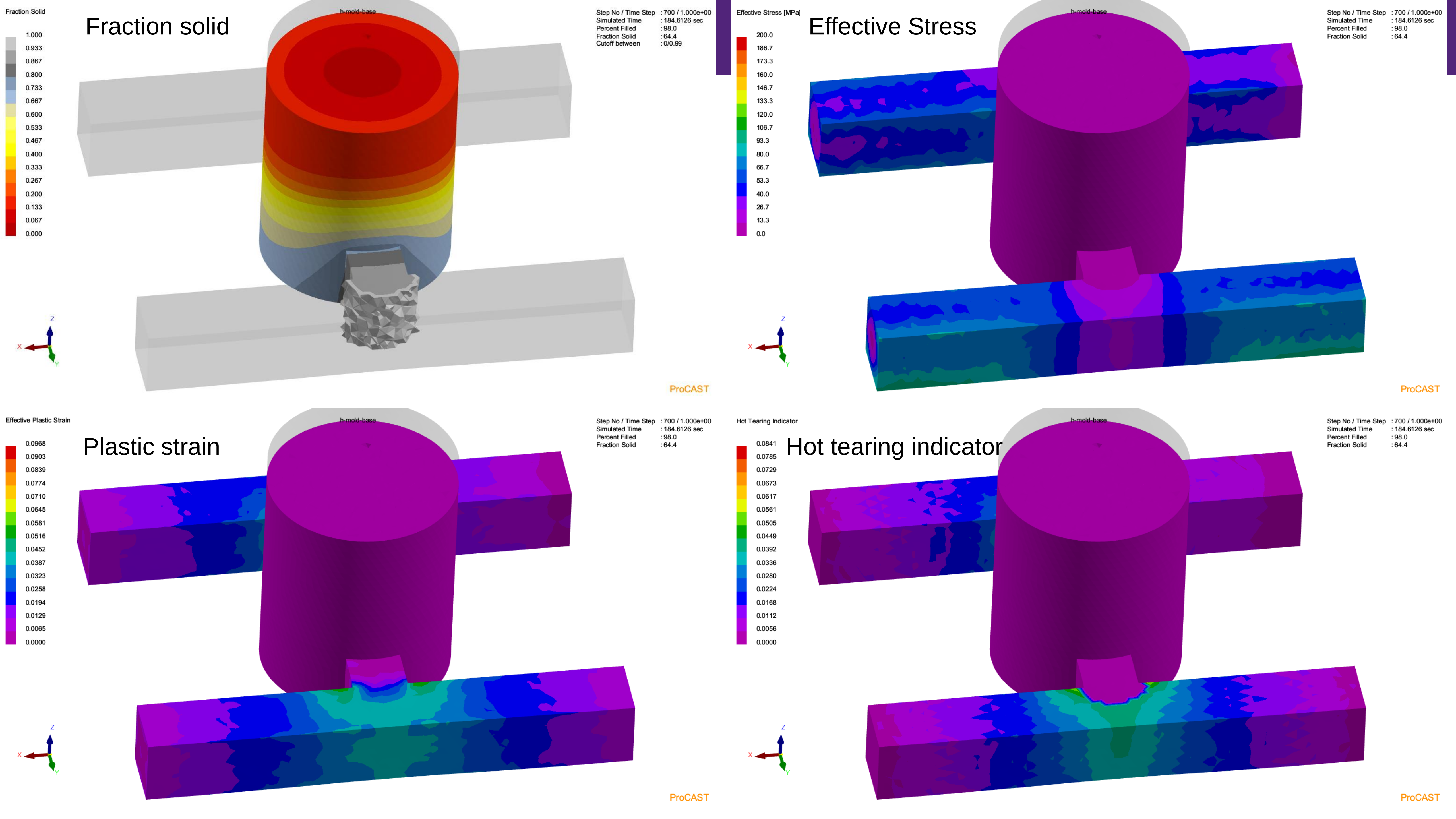
h-mold-base
Step No / Time Step : 690 / 1.000e+00
Simulated Time : 174.6126 sec
Percent Filled : 98.0
Fraction Solid : 62.3
ProCAST


Fraction Solid
Fraction solid
1.000
0.933
0.867
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0.733
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0.333
0.267
0.200
0.133
0.067
0.000
h-mold-base
Step No / Time Step : 700 / 1.000e+00
Simulated Time : 184.6126 sec
Percent Filled : 98.0
Fraction Solid : 64.4
Cutoff between : 0/0.99
ProCAST
Effective Stress [MPa]
Effective Stress
200.0
186.7
173.3
160.0
146.7
133.3
120.0
106.7
93.3
80.0
66.7
53.3
40.0
26.7
13.3
0.0
h-mold-base
Step No / Time Step : 700 / 1.000e+00
Simulated Time : 184.6126 sec
Percent Filled : 98.0
Fraction Solid : 64.4
ProCAST
Effective Plastic Strain
Plastic strain
0.0968
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0.0710
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h-mold-base
Step No / Time Step : 700 / 1.000e+00
Simulated Time : 184.6126 sec
Percent Filled : 98.0
Fraction Solid : 64.4
ProCAST
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Hot tearing indicator
0.0841
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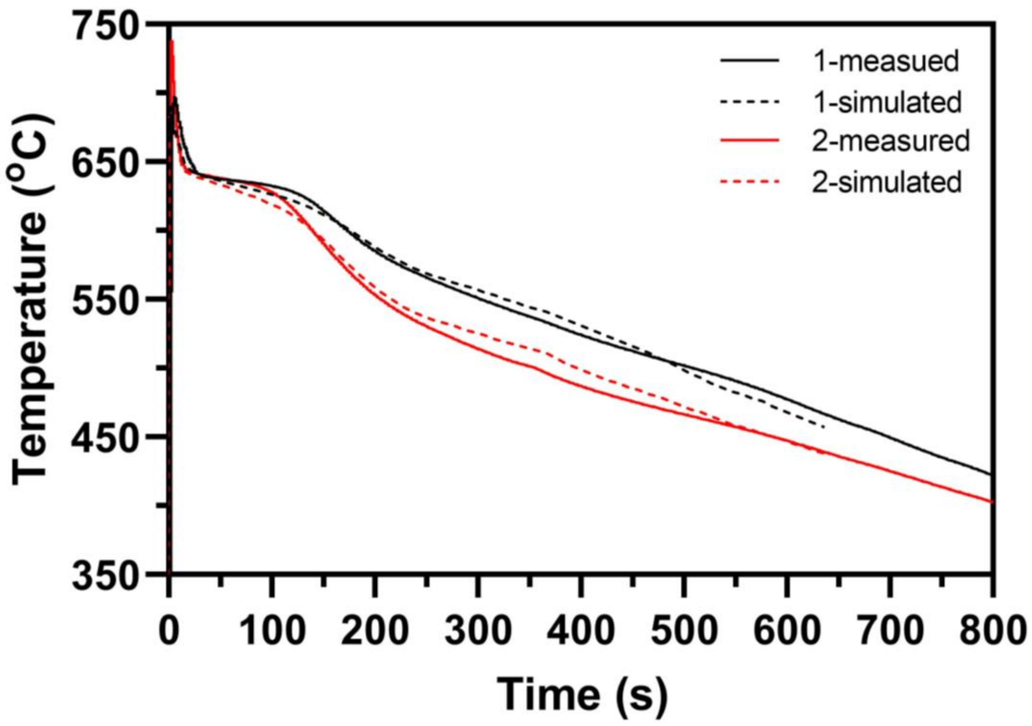
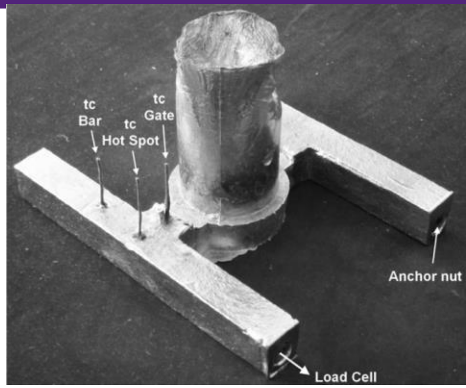
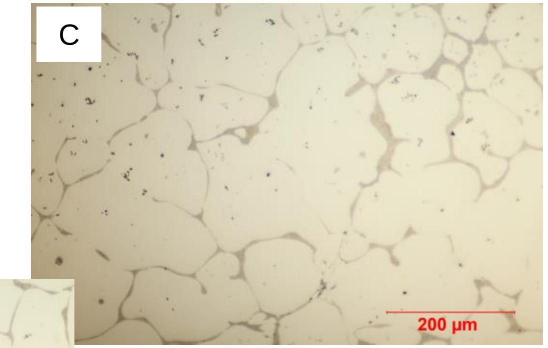
h-mold-base
Step No / Time Step : 700 / 1.000e+00
Simulated Time : 184.6126 sec
Percent Filled : 98.0
Fraction Solid : 64.4
ProCAST

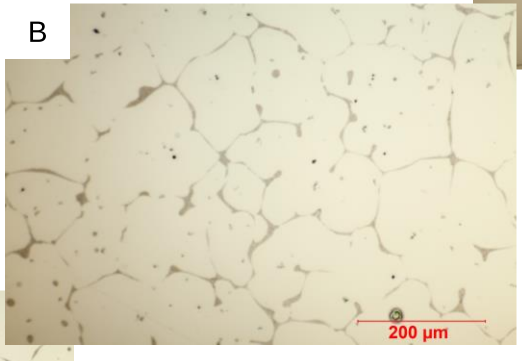
Experiments and results

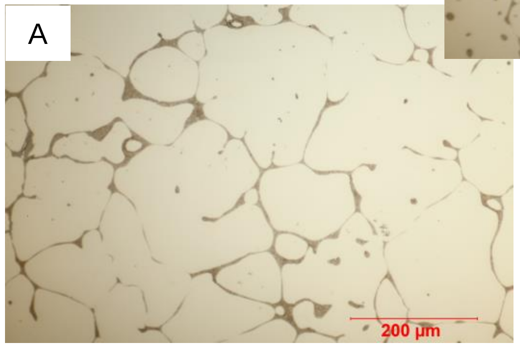
- Cooling curves and microstructure of 7075 alloy

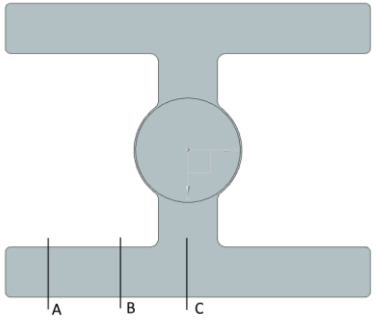






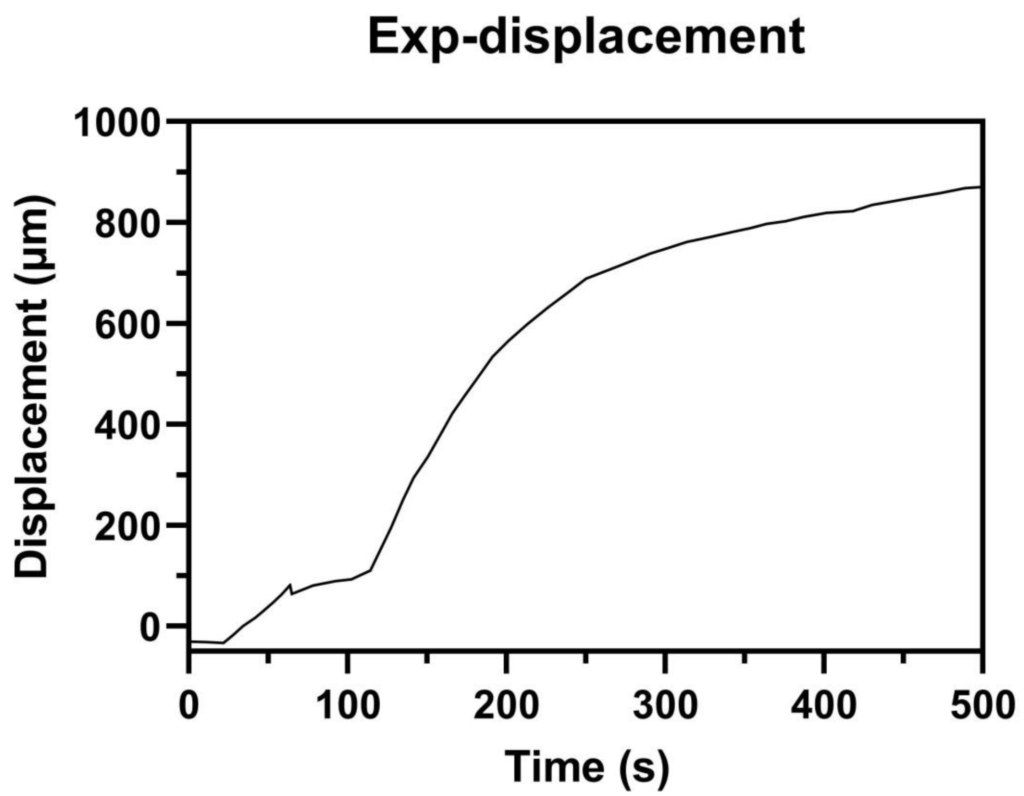


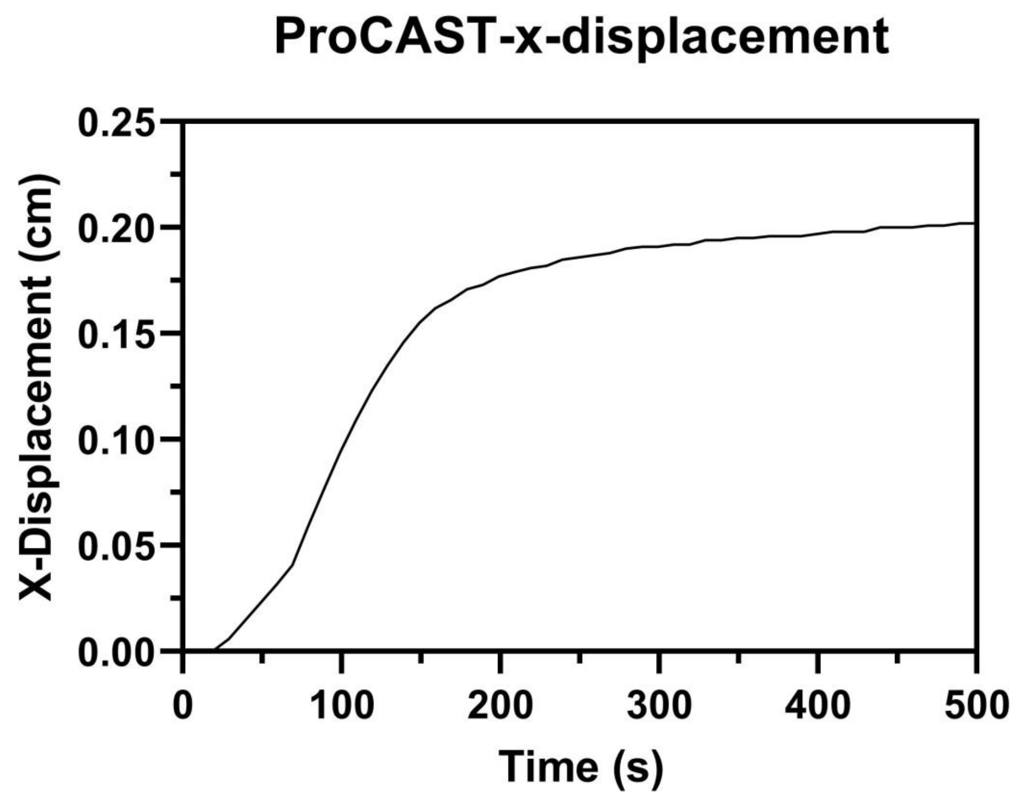




Experiments and results

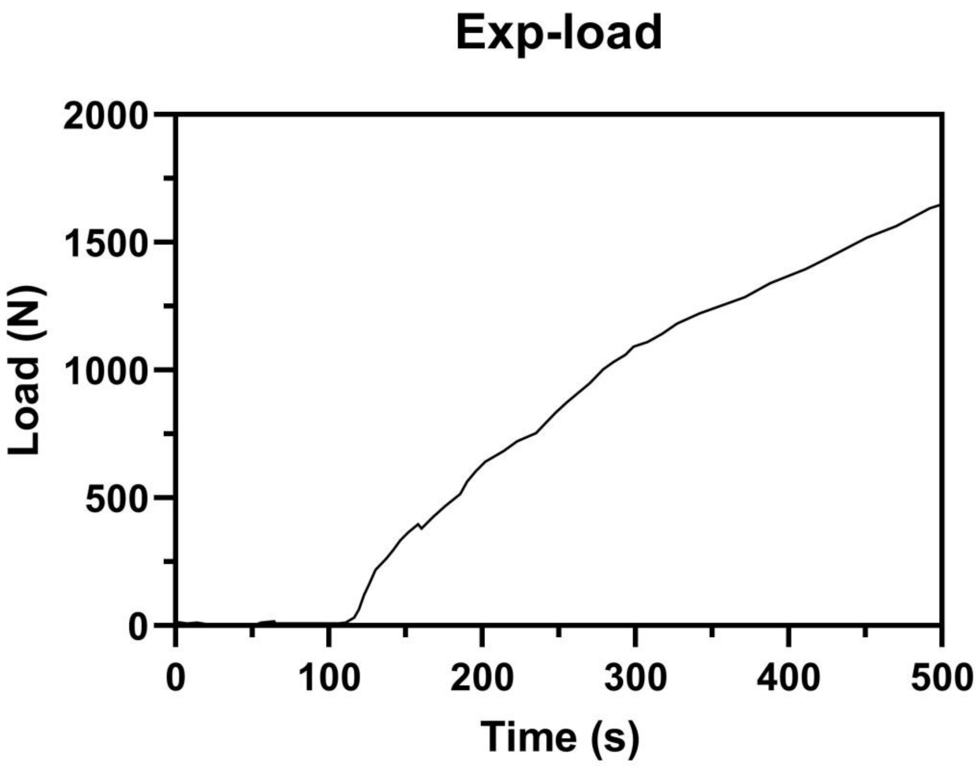
- Measured displacement (restraint movement) and ProCAST calculated displacement (free movement) of 7075 alloy

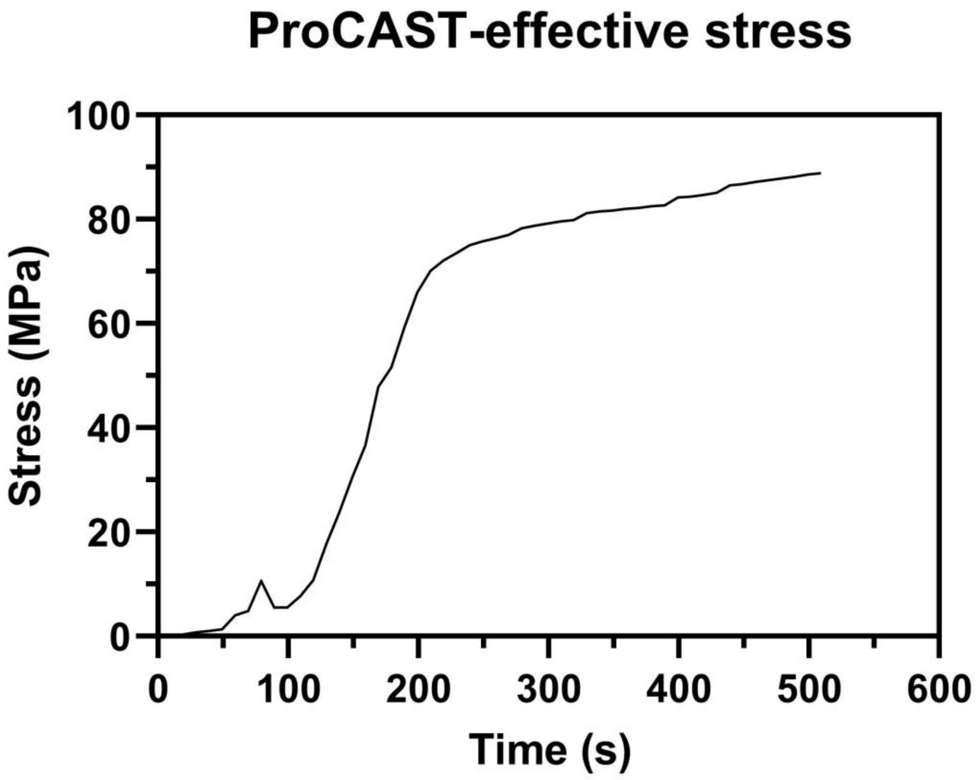


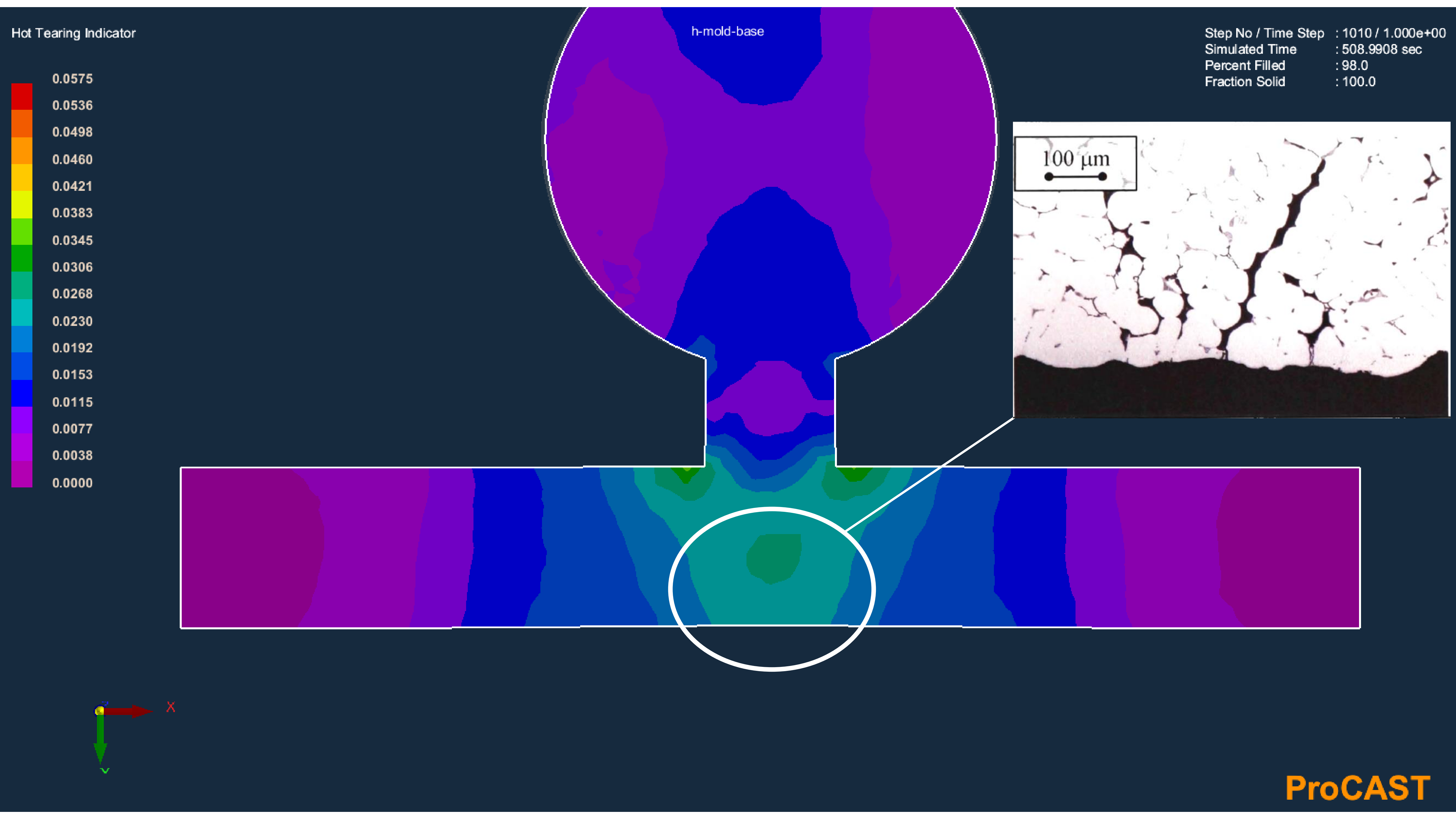


Experiments and results

- Measured load and ProCAST calculated stress of 7075 alloy






Hot Tearing Indicator
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0.0536
0.0498
0.0460
0.0421
0.0383
0.0345
0.0306
0.0268
0.0230
0.0192
0.0153
0.0115
0.0077
0.0038
0.0000
h-mold-base
Step No / Time Step : 1010 / 1.000e+00
Simulated Time : 508.9908 sec
Percent Filled : 98.0
Fraction Solid : 100.0
100 µm
X
ProCAST

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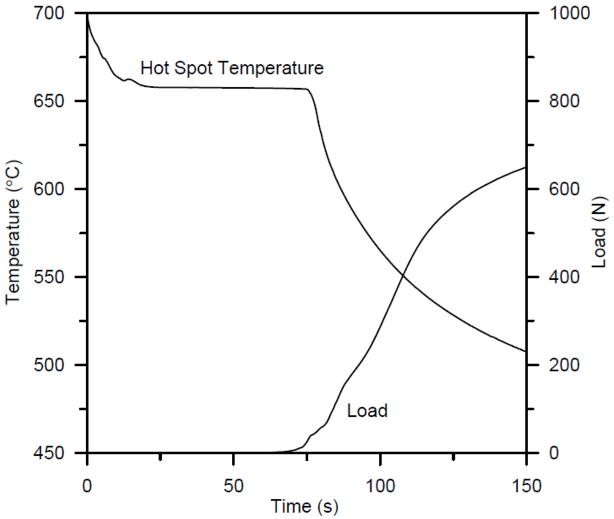
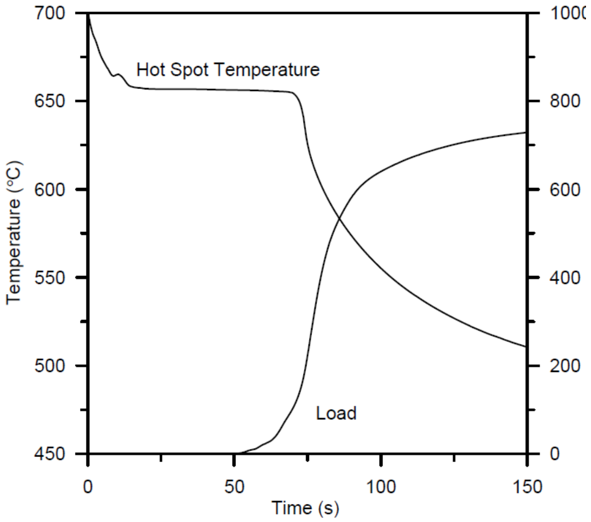
Experiments and results

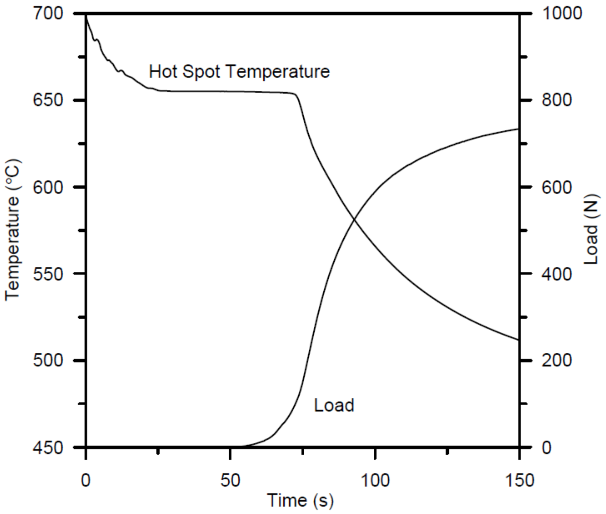
- Load development during the solidification and cooling of Al-Zn alloys



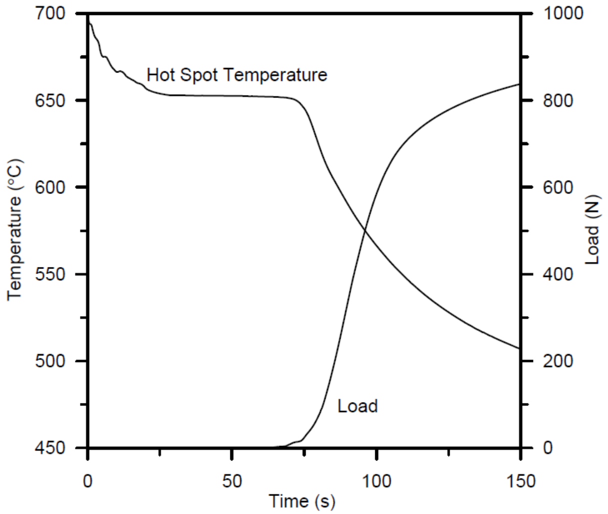
1.0 wt% Zn



2.0 wt% Zn



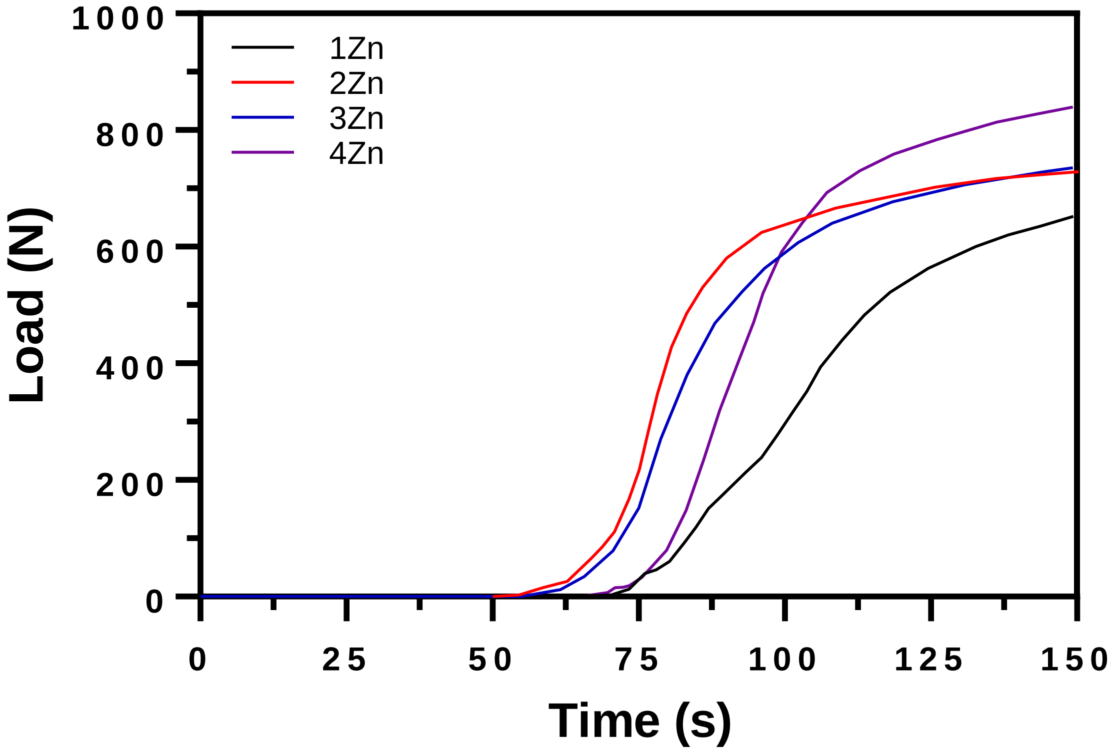
3.0 wt% Zn

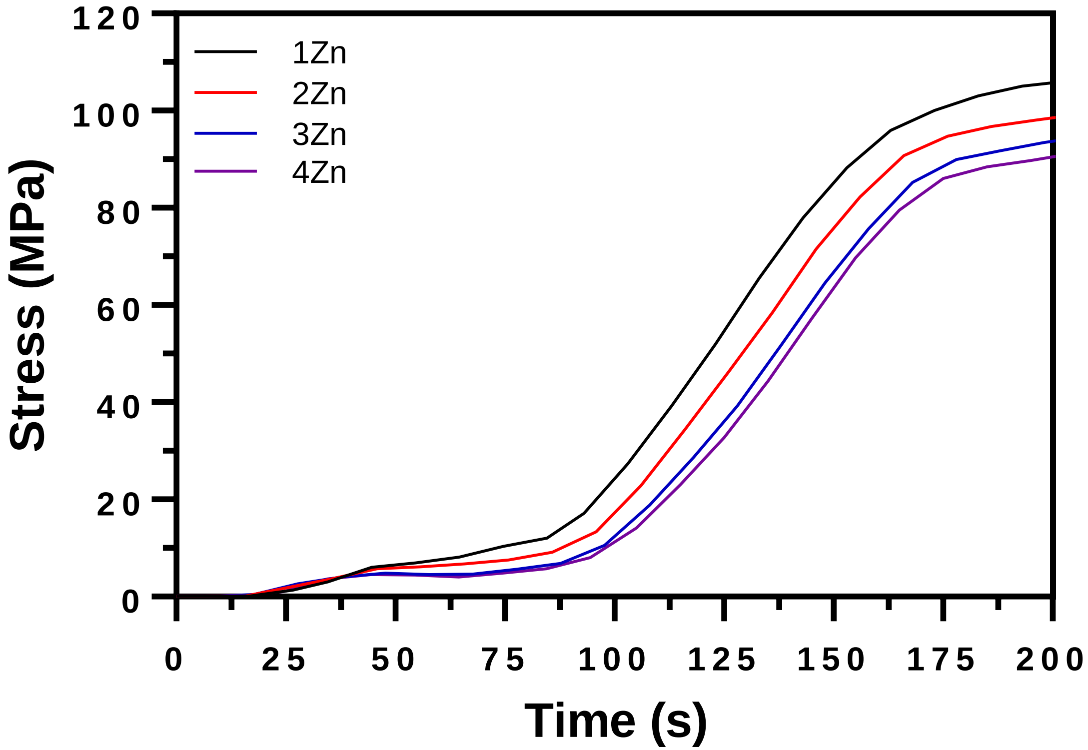


4.0 wt% Zn

Experiment and simulations

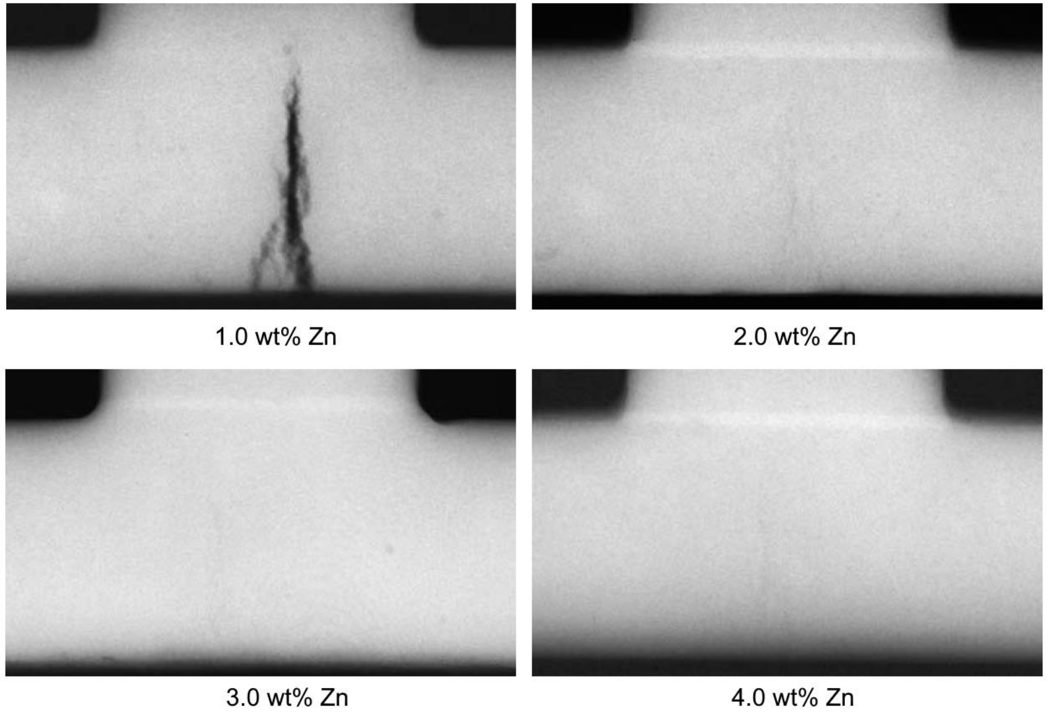
- Comparison between measured load and simulated stress





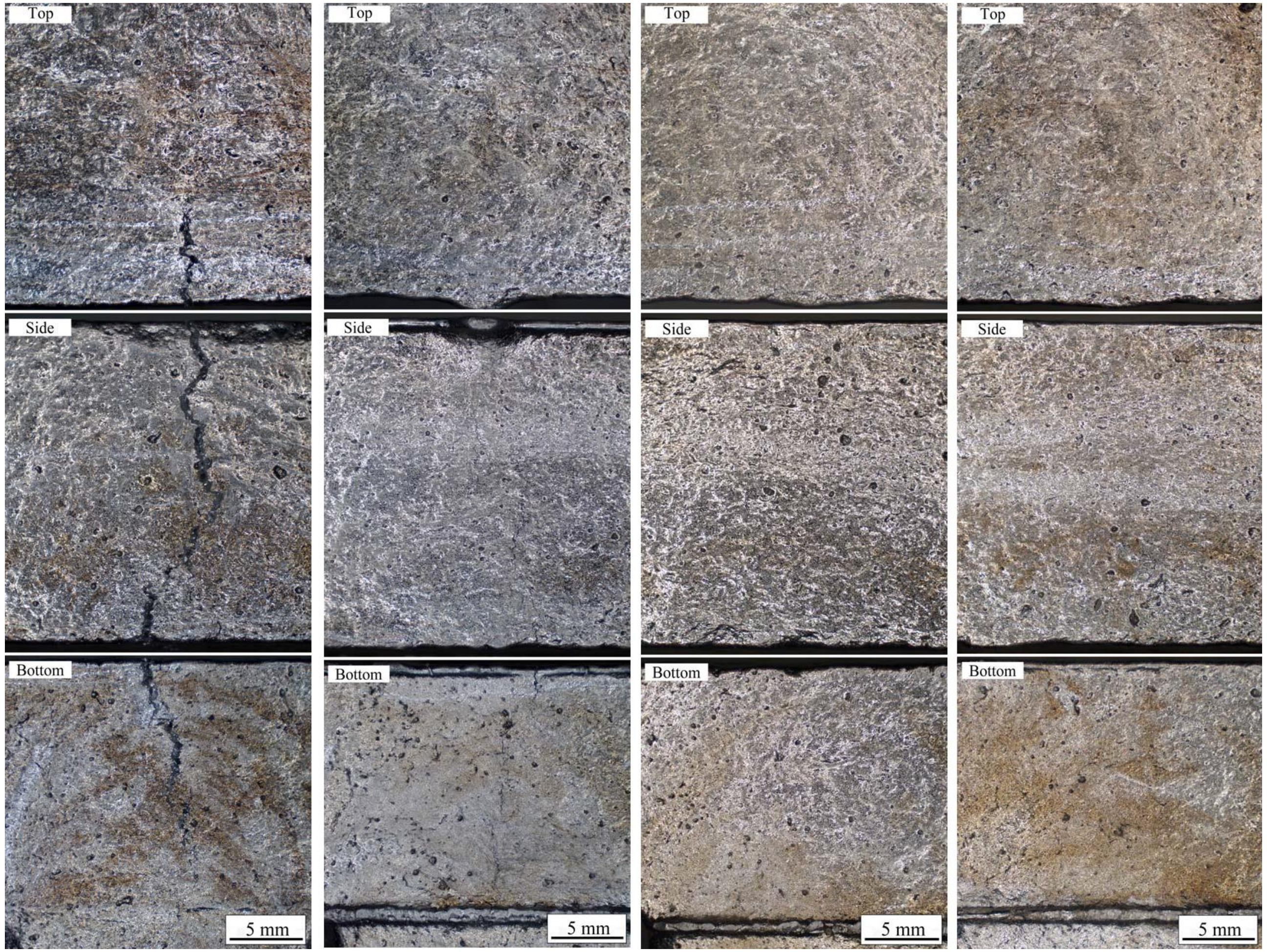
Experiments and results

Radiographs and macro photographs of casting



Radiographs of the hot spots

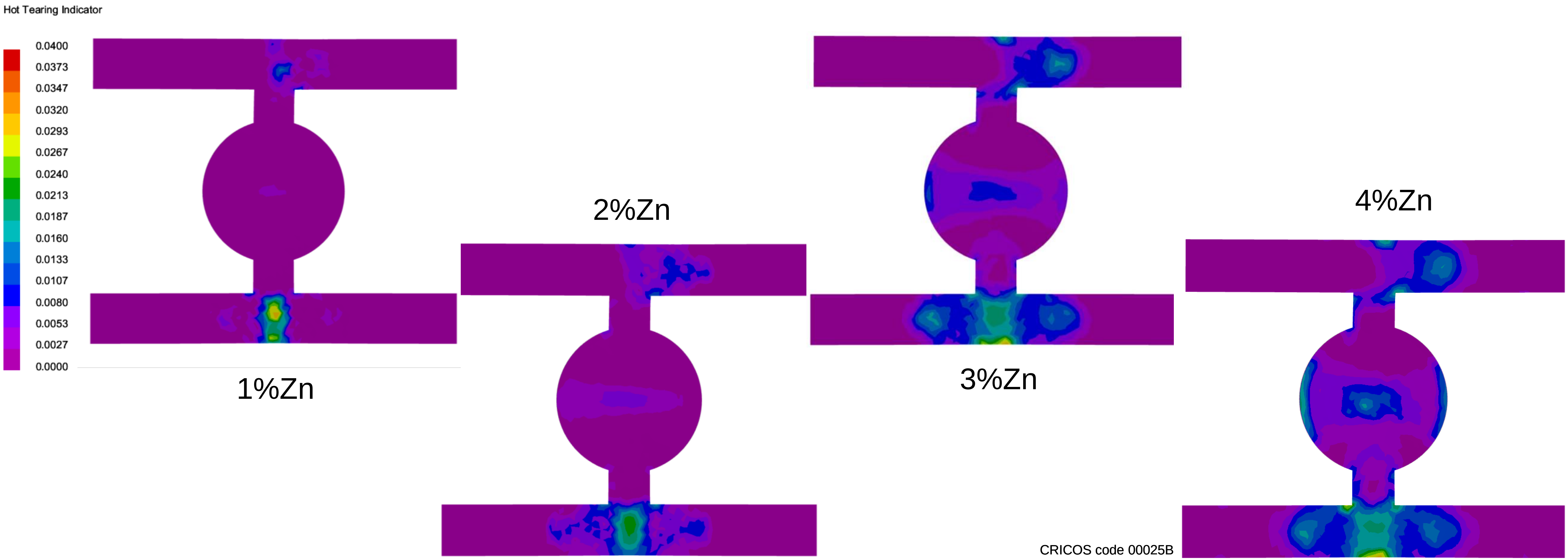
Macro photographs



1.0 wt% Zn 2.0 wt% Zn 3.0 wt% Zn 4.0 wt% Zn

Experiments and results

- Calculated Hot Tearing Indicator of the castings

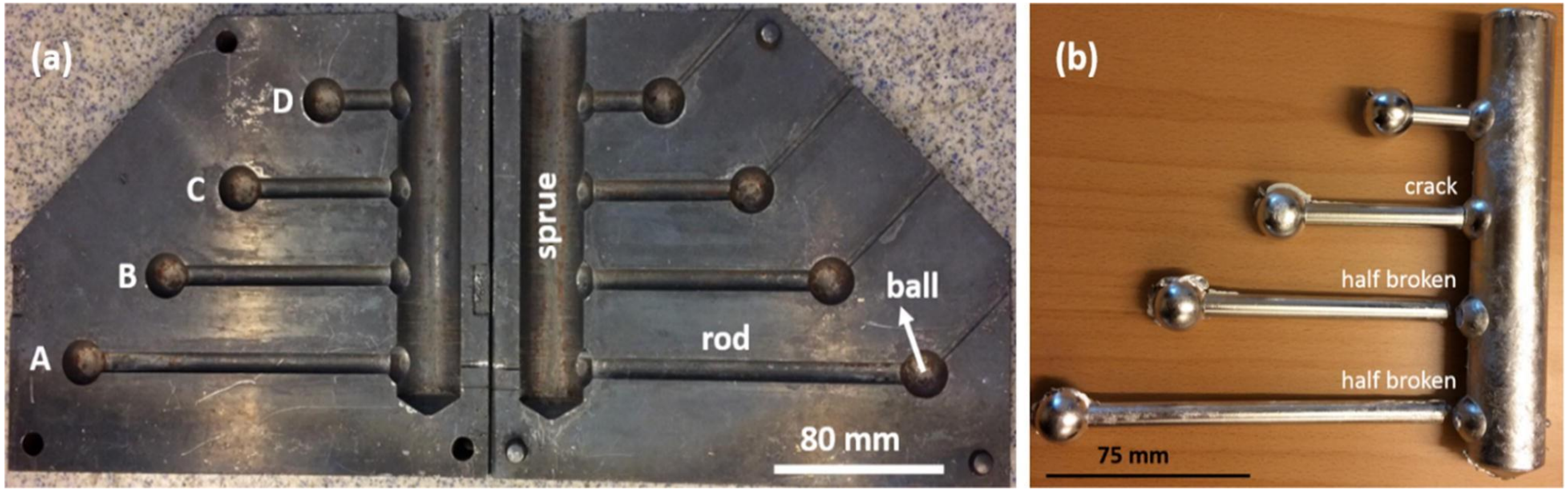


Experiments and results

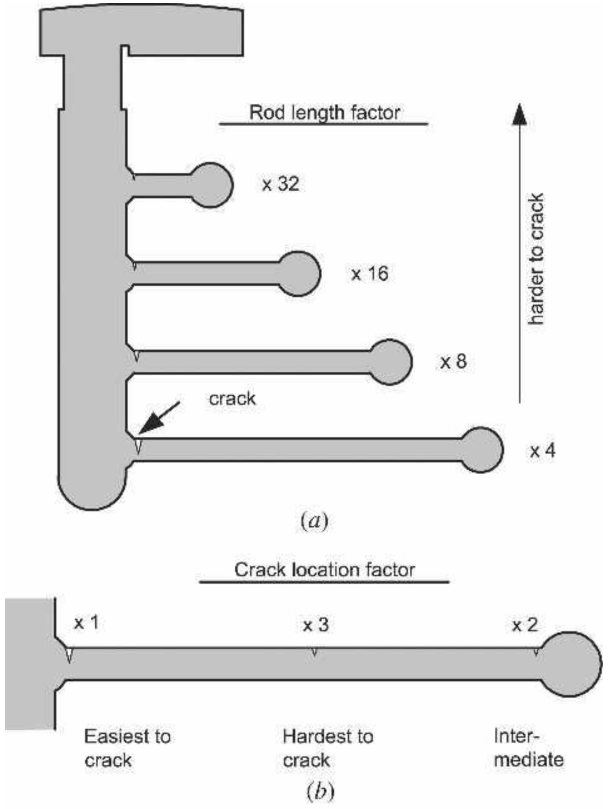
- Validation using the Constrained Rod Casting (CRC)

$$HCS = \sum f_{\mathrm{crack}} f_{\mathrm{length}} f_{\mathrm{location}}.$$

Cracking Severity	f_{crack}
Short Hairline	1
Full Hairline	2
Crack	3
Half Broken	4



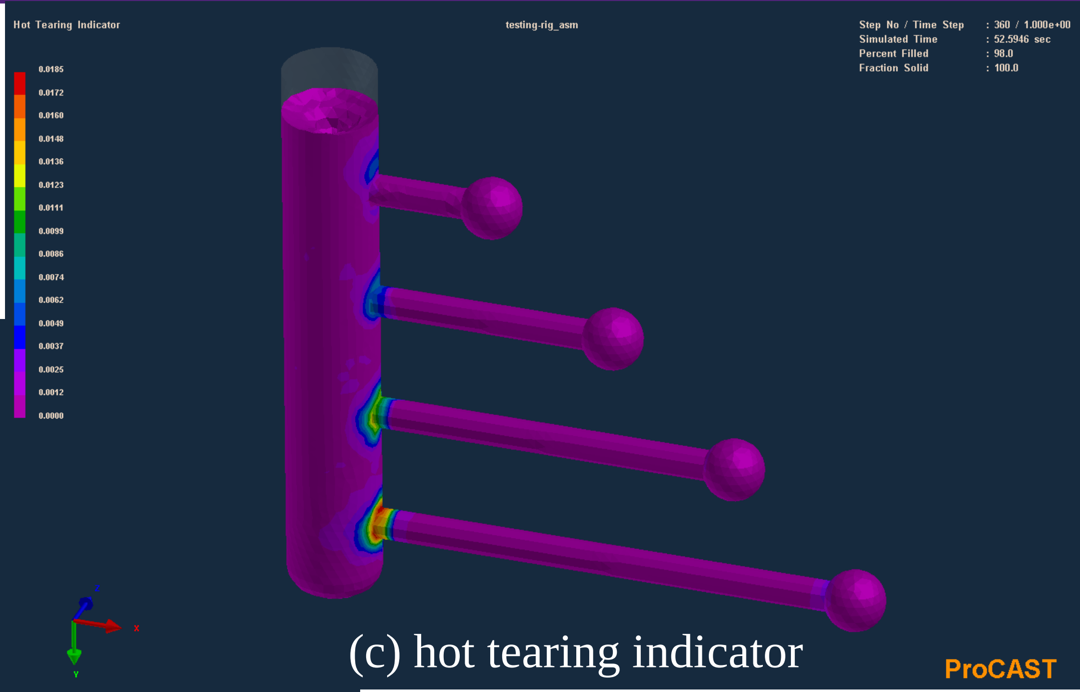
Hot Tearing Susceptibility of Aluminum Alloys (*a*) Steel mold for constrained rod casting, (*b*) image of a sample cast with the CRC mold showing cracks



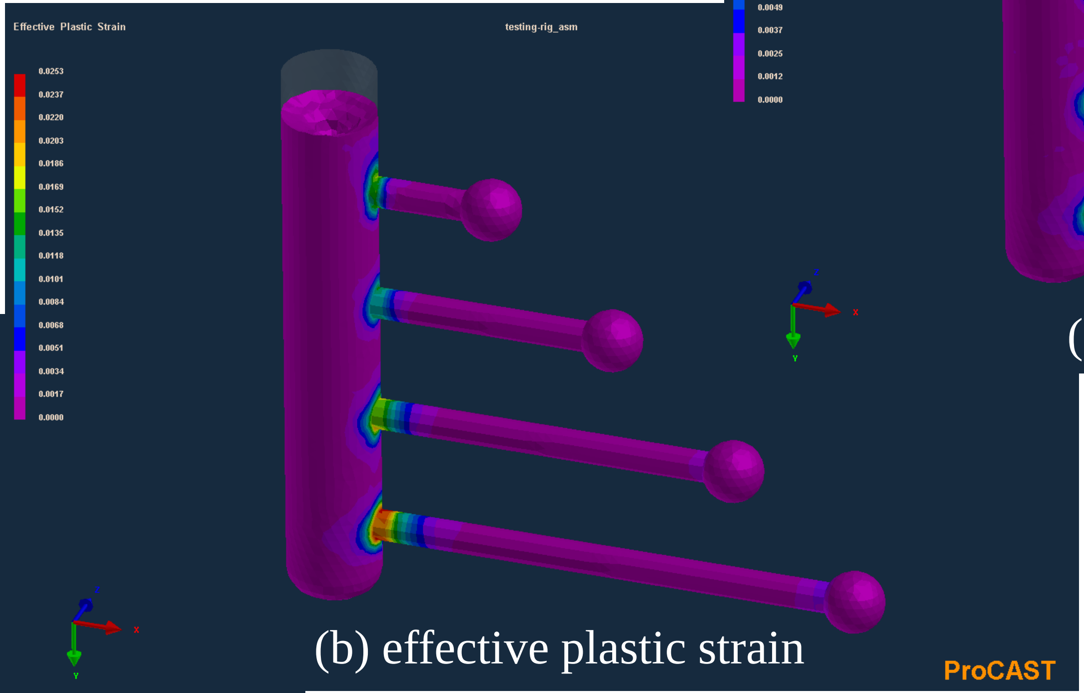
J. Song, F. Pan, B. Jiang, A. Atrens, M.X. Zhang, and Y. Lu: J. Magnes. Alloys, 2016, vol. 4, pp. 151–72.

Experiments and results

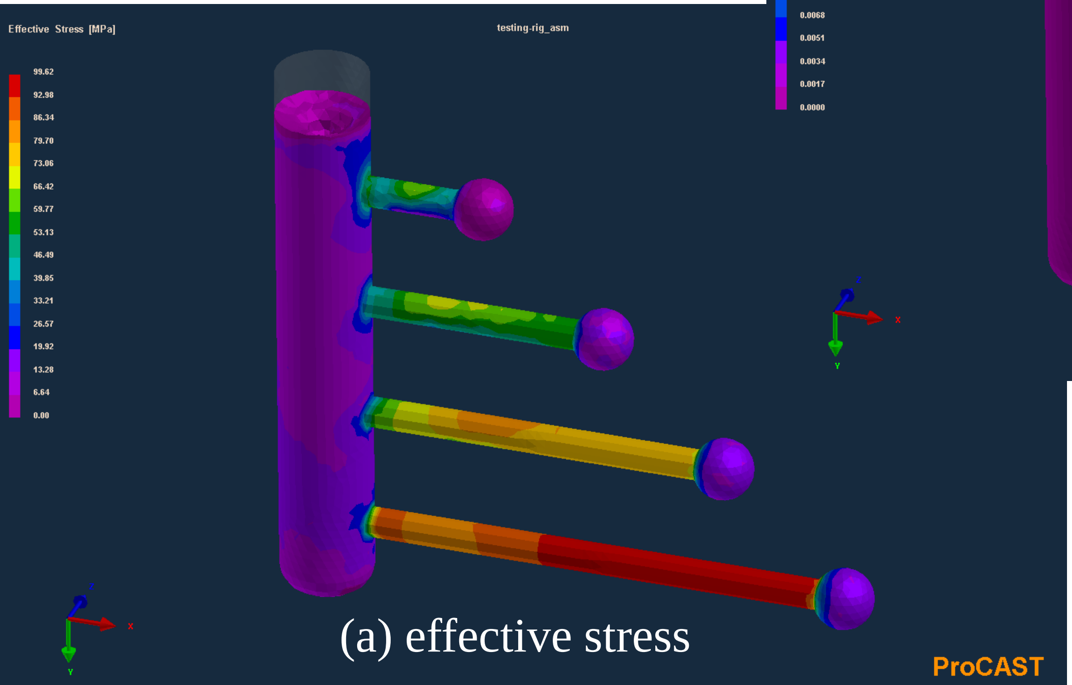
- Validation using the Constrained rod casting (CRC)



(c) hot tearing indicator



(b) effective plastic strain

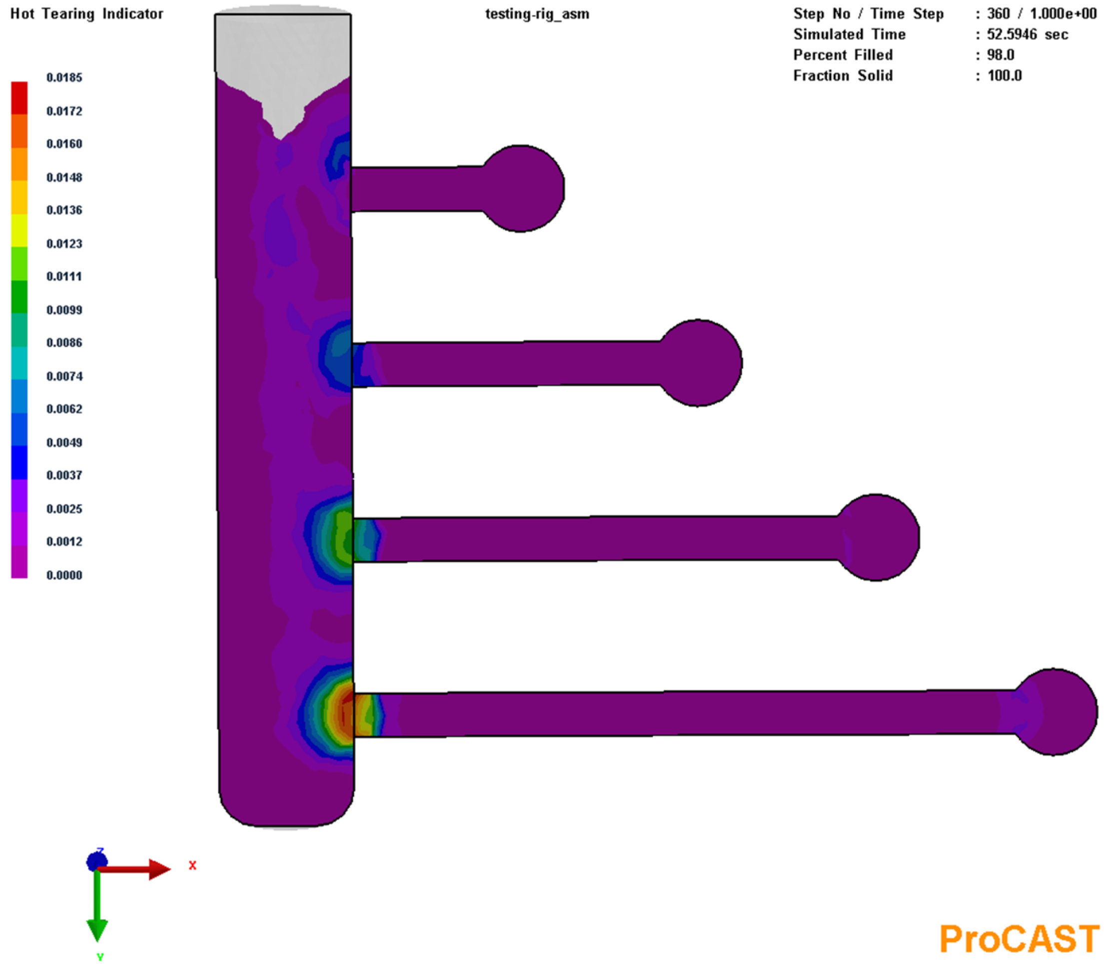


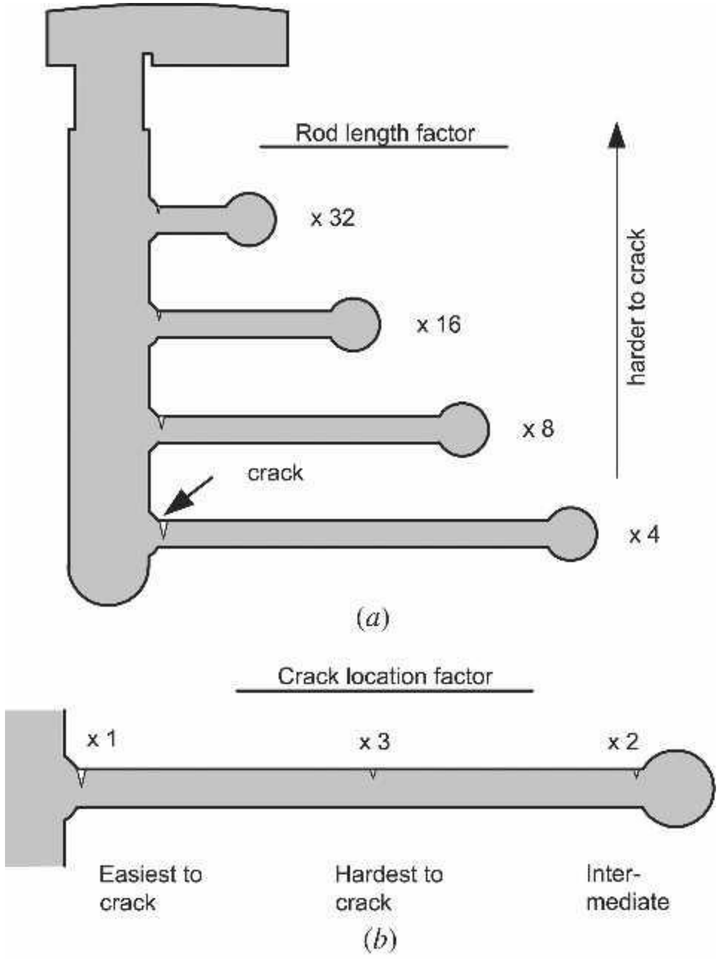
(a) effective stress

Simulation results for constrained rod casting (a) effective stress, (b) effective plastic strain, (c) hot tearing indicator

Experiments and results

- Validation using the Constrained rod casting (CRC)





Conclusions

- Hot tearing is a common defect in casting and is one of the key issues defining an alloy's castability
- The objective of this study is to access the capability and reliability of ProCAST to predict the hot tearing of aluminium alloys
- A specifically designed hot tear rig has been used to measure load and displacement development, and hot tearing, the experimental results of which have been compared with ProCAST simulation
- ProCAST can predict the formation of the hot tearing qualitatively under the experimental conditions, and we are working further on the prediction of that hot tearing quantitatively
- We are always open to industrial collaboration projects in this field – research@esi.com.au