Open Source LASER Boundary Condition with Linear and Circular Spot Motion and Additional Heat-Transfer

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Outline

- Motivation
- Mathematic description
- Programming description
- Capabilities and example
- Summary

Motivation

- Common heat treatment vs. a local heat treatment of aluminum alloys
- Using OpenFOAM for calculating the temperature distribution in the material
- Heat treatment is done using a LASER source, hence a new boundary condition needed to be developed
- Heat treatment and quenching should be possible
- Adjusting the LASER power based on the temperature or stresses

laserConvectionBC

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Mathematic description

❖ Gaussian profile of the LASER

$$f_{Gauss}(x,y) = \frac{1}{2\,\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}\exp\left[\frac{-1}{2(1-\rho^2)}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}-\frac{2\rho\,x\,y}{\sigma_x\sigma_y}\right)\right]$$

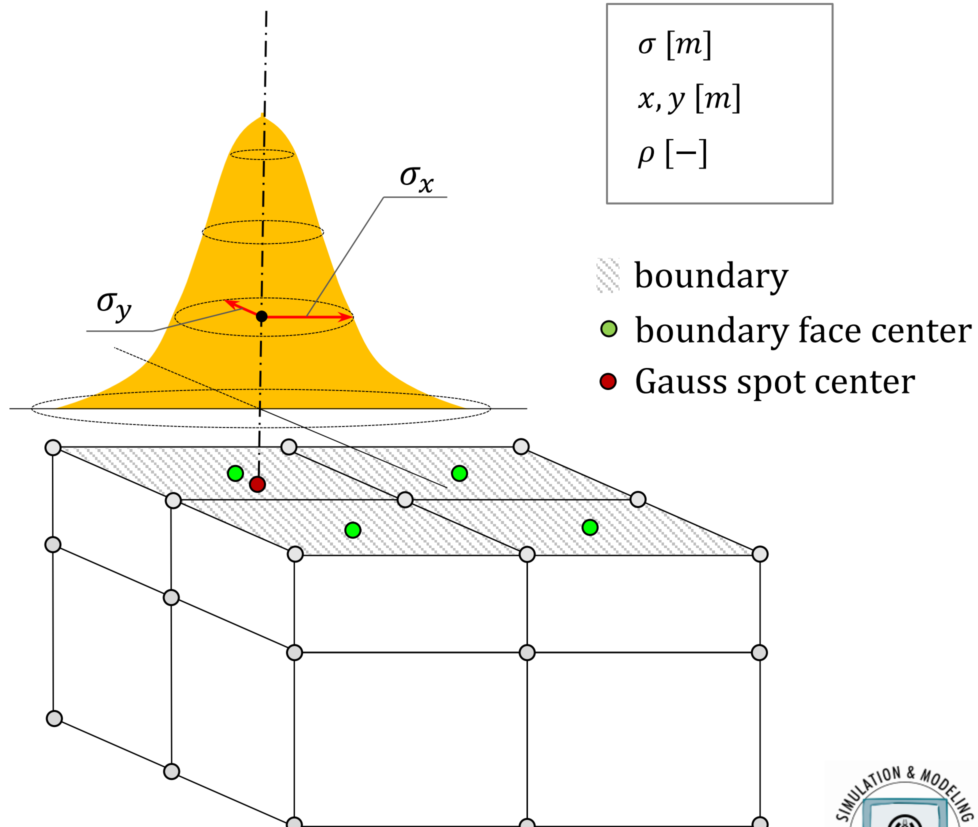
$$x = \underbrace{x_{spotCenter}} - \underbrace{x_{Face}}$$

$$y = \underbrace{y_{spotCenter}} - \underbrace{y_{Face}}$$

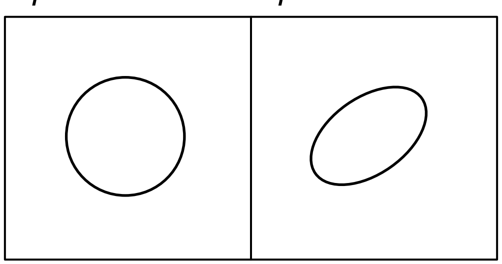
$$\rho \coloneqq Correlation\ Factor$$

Nomenclature

$\sigma\ [m]$
$x, y\ [m]$
$\rho\ [-]$



$\rho = 1$ $\rho = 0.8$



❖ In addition, the heat transfer has to be implemented for cooling during the heat treatment and for quenching (convection)

$$\alpha\,(T_{Face} - T_{amb}) = \lambda\,\frac{T_{Cell} - T_{Face}}{\delta}$$

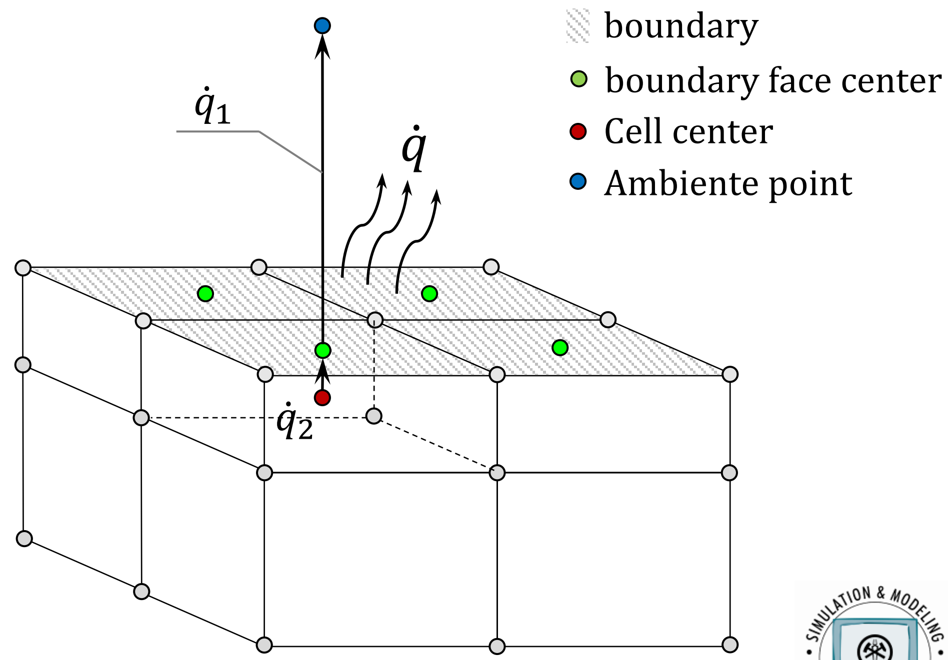
Nomenclature

$T\ [K]$	$\delta\ [m]$
	$\alpha\ \left[\frac{W}{m^2K}\right]$
$\lambda\ \left[\frac{W}{mK}\right]$	$\dot{q}\ \left[\frac{W}{m^2}\right]$

$$\dot{q}_1 = \dot{q}_2$$

$$-\dot{q}_1 = \alpha\,(T_{Face} - T_{amb})$$

$$-\dot{q}_2 = \lambda\frac{\partial T}{\partial \boldsymbol{n}} = \lambda\,\frac{T_{Cell} - T_{Face}}{\delta}$$



- Mathematic treatment of the boundary faces in OpenFOAM®

$$T_{Face} = f \cdot valueExpression + (1-f)(T_{Cell} + gradExpr \cdot \delta^*)$$

$$\alpha\,(T_{Face} - T_{amb}) = k\,\frac{T_{Cell} - T_{Face}}{\delta}$$

$$T_{Face} = \underbrace{\frac{\alpha}{k\left(\frac{\alpha}{k}+\frac{1}{\delta}\right)}}_{f} T_{amb} + \underbrace{\frac{1}{\delta\left(\frac{\alpha}{k}+\frac{1}{\delta}\right)}}_{1-f} T_{cell}$$

- Comparing the first expression with the last one

$$T_{Face} = f \cdot T_{amb} + (1-f)(T_{cell} + \cancelto{0}{gradExpr} \cdot \delta^*)$$

- Mixed boundary condition without gradient expression for convective heat transfer
  Also known as Robinson or Cauchy boundary condition

Mathematic description

❖ Mathematic treatment of the boundary faces in OpenFOAM®

$$\boxed{T_{Face} = f \cdot valueExpression + (1-f)(T_{Cell} + gradExpr \cdot \delta^*)}$$

❖ The LASER is set up with a specific power Q

$$Q = k\ A\ \Delta T$$

$$Q = \frac{\lambda}{\delta} A\,(T_{cell} - T_{Face})$$

$$\frac{(T_{cell} - T_{Face})}{\delta} = \frac{Q}{A\lambda} = \frac{\dot{q}}{\lambda} = \frac{Q \cdot f_{Gauss}}{\lambda}$$

$$\boxed{(T_{cell} - T_{Face})\delta^* = \frac{Q \cdot f_{Gauss}}{\lambda}}$$

Nomenclature

$Q\ [W]$

$k\ \left[\frac{W}{m^2 K}\right]$

$A\ [m^2]$

❖ The final mixed boundary condition that is implemented

$$\boxed{T_{Face} = f\ T_{amb} + (1-f)(T_{cell} + \frac{Q \cdot f_{Gauss}}{\lambda})}$$

Mathematic description

❖ Circular motion of the Gaussian spot center

- ❖ Defining the Gaussian spot center as point
- ❖ Defining the center of rotation as point
- ❖ Defining the angular speed in radian
- ❖ Defining starting time of motion
- ❖ Defining the number of cycles

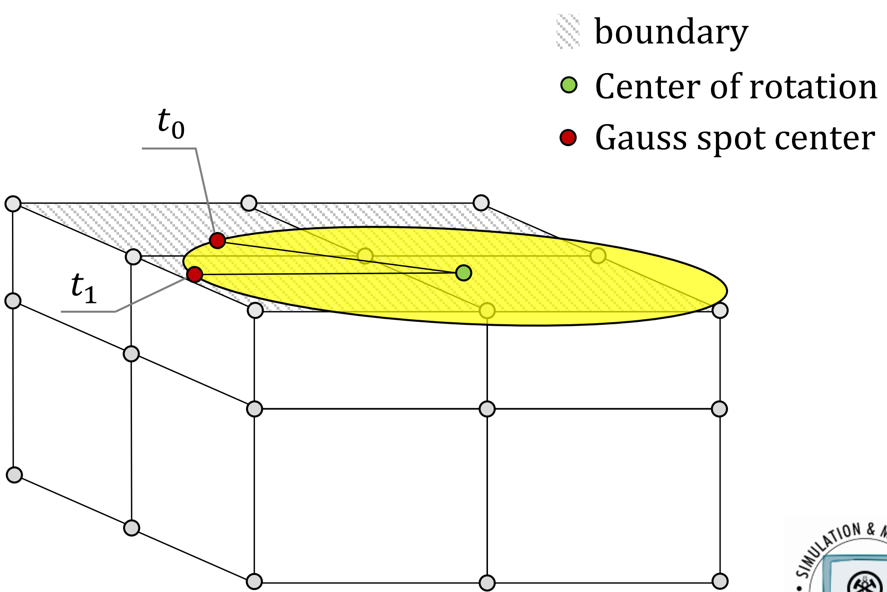
For each time step the Gaussian spot center is updated

$$\Delta x = \cos(\omega + \omega_{t_0})R$$

$$\Delta y = \sin(\omega + \omega_{t_0})R$$

$$\mathrm{x}_{\mathrm{Gauss}_{\mathrm{new}}} = x_{COR} + \Delta x$$

$$\mathrm{y}_{\mathrm{Gauss}_{\mathrm{new}}} = y_{COR} + \Delta y$$



Mathematic description

- Linear motion of the Gaussian spot center

    - Defining a point list that span the linear motion
    - The spot center is set to the first point
    - Defining the linear speed

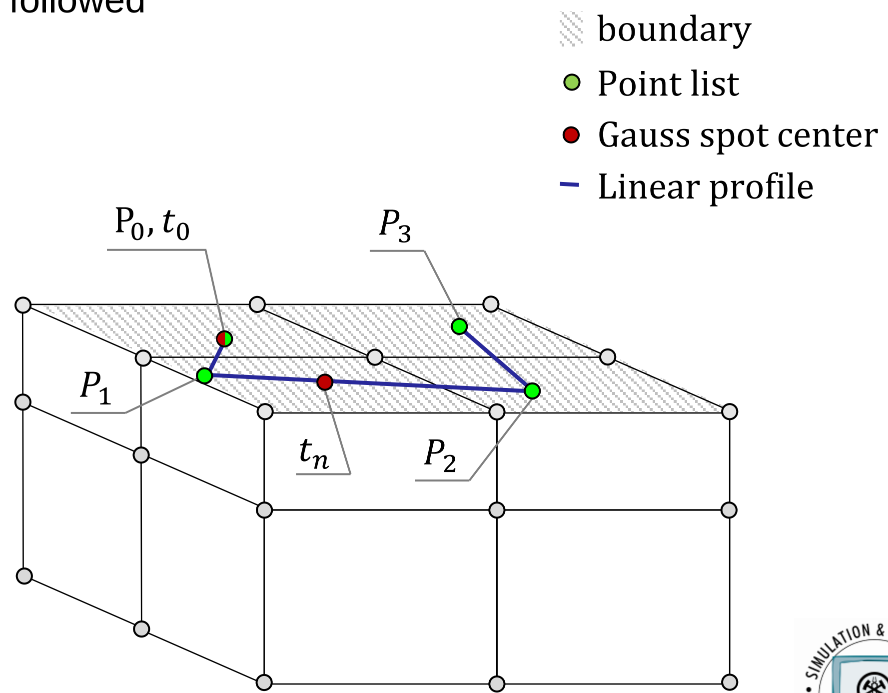
  For each time step the Gaussian spot center is updated

  Any arbitrary figure / schematic can be followed

$$l = \sum |P_{n+1} - P_n|$$

$$t_{P_n,P_{n+1}} = \frac{\sum_{i=0}^{n} |P_{i+1} - P_i|}{U_{LASER}}$$

- Based on the time and the velocity, we know the exact position of the Gauss spot center



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Programming description

- Derived from mixedFvPatchField
- Main functions in the class are

updateSpotCenter()	Motion calculation (change spot center)
updateValueFraction()	Value fraction depend on heating or quenching
updateGaussDistribution()	Recalculate Gauss Distribution if motion is active
updateHeatFluxDistribution()	Calculating the heat flux distribution
updateRefTemperature()	RefTemperature depend on heating / quenching

- Implementing of other distribution functions can be easily done
- For each patch we can create *n* arbitrary LASER sources with subdicts

```
if(dict.isDict(contentOfTable[c])
 {
      //- New source found
      nSources_++;
      .
      .
```

Programming description

❖ Boundary condition set-up for free convection without sources

```
myPatch
{
    type            laserConvection;
    value           uniform 300;

    HTCheating      50;
    HTCquenching    15000;
    TfH             300;
    TfQ             290;
    heatingTime     100;

    powerReduceName none;
    kName           none;
    k               80;
}
```

Programming description

❖ Boundary condition set-up for free convection and LASER sources

```
myPatch
{
    type                laserConvection;
    value               uniform 300;

    HTCheating          50;
    HTCquenching        15000;
    TfH                 300;
    TfQ                 290;
    heatingTime         100;

    mySource1
    {
        power          1000;
        spotCenter     (0 0 0);
        sigmaX         0.03;
        sigmaY         0.03;
        correlation    0;

        motion
        {
            start          2;
            mode           circle;
            center         (0 0.2 0);
            omega          6;
            nCycles        1;
        }
    }

    powerReduceName none;
    kName               lambda;
    lambda              80;
}
```

```
motion
{
    start       0;
    mode        linear;
    points
    {
        p0  (0 0 0);
        p1  (0.1 0.3 0);
        p2  (0.4 0.2 0);
    }
    linearVelocity 0.4;
}
```

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Capabilities and example

- Video https://www.youtube.com/watch?v=u6K8ngHtVTs

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Capabilities and examples

- BC can be used as free convection without any LASER source
- Limited to x-y plane (no coordinate transformation implemented)
- Creating of arbitrary Gaussian LASER profiles within one patch with different settings
- Simple to use and offeres a lot of features like
    - Reducing the LASER power based on some user function
    - Using temperature depended thermal conductivity field
    - Heating and quenching
    - Two different motion modes
    - Arbitrary LASER sources
- Fully explicit. This lead to a time step limit if motion is used

Thank you for your attention

Source Code under https://bitbucket.org/shor-ty/laserconvectionbc

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