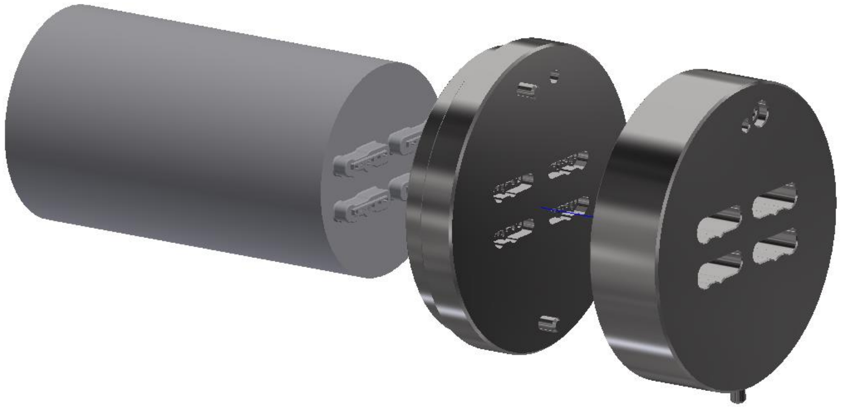
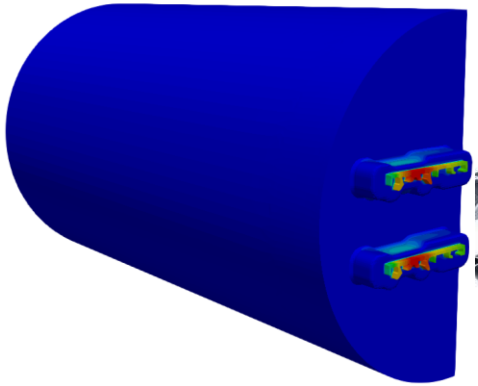
Universidade do Minho
Escola de Engenharia





A NOVEL OPENFOAM SOLVER FOR ALUMINIUM ALLOY PROFILE EXTRUSION

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[1] PORTALUM - PORTUGUESA DE ALUMÍNIO, LDA, R. de Casares 670, 4820 Fafe, Portugal, antoniopedro.adf@hotmail.com
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Contents

1 Introduction

Industry

- Architecture/construction;
- Automobile and transportation industry.

Properties

- Low density;
- Good electrical and thermal conductivity;
- Reflectivity;
- Low toxicity.

Application of aluminum extrusion profiles

Heat sinks

Door handles

Window structures

CAIXAFÁCIL, “JANELA DE ALUMÍNIO COM CORTE TÉRMICO O QUE É?” [Online]. Available: http://www.caixifacil.com/o-que-e-uma-janela-de-aluminio-com-corte-termico/. [Accessed: 19-Mar-2020].
Perfilesdealuminio.net, “¿Por qué se usa aluminio en los disipadores?” [Online]. Available: https://perfilesdealuminio.net/articulo/ipor-que-se-usa-aluminio-en-los-disipadores/36. [Accessed: 19-Mar-2020].
madeiras gasometro, “Perfil de Alumínio SP-3528L com Puxador Acabamento Jateado Fosco - SP Alumínio.” [Online].

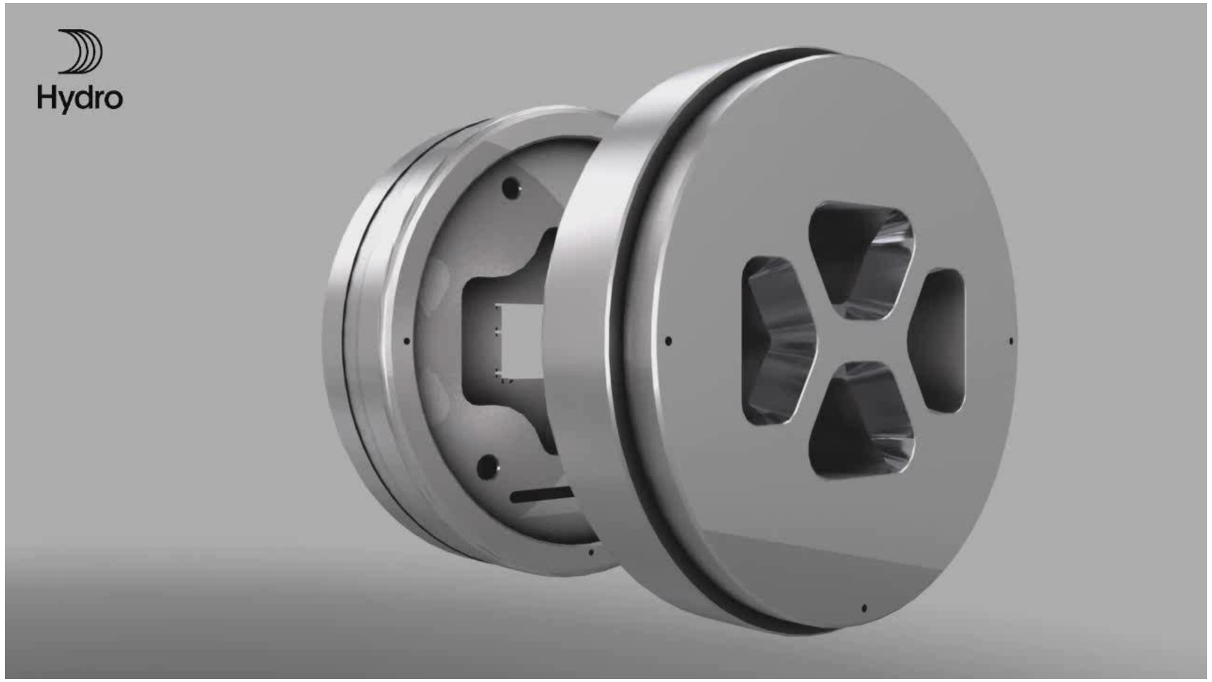
1 Introduction

Direct extrusion

Extrusion Types:

- Direct extrusion;
- Indirect extrusion;
- Hydrostatic;
- Side extrusion;
- Impact extrusion;
- Etc.

Direct extrusion press :



N. Hydro, *Aluminium Extrusion Process*. Available in https://www.youtube.com/watch?v=Bc7o_sEdX8U.

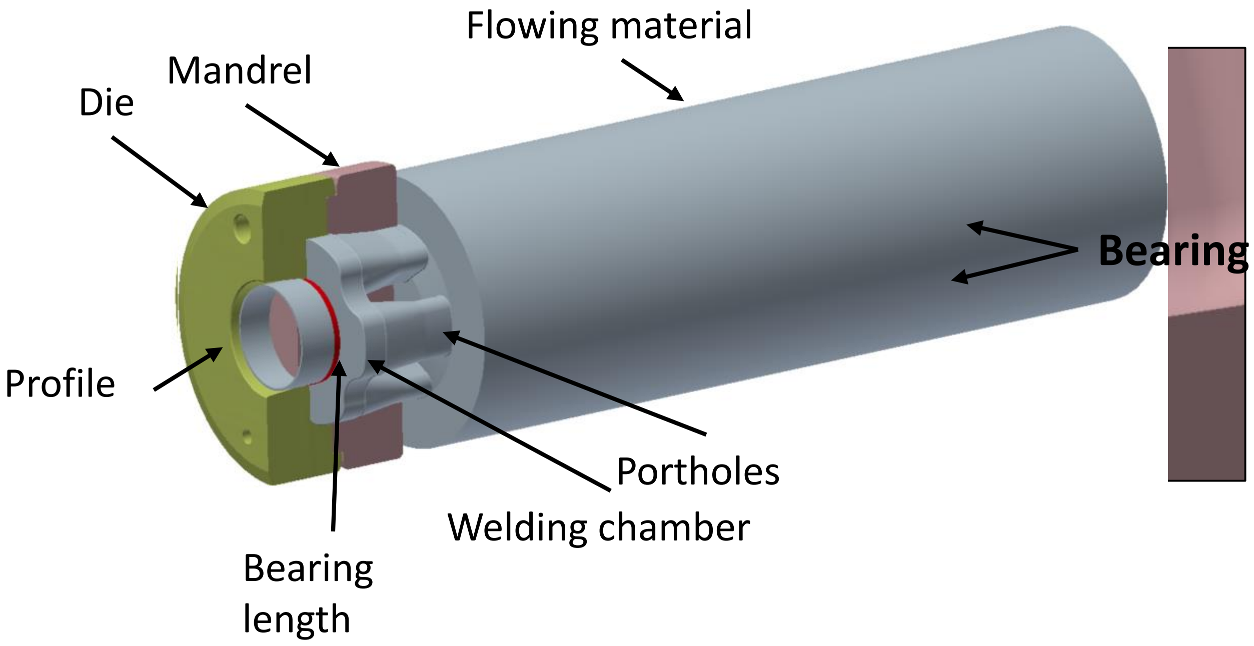
1 Introduction

Extrusion dies

Challenge: Assure that the material flows through the die outlet with the same average velocity

Bearing:

1. Is the parallel zone located at the die exit;
2. Will settle the shape of the extruded profile;
3. Longer bearing length higher resistance to the flow;
4. Aims promoting a balanced flow distribution.



1 Introduction

Extrusion dies: Flow balancing checks

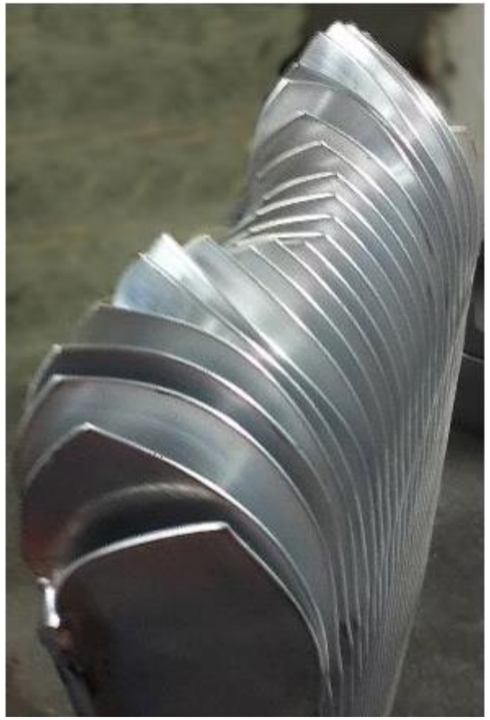
Physical tests

- Experimental trial-and-error iterations with bearing length corrections;
- Time consuming;
- Expensive method (400€/test).

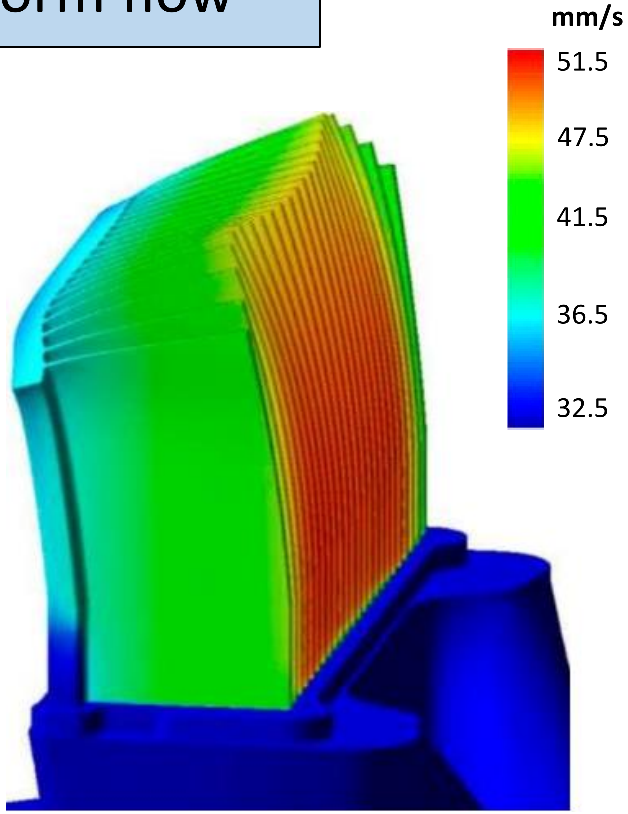
Computational modelling

- Optimize the bearing length with process simulation;
- Reduce the resources spent in physical tests.

non-uniform flow



Experimental



Simulation

N. Biba, S. Stebunov, and A. Lishny, "Simulation of material flow coupled with die analysis in complex shape extrusion," *Key Eng. Mater.*, vol. 585, pp. 85–92, 2014, doi: 10.4028/www.scientific.net/KEM.585.85.

1 Introduction

portalum
PORTUGUESA DE ALUMINIO.LDA

- Aluminum alloy casting and extrusion company;
- Located in Fafe, Portugal;
- Casting division - capacity of 40 tons per day;
- Extrusion division - capacity of 15 tons per day;

2 Motivation and goals

Motivation

- Increase the knowledge about aluminum extrusion;
- Improve design methodology;
- Reduce production costs, without affecting the product performance.

Goals

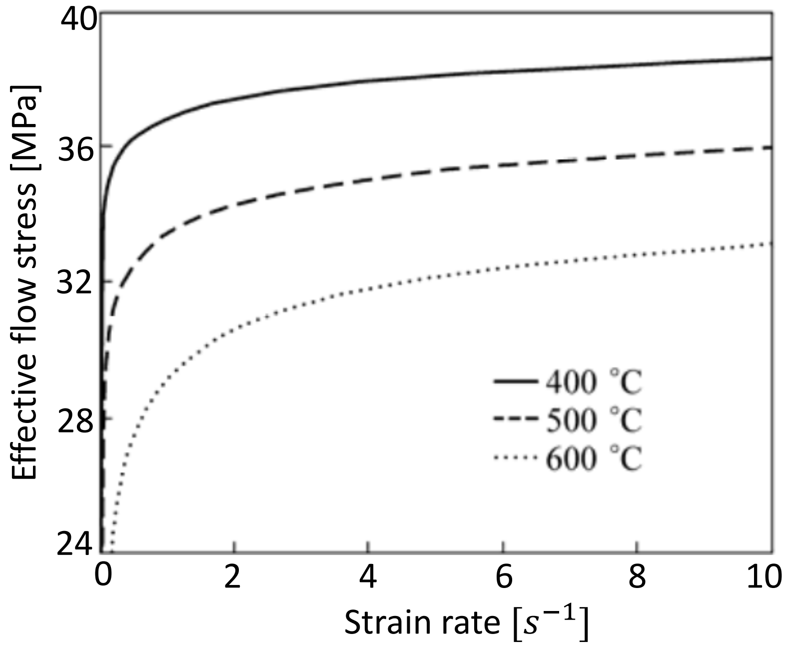
- Create a computational code capable of simulating the extrusion process of aluminum alloys (alExtFoam);
- Verify and validate the developed code;
- Test the application of the code in an industrial relevant problem.

3 State of art

Constitutive equations for the aluminum alloys

The effective flow stress for hot aluminum alloys:

$$\bar{\tau} = f(\dot{\bar{\varepsilon}}, T)$$



Constitutive models to predict effective flow stress:

- Norton-Hoff

$$\bar{\tau}_{ij,NH} = 2K_{NH}\left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{e-1}\dot{\varepsilon}_{ij}$$

- Hansel-Spittel

$$\bar{\tau}_{HS} = \mathrm{A}e^{m_1 T}T^{m_9}\varepsilon^{m_2}e^{\frac{m_4}{\varepsilon}}(1+\varepsilon)^{m_5 T}e^{m_7\varepsilon}\dot{\bar{\varepsilon}}^{m_3}\dot{\bar{\varepsilon}}^{m_8 T}$$

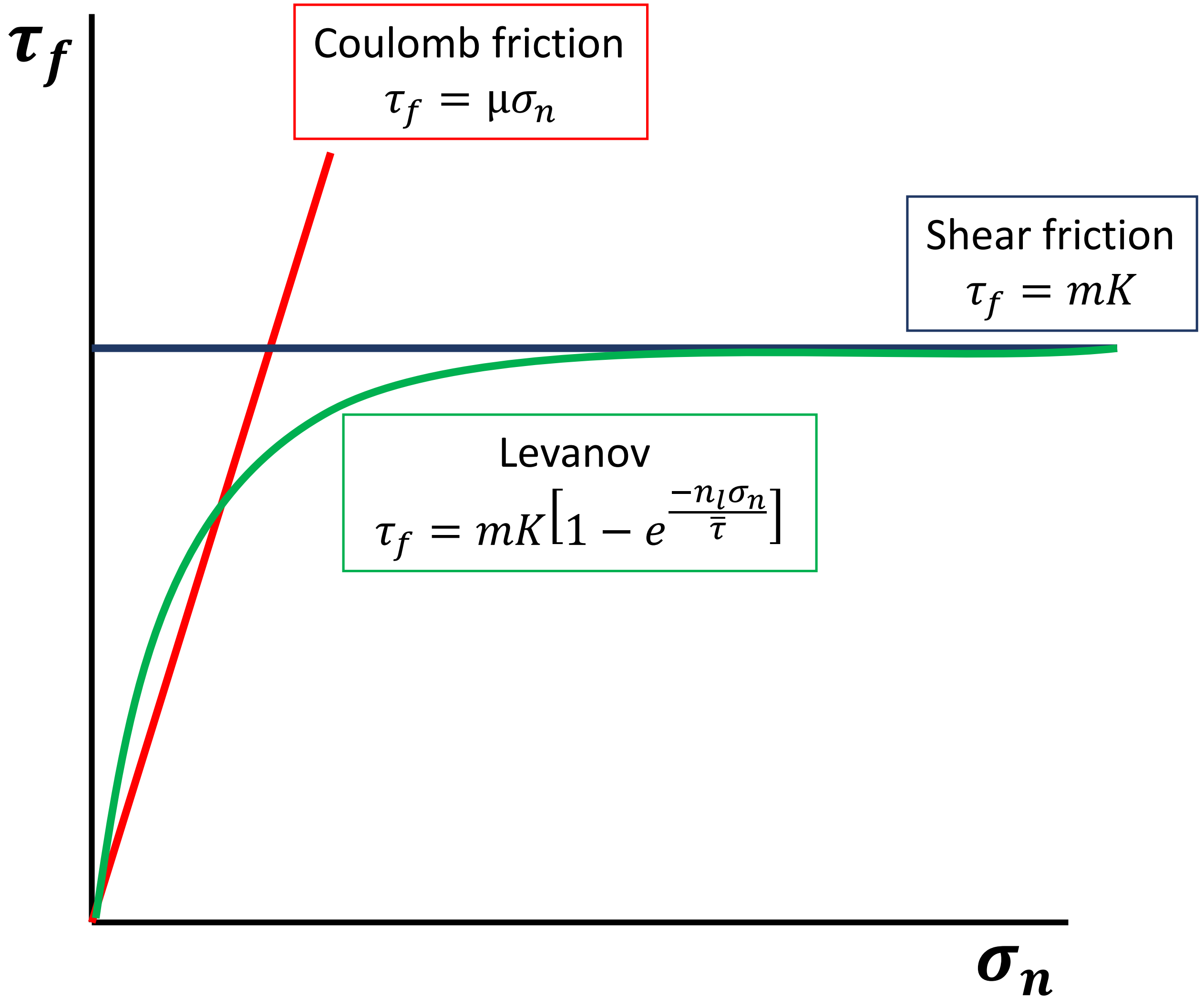
- Zener-Hollomon

$$\bar{\tau}_{ZH} = \frac{1}{\alpha}\sinh^{-1}\left(\left(\frac{Z}{A}\right)^{1/n}\right), \quad Z = \dot{\bar{\varepsilon}}e^{\frac{Q}{RT}}$$

G. Fang, J. Zhou, and J. Duszczyk, “FEM simulation of aluminium extrusion through two-hole multi-step pocket dies,” J. Mater. Process. Technol., vol. 209, no. 4, pp. 1891–1900, 2009, doi: 10.1016/j.jmatprotec.2008.04.036.

3 State of art

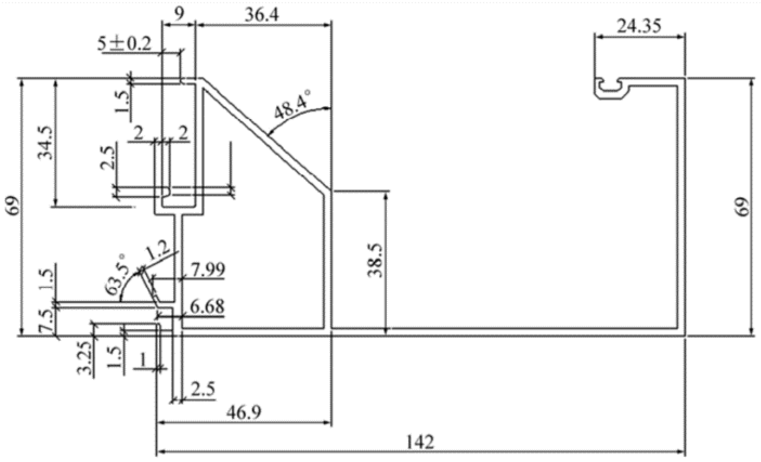
Wall boundary conditions

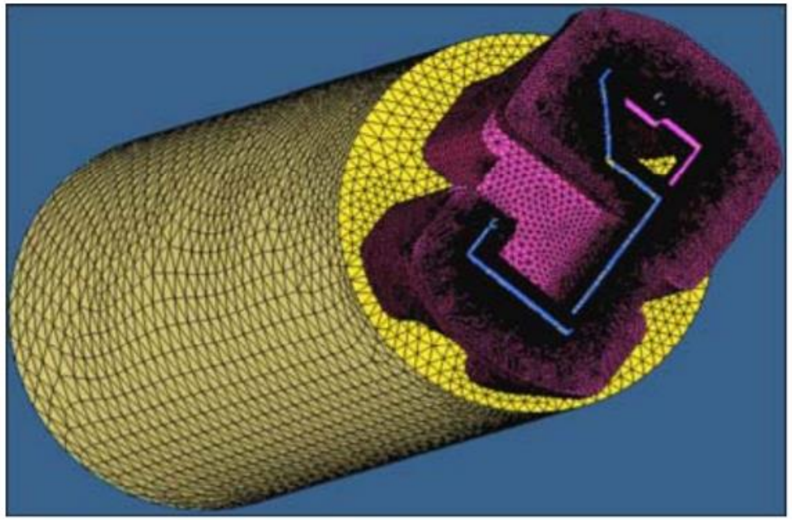


3 State of art

Illustrative study*

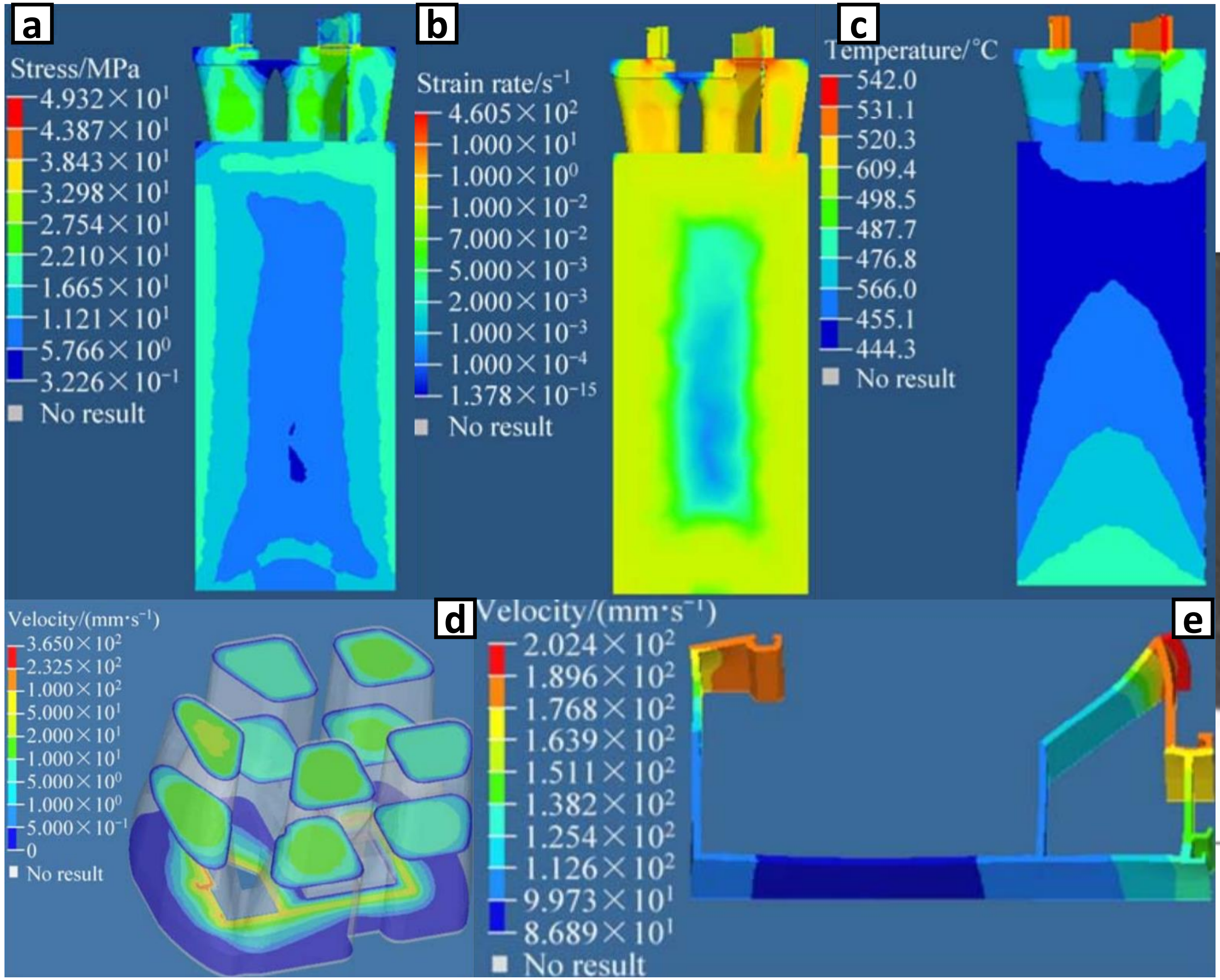
- AA6063
- Zener-Hollomon constitutive model
- Shear friction and Coulomb friction models





Z. HE, H. Wang, M. Wang, and G. LI, “Simulation of extrusion process of complicated aluminium profile and die trial,” Trans. Nonferrous Met. Soc. China, vol. 22, no. 7, pp. 1732–1737, 2012

3 State of art

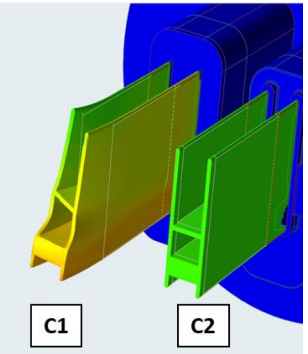


Z. HE, H. Wang, M. Wang, and G. LI, “Simulation of extrusion process of complicated aluminium profile and die trial,” Trans. Nonferrous Met. Soc. China, vol. 22, no. 7, pp. 1732–1737, 2012

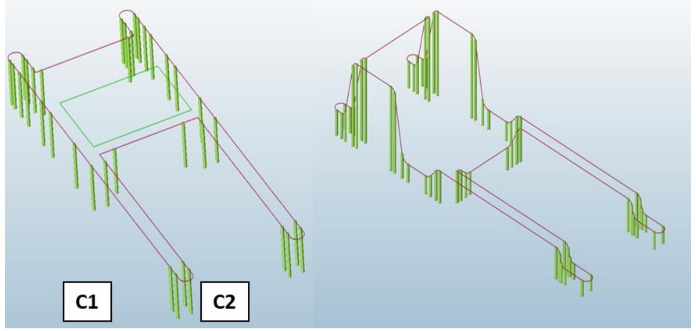
3 State of art

QFORM

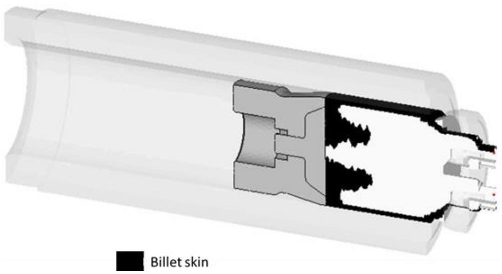
Altair Inspire™ Extrude Metal



Nose cone prediction

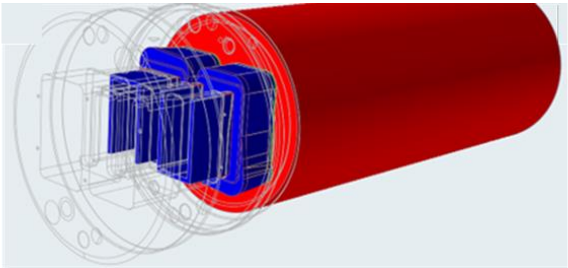


Bearing optimization

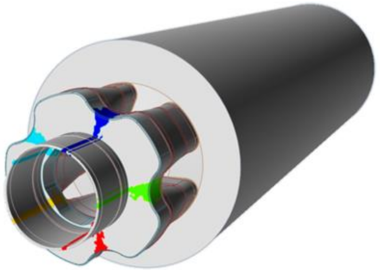


Skin tracking

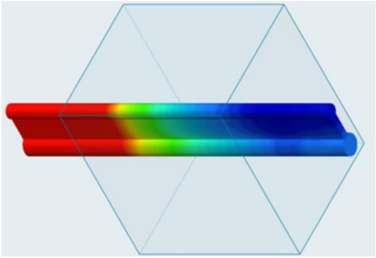
Profile quality



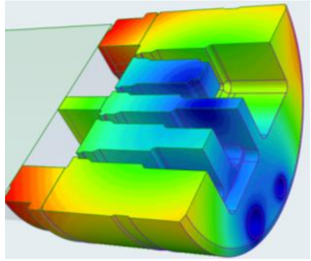
Transverse weld length



Weld quality and location



Quenching



Tool deflection

S. Altair, “Support/Training for Inspire Extrude Metal.” [Online]. Available: https://solidthinking.com/support-training/inspire-extrude-metal/. [Accessed: 16-Dec-2019]
C. Overview, “Click2Extrude^{TM} Metal 2017,” no. November 2016, 2017.

4 alExtFoam implementation and verification

Solver implementation

Base code: *SimpleFOAM*

1. Linear momentum conservation law

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

2. Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0$$

SimpleFOAM

```
Info << "\nStarting time loop\n" << endl;

while (simple.loop())
{
    Info<< "Time = " << runTime.timeName() << nl << endl;

    {
        #include "UEqn.H"
        #include "pEqn.H"
    }

    laminarTransport.correct();
    turbulence->correct();

    runTime.write();

    runTime.printExecutionTime(Info);
}

Info << "End\n" << endl;
return 0;
```

Extrusion process:

- Incompressible;
- Non-Newtonian;
- Non-isothermal;
- Steady-state.

4 alExtFoam implementation and verification

Solver implementation

Base code: *SimpleFOAM*

1. Linear momentum conservation law

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

2. Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0$$

3. Energy conservation equation

$$\frac{\partial (T u_i)}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\alpha_{td}\frac{\partial T}{\partial x_i}\right) = \frac{1}{\rho c_p}\tau'_{ij}\frac{\partial u_i}{\partial x_j}$$

alExtFoam

```
Info << "\nStarting time loop\n" << endl;

while (simple.loop())
{
    Info<< "Time = " << runTime.timeName() << nl << endl;

    {
      #include "UEqn.H"
      #include "pEqn.H"
    }

    #include "TEqn.H"

    laminarTransport.correct();
    turbulence->correct();

    runTime.write();

    runTime.printExecutionTime(Info);
}

Info << "End\n" << endl;
return 0;
```

4 alExtFoam implementation and verification

alExtFoam

Solver implementation

Energy conservation equation

$$\underbrace{\frac{\partial(Tu_i)}{\partial x_i}}_{advection} - \underbrace{\frac{\partial}{\partial x_i}\left(\alpha_{td}\frac{\partial T}{\partial x_i}\right)}_{diffusion} = \underbrace{\frac{1}{\rho c_p}\tau'_{ij}\frac{\partial u_i}{\partial x_j}}_{source}$$

1 2 3

Energy conservation equation

```
while (simple.correctNonOrthogonal())
{
 volTensorField gradU = fvc::grad(U);
 tmp <volScalarField> nu = laminarTransport.nu();
 tmp <volSymmTensorField> taurho = scalar(2)*nu*symm(gradU);
    //taurho = tau divided by rho

   fvScalarMatrix TEqn
    (
        fvm::div(phi, T)
      - fvm::laplacian(DT, T)
      - (1/c)*(taurho && gradU)
     ==
        fvOptions(T)
    );
    TEqn.relax();
    fvOptions.constrain(TEqn);
    TEqn.solve();
    fvOptions.correct(T);
}
```

4 alExtFoam implementation and verification

Constitutive equation - Zener-Hollomon model Implementation

1
```
volScalarField& T=U_.mesh().lookupObject<volScalarField>("T");
Tw_ = (min(max(T, Tmin_)), Tmax_);
```

2
```
volTensorField gradU = fvc::grad(U_);
strainRate_ = symm(gradU);
```

3
```
effectiveStrainRate_ = ( max(sqrt(scalar(2.0/3.0)*magSqr(strainRate_))(),(eSRMin_));
```

4
```
 ZenerHollomon_ = effectiveStrainRate_*exp(Q_/(Tw_*R_));
```

5
```
effectiveFlowStress_ =        (asinh(pow( ZenerHollomon_/A_,(scalar(1)/n_))))/alpha_;
```

6
```
dynamicViscosity_ = (effectiveFlowStress_/(scalar(3)*effectiveStrainRate_));

return
    (
            dynamicViscosity_/rho_
    );
```

$$\mathrm{T} = \begin{cases} \mathrm{T} > T_{min} \\ \mathrm{T} < T_{max} \end{cases}$$

1

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

2

$$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} > eSRMin$$

3

$$Z = \dot{\bar{\varepsilon}} \mathrm{e}^{\frac{Q}{RT}}$$

4

$$\bar{\tau} = \frac{1}{\alpha}\sinh^{-1}\left(\left(\frac{Z}{A}\right)^{1/n}\right)$$

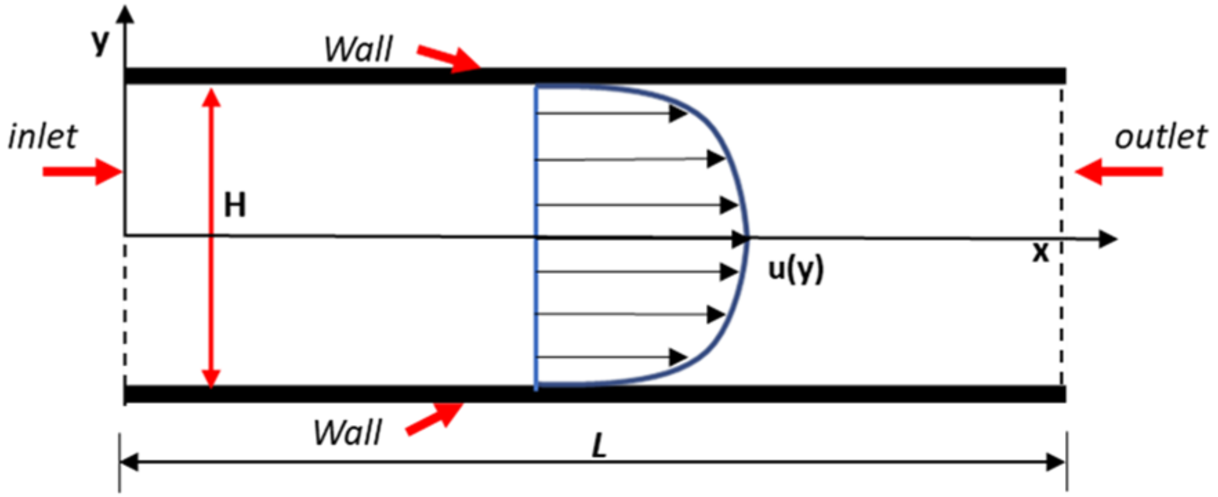
5

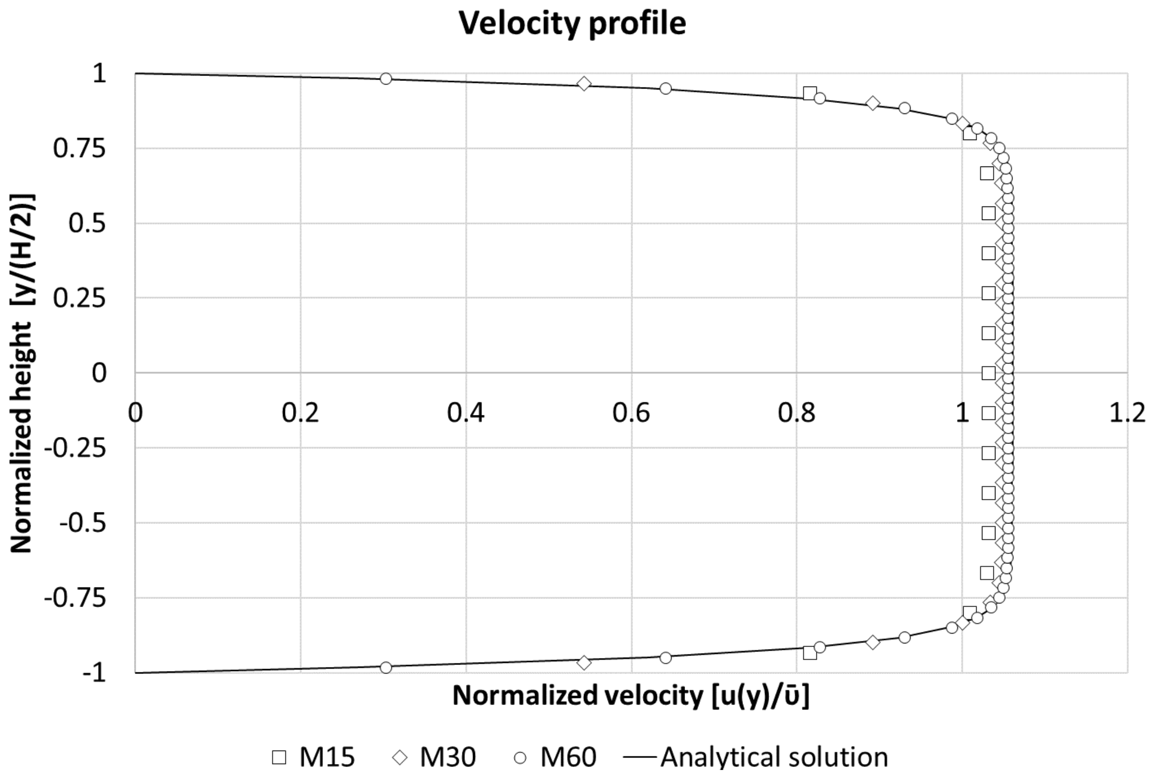
$$\nu = \frac{1}{3\rho}\frac{\bar{\tau}}{\dot{\bar{\varepsilon}}}$$

6

4 alExtFoam implementation and verification

Constitutive equation - Flow between parallel plates





	M15	M30	M60
RMSE %	2	0.6	0.3

4 alExtFoam implementation and verification

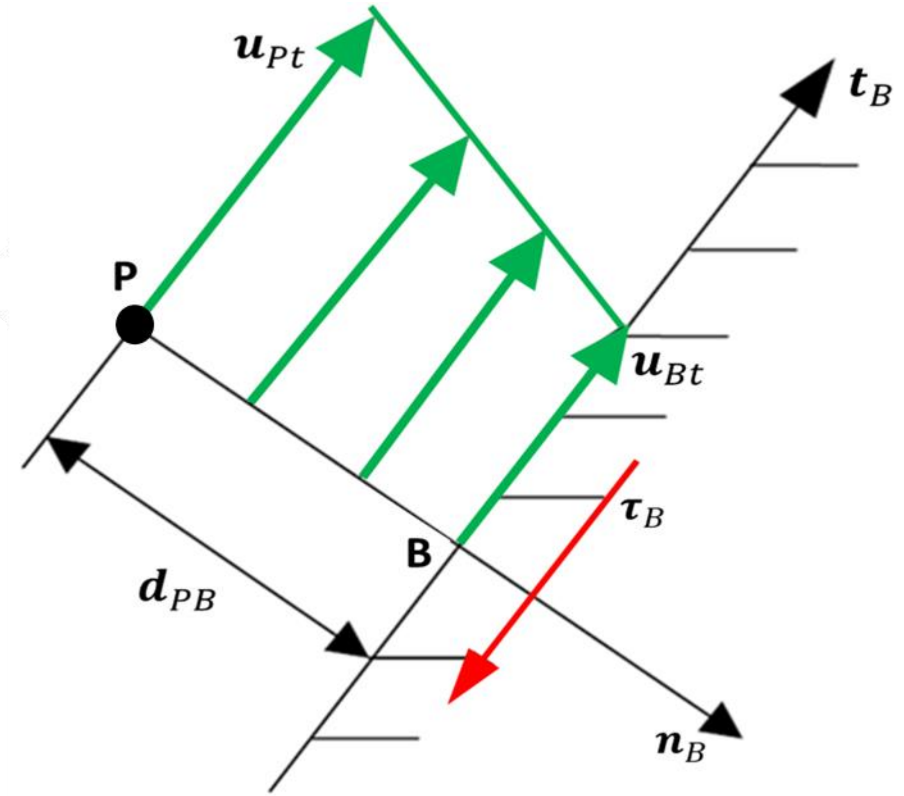
Slip boundary condition - Implementation

Shear friction law

$$\tau_B = mK$$

Velocity in the boundary:

$$u_{Bt} = \begin{cases} u_{Pt}\left(1 - f\left(\dot{\varepsilon}_{ij}\right)\right), & f\left(\dot{\varepsilon}_{ij}\right) < 1 \\ 0, & f\left(\dot{\varepsilon}_{ij}\right) \geq 1 \end{cases}$$



4 alExtFoam implementation and verification

Slip boundary condition - Implementation

Shear friction law

$$\tau_B = mK$$

Velocity in the boundary:

$$u_{Bt} = \begin{cases} u_{Pt}\left(1 - f\left(\dot{\varepsilon}_{ij}\right)\right), & f\left(\dot{\varepsilon}_{ij}\right) < 1 \\ 0, & f\left(\dot{\varepsilon}_{ij}\right) \geq 1 \end{cases}$$

6

2 3

5 $f\left(\dot{\varepsilon}_{ij}\right) = \left(\quad \text{——} \quad \right)$

1 4

shearFrictionModelFoam

1
```
const volScalarField& dynamicViscosity =this->db().objectRegistry::lookupObject<volScalarField> ("dynamicViscosity");
scalarField Dvw= dynamicViscosity.boundaryField()[patchI];
```

2
```
const volScalarField& effectiveFlowStress =this->db().objectRegistry::lookupObject<volScalarField> ("effectiveFlowStress");
volScalarField k = effectiveFlowStress/sqrt(scalar(3));
scalarField kw = k.boundaryField()[patchI];
```

3
```
scalarField dist = scalar(1)/(this->patch().deltaCoeffs());
```

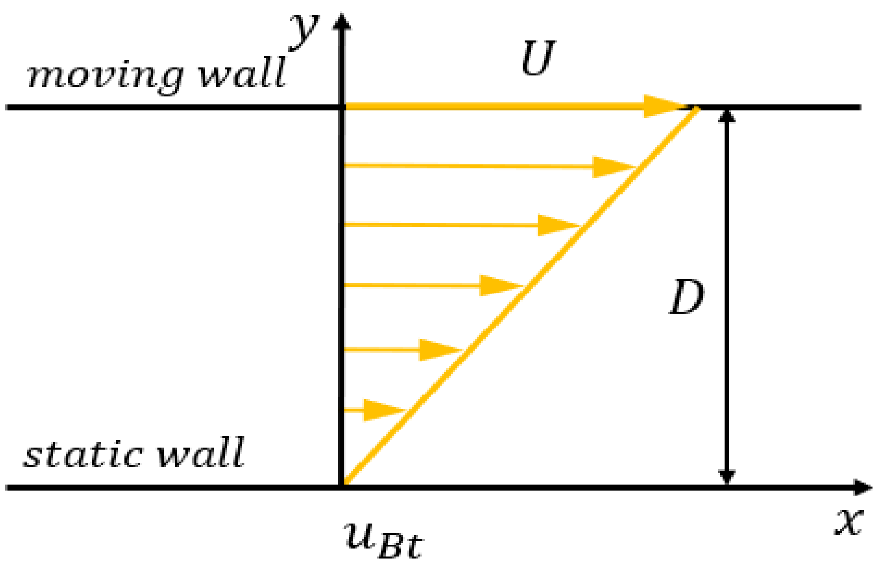
4
```
vectorField velInt = this->patchInternalField();
vectorField velIntTg = transform(I - sqr(nHat), velInt);
scalarField magVelIntTg = mag(velIntTg);
```

5
```
scalarField strainFunction = (slipFactor_*kw*dist)/(Dvw*(magVelIntTg + SMALL))
```

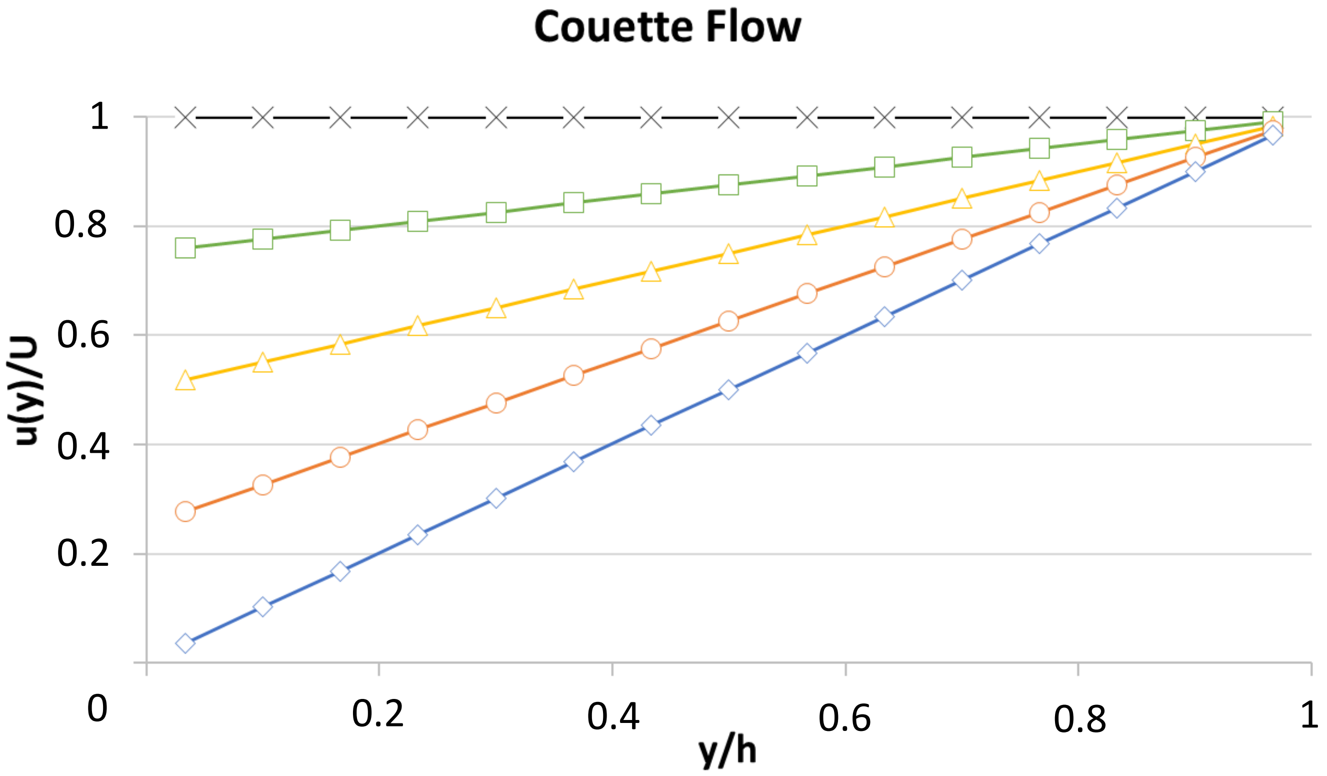
6
```
forAll(this->patch(), faceI)
{
    if (strainFunction[faceI] < scalar(1.0))
    {
            u_wallslip[faceI] = velIntTg[faceI]*(1.0 - strainFunction[faceI]);
    }
    else
    {
            u_wallslip[faceI] = vector::zero;
    }
}
```

4 alExtFoam implementation and verification

Slip boundary condition – Couette Flow



$$u(y) = U - m\sqrt{3}\dot{\bar{\varepsilon}}(y - D)$$



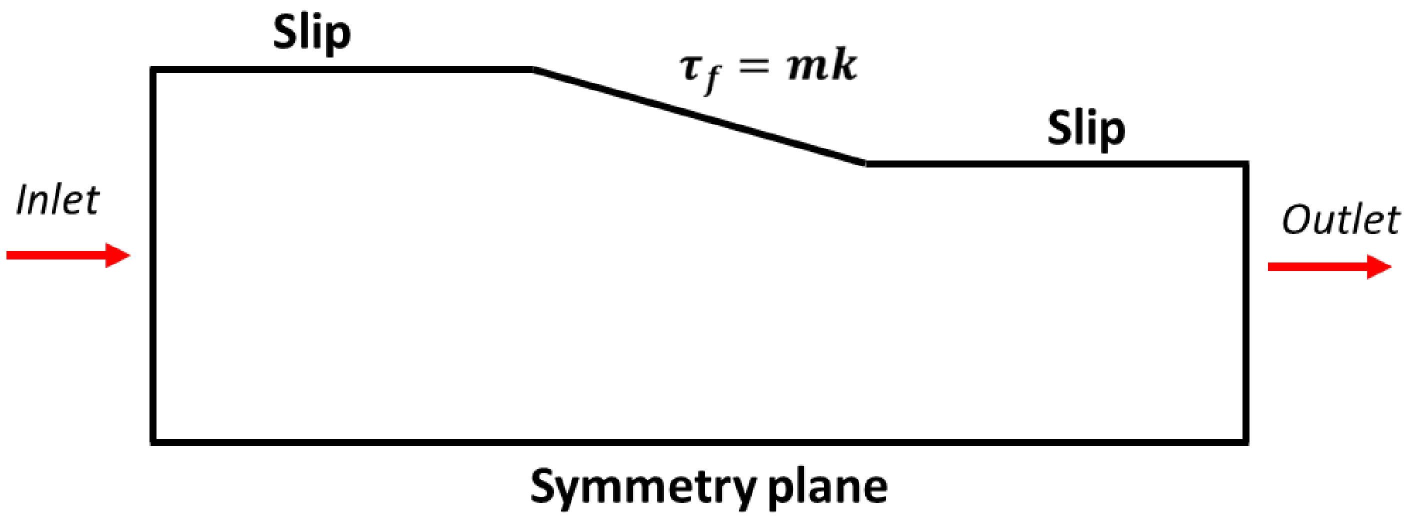
m	0	0.25	0.5	0.75	1
Numerical solution	×	□	△	○	◇
Analytical solution	—	—	—	—	—

4 alExtFoam implementation and verification

Slip boundary condition - Convergent die

Considerations:

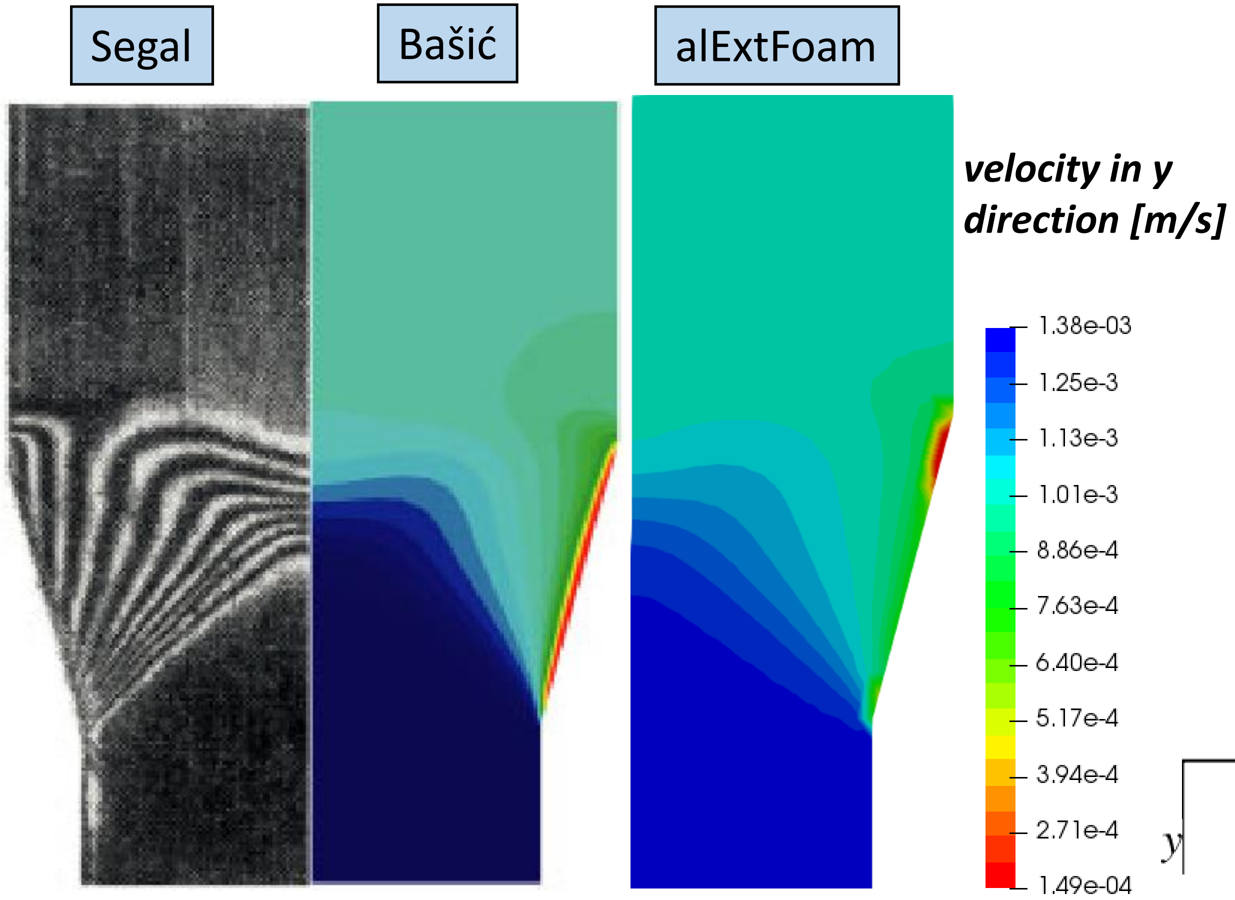
- Plane strain forward extrusion through a convergent die;
- Verify *shearFrictionModelFoam*:
    - Segal experimental case;
    - Bašić numerical simulation.
- Constant yield stress;
- **shearFrictionModelFoam (**m = 1)

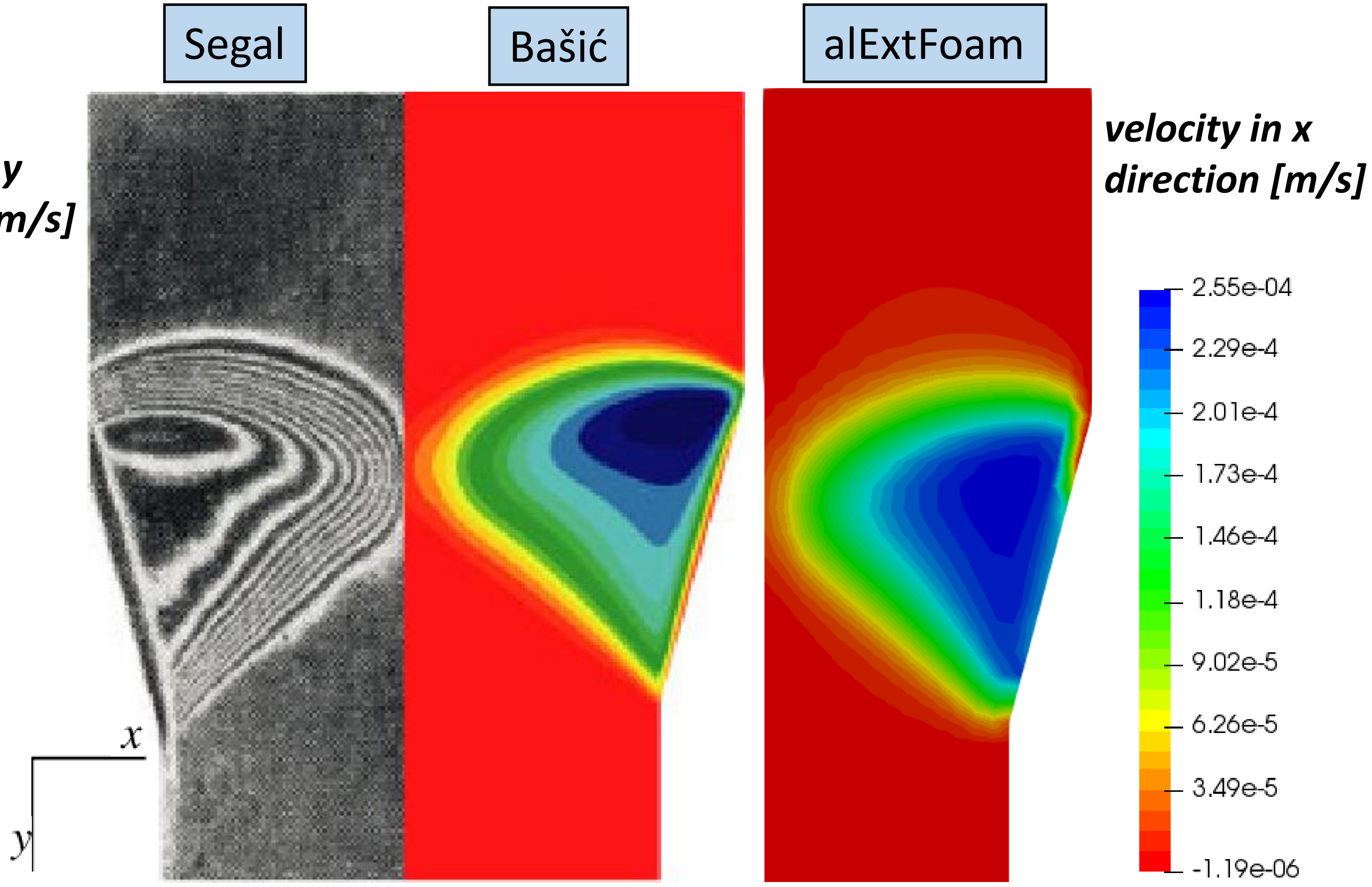


V. Segal and E. Makušok, “Analysis of Plastic Metal Deformation by Moire Method.,” *Metallurgical*, vol. VI, 1974.
H. Bašić, I. Demirdžić, and S. Muzaferija, “Finite volume method for simulation of extrusion processes,” 2005.

4 alExtFoam implementation and verification

Slip boundary condition - Convergent die





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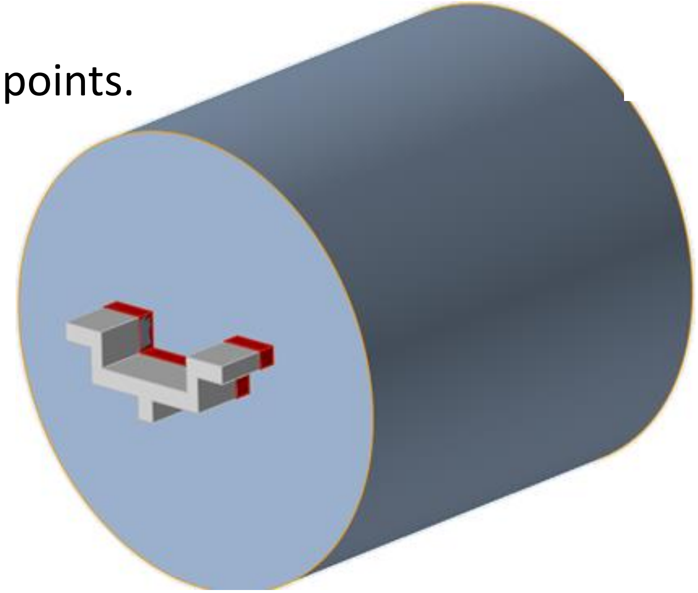
H. Bašić, I. Demirdžić, and S. Muzaferija, "Finite volume method for simulation of extrusion processes," 2005.

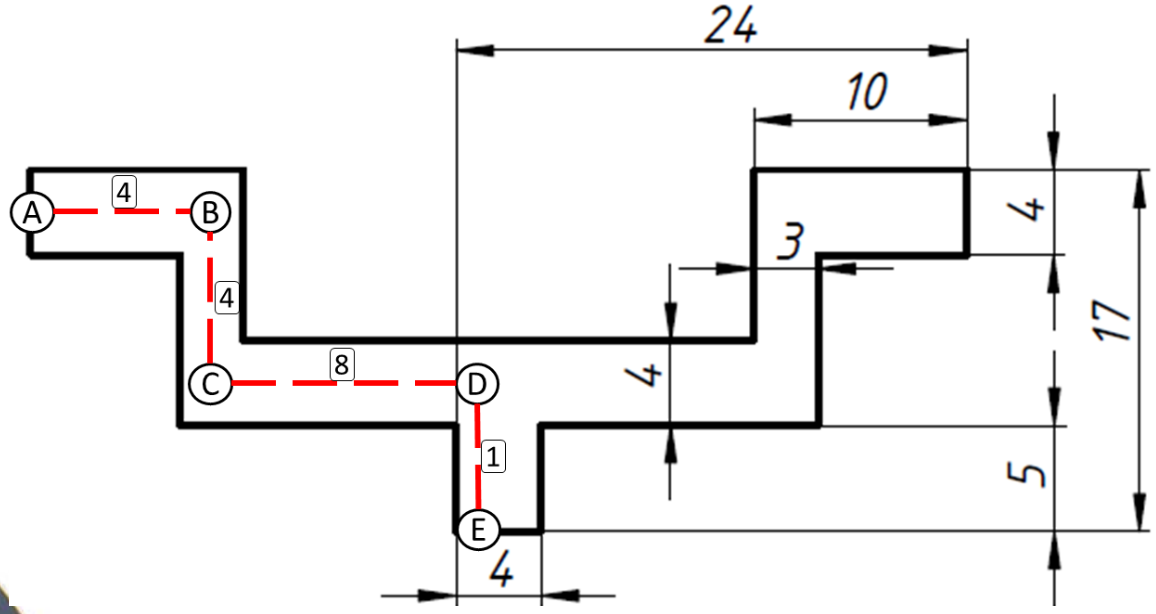
5 alExtFoam verification and validation

U-shaped profile

Considerations:

- Comparison of *alExtFoam* with *IEM;*
- Zener-Holomon Constitutive model;
- *ShearFrictionModelFoam* with different friction coefficient;
- Velocity checked in 22 central points.

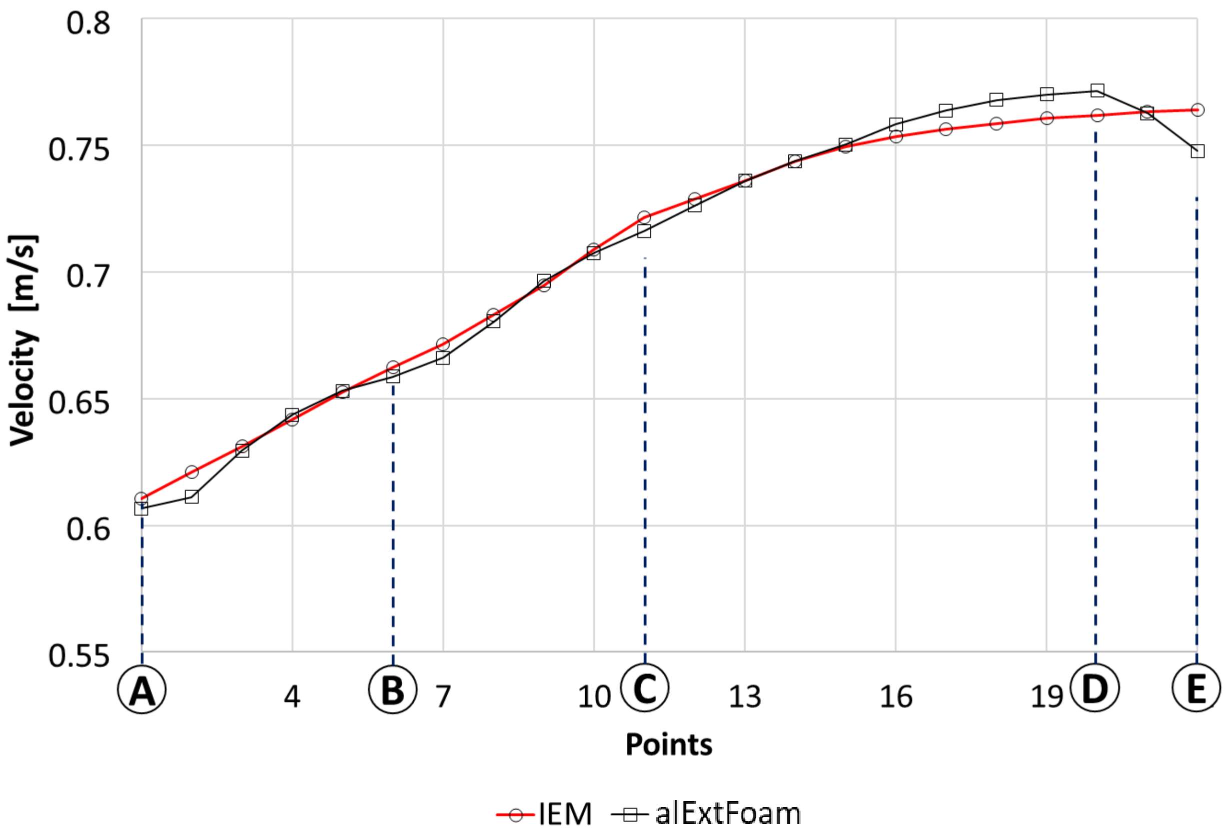


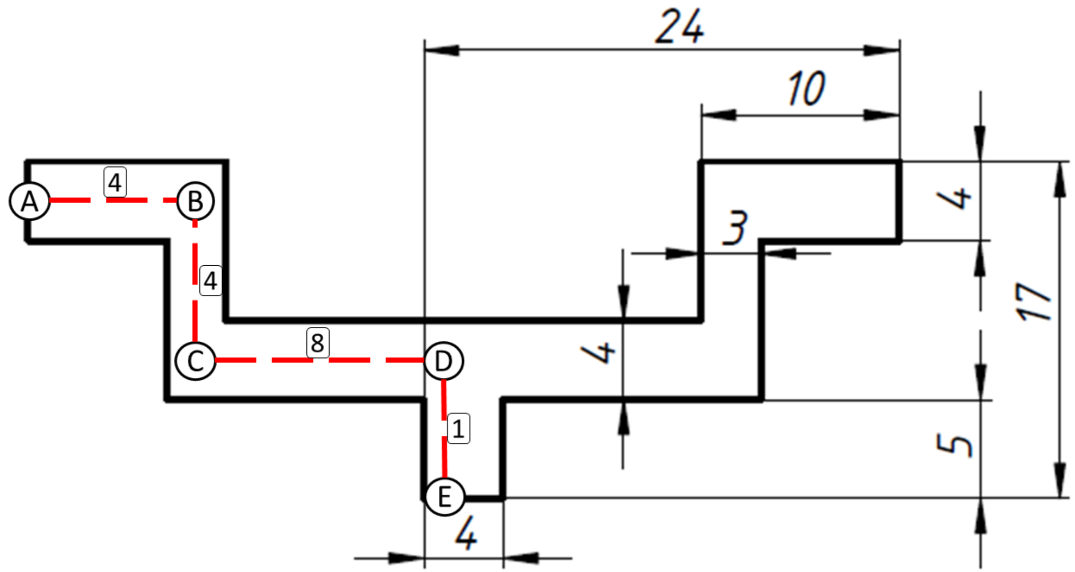


Dimensions in [mm]

5 alExtFoam verification and validation

U-shaped profile: Results





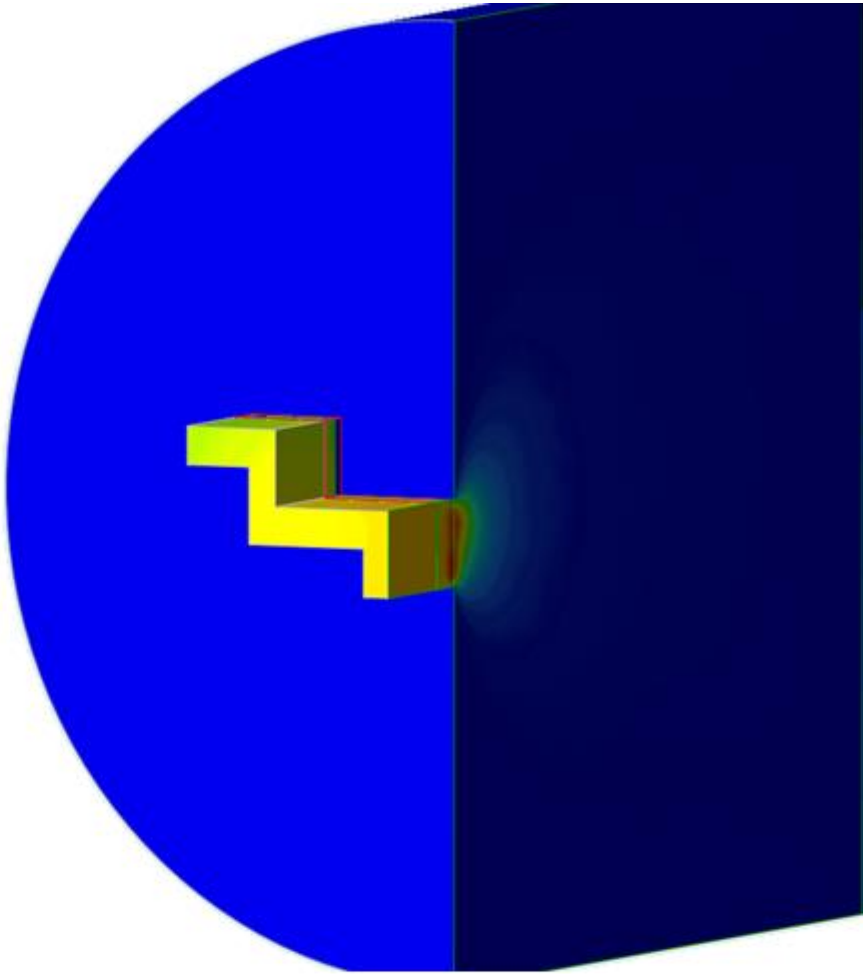
Dimensions in [mm]

5 alExtFoam verification and validation

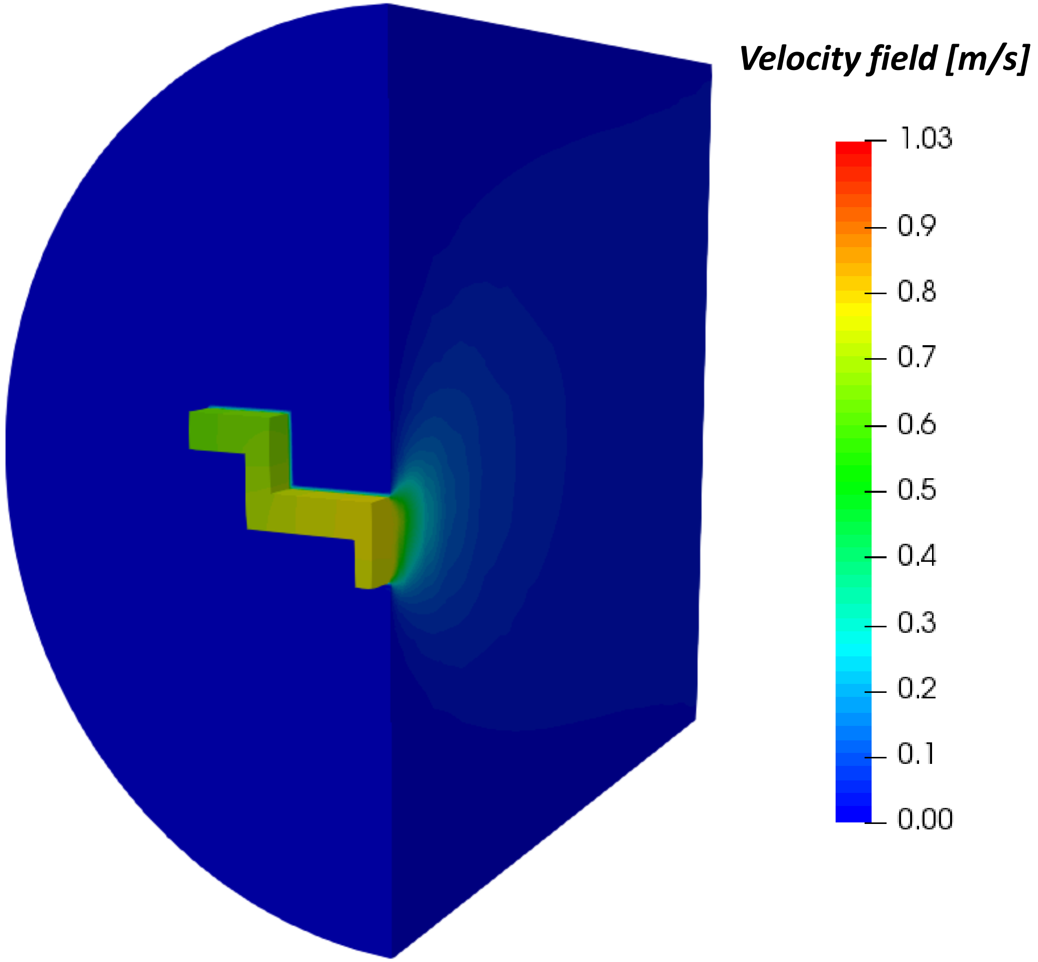
U-shaped profile: Results

Velocity field

IEM



alExtFoam

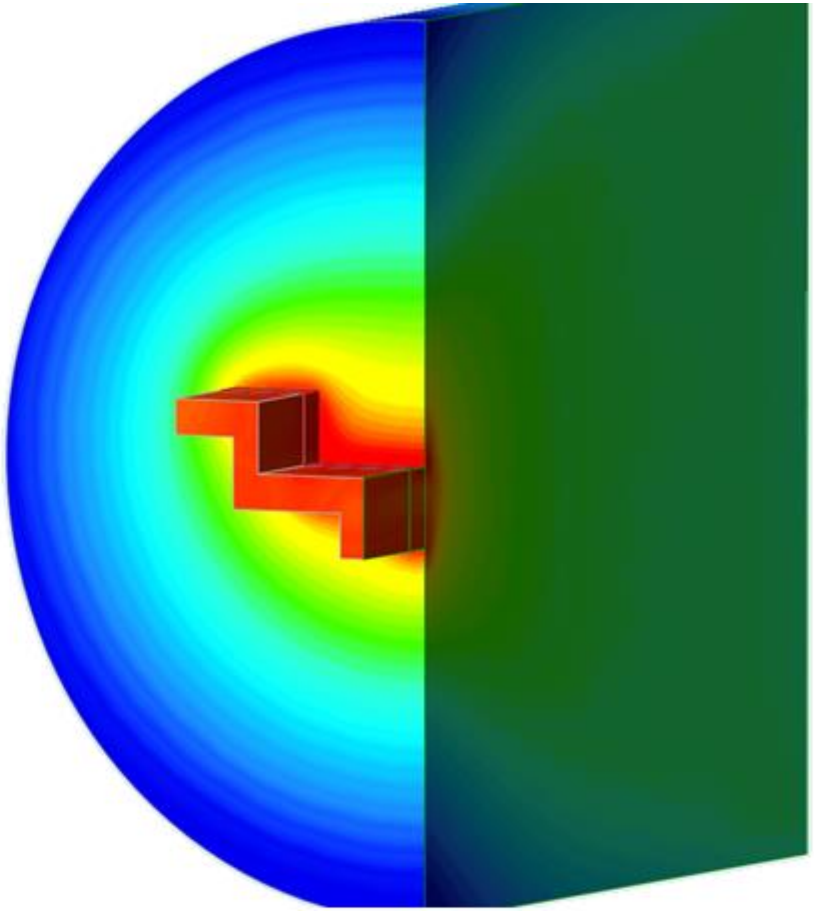


5 alExtFoam verification and validation

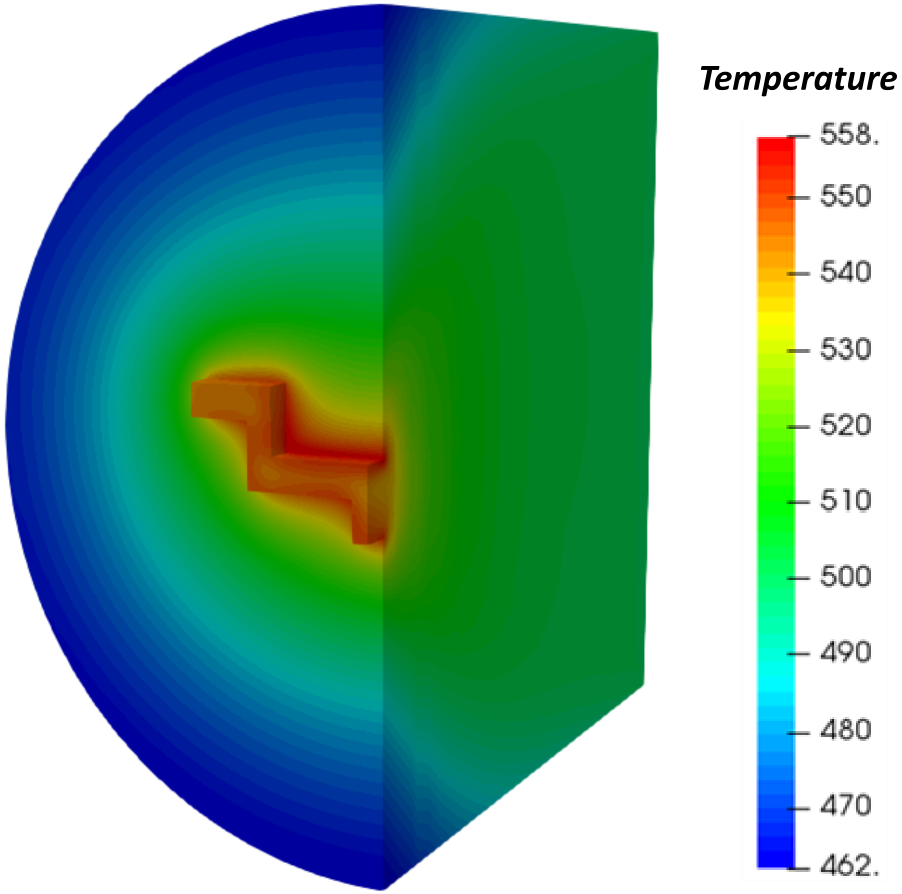
U-shaped profile: Results

Temperature field

IEM



alExtFoam

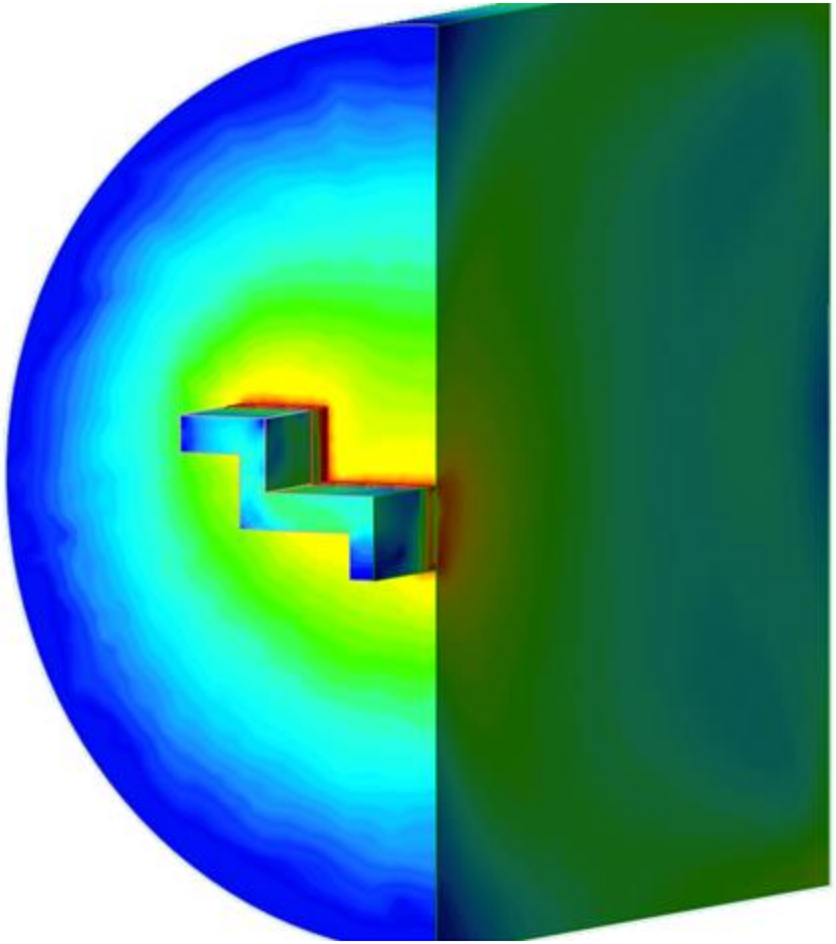


5 alExtFoam verification and validation

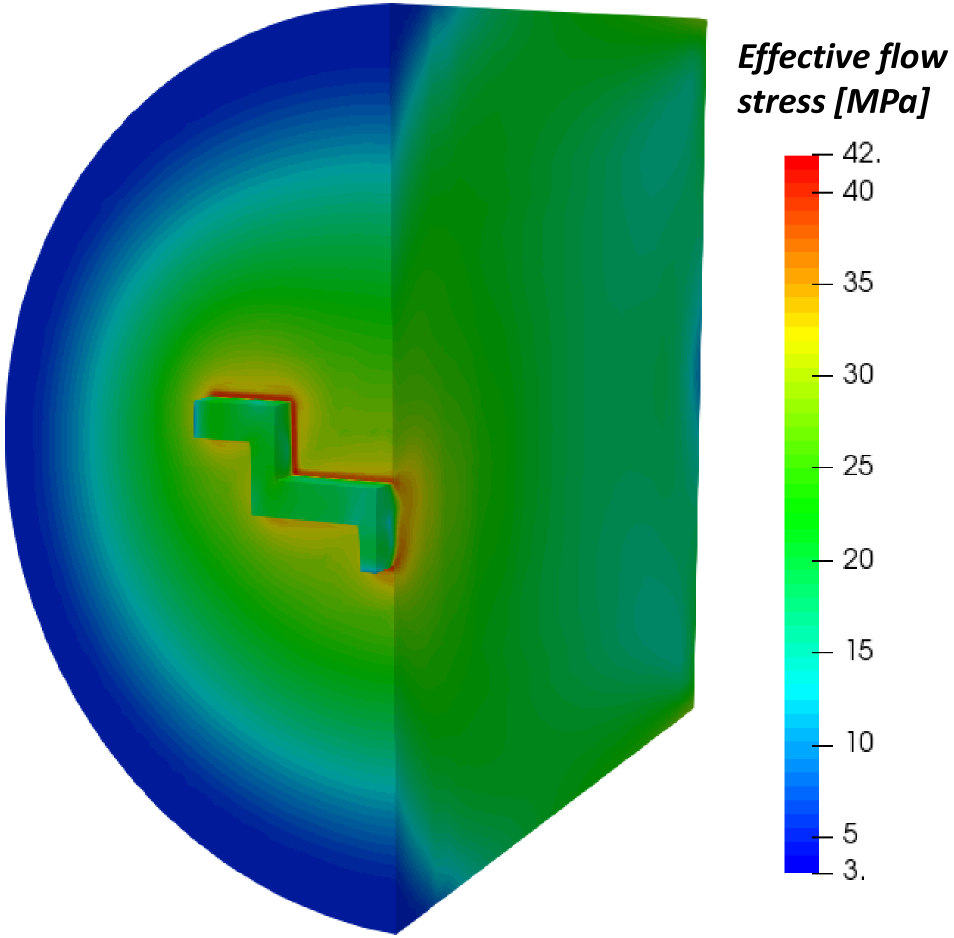
U-shaped profile: Results

Effective flow stress field

IEM



alExtFoam

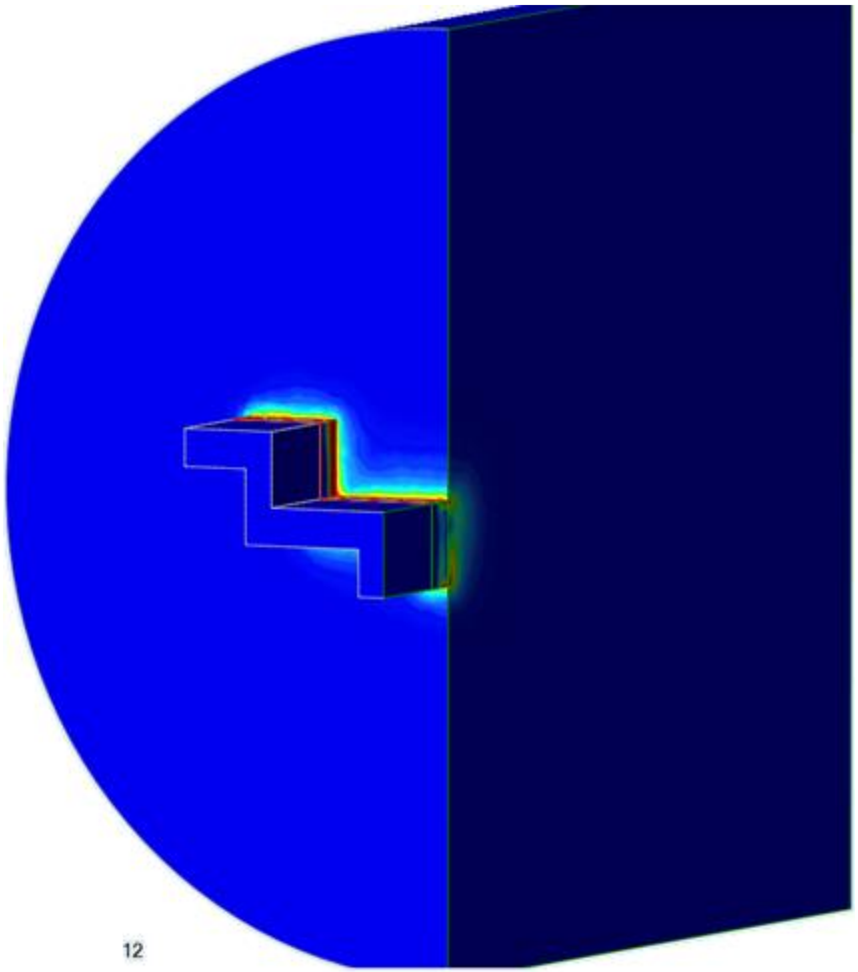


5 alExtFoam verification and validation

U-shaped profile: Results

Strain rate field

IEM



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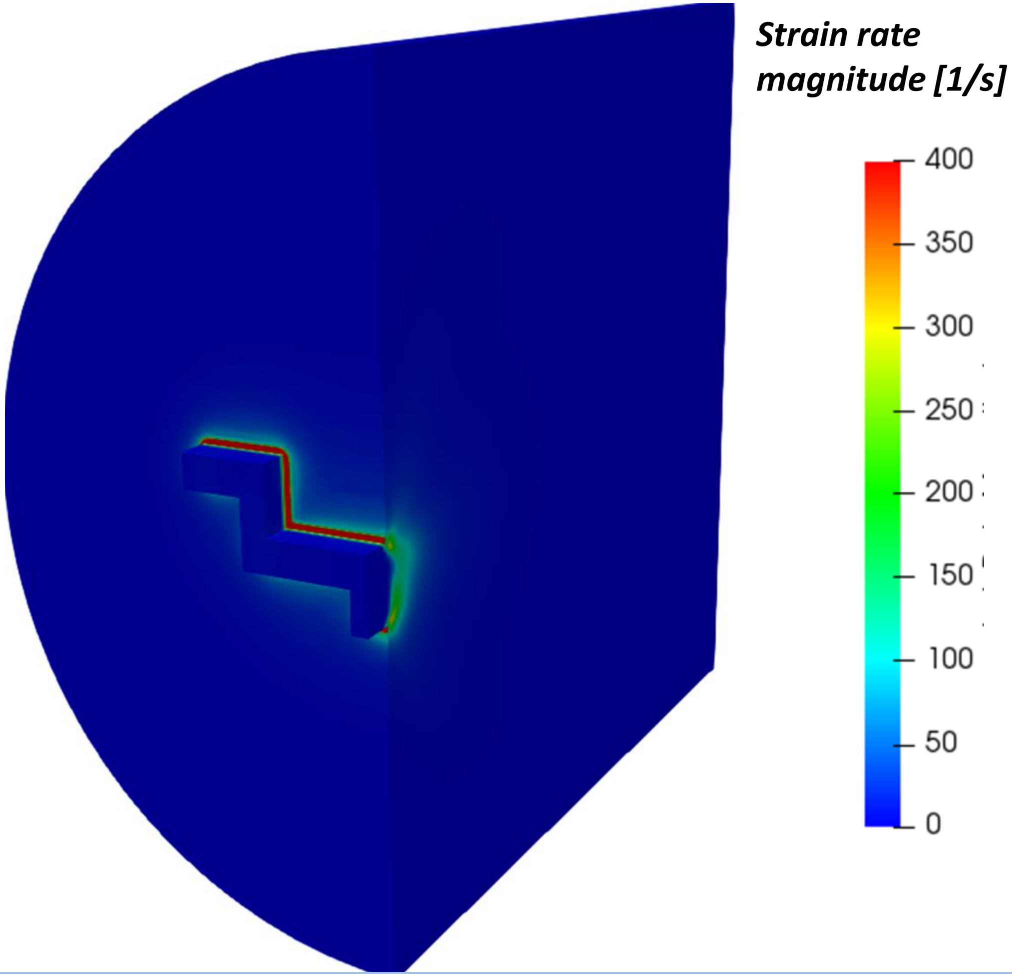
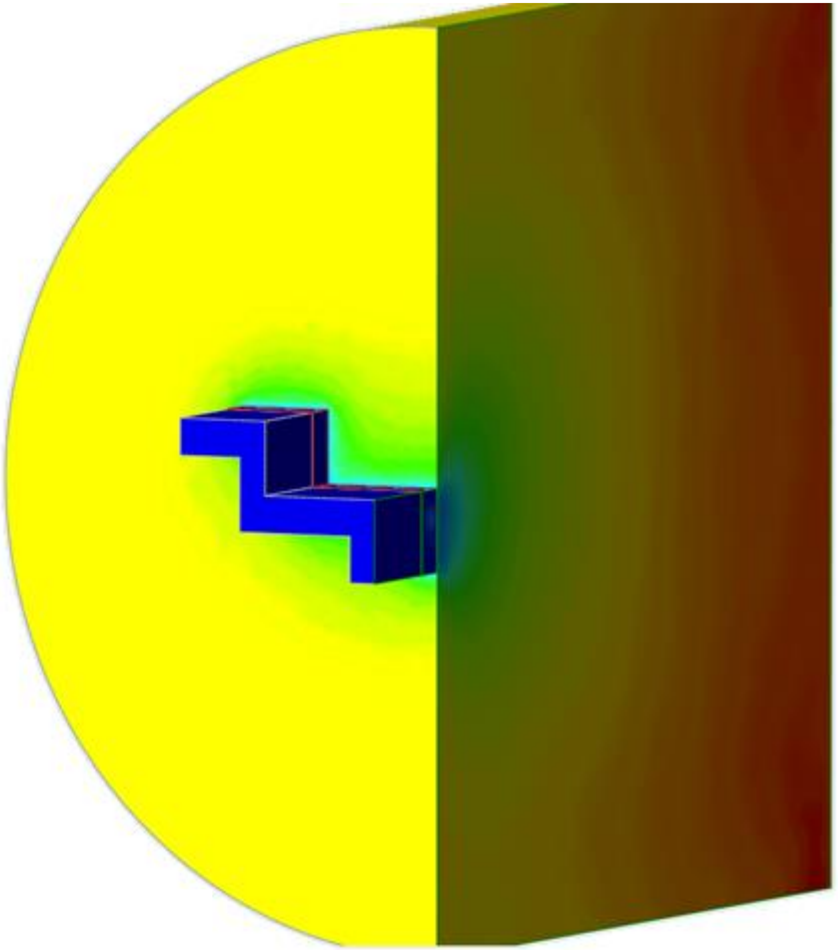


5 alExtFoam verification and validation

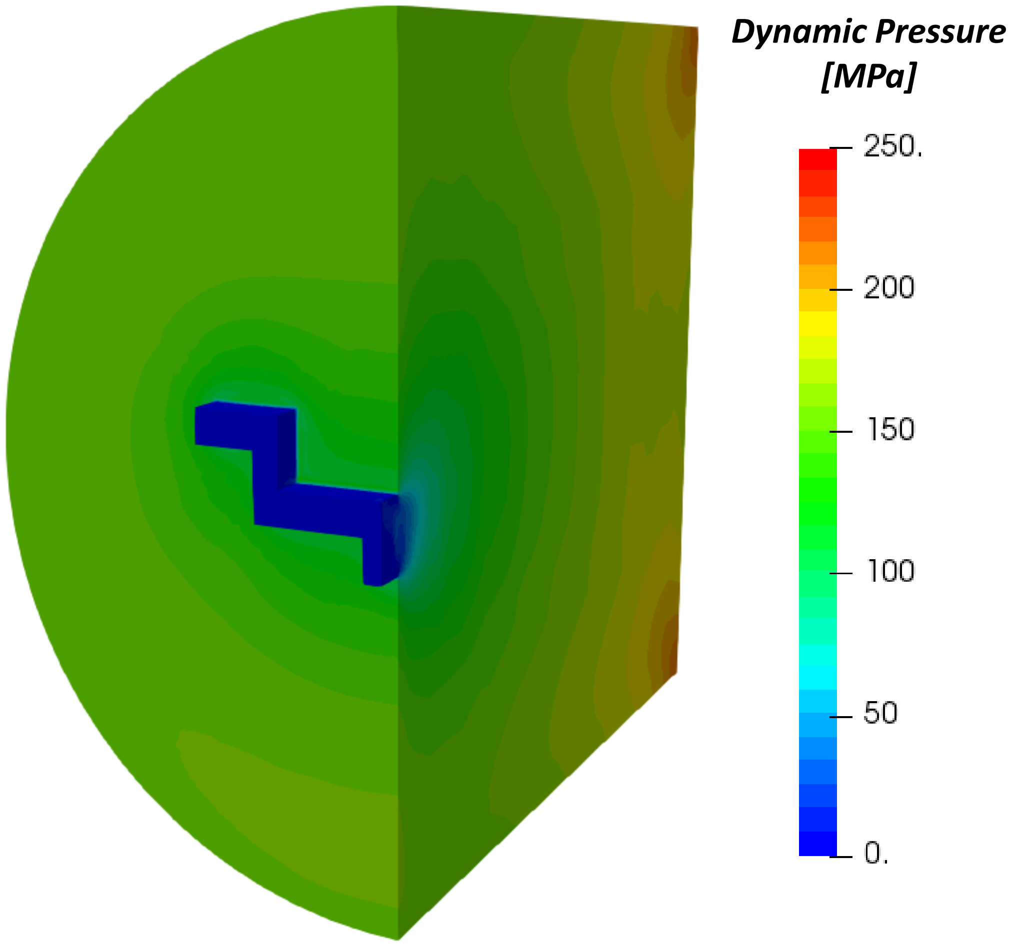
U-shaped profile: Results

Pressure field

IEM

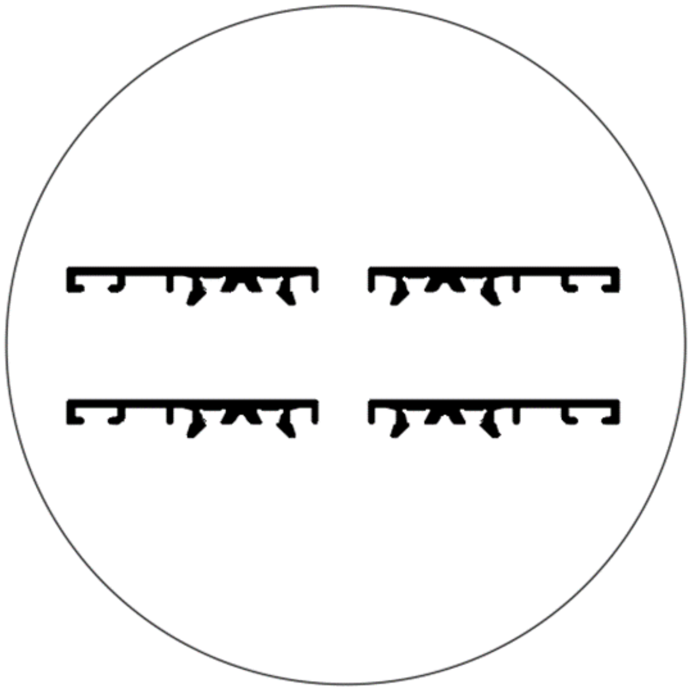


alExtFoam



5 alExtFoam verification and validation

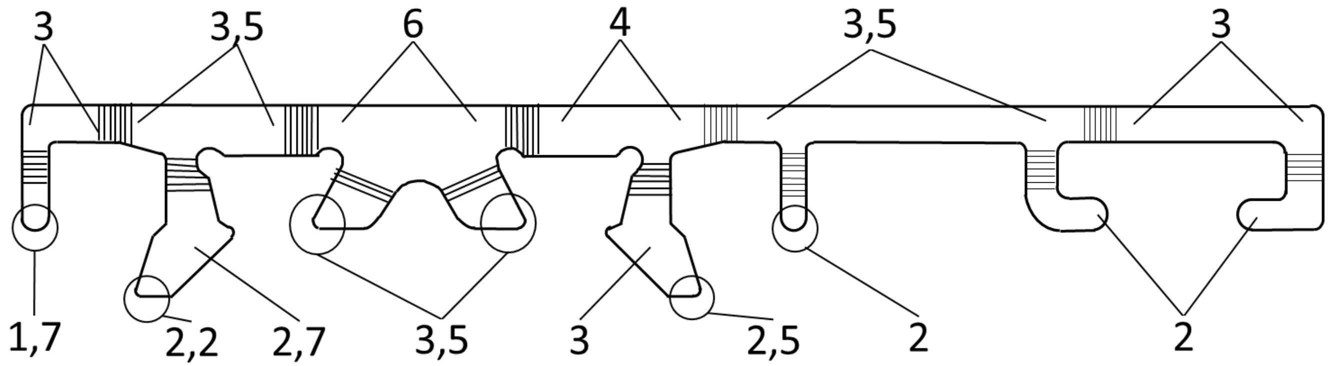
Multi-hole extrusion profile



Goal

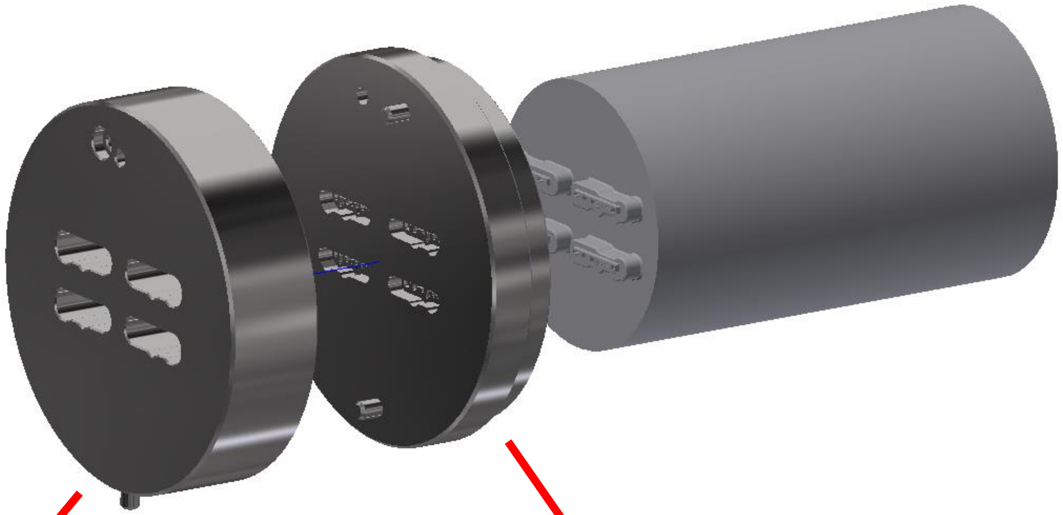
- Validate the *alExtFoam* with a industrial relevant extrusion geometry;
- Verify if the velocity distribution is consistent with the dimensions assigned by the designer in the bearing zone.

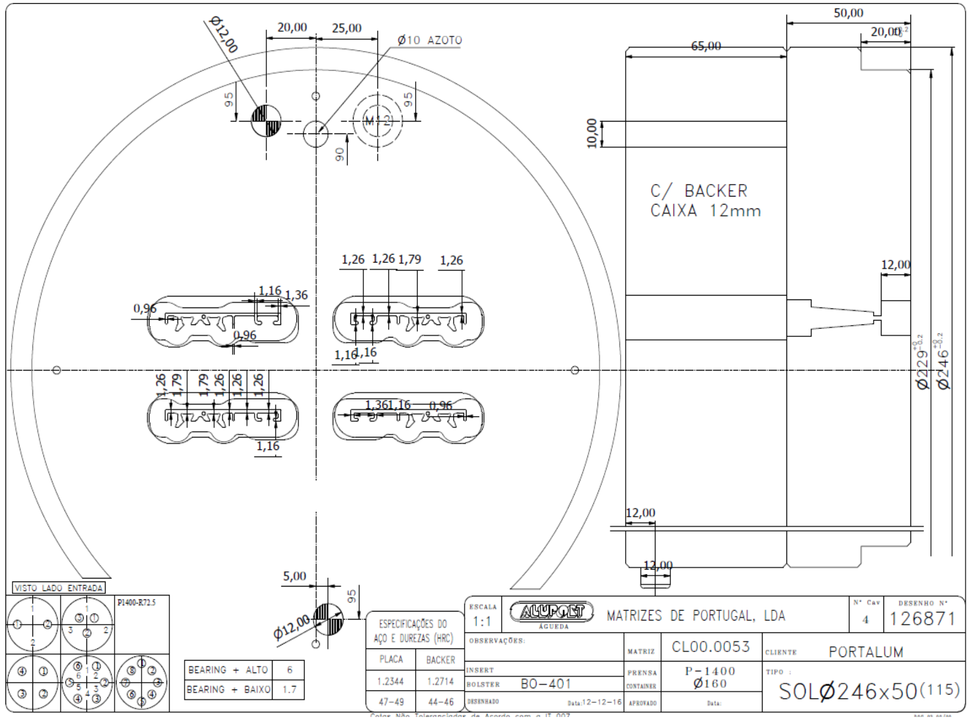
Proposed bearing length [mm]



5 alExtFoam verification and validation

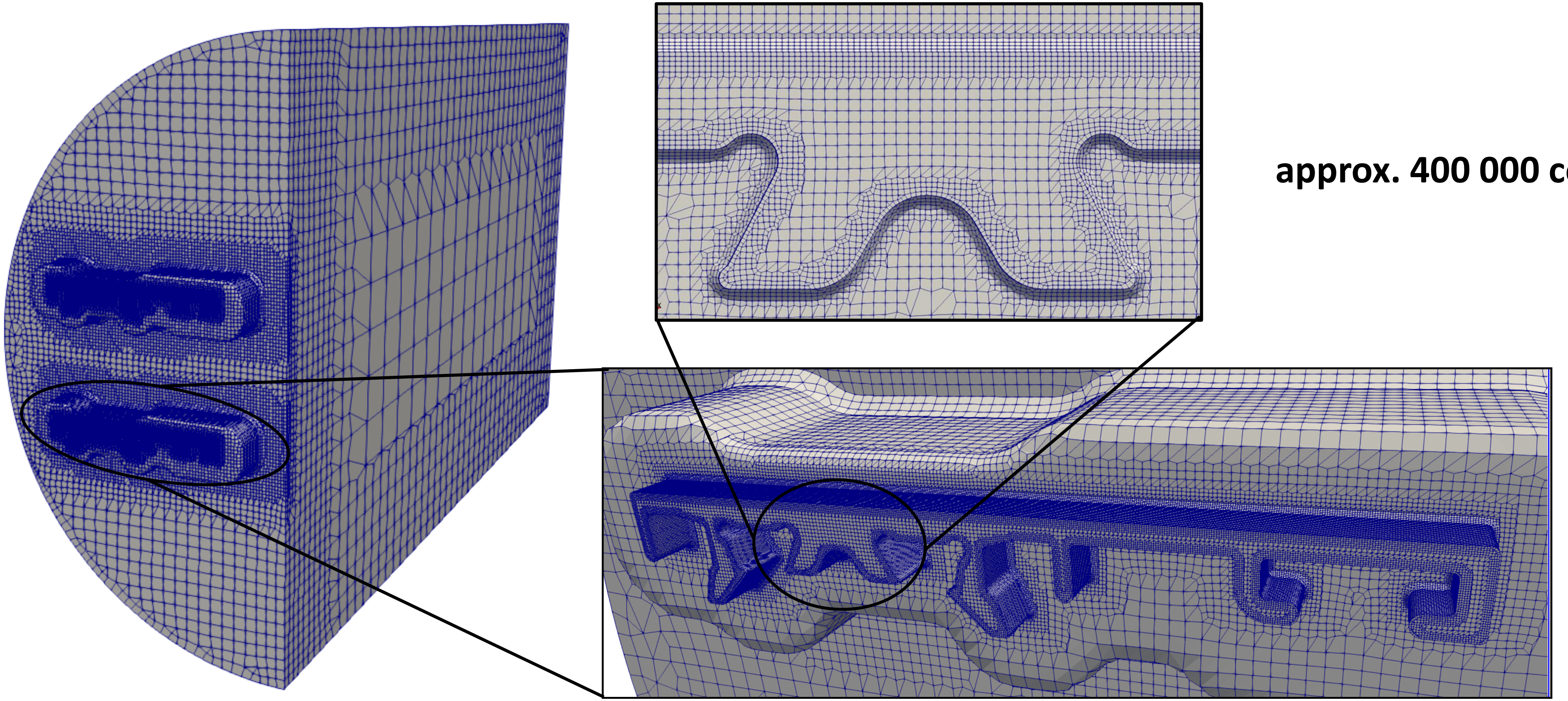
Multi-hole extrusion profile: CAD Model





5 alExtFoam verification and validation

Multi-hole extrusion profile: Mesh generation (cfmesh)

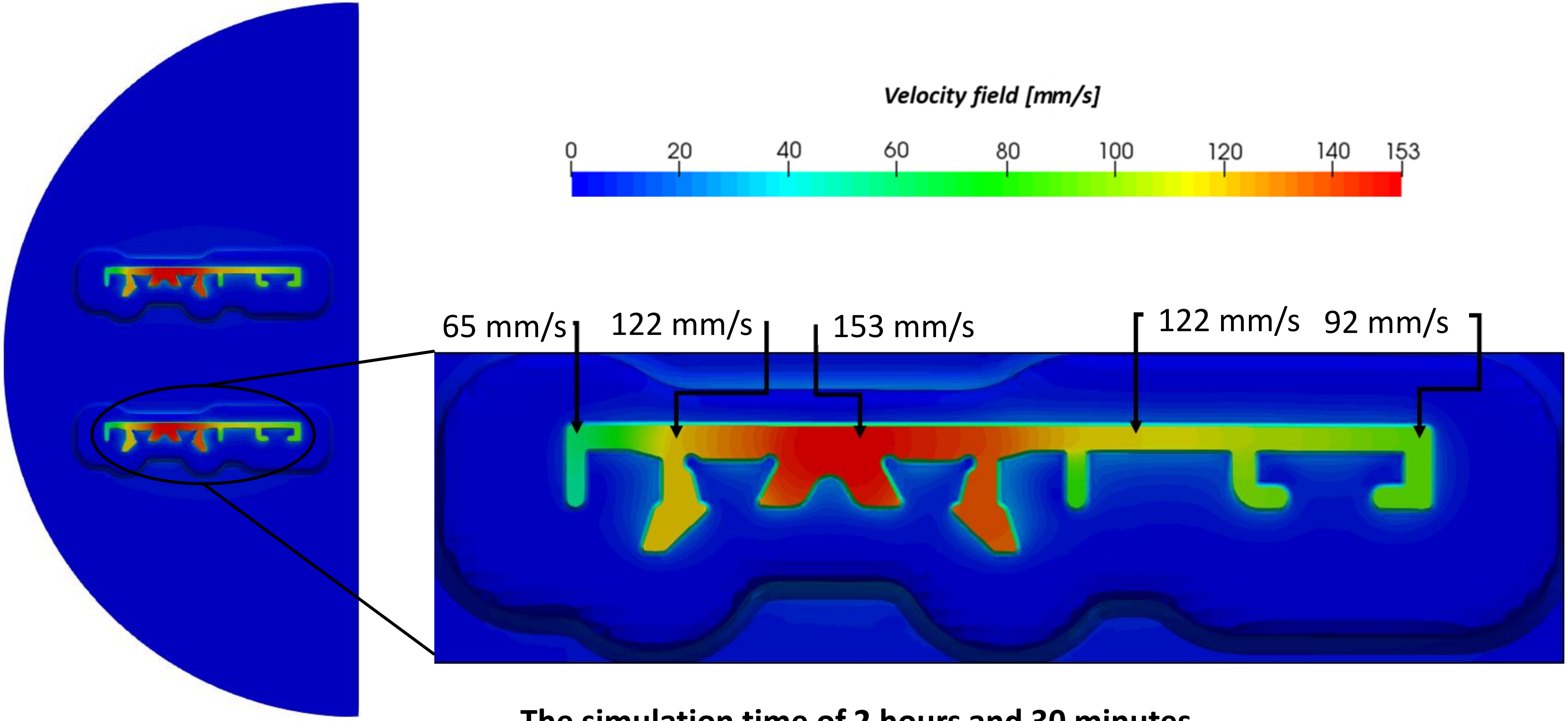


approx. 400 000 cells

“CFD MESHING MADE SIMPLE.” [Online]. Available: https://cfmesh.com/

5 alExtFoam verification and validation

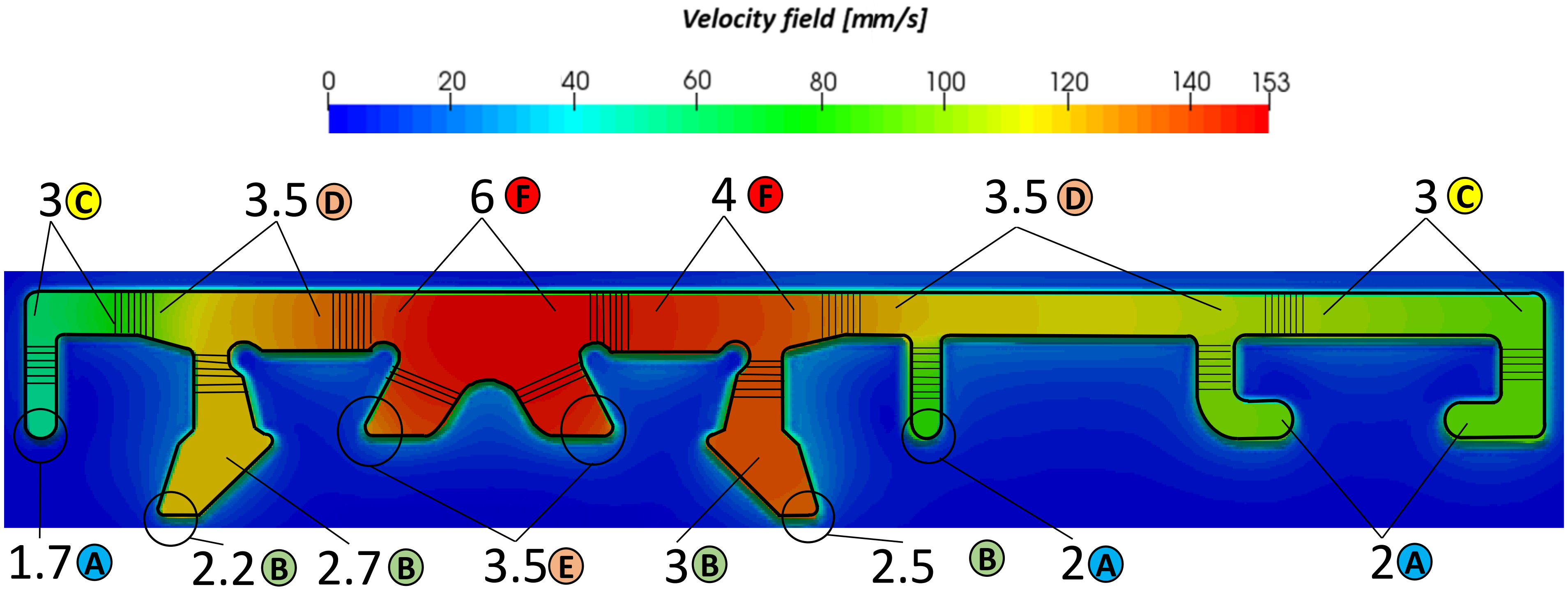
Multi-hole extrusion profile: Velocity field



The simulation time of 2 hours and 30 minutes

5 alExtFoam verification and validation

Multi-hole extrusion profile: Velocity field



Bearing length rules:

- Bearing is longer for thicker sections and towards the center of the die;
- Bearing is shorter for high restriction areas;

6 Conclusions and Future work

- alExtFoam is a tool capable of simulating the extrusion of aluminum alloys;
- The Parallel plates, Couette and Convergent die flow cases allowed to verify the implementation of the constitutive and wall boundary condition;
- Calculation errors are very low when compared with analytical, experimental and numerical solutions;
- alExtFoam provides solutions similar to Inspire Extrude Metal;
- alExtFoam has proven to be able to evaluate the extrusion die design typical of the industry;
- 2h 30 min is an efficient simulation time that can be easily introduced into the production process;

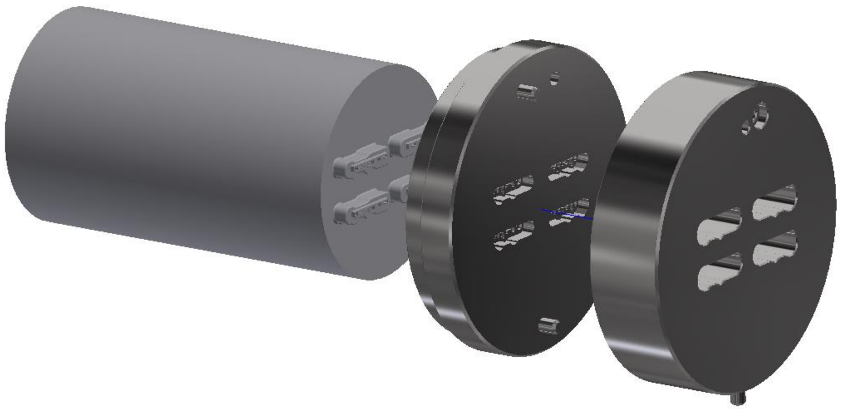
6 Conclusions and Future work

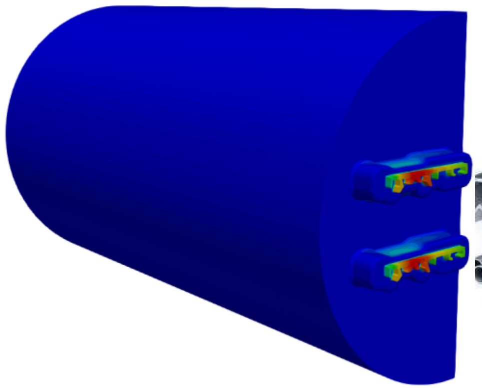
alExtFoam can now help the company:

- To improve the understanding about the influence of the process parameters (temperature and velocity) on the extrusion process;
- To reduce the costs related to the die design and the extrusion parameters.

6 Conclusions and Future work

- Bearing length automatic optimization;
- Levanov friction model implementation;
- Automatic mesh generation algorithm for different mesh refinement levels;
- Code optimization;
- Improve solver to be able to cope unsteady problems.





A NOVEL OPENFOAM SOLVER FOR ALUMINIUM ALLOY PROFILE EXTRUSION

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